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On the Pacific Cod (*Gadus macrocephalus*) in British Columbia Waters, and a Comparison with Pacific Cod Elsewhere, and Atlantic Cod (*G. morhua*)

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by

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ABSTRACT

Westrheim, S. J. 1996. On the Pacific cod (*Gadus macrocephalus*) in British Columbia waters, and a comparison with Pacific cod elsewhere, and Atlantic cod (*G. morhua*). Can. Tech. Rep. Fish. Aquat. Sci. 2092: 390 p.

This report is based on a literature survey, and has two purposes: (1) provide an overview, for the scientific community, of the available information on Pacific cod (Gadus macrocephalus) in the waters off British Columbia, Canada; and (2) compare this information with that for Pacific cod elsewhere, Atlantic cod (G. morhua), and to a limited extent, Greenland cod (G. ogac). General subjects dealt with are nomenclature, distribution, biology, fishery, stock assessment, and abundance prediction. Comparisons with Greenland cod are limited to nomenclature and distribution due to the limited available information on the species, and its minor commercial importance,

Nomenclature. Pacific cod is well differentiated from Atlantic cod, based on physical morphology, biochemical genetics, and karyological genetics, but not so for Greenland cod. Greenland cod may be a precursor of Pacific cod.

Distribution. Pacific and Atlantic cod are transoceanic, at depths of shoreline to 600 m. Southern limits are 34 N lat in the Pacific and northwest Atlantic, and 44 N lat in the northeast Atlantic. Northern limits are 63 N lat in the Pacific, and ~74 N lat in the Atlantic. Greenland cod inhabits the northwest Atlantic (north of 46 N lat) and eastern Arctic ocean (east of 131 W long), off Canada and Greenland, and is commonly found in inshore and estuarine waters.

Biology. Eleven aspects were reviewed: size composition, sex ratio, age determination, age composition, growth, reproduction, early life history, diet, predators, parasites, and pathogenic parasites and diseases. Maximum length reported for Pacific cod was 100 cm off Canada, and 114 cm elsewhere (Russia), compared to ~185 cm (U.S.A.) for Atlantic cod. For both species, length-frequencies are generally multi-modal, and sex ratios among length intervals are approximately 50% males up to about 62-65 cm, but decline sharply to about 18% at 80 cm. No report of a validated age-determination method was found for Pacific cod, although numerous structures have been tried, in Canada and elsewhere. Atlantic cod are aged by otolith cross-sections, and some validation has been reported. Production ageing of Pacific cod off Canada is undertaken with a computerized iterative method applied to length-frequencies. Elsewhere, age-length keys (ALKs) are used in Alaska, and for Atlantic cod, but their validity is questionable, based on empirical tests. Pacific cod generally comprise few age classes (84-95% ages 2-4 off Canada), compared to numerous age classes for Atlantic cod, except in the Baltic and North seas.

Growth was reviewed with respect to length-weight, length-girth, age-length, and age-weight. Pacific cod off Canada are heavier, per length interval, than those off Washington State and Alaska, and Atlantic cod off Canada, Norway, and in the North Sea. They are lighter than Pacific cod off west Kamchatka and in the Yellow Sea, and Atlantic cod in the New York Bight. Girths of Pacific cod were greater than those of Atlantic cod off Canada and in the North Sea. Age-length relationships of Pacific and Atlantic cod varied inversely with latitude. Mean lengths of Pacific cod off Canada were generally larger than those of Atlantic cod at the same latitude. Age-weight relationships were expectedly sigmoidal for both species. Weight-increments of Pacific cod off Canada peaked between ages 3 and 4 in the southern sector, and between 4 and 5 in the northern sector and in the eastern Bering Sea. Comparable values for Atlantic cod were ages 7 and 8 in the eastern Baltic Sea, and 9 and 10 off Norway.

Reproduction was reviewed with respect to spawning, spawning season, length at maturity, and fecundity. Pacific cod are single-batch spawners, while Atlantic cod are multi-batch spawners. Spawning season in the Pacific Ocean is

December-May, but January-December in the Atlantic Ocean. Atlantic cod spawning seasons are relatively short in most individual areas. Length at 50% maturity (L/50) varied by sex, location, and year, for Pacific cod off Canada. L/50 values varied directly with latitude in the northeast Pacific, and were substantially larger in the northwest, off Kamchatka, and the Atlantic (except for the Baltic and North seas). Fecundity at length of Pacific cod off Canada varied little with time or area, and was similar to that off Russia. For Atlantic cod, values varied among areas, and among years within some areas. Fecundities of Norwegian Coastal and West Baltic cod were similar to those of Pacific cod, but those elsewhere were smaller.

Early life history of Pacific cod is not well documented. Pacific cod eggs are demersal, slightly adhesive, and relatively small (1.02 mm diam.). Atlantic cod eggs are pelagic, non-adhesive, and relatively large (1.2-1.6 mm). Distribution of Pacific cod larvae may be demersal or bathypelagic, while Atlantic cod are pelagic. No report was found on duration of the larval stage of Pacific cod.

Diet of Pacific cod larvae is unknown, or unreported. Juveniles and adults of both species are omnivorous, opportunistic, and occasionally cannibalistic (especially Atlantic cod). Diet varies with body length--inversely with invertebrates, and directly with fish. For both species, the "boundary" length between invertebrates and fish is ~50 cm. Depending on location, principal invertebrates are euphausiids, shrimp, and/or crabs, and principal fish species are capelin, cod, flatfishes, herring, salmon fry, sandlance, sardine, and/or walleye pollock. Both Pacific and Atlantic cod were reported to be serious predators on pandalid shrimp. One detrimental diet item for Atlantic cod is a pelagic pteropod (Limacina) which causes odoriferous flesh. One isolated incident was reported for Pacific cod, off Canada.

Predators on Pacific cod eggs are unknown, or unreported. Reported predators on larvae of Pacific cod were hydrozoa and scyphozoa, and for Atlantic cod, copepods, euphausiids, and scyphozoa. Reported predators on juvenile and adult Pacific and Atlantic cod were similar--birds, fish, seals, sealions (Pacific cod), and whales (Atlantic cod). None of the predators on Pacific cod were reported to be serious, and only cannibalism for Atlantic cod.

Parasites on eggs and larvae of both species are unknown, or unreported. For juvenile and adult Pacific cod, 46 parasite species were reported, of which 23 were reported on Pacific cod off Canada. For juvenile and adult Atlantic cod off Canada, 66 species were reported, of which 23 were also reported for Pacific cod. The sealworm (or codworm) was reported for both species, but was only reported to be detrimental to the Atlantic cod fishery.

Diseases and pathogenic parasites involved 34 ailments (14 unnamed)--5 for Pacific cod, and 29 for Atlantic cod. Causative agents were viruses, fungi, bacteria, "protozoa", trematodes, nematodes, amphipods, copepods, and "complexes". None applied to eggs of either species. The only ailment reported for Pacific cod off Canada was parabranchial X-cell lesions, caused by a protistan amoeboid. The ailment was also reported elsewhere in the northeast Pacific, and in the Atlantic. Prevalence was relatively low, except in two areas off western Canada. There, the effects were retarded growth, delayed maturity, and increased mortality rate (Z). Afflicted, tank-held Atlantic cod exhibited retarded gonad development, and a high mortality due to bacterial infections.

Fisheries. Four aspects were reviewed--aboriginal, commercial, and recreational fisheries, and artificial propagation (Atlantic cod only). Aboriginal fisheries records were found for Pacific and Atlantic cod, but were limited to qualitative data. Commercial fisheries for Pacific cod were established relatively recently--~17th Century in Japan; 19th Century in North America; and mid-20th Century in Canada. Corresponding times for Atlantic cod were the 8th Century off Europe, and the 16th Century off North America. Line fisheries predominated, for both species, until the otter trawl became important in the 1920s. FAO began reporting world fisheries statistics in 1958. During 1958-91, peak production for the combined species was 4.0 million tonnes, in

1968--143,00 t of Pacific cod, and 3,867,000 t of Atlantic cod. Subsequently, Pacific cod catch has generally increased (420,000 t in 1991), while Atlantic cod catch has decreased (1,399,000 t in 1991). Pacific cod catch off Canada has rarely exceeded 20,000 t/y. During 1985-91, range of the northeast Pacific cod catch was 140,000-260,000 t/y (increasing), while that for the northwest Pacific was 160,000-270,000 t/y (decreasing). Minor recreational fisheries for Pacific cod were reported for British Columbia and Alaska, and a major fishery (up to 160,000 cod/y) in Washington State. In the Atlantic, a major fishery exists off U.S.A. (1.5-5.0 million cod/y). Lesser fisheries were reported for the Baltic Sea, England, and Norway.

Stock assessment. Aspects reviewed were stock delineation, mortality and exploitation rates, and stock assessment. Stock delineation criteria were similar for both species--tagging, parasites, spawning-ground location, and such biological parameters as growth rate, size at maturity, and spawning time. Stock delineation appears to be reasonably complete in most regions, except for Pacific cod off Alaska.

Total mortality rate (Z) estimates were relatively high for Pacific cod stocks off Canada (1.01-1.63) and Washington State (1.01-1.85), but not in the eastern Bering Sea (0.6). No estimates were found for cod in the northwest Pacific. Comparable estimates for Atlantic cod were also high for most stocks (>1.15). Estimates of M were relatively high off western Canada (0.58-0.78) and Washington State (0.7-0.8), but relatively low (0.22-0.29) in the eastern Bering Sea, according to the most recent estimates. Comparable estimates for Atlantic cod were 0.2-0.3. Exploitation-rate estimates were 0.13-0.35 off western Canada, and 0.1-0.2 elsewhere in the northeast Pacific. Estimates for Atlantic cod were only found for stocks off Canada, 0.18-0.66.

Stock assessments for both species usually involved groups of stocks. Off western Canada, eight (nine?) stocks were grouped into four for assessment. No stock assessment reports were found for cod in the northwest Pacific. Until recently, stock fluctuations in the Pacific were attributed to natural causes. Current analyses suggest that two stocks off Canada, and possibly the stock in the eastern Bering Sea, are now vulnerable to recruitment overfishing, at present levels of fishing effort. In the Atlantic, all important cod stocks are currently assessed to be in critical condition, due to excessive fishing effort. Three of these (Baltic Sea, Iceland, and West Greenland) are also suffering from adverse environmental conditions. Recent substantial reductions in fishing effort imposed on the Arcto-Norwegian stock has resulted in a substantial increase in stock size.

Abundance prediction. Aspects reviewed were: atmospheric and oceanic environments (and their interactions); environment vs recruitment; and long-term abundance prediction. Environmental variability begins with the incoming, and variable, solar energy. The critical point of contact appears to be the tropical Pacific, where energy is transmitted by advection and/or teleconnections to extra-tropical regions. Neither the variations nor the atmosphere-ocean interactions are understood at this time. In the north Pacific, the principal atmospheric factor is the Aleutian Low, at mid-latitude, whose location and strength affects the surface flow of the ocean below it. An eastward location produces a flow of warmer water into the northeast sector, while a westward location produces a flow of warmer water into the northwest sector. Secondary factors in the Pacific are the ENSO events and warm/cold water masses. The former, originating in the tropical Pacific causes a warming of surface waters in the northeast sector. The latter, at mid-latitudes, is suspected of affecting the location and partitioning of the Subarctic Current (West Wind Drift) as it approaches North America--a northern shift produces warmer water off Canada, and vice versa. In the north Atlantic, the principal factor is the Icelandic Low, which produces the same effects as its counterpart in the Pacific. Secondary factors are warm-core rings and the Great Salinity Anomaly. The former, on the shore side of the Gulf Stream, entrain shelf water (containing eggs and larvae in season) and advects it offshore. The latter is an infrequent phenomenon which consists of a vast body of low-saline, cold, water which is formed north of Iceland, and circulates counter-clockwise around the Atlantic Gyre, during

approximately a 14-y period. ENSO events appear to affect the circulation of the north Atlantic, but few details were found.

Environment as a factor in recruitment of cod was first recognized in 1956 for Pacific cod, but in 1914 for Atlantic cod. For both species, the most common environmental factor studied was water temperature, and in each case, recruitment varied directly with temperature poleward, and inversely equatorward. Thus a warmer ocean is detrimental to Pacific cod off Canada, but favourable off Alaska. In the Atlantic, both the warm-core rings and the Great Salinity Anomaly are detrimental to cod--the former due to advection of eggs and larvae off the continental shelf; and the latter to low temperature and salinity. No reports were found which dealt with long-term effects of climate on cod recruitment, but the recent warm period during 1920-60 was shown to favourably affect cod abundance in both oceans.

Few reports were found which predicted abundance of Pacific or Atlantic cod. The "best" was that for Pacific cod in Hecate Strait (Canada) which was based on transport/SSB during the spawning season--55% accurate. For Atlantic cod, tree-ring data were reasonably useful off Norway (to 1958), and salinity/SSB off Labrador-Newfoundland. Global warming was predicted to adversely affect cod abundance in the west Greenland-Gulf of Maine Region.

RÉSUMÉ

Westrheim, S.J. 1996. On the Pacific cod (*Gadus macrocephalus*) in British Columbia waters, and a comparison with Pacific cod elsewhere, and Atlantic cod (*G. morhua*). Can. Tech. Rep. Fish. Aquat. Sci. 2092: 390 p.

Le présent rapport est fondé sur une recherche bibliographique et vise un double objectif : 1) fournir un aperçu, à l'intention de la communauté scientifique, des données existantes sur la morue du Pacifique (*Gadus macrocephalus*) dans les eaux de la Colombie-Britannique au Canada, et 2) comparer ces données avec celles que nous possédons sur cette espèce dans d'autres eaux, sur la morue de l'Atlantique ou morue franche (*G. morhua*), et dans une moindre mesure, sur l'ogac (*G. ogac*). Parmi les thèmes généraux abordés, nous pouvons mentionner la nomenclature, la répartition, la biologie, les pêches, l'évaluation des stocks et les prévisions d'abondance. Dans le cas de l'ogac, les comparaisons ne concernent que la nomenclature et la répartition en raison du peu de données sur cette espèce et de sa faible valeur commerciale.

Nomenclature. La morphologie physique, l'aspect biochimique de la génétique et la caryologie permettent de bien différencier la morue du Pacifique de la morue de l'Atlantique, mais il en est autrement de l'ogac qui serait un précurseur de la morue du Pacifique.

Répartition. La morue du Pacifique et la morue de l'Atlantique sont deux espèces transocéaniques, se tenant à hauteur variable depuis les eaux côtières jusqu'à une profondeur de 600 m. Les limites méridionales de son aire de répartition sont de 34 ° de latitude nord dans le Pacifique et l'Atlantique Nord-Ouest, et de 44 ° de latitude nord dans l'Atlantique Nord-Est. Les limites septentrionales sont de 63 ° de latitude nord dans le Pacifique et d'environ 74 ° de latitude nord dans l'Atlantique. L'ogac vit dans l'Atlantique Nord-Ouest (au nord du 46 ° de latitude nord) et dans la partie est de l'océan Arctique (à l'est du 131 °de longitude ouest), dans les eaux du Canada et du Groenland, et on le rencontre communément dans les zones côtières et estuariennes.

Biologie. L'étude a porté sur onze aspects : la composition selon la taille, la proportion des sexes, la détermination de l'âge, la composition selon l'âge, la croissance, la reproduction, les premiers stades biologiques, le régime alimentaire, les prédateurs, les parasites, et enfin les parasites pathogènes et les maladies. La longueur maximale signalée pour la morue du Pacifique était de 100 cm dans les eaux canadiennes, et de 114 cm ailleurs (Russie) comparativement à environ 185 cm (É.-U.) pour la morue de l'Atlantique. Pour ces deux espèces, les fréquences de longueur sont en général plurimodales; la proportion des sexes dans les intervalles de longueur est d'environ 50 % de mâles jusqu'à 62-65 cm, mais celle-ci chute brusquement à 18 % environ pour une longueur de 80 cm. Aucune mention n'est faite d'une méthode de détermination de l'âge validée pour la morue du Pacifique, bien que de nombreuses structures aient fait l'objet d'études au Canada et ailleurs. Les coupes transversales d'otolithes servent à déterminer l'âge de la morue de l'Atlantique, et certains résultats ont été validés. La détermination de

l'âge des prises commerciales de morue du Pacifique dans les eaux canadiennes est effectuée au moyen d'une méthode informatisée itérative appliquée aux fréquences de longueur. Par ailleurs, des clés âge-longueur sont utilisées en Alaska et pour la morue de l'Atlantique, mais des tests empiriques remettent en question leur validité. En général, la morue du Pacifique compte peu de classes d'âge (84-95 % d'âges 2 à 4 sur les côtes du Canada) comparativement à de nombreuses classes d'âge pour la morue de l'Atlantique, sauf en mer Baltique et en mer du Nord.

La croissance a été analysée en fonction des paramètres suivants : longueur-poids, longueur-circonférence, âge-longueur, âge-poids. Le poids de la morue du Pacifique dans les eaux du Canada est supérieur, par intervalle de longueur, à celui de cette morue dans les eaux de l'État de Washington et de l'Alaska, et de la morue de l'Atlantique dans les eaux du Canada et de la Norvège et en mer du Nord. Son poids est inférieur à celui de la morue du Pacifique dans les eaux de la partie occidentale du Kamtchatka et en mer Jaune, et à celui de la morue de l'Atlantique dans le golfe de New York. La circonférence de la morue du Pacifique est supérieure à celle de la morue de l'Atlantique sur les côtes canadiennes et en mer du Nord. Les relations âge-longueur pour la morue du Pacifique et la morue de l'Atlantique variaient inversement avec la latitude. Les longueurs moyennes de la morue du Pacifique dans les eaux canadiennes étaient en général supérieures à celles de la morue de l'Atlantique à la même latitude. Les relations âge-poids étaient, comme on s'y attendait, de nature sigmoïde pour les deux espèces. Les augmentations de poids de la morue du Pacifique dans les eaux canadiennes étaient maximales entre 3 et 4 ans dans la partie méridionale, et entre 4 et 5 ans dans la partie septentrionale et dans l'est de la mer de Béring. Des valeurs comparables pour la morue de l'Atlantique ont été obtenues pour le groupe de 7 et 8 ans dans l'est de la Baltique et de 9 et 10 ans sur les côtes de la Norvège.

Quant à la reproduction, nous avons étudié les différents paramètres suivants : la fraye, la saison de fraye, la longueur à la maturité et la fécondité. Chez la morue du Pacifique, on observe une seule ponte au cours de la saison, tandis que la morue de l'Atlantique en a plusieurs. Dans l'océan Pacifique, la saison de fraye s'étend de décembre à mai, mais elle va de janvier à décembre dans l'océan Atlantique. La saison de fraye de la morue de l'Atlantique est relativement courte dans la plupart des régions. La longueur à laquelle 50 % du stock atteint la maturité (L/50) variait selon le sexe, l'emplacement, et l'année dans le cas de la morue du Pacifique dans les eaux canadiennes. Les valeurs de la L/50 variaient directement avec la latitude dans le Pacifique Nord-Est, et elles étaient considérablement plus élevées dans le nord-ouest, dans les eaux du Kamtchatka et dans l'Atlantique (à l'exception de la Baltique et de la mer du Nord). En ce qui concerne la fécondité en fonction de la longueur chez la morue du Pacifique, la variation était peu importante en fonction du temps ou de la zone, et elle était semblable à celle de la morue dans les eaux russes. Pour la morue de l'Atlantique, les valeurs différaient d'une région à l'autre, et d'une année à l'autre dans certaines régions. La fécondité de cette morue sur les côtes de la Norvège et dans l'ouest de la Baltique était semblable à celle de la morue du Pacifique, mais celle relevée ailleurs était plus faible.

Nous possédons peu de données sur les premiers stades biologiques de la morue du Pacifique. Ses oeufs sont démersaux, légèrement adhésifs et

assez petits (1,02 mm de diamètre). Les oeufs de la morue de l'Atlantique sont pélagiques, non adhésifs et assez gros (1,2 à 1,6 mm). Les larves de la morue du Pacifique peuvent être démersales ou bathypélagiques, tandis que celles de la morue de l'Atlantique sont pélagiques. Aucune mention n'a été faite relativement à la durée du stade larvaire chez la morue du Pacifique.

Le régime alimentaire des larves de morue du Pacifique est inconnu ou non signalé. Les juvéniles et les adultes des deux espèces sont omnivores, opportunistes, et manifestent parfois une propension au cannibalisme (surtout la morue de l'Atlantique). Le régime varie avec la longueur corporelle - inversement pour les invertébrés et directement pour les poissons. Pour les deux espèces, le seuil de passage des invertébrés aux poissons est d'environ 50 cm. Selon l'endroit, les principaux invertébrés consommés sont les euphausiacés, les crevettes et(ou) les crabes, et les principales espèces de poisson sont le capelan, la morue, les poissons plats, le hareng, les alevins de saumon, le lançon, la sardine et(ou) la goberge de l'Alaska. On a signalé que la morue du Pacifique et la morue de l'Atlantique étaient des prédateurs importants de crevettes Pandalidae. Un ptéropode pélagique (*Limacina*) est un élément néfaste du régime alimentaire de la morue de l'Atlantique car sa consommation donne à la chair une odeur désagréable. On a signalé un cas isolé chez la morue du Pacifique dans les eaux canadiennes.

On ne connaît pas les prédateurs des oeufs de morue du Pacifique ou ceux-ci n'ont pas été signalés. On sait que les hydrozoaires et les scyphozoaires se nourrissent de larves de morue du Pacifique; les larves de morue de l'Atlantique sont au menu des copépodes, des euphausiacés et des scyphozoaires. Les juvéniles et les adultes des deux espèces de morue (Pacifique et Atlantique) sont la proie des mêmes prédateurs - oiseaux, poissons, phoques, otaries (morue du Pacifique) et baleines (morue de l'Atlantique). Aucun des prédateurs de la morue du Pacifique ne présente une menace grave; seul le cannibalisme constitue un danger pour la morue de l'Atlantique.

Les parasites des oeufs et des larves des deux espèces sont inconnus ou ne sont pas signalés. Chez des juvéniles et des adultes de la morue du Pacifique, on a recensé 46 espèces de parasites, dont 23 chez la morue du Pacifique des eaux canadiennes. Chez des juvéniles et des adultes de la morue de l'Atlantique des côtes du Canada, on a dénombré 66 espèces dont 23 se retrouvaient également chez la morue du Pacifique. Le ver du phoque (ou ver de la morue) a été détecté chez les deux espèces, mais il ne présentait un effet néfaste que pour les pêches de la morue de l'Atlantique.

Les maladies et les parasites pathogènes sont à l'origine de 34 affections (14 non déterminées) -- 5 pour la morue du Pacifique, et 29 dans le cas de la morue de l'Atlantique. Les agents responsables étaient des virus, des champignons, des bactéries, des « protozoaires », des trématodes, des nématodes, des amphipodes, des copépodes et des « facteurs complexes ». Aucun ne vise les oeufs d'une espèce ou de l'autre. La seule affection signalée chez la morue du Pacifique dans les eaux canadiennes était des lésions des cellules X parabranchiales causées par un protiste amiboïde. L'affection a également été signalée ailleurs dans le Pacifique Nord-Est et dans l'Atlantique. La prévalence était relativement faible, sauf dans deux zones dans l'ouest du Canada où on a observé un retard de croissance, une maturité retardée et un taux de mortalité (Z) accru. Les morues de

l'Atlantique atteintes et conservées dans un vivier présentaient un retard de développement des gonades et un taux de mortalité élevé en raison d'infections bactériennes.

Pêches. Quatre aspects des pêches ont été étudiés : les pêches autochtones, les pêches commerciales, les pêches sportives et la reproduction artificielle (morue de l'Atlantique seulement). Des registres des pêches autochtones pour la morue du Pacifique et la morue de l'Atlantique ne comportaient que des données qualitatives. Les pêches commerciales de la morue du Pacifique sont assez récentes : elles remontent au XVII° siècle au Japon, au XIX° siècle en Amérique du Nord et n'existent que depuis le milieu du XX° siècle au Canada. Les périodes correspondantes pour la morue de l'Atlantique étaient le VIII° siècle en Europe, et le XVI° siècle dans les eaux de l'Amérique du Nord. Jusqu'à ce que la pêche au chalut à panneaux s'impose dans les années 1920, les deux espèces étaient pêchées à la ligne. C'est en 1958 que la FAO a commencé à publier des statistiques sur les pêches à l'échelle mondiale. Entre 1958 et 1991, la production maximale des espèces combinées atteignait 4,0 millions de tonnes en 1968 (143 000 t pour la morue du Pacifique et 3 867 000 t pour la morue de l'Atlantique). Par la suite, les prises de morue du Pacifique ont augmenté en général (420 000 t en 1991), tandis que celles de morue de l'Atlantique ont diminué (1 399 000 t en 1991). Les prises de morue du Pacifique dans les eaux canadiennes ont rarement dépassé 20 000 t par année. Entre 1985 et 1991, la plage de captures de cette espèce dans le Pacifique Nord-Est se situait entre 140 000 et 260 000 t par année (en hausse), tandis que celles dans le Pacifique Nord-Ouest variaient entre 160 000 et 270 000 t par année (en baisse). La morue du Pacifique en Colombie-Britannique et en Alaska est faiblement exploitée par les pêcheurs sportifs; par contre, dans les eaux de l'État de Washington, on relève une forte activité (jusqu'à 160 000 morues par année). Dans l'Atlantique, on observe d'importantes captures dans les eaux américaines (1,5 à 5,0 millions de morues par année). Une exploitation de moindre importance a été enregistrée dans la Baltique, en Angleterre et en Norvège.

Évaluation des stocks. La délimitation des stocks, les taux de mortalité et d'exploitation et l'évaluation des stocks étaient les aspects examinés. Les critères de délimitation des stocks étaient les mêmes pour les deux espèces, soit le marquage, les parasites, l'emplacement des frayères, et des paramètres biologiques comme le taux de croissance, la taille à maturité et la période de reproduction. Il semble que la délimitation des stocks soit assez complète dans la plupart des régions, sauf en ce qui concerne la morue du Pacifique dans les eaux de l'Alaska.

Les estimations du taux de mortalité totale (Z) étaient relativement élevées en ce qui concerne les stocks de morue du Pacifique dans les eaux canadiennes (1,01-1,63) et au large de l'État de Washington (1,01-1,85), mais pas dans la partie orientale de la mer de Béring (0,6). Nous ne disposons d'aucune estimation pour la morue dans le Pacifique Nord-Ouest. Des estimations comparables pour la morue de l'Atlantique présentaient aussi des valeurs élevées pour la plupart des stocks (> 1,15). Les estimations de M étaient assez élevées dans les eaux de l'ouest du Canada (0,58-0,78) et de l'État de Washington (0,7-0,8), mais relativement faibles (0,22-0,29) dans l'est de la mer de Béring, selon les plus récentes estimations. Dans le cas de la morue de l'Atlantique, les estimations étaient comparables (0,2-0,3). Dans l'ouest du Canada, on estimait les taux d'exploitation entre 0,13 et 0,35

et entre 0,1 et 0,2 ailleurs dans le Pacifique Nord-Est. Les seules estimations disponibles concernaient les stocks de morue de l'Atlantique dans les eaux canadiennes (0,18-0,66).

Les évaluations de stocks pour les deux espèces intéressaient en général des groupes de stocks. Dans les eaux de l'ouest canadien, huit (neuf?) stocks étaient regroupés en quatre stocks aux fins de l'évaluation. On ne dispose d'aucun rapport d'évaluation des stocks pour la morue dans le Pacifique Nord-Ouest. Jusque tout récemment, les fluctuations des stocks dans le Pacifique étaient attribuées à des causes naturelles. D'après les analyses courantes, il semble que deux stocks des eaux canadiennes et probablement le stock de la partie est de la mer de Béring soient maintenant vulnérables à la surpêche du potentiel reproducteur, aux niveaux actuels de l'effort de pêche. À l'heure actuelle, tous les stocks importants de morue dans l'Atlantique sont considérés dans un état critique en raison d'un effort de pêche excessif. Trois de ceux-ci (mer Baltique, Islande et ouest du Groenland) sont également victimes de mauvaises conditions environnementales. En raison des réductions considérables de l'effort de pêche récemment imposées pour le stock arcto-norvégien, on a enregistré une forte augmentation des effectifs.

Prévisions de l'abondance. Les études ont porté sur les milieux atmosphérique et océanique (et leurs interactions); l'environnement par rapport au recrutement, et les prévisions à long terme de l'abondance. La variabilité environnementale commence avec l'apport variable d'énergie solaire. Il semble que le point de contact critique se trouve dans l'océan Pacifique tropical, où l'énergie est transmise par advection et (ou) par des téléconnexions à des régions extra-tropicales. En ce moment, on ne comprend ni les variations ni les interactions entre l'atmosphère et l'océan. Dans le Pacifique Nord, le principal facteur atmosphérique est la dépression des Aléoutiennes, aux latitudes moyennes, dont la situation et la force agissent sur l'écoulement superficiel de l'océan sous-jacent. Si elle se trouve à l'est, elle produit un écoulement d'eau chaude vers le secteur nord-est, tandis que si elle se trouve vers l'ouest, elle engendre un écoulement d'eau chaude vers le secteur nord-ouest. Les phénomènes ENSO et des masses d'eau chaude et d'eau froide sont des facteurs secondaires observés l'océan Pacifique. Le premier, qui prend naissance dans l'océan Pacifique tropical, provoque un réchauffement des eaux superficielles dans le secteur nord-est. Quant à l'autre facteur, observé aux latitudes moyennes, il est soupçonné de modifier l'emplacement et le fractionnement du courant subarctique (dérive due aux vents d'ouest) lorsqu'il approche de l'Amérique du Nord - un décalage vers le nord produit un réchauffement des eaux canadiennes, et *vice versa*. Dans l'Atlantique Nord, le principal facteur est la dépression d'Islande, qui produit les mêmes effets que son équivalent dans le Pacifique. Les anneaux à noyau chaud et la grande anomalie de salinité sont des facteurs secondaires. Le premier, que l'on observe du côté continental du Gulf Stream, entraîne les eaux de la plate-forme (dans lesquelles se trouvent les oeufs et les larves en saison) et par advection les emporte au large. L'autre facteur, phénomène rare, touche une immense masse d'eau froide de faible salinité formée au nord de l'Islande et qui circule dans le sens inverse des aiguilles d'une montre autour du courant giratoire de l'Atlantique, pendant une période d'environ 14 ans. Les phénomènes ENSO affecteraient la circulation des eaux dans l'Atlantique Nord, mais nous possédons peu de détails à ce sujet.

C'est en 1956 que l'on admettait, pour la première fois, que l'environnement était un facteur de recrutement de la morue du Pacifique, mais il était reconnu depuis 1914 dans le cas de la morue de l'Atlantique. Pour les deux espèces, la température de l'eau était le facteur environnemental le plus communément étudié, et dans chaque cas, le recrutement variait directement avec la température vers les pôles, et inversement vers l'équateur. Donc, des eaux océaniques chaudes sont néfastes pour la morue du Pacifique dans les eaux canadiennes, mais favorables dans les eaux de l'Alaska. Dans l'océan Atlantique, les anneaux à noyau chaud et la grande anomalie de salinité sont nocifs pour la morue - le premier en raison de l'advection qui éloigne les oeufs et les larves de la plate-forme continentale, et l'autre, à cause de la basse température et de la faible salinité. Nous ne possédons aucun rapport sur les effets à long terme du climat sur le recrutement de la morue, mais la dernière période chaude, entre 1920 et 1960, a eu un effet favorable sur l'abondance de la morue dans les deux océans.

Peu de rapports prévoyaient une abondance de la morue du Pacifique ou de la morue de l'Atlantique. La meilleure prévision concernait la morue du Pacifique dans le détroit d'Hécate (Canada); elle reposait sur le transport et la biomasse du stock reproducteur pendant la saison de fraye (précision à 55 %). Pour ce qui est de la morue de l'Atlantique, des données des anneaux de croissance ont été assez utiles dans le cas des eaux norvégiennes (jusqu'en 1958), et les données sur la salinité et la biomasse du stock reproducteur pour les eaux du Labrador et de Terre-Neuve. On a prédit que le réchauffement global aurait des effets néfastes sur l'abondance de la morue dans la région de l'ouest du Groenland et le golfe du Maine.

1. INTRODUCTION

Pacific cod (Gadus macrocephalus) is one of the important species in the groundfish fishery off western Canada. Virtually all of the catch is taken by demersal (on-bottom) trawls. Although the modern trawl fishery in British Columbia began in the 1940s, cod landings were relatively unimportant until the late 1950s. Subsequently, Pacific cod increased irregularly in importance.

As is often the case, research activity reflects relative importance of fishery resources. Canadian scientific reports dealing directly with Pacific cod have increased steadily since 1959--26 during 1960-69, 42 during 1970-79, and 73 during 1980-89. However, 64% (90) were sub-publications, most with limited distribution.

In the author's opinion, sufficient information is now available to justify a summary of the information available on Pacific cod in the waters off western Canada. The purpose of this report is to provide the scientific community with such an overview, as well as comparisons with Pacific cod elsewhere, and Atlantic cod (G. morhua). The general subjects dealt with are nomenclature, distribution, biology, fishery, stock assessment, and abundance prediction.

2. MATERIALS AND METHODS

2.1 MATERIALS

Principal sources of information have been scientific reports published in journals, and sub-publication series such as data reports, manuscript reports, and technical reports. Rarely used were internal documents of national and international agencies, or any other reports which required the author's permission to cite. Scientific names of North American species have been taken from Robins (1991).

Geographical illustrations have been minimized, largely to reduce the publication cost. Appropriate marine fisheries statistical areas, and various subdivisions, were used as reference points wherever possible. For the northeast Pacific Ocean, two sets were used in this report. Figure 2.1 shows the 17 statistical areas (1A-5E), for the California-British California Region, established by the Pacific Marine Fisheries Commission (PMFC), and now more often referred to as International Statistical Areas (ISAs). Figure 2.2 shows the 11 areas (Conception-Shumagin) created by the International North Pacific Fisheries Commission (INPFC) for the California-Gulf of Alaska Region. In both cases, additional areas to the northward were not included here.

The north Atlantic Ocean has two sets of statistical units--one each for the northeast and northwest sectors. Their common boundary is 42 W long, except for a minor anomaly at the south tip of Greenland. Figure 2.3 shows the ICES Area, its 14 subareas (I-XIV), and associated divisions and subdivisions, created by the International Council for the Exploration of the Sea. Divisions are designated by lower-case letters, and subdivisions by Arabic numbers. Figure 2.4 shows the ICNAF/NAFO Area, its seven subareas (0-6), and associated divisions and subdivisions, created by the International Commission for the Northwest Atlantic Fisheries (ICNAF), and maintained by its successor, the Northwest Atlantic Fisheries Organization (NAFO). Divisions are designated by upper-case letters, and subdivisions by lower-case letters.

Bibliographies and synopses utilized were those of Wise (1963), Margolis (1969), Margolis and Arthur (1979), Dewar et al. (1983), Harrison et al. (1984), and Westrheim and Miller (1987). The present study includes reports published through 1993, where possible.

2.2 METHODS

This report is organized into nine independent chapters--Introduction, Materials and Methods, Nomenclature, Distribution, Biology, Fisheries, Stock Assessment, Abundance Prediction, and Summary and Discussion. Each chapter has its own Literature Cited section, if appropriate, but pagination is continuous throughout the report.

2.3 ACKNOWLEDGMENTS

The author is grateful to the following for providing publishable copies of the four figures cited in this chapter: Groundfish Staff, Pacific Biological Station (Figure 2.1); Secretariat, International Council for the Exploration of the Sea, Charlottenlund, Denmark (Figure 2.3); Secretariat, International North Pacific Fisheries Commission. Vancouver, B.C., Canada (Figure

2.2); and Secretariat, Northwest Atlantic Fisheries Organization, Dartmouth, Nova Scotia, Canada (Figure 2.4).

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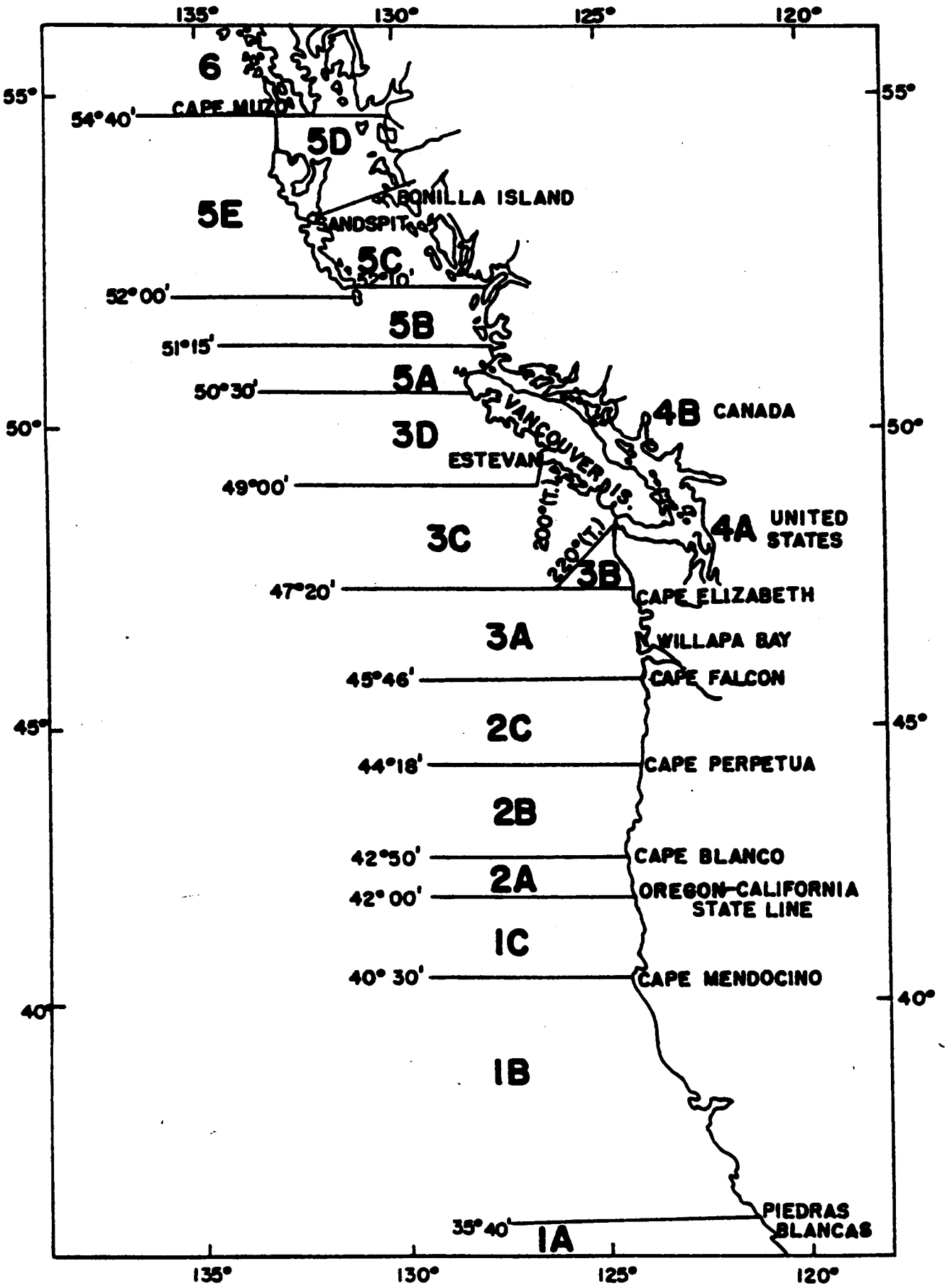


Fig. 2.1. PMFC groundfish statistical areas in the California-British Columbia Region.

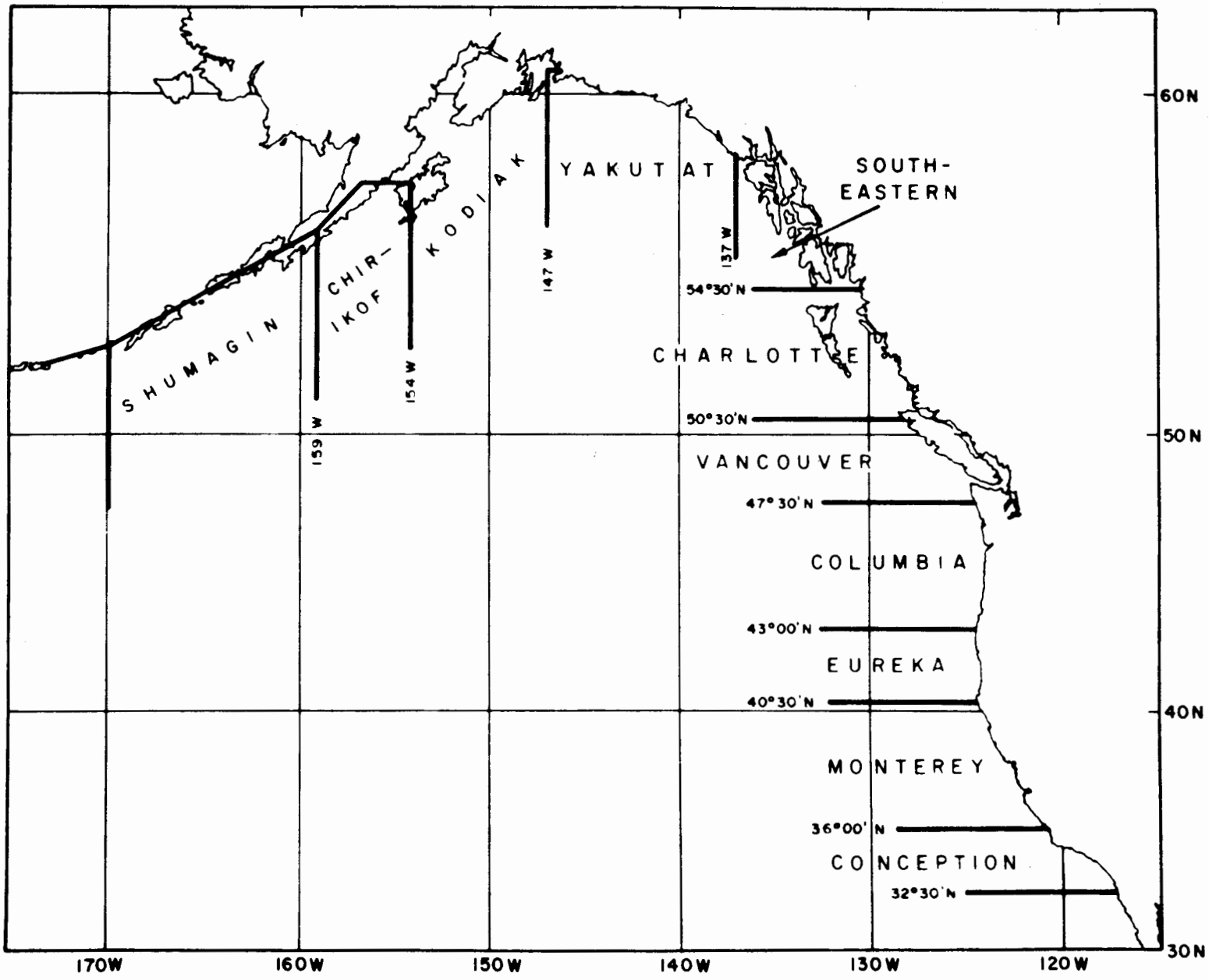


Fig. 2.2. INPFC groundfish statistical areas in the California-Gulf of Alaska Region.

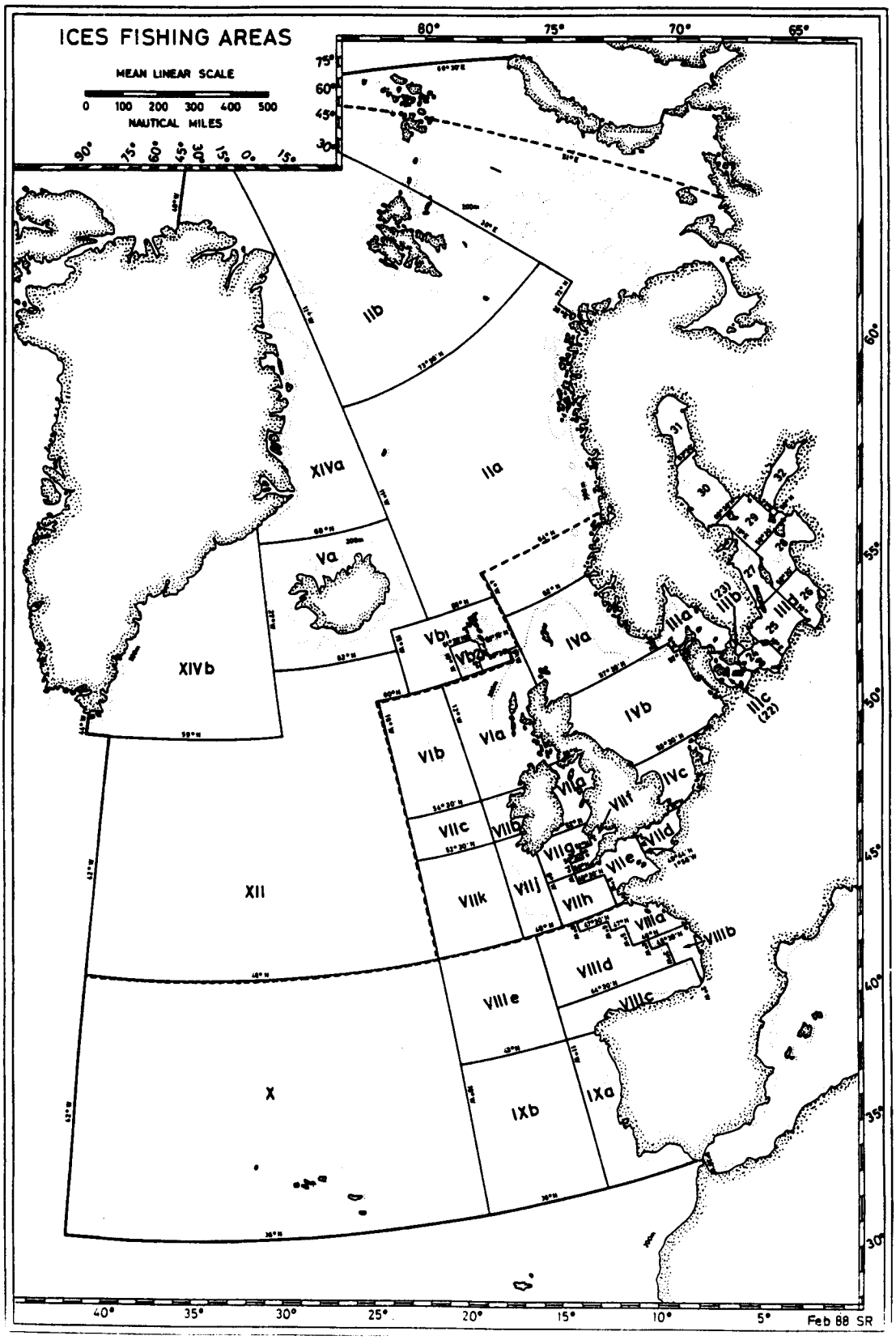


Fig. 2.3. Marine fisheries statistical subareas, divisions, and subdivisions, of the ICES Area, northeast Atlantic Ocean.

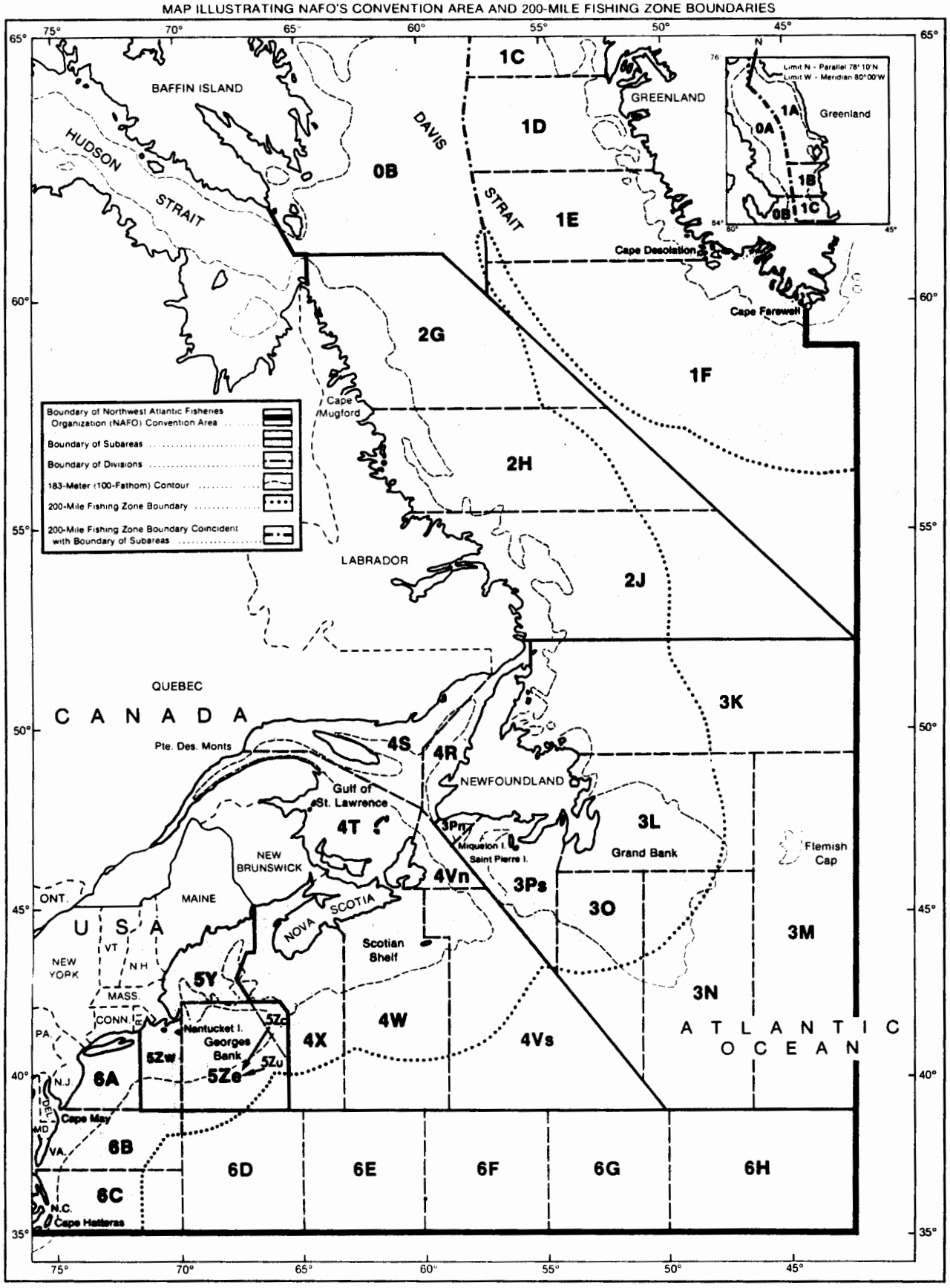


Fig. 2.4. Marine fisheries statistical subareas, divisions, and subdivisions, in the NAFO/ICNAF Area, northwest Atlantic Ocean.

3. NOMENCLATURE

INTRODUCTION

Nomenclature of Pacific cod has varied substantially since the species was first described by Tilesius (1810). A relatively recent cladistic hierarchy of fishes, down to genus, was reported by Nelson (1984). Following is an abbreviated form of his analysis:

Phylum:	Chordata
Class:	Osteichthyes
Order:	Gadiformes
Family:	Gadidae
Subfamily:	Gadinae
Genus:	Gadus

Gadinae (cod and haddock) contains 12 genera, including Gadus, Microgadus, and Theragra which are present in British Columbia waters (Hart 1973). Merluccius, the other genus common to British Columbia shelf waters, is the sole occupant of the related family Merluccidae.

The generic name, Gadus, was proposed by Linnaeus (1758), for the Atlantic cod (G. morhua), and has remained unchallenged.

For Atlantic cod, the scientific name is now accepted as G. morhua, but in the past was also reported as G. morhua morhua (Svetovidov 1948); G. callarias, and G. morrhua (misspelled)(Cohen 1959).

For Pacific cod, the scientific name is now accepted as G. macrocephalus, as described by Tilesius (1810). Synonymies were published by Svetovidov (1948), and Wilimovsky et al. (1967), which together listed ten additional scientific names applied to this species--from G. morhua (W. Pacific Ocean) and G. pygmaeus (E. Pacific Ocean) of Pallas (1811) to G. morhua macrocephalus of Berg (1933), Svetovidov (1948), McAllister (1960), and Lindberg and Legeza (1965) (Table 3.1). Among Canadian checklists and books, three scientific names have been used: G. callarias (Vladykov 1933); G. morhua macrocephalus (McAllister 1960); and G. macrocephalus (Halkett 1913; Clemens and Wilby 1946, 1949, and 1961; Hart 1973).

Essentially, the remaining controversy involves whether the Pacific cod is a unique species, or merely a subspecies of the Atlantic cod, as proposed by Svetovidov (1948).

Despite the controversy involving the taxonomic status of the Pacific cod, no problems appear to be present with respect to distinguishing it from other gadoid species in the north Pacific Ocean. Hart (1973) provided a recent, and satisfactory, key to the adult marine gadoids of western Canada, based largely on external physical morphology. Keys based on scales and/or otoliths were prepared by Casteel (1979) and Morrow (1979). Larvae identification has been dealt with by Dunn and Vinter (1984), and Walters (1984). Tsuyuki et al. (1965) differentiated Pacific cod from walleye pollock (Theragra chalcogramma) and Pacific tomcod (Microgadus proximus) on the basis of starch-gel electrophoresis of muscle myogen proteins.

The remainder of this section will deal with the evidence available to resolve the controversial status of the scientific name of Pacific cod, viz., physical morphology, biochemical genetics, and karyological genetics.

3.1 PHYSICAL MORPHOLOGY

Six substantive studies were reviewed which compared the physical morphology of Pacific cod with that of Atlantic and/or Greenland cod (Gadus ogac).

Schultz and Welander (1935) produced the first comprehensive study of the distinctness of Pacific cod. They examined Gadus specimens collected from Japan, Alaska-California, Greenland, and Europe (Figs. 3.1, 3.2); reviewed the limited efforts of Bean (1881), Jordan and Evermann (1898), Vladykov (1933), Bigelow and Walsh (1925), and Cobb (1927); and concluded that the important distinguishing features were not the size of head or size of the air bladder. Instead, they proposed five key features: (1) length and amount of coiling of the two anterolateral horns of the air bladder; (2) color of the peritoneum; (3) length of the depressed dorsal fin; (4) color around the margins of the dorsal and caudal fins; and (5) length of the barbel. Results of their comparisons are shown in Table 3.2. They further noted that "Gadus macrocephalus does not seem to differ from G. morhua or G. ogac in regard to the number of fin rays, vertebrae or numerous measurements involving various parts of the body and fins" (op. cit., p. 132). Of further interest were their specimens from Japan which seemed to differ from the Alaska and Puget Sound specimens "chiefly in having a shorter barbel, a longer dorsal fin, a darker lateral line, a more slender body in the adult, and possibly a wider interorbital space" (op. cit., p. 133). They noted that Tilesius' specimens from Kamchatka were the "common Alaska codfish", based on his illustrations, and declined to "pass judgement on the Japanese form" pending examination of Russian literature on Arctic cods. However, they expressed the opinion that "our specimens from Japan are somewhat intermediate between G. ogac and G. macrocephalus, as the latter is represented by specimens from the northeastern Pacific Ocean.

Svetovidov (1948) recognized one species of Gadus (morhua), and six subspecies--G. m. callarias, G. m. kildinensis, G. m. macrocephalus, G. m. marisalbi, G. m. morhua, and G. m. ogac. He discounted the analysis of Schultz and Welander(1935) because they relied on the shape of the air-bladder horns, whose structure, he stated "is most closely associated with the habitat of the cod" (op. cit., p. 172). His basic morphological character was the skull shape, and he divided his subspecies into two groups, narrow heads and broad heads. The Atlantic cod belonged to the former group, while the Greenland and Pacific cod belonged to the latter group. In his diagnostic key to the subspecies he listed the Atlantic cod under "Head narrow, interorbital space represents 15-22% of head length"; and listed Greenland and Pacific cod under "Head broad, interorbital space constituting 18-25% of its length" (op. cit., p. 173). Greenland and Pacific cod were distinguished by the caudal peduncle depth, and body color: "Caudal peduncle deep, about 4.5-5% of body length. Coloration usually dark." for Greenland cod; and for Pacific cod, "Caudal peduncle somewhat lower, 3.5-4.5% of body length. Coloration paler." (op. cit., p. 174). Svetovidov (op. cit.) also noted that cod from the Japan Sea "differs from the Bering Sea cod by its much shorter barbel and some other features" (op. cit., p. 191), albeit based on a small number of specimens available to him. He further noted that the "restriction of Pacific cod to a narrow range in its habitat and its limited migrations offer broad possibilities for formation of local forms" (op. cit., p. 191), and cited some examples in the northwest Pacific Ocean.

Mukhacheva and Zviagina (1960) noted that although adult Pacific cod were poorly differentiated externally from Atlantic cod, they were "easily distinguished in the early stages of development" (op. cit., p. 29). Pacific cod eggs were demersal rather than pelagic; not transparent; and smaller (mean diameter = 1.0 mm vs 1.46 mm). Pacific cod larvae possessed less pigmentation, in the early stages, and their pigmented bands were longer.

Vladykov et al. (1985) were the first to compare the breeding tubercles of the Atlantic, Greenland, and Pacific cod. Tubercles differed

substantially between the three species[1] "few and very small" on Pacific cod; "numerous, medium in length, and horn-shaped" on Atlantic cod; and "numerous, long, and club-shaped" on Greenland cod (op. cit., p. 608). These descriptions suggest a substantial difference in breeding behaviour between the Pacific cod and the other two species. Pacific cod eggs are demersal in British Columbia waters (Thomson 1963), and in the western Pacific Ocean (Mukhacheva and Zviagina 1960), while Atlantic cod eggs are pelagic (Mukhacheva and Zviagina op. cit.). Greenland cod eggs are demersal and slightly adhesive, according to unpublished studies during 1958-60 (Dr. Holger Hovgard; Greenland Fisheries Research Institute; Copenhagen, Denmark; pers. comm. 28 June 1988). Furthermore, Hansen (1949) noted that demersal eggs were collected during February-March in Disko Fjord which were definitely "gadoid", and were assumed to be those of the Greenland cod.

Renaud (1989a) noted that the shape of the testicular lobes appeared to be a diagnostic character separating Pacific cod from Greenland cod, but not Greenland cod from Atlantic cod. He found that testicular lobes were unindented (smooth) in three ripe specimens of Pacific cod collected from the northeastern Pacific Ocean, off Canada (southwest coast of Vancouver Island, British Columbia). In contrast, the testicular lobes of Greenland cod were crenate (scalloped) in several specimens collected in the Arctic Ocean, off northern Canada (Cambridge and Bathurst bays, Northwest Territories), and in the northwest Atlantic Ocean, off Canada (Labrador and Gulf of St. Lawrence) (Vladykov 1972). His observations were corroborated by those of Renaud (op. cit.) on one specimen from Bathurst Inlet, N.W.T., and seven from the Labrador coast. Vladykov (op. cit.) reported that the testicular lobes of Atlantic cod collected off Newfoundland and Nova Scotia were smooth. However, Renaud (op. cit.) reported that condition of the lobes was variable for this species. Lobes were crenate in two of three specimens from Labrador, two of two from Nova Scotia, and two of two from the Baltic Sea. He cautioned that condition of testicular lobes might be variable in Pacific and Greenland cod as well.

Renaud (1989b) analyzed morphometrics, meristics, and miscellaneous characters. The latter consisted of: pigmentation of body, fins, and ovary; lateral line shape and interruption point; origin of first anal fin relative to dorsal fins; origin of second anal fin relative to dorsal fins; caudal fin shape; nuptial tubercles; shape of testicular lobes; gas-bladder horns; and drumming and retractor dorsalis muscles. His analyses involved Gadus specimens representing the six putative sub-species of Svetovidov (1948). Specimens were collected from a wide selection of warm, temperate, and arctic regions of the Northern Hemisphere. With some exceptions, the data were subjected, after suitable transformations, to principal coordinates analysis and canonical discriminant analysis, for specimens >= 100 mm SL. Results indicated that the genus Gadus likely comprised three species: G. macrocephalus, G. morhua, and G. ogac. The author synonymized callarias (Baltic Sea), kildinensis (Barents Sea), and marisalbi (White Sea) with morhua, but added that for the latter two, synonymization remains an hypothesis.

The characters excluded from the above analysis were nuptial tubercles (breeding tubercles of Vladykov et al. 1985), testicular lobes, gas-bladder horns, drumming muscles, and retractor dorsalis muscles--all discussed below.

Nuptial tubercles

The study provided additional information to that reported by Vladykov et al. (1985) and Renaud (1989a) with respect to frequency of occurrence between the three species now recognized, by sex and length. Nuptial tubercles were detected with the naked eye in 9% of Pacific cod specimens (N = 55), 12% for

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[1] The authors referred to the "three known species of Gadus" as macrocephalus, morhua, and ogac.

Atlantic cod (N = 91), and 76% for Greenland cod (N = 50). Presence of tubercles was not dimorphic in any of the specimens. In both Atlantic and Greenland cod specimens, tubercles were present in some small individuals, 230 and 222 mm SL, respectively. Also unique was the absence of tubercles in large specimens of Atlantic cod.

Testicular lobes

The study provided additional data (for specimens >= 300 mm SL) from that reported by Vladykov (1972) and Renaud (1989a), from a wider range of localities for the three species. Four additional specimens of Pacific cod possessed smooth lobes--two from southern California, and one each from the eastern and western Bering Sea. Twelve additional specimens of Atlantic cod were examined--one from Baffin Island, three from the Baltic Sea, and eight from the White Sea. Eight exhibited smooth lobes, and four exhibited scalloped lobes. Overall ratio from Atlantic cod (N = 23) was 65% smooth and 35% scalloped. Ten additional specimens of Greenland cod were examined, and all had scalloped lobes. Distribution of samples ranged from Baffin Island southward to New Brunswick.

Gas-bladder horns

The study found that the relative length of the horns was useful to separate Pacific cod from Atlantic cod, but not from Greenland cod. In Renaud's Table 14, the ratios of horn length/SL, in percent, were reported as follows:

Species (mm SL)	N	Mean	Range	No. of horns
macrocephalus (319-913)	8	4.3	2.3-5.7	16
morhua (438-529)	2	9.3	5.9-12.3	4
ogac (276-512)	3	5.2	3.7-6.9	6

He concluded that the arrangements of gas-bladder horns were not taxonomically useful at the specific level.

Drumming and retractor dorsalis muscles

The author reported that these muscles were not taxonomically useful at the specific level.

3.2 BIOCHEMICAL GENETICS

Five published reports were reviewed which compared the biochemical genetics of Pacific cod with Greenland and/or Atlantic cod.

Sick (1965) compared the hemoglobin types of Atlantic cod (2282 specimens) collected from the North Sea to eastern North America; Greenland cod (N = 207) from west Greenland; and Pacific cod (N = 77) from Puget Sound, Washington State (northeast Pacific Ocean). He reported that both the Greenland

cod and the Pacific cod differed from the Atlantic cod, but were indistinguishable from one another.

Mackie and Ritchie (1981) utilized protein electrophoresis and isoelectric focusing, of muscle myogen proteins, to investigate differences between Atlantic cod, haddock (Melanogrammus aeglefinus), and Pacific cod. They concluded that the three species were readily differentiated either by electrophoresis or isoelectric focusing. Furthermore, with reference to Atlantic and Pacific cod, they suggested that "differences between the patterns of these two types of cod are of the order of those found between separate species rather than variants of a single species" (op. cit., p. 173). They discounted Svetovidov's (1948) subspecies differentiation because his criteria were known to be "affected by the environment and that reliance on morphological data only can be inadequate for identification of a particular form or variant of cod" (op. cit., p. 174).

Renaud et al. (1986) conducted an allozyme analysis of four subspecies recognized by Svetovidov (1948), viz., Atlantic cod, Baltic cod (G. m. callarias), Greenland cod, and Pacific cod. Specimens were collected from the Baltic Sea (Baltic cod), Labrador-Strait of Belle Isle (Atlantic and Greenland cod), and Gulf of Alaska (Pacific cod). The analysis involved 13 enzymes encoded by 21 presumptive gene loci. Based on a phenogram (UPGMA) of mean genetic distances (D; Nei 1972) between the four subspecies, they concluded that Atlantic and Baltic cod were "specifically distinct" from Greenland and Pacific cod (D = 0.48), but that they could not "reject conspecificity" between the Atlantic and Baltic cod (D = 0.00), or between Greenland and Pacific cod (D = 0.00) (op. cit., p. 1563). However, the sympatric samples of Atlantic and Greenland cod from the Strait of Belle Isle indicated no gene flow between the two "groups".

Grant (1987) summarized results of isozyme analyses applied to temperate and tropical congeneric fishes from the Atlantic and Pacific oceans. For Atlantic and Pacific cod, they reported that average interspecies distance (D) was 0.390 (op. cit., Table 9.2)--large enough to reject conspecific status. Results for the other three temperate-water "pairs" were: herring (Clupea), D = 0.264; halibut (Hippoglossus), D = 0.123; and Greenland halibut (Reinhardtius hippoglossoides), D = 0.013.

Grant and Stahl (1988) employed allozyme analysis to the gene products of 41 protein-coding loci of Atlantic and Pacific cod. Their specimens were collected from the Baltic Sea, Georges Bank (northwest Atlantic), Bering Sea (northeast Pacific), and the northwest Pacific Ocean. Results indicated that Atlantic and Pacific cod were separate species, based on cluster analysis of genetic distances between populations .

3.3 KARYOLOGICAL GENETICS

Renaud (1989a) noted that karyological data provided some evidence for rejecting conspecificity of Atlantic and Pacific cod. Nygren et al. (1974) reported the modal diploid count (kidney cells) of 2N = 46, and a haploid count of N = 23 (testes), for Atlantic cod specimens collected off the west coast of Sweden. Ishii and Yabu (1985) reported the modal diploid count (gill and fin tissues) to be 2N = 44, for a single female specimen of Pacific cod collected off northern Japan (Usujiri, Hokkaido).

3.4 SUMMARY

Pacific cod has been well differentiated from Atlantic cod, based on physical morphology, biochemical genetics, and karyological genetics. However, differentiation from Greenland cod is not well established at this time. Of the

five physical criteria of Schultz and Welander (1935), shape of the air-bladder horns and color of the peritoneum failed to delineate the two species. Furthermore, hemoglobin analyses (Sick 1965) and allozyme analyses (Renaud et al. 1986) failed to differentiate the two species, although they differentiated both from Atlantic cod. The lack of differentiation between Pacific cod and Greenland cod is a minor problem in nomenclature. Should the Greenland cod prove to be conspecific with Pacific cod, it would have to be renamed G. macrocephalus on the basis of priority, as Greenland cod was described later (Richardson 1836). Moiseev (1953) concluded that Greenland cod was at least the precursor of Pacific cod.

Of some interest was the corroboration, via allozyme analysis of 41 loci (Grant et al. 1987), of the suggestion by Schultz and Welander (1935) that the Pacific cod in Japanese waters were "different" from those in the northeast Pacific Ocean (Bering Sea to Washington State). Genetic distance (D) was 0.025 between Asiatic and North American samples; 0.0041 between Asiatic samples; and 0.0007 between North American samples.

3.5 ACKNOWLEDGMENTS

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Table 3.1. Synonymy of Pacific cod (*Gadus macrocephalus* Tilesius 1810). (Sources: Svetovidov 1948; Wilimovsky *et al.* 1967; this study)

Name	Year	Author
G. morhua (N. America & Kamchatka)	1811	Pallas
G. pygmaeus (N. America)	1811	Pallas
G. pseudomorhua	1873	Bleeker
G. auratus	1873	Cope
G. brandti	1875	Hilgendorf
G. callarias	1892	Eigenmann & Eigenmann
G. callarias var. *macrocephalus*	1904	Smitt
Pollachius brandti	1913-14	Jordan & Metz
G. callarias macrocephalus[a]	1931	Rendahl
G. morhua macrocephalus	1933	Berg
	1948	Svetovidov
	1960	McAllister[b]
	1965	Lindberg & Legeza[b]

a. Listed only by Svetovidov (1948).
b. Listed only by this study.

Table 3.2. Key physical features selected by Schultz and Welander (1935) to delineate Atlantic, Greenland, and Pacific cod.

Feature	Atlantic cod	Greenland cod	Pacific cod
Horns of the air bladder	long, slender, flexible[a]	same as Pacific cod	short, stout, non-flexible
Color of the peritoneum	leaden silvery, black stippling	same as Pacific cod[b]	brownish black to jet black
Length of depressed first dorsal fin	extends considerably behind origin of second dorsal fin; overlaps ca. 1/6 to 1/4 its own length	similar to Atlantic cod	extends barely to origin of second dorsal fin rarely beyond and never by 1/6 its own length
Color of fins	distal margins of all vertical fins, except anals, not whitish	similar to Atlantic cod	distal margins of all vertical fins whitish
Length of barbel (adults only)[c]	shorter than eye	intermediate; equal to, or longer than eye[d]	longer than eye

a. At "about six inches in length, the horns differ little from those of Pacific cod 18 to 24 inches in length." (op. cit., p. 131)

b. The authors noted that this was an added character to the six which Dresel (1884) used to clearly distinguish Greenland cod from Atlantic cod.

c. For juvenile Atlantic and Pacific cod, barbel is equal to or a little shorter than the eye.

d. Cited by the authors from Kendall (1909, p. 239).

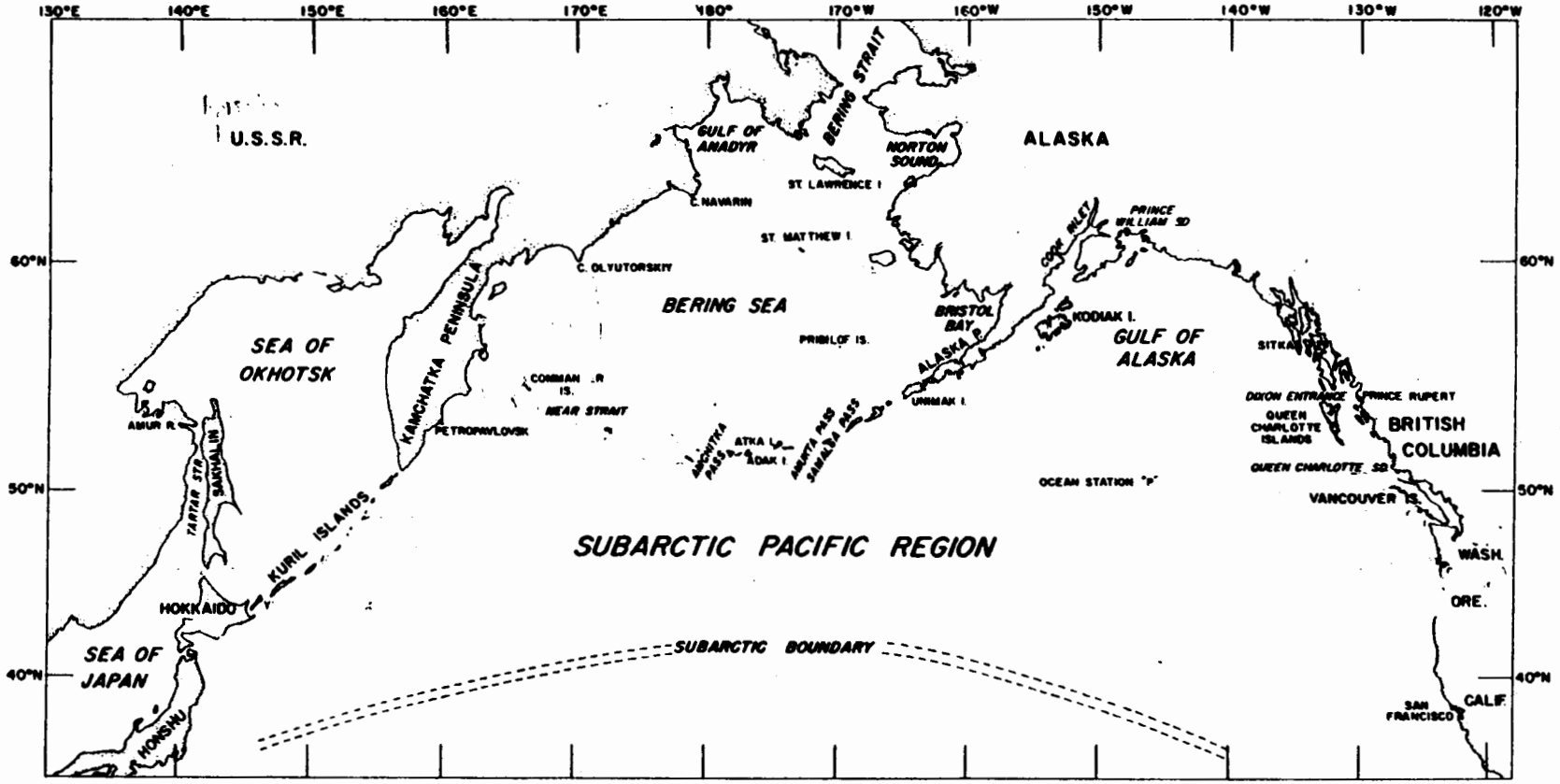


Fig. 3.1. Map of the north Pacific Ocean, and adjacent seas. (Adapted from the Frontispiece in Favorite et al. 1976)

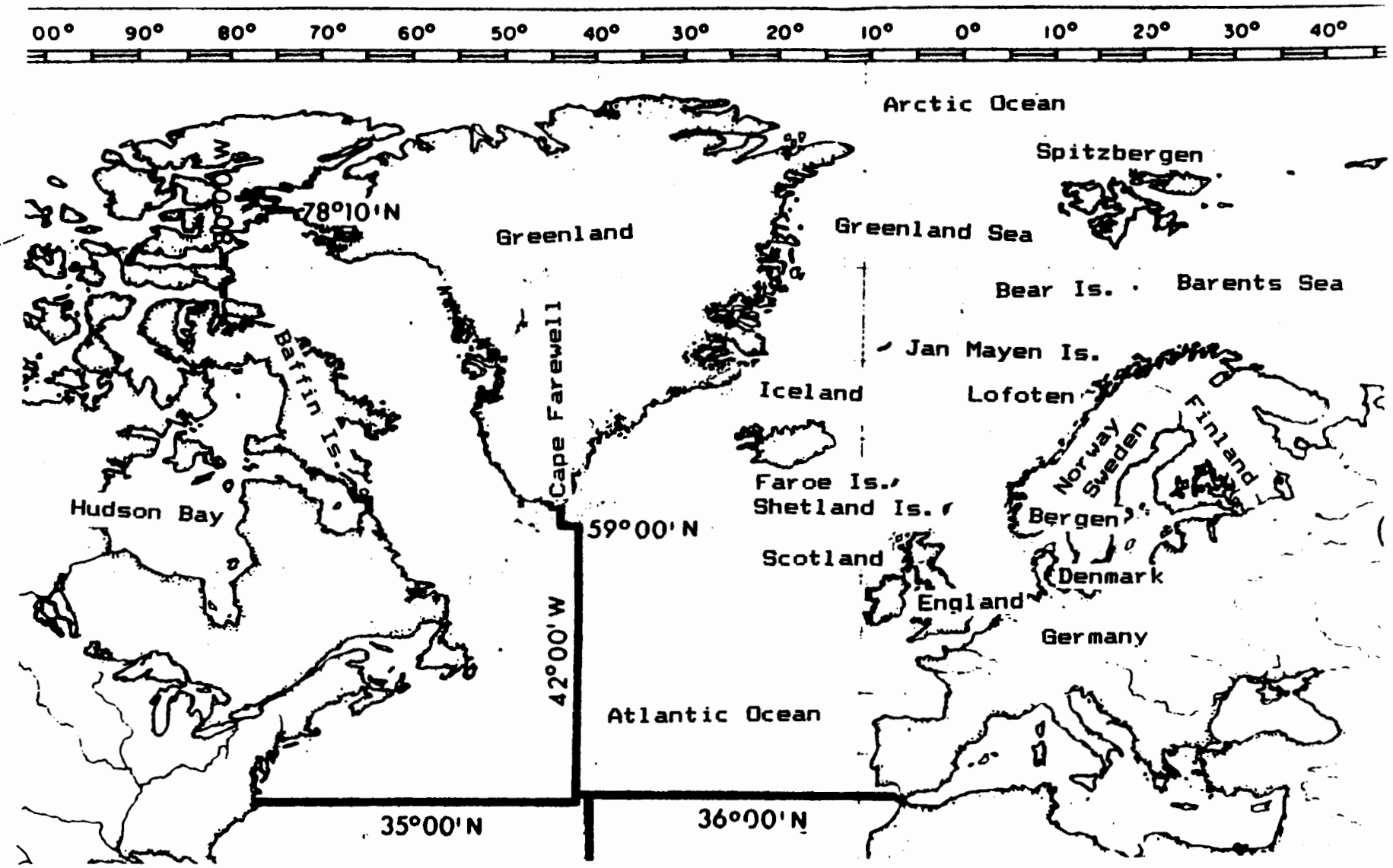


Fig. 3.2. Map of the north Atlantic Ocean, and adjacent seas. (Adapted from the map in FAO 1992)

4. DISTRIBUTION

INTRODUCTION

This chapter deals with the geographic and bathymetric distributions of Pacific, Atlantic, and Greenland cod. Primary emphasis is placed on Pacific cod.

4.1 GEOGRAPHIC DISTRIBUTION

PACIFIC COD

Adults and Juveniles

Hart (1973) reported the geographic range as Santa Monica, California, U.S.A., to Port Arthur (Yellow Sea), Peoples Republic of China, including the Aleutian Islands, Bering Sea, and Chukchi Sea (Fig. 3.1). Bakkala et al. (1984) noted the same southern range limit (34 N lat) on both the North American and Asian coasts, but reported the northern limit to be St. Lawrence Island and Norton Sound (ca. 63 N lat) (Figure 4.1). Neither Alverson et al. (1964, Fig. 55) nor Sample and Wolotira (1985) reported catches in the Chukchi Sea, nor did any of the references cited by Hart (op. cit.). Andriashev (1937, p. 80) specifically stated that Pacific cod were "absent from all hauls north of St. Lawrence Island." Maximum depth reported off North America was 875 m, with 98% of occurrences at <300 m (Allen and Smith 1988).

Eggs and Larvae

Geographical distribution of eggs is probably limited to the individual spawning grounds, because the eggs are demersal and slightly adhesive, based on laboratory studies in Japan (Kamiya 1925[1]; Inaba 1931[1]; Yamamoto and Nishioka 1952), Korea[1] (Uchida 1935[1]), Russia (Mukhacheva and Zviagina 1960), and Canada (Thomson 1963). However, this may not be true for the larvae. No reports were found which dealt with drift of eggs or larvae.

British Columbia and vicinity. Two field studies, both unsuccessful, were undertaken to locate cod eggs. The first took place on a major spawning ground off southwest Vancouver Island, using an underwater camera and bottom grab (Westrheim et al. 1977). The second took place on a shallower spawning ground, off Port Townsend, Washington, Juan de Fuca Strait (Fig. 4.2), using SCUBA divers (Karp 1982). Also at the Port Townsend study site, a benthic sled-net caught larvae lying just off the bottom, at 5-11 m, in a nearby, shallow inlet (Walters 1984).

The only successful catch of cod eggs was fortuitous, and resulted from field tests, in Georgia Strait, of a new, demersal sled-type sampler (Phillips and Mason 1986). Cod eggs were reportedly caught at several stations in Baynes Sound (near Comox). Sand grains were adhering to the chorion, and substrates at the catch sites were coarse sand and cobble.

A review of reports dealing with Canadian ichthyoplankton and/or midwater-trawl surveys yielded little information on Pacific cod (Tables 4.1, 4.2). These studies were undertaken in the Strait of Georgia, coastal waters,

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[1] Cited by Yamamoto and Nishioka (1952).

and offshore waters well beyond the continental shelf. They were aimed primarily at catching eggs and larvae of commercially important fishes, or determining the occupants of echo-scattering layers. Juvenile specimens were also caught on occasion. Eggs, larvae, and/or juveniles of other gadoids, Pacific hake (Merluccius productus) and walleye pollock (Theragra chalcogrammus), were frequently caught, but in all cases, catches of Pacific cod larvae were small to nil, and no eggs or juveniles were caught.

Elsewhere. In the western Gulf of Alaska, during 1972-85, ichthyoplankton surveys yielded catches of larvae, but none of eggs or juveniles (Rugen and Matarese MS 1988[2]). Larvae were widely distributed over the continental shelf, but few were caught seaward of the 200-m isobath, and none seaward of 2000-m isobath.

Off Siberia, Mukhacheva and Zviagina (1960) also reported catches of larvae, but none of eggs or juveniles. No information on geographical distribution was reported.

ATLANTIC COD

Adults and Juveniles

Geographic range spans the north Atlantic Ocean, from Cape Lookout, North Carolina, U.S.A. (34° 34' N lat), to the Bay of Biscay, Portugal (ca. 44 N lat), including Greenland, Iceland, Barents Sea, North Sea, and Baltic Sea (Fig. 3.2) (Scott and Scott 1988).

Eggs and Larvae

Eggs are pelagic, and both eggs and larvae of some stocks drift substantial distances between spawning and rearing areas (Wheeler 1969; Scott and Scott 1988) (see Section 7.1. Stock Delineation).

GREENLAND COD

Adults and Juveniles

Geographic distribution is limited to the northwest Atlantic and Arctic oceans. It overlaps that of Atlantic cod, but not of Pacific cod. The southern range limit is Cape Breton, Nova Scotia (ca. 46 N lat) (Scott and Scott 1988), and the northwestern limit is Eskimo Lakes, N.W.T. (69° 34' N lat x 131° 15' W long) (Renaud 1989). The northwestern range limit lies ca. 2,000 km east of the northeastern limit of Pacific cod, based on museum specimens reported by Hunter et al. (1984). Renaud (op. cit.) dismissed previous limits of Point Barrow, Alaska (Leim and Scott 1966), and Point Barrow to Smith Bay (Walters 1955) for lack of evidence--"no voucher specimen originally and no confirmatory record since" (op. cit., p. 66).

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[2] Rugen, W. C. and A. C. Matarese. MS 1988. Spatial and temporal distribution and relative abundance of Pacific cod (Gadus macrocephalus) larvae in the western Gulf of Alaska. U.S. Nat. Mar. Fish. Serv., Northwest and Alaska Fisheries Center, Seattle, Washington. Proc. Rep. 88-18: 53 p.

Eggs and Larvae

Eggs are believed to be demersal, but no formal confirmation has been published. Although no published reports were found which described the distribution of eggs or larvae, spawning season is in winter (Jensen 1948[3]; Morin et al., 1991) when the ocean is covered with ice. Seemingly, conditions are not conducive to extensive drifting of either eggs or larvae.

4.2 BATHYMETRIC DISTRIBUTION

PACIFIC COD

Adults and Juveniles

Pacific cod occupy the continental shelf and upper slope off North America and Asia (Hart 1973).

British Columbia. Hart (1973) reported the maximum depth of capture to be 300 fath (550 m). Further details were obtained from the results of surveys (beach-seine, purse-seine, and demersal trawl) and commercial landing statistics.

Survey locations were Georgia Strait (Area 4B), Burke Channel (a fjord at the east end of Area 5B), and Hecate Strait (Areas 5C+5D) (Fig. 2.1). Sampling gears were beach seine, pelagic purse-seine, and/or demersal trawls. In Georgia Strait, surveys with pelagic purse-seines and beach-seines yielded negligible catches of cod during 1972-76 (Table 4.3). Target species were Pacific hake, walleye pollock, and/or salmonids. Pacific cod were absent in all catches, except three purse-seine sets near Nanaimo (Fig. 4.2). No more than two or three cod were caught per set, and lengths were not recorded.

In Burke Channel, purse-seine surveys undertaken to study parasite incidence in juvenile pink salmon (Oncorhynchus gorbushcha) also yielded catches of juvenile Pacific cod, Pacific sandlance (Ammodytes hexapterus), juvenile lingcod (Ophiodon elongatus), and Pacific herring (Clupea harengus pallasi) (Arai 1969). Quantities caught were not reported.

In Hecate Strait, surveys were conducted with pelagic purse-seines and demersal trawls. During July-August 1986-87, purse seines were used to survey salmonid and other pelagic species (Healy and Morris 1989). No cod were caught. Catches consisted of Pacific herring, rockfish (Sebastes spp.), sablefish (Anoplopoma fimbria), salmon (five species of Oncorhynchus), and spiny dogfish (Squalus acanthias).

Demersal-trawl surveys were undertaken in two series in Hecate Strait. The first, during August 1980-81 and April 1982-85, was designed to measure the relative and absolute abundance of juvenile flatfish, primarily English sole (Pleuronectes vetulus) and rock sole (Pleuronectes bilineata), over a depth range of 10-79 fath (18-145 m) (Fargo and Westrheim 1986). Catches of Pacific cod were too small to delineate the depth distribution of juveniles or adults. The second series, during February-March 1986 and May-June 1984 and 1987, was designed to investigate species assemblages over a depth range of 10-79 fath (18-145 m) (Fargo and Tyler 1989). Catch rates, by 10-fath depth interval, ranged from 5 to 211 cod/haul for the three surveys (Table 4.4). Modal catch

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[3] Cited by Morin et al., 1991.

rates occurred at 20-29 fath (167-211 cod/haul) in each survey; at 50-59 fath in February-March 1986 (121) and May-June 1987 (133); and at 60-69 fath in May-June 1984 (15). No explanation was offered for the bimodalities in catch rate. Catches during February 1986 consisted primarily of juvenile cod (~<50 cm) throughout the bathymetric range of the survey (Fig. 4.3). Catches of adult cod were small, but relatively larger beyond 59 fath. During May-June 1984 and 1987, juvenile and adult cod were distributed throughout the bathymetric range. However, the smaller cod (~<32 cm) were more prevalent at 10-49 fath.

Landing statistics were employed in three studies to delineate the bathymetric distribution of Pacific cod. Alverson (1960), using records of U.S. trawlers, noted that cod occupied shallower depths during spring-summer than during autumn-winter. Ketchen (1961), using records of Canadian trawlers, correlated the seasonal bathymetric migrations to water temperature, and concluded that the "preferred" temperature range was 7-9 C off southern British Columbia (Areas 3C and 4B), and 6-7 C off northern British Columbia (Areas 5A-5D). Westrheim and Tagart (1984) used the trawl landing statistics for British Columbia (1954-78) and Washington State (1967-78) for important areas off British Columbia and the northwest coast of Washington State. Results corroborated those of Alverson (op. cit.) and Ketchen (op. cit.) (Fig. 4.4). The migration to deeper water coincided with seasonal warming of the shallower waters during autumn and winter (Lane 1963; Crean 1967; Dodimead 1980). The anomalous migration off southwest Vancouver Island, to shallower water during autumn-winter, was not discovered until a fishery for spawning cod developed in the late 1960s. This inshore concentration was due to cooling of inshore waters by an alongshore, northward-flowing cold current (Lane op. cit.). Bathymetric distribution of cod in Queen Charlotte Sound (Areas 5A+5B) was not well delineated, because of extensive untrawlable bottom in shallower water, and minimal fishing effort (and landings) during autumn and winter due to adverse weather and the lack of nearby safe harbors.

Temperature was not the only factor in the bathymetric distribution of cod in British Columbia waters. Westrheim and Tagart (1984, Table 5) noted a bimodal distribution of commercial trawl catches in May, as follows:

Area	Year	Modal Depth (fath)	Landings (t)	Bottom Temperature (C)
3Cn	1978	40-49	111	8.1
		80-89	85	6.8
		50-59	134	7.9
		70-79	68	7.3
5A + 5B	1979	40-49	95	7.0
		70-79	73	6.7

No explanation for the phenomenon was provided.

Elsewhere. Bathymetric distributions of cod were reported for the Gulf of Alaska (Alverson et al. 1964; Zenger and Thompson 1989), eastern Bering Sea (Bakkala 1984; Bakkala et al. 1986), West Kamchatka and northwest Sea of Japan (Moiseev 1953), northern Japan (Mishima 1984), and South Korea (Zhang 1984). All were based on demersal-trawl surveys.

In the Gulf of Alaska, catch rates of cod during exploratory trawling expeditions varied inversely with depth, among depth intervals of 1-49 fath (2-90 m) to 200-299 fath (366-547 m) (Alverson et al. 1964, Table 82). A similar bathymetric cline was reported for the western Gulf, during the 1984 and 1987 U.S.-Japan cooperative bottom-trawl surveys (Zenger and Thompson (1989).

In the eastern Bering Sea, juvenile cod inhabited nearshore waters during their first year of life, and thereafter moved into deeper water (Bakkala

1984). The major concentration of cod occurred at 20-69 fath (37-126 m). Cod age-4 and older were mainly found on the outer continental shelf and upper slope. The author reported a seasonal migration to deeper water during winter. However, some cod were found at 450 m throughout the year.

Off West Kamchatka, Moiseev (1953) reported a seasonal migration inshore during summer, and a bi-modal bathymetric distribution during June-August. Peak depths were 250 m in January-February (27.8 centners/haul)[4] and March (4.5 c/haul)[4]; 50 m (67.1 c/haul) and 100 m (52.1 c/haul) in June: 50 m (49.3 c/haul) and 150 m (6.2 c/haul) in July-August; and 150 m in October (7.5 c/haul) and December (28.0 c/haul) (op. cit., Table 3). A similar phenomenon was noted for the northwestern Sea of Japan, albeit with substantially smaller catch rates (op. cit., Table 9). The two simultaneous bathymetric groups of cod were categorized "littoral" and "deep". Littoral cod comprised primarily post-spawners, with numerous large females, in relatively poor condition. Deep cod comprised primarily non-spawners, in good condition.

Off northern Japan, Mishima (1984) reported a seasonal migration inshore to spawn, and bathymetric bimodality--"bank" and "offshore". The bank cod were ages 3-6, and in relatively good condition, while the offshore cod were ages 2-5, and in relatively poor condition.

Off South Korea, Zhang (1984) reported seasonal migrations primarily to escape warm water temperatures. Off the east coast, tagged cod migrated northward in spring, and southward in autumn. Off the west coast, cod migrated into deeper waters during summer.

Eggs and Larvae

British Columbia and vicinity. Available data were inadequate to delineate the bathymetric distribution of eggs or larvae. Of interest was the report of larvae found near the bottom of a shallow inlet near Port Townsend, Washington (Fig. 4.2) (Walters 1984).

Elsewhere. In the western Gulf of Alaska, during 1972-85, results of ichthyoplankton surveys indicated that cod larvae began rising in the water column shortly after hatching, and eventually reached the upper 45 m of the water column (See Footnote 2). Larvae size varied inversely with depth of capture, and only very small larvae were caught near the bottom. Some corroboration was found in the laboratory observations by Yamamoto and Nishioka (1952, p. 15) who reporteed "larvae rising to the surface 3 days after hatching".

Off eastern U.S.S.R., Mukhacheva and Zviagina (1960) reported a scarcity of material on depth distribution of larvae, and no catches of eggs or juveniles. In one case they found larvae in the water column off Cape Shipun, where catches increased with depth: 4 (12-16 mm) at 0-25 m; 13 (11-19 mm) at 25-50 m; and 18 (10-23 mm) at 50-88 m (op. cit., Table 8). Depth of water at the sampling site was not reported.

ATLANTIC COD

Adults and Juveniles

Atlantic cod are bathypelagic, and occupy the continental shelf and upper slope (Wheeler 1969; Scott and Scott 1988). Depth range is shoreline to at least 600 m in the northeast Atlantic, and to 457 m in the northwest Atlantic.

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[4] One centner = 100 g.

Depth distribution is variable throughout the geographic range, and is probably affected by season, temperature, and food.

Eggs and Larvae

Eggs and larvae are pelagic (Wheeler 1969; Scott and Scott 1988). Metamorphosis occurs pelagically. Demersal life begins at a length of ca. 2 cm, usually in inshore waters, in the northeast Atlantic, and 2.5-5.0 cm in the northwest Atlantic.

Of some interest, was the discovery in 1869 that Atlantic cod eggs were pelagic (Sars 1869). Before then, Atlantic cod eggs were assumed to be demersal, because other important commercial species, such as herring, laid demersal eggs (Mukhacheva and Zviagina 1960). In the Pacific Ocean, the opposite situation occurred as studies began in the 20th Century. Since Atlantic cod eggs were, by then, known to be pelagic, the Pacific cod eggs were assumed to be pelagic (Rass and Zheltenkova 1948[5]; Clemens and Wilby 1946, 1949, 1961), until demonstrated otherwise by Yamamoto and Nishioka (1952) in the northwest Pacific, and Thomson (1963) in the northeast Pacific. Early records of pelagic cod eggs were due in part to misidentification of walleye pollock eggs (Mukhacheva and Zviagina op. cit.). Indeed, they noted that while Kamiya (1925) demonstrated that in the laboratory fertilized cod eggs were demersal, he also reported that in plankton catches free-floating eggs were caught.

GREENLAND COD

Adults and Juveniles

Scott and Scott (1988) reported the bathymetric distribution to be mostly inshore and estuarine. Renaud (1989) listed specimens collected in 175 m (Labrador) and 260 m (west Greenland), as well as in shallow water, 2-50 m. In Hudson Bay, Greenland cod appeared to be distributed primarily from shoreline to 35 m, with a migration into estuaries in winter (Mikhail and Welch 1989; Morin et al. 1991).

Eggs and Larvae

No reports were found which dealt with the bathymetric distribution of eggs or larvae.

4.3 SUMMARY

Geographical ranges of adult and juvenile Pacific and Atlantic cod were similar. Both were trans-oceanic, and the southern limits were ca. 34 N lat, except 44 N lat in the northeast Atlantic. Northern limit was greater for Atlantic cod--ca. 74 N lat vs 63 N lat. Geographic range of Greenland cod, the closer relative to Pacific cod, was the northwest Atlantic, off west Greenland and Canada, and in the Arctic Ocean, off Canada.

Geographical distribution of Pacific cod eggs, which are demersal and slightly adhesive, is probably limited to the vicinity of the individual spawning grounds. Atlantic cod eggs, in contrast, are pelagic, and in some cases eggs drift considerable distances from the spawning grounds to the nursery areas.

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[5] Cited by Mukhacheva and Zviagina (1960).

Greenland cod eggs are probably demersal, and hence their distribution is likely to be similar to that of Pacific cod.

Pacific cod larvae may be semi-pelagic, but results from the few reports found were contradictory. In the Gulf of Alaska, larvae were largely found on the continental shelf. Atlantic cod larvae are also involved in the spawning ground-nursery area migration, which can be considerable in some cases.

Bathymetric range of adult and juvenile Pacific and Atlantic cod was the continental shelf and upper slope--shoreline to ca. 600 m. Both species usually occupied deeper water during autumn and winter, but temperature appeared to be the primary factor in determining the distribution. Seasonal migrations were usually substantially greater for Atlantic cod. Greenland cod were mostly found inshore, and moved into shallower, and estuarine, areas during autumn-winter. However, some specimens were collected as deep as 260 m off west Greenland.

The limited information available on Greenland cod precluded any further discussion in this report. The first bibliography, to the author's knowledge, on Greenland cod was prepared by Nielsen and Morin (1993).

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Table 4.1. Presence of larval and/or juvenile Pacific cod, Pacific hake, and walleye pollock, in catches, by time, gear, and source during pelagic surveys in Georgia Strait and Saanich Inlet, 1960-81.

Year	Month	Gear[a]	Catch[b] C	H	P	Source
			Georgia Strait			
1962	Feb,May, & Jul[c]	MWT	-	+	+	Barraclough & Herlinveaux (1965)
1966	Apr	ST	-	+	+	Barraclough (1967a)
		IK	-	+	+	Barraclough (1967b)
	Jun	ST	-	+	-	Barraclough (1967c)
	Jul	ST	-	-	-	Barraclough & Fulton (1967)
1967	Feb-May	IK	-	-	-[d]	LeBrasseur et al. (1969)
	May	ST	-	+	+	Robinson et al. (1968a)
	Jun	ST	-	+	+	Robinson et al. (1968b)
	Jul	ST	-	+	-	Robinson (1969a)
1968	Apr	ST	-	+	+	Robinson (1969b)
1981	Feb-Mar	BN	+	+	+	Mason et al. (1982a)
	Mar-May	BN	+	+	+	Mason et al. (1982b)
	May-Jun	BN	-	+	+	Mason et al. (1982c)
			Saanich Inlet			
1060	Oct	MWT	-	-	-	Herlinveaux (1962)
1961	Mar	MWT	-	+	+	Barraclough & Herlinveau (1961)
1962	Jan,May	MWT	-	+	+	Barraclough & Herlinveau (1965)

Table 4.1. (cont.)

Year	Month	Gear[a]	Catch[b] C	H	P	Source
1966	Jun-Jul	ST	-	+	-	Barraclough & Fulton (1968)
1968	Apr-Jul	ST	+	+	+	Barraclough et al. (1968)
1974	Feb	MWT	-	+	+	Westrheim (1974)

a. BN = bongo net--oblique hauls; IK = Isaacs-Kidd trawl--surface haul; MWT = midwater trawl--horizontal haul through echo-scattering layer; ST = two-boat surface trawl.

b. C = Pacific cod; H = Pacific hake; P = walleye pollock; - = absent; + = present.

c. Only off the Ballenas Islands.

d. Catches nil or insignificant. Detailed records not provided.

Table 4.2. Presence of larval and/or juvenile Pacific cod, Pacific hake, and walleye pollock, in catches, by time, gear, and source, during pelagic surveys in offshore waters of British Columbia, 1956-59 and 1980.

Year	Month	Gear[a]	Catch[b]			Source
			C	H	P	
1956-59	--	NN	-	-	-	LeBrasseur (1970)
1980	Jan	BN	-	+	+	Mason et al. (1981a)
	Feb	BN	-	+	+	Mason et al. (1981b)
	Mar	BN	-	+	+	Mason et al. (1981c)
	Apr	BN	-	+	+	Mason et al. (1981d)

a. BN = bongo net--oblique hauls; NN = Norpac net--mostly vertical hauls.

b. C = Pacific cod; H = Pacific hake; P = walleye pollock; - = absent; + = present.

Table 4.3. Presence of juvenile Pacific cod, Pacific hake, and walleye pollock, in seine catches, by time, gear, and source, during pelagic and shoreline surveys in Georgia Strait, 1972-76.

Year	Month	Gear[a]	Catch[b] C	H	P	Source
1972-73	Jul-Mar	PS[c]	-	-	+	Parker & Kask (1974)
1974	Jul-Aug	PS[d]	-	-	-	Beamish et al. (1976)
1975-76	Jul-Aug	BS	-	-	-	Schmidt et al. (1978a)
		BS	-	-	-	Schmidt et al. (1978b)
1975	Jul-Aug	PS-50	+	-	+	Schmidt et al. (1978c)
		PS-120	-	-	+	Schmidt et al. (1978d)
1976	Jun	PS-50	-	-	-	Schmidt et al. (1979)

a. BS = beach seine; PS = purse seine; PS-50 = 50-fath (92-m) seine; PS-120 = 120-fath (220-m) seine.

b. C = Pacific cod; H = Pacific hake; P = walleye pollock; - = absent; + = present.

c. Two types of purse seines: (1) ca. 434 m long, 31 m deep; fishes ca 1.50 ha; (2) 137 m long, 8 m deep; fishes ca. 0.74 ha.

d. 402 m long, 33 m deep; fishes ca. 6.36 ha.

Table 4.4. Catch rates (no./haul), by 10-fath (18-m) depth interval, of Pacific cod caught during demersal trawl surveys in Hecate Strait, February-March 1986, and May-June 1984 and 1987.

Depth interval (fath)	February-March 1986[a]		May-June 1984[b]		1987[c]	
	N/haul	hauls	N/haul	hauls	N/haul	hauls
10-19	6	10	11	5	11	7
20-29	167	13	211	6	209	6
30-39	96	14	15	11	130	8
40-49	45	19	8	19	5	8
50-59	121	17	10	20	133	9
60-69	19	13	15	16	24	5
70-79	33	16	5	12	16	8

a. Fargo & Davenport 1986; Foucher et al. 1988.
b. Fargo et al. 1984; Westrheim et al. 1984.
c. Fargo et al. 1987.

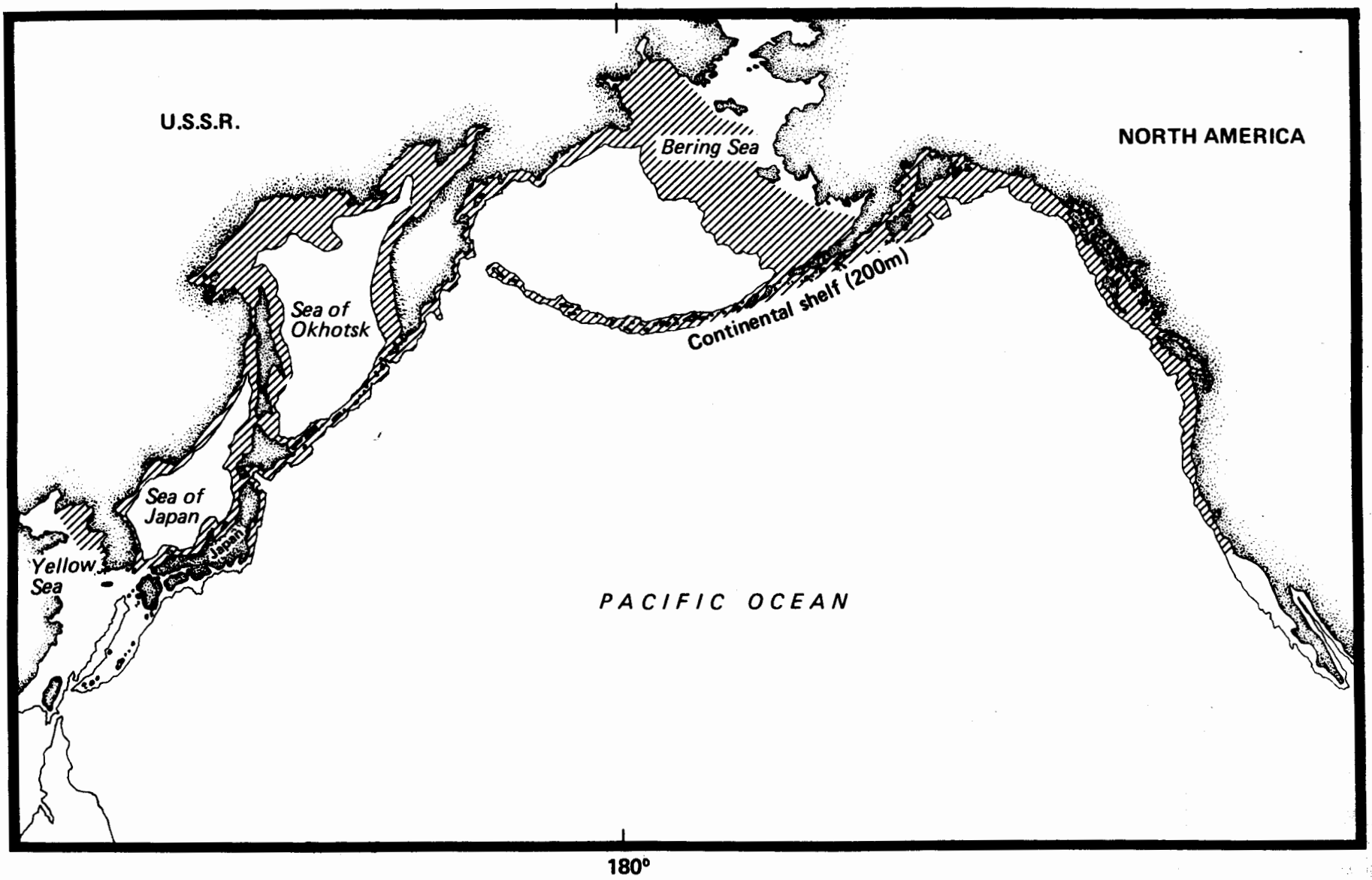


Fig. 4.1. Distribution of Pacific cod in the north Pacific Ocean. (Fig. 1 in Bakkala et al. 1984)

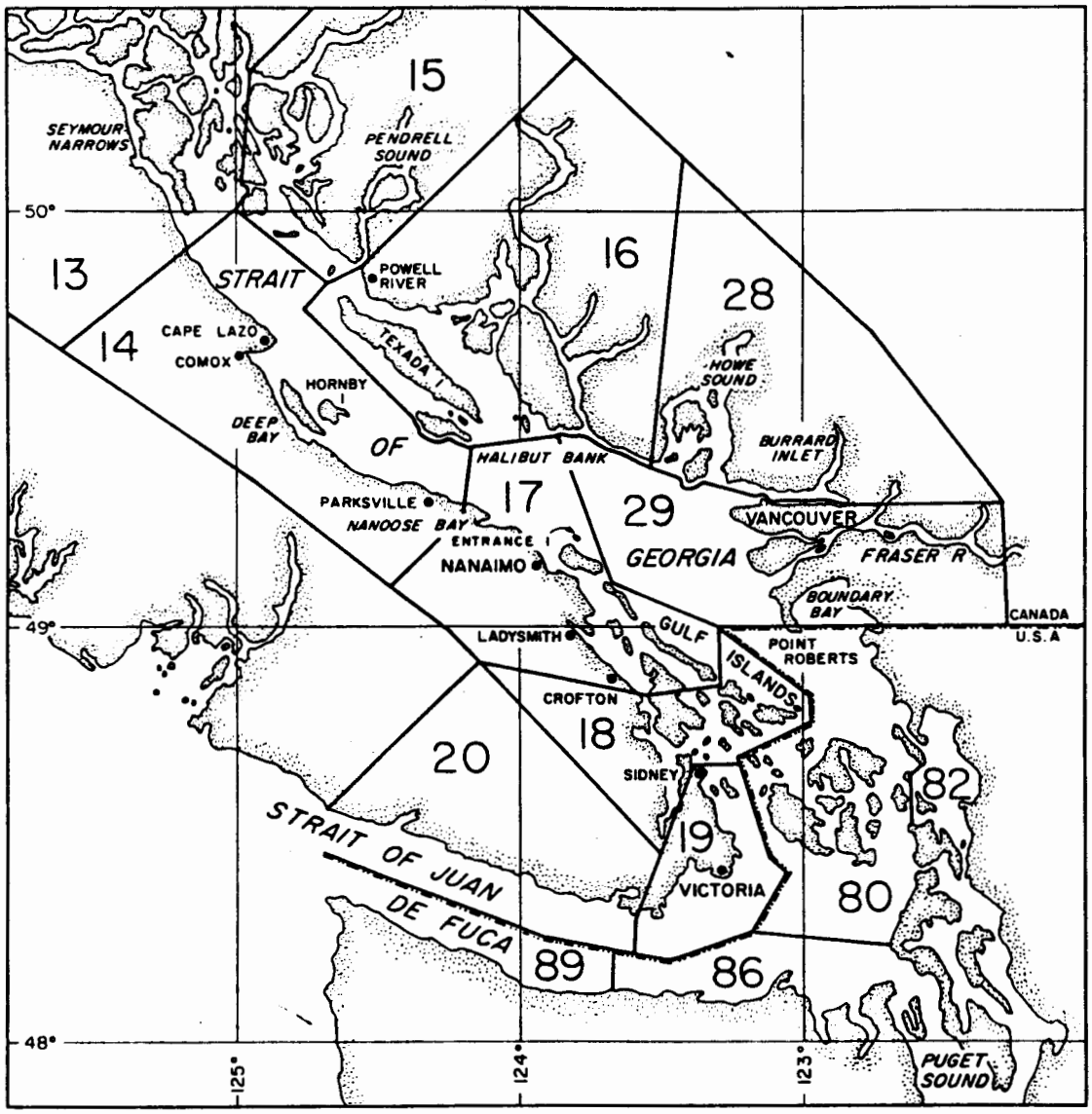


Fig. 4.2. Minor statistical areas (MSAs) in Georgia and Juan de Fuca straits.

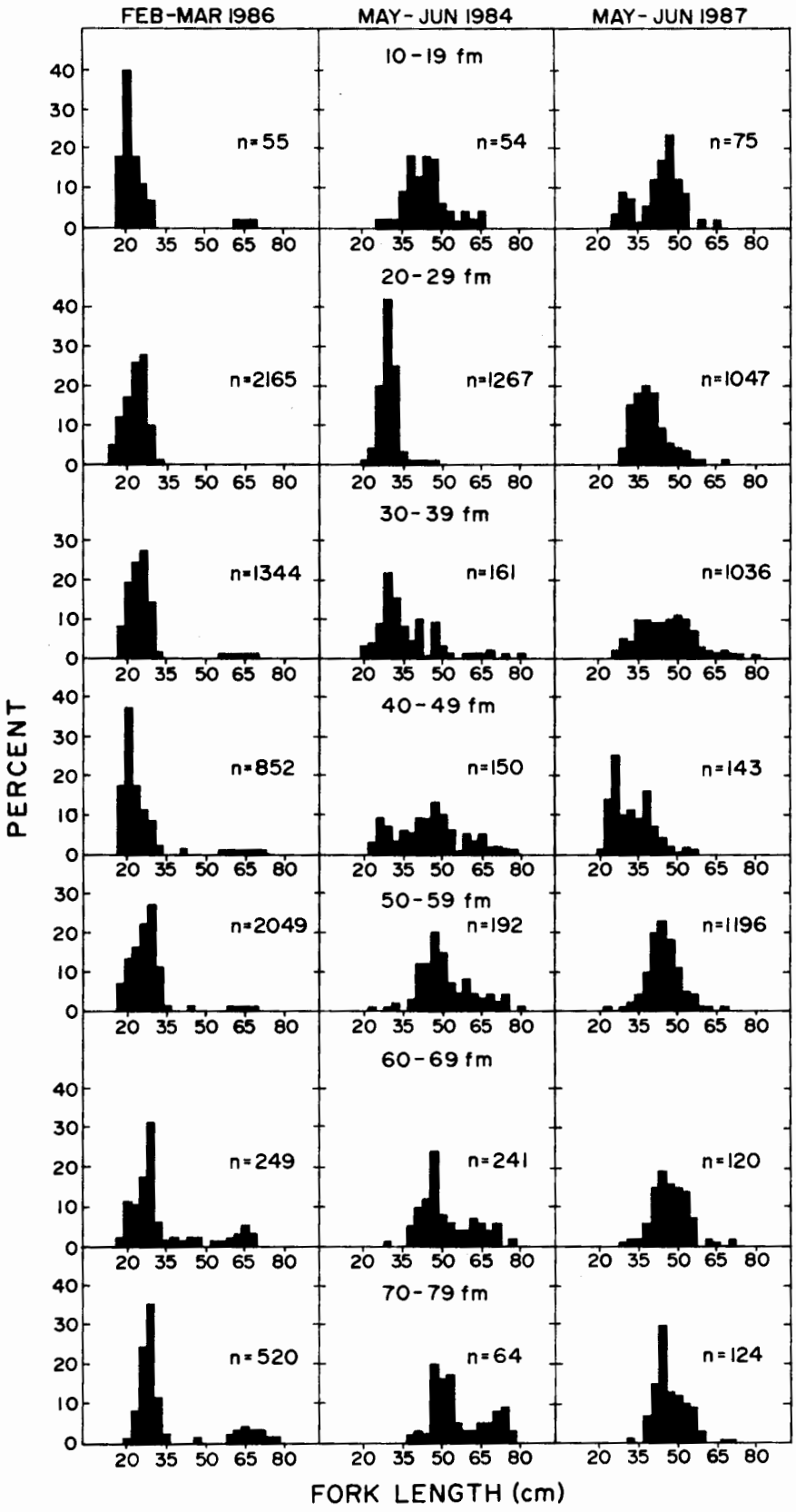


Fig. 4.3. Length-frequencies (%), by 10-fath depth interval, of Pacific cod caught by demersal-trawl surveys in Hecate Strait during February-March 1986 and May-June 1984 and 1987. (Sources: see Section 5.1)

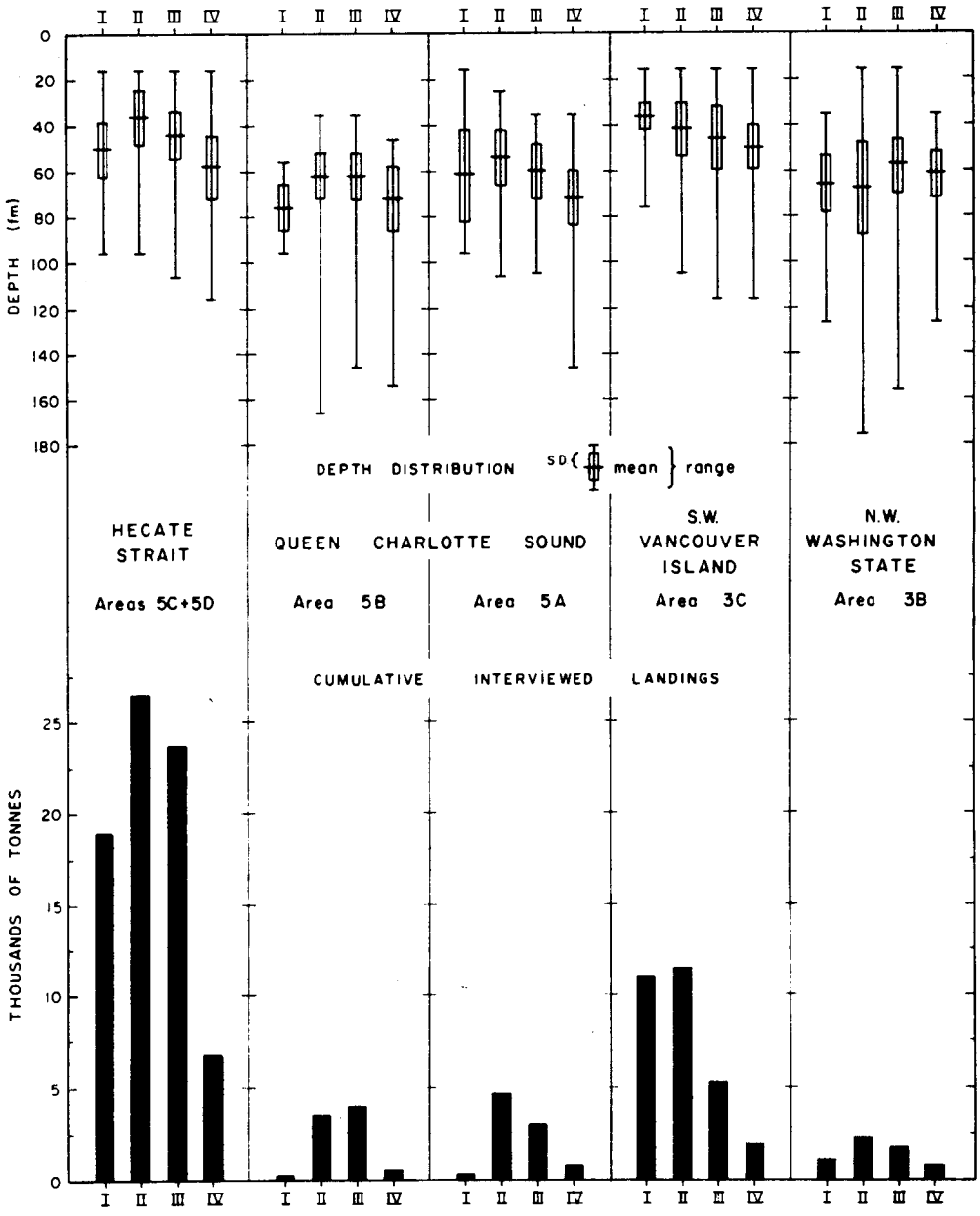


Fig. 4.4. Mean depth (fath) of capture, by area and quarter-year, for cumulative interviewed landings (t) of Pacific cod in Canada (1954-78) or the United States (1967-78). (Source: Fig. 6 in Westrheim and Tagart 1984)

5. BIOLOGY

INTRODUCTION

This chapter will deal with size composition, sex ratio, age determination, age composition, growth, reproduction, early life history, diet, predators, parasites, and diseases (including pathogenic parasites) of Pacific and Atlantic cod.

5.1 SIZE COMPOSITION

INTRODUCTION

For British Columbia waters, Hart (1973) reported the maximum length of Pacific cod to be 3 feet 3 inches (100 cm). Maxima reported elsewhere were 109 cm in the western Gulf of Alaska (Cobb 1927), 110 cm in the eastern Bering Sea (Bakkala 1984), and 114 cm off Russia (Moiseev 1953) (Fig. 3.1).

The largest Atlantic cod reported was ~185 cm ("greater than six feet long"; 95.9 kg), and was taken by line trawl off Massachusetts in May 1895 (Jensen 1972) (Fig. 3.2). Moiseev (1953) reported the maximum size, presumably for the northeast Atlantic, as 160 cm.

PACIFIC COD

British Columbia

Length-frequency samples were available from research-vessel catches and commercial landings. Samples from the former source provided some insight into the size composition of all cod on the grounds, rather than only those of marketable size, in commercial landings. In all cases fishing gear was an on-bottom trawl. Mesh size was not always reported.

Research vessel catches. Length-frequency samples were reported from Georgia Strait (Area 4B), off southwest Vancouver Island (Area 3Cn), and in Hecate Strait (5C+5D)(Fig. 2.1). All were multi-modal.

In Georgia Strait, samples were available from the 1954-58 tagging studies (Ketchen 1961) and the 1975-77 near-monthly juvenile gadoid surveys (Beamish et al. 1978). Trawl mesh size was not reported for the tagging studies. A shrimp trawl (38-mm mesh) was used in the juvenile gadoid surveys. In the 1954-58 data, size range of tagged cod was 16-85 cm FL (op. cit., Fig. 9, Table VII). Two prominent modes were evident in each sample, e.g., 26 and 50 cm in the March 1958 sample. Size range of the 1975-77 data was 4-80 cm FL. Modes in the comparable period of March-April 1976 were located at 27, 46, and 57 cm (Fig. 5.1.1).

Off southwest Vancouver Island, length-frequency samples were collected during biological studies in 1975-76 (Westrheim 1977). The trawl was

equipped with a 38-mm cod-end liner. Sampling was conducted here, and in Hecate Strait, during April, July, and October 1975, and February 1976. Few cod caught were less than 20 cm FL, or greater than 80 cm FL (Fig. 5.1.2). Most samples were clearly multi-modal. For example in April 1975, prominent modes were located at approximately 26, 47, and 59 cm.

In Hecate Strait, length-frequencies were also multi-modal, in tagging studies during 1960-61 (Ketchen 1964), biological studies during 1975-76 (Westrheim 1977), and species-assemblage studies during 1984-87 (Fargo and Tyler 1989). Trawl mesh size was not reported for the tagging studies, but a 38-mm cod-end liner was used in the biological and species-assemblage studies. Size range of the cod tagged during 1960-61 was ca. 20-85 cm (op. cit., Fig. 3). In the February 1960 sample, prominent modes were located at ca. 26, 43, and 55-57 cm, and for the January-February 1961 sample, ca. 43 and 55-57 cm. In the February 1976 sample, prominent modes were located at approximately 26, 40, and 56 cm (Fig. 5.1.2). Species-assemblage studies were conducted during January-March 1986 (Fargo and Davenport 1986; Foucher et al. 1988), May-June 1984 (Fargo et al. 1984; Westrheim et al. 1984) and May-June 1987 (Fargo et al. 1988). Few cod caught were less than 20 cm FL or greater than 80 cm FL (Fig. 4.3). In the February 1986 sample, modal sizes varied with depth, but occurred most commonly at 20-29 cm, 44-47 cm, and 62-68 cm.

Commercial landings. Length-frequency sampling of Pacific cod from commercial landings began in 1951 for the southern areas (3Cn and 4B), and in 1954 for the northern areas (5A-5D) (Ketchen 1967). Data for 1951-85, by ground and quarter year, were obtained from Ketchen (op. cit.), Chilton and Smith (1975), and Foucher (1987). The former two sources reported length-frequencies in 3-cm intervals (38, 41, 44, etc.), while the latter reported length-frequencies in 1-cm intervals. Trawl-mesh sizes varied with time and vessel, but have not been formally documented. Probable range was 88-140 mm. Few cod were less than 41 cm FL, due to processor-imposed minimum size limits, or greater than 80 cm FL. For this study, January-March and April-June were selected to represent the spawning and feeding periods, respectively. Specific grounds were selected based on their relative importance and continuity of samples. During 1951-85, winter fisheries for cod were negligible in Queen Charlotte Sound (Areas 5A+5B), and negligible or intermittent (due to regulations) off southwest Vancouver Island (Area 3Cn).

Multi-modality varied with time and location, among 5-y periods (Table 5.1.1). During January-March, principal modes were at 47 and/or 56-62 cm. Bi-modality was common in samples from both grounds in Area 4B, but uncommon in samples from White Rocks-Bonilla Ground (5D; Fig. 5.1.3.)[1]. During April-June, principal modes were at 50-53 and/or 59-65 cm. Bi-modality was common on Amphitrite-Swiftsure grounds (3Cn; Fig. 5.1.4)[2], Goose Island Bank (5B; Fig. 5.1.5), and Two Peaks-Butterworth Ground[3](5D). Samples from Cook Bank (5A) were unimodal. Despite the variable incidence of bi-modality, configurations of the length-frequencies were remarkably constant among 5-y periods. Mean lengths usually varied less than three centimeters, and coefficients of variation were usually less than four percentage points. The slight decline of mean length with time is likely due to a corresponding decrease in minimum size at processing plants.

Among-year variation in length-frequencies can be substantial, depending on the relative strength of individual year-classes. One example of this is the sample series for cod landed from Two Peaks Ground during May-June

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[1] Hereafter referred to as White Rocks Ground.

[2] Reported as Ucluelet Ground during 1951-73. Length-frequencies were combined with those from Swiftsure Bank in Ketchen (1967) and Chilton and Smith (1975).

[3] Hereafter referred to as Two Peaks Ground.

1964-66 (Fig. 5.1.6). Principal mode was 53 cm in 1964, 57 cm in 1965, and 65 cm in 1966. This modal progression was attributed to passage of the super-abundant 1962 year-class through the fishery (see Section 5.3, Age Composition).

Puget Sound and Vicinity (Area 4A)

Length-frequencies were usually multi-modal in catches from both commercial (trawl and setnet) and recreational fisheries during 1970-88 (Palsson, 1990). For example, the following results were reported for 1981 (modes are listed in order of magnitude):

Gear	Location (see Fig. 5.1.7)	Mode (cm)	N
Trawl	Gulf-Bellingham	42	1,200
	Juan de Fuca	42;52;58	313
	Port Townsend	46	443
Setnet	Port Townsend	48	445
Angling	Juan de Fuca	44;39;53;63	1,893
	C. Puget Sound	42	814
	S. Puget Sound	47;50;43;61	758

Alaska

Cod length-frequencies were multi-modal in the Gulf of Alaska (Blackburn 1984; Brown et al. 1984; Foucher et al. 1984; Smith et al. 1984; Zenger and Thompson 1989) and in the eastern Bering Sea (Bakkala 1984; Foucher et al., op. cit.; Bakkala et al. 1986b; Thompson and Shimada 1988). Few fish exceeded 90 cm FL. Bakkala et al. (op. cit.) reported mean lengths, in research-vessel catches, increasing with depth--24.9-33.1 cm @ <20 fath (37 m) to 51.9-59.5 cm @ 100-400 fath (183-732 m).

Modal progressions were present in all time series. As an example, the following data were summarized from Foucher et al. (1984) (modes are listed in order of magnitude):

Source	Month	Year	Gulf of Alaska	Eastern Bering Sea
Research (Fig. 5)	May-Aug	1978	--	18
		1979	--	35;19
		1980	--	42;19
		1981	--	51;35;21
Commercial (Figs. 1,2)	July-Sept	1978	59	61
		1979	66	66
		1980	42	51

The modal progression in Bering Sea research-vessel catches, from 18 cm in 1978 to 51 cm in 1981, was attributed to the strong 1977 year-class. Similarly, the sharp reduction in modal length in the 1980 commercial samples from both regions, was attributed to the recruitment of the 1977 year-class. In the Gulf of Alaska, research-vessel samples, collected inshore during September-October 1981, yielded length-frequency modes at 10, 24, 33, 46, and 57

cm (Smith et al. 1984, Fig. 17).

Northwest Pacific

During 1930-40, cod mean lengths varied directly with latitude (Moiseev 1953, Table 18). Mean lengths of trawl-caught cod were 71.3-72.25 cm in west Bering Sea; 72.54 cm off east Kamchatka; 64.2-67.5 cm in the Okhotsk Sea; and 52.40-62.80 cm in the Sea of Japan.

Recent information for the western Bering Sea, from trawl and longline surveys, indicated that Pacific cod were now smaller, and length-frequencies were usually unimodal (T. Sasaki pers. comm., April 1991). For example, mean lengths of trawl-caught cod, during July-August 1969, in the western Bering Sea were 39.9 cm (modes at 29 and 61 cm) on the continental shelf, and 61.4 cm (mode at 59-61 cm) on the continental slope.

Off South Korea, during 1962-67, cod length-frequencies from the east and west coasts were substantially different (Zhang 1984, Fig. 9). Mean lengths were 40.5-68.8 cm for the east coast, and 23.4-35.8 cm for the west coast. No cod sampled from the west coast were more than 53 cm long.

ATLANTIC COD

Numerous reports have been published which contain length-frequency data. For this report a few examples of modal size and size range were selected which are hopefully representative. Modal lengths of Atlantic cod varied within and among regions. In research samples modal lengths ranged from 7 to 42 cm in the Baltic Sea (ICES Subdivisions III/22,24-32; Fig. 2.3), and were 25 cm in the North Sea (ICES Subarea IV) (Table 5.1.2). In commercial samples, modal lengths were 35-110 cm in the northeast Atlantic, and 46-62 cm off Canada. Appreciable numbers of cod exceeded 100 cm in length, particularly in samples from the northeast Atlantic. Modal progressions were evident in all time series. For example, see Rollefsen (1954, Fig. 4) and Jonsson (1954, Fig. 3). These were demonstrated to reflect the passage of strong year-classes.

5.2 SEX RATIO

PACIFIC COD

British Columbia

Sex was usually not reported for cod sampled in research vessel catches, nor for cod sampled from commercial landings during the early years of the fishery, when cod were usually gutted at sea. Sex was recorded regularly once gutting at sea was phased out. However, few published records reported length-frequencies by sex.

Research vessel catches. During 1979, biological studies in Hecate Strait yielded sex ratios of 51% males in June-July, and 48% males in September (Table 5.2.1). Among grounds, the sex ratio ranged from 46 to 54% during June-July, and 48-49% during September. Length-frequencies, by sex, were similar, although few cod >50 cm were caught and sampled. Among length intervals, sex ratio was somewhat dome-shaped. For example, on Two Peaks Ground, sex ratios per 3-cm length interval increased from 46% males at 32 cm to 59% at 68 cm, then declined

sharply to 16% at >81 cm (Fig. 5.2.1). At <32 cm, sex ratio was 63% males.

Commercial landings. Samples collected during 1982 were selected as an example, because this was the latest year in which all important areas were reasonably well represented. January-March and April-June were selected as representative of the spawning and feeding periods, respectively. Records were extracted from the groundfish data bank at the Pacific Biological Station. Overall sex ratio was 46% males in the January-March samples, and 49% in the April-June samples (Table 5.2.1). Among areas, sex ratio was 43-49% in January-March, and 44-56% in April-June. Total annual length-frequencies for males and females were also relatively similar (Fig. 5.2.2). Among 3-cm length-intervals, incidence of males was a relatively stable 50-59% at 41-56 cm, and 45-48% at 59-65 cm; but then declined sharply to 12% at >81 cm--similar to the situation noted in research vessel samples. Recent studies by Foucher and Tyler (1990a) yielded comparable results for Amphitrite Bank (Area 3Cn) during February 1977 and 1978, south Queen Charlotte Sound (5A) during April-June 1977-82, and Two Peaks Ground (5D) during September 1979

Alaska

In the Gulf of Alaska, sex ratios were determined from Figure 3 in Blackburn (1984). In research-vessel trawl catches, during July-August 1981, males comprised 48% of the sample (N = 803) from Shelikof Strait (INPFC Kodiak Area; Fig. 2.2), and 33% of the sample (N = 2,280) from the Chignik Area.

In the Eastern Bering Sea, sex ratios were 49 and 52% males in research-vessel catches during 1975 and 1976, respectively (Bakkala 1984, Table 3). Among age-classes 1-6, no trend was evident in 1975 (38-62%). In 1976, percent males increased from 47% at age 1 to 58% at age 5, but then declined to 25% at age 6. Numbers sampled was not reported for either year. For 1979, Bakkala et al. (1986b) reported an overall sex ratio of 51.6% males (49.1-53.9% among subareas with large concentrations of cod), but 39.8-41.8% males for age-3 and age-4 cod. For 1980, Bakkala et al. (1986a) cited Umeda and Bakkala (1983) as reporting that females comprised 50.5% of the "population".

Northwest Pacific

Sex ratios ranged from 46.0 to 52.6% males (in reasonably large samples), from the western Bering Sea to the Sea of Japan, without latitudinal or seasonal trend (Moiseev 1953, Tables 37 and 38). However, among 5-cm length intervals, in a sample of 3,019 males and 3,442 females, males predominated at 30-44 cm (50-57%); neither sex predominated at 45-69 cm (48-54%); and females predominated at 70-109 cm (57-100%). No males were found in the 100-109 cm interval. Sasaki (pers. comm. April 1991) noted that females predominated in the larger sizes of cod caught during recent surveys in the western Bering Sea.

ATLANTIC COD

Published records of sex ratios were only found for cod in the northwest Atlantic. There, sex ratios by length interval, off Labrador (NAFO/ICNAF Subarea 2; Fig. 2.4) and eastern Newfoundland (NAFO/ICNAF Divisions 3KL) during May 1951 (Ancellin 1954) exhibited the same pattern as that of Pacific cod off Canada. Off Labrador, sex ratio, per 5-cm interval, was 53% males at 40-54 cm (N = 450-738), then declined steadily to 16% at 70-74 cm (N = 43)(op. cit. Table II). Off Newfoundland, sex ratio, per 10-cm interval, was

50-53% at 41-80 cm (N = 113-177); 36-41% at 81-100 cm (N = 37-175); and 7% at 101-130 cm (N = 14).

5.3 AGE DETERMINATION

PACIFIC COD

Despite considerable effort by the scientists at the Pacific Biological Station (Nanaimo, B.C.), and elsewhere, age determination of Pacific cod has not been resolved. To date (1993), no validated method has been established, or at least published. A historical review follows, by region.

British Columbia

Ketchen (1970) provided the first review of efforts at the Pacific Biological Station to determine the age of Pacific cod. Scales, vertebrae, otoliths, and opercular bones were all investigated, but none proved satisfactory. With respect to otoliths, he noted that the readability (under reflected light) of the "best" local otoliths, and those collected elsewhere in the Pacific Ocean, were worse than the "worst" otoliths collected from cod in the western or eastern Atlantic Ocean. He concluded with the recommendations that: (1) a substantial tagging program, involving tetracycline-injected cod, should be launched to resolve the age determination problem; and that further studies of scales should be undertaken "by persons thoroughly experienced in such studies" (op. cit., p. 23).

Subsequently, further studies were undertaken which involved scales, fin-rays, otoliths, and length-frequencies.

Chilton and Beamish (1982) provided the second review of efforts to determine the age of Pacific cod in British Columbia waters. They noted that even the "new" break-and-burn method failed to yield satisfactory readings of otoliths, and that the scale method, abandoned in 1978, was slow and tedious. However, they reported promising results with cross-sections of fin rays from the second-dorsal and pectoral fins, and concluded that "A judicious mixture of scale and fin-ray ages and a computer analysis of length-frequencies may ultimately prove to be the most efficient age determination method for Pacific cod in the Canadian zone." (op. cit., p. 22)

Scales. Kennedy (1970) developed a method for ageing Pacific cod scales which utilized the Eberbach microprojector, a commercial version of the apparatus described by Van Oosten et al. (1934). Previous efforts had involved only a binocular microscope. Scales were collected from trawl-caught cod landed from Hecate Strait during September 1967-August 1968. Size range of specimens was not provided, but apparently few fish were less than 48 cm FL (op. cit., Table 1). Tests of consistency and reliability of readings was deemed satisfactory, and the method was adopted for use at the Pacific Biological Station. Chilton (1970) described the "production" method of processing the scales. Unfortunately, both processing and reading procedures were time-consuming. One technician could process scale samples from about 60 cod per day.

A test of the Kennedy method was provided from data collected during a juvenile gadoid survey in Georgia Strait in 1974-77 (Beamish et al. (1978). Time-series of Pacific cod length-frequencies clearly delineated age-classes I and II. Readings of scales from the September-October 1976 sample were substantially in error, particularly for age-1 specimens. A second test of new readings one year later provided only slight improvement. As a result, all

cod-scale processing and reading were suspended in 1978 pending validation of age determination, and development of a more rapid method of processing and ageing (Chilton and Beamish 1982).

Studies to investigate the feasibility of tagging juvenile cod of known age, based on length-frequencies, for subsequent age-validation studies were conducted in Georgia Strait during January-February 1978 (Leaman et al. 1979) and January 1979 (Foucher et al. 1979). Results were promising in both cases, and a "production-scale" program was undertaken off southwest Vancouver Island during February-March 1979 (Foucher et al. 1980). For the three studies combined, 3,380 cod were tagged and released, and 589 (17.4%) were recovered (Westrheim 1985). Age composition (based on length-frequencies), of the released cod was 11% age 1 (= 23-26 cm), 81% age 2 (= 44 cm), and 8% age 2+ (>54 cm). Recapture rate varied directly with "age" and inversely with sea-state code, at time of release. The author concluded that the optimal time for tagging juvenile, pre-recruit cod would be September, at age 1+. To date (1993) no further taggings have been undertaken.

Readings of scales, and fin-ray cross-sections, from the aforementioned recaptured cod were made and tested for "accuracy" (Westrheim and Shaw 1982). Results were mixed. Accuracy of scale readings was good for age-1 (100%), age-2 (91%), and age-3 cod (88%), although only eight age-3 scales were read. Of some interest was the among-reader consistency in detecting false checks in the first year of scale growth. These appeared intermittently among scale samples, and met the Kennedy (1970) criteria for annuli. False checks elsewhere on the scales were readily distinguished from annuli.

Fin-rays. Fin-ray cross-sections were investigated initially by Beamish (1981), who compared readings of fin-ray cross-sections with those of scales from cod collected off the west coast of Vancouver Island. He noted that "It was possible to find distinct annuli on sections of fin rays from the first dorsal fin, particularly for older fish." (op. cit., p. 293). Among size classes, readings were similar for the two structures, except for the larger fish whose fin-ray sections produced older ages than did scales. For example, for a 75-cm cod, the fin-ray cross-section age was four years older than the corresponding scale age.

Results of the 1979 tagging study indicated that the accuracy of fin-ray readings was poor, based on comparisons with scale readings from the same specimens (Westrheim and Shaw 1982). Agreement was 27% (78% $\pm$ 1 y) in 27 tests between scale and second-dorsal fin-ray readings of age-2 cod. Fin-ray readings overestimated the age of cod in all cases.

Beamish et al. (1990) compared results from fin-ray readings with those from the Foucher-Fournier iterative length-frequency method (see below). They used three samples, selected to represent the range of ageing problems associated with fin rays, collected in April 1987 and June 1989 from Hecate Strait, and in November 1987 from off southwest Vancouver Island. The Foucher-Fournier method readily delineated the strong 1985 year-class, but the fin-ray method did not, without prior knowledge of the presence of that year-class. The fin-ray method was thought to provide better information, if accurate, on growth among year-classes, based on the relative width of growth zones. The authors noted that the problem with fin-rays was not finding a pattern to interpret, but interpreting the pattern. They reiterated the need for validation, and suggested that the best method was tagging, with or without injections of oxytetracycline, and excision, at tagging, of the first three rays of the dorsal fin.

Length-frequencies. Foucher and Fournier (1982) developed a computerized iterative method for deriving age-frequencies and growth data from length-frequencies. It was a modification of the general program developed by Schnute and Fournier (1980). The method had the advantage of processing large numbers of fish in a relatively short time, but provided no information on the age of individual specimens. Circumstantial evidence for validation of the method was provided by comparing results with those obtained using two other

methods--graphical (Harding 1949; Cassie 1954) and scale (Kennedy 1970). A further comparison with tagged cod indicated that the computer method produced reasonable estimates of the mean lengths of age-groups 1-8. The Foucher-Fournier method has not been fully validated, and does exhibit some weaknesses. Perhaps the most important of these is the underlying assumptions that the length-frequencies of each age-class are unimodal and reasonably symmetrical, and that growth rate does not vary substantially among year-classes. For age-1 cod, this assumption may not be true, based on length-frequency samples from research vessel catches during January-March in Areas 4B, 3Cn, and 5D (Table 5.3.1), and 5C+5D (Table 5.3.2). Modal sizes ranged from 16 to 29 cm; varied by gear and/or depth; and distributions were frequently multi-modal. Multi-modal length-frequencies were also noted for cod during their second year of life, for example in April 1982-84 (Fargo and Westrheim 1986), May-June 1984 (Fargo et al. 1984; Westrheim et al. 1984), and September-October 1985 (Saunders et al. 1986). Nevertheless, the Foucher-Fournier method was adopted at the Pacific Biological Station, and was in use until 1992 (C. M. Hand, pers. comm., October 1992), when it was supplanted by the MULTIFAN method (see below).

The MULTIFAN method (Fournier et al. 1990) also derives age-frequencies and growth data from length-frequencies. Principal difference from the Foucher-Fournier method is the ability of MULTIFAN to simultaneously analyze multiple length-frequency data sets. Validation was based on a favorable comparison with age-frequencies and growth data derived from scales, otoliths, and tagging data, for the southern bluefin tuna (Thunnus maccoyii). No validation with Pacific cod has been reported to date (1993).

Washington State

For cod from Port Townsend (4A), Karp (1982) found the Kennedy scale method unsatisfactory, and instead used the unvalidated computerized iterative method of Macdonald and Pitcher (1979), similar to the Foucher-Fournier method.

Alaska

Numerous ageing structures have been investigated, as well as length-frequency processing. Most of the studies involved cod from the eastern Bering Sea. As of 1988, all previous age-determination methods for cod in the Gulf of Alaska had been abandoned as unsatisfactory (Zenger and Thompson 1989).

Scales. In the 1970s, scales were used for age determination, by the Kennedy method. However, Foucher et al. (1984) demonstrated the method to be unsatisfactory in the Gulf of Alaska and the eastern Bering Sea, based on a comparison of results using the Foucher-Fournier iterative method. The latter method produced more "reasonable" results, based on the delineation of the strong 1977 year-class in research-vessel and commercial-vessel catches during 1978-80. For the Gulf of Alaska data, mean lengths-at-age derived by the Foucher-Fournier method (op. cit., Table 3) were corroborated by the modal lengths-at-age in independent length-frequency samples collected by Blackburn (1984, p. 154), as follows:

	Age-Class			
	1	2	3	4
Foucher et al. (May-Aug 1978-89)	24.2-30.0	37.6-42.9	45.4-51.9	52.5-59.9
Blackburn	27	42	51	57

Dorsal fin-rays. For the Gulf of Alaska, Zenger and Thompson (1989) noted that the fin-ray method had not been validated, and hence no samples were collected for "production reading".

For the eastern Bering Sea, dorsal fin-ray cross-sections were used to create age-length keys for estimating age-frequencies from length-frequencies in the 1985 (Bakkala et al. 1986a) and 1986-87 (Thompson and Shimada 1987,1988) stock-assessments. In all three cases the age-length key was based on fin-rays from 326 cod collected during the 1984 trawl survey, and the criterion for acceptance of the method was the delineation of strong year-classes--1977 and 1978 in this case. For the 1985 study, a conventional key was employed to derive age-frequencies (op. cit., 1986). The authors conceded that bias was introduced, as per Kimura (1977), because cod recruitment was variable. For the 1986 and 1987 stock-assessments, a new, and allegedly less biased, iterative age-length key (Kimura and Chikuni 1987) was applied (op. cit., 1987,1988). The authors acknowledged that the fin-ray method was not validated, but the results were "reasonable".

Otoliths. For the Gulf of Alaska, Zenger and Thompson (1989) noted that in 1988, otoliths were identified as the preferred structure for age determination of cod, but sampling and "production readings" had not begun.

Mosher (1954) produced the first report on otoliths for age-determination of cod in the eastern Bering Sea. He examined otoliths collected from 123 cod (14-92 cm) in 1949, and reported "satisfactory" results from reading the polished cross-section of each otolith, with special side-lighting. The first two readings agreed in 64.2% of the cases, and all but seven of the pairs differed by no more than one year. No measure of reliability was reported. Estimated age range was 1-12, modal age was 5 (N = 23), and 70% of the cod were ages 4-8.

First reported use of otoliths on a "production scale" was that of Thompson and Shimada (1990). They created a Kimura-Chikuni age-length key for use in the 1988 stock-assessment of cod in the eastern Bering Sea. The age-length key was created from otoliths of 623 cod collected during the 1985 trawl survey. No details were provided on the method of otolith reading, and the authors conceded that the method was not validated.

Multiple Structures. Lai et al. (1987) examined five structures (dorsal and pectoral fin-rays, scales, otoliths, and coracoids) from 230 Pacific cod collected in the eastern Bering Sea during September 1983-March 1984. Dorsal fin-rays were deemed most reliable, based on how well the resulting age-class length-frequencies matched the progression of length-frequencies of the strong 1977 year-class during 1978-83. Analysis of length-frequencies appeared to be unreliable for age-classes older than about five years.

Kimura and Lyons (1990) examined scales, otoliths, and dorsal fin-rays of 623 cod collected from a research-vessel trawl survey in the eastern Bering Sea during June-July 1985. They concluded that the most practical ageing method would involve broken and burnt otoliths, with scales as a backup for younger fish. Neither otoliths nor fin-rays were deemed satisfactory for younger cod. With fin-rays, both the location and thickness of the section affected the readability, and ageing, of the structure.

Length-frequencies. The Macdonald-Pitcher computerized iterative method was first utilized in the 1982 abundance-prediction study for the eastern Bering Sea (Wespestad et al. 1982). Use was justified on the basis that its estimates of length-at-age and annual growth rates were comparable to those determined from modal lengths of the abundant 1977 year-class in trawl-survey catches during 1978-81. Subsequently, the method was used in the stock-assessment studies of 1982 in the Gulf of Alaska (Zenger and Cummings 1983), and 1983 (Bakkala and Wespestad 1984) and 1984 (op. cit., 1985) in the eastern Bering Sea. It was abandoned thereafter, because it was deemed unsatisfactory for cod older than age 2 (op. cit., 1985).

Northwest Pacific

Moiseev (1953) used a combination of scales for younger cod and otoliths for older cod, for collections from the western Bering Sea southward to the Yellow Sea. He reported that scales were satisfactory up to age 6 or 7, and otoliths thereafter. The first and second annuli on otoliths were difficult to detect. He acknowledged that no validation of the age-determination methods was achieved.

ATLANTIC COD

Otolith cross-sections have become the "accepted" structure for age determination throughout the north Atlantic. Scales were initially used (for example, Hjort 1914; Winge 1915; Graham 1934; Thompson 1943), but were subsequently replaced by otoliths (Saemundssen 1923; Schroeder 1930; Dannevig 1933). Scales were deemed satisfactory for younger cod by some authors (Dannevig op. cit.; Hansen 1949, 1954; Schroeder op. cit.), but Pentilla (1988) reported scales were generally unreliable even for younger cod, collected off the United States.

Winge (1915) pioneered age validation using tagged fish off Iceland. Scales were collected at tagging and recovery, and he reported good results for younger cod (age 1-3), and fair results with older cod, up to age 14.

Validation of otolith readings was reported for the northeast Atlantic by Dannevig (1933), Rollefsen (1954), Jonsson (1954), Jensen (1961), and Joensen (1954); and for the northwest Atlantic by Hansen (1949, 1954), Fleming (1960), Kohler (1964a), May (1965, 1967), Wiles and May (1968), Pinhorn (1969), and Jensen 1970). Validation methods involved one or more of the following: (1) Petersen (1892) method (modal length-frequency progressions), for juvenile cod; (2) demonstrating the annual formation of only one hyaline ring and one opaque ring; and (3) identifying strong year-classes, in commercial catches, which were verified by long time series of length-frequencies or length-frequency anomalies.

One discordant note for the northwest Atlantic region was the inconsistent interpretation of otoliths among national readers (Kohler 1964b; Sreedharan 1969; Blacker 1974; Lopez-Veiga et al. 1977). Sreedharan (op. cit.) found that age-length keys from different countries produced excessively variable estimates of age composition when applied to the same length-frequency sample, and concluded that in some cases either ageing techniques or sampling methods between countries were different. He noted that this was not new information, but "lends support to the need for an attempt to standardize ageing and sampling techniques" (op. cit. p. 98). Blacker (op. cit.) noted that in an international exchange of otolith photographs, during 1963-67, there were among-reader differences in interpretation of the otoliths, not only in estimated age, but also in how the age was determined. Thus, identical age-determinations did not

necessarily indicate identical interpretations of an otolith. He emphasized that a validated method in one area was not necessarily applicable elsewhere. Each location required individual validation.

All reports recommended further studies to reduce errors. A number of workshops were subsequently held, but for none after the latest reported here were results published (J.C. Rice, Pacific Biological Station, Nanaimo, B.C., pers. comm., February 1992).

5.4 AGE COMPOSITION

PACIFIC COD

British Columbia

Detailed records of commercial landings, by important area-time cells, were reported for Area 4B (minor statistical area(MSA)-quarter year) during, 1945-84 (Foucher and Giudici 1985); and for Areas 3C+3D and 5A-5D (trawling ground-quarter year) during 1956-82 (Foucher and Westrheim 1984). Corresponding age-frequencies were derived from length-frequencies by the Foucher-Fournier method.

Three age classes comprised 84-95% of the cod landed from Areas 4B (Fig. 5.4.1), and 3Cn and 5A-5D (Fig. 5.4.2). These were age-classes 2-4 in all important area-time cells, except MSA 19 (Area 4B), where age-classes 1-3 comprised 94% during October-December. Modal age-classes were 2 or 3 in all areas. No cod were reported to be older than 10 y in Area 4B, nor older than 11 y in the other areas.

Year-class abundance fluctuated relatively modestly in Area 4B (Westrheim and Foucher 1986), but substantially, and quasi-cyclically, in the offshore areas (Fig. 5.4.3). Among year-classes 1953-76, those prominent in at least two areas were 1961-62, 1969-70, 1972-73, and 1975. In three cases, strong year-classes in Areas 5A and 5B (1961, 1969, 1972) were one year younger than those in Areas 5C and 5D (1962, 1970, and 1973). The next prominent year-class, after 1975, was 1985, in all three offshore regions (Tyler and Hand 1992, Tables 3.2, 3.7, and 3.8). Among areas, ratios of maximum/minimum abundance of individual year-classes ranged from 7.3 (3Cn) to 33.7 (5D).

In addition to the unvalidated method for deriving age-frequencies, a second problem, infrequently reported, was the representativeness of the length-frequency samples from which age-frequencies were derived. Tyler and Foucher (1989) tested 54 length-frequency samples, collected in processing plants, of cod caught on Two Peaks Ground (Area 5D), and reported that 41 failed a Chi-square test of among-sample homogeneity. The tests involved 5-8 samples in each of eight years, during 1959-87. They were collected primarily during summer. Each sample was tested against the total for that year, excluding the sample tested. The best record was for July 1961, when only two of the six samples failed the test. In five of the eight years, only one sample did not fail the test. The authors noted that sampling effort was generally less than that in the test groups, and concluded that it was quite possible that the degree of error due to the level of sampling often exceeded that due to errors in the age determination method. They further noted that the current level of sampling could lead to a high degree of measurement error with respect to mortality rate calculations and virtual population analysis.

Alaska

Gulf of Alaska. Age-frequencies for 1978-80 were derived by the Foucher-Fournier method (Foucher et al. 1984). Annual modal age-classes were 1 & 3, 2 & 5, and 3, respectively, in samples from research vessels, and 5, 5, and 3, respectively, in samples from commercial vessels. Maximum age reported was 10 y in research-vessel samples, and 11 y in commercial samples.

Age-frequencies for 1973-81 were derived by the Macdonald-Pitcher method (Zenger and Cummings 1983). No age-frequencies were provided, but the 1977 year-class was reported to be dominant.

Subsequent analyses were limited to examining length-frequencies. The latest published report (Zenger and Thompson (1989) noted that the strong 1977-78 year-classes were declining, and no subsequent year-class was equivalent. The 1982 and 1984 year-classes were relatively strong.

Eastern Bering Sea. Age-frequencies reflected substantial variation in recruitment, but the identity of strong year-classes varied with the method of age determination (Table 5.4.1). The 1977, 1982, and 1984 year-classes were consistently identified, but the 1976 and 1978 year-classes were also identified occasionally--1976 by an otolith-based key, and 1978 by a simple length-frequency examination and a fin-ray-based key.

The Kimura-Chikuni method, utilizing fin-rays, appeared to exhibit a strong bias when applied to research-vessel samples collected during 1978-85. The key was based on age readings of 263 fin-rays collected in 1984 (Bakkala et al., 1986a). The only strong year-class delineated was 1977. Calculated modal age-classes (from length-frequencies), by year, were: 1, 2/9, 3/9, 3/9, 3/9, 3/6/9, 2/6/9, and 3/6, respectively (op. cit., Table 13). The modal age-classes in the key were 2, 6, and 9 (op. cit., Fig. 11). Westrheim and Ricker (1978) reported the same form of bias for Pacific ocean perch (Sebastes alutus), and noted that age-length keys tended to reproduce their own age-frequencies.

Northwest Pacific

W. Bering Sea-Hokkaido. Moiseev (1953, Table 28) reported age compositions, based on otolith readings, for the western Bering Sea, Okhotsk Sea, Japan Sea, and East Hokkaido, during 1932-48. No time series were presented. Modal age-classes ranged from 4 to 7, and varied directly with latitude. Maximum age was 11 y, except for East Hokkaido (6). In all cases, the four medial age-classes comprised at least 72% of each age composition, except for an anomalous sample from South Sakhalin (40.0% age-1, 16.4% age-3, 0.5% age-6, and 8.0% age-8).

Japan. Mishima (1984) reported that off northern Japan, primarily Hokkaido, age compositions varied by area, gear, and method of age determination (scales and vertebrae). For example, line-caught cod ranged in age from 3 to 10 (85% ages 5-7), and for trawl-caught cod, ages 1-6. In both cases, ages were based on scales.

Korea. Zhang (1984) provided indirect information on age composition of cod from the southeast or southwest coasts. The length-frequency modal progressions in his Fig. 9 suggest a minimum age range of 1-6 y for cod off the southeast coast and 1-3 off the southwest coast.

ATLANTIC COD

Few reports were found which provided details on derivation of age-compositions. Age-length keys (ALKs) were employed for cod landed in England from Iceland and/or the North Sea (Brander 1974; Daan 1974), and off Canada (Pinhorn and Fleming 1965; ICNAF 1974). Few dealt with validation, and none dealt with the tendency for ALKs to reproduce their own age-frequency, as was demonstrated for Pacific cod in Alaska (Bakkala et al. 1986a), Pacific ocean perch, in British Columbia (Westrheim and Ricker 1978), and perhaps Atlantic cod off North America (Sreedharan 1969). Sreedharan's discovery that age-length keys from different countries produced excessively variable estimates of age composition when applied to the same length-frequency sample, could be another example of ALKs reproducing their own age compositions. As noted in Section 5.3, he had concluded that either ageing techniques or sampling methods between countries were different.

Brander (1974) investigated the reliability of age-length keys (ALKs) and maximum likelihood analyses of length-frequencies to estimate age-frequencies of cod landed in England, from the North Sea and Iceland. He demonstrated statistically that ALKs were satisfactory under certain circumstances. With respect to maximum likelihood analyses of length-frequencies, he discussed the history of the method, and noted that a local program (MIXMLP) produced results comparable to those from ALKs. MIXMLP incorporatated a growth formula derived elsewhere so as to eliminate subjective judgement in the analysis. Neither method was suitable for partially recruited younger age-classes, nor for the older, less abundant, age-classes.

Validation of ALKs for cod off Newfoundland were reported by Pinhorn and Fleming (1965). They reported similar results with random and stratified samples for estimating age-frequencies and mean lengths-at-age of cod sampled from the inshore fisheries (trap, longline, and line trawl). These cod were younger than those caught by line and trawl on the offshore grounds.

Throughout the North Atlantic, modal age ranged from 3 to 18, and generally varied directly with latitude (Table 5.4.2). The extensive age range was due to the longevity of dominant year-classes. Overall, the age range in commercial catches was 1-23 y. Year-class abundance varied substantially within each geographical region, and the respective standard deviations varied directly with latitude (Garrod and Knights 1979). In the northeast Atlantic, declines in standard deviations of the $\log_e$ of year-class abundance, among stocks[4], ranged from 0.36 (Irish Sea) to 0.90 (Arcto-Norwegian) in the northeast sector of the north Atlantic, and for the northwest sector, 0.28 (Gulf of St. Lawrence) to 0.95 (East Greenland) (Table 5.4.3). Technically, of course, east Greenland lies within the ICES Area.

5.5 GROWTH

INTRODUCTION

Four growth relationships will be dealt with--length-weight, length-girth, age-length, and age-weight.

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[4] See Section 7.1 (Stock Delineation) for explanation of term.

5.5.1 Length-Weight

PACIFIC COD

British Columbia

Westrheim (1977) completed the first comprehensive investigation of the length-weight relationship for Pacific cod in British Columbia waters. His computations were based on stratified samples[5] of each sex, from two important cod-producing areas (southwest Vancouver Island, 3Cn; and Hecate Strait, 5C+5D), and during each "season" (April, July, and October 1975; February 1976). Relationships were established for both round weight and dressed weight (gills and viscera removed).

Empirical tests of the "final" formulae were conducted by calculating the weight for length-frequency samples of known weight. Absolute error was the percentage deviation of the calculated weight from the known weight. Covariance tests for homogeneity among regression parameters were not employed, because earlier studies with Pacific ocean perch had revealed the hypersensitivity of such tests (Westrheim and Thomson 1971). Covariance analysis had yielded statistically significant differences when the absolute error was 2-8%. Such errors are very likely smaller than the accuracy of landing weights. No other empirical tests of length-weight formulae were discovered for Pacific or Atlantic cod.

Round weights. No appreciable differences were apparent in calculated weights between sexes, areas, or three of the four "seasons" (April, July, October) (Westrheim 1977, Table 3). For example, in Hecate Strait, calculated weights for males at 70 cm were 3,553-3,853 g during April, July, and October, but 4,161 g in February. Comparable values for females were 3,785-3,980 and 4,133 g, and for sexes combined, 3,687-3,941 and 4,139 g. The larger weights in February were presumably due to the ripe gonads. Two formulae were thus accepted, and deemed applicable to all areas, sexes combined, as follows:

January-March: $W = 0.004988\ L^{3.2117}$

April-December: $W = 0.007377\ L^{3.0963}$

where W = round weight in grams

and L = fork length in centimeters

Empirical tests of the round-weight formulae totalled 30 for the January-March formula, and 95 for April-December formula, and were based on samples collected during 1970-75 (Table 5.5.1). For the January-March formula, mean absolute error was -0.1% (62% <= ± 5%; 93% <= ± 10%). Among areas, mean errors ranged from -1.4 to +1.8%. For the April-December formula, mean absolute error was -5.5% (39% <= ± 5%; 71% <= ± 10%). Among areas, mean error ranged from -8.8% to +2.0%. Among-year variation in mean error was substantial for cod off west Vancouver Island (-10.4% to +3.0%) (Table 5.5.2). Similar tests for cod from Queen Charlotte Sound (5A+5B) (mean = -8.3%) were precluded by inadequate data. It is evident that any length-weight formula used should be tested empirically on a regular basis.

Dressed weights. The individual formulae yielded similar calculated weights, regardless of month, sex, or area (Westrheim 1977, Table 6). For example, in Hecate Strait, calculated weights for males at 70 cm were

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[5] A maximum of 10 males and 10 females each from selected 1-cm length intervals (17, 20, 23, etc.), except that all cod >71 FL were processed.

3,051-3,132 g among the four "seasons". Comparable values for females were 3,234-3,395 g, and for sexes combined, 3,164-3,370 g. As a result, one overall formula was computed for empirical testing, as follows:

$$W = .008289\ L^{3.0333}$$

where W = dressed weight in grams

and L = fork length in centimeters

Empirical tests of the dressed-weight formula were based on samples collected during 1970-75, and totalled 41 for January-March, and 95 for April-December (Table 5.5.1). Mean error was +0.4% (66% <= $\pm$ 5%; 78% <= $\pm$ 10%) for January-March samples, and -5.7% (37% <= $\pm$ 5%; 80% <= $\pm$ 10%) for April-December samples. Among areas, mean error ranged from -1.4 to +1.8% for January-March samples, and -7.5% to -2.8% for April-December samples. Among-year variation in mean error was -7.5 to +3.0% for samples collected off Vancouver Island during April-September (Table 5.5.2).

By-products of these studies were the conversion factors for transforming landed weights of dressed cod to those of round cod. For January-March the factor was 1.28, and for April-December, 1.13.

Elsewhere

Results elsewhere were compared with respect to calculated weights at selected length intervals (Table 5.5.3), sexual dimorphism, and seasonal variation in the length-weight relationship. Relationships were evaluated by comparing the deviations (%) from the calculated round (April-October) and dressed (February-October) weights for Pacific cod in British Columbia waters.

Weight per length interval. Strict comparisons of round weights from all regions was difficult because of the variable data-collection timing (Table 5.5.4). However, in general, British Columbia cod appeared to be heavier per length (4-21% @ 50 cm) than those off Washington State and in the Gulf of Alaska, and Atlantic cod, except in the New York Bight (27%), and perhaps the Gulf of St. Lawrence (2%). They were lighter (7-19% @ 50 cm) than Pacific cod in the eastern Bering Sea, off the Aleutian Islands and West Kamchatka, and in the Yellow Sea (37% @ 30 cm).

Dressed-weight data were only found for cod off the east coast of Canada (Tables 5.5.3, 5.5.4). At 50 cm, Atlantic cod weights were 10.3-21.9% lighter than comparable weights of Pacific cod in British Columbia waters.

Sexual dimorphism. In the eastern Bering Sea, no sexual dimorphism was noted for 940 cod collected during August-October 1975, and 650 cod collected during April-June 1976 (Bakkala 1984). At 30, 50, and 70 cm, calculated weights of female cod differed from those of male cod by only -3.1 to +2.6%, for both samples. No comparable data were available for Pacific (except British Columbia) or Atlantic cod.

Seasonal variability. In the eastern Bering Sea, calculated round weights of cod collected during April-June 1976 were consistently lighter, at selected lengths, than those collected during August-October 1975 (Table 5.5.3). For example, at 50 cm, round weight was 1,398 g in April-June 1976, and 1,549 g in August-October 1975. Presumably, this reflected the post-spawning "recovery". No other data were found.

ATLANTIC COD

Round weights per length-interval appeared to vary inversely with latitude throughout the north Atlantic (Table 5.5.3). At 70 cm, for example, in the northeast Atlantic, calculated weights were 3,567 g in the North Sea and 2,824 g in the Barents Sea. Comparable values in the northwest Atlantic were 4,833 g in the New York Bight (6A), 3,636 g in the southwest Gulf of St. Lawrence, and 2,964-3,187 g along the Canadian coast.

No information was found on sexual dimorphism or seasonal variations in the length-weight relationship, and little on dressed weight.

5.5.2 Length-Girth

PACIFIC COD

British Columbia

Westrheim (1977) completed the only comprehensive investigation of the length-girth relationship for Pacific cod in British Columbia waters. His computations were based on the same stratified samples collected to investigate the length-weight relationship. Overall, the length-girth relationship was linear. Calculated girths by sex, area, and time, exhibited little variation. Among sexes, calculated values for selected lengths varied by -2.9% to +1.9%. Among areas, sexes combined, differences were 0.6-0.7%. As a result, one formula, based on all data, was adopted:

$$G = 0.634\ L - 3.275,$$

where G = girth in centimeters,
and L = fork length in centimeters.

Results were similar with those of other investigations (Table 5.5.5). For example, at 50 cm estimated girths ranged from 25.2 to 28.2 cm.

Elsewhere

No other reports on Pacific cod were found.

ATLANTIC COD

Results were generally similar to those for Pacific cod (Table 5.5.5). North Sea cod deviated from the British Columbia values by +14.0% at 20 cm, +0.6% at 30 cm, and -11.8% at 70 cm (Table 5.5.6). Comparable values for Labrador cod were +4.3%, -5.8%, and -15.0%, respectively. These differences are probably real, since the Atlantic cod weighed less at comparable lengths (Table 5.5.3).

5.5.3 Age-Length

PACIFIC COD

British Columbia

Mean length-at-age (sexes combined) is a by-product of the Fournier-Foucher method for deriving age-frequencies from length-frequencies. The von Bertalanffy growth parameters currently in use were provided by R.P. Foucher (Pacific Biological Station, pers. comm.), and are as follows:

Region	K	L_{oo}	t_o
Georgia Strait	0.387	87.5	no estimate
S. W. Vancouver Island	0.307	89.48	-0.116
Hecate Strait	0.203	84.008	-0.806

Mean length-at-age generally declined northward (Table 5.5.7). For example, mean lengths at age 3 (methods CL-3 & -4) were 58.3 cm in Georgia Strait, 55.1 cm off southwest Vancouver Island, and 54.6 cm in Hecate Strait.

Recent studies have indicated that it is not necessary to segregate the length frequencies by sex prior to calculating age composition (Foucher and Tyler 1990a). Differences in mean length-at-age were minimal. Furthermore, they noted that although virtually all large cod were females, minor size-at-age differences would be unlikely to influence the modal analysis.

Elsewhere

Mean lengths-at-age varied inversely with latitude for Pacific cod. Off western North America, mean length at age 3 (based on the Foucher-Fournier method) declined northward from 58.3 cm in Georgia Strait, British Columbia, to 50.4 cm in the Gulf of Alaska, and 39.9 cm in the eastern Bering Sea (Table 5.5.7). Off Asia, corresponding values (based on scales and/or otoliths) increased southward from 35.5 cm in the western Bering Sea to 57.5 cm off the east coast of Korea. The west coast of Korea is probably an exception, based on anomalous length-frequency data from that region.

ATLANTIC COD

As with Pacific cod, mean lengths-at-age varied inversely with latitude, except for the Baltic Sea. For example, at age 5 mean length was 56.6 cm in the Barents Sea and 87.9 cm in the southern North Sea, but 49.4 cm in the Baltic Sea (Table 5.5.8). In the northwest Atlantic, comparable values were 43.6 cm off Labrador and 72.6 cm on Georges Bank. The factor of temperature could be substituted for latitude in some cases. For example, off Iceland, the sea temperature gradually decreases clockwise around the island, from the maximum off the south and southwest coast to the minimum off the east coast (Jonsson 1965). During a two-week period in August 1950, the following mean lengths-at-age were obtained from survey data, together with mean temperatures at 50 m during July-August 1948-50:

Sector	Mean				Temp. (C)
	3	4	5	6	
SW	61.6	68.7	77.6	81.2	8.51
NW	--	58.0	70.5	77.8	6.66
N	43.4	51.0	60.5	68.7	4.44
E	39.2	46.9	56.6	65.0	3.57

Spawning occurs off the south and southwest coast, and currents carry the pelagic eggs and larvae clockwise around Iceland. After becoming demersal, cod remain relatively stationary until the onset of maturity, primarily at ages 7-9. Laboratory studies seemed to corroborate the author's conclusion that temperature was the primary factor affecting the growth of juvenile Iceland cod.

In the Newfoundland region (ICNAF 2HJ3KLMNOP), May et al. (1965) reported that growth varied with the surface temperature and volume of cold (<0 C) water in the Labrador Current. Their results, contrary to conventional wisdom, were that K varied directly, and L_{∞} inversely, with latitude. They considered one possible cause could be the direct relationship between length at maturity and latitude. They also acknowledged that estimates of the growth parameters were particularly sensitive to the range of data used. In their case, the ranges varied among individual data sets, and juvenile fish were not uniformly represented. In some cases, mean lengths at ages 1-4 were not included in the computations.

In some regions, mean lengths-at-age varied substantially among years--as much as 10 cm. Some notable examples were northern Norway (Rollefsen 1938, 1954; Borisov 1978; Joergensen 1992), southern Norway (Dannevig 1954), Baltic Sea (Jensen 1954; Dementjeva 1959), North Sea (Daan 1986; Rijnsdorp et al. 1991), and the southwest Gulf of St. Lawrence (Paloheimo and Kohler 1968; Halliday 1972, 1976; Lett et al. 1975). Inverse relationship between stock biomass and growth rate was one factor considered in all four regions. Other factors listed were: genetic selection by the fishery (Borisov, op. cit.) and food abundance (Rollefsen 1954; Joergensen op. cit.), off northern Norway; fishery "targetting" on strong year-classes, in the North Sea (Daan op. cit.); temperature (Joergensen op. cit.); temperature-egg production (Lett et al., op. cit.) and food abundance (Paloheimo and Kohler op. cit.), in the southwest Gulf of St. Lawrence.

5.5.4 Age-Weight

PACIFIC COD

British Columbia

Predictably, the age-weight relationship was described by a sigmoid curve, and for annual weight increments at age, a dome-shaped relationship. Annual weight increments peaked between ages 3 and 4 in Georgia Strait and off Southwest Vancouver Island, and between ages 4 and 5 in Hecate Strait (Table 5.5.9). However, the differences were relatively small between the largest and second largest increment in each area--1.7-3.9%.

For Hecate Strait, a second age-weight relationship was used by Tyler (1990, Table 1) and Tyler and Foucher (1990, text table, p. 68). This yielded heavier weights at age (352-9,240 g @ ages 1-10), because they used: (1) the length-weight relationship of females in July (Westrheim 1977, Table 10); and (2) larger lengths at age, for example: 32.9 cm (352 g) at age 1; 49.1 cm (1274 g) at age 2; 58.1 cm (2188 g) at age 3.

Elsewhere

In the eastern Bering Sea, annual weight increment peaked between ages 4 and 5 (Table 5.5.9). No other records were found.

ATLANTIC COD

Annual weight increments peaked between ages 7 and 8 off Finland (Baltic Sea) (Aro and Sjoeblom 1985, Table 39), and between ages 9 and 10 off northwest Norway (Lebed and Ponomarenko 1985, Table 41).

5.6 REPRODUCTION

INTRODUCTION

Four aspects of reproduction are discussed in this section--spawning, spawning season, length at maturity, and fecundity. Age at maturity could not be dealt with effectively for Pacific cod because of age-determination problems. Hence, no comparison with Atlantic cod was possible, and age-maturity data for Atlantic cod were not included in this report.

5.6.1 Spawning

Pacific cod are single-batch spawners (Foucher and Tyler 1990a), and Atlantic cod are multiple-batch spawners (Hardy 1978). Kjesbu (1989) reported that reared Norwegian Coastal cod, all age 4 and not recruit spawners, spawned 17-19 batches, at intervals of ca. 62-76 h. Interval time varied inversely with water temperature. Numbers of eggs released per batch followed a dome-shaped curve with time. Egg size and dry weight declined with time.

5.6.2 Spawning Season

PACIFIC COD

British Columbia

Although the spawning season for Pacific cod was generally acknowledged to be January-March (Ketchen 1961; Thomson 1962), the first systematic attempt at documentation began in 1975 (Westrheim 1977). During April 1975-February 1976, the same samples used for the aforementioned length-weight

and length-girth studies, off Vancouver Island and in Hecate Strait, provided data for a set of seven gonad-condition criteria, for each sex, specifically designed for field studies at sea or dockside (Table 5.6.1). These criteria were then applied by port liaison officers to trawl-caught cod sampled at the processing plants. Their sampling began on a limited basis in 1976, and has continued uninterrupted to date (1993). An expanded description of the seven maturity stages of ovaries was reported by Bowden et al. (1990).

1975-76 studies. Results were similar for both Vancouver Island and Hecate Strait (Westrheim 1977, Fig. 6). Gonad condition progressed in a similar manner for males and females. Predominant condition was 7 (resting) in July, and 3 (mature) in October. However, in February, conditions 4 (mature), 5 (ripe), and 6 (spent) were reported for cod off West Vancouver Island, but conditions 3 and 4 in Hecate Strait. The author reported that the 1976 spawning season was probably February-March off Vancouver Island, and March in Hecate Strait, and speculated that the differential gonadal development might have been due to water temperature. In February 1976, at 20-49 fath, bottom-water temperatures were 7.6-7.7 C off southwest Vancouver Island, and 6.5-6.9 C in Hecate Strait (op. cit., p. 6).

1976-85 studies. Foucher and Westrheim (1990) reported the results of dockside sampling during 1976-85. Principal sources of the cod sampled at processing plants were Areas 4B, 3Cn, 5C, and 5D. Limited data were available for: all areas in 1976; Areas 5A and 5B (few landings during November-March due to inclement weather); Areas 3D and 5E (negligible cod stocks). No samples were collected from areas south of 3Cn and north of 5E (U.S. zone; no Canadian trawling).

Among months, years combined, gonad development exhibited a similar pattern among areas for both sexes, except that development was slightly slower, or more prolonged, in Area 5D (Fig. 5.6.1). Spawning was essentially complete by April-- incidence of female conditions 6+7 was 80% in Area 5D, and 92-100% elsewhere. To define more closely the spawning duration, Foucher and Westrheim (1990) applied the maximum likelihood method of Welch and Foucher (1988) to fit an ogive to the plot of the proportion of conditions 6+7 vs day of year (Fig. 5.6.2). The ogive formula was used to estimate the day of year at which 50% (D/50) and 90% (D/90) of the females had spawned. Spawning was later and more prolonged in Area 5D, than in Areas 4B, 3Cn, and 5C. D/50 was 76 (March 17) in Area 5D, and 58-68 (February 22-March 9) elsewhere (op. cit., Table 5). Estimates of D/90 were 51 d after D/50 in Area 5D, and 22-33 d elsewhere. Among-area plots of slope at D/50 on D/50 indicated that: (1) Area 4B had the shortest spawning season (steepest slope); (2) Area 5D had the longest spawning season (largest D/50, and shallowest slope); and (3) each area was unique (no overlap among plausibility regions) (Fig. 5.6.3).

Among years, within months, gonad-condition incidences exhibited considerable variability among months for which at least five years of data were collected (Table 5.6.2). For example, in February, incidence of condition-5 females had an overall range of 0 to 50%.

Substantial among-haul variation, on the same ground, was revealed during a research cruise in Area 3Cn during February-March 1978 (Harling et al. 1978). On Amphitrite Bank, the principal spawning ground, relatively substantial catches of cod (603-3,794 cod/h) were made in three hauls. Incidence of conditions 6+7 ranged from 26.0% to 75.4% for males (N = 205-235), and 21.1-76.5% for females (N = 71-328).

Elsewhere

The limited available information suggested that the spawning season was relatively short (Table 5.6.3). Earliest month was December, off northern

Japan and southeast Korea, and latest month was May, off eastern Kamchatka and in the western Bering Sea. In the Gulf of Alaska, the principal spawning months were February-April (Hirschberger and Smith 1983).

ATLANTIC COD

In contrast to Pacific cod, Atlantic cod can be found spawning somewhere in the Atlantic at virtually any time throughout the year, but spawning seasons are distinct and usually relatively short in individual areas (Table 5.6.4). Hardy (1978) noted that peaks occurred from February to mid-September in European waters, and January to December off North America. He also noted that on the New England coast, a "smaller race of cod" spawned from November to April while larger cod began in July.

Brander (1993) summarized published and unpublished information on spawning seasons of Atlantic cod, from the English Channel (ICES VIId,e) to the Gulf of Maine (NAFO 5Y). For the northeast Atlantic, he found a near-consistent direct relationship between latitude and principal spawning month, but not for the northwest Atlantic (Table 5.6.4). In the northeast Atlantic, principal month was February in the English Channel and south North Sea (IVc); March in the Celtic Sea (VIIh), Irish Sea (VIIa), north North Sea (IVa,b), and west Baltic Sea (III/22,24), and April in the east Baltic Sea (III/25-32), Faroes (Vb), off northwest Norway (IIa), and Iceland (Va) (op. cit., Fig. 3).

In the northwest Atlantic, the pattern was not as consistent (Brander 1993). Principal month advanced from February in the Gulf of Maine (NAFO 5Y) to June in the south Gulf of St. Lawrence (4T), but regressed to April-May in the north Gulf of St. Lawrence (4R) (op. cit., Fig. 4). The regression continued off Newfoundland and Labrador--April-May in 3L, April in 3K, and March-April in 2J. Off western Greenland, the pattern of the northeast Atlantic returned--April off south Greenland and May off southwest Greenland (op. cit. Fig. 3).

Two or more spawning seasons per year were reported for the North Sea, Bay of Fundy, and the Scotian Shelf (Table 5.6.4). In the North Sea, a secondary, autumn spawning was discovered by Fulton (1904) which was subsequently deemed of minor importance by Graham (1934). Rae (1964) concluded that the autumn spawning was more regularly observed during 1900-30 than in the most recent period. For the Bay of Fundy, no detailed information was found on autumn spawning. On the Scotian Shelf, important spawnings occurred during March-May and November-December, based on bi-monthly egg and larvae surveys conducted during 1978-82 (Gagne and O'Boyle 1984). The authors hypothesized that the seasonal lulls in spawning were due to adverse temperatures of surface waters--too cold in winter and too warm in summer. They further noted that the late autumn-early winter spawning occurred in the absence of a plankton bloom, in apparent contradiction to the match-mismatch hypothesis of Cushing (1982).

Cushing (1969) remarked on the consistent timing of cod spawning. An apparent exception was the Arcto-Norwegian cod, which spawn off northwest Norway. In this case, a long-term change in peak spawning time was related to a corresponding decrease in mean age of the spawners (Pedersen 1984). Date of peak spawning was delayed about a week over the period 1929-82. Younger cod spawn later than older cod, and heavy exploitation substantially reduced the numbers of older cod in the spawning stock. The author noted that this interpretation contradicted Cushing's (op. cit.) hypothesis that the change indicated an adjustment to climatic change, however it appears to strengthen it.

5.6.3 Length-Maturity

PACIFIC COD

British Columbia

Published estimates of length at which 50% of the cod are mature (L/50) have ranged from 41 to 53 cm for males, and 47-56 cm for females (Table 5.6.5). All estimates except those of Welch and Foucher (1988) were based on visual examination of length-maturity ogives, or linear interpolation of tabular data.

Welch and Foucher (1988) developed a new method to quantify length-maturity and age-maturity relationships, and applied it to length-maturity data for female Pacific cod landed from Hecate Strait during January-March 1960-87. Methodology involved maximum likelihood treatment which explicitly accounted for the binomial nature of maturity data. They concluded that lengths at 50% maturity varied among grounds in Hecate Strait, at least in one year, and among years within grounds. In 1980, estimates of L/50 were 57.0 cm on Two Peaks Ground (feeding ground; 5D), 52.3 cm on White Rocks Ground (spawning ground; 5D), and 43.1 cm on Reef Island Ground (spawning ground; 5C) (op. cit., Table 2). Among years, on White Rocks Ground, available data permitted estimates of L/50 for 1960-61, 1975-76, 1978-80, 1982-83, and 1985-87 (op. cit., Table 3). Estimates ranged from 37.5 cm (1978) to 55.6 cm (1960 & 1976) (Table 5.6.6). However, from their Figure 4, it is evident that the data arrays for 1975, 1978, and 1985-86 exhibited wide error ranges. The remaining data yielded three groups of L/50 estimates: 49.7 cm (1979, 1982-83); 52.3 cm (1980); and 55.1-55.6 cm (1960-61, 1976, 1987). The authors noted that the inter-year differences "correspond to shifts of slightly more than 1 y in the median age-at-maturity" (op. cit., p. 333), if somatic growth remained constant. However, they noted that age-determination of these cod was not validated, and inter-annual changes in growth of individual year-classes could not be established.

Linear interpolation was applied to the data for male and female Pacific cod lacking parabranchial lesions which were sampled from Areas 4B, 3Cn, and 5D (Table 5.6.7). Parabranchial lesions inhibit gonad maturation, but their incidence is relatively high only in cod from Areas 3Cn, 3D, and 5A (Westrheim 1987)(see Section 5.10 for details). Interpolated estimates of L/50 appeared to be satisfactory, based on comparisons with selected samples from Hecate Strait which were also processed with the Welch-Foucher maximum likelihood method (Table 5.6.8). Among-method differences for Two Peaks and White Rocks were small, -1.1% to +1.2%. No linear interpolation was possible for the Reef Island sample.

Elsewhere

In the eastern Bering Sea, L/50 estimates were 60 cm for males and 62 cm for females (Table 5.6.5). These were based on gonadosomatic indices, by size interval, of 1,899 cod collected during July-December 1981 and 1982 (Teshima 1985). Size intervals were <499 mm, 500-599 mm, 600-699 mm, and >700 (sic) mm. Off west Kamchatka, L/50 estimate was 69 cm for sexes combined, based on an interpolation of data in Moiseev (1953, Table 41).

ATLANTIC COD

Northeast Atlantic

In the North Sea, L/50 for both males and females has declined substantially from the late 19th Century to 1972 (Table 5.6.9). For males the decline was from 72 cm to 53 cm, and for females, 74 cm to 60 cm. In the Baltic Sea, L/50 values, by sex, were approximately 25 and 28 cm (Poulsen 1931).

Northwest Atlantic

L/50 values were 36-66 cm for males, and 34-72 cm for females (Table 5.6.9). They varied inversely with latitude and among years, within areas. The west Greenland values (64-66 cm, 72 cm) were substantially larger than those in the Labrador-Scotian Shelf region, but were also collected at a much earlier time--<1931 *vs* 1947-79. In the Labrador-Newfoundland region, recent studies by Xu *et al*. (1993) provided further complications (see below). Temporal variations were substantial in the southwest Gulf of St. Lawrence and on the Scotian Shelf. For both the southwest Gulf of St. Lawrence and the Scotian Shelf (Beacham 1983b), L/50 values decreased substantially during 1955-79 and 1959-79, respectively. Beacham (1983a,b) attributed the decline in L/50 primarily to the substantial increase in exploitation by the fishery.

Xu *et al*. (1993) investigated L/50 (and A/50) of cod in NAFO Divisions 2J, 3K, and 3L. Collections, by research vessel, occurred only in autumn--1978-90 for 2J and 3K, and 1981-90 for 3L (Table 5.6.10). L/50 was estimated with a logistic equation. They noted an inverse relationship with latitude and year (only 2J and 3K), but offered no explanation. Water temperature seemed to have a two-year lagged effect, and an optimum temperature may exist. Cod biomass seemed to have a one-year lagged effect, which varied inversely with size of biomass.

5.6.4 Fecundity

INTRODUCTION

All length-fecundity relationships reported for Pacific and Atlantic cod, except that of Postolakii (1967), were exponential ($F = aL^b$). Results are summarized in Table 5.6.11. Because Atlantic cod are multiple-batch spawners, determining the number of oocytes which will mature each year is not as simple as for Pacific cod, a single-batch spawner. Kjesbu *et al*. (1990) provided a method for determining the stage of spawning for Atlantic cod.

PACIFIC COD

British Columbia

For British Columbia, two cod fecundity studies were reported (Thomson 1962; Foucher and Tyler 1990b). Thomson's specimens were collected in Hecate Strait during February 1961. Foucher and Tyler collected specimens in Hecate Strait, during January-February 1986-89, and off southwest Vancouver Island, during January-February 1988 and 1990. They also described the

histological development of the gonads. Foucher and Tyler (op. cit.) reported little variation in the length-fecundity relationship by year, geographic area, or temperature, within the range of their data. Overall formula was: log F = -5.890 + 3.386(log L); N = 355; r = 0.91. Their estimates for Hecate Strait were 6-12% greater than those of Thomson, 25-28 years earlier. Estimated fecundities, for their combined data were 1,352,000 ova at 60 cm and 3,580,000 at 80 cm (Table 5.6.11).

Washington State

The only other reported study in the northeast Pacific was by Karp (1982), in nearby Juan de Fuca Strait (Port Townsend; Area 4A) during February 1977 and 1978. Estimated fecundities were substantially larger than those reported for Canadian waters. For example, his estimated fecundity at 60 cm was 2,200,000 ova, compared to 1,390.000 off southwest Vancouver Island, and 1,326,000 in Hecate Strait (Table 5.6.11).

Northwest Pacific

Moiseev (1953) reported on the fecundities of specimens collected during 1939 off west and southeast Kamchatka, and during 1947 off west Sakhalin Island. No formula was reported, but estimated fecundities were reported for selected lengths (op. cit., Table 50). Fecundities were 1,809,000-1,986,000 at ~60 cm, and 3,055,000-4,745,000 at ~80 cm (Table 5.6.11).

ATLANTIC COD

Northeast Atlantic

Fecundities were reported for cod off Norway (Arcto-Norweigian and Coastal "stocks") and Iceland, and in the North and Baltic seas (Table 5.6.11). Fecundity was relatively low for the Arcto-Norwegian cod; intermediate for North Sea and Iceland cod; and relatively high for the Norwegian Coastal and Baltic Sea cod. Fecundities of Norwegian Coastal and West Baltic cod were similar to those off western Canada. Kjesbu (1988) noted that the actual inter-stock difference between Arcto-Norweigian and Coastal cod may be smaller. Stock identification of individual specimens was based on otolith interpretations, and 40% of each group "were placed with lesser certainty" (op. cit., p. 54).

Kjesbu et al. (1991) reported that actual fecundity of Atlantic cod was 20-80% of potential fecundity, depending on nutritional condition of the spawner. His conclusion was based on studies of aquarium-held cod fed at four ration levels 6-9 months prior to, and during, spawning.

Oosthuizen and Daan (1974) established five length- or weight-fecundity relationships for North Sea cod. Correlation ratios ranged from 0.725 to 0.865. The highest correlation was observed in the linear fecundity-weight function, but the second highest (r = 0.825) was for the exponential fecundity-length function. They compared the weight-fecundity relationships of Atlantic cod elsewhere, and concluded that the highest fecundity was attributed to cod off southern Norway (IVa) and in the west Baltic Sea. Intermediate values were noted for cod from the North Sea, Iceland, and the Gulf of St. Lawrence. Low values were attributed to cod off Labrador and Newfoundland.

Rijnsdorp et al. (1991) reported that for North Sea cod fecundity was positively correlated with spawning biomass.

Northwest Atlantic

Fecundities were reported for Labrador (2GHJ), Labrador and Newfoundland (2J3KLNO), Newfoundland (3LPs), and the Gulf of St. Lawrence (4T), and generally varied inversely with latitude (Table 5.6.11). For Labrador, Postolakii (1967) reported a linear length-fecundity relationship (F = 0.022L - 0.800; N = 65; 45-77 cm), which yielded unreasonable fecundities (not included in Table 5.6.11). However, a log-log regression of the data in his Table 2 yielded a good fit ($F = 0.0755L^{2.164}$; r = 0.919).

May (1967) collected samples from four areas in the Labrador-Newfoundland region, and noted no difference in regression slopes among areas, but intercepts varied such that fecundity-length was greater for northern fish. He compared length-fecundity relationships for Atlantic and Pacific cod, and noted greater fecundities for cod from southern Norway, west Baltic Sea, and western Canada, than for those from Labrador-Newfoundland and the southwest Gulf of St. Lawrence.

Pinhorn (1984) collected samples from four inshore areas of Newfoundland, and one offshore bank, and also reported significant differences in regression intercepts, but not slopes. Inter-year differences within areas precluded testing for inter-area differences in intercepts. After re-arranging the data of May (1967) to conform with bottom-water temperatures, the relationship of length-fecundity (and age-fecundity) regression slopes vs bottom temperature was dome-shaped, with the peak at 2.0 C, over a range of -0.5 to +3.5 C (op. cit., Fig. 4).

Buzeta and Waiwood (1982) noted that the only fecundity study, prior to theirs, in the southwest Gulf of St. Lawrence was undertaken during 1955-56 (Powles 1958) when the cod exhibited accelerated growth, probably due to increased predation on herring suffering an epizootic outbreak (Ichthyosporidium hoferi). Hence, fecundities at that time might not have been "normal". Their tests suggested that there was no significant difference between the length-fecundity relationships of 1955-56 and 1981.

5.7 EARLY LIFE HISTORY

INTRODUCTION

Few field or laboratory studies have been undertaken in British Columbia, or elsewhere, on the early life history of Pacific cod. As was noted in Chapter 4 (Distribution), life history studies of other gadoids yielded little ancillary information.

A substantial literature exists concerning the early life history of Atlantic cod, including the extensive drift of the pelagic eggs and larvae in most regions. However, comparisons with Pacific cod are handicapped, because of the limited information on Pacific cod, and the contrasting demersal nature of at least its eggs.

5.7.1 Eggs

PACIFIC COD

Table 5.7.1 summarizes selected parameters of Pacific cod eggs, all based on laboratory studies. Mean diameter of fertilized ova was 1.02 mm in British Columbia and the "northeast Pacific", 0.96 off Washington State, and 0.98 mm off Asia. All laboratory studies reported the eggs to be demersal, and adhesive. Optimum incubation conditions of temperature (C), salinity (o/oo), and oxygen (ppm), in British Columbia waters, were determined to be 3-5 C, 13-23 o/oo, and 2-3 ppm to saturation. Optimum salinity was estimated to be <30 o/oo off Asia. Incubation times were roughtly similar among regions-- 15-17 d @ 3-5 C off British Columbia, 12 d @ 8-9 C off Washington State, and 9-14 d @ 7-11 C off Asia.

The British Columbia studies involved live cod caught by trawl on a nearby spawning ground in Georgia Strait (Nanoose; MSA 17n; Fig. 4.2) and transported to the Pacific Biological Station, where the ova were fertilized, and the experiments were conducted (Forrester 1964; Forrester and Alderdice 1966; and Alderdice and Forrester 1971). The authors emphasized that coroborative field studies should be undertaken.

A field study was undertaken, during 1976-78, to locate concentrations of the demersal, incubating eggs, and to determine the surficial sediments selected by the cod for egg deposition. The major spawning ground (Amphitrite Bank) off southwest Vancouver Island was selected, because of its relatively small size and shallow depth (<65 m). Results were summarized in Luternauer et al. (1986). Briefly, surficial sediments were sampled with a Shipek grab and a boulder dredge (1-m diam. mouth); the entire bank was "mapped" for bottom type, by echo sounder and side-scan SONAR; photographs of the sea floor were taken at 10 stations; and a visual inspection of a portion of the bank was completed with the research submersible PISCES IV. No eggs were located. Interviews with trawler captains revealed that "actively spawning" cod were only found over sites where the surficial sediments were determined to be coarse or fine, non-rippled, sandy gravel. Contents of Shipek grab samples collected on other trawling grounds where spawning cod congregated were: sand at Nanoose (Area 4B, MSA 17n; Westrheim et al. 1977); muddy sandy gravel, sand, gravelly sand, and/or shell at Reef Island (Area 5C; Westrheim et al. 1980a); and sand or muddy sand at White Rocks (Area 5D)(Westrheim et al., op. cit.; Westrheim et al. 1984). In addition, as noted in Chapter 4, cod eggs were reportedly caught in Baynes Sound (Area 4B, MSA 14) on a substrate of coarse sand and cobble during field tests of an on-bottom sled-net (Phillips and Mason 1986).

ATLANTIC COD

Eggs are pelagic after fertilization; are larger (1.2-1.6 vs 0.96-1.02 mm diameter) than those of Pacific cod; and incubation time varies inversely with surface water temperature--50-60 d @ -1.5 to 0 C to 14 d @ 6 C (Scott and Scott 1988). Studies on the effects of temperature and salinity on egg incubation have been conducted in the northeast and northwest Atlantic.

Northeast Atlantic

Kjesbu and Kryvi (1989) described oogenesis for Norwegian Coastal cod, based on reared specimens.

For North Sea cod, Thompson and Riley (1981) incubated eggs, from laboratory-reared specimens, at a series of temperatures (0-14.03 C) to define developmental stages. They reported that all eggs died at temperatures >12 C, prior to blastula stage, and temperatures >15 C at early stages of cleavage. For Norwegian Coastal cod, experiments in relation to thermal pollution from a nuclear power plant (6-18 C; constant salinity) also yielded substantial egg mortality at temperatures >12 C (Iversen and Danielssen 1984). Kjorsvik et al. (1984) investigated the effects of salinity (13, 20, 27, 34, 41, and 48 o/oo; temperature constant) on fertilization and incubation. Egg quality varied among females. For good quality eggs, fertilization success was optimal at 27-41 o/oo (>80% success), and hatching success was good (50-80%) at 34-48 o/oo. Osmolarity of eggs was adversely affected by sub-optimal salinity only during the first 24 h after fertilization.

Kjesbu et al. (1992) reported that for reared Norwegian Coastal cod, buoyancy varied directly with egg size; egg size declined with time among batches from the same fish; and egg size in the first batch varied directly with fish weight. They concluded that repeat spawners probably had a higher reproductive success.

Northwest Atlantic

In northeast United States, the first laboratory study involved eggs collected from cod in Ipswich Bay, Massachusetts (Bonnet 1939). Eggs were incubated at variable temperatures (6-14 C) and constant salinity (32.31 o/oo). Mortality varied directly with temperature. A subsequent study involved temperature (2-12 C) and salinity (26-36 o/oo)(Laurence and Rogers 1976). Mortality was independent of temperature, but varied inversely with salinity.

In contrast to the variable quality of eggs of tank-held recruit and repeat spawners in the northeast Atlantic (Kjesbu et al. 1992), Trippel and Neilson (1992) found no difference in fertility or quality of sperm between tank-held recruit and repeat spawners in the northwest Atlantic.

5.7.2 Larvae

PACIFIC COD

Selected parameters are summarized in Table 5.7.1. No catches of Pacific cod larvae have been reported from British Columbia waters, but laboratory studies reported the length at hatching was 4.1-4.5 mm TL. Estimates elsewhere were 3.2-3.5 mm at Port Townsend, Washington, and 3.6 mm off Asia. For Port Townsend, Walters (1984) reported modal lengths of larval cod to be 4.7 mm in March 1979, and 5.6-12.7 mm in May 1978. All specimens were caught close to the bottom at depths of 5-11 m. For the north Pacific, estimates of length at metamorphosis ranged from >25 mm to <40 mm.

ATLANTIC COD

Scott and Scott (1988) reported length at hatching was 3.3-5.7 mm, and the young ended their pelagic phase at 25-50 mm. Larvae metamorphose at ca. 10 mm in the North Sea (Graham et al. 1926) and off Iceland (Thorisson 1989), and

at 10-12 mm (at 7-10 C) off northern Norway (Bergstad et al. 1987, Table II). Demersal existence begins at 2-3 cm in the North Sea (Graham et al., op. cit.), and off Newfoundland (Thompson 1943).

5.8 DIET

5.8.1 Larvae

No information was found on the diet of Pacific cod larvae in British Columbia waters. In northern Honshu, tank-held larvae were selective feeders on crustacean and mollusc larvae (Yamamoto and Nishioka 1952). Principal component in the diet of Atlantic cod larvae was copepods (Graham et al. 1926; Ellertsen et al. 1981; Skreslet 1989; Thorisson 1989). The latter author noted that off Iceland, capelin larvae were an important component during the late stages of larval life.

Juveniles and Adults

PACIFIC COD

British Columbia

The omnivorous nature of the Pacific cod diet was reported by Hart (1949), Black (1984), and Westrheim et al. (1989). Hart (op. cit.) examined 491 stomachs, mostly collected coastwide during winter, and reported 26 invertebrate and fish components, as well as kelp and gravel. Black (op. cit.) examined the stomach contents of 615 cod (2-59 cm SL) collected during 1978-81 in a kelp-ecology study off northeast Vancouver Island (Area 4B, MSA 12). The invertebrate category contained 159 categories, representing 7 phyla, while the fish category contained 11 families, 12 species, clupeid eggs, and unidentified eggs and larvae. The miscellaneous category included algae, stones, and wood. Westrheim et al. (op. cit.) reported on the results, with respect to Pacific cod, of a study conducted during 1982-83 to investigate the frequency of Pacific herring in the diet of commercially important groundfish species. Stomachs were collected from 1,395 cod (32-89 cm FL) landed at processing plants during September-November 1982. Principal locations of catch were Queen Charlotte Sound and Hecate Strait. Invertebrate categories totalled 26, and fish categories totalled 18.

The "boundary" size between invertebrate- and fish-feeders was approximately 50 cm (mostly age 2+) for cod from west Vancouver Island and Hecate Strait during April 1975-February 1976 (Westrheim 1977). In Queen Charlotte Sound and Hecate Strait, during September-October 1982, the boundary was approximately 56 cm (mostly age 3+) (Westrheim et al. 1989).

Principal invertebrate and fish components are listed in Table 5.8.1. Important invertebrates were amphipods, euphausiids, crangonids, pandalids, and crab (principally Cancer spp.). Important fish species were pleuronectids, bothids, herring, and sandlance. During the seasonal bathymetric migrations of Pacific cod (Westrheim and Tagart 1984), sandlance was important while cod occupied shallower water (usually April-September), while herring was important while cod occupied deeper water (usually October-March). Miscellaneous components regularly reported were algae, stones, and wood.

Commercially important prey of Pacific cod were pink shrimp (Pandalus borealis and P. jordani) and Pacific herring. No evidence was found that indicated that cod predation was a threat to the shrimp resource. Ware and McFarlane (1986) provided the first quantitative evaluation of herring predation by cod (>= age 2), adult Pacific hake, and juvenile sablefish, off southwest Vancouver Island. They concluded that during 1960-81 survival of juvenile herring was most sensitive to the variations in biomass of adult Pacific hake.

Periodicity in the inter-annual incidence of important prey was reported by Westrheim and Harling (1983). Their data base was the qualitative estimates of stomach contents recorded, during 1950-80, by port samplers collecting length-frequency samples from commercial landings at processing plants. Periodicities were 3.9 y for sandlance (all areas); 4.7 y for herring (west Vancouver Island); and ~ 7-9 y for sablefish (Hecate Strait).

Incidence of empty stomachs was maximal during the spawning season--41-46% during February; 3-15% during April-October (Westrheim 1977). A complex relationship was noted between maximum weight of stomach contents and length interval. That is, there was both an exponential and dome-shaped relationship (op. cit., Figs. 11-14). During the spawning season the predominant relationship was dome-shaped (mode at ca. 60 cm). Seemingly, most of the larger (older) cod were not feeding, and hence might not survive long after the spawning season.

An unusual diet-related contamination of trawl-caught Pacific cod and English sole was reported by Lippa (1965). The species were caught on Two Peaks Ground (Hecate Strait) in June 1964. The entire landing was condemned as being spoiled and unfit for human consumption. The flesh smelled like hydrogen sulfide. Stomach contents of the English sole consisted entirely of Limacina sp., a pelagic pteropod (~2-mm shell). The vessel crew reported that the cod stomachs emitted an unpleasant odor during dressing operations at sea. No other vessels fishing nearby encountered this problem, nor did the vessel on subsequent trips to the same ground.

Elsewhere

Walters (1984) provided the only information on the diet of very young juvenile cod (Age-0, 20-100 mm). The specimens were collected near Port Townsend, Washington (Juan de Fuca Strait, Area 4A), during May-June 1978. The four major food items were calanoid copepods, harpacticoid copepods, mysids, and gammarid amphipods, in chronological order of importance as the fish grew. Harpacticoid copepods were most important in stomachs of cod 35-75 mm.

General results were similar for Pacific cod off Alaska and in the northwest Pacific. with respect to omnivorous diet (Cobb 1927; Moiseev 1953; Krivobok and Tarkovskaya 1964; Jewett 1978; Hashimoto 1974; Clausen 1981; Livingston 1991; Tokranov and Vinnikov 1991), diet-length relationship (Moiseev op. cit.; Mito 1974; Jewett op. cit.; Clausen op. cit.; Livingston et al., 1986; Livingston op. cit.; Tokranov and Vinnikov, op. cit.), and season (Moiseev op. cit.; Hashimoto op. cit.; Livingston et al., op. cit.; Livingston, op. cit.; Tokranov and Vinnikov, op. cit.). However, with respect to omnivorousness, Moiseev (op. cit., p. 165) cogently observed that "In the regions where the cod feed simultaneously on a great number of objects, we observed no accumulations of these fish". Stomach-content studies may be seriously biased which do not include, as a factor, the magnitude of catches, from which the cod are collected.

Principal invertebrate components were crab (Cancer, Chionoecetes, Paralithodes) and shrimp (Pandalus), from the Gulf of Alaska to the Japan Sea (Table 5.8.2). Principal fish species was walleye pollock, from the Gulf of Alaska to the Okhotsk Sea. Other important species, reported in some area-time cells, included "atherina" (Atherinops?)(Moiseev, 1953), capelin, (Mallotus villosus), herring, Pacific cod, salmon smolts (in estuaries), sandlance, and

sardine (Sardinops melanosticta).

Cod predation was hypothesized to be an important factor in the abundance decline of pink shrimp in the Gulf of Alaska (Blackburn 1986). The dramatic decline during 1978-84 was attributed to three factors--the shrimp fishery, the coincident rise in abundance of Pacific cod and walleye pollock, and increasing water temperatures. In the eastern Bering Sea, cod was determined to be an important predator on snow (Chionoecetes opilio) and Tanner (C. bairdi) crabs (Livingston 1989,1991). For 1981, 1984, and 1985, Livingston (1989) estimated predation on age-1 snow crabs as 28, 57, and 27%, respectively, based on "reconstructed" populations of crab. Comparable values for Tanner crab were 84, 95, and 95%. Livingston (1991) estimated removals by cod in 1984 and 1985 of age-1 crabs to be 41.6 and 31.0%, respectively, for snow crab, and 89.4 and 94.2% for Tanner crab.

ATLANTIC COD

The omnivorous nature of Atlantic cod was presciently noted by Brook (1886, p. 145), when he stated that "On what will a cod feed? On anything or almost anything". General results were similar to those for Pacific cod with respect to omnivorous diet, diet-length relationship, and season (for example, Bergstad et. al. 1987; Brown and Cheng 1946; Daan 1973, 1989; Jensen 1972; Langton and Bowman 1980; Lilly and Fleming 1981; Scott and Scott 1988; Waiwood and Majkowski 1984). Rice (1988) proposed a method of repeated k-means cluster analysis for exploratory analysis of stomach contents, and objective rules for setting the clustering parameters. He illustrated the method with a data set of 1,771 cod stomachs collected from the Grand Bank in the spring of 1979.

Numerous invertebrates were listed as important in one or more areas, but the more universal items were euphausiids, shrimp (Crangonidae and Pandalidae), and decapod crabs (Table 5.8.3). The most universal fish species was herring. Other important species were capelin (Barents Sea, Iceland, Greenland, Labrador, and Newfoundland) and sandlance (North Sea, Faroe Islands, Iceland, Greenland, and Scotia Bank). Daan (1973) noted that the fish components in the diet of adult cod in the North Sea were primarily commercially important species, including cod. Cod (usually age 0) were important diet components in the Barents Sea, North Sea, Baltic Sea and off Canada. Cod were considered to be an important negative factor in the survival of brown shrimp (Crangon crangon) in the coastal waters of Germany (Tiews 1978) and the Netherlands (Boddeke 1978).

Odoriferous cod is not an unusual event off Labrador, Newfoundland, Greenland, and Norway. The phenomenon has been variously called blackberry, black, or gunpowder (Sipos and Ackman 1964). They identified the source, but not the causative agent, of the smell as dimethyl sulfide (DMS), resulting from the breakdown of dimethyl-beta-propiothetin (DMPT). DMPT fed directly to cod held in aquaria failed to breakdown to DMS (Ackman et al. 1966). Causative agent was found to be Limacina helicina, an arctic-water pteropod, which cod feed on at times (Ackman et al. 1967). DMS is broken down from DMPT by an enzyme presumably in the algae eaten by Limacina. Incidence of odoriferous cod was particularly serious in 1963 and 1981 off Labrador and northern Newfoundland. The problem first arose off Canada when the inshore fishery began changing from salting to icing or freezing the catches. Presumably salting prevented the creation of DMS. The solution to the problem was prolonged cold storage of odoriferous cod fillets (Botta et al. 1985). Minimum storage to remove the odor was 8 weeks at -15 C.

5.9 PREDATORS

5.9.1 Eggs and Larvae

PACIFIC COD

No reports were found which dealt with predation on eggs of Pacific cod. The scyphozoa Phacellophora camtschatica and the hydrozoa Aequorea victoria were reported as predators on Pacific cod larvae in British Columbia waters (Purcell 1985).

ATLANTIC COD

Daan et al. (1985) reported that herring (chiefly age-groups 2-3) consumed cod and plaice eggs in the southern North Sea. Rough estimate of consumption of cod eggs was 0.04-1.9% of the initial numbers produced. For cod larvae, Bailey (1984) reported on the predatory behavior, from laboratory studies in Europe, of scyphozoa (Aurelia aurita), euphausiids (Thysanoessa rashi), and copepods (Euchaeta norvegica). Predation success varied inversely with larva size. A more detailed account of the mechanism of scyphozoan predation was reported by Bailey and Batty (1984). Purcell (1985) reported similar results, from laboratory studies in Newfoundland, for predation by Aurelia aurita.

5.9.2 Juveniles and Adults

PACIFIC COD

Reported predators totalled 15 species--6 fish, 2 birds, 5 seals, and 2 sealions (Table 5.9.1). Of these, three fish species, one bird species, and two seal species were reported to prey on cod in British Columbia waters. The single report of cannibalism involved one 17-cm specimen found in the stomach of a 37-cm female caught in Hecate Strait in September 1979 (Westrheim et al. 1980b). In all cases, Pacific cod was a minor component in the predator's diet.

ATLANTIC COD

The list of predators is similar to that for Pacific cod. Included were 9+ fish species, 2 bird species, 5 seal species, and 3 whale species (Table 5.9.1). Cod was reported to be a minor component in the diet of all predators except grey seals off Iceland (Hauksson 1984) and Atlantic cod in the Barents Sea (Graham et al. 1954; Ponomarenko 1965), Baltic Sea (Poulsen 1931), and North Sea (Daan 1973). Cannibalism involved both adults on juveniles, and juveniles (ages 1-3) on juveniles (age-0).

5.10 PARASITES

INTRODUCTION

The parasite literature is relatively limited for Pacific cod, but voluminous for Atlantic cod. For the latter species, a detailed treatment is beyond the scope of this report. Hence, reports for Atlantic cod are limited to those dealing with parasites also found on Pacific cod, and those on Atlantic cod in Canadian waters.

In this Section, and the next (5.11. Diseases and Pathogenic Parasites), the terms describing "frequency" will be those used by the American Society of Parasitologists (Margolis et al. 1982) as follows:

Prevalence =	the percentage of an animal group infected by a parasite species.
Incidence =	the percentage of animals that have become parasitized or diseased in a defined period of time. (laboratory studies)
Intensity =	the number of individuals of a parasite species in a host.

5.10.1 Eggs and Larvae

No reports were found which dealt with parasites of eggs or larvae of Pacific cod, or Atlantic cod in Canadian waters.

5.10.2 Juveniles and Adults

At least 46 species of parasites were reported in Pacific cod, of which 21 were also attributed to Pacific cod in British Columbia waters (Table 5.10.1). Total species reported for Atlantic cod in Canadian waters was 66, of which 23 were also reported for Pacific cod. Among these, the "sealworm" (= "codworm"), in cod musculature, and a protistan amoeboid, in parabranchial X-cell lesions, deserve additional attention.

The "sealworm" is the larval form of Pseudoterranova decipiens, and infests cod and other marine species (Bowen 1990). The adult form infests seals. No reports were found which dealt with the sealworm in British Columbia waters, and presumably it is not detrimental to the local cod fishery. The sealworm was the only parasite reported to be detrimental to the Atlantic commercial industry, and humans. The relatively large larvae (9-58 mm) are encapsulated in the musculature, and their presence repels the potential consumer, and consequently adversely affects market demand (see Margolis (1977) for reviews of research on this problem). Hence, cod fillets must be "candled", and the larvae removed prior to freezing and packaging (Power 1961). Adequate freezing or cooking kills the larvae and renders them harmless, but the larvae are potentially dangerous to consumers of raw, unfrozen, or inadequately cooked cod flesh (Margolis op. cit.). The ingested live larvae may penetrate the stomach wall, and cause acute abdominal pain as well as infection. The only cure is physical removal of the

larva. However, even in Japan, where consumption of raw fish is common, the incidence of such events is rare. Margolis (op. cit.) noted that only 69 cases were documented in Japan up to 1969, of which at least eight were believed to have involved Pacific cod.

Recently, a comprehensive workshop on the sealworm was completed (Bowen 1990). At the workshop, Brattey et al. (1990) provided a detailed report on the geographic distribution and abundance of the sealworm in the musculature of Atlantic cod from Newfoundland and Labrador. During 1985-87, they examined 12,652 specimens of Atlantic cod from 21 localities in the Labrador-Newfoundland region. More parasites were found on the left side of each cod, and the number in the flesh surrounding the body cavity increased with cod length. Prevalence and abundance was generally low (<18%; <0.3 worms/fish) in cod collected off Labrador, northeast Newfoundland, and on the Grand Bank. Comparable values were higher, and more variable, off south Newfoundland (20-100%; 0.3-22 worms/fish), and were up to three times higher than those reported off south Newfoundland during 1947-53.

Parabranchial X-cell lesions are currently attributed to a protistan parasite, tentatively identified as a member of the family Hartmannellidae (Dawe 1981). Since 1929, when the lesions were first reported, they have been variously identified as adenocarcinomas, adenomas, carcinoids, chemodectoma-like tumors, and "tumors" (Westrheim 1987). Prevalence in Pacific cod from British Columbia waters ranged from 0.7 to 18.0% for 238,699 trawl-caught cod examined during 1968-85. Prevalence varied inversely with cod length; poorly with cod abundance; and directly with abundance of nearby sealions. Lesion prevalence was reported to be low elsewhere in the Pacific Ocean (McCain et al. 1978, 1979) and in the Atlantic Ocean (Dethlefsen 1980; Egidius et al. 1981; Morrison et al. 1982; Waterman and Dethlefsen 1982).

5.11 DISEASES AND PATHOGENIC PARASITES

INTRODUCTION

In contrast to the limited information reported for parasites in Section 5.10, all records of diseases and pathogenic parasites, for both Pacific and Atlantic cod, have been included here. Two reasons underlie this procedure. First, few reports were found which dealt with either species, especially Pacific cod. Second, most of the diseases and pathogenic parasites reported for Atlantic cod may also be a threat to, or afflict, Pacific cod.

5.11.1. Eggs and Larvae

No reports were found which dealt with diseases of Pacific or Atlantic cod eggs, and only one of Atlantic cod larvae. Moeller and Anders (1986) reported that black spot disease was fatal to larval and juvenile Atlantic cod if the digenean causative agent (usually Cryptocotyle lingua) penetrated the brain or heart.

5.11.2. Juveniles and Adults

Limited information was found on diseases or pathogenic parasites of juvenile or adult Pacific and Atlantic cod, and even less on the effects thereof.

A total of 34 different "ailments" (14 unnamed) were reported--5 for Pacific cod, and 29 for Atlantic cod (Table 5.11.1).

PACIFIC COD

Only three of the five ailments had names assigned to them (Pacific cod herpesvirus, vibriosis, and parabranchial X-cell lesions) (Table 5.11.1), and only one was reported in British Columbia waters (parabranchial X-cell lesions). Causative agents were viruses, bacteria, and "protozoa". Pathogenic effects were only reported for the parabranchial lesions. However, the epidermal ulcers, on Alaskan cod, were noted by Munro et al. (1983) to be similar to those of the ulcus syndrome "complex" in Baltic Sea cod (see below).

Parabranchial X-cell lesions were also reported elsewhere in the northeast Pacific Ocean, and in the northeast and northwest Atlantic Ocean, but prevalence was relatively low except for two areas in British Columbia (3Cn and 5A) (Westrheim 1987). At high prevalence levels, the adverse effects were delayed maturity, inhibited growth, and increased mortality rate (Z).

ATLANTIC COD

Causative agents of the 29 ailments (13 unnamed) included viruses, fungi, bacteria, "protozoa", trematodes, nematodes, amphipods, copepods, and two "complexes (vibriosis and ulcus syndromes). Principal ailments were debilitation, hemorrhagic septicemia, anemia, organ atrophy, and epidermal ulcers. The two "complexes" were serious in the Baltic Sea. Factors associated with the vibriosis complex were high cod abundance, low food abundance, and bacteria (Aeromonas, Pseudomonas, and Vibrio) (Ipatov 1989). For the ulcus syndrome, the factors were viruses, pollution, and bacteria (Jensen 1983: Larsen 1983; Munro et al. 1983). The copepod Clavella adunca was reported to adversely affect the length-weight relationship, condition factor, and mean length-at-age of Atlantic cod off Labrador and Newfoundland (Janusz 1980). Morrison et al. (1982) reported that tank-held Atlantic cod with parabranchial X-cell lesions exhibited retarded gonad development, and suffered a high mortality due to bacterial infections.

5.12 SUMMARY

Size Composition

Pacific cod. Maximum length reported in British Columbia waters was 100 cm; and elsewhere, 109 cm in the Gulf of Alaska, 110 cm in the eastern Bering Sea, and 114 cm off Russia. Size range of cod landed at British Columbia processing plants, during 1951-85, was ca. 41-80 cm, with one or two modes at 47-65 cm, but no temporal long-term trend in mean length. Corresponding size range of cod caught in research-vessel catches was 4-80 cm, and multi-modality was the rule. Modal progressions were attributed to the passage of strong year-classes. Multi-modality suggested rapid growth, and temporal stability suggested that the fishery had no appreciable effect upon the stock. Similar data were reported for cod off Washington State and Alaska. Off Asia, mean lengths varied directly with latitude, from the west Bering Sea (61-72 cm) south to the west coast of South Korea (23-36 cm).

Atlantic cod. Maximum length reported was ~185 cm (98.5 kg), for a cod caught off Massachusetts. Modal lengths in commercial catches were 35-110 cm in the northeast Atlantic, and 46-62 cm off Canada. In research-vessel catches, modal length ranged from 7 to 42 cm in the Baltic Sea, and was 25 cm in the North Sea.

Sex Ratio

Pacific cod. Sex ratio, among length intervals, in British Columbia waters was approximately 50% males up to about 62-65 cm, then declined sharply to about 12-16% at >81 cm. The differential sex ratio was reported in samples from both commercial landings and research-vessel catches. The sharp decline in percent males among the larger cod suggested that males either have a shorter life span, slower growth after maturity, or differential availability to the trawl nets. Similar results were reported elsewhere in the Pacific.

Atlantic cod. In the Labrador-East Newfoundland region, sex ratio among length intervals also declined among larger cod. Off Labrador, sex ratio per 5-cm interval was 53% at 40-53 cm, then declined steadily to 16% at 70-74 cm. Off Newfoundland, sex ratio per 10-cm interval was 50-53% at 41-80 cm, then declined to 7% at 101-130 cm. No other published records were found.

Age Determination

Pacific cod. To date (1993), no report has been published which validates any method for determining the age of Pacific cod in British Columbia waters, or elsewhere. In British Columbia waters, scales appear to be reasonably satisfactory for juvenile cod (age 0-2), and dorsal fin-ray cross-sections show promise for adult cod. Meanwhile, production ageing of B.C. cod continues to involve a length-frequency iterative method, currently the MULTIFAN. Multi-modal length-frequencies of age-1 cod sampled during January-March cast some doubt on the validity of the iterative method, and also suggest that the spawning season may be prolonged, at least in some areas. In Alaskan waters, scales and length-frequency iterations have been abandoned, and otolith cross-sections are reported to be promising. In the northwest Pacific, a Russian report recommended scales for juvenile cod, and otoliths for adult cod.

Atlantic cod. Otolith cross-sections are the established method of age determination. However, results of recent workshops indicate that regional, and perhaps national, interpretation problems still exist.

Age Composition

Pacific cod. In British Columbia waters there are few age-classes, and age composition is dynamic due to the substantial fluctuations in abundance of year-classes. Age-classes 2-4 comprised 84-95% of the landings, and no cod were reported to be older than 11 y. Among year-classes 1953-76, those prominent in at least two areas were 1961-62, 1969-70, 1972-73, and 1975. Among areas, ratios of maximum/minimum year-class abundance ranged from 7.3 to 33.7. One study reported that length-frequency sampling of commercial landings from Hecate Strait was inadequate, and could adversely affect estimates of age composition, and results of virtual population analysis. Pacific cod elsewhere exhibited similar fluctuations in year-class abundance. The principal strong year-class in the Gulf of Alaska and the eastern Bering Sea was 1977, which contributed to the fishery during 1980-85. Maximum reported age was 11 y. An age-length key (ALK) used in the eastern Bering Sea was found to reproduce its own modal age-classes when applied to length-frequencies collected over an 8-y period. In

the northwest Pacific Ocean, modal age-classes ranged from 4 to 7, and varied directly with latitude. Maximum age reported was 11 y.

Atlantic cod. Commercial and research-vessel catches contained many more age-classes than reported for Pacific cod. Modal age, for the north Atlantic, ranged from 3 to 18 y, and generally varied directly with latitude. Maximum age reported was 23 y. Year-class abundance varied substantially, and standard deviations varied directly with latitude. ALKs were commonly used to compute age compositions. The method received mixed reviews, mostly negative.

Growth

Four growth relationships were dealt with--length-weight, length-girth, age-length, and age-weight.

Length-weight. In British Columbia, stratified samples of males and females were collected off southwest Vancouver Island and in Hecate Strait in April, July, and October 1975, and February 1976. Formulae were calculated, by sex, area, and time, for round and dressed (gutted, head on) weight vs length. Empirical tests, involving samples from all important production areas, indicated that two formulae were sufficient for round weight, and one for dressed weight. Round weight formulae (sexes and areas combined) were: $W = 0.004988\ L^{3.2117}$, for the spawning season; and $W = 0.007377\ L^{3.0963}$, for the rest of the year. (W = grams; L = centimeters, fork length). The dressed-weight formula was $W = 0.008289\ L^{3.0333}$. Interannual variations in the length-weight relationship (round and dressed weights) were detected for two areas during empirical tests of the formulae. Results from elsewhere indicated that British Columbia cod were heavier per length than Pacific cod from Washington State, Gulf of Alaska, and Atlantic cod off Canada and in the North Sea. They were lighter per length than Pacific cod in the eastern Bering Sea, off West Kamchatka, and in the Yellow Sea, and Atlantic cod in the New York Bight. No sexual dimorphism was noted for cod in the eastern Bering Sea, but some seasonal variation was evident. Atlantic cod weights at length varied inversely with latitude.

Length-girth. In British Columbia, the same samples collected for computing the length-weight relationships also provided length-girth formulae. No variation was noted with respect to sex, location, or time, and one formula sufficed ($G = 0.634\ L - 3.275$, where G = girth in centimeters, and L = centimeters, fork length). Girths at comparable lengths were greater than those of Atlantic cod off Canada and in the North Sea.

Age-length. For British Columbia cod, estimates of growth parameters were a by-product of the iterative method of deriving age-frequencies from length-frequencies. Growth varied inversely with latitude, from Georgia Strait to Hecate Strait--K = 0.387- 0.203; L_{∞} = 87.5-84.008; and t_o, no estimate to -0.806. The same results were reported for Pacific cod elsewhere, and Atlantic cod. Mean lengths of age-3 Pacific cod declined from 58.3 cm in Georgia Strait, British Columbia, to 39.9 cm in the eastern Bering Sea, and 35.5 cm in the western Bering Sea; then increased to 57.5 cm on the east coast of South Korea. Comparable values for age-5 Atlantic cod were 56.5 cm in the Barents Sea vs 87.9 cm in the North Sea (but 49.4 cm in the Baltic Sea); and 43.6 cm off Labrador vs 72.6 cm on Georges Bank. Within-year variation in mean length-at-age was as large as 10 cm in both the northeast and northwest Atlantic.

Age-weight. For both Pacific and Atlantic cod, a sigmoid curve represented the age-weight relationship, and inter-age weight increments were dome shaped. Weight-increment values peaked between ages 3 and 4 in Georgia Strait and off Vancouver Island, but between ages 4 and 5 in Hecate Strait and the eastern Bering Sea. Off Norway, weight increments peaked between ages 9 and 10, and in the eastern Baltic Sea, between ages 7 and 8.

Reproduction

Spawning. Pacific cod are single-batch spawners, while Atlantic cod are multiple-batch spawners. In a laboratory study, individual, reared, first-time spawning, age-4 Atlantic cod spawned 17-19 batches at intervals of 62-76 h. Interval time varied inversely with water temperature; numbers of eggs per batch followed a dome-shaped curve with time; and egg size and dry weight declined with time.

Spawning season. In British Columbia waters, spawning begins in January and is essentially complete in April. The season is more prolonged in northern Hecate Strait. Elsewhere in the north Pacific Ocean, spawning season was similarly compact, but varied with latitude. Earliest month was December, off northern Japan and the east coast of South Korea. Latest month was May, off Kamchatka and the Komandorski Islands. In contrast, overall spawning season was more prolonged for Atlantic cod: January-September in European waters, and virtually year-round off Canada and the United States, albeit relatively short in most areas. The relatively prolonged spawning season for Atlantic cod was attributed in part to multi-batch spawning.

Length at maturity. For Pacific cod in British Columbia waters, estimates of L/50 were 41-53 cm, for males, and 47-56 cm, for females. In Hecate Strait, estimates varied among grounds, within years, and among years on one ground. Elsewhere, L/50 estimates for the eastern Bering Sea were 60 cm for males and 62 cm for females, and off west Kamchatka, 69 cm, sexes combined. In the northeast Atlantic, L/50 estimates in the North Sea declined substantially from the late 19th Century to 1972 (72 to 53 cm for males; 74 to 60 cm for females). Estimates for the Baltic Sea were 25 cm for males, and 28 cm for females. In the northwest Atlantic, estimates were 36-66 cm for males, and 34-72 cm for females; varied directly with latitude; and declined substantially with time in three areas--Labrador-East Newfoundland, south Gulf of St. Lawrence, and Scotian Shelf.

Fecundity. In British Columbia, a 1986-90 study revealed little temporal or geographical variation, and little variation from the results of a similar study in 1961. The overall length-fecundity formula, based on the 1986-90 data, was: $\log F = -5.890 + 3.386(\log L)$; $N = 355$; $r = 0.91$. Cod in the northeast and northwest Pacific Ocean appear to have similar length-fecundity relationships. Atlantic cod fecundities were relatively high for the Norwegian Coastal and the western Baltic Sea stocks (similar to Pacific cod); intermediate in the North Sea, off Iceland, and in the southwest Gulf of St. Lawrence; and low off Labrador and Newfoundland. In the Labrador-Newfoundland region, fecundity within length-intervals varied among years, in the same area. Among areas, length-fecundity regressions exhibited similar slopes, but different intercepts. However, regression slopes exhibited a dome-shaped relationship with bottom-water temperature.

Early Life History

To date (1993), few field studies have been undertaken on the early life history of Pacific cod in British Columbia waters, and all have been unsuccessful. A field test, in Georgia Strait, of a benthic sled net did yield an incidental catch of cod eggs. Laboratory studies indicated the egg was slightly adhesive and demersal, with a mean diameter of 1.02 mm. Furthermore the egg was stenothermal, euryhaline, and euryoxic. Optimum development occurred at low temperature (3-5 C), intermediate salinity (ca. 15-19 o/oo), and a wide range of oxygen concentrations (as low as 2-3 ppm). Under these conditions, time to 50% hatching was ca. 15-17 d, and mean length of larvae, at that time, was 4.1-4.5 mm. Off Asia, similar descriptions of the egg were reported, but length of larvae at hatching was somewhat smaller (3.6-4.5 mm).

Duration of the larval stage was not reported anywhere for Pacific cod, and bathymetric distribution may be variable geographically (see Section 4.2 of DISTRIBUTION). Circumstantial evidence suggested that size at metamorphosis was >32 mm, but <40 mm.

Atlantic cod eggs are larger (1.2-1.6 vs 1.02 mm diameter) than those of Pacific cod; are pelagic after fertilization; and incubation time varies inversely with surface water temperature--50-60 d @ -1.5 to 0 C to 14 d @ 6 C. Hatching occurs at 3.3-5.7 mm, and metamorphosis at ca. 10 mm.

Diet

The only information found on the diet of Pacific cod larvae came from northern Japan, where tank-held larvae fed selectively on copepod and molluscan larvae. Principal component in the diet of Atlantic cod larvae was copepods. Off Iceland, an important component was capelin larvae, during the late stages of larval life.

Juvenile and adult Pacific and Atlantic cod are omnivorous, opportunistic, often cannibalistic, and their diet varies with their size--inversely with invertebrates and directly with fish. Although all detailed studies yielded long lists of diet items, only a few items were important in any area-time cell. Moiseev's (1953) comment on the inverse relationship between cod abundance (in catches) and diversity of stomach contents has not received the attention it deserves.

In British Columbia waters, principal diet components were pandalid and crangonid shrimp, Pacific herring, and Pacific sandlance. The "boundary" size between the invertebrate and fish dominance was ca. 50 cm. Prey-incidence periodicity, during 1950-80, was demonstrated for Pacific sandlance (3.9 y; all areas), Pacific herring (4.7 y; West Vancouver Island), and sablefish (~7-9 y; Hecate Strait). Miscellaneous components were algae, stones, and wood. Incidence of empty stomachs was maximal during the spawning season. An unusual diet-related contaminant, the pelagic pteropod Limacina sp., was reported, in a 1964 trawl catch from Hecate Strait. The cod, and English sole, smelled like a hydrogen sulfide, and the entire catch was rejected at the processing plant. The explanation was subsequently reported for Atlantic cod (see below).

Elsewhere in the north Pacific Ocean, principal invertebrate components were crab (Cancer, Chionoecetes, Paralithodes), and/or shrimp (Pandalus), from the Gulf of Alaska to the Japan Sea. Principal fish species was walleye pollock, from the Gulf of Alaska to the Okhotsk Sea. Other species, in one or more area-time cells, were "atherina" (Atherinops ?), capelin, herring, Pacific cod, salmon fry, sandlance, and sardine. In the Gulf of Alaska, cod were suspected of contributing to the decline, and sustained low abundance, of pink shrimp. In the eastern Bering Sea, cod were reported to be serious predators on Tanner crab.

In the north Atlantic Ocean, principal invertebrate components were euphausiids, crangonid and pandalid shrimp, and decapod crabs for juveniles and adults. No single fish species predominated throughout the region. Important components were capelin, cod, flatfishes, herring, and sandlance. In the North Sea, adult cod fed on all the important commercial species. Cannibalism, by juvenile and/or adult cod, was commonly reported in the Barents Sea, North Sea, Baltic Sea, and off Canada. The phenomenon of odoriferous cod (called blackberry, black, or gunpowder) is common off Norway, Greenland, and Newfoundland, primarily where the fishery shifted away from salting cod. The indirect cause is ingestion of the arctic pteropod Limacina helocina. The direct cause is dimethyl sulfide (DMS), a by-product of the breakdown of dimethyl-beta-propiothetin (DMPT). DMPT is apparently broken down by an enzyme in the algae eaten by Limacina. Prolonged cold storage eliminates the odor.

Predators

Pacific cod. No reports were found which dealt with predation on Pacific cod eggs. Reported predators on larvae in British Columbia waters were the scyphozoa Phocellophora camtschatica and the hydrozoa Aequorea victoria. Reported predators of juvenile and adult Pacific cod in British Columbia waters were Pacific cod, Pacific halibut, spiny dogfish, rhinoceros auklet, harbor seal, and northern fur seal. None were listed as serious predators. Elsewhere, reported predators included Pacific cod, Pacific halibut, salmon shark, sculpins, tufted puffin, five species of seals, and the Steller sealion. None were listed as serious.

Atlantic cod. Atlantic cod eggs were consumed by herring in the southern North Sea. Laboratory studies of larvae demonstrated predatory behavior of scyphozoa, euphausiids, and copepods. The list of predators on juveniles and adults included 9+ fish species. 2 bird species, 5 seal species, and 3 whale species. Cannibalism was important in the Barents Sea, Baltic Sea, and North Sea.

Parasites

Pacific cod. No reports were found which dealt with parasites of eggs or larvae. At least 46 parasite species were reported, of which 21 were attributed to Pacific cod in British Columbia waters.

Atlantic cod. No reports were found which dealt with parasites of eggs or larvae. At least 66 species were reported in Canadian waters, of which 23 were also reported for Pacific cod. The "sealworm" was the only parasite reported to be detrimental to humans. It was also detrimental to the Atlantic commercial industry, because the presence of relatively large larvae encysted in the musculature repels the potential consumer, and thus adversely affects market demand. Hence, the cysts must be removed, at additional expense, prior to sale to the consumers. Adequate freezing or cooking kills the larvae and renders them harmless, but the larvae are potentially dangerous to consumers of raw, unfrozen, or inadequately cooked cod flesh. The ingested live larvae may penetrate the stomach wall, and cause acute abdominal pain as well as infection. The incidence of such events is rare. No reports were located which indicated that the "sealworm" was an industrial problem in the Pacific cod fisheries.

Diseases and Pathogenic Parasites

A total of 34 different ailments (17 unnamed) were found--5 for Pacific cod, and 29 for Atlantic cod. Causative agents were viruses, fungi, bacteria, "protozoa", trematodes, nematodes, amphipods, copepods, or "complexes".

Pacific cod. No reports were found which dealt with eggs or larvae. Five ailments were reported for juveniles and/or adults whose causative agents were viruses, bacteria, or "protozoa". These were Pacific cod herpesvirus, vibriosis, epidermal lesions, epidermal ulcers, and parabranchial X-cell lesions. Only parabranchial X-cell lesions were reported in cod from British Columbia waters. They were also reported for Pacific cod elsewhere, and Atlantic cod. Causative agent was tentatively identified as a protistan parasite (Hartmannellidae). Prevalence was relatively low everywhere, except in two areas off British Columbia (3Cn and 5A). At relatively high prevalence, detrimental effects on Pacific cod were retarded growth, delayed maturity, and increased mortality rate (Z). Tank-held, infected Atlantic cod exhibited retarded gonad development, and suffered a high mortality due to bacterial infections.

Epidermal ulcers, found on Alaskan cod, were similar to those of the ulcus syndrome "complex" in Baltic cod.

Atlantic cod. No report was found which dealt with eggs, but one noted that black spot disease was fatal to larvae and juveniles, if the causative agent (digenean trematode) penetrated the brain or heart. For juveniles and adults, 24 ailments were reported. Causative agents included viruses, fungi, bacteria, "protozoa", trematodes, nematodes, amphipods, copepods, and two "complexes" (vibriosis and ulcus syndromes), both serious in the Baltic Sea. Principal ailments were debilitation, hemorrhagic septicemia, anemia, organ atrophy, and epidermal ulcers. Causative agent of the vibriosis "complex" was a combination of high cod abundance, low food abundance, and bacteria (Aeromonas, Pseudomonas, and Vibrio). Causative agent for the ulcus syndrome "complex", was a combination of a virus, pollution, and bacteria (primarily Vibrio anguillarum). The copepod Clavella adunca was reported to adversely affect the length-weight relationship, condition factor, and mean length-at-age of Atlantic cod off Labrador and Newfoundland.

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Table 5.1.1. Modes (cm), means (cm), and coefficients of variation (C.V.,%) for length-frequencies of trawl-caught Pacific cod sampled from commercial landings in British Columbia, by ground[a] and 5-year period, January-March and April-June, 1951-84. (Sources: Chilton & Smith 1975; Foucher 1987; Ketchen 1967)

	January-March			April-June		
	Mode (cm)	Mean (cm)	C.V. (%)	Mode (cm)	Mean (cm)	C.V. (%)
Years	GI (4B)			A-S (3Cn)		
1951-54	47	54.1	17	65;59	62.5	11
1955-59	47;59	55.4	14	59	60.0	11
1960-64	47;62	54.9	17	62;50	58.7	13
1965-69	47	51.5	15	59	59.1	13
1970-74	47;62	53.1	17	53;62	59.7	14
1975-79	47;56	52.6	17	59	58.5	13
1980-84	--	--	--	53;38	53.2	16
	CL-FC (4B)			SB (5A)		
1955-59	59	59.0	13	53	57.8	12
1960-64	59	58.8	14	62	60.6	15
1965-69	47;59	55.1	15	62	60.3	14
1970-74	62;44	55.9	17	59	57.2	13
1975-79	62;47	58.9	15	50	54.0	13
1980-84	56;68	57.3	11	50	53.0	12
				GIB (5B)		
1955-59	--	--	--	59	62.1	15
1960-64	--	--	--	65;53	65.3	17
1965-69	--	--	--	65	65.7	15
1970-74	--	--	--	65;50	63.0	18
1975-79	--	--	--	59;50	56.9	16
1980-84	--	--	--	62	59.9	14
	WR (5D)			TP (5D)		
1955-59	59	61.0	11	59	59.2	12
1960-64	59	58.7	13	59	60.0	12
1965-69	56	60.3	12	59;65	60.8	13
1970-74	56;47	56.6	14	50;59	56.1	14
1975-79	56	56.6	15	62;50	58.8	15
1980-84	59	59.3	15	62;50	59.2	14

a. A-S = Amphitrite-Swiftsure; CL-FC = Cape Lazo-French Creek; GI = Gulf Islands; GIB = Goose Island Bank; SB = Scott Bank; TP = Two Peaks; WR = White Rocks.

Table 5.1.2. Modes (cm) and ranges (cm) for length-frequencies of trawl-caught Atlantic cod from selected locations, by time, sample type, and source, 1913-82.

Location	Time	Sample type[a]	Mode(s) (cm)	Range (cm)	Source
N.E. Atlantic[b]					
Barents Sea-	1913-53	C	65-110	<50-120+	Rollefsen (1954
Lofoten[c]	1981-82	C	63	31-135	Lebed & Ponomarenko
(I+II)					(1985)
Baltic Sea	1951-56	R	17	5-69	Jensen (1961)
(III/22,24-32)	1957	R	7:32	5-75+	
	1958	R	17;42	5-75+	
	1959	R	7;17	5-72	
North Sea					
(IV):	1973	R	25	5-90+	
North	1973	R	25	5-90+	
South	1919-27	C	35	12-114	
Faroe Islands (Vb):					
North	1933-38	C	52-72	30-124	Daan (1974)
	1951-52	C	57-72	30-119	Graham (1934)
West	1933-38	C	37-87	20-129	Joensen (1954)
	1951-52	C	82;87	50-129	
Iceland (Va)[c]	1928-53	C	58-110	40-130	Jonsson (1954)
N.W. Atlantic[d]					
W. Greenland (1)	<1931	C	---	64	Jensen & Hansen (1931)
W. Greenland-Georges Bank:	1972				ICNAF (1974)
1C	Apr	C	55	39-92	
2J	Apr	C	58	27-98	
3L	May	C	46	33-125	
4T	May	C	49	24-107	
5Z	Apr	C	49	36-101	
S. Newfoundland (3NOP)	1959-66	C	61-62	---	Pinhorn (1969)
N. Gulf of St. Lawrence:					
4R	1953-65	C	61	---	Wiles & May (1968)
4S	1953-65	C	47;61	---	

a. C = commercial vessel; R = research vessel.
b. ICES Area. See Fig. 2.3.
c. Spawners only.
d. ICNAF/NAFO Area. See Fig. 2.4.

Table 5.2.1. Sex ratios (% males), by location, of Pacific cod sampled from research-vessel catches in Hecate Strait during June-July and September 1979, and from commercial landings in British Columbia from major production areas during January-March and April-June 1982.

Location	%M	Hauls	M+F	%M	Hauls	M+F
			Research Vessels--1979			
		June-July[a]			September[b]	
Horseshoe	51	9	51	49	3	49
Shell	46	1	241	48	1	166
White Rocks	49	2	68	48	3	166
Two Peaks	54	10	478	48	11	2562
Total	51	22	1936	48	18	2901
			Commercial Landings--1982[c]			
		January-March			April-June	
4B	43	2	568	--	0	--
3Cn	49	3	584	56	2	498
5A+5B	--	0	--	44	4	880
5C	47	2	407	49	2	508
5D	45	3	591	51	1	207
Total	46	10	2150	49	9	2093

a. Westrheim et al. (1980a).
b. Westrheim et al. (1980b).
c. PBS files.

Table 5.3.1. Modal lengths (cm) and frequencies (N), by area, time, gear, and source, of Pacific cod in research-vessel catches, January-March 1960-79.

Area	Time	Gear[b]	Mode (cm)	Modal freq.[a] (N)	Source
4B	1978	G	26	254	Westrheim
	1979	G	23	217	(1985)
3Cn	1979	G	20	19	Westrheim (1985)
5D	1960	G	26	NR[c]	Ketchen (1964)
	1965	S	23	164	Ketchen (1970)

a. Modal frequencies (numbers of specimens measured).
b. G = groundfish trawl; S = shrimp trawl (small mesh).
c. NR = not reported.

Table 5.3.2. Length-frequencies (o/oo), by 10-fath depth interval, of Pacific cod caught by the M/V DOUBLE DECKER[a] and the R/V G.B. REED[b] during the species-assemblage study in Hecate Strait, January-February 1986.

Fork length (cm)	Depth interval (fath) 10-19	20-29	30-39	40-49	50-59	60-69	70-79
13	--	4	--	--	--	--	--
14	--	14	--	--	--	--	--
15	97	37	2	--	--	--	--
16	32	51	8	6	5	--	--
17	86	32	25	52	19	12	--
18	108	33	44	119	41	12	--
19	97	46	62	141	35	28	4
20	182	50	69	134	42	56	4
21	75	73	60	99	49	24	2
22	86	73	85	59	51	24	8
23	43	86	73	54	52	48	21
24	32	100	85	52	52	28	52
25	54	101	97	42	48	48	62
26	22	107	91	38	72	44	91
27	22	79	83	30	96	72	87
28	32	46	78	37	91	103	117
29	0	33	38	27	89	122	133
30	0	19	26	10	86	80	102
31	0	10	9	14	64	24	67
32	0	1	2	1	34	24	33
33	0	0	2	3	16	12	12
34	0	0	0	0	8	4	2
35	0	0	1	1	1	0	6
36	0	0	1	0	0	4	0
37	0	0	3	0	0	4	0
38	0	0	0	0	0	4	2
39	0	T	1	1	0	8	0
40	0	T	0	1	0	0	2
>40	32	5	55	79	49	215	185
Total	1000	1000	1000	1000	1000	1000	1000
N[c]	93	2138	1327	858	2049	251	519
No. of hauls	10	13	14	19	17	13	16

a. Source: Fargo & Davenport (1986), Appendix table 23.
b. Source: Foucher et al. (1988), Appendix table 6.
c. N = numbers measured.

Table 5.4.1. Strong year-classes of Pacific cod in the eastern Bering Sea, by age-determination method, time, and source, 1975-89.

Method	Year-class	Time	Source
L-F modes	1977	1978-81	Foucher et al. (1984)
	1977-78	1975-86	Thompson & Shimada (1987)
Foucher-Fournier	1977	1978-81	Foucher et al. (1984)
Macdonald-Pitcher	1977	1978-81	Bakkala et al. (1983)
	1977,1982	1978-84	Bakkala & Wespestad (1985)
	1977,1982	1978-85	Bakkala et al. (1986a)
A-L key (fin-ray) (conventional)	1978,1982	1981-85	Thompson & Shimada (1987)
A-L key (fin-ray) (Kimura-Chikuni)	1977-78 1981-85	1981-87	Thompson & Shimada (1988)
A-L key (otolith) (Kimura-Chikuni)	1976-77 1982,1984	1975-85	Thompson & Shimada (1990)

Table 5.4.2. Modal ages (y) and age ranges (y), by location, time, fishery type, and source, in age-frequencies of trawl-caught Atlantic cod.

Location	Time	Fishery Type[a]	Mode(s) (y)	Range (y)	Source
N.E. Atlantic[b]					
Barents Sea-Lofoten[c]	1932-53	C	8-13	6-17	Rollefsen (1954)
(I+II)	1981-82	C	6	2-15	Lebed and Ponomarenko (1985)
Baltic Sea: (III/22,24-32)					
East	1960-74	R	4	1-7+	Baranova
	1976-86	R	4	1-7+	(1989)
	1982	C	3	1-8	Baranova and Herbste (1985)
Finland	1982	C	6;3	1-10	Aro and Sjoeblom (1985)
South	1982	R	3;5	1-10	Tiews (1985)
West	1957-59	C	1-4	1-6+	Jensen (1961)
North Sea: (IV)					
South	1959-77	C	2-4	1-10	Houghton and Flatman (1981)
Faroe Islands:[c] (Vb)					Joensen (1954)
North	1933-38	C	5-12	3-16	
	1951-52	C	4-6	2-17	
West	1933-38	C	3-7	2-11	
	1951-52	C	4-12	2-16	
Iceland:[c] (Va)					
Total	1928-53	C	6-18	3-23	Jonsson (1954)
S.W.	1982	C	9;6	2-11+	Schopka (1985)
N./W./N.E.	1982	C	6	2-11+	

Table 5.4.2. (cont.)

Location	Time	Fishery Type[a]	Mode(s) (y)	Range (y)	Source
N.W. Atlantic[d]					
W. Greenland-Scotian Shelf:	1972				ICNAF (1974)
1C	Apr	C	6	4-15	
2J	Apr	C	7	4-15+	
3L	May	C	4;13	3-15	
4T	May	C	7;4	2-15+	
S. Newfoundland (3NOP)	1959-66	C	--	3-16+	Pinhorn (1969)
N. Gulf of St. Lawrence:					
4R	1953-65	C	8-9	---	Wiles & May
4S	1953-65	C	6	---	(1968)

a. C = commercial vessels; R = research vessels.
b. ICES Area. See Fig. 2.3.
c. Spawners only.
d. ICNAF/NAFO Area. See Fig. 2.4.

Table 5.4.3. Standard deviations (S.D.) of year-class strength for selected Atlantic cod stocks[a]. (Source: Garrod Knights 1979, Table III)

Location	Code[b]	S.D.	N[c]
N.E. Atlantic			
Arcto-Norwegian	I,IIb	0.90	32
North Sea (south)	IVc	0.50	11
Irish Sea	VIIa	0.36	11
Faroe	Vb	0.40	15
Iceland	Va	0.30	47
East Greenland	XIV	0.95	14
N.W. Atlantic			
West Greenland	1	0.68	48
Labrador	2	0.50	11
South Newfoundland	3P	0.34	17
Gulf of St. Lawrence	4RST	0.27	30
Nova Scotia	4VWX	0.32	15

a. See Section 7.1 (Stock Delineation) for definition of term.

b. Northeast Atlantic: ICES Area. See Fig. 2.3. Northwest Atlantic: ICNAF/NAFO Area. See Fig. 2.4.

c. Number of years in time series.

Table 5.5.1. Empirical tests of length-weight formulae for round and dressed Pacific cod collected from important areas off British Columbia during 1970-75. (Source: Westrheim 1977, Tables 4 and 6).

Location	Time[a]	No. of tests	Mean error (%)	% of tests with errors of: <= ± 5%	<= ± 10%
			Round weight[b]		
Georgia Strait (4B)	Jan-Mar	12	-1.0	50	75
	Apr-Dec	14	-3.0	50	79
Vancouver Is. (3Cn + 3D)	Jan-Mar	10	+1.1	70	100
	Apr-Dec	35	-8.3	29	72
Queen Charlotte Sound (5A+5B)	Jan-Mar	0	--	--	--
	Apr-Dec	16	-8.8	19	56
Hecate Strait (5C+5D)	Jan-Mar	8	-0.3	63	100
	Apr-Dec	31	-2.0	55	87
Total	Jan-Mar	30	-0.1	62	93
	Apr-Dec	96	-5.5	39	71
			Dressed weight[c]		
Georgia Strait (4B)	Jan-Mar	13	-1.4	62	85
	Apr-Dec	16	-5.2	63	81
Vancouver Is. (3Cn + 3D)	Jan-Mar	15	+0.9	80	100
	Apr-Dec	43	-7.0	33	79
Queen Charlotte Sound (5A+5B)	Jan-Mar	0	--	--	--
	Apr-Dec	12	-7.5	17	67
Hecate Strait (5C+5D)	Jan-Mar	13	+1.8	54	85
	Apr-Dec	24	-2.8	79	88
Total	Jan-Mar	41	+0.4	66	78
	Apr-Dec	95	-5.7	37	80

a. Time samples collected
b. Jan-Mar formula: $W = 0.004988\ L^{3.2117}$
   Apr-Dec formula: $W = 0.007377\ L^{3.0963}$
c. Jan-Dec formula: $W = 0.008289\ L^{3.0333}$

Table 5.5.2. Empirical tests, among years, of length-weight formulae for round and dressed Pacific cod collected off Vancouver Island (Areas 3Cn+3D) during April-September 1970-75. (Source: Westrheim 1977, Tables 5 and 7).

Year	No. of tests	Mean error (%)	% of tests with errors of: <= ± 5%	<= ± 10%
		Round weight[a]		
1970	2	+3.0	100	100
1971	10	-10.4	20	40
1972	12	-3.8	25	75
1973	12	-4.9	33	92
1974	23	+2.0	52	65
1975	14	-4.1	71	86
		Dressed weight[b]		
1970	22	-4.2	59	95
1971	20	-7.5	25	60
1972	10	-6.5	40	90
1973	5	-2.4	100	100
1974	0	--	--	--
1975	2	+3.0	100	100

a. $W = 0.007377\ L^{3.0963}$
b. $W = 0.008289\ L^{3.0333}$

Table 5.5.3. Calculated round and dressed weights (g) for selected fork lengths (cm) of Pacific and Atlantic cod, by location and time of sampling, and source, 1907-86.

Location	Time	N	Calculated weight (g) at: 30cm	50cm	70cm	Source
N. E. Pacific			Round Weight			
Washington State (4A)	Jan-Apr 1977-78	1271	268	1372	4017	Karp (1982)
	Jun 1979-Dec 1980	626	297	1345	3642	Wildermuth (1983)
		98-	240-	1249-	2993-	
British Columbia	Jan-Oct 1967-69	184	346	1586	4389	Forrester &
	Apr-Oct 1975	1844	276	1344	3809	Thomson (1969)
	Feb 1976	522	277	1430	4214	Westrheim (1977)
Gulf of Alaska	Jan-Apr 1980	1198	248	1197	3373	Brown et al. (1984)
E. Bering Sea	Aug-Oct 1975	940	299	1549	4580	Bakkala (1984)
	Apr-Jun 1976	650	285	1398	3983	
	------- 1975-83	3000	286	1441	4177	Bakkala et al. (1986)
Aleutian Islands	Jun-Nov 1980	119	350	1605	4377	Ronholt et al. (1986)
N. W. Pacific						
W. Kamchatka (USSR)[b]	Jun 1938-Aug 1939	1854	(500)[a]	1540	4740	Moiseev (1953)
Yellow Sea	Apr-May 1964	247[c]	378	--	--	Chung & Kim (1971)
N. E. Altantic[d]						
Barents Sea[e] (I)	------- 1907/1913	--	199	995	2824	Hjort (1914)
N. W. Norway[f] (IIa)	Mar 1986	50	148	872	2084	Kjesbu (1988)
North Sea (IV)	Feb-Nov 1969-71	472	258	1257	3567	Daan (1974)
N. W. Atlantic[g]						
Canada Coast (2-4)	Jan-Oct 1968-69	244-613	220-266	1063-1187	2964-3187	Kohler et al. (1970)
S. W. Gulf of St. Lawrence[h] (4TVn)	------- 1959	--	309	1366	3636	Buzeta & Waiwood (1982)
New York Bight (6A)	Jun 1974-75	200[i]	(350)	1704	4833	Wilk et al. (1978)
			Dressed Weight			
British Columba	Apr 1975-Feb-1976	1844	241	1180	3275	Westrheim (1977)
E. Canada (2-4)	Apr-Dec 1960-69	1052	243	1058	2797	Kohler et al. (1970)

a. Based on 5 speciments.
b. Mean values per 5-cm interval (30-34,50-54,70-74), from Table 14. No formula presented.
c. Size range of data: 160-339 mm.
d. ICES Area. See Fig. 2.3.
e. Feeders. Calculated from data on pp. 142 & 143.
f. Spawners. Formula in Table I, p. 71.
g. ICNAF/NAFO Area. See Fig. 2.4
h. Unpublished data. Cited by Buzeta & Waiwood (1982).
i. Size range of data: 474-981 mm.

Table 5.5.4. Deviations (%) of calculated round and dressed weights, at selected fork lengths (cm) of Pacific and Atlantic cod from their respective British Columbia standards, by location and time, 1907-86.

Location	Time		N	% Deviation at: 30cm	50cm	70cm
				Round Weight[a]		
N.E. Pacific						
Washington State	Jan-Apr	1977-78[b]	1271	-2.9	-4.1	-4.7
(4A)	Jun 1979-Dec 1980		626	+7.6	+0.1	-4.4
Gulf of Alaska	Jan-Apr	1980[b]	1198	-10.5	-16.3	-20.0
E. Bering Sea	---	1975-83	3000	+3.6	+7.2	+9.7
Aleutian Islands	Jun-Nov	1980	119	+26.8	+19.4	+14.9
N.W. Pacific						
W. Kamchatka	Jun-Aug	1938-39	1854	---	+14.7	+24.4
Yellow Sea	Apr-May	1964	247	+37.0	---	---
N.E. Atlantic[c]						
Barents Sea (I)	--	1907/1913[b]	--	-20.7	-15.7	-13.8
N.W. Norway (IIa)	Mar	1986[b]	50	-41.0	-26.1	-36.3
North Sea (IV)	Feb-Nov	1969-71	472	-6.5	-6.5	-6.4
N.W. Atlantic[d]						
Canada (2-4)	Jan-Oct	1960-69	244-673	-20.3--3.6	-20.9--11.7	-22.2--16.3
W. Gulf of St. Lawrence (4TVn)	---	1959	--	+12.0	+1.6	-15.0
New York Bight (6A)	Jun	1974-75	200	--	+26.8	+26.9
				Dressed Weight[e]		
E. Canada (2-4)	Apr-Dec	1960-69	1053	-17.6--3.2	-21.9--10.3	-25.2--14.6

a. Unless otherwise noted, "standard" round weights are based on the B.C. April-October 1975 formula of Westrheim (1977), and are: 276 g @ 30 cm; 1344 g @ 50 cm; and 3809 g @ 70 cm.

b. "Standard" round weights are based on the B.C. February 1976 formula of Westrheim (1977), and are: 277 g @ 30 cm; 1430 g @ 50 cm; and 4214 g @ 70 cm

c. ICES Area. See Fig. 2.3.

d. ICNAF/NAFO Area. See Fig. 2.4.

e. "Standard" dressed weights are based on the B.C. January-December formula of Westrheim (1977), and are: 251 g @ 30 cm; 1180 g @ 50 cm; and and 3275 g @ 70 cm.

Table 5.5.5. Calculated girths (cm) for selected fork lengths (cm) of Pacific and Atlantic cod, by location, time, and source, 1957-76.

Location	Time	N	Size range (cm)	Calculated girth (cm) at: 20cm	30cm	50cm	70cm	Source[a]
N.E. Pacific								
Georgia Strait (4B)	Jan 1959	60	19-47	10.7	16.2	27.1	38.0	Forrester (1974)[b]
S.W. Vancouver Island (3Cn)	Apr 1975	43	44-76	12.0	16.9	26.8	36.7	PBS files[c]
Areas 3Cn + 5C+5D	Apr 1975-Feb 1976	2365	17-91	9.3	15.6	28.2	40.8	Westrheim (1977)
Hecate Strait (5C+5D)	Feb 1960	148	18-49	10.5	15.4	25.2	35.0	Forrester (1974)[b]
N.E. Atlantic[d]								
North Sea (IV)	Aug 1957	119	18-73	10.6	15.7	25.8	36.0	Margetts (1957)
N.W. Atlantic[e]								
Labrador (2)	Aug 1962	1503	20-78	9.7	14.7	24.7	34.7	Hodder & May (1965)[f]
				9.5	14.2	23.6	33.0	
	Oct 1963	589	24-76	9.4	15.1	26.5	37.9	
				9.0	14.1	24.3	34.5	
W. Newfoundland (4R)	Jul 1962-64	---	25-105	10.3	15.9	27.1	38.3	Wiles & May (1968)

a. Forrester (1974): Hecate Strait, Constricted, G = 0.490 FL + 0.667
Georgia Strait, Constricted, G = 0.546 FL - 0.214
Hodder & May (1965): Aug 1962: Maximum: G = 0.50 FL - 0.35
Pectoral: G = 0.47 FL + 0.07
Oct 1963: Maximum: G = 0.57 FL - 2.03
Pectoral: G = 0.51 FL - 1.23
Margetts (1957): Natural: G = 0.507 FL + 0.468
Constricted: G = 0.486 FL + 0.157
PBS files: Constricted: G = 0.494 FL + 2.109
Westrheim (1977): Constricted: G = 0.630 FL - 3.275

b. Computed from data in his Table 4.

c. Groundish data bank at the Pacific Biological Station, Nanaimo, B.C., Canada.

d. ICES Area. See Fig. 2.3.

e. ICNAF/NAFO Area. See Fig. 2.4.

f. Computed from data in their Table 2.

Table 5.5.6. Deviations (%) of calculated girths (cm) of Pacific and Atlantic cod from the British Columbia standard[a], by location and time, 1957-75.

Location	Time	N	% Deviation at: 20cm	30cm	50cm	70cm
N.E. Pacific						
Georgia Strait (4B)	Jan 1959	60	+29.0	+3.8	-3.9	-6.9
S.W. Vancouver Island (3Cn)	Apr 1975	43	+37.6	+8.3	-5.0	-10.0
Hecate Strait (5C+5D)	Feb 1960	148	+12.9	-1.3	-10.6	-14.2
N.E. Atlantic[b]						
North Sea (IV)	Aug 1957	119	+14.0	+0.6	-8.5	-11.8
N.W. Atlantic[c]						
Labrador (2)	Aug 1962	1503	+4.3	-5.8	-12.4	-15.0
			+2.2	-9.0	-16.3	-19.1
	Oct 1963	589	+1.1	-3.2	-6.0	-7.1
			-3.2	-9.6	-13.8	-14.5
	1962-					
W. Newfoundland (4R)	Jul 64	--	+10.8	+1.9	-3.9	-6.1

a. "Standard" girths are based on the B.C. formula of Westrheim (1977), and are: 9.3 cm @ 20 cm; 15.6 cm @ 30 cm; 28.2 cm @ 50 cm; and 40.8 cm @ 70 cm.

b. ICES Area. See Fig. 2.3.

c. ICNAF/NAFO Area. See Fig. 2.4.

Table 5.5.7. Mean lengths-at-age (cm), by region and age-determination method (and user), for Pacific cod.

Region	Method[a]	Mean length (cm) at age (y): 1	2	3	4	5	6	7	8	9	10
N.E. Pacific											
Juan de Fuca Strait (4A)	CL-1	26.8	40.9-43.9	51.3-55.9	63.6-67.0	--	--	--	--	--	--
	T-1	27.0	43.6	55.5	64.2	--	--	--	--	--	--
Georgia Strait (4B)	L/T-1	26.1	49.9	61.4	67.3	72.6	76.2	--	--	--	--
	T-3	31.0	50.8	63.5	71.6	76.8	80.1	--	--	--	--
	CL-3	26.1	47.6	58.3	65.8	71.7	76.4	80.2	82.9	--	--
W. Vancouver Is. (3Cn)	T-3	28.8	46.4	57.2	63.7	67.7	70.2	71.7	72.6	--	--
	CL-4	26.0	42.7	55.1	64.2	70.9	75.8	79.4	82.1	84.0	85.5
Hecate Strait (5C+5D)	L/T-2	26.0	43.5	55.2	64.2	71.1	76.4	80.5	83.6	--	--
	S-1	48.3	53.7	61.6	67.3	73.5	78.7	76.9	--	--	--
	CL-2	--	51.8	61.4	68.3	74.7	79.0	83.3	86.5	90.0	--
	T-2	--	43.5	57.2	66.8	73.5	78.1	81.3	83.6	--	--
	CL-4	27.7	42.8	54.6	63.7	70.9	76.5	80.9	84.4	87.0	89.1
Gulf of Alaska	CL-2	29.9	41.5	50.4	56.7	62.7	68.7	74.1	78.9	83.9	88.3
E. Bering Sea	S-1	26.9	40.6	54.0	66.2	75.7	84.5	93.2	94.0	--	--
	CL-2	23.9	34.1	39.9	48.7	56.8	62.1	67.4	72.0	76.8	82.1
	CL-5	22.2	33.8	41.8	49.9	57.5	61.6	66.4	71.6	75.5	--
	FR	25.5	36.1	45.2	52.4	58.2	62.9	66.8	70.0	72.5	74.6
N.W. Pacific											
W. Bering Sea	S/O	18.0	29.5	35.5	45.7	54.2	64.2	77.4	79.8	83.6	87.0
Okhotsk Sea	S/O	22.8	34.6	44.8	53.4	60.8	67.7	75.1	84.0	84.1	85.5
S.E. Korea	S-1	23.5	39.0	57.5	69.0	(80)	(90)	--	--	--	--

a. CL-1 = Macdonald-Pitcher iterative (Karp 1982)
CL-2 = Foucher-Fournier iterative (Foucher et al. 1984, Table 5)
CL-3 = Foucher-Fournier iterative (Westrheim and Foucher 1987, Table 3)
CL-4 = Foucher-Fournier iterative (R.P. Foucher, pers. comm.)
CL-5 = Macdonald-Pitcher iterative (Bakkala et al. 1986b)
FR = dorsal fin rays (Lai et al. 1987)
L/T-1 = L-F progression/tagging (Ketchen 1961)
L/T-2 = L-F progression/tagging (Ketchen 1964)
S-1 = scales (Foucher et al. 1984, Table 5)
S/O = scales + otoliths (Foucher et al. 1984, Table 5)
T-1 = tagging (Karp 1982)
T-2 = tagging (Ketchen 1984)
T-3 = tagging (Westrheim 1985, Tables 30 & 31)

Table 5.5.8. Mean lengths-at-age (cm), by location and time, for Atlantic cod, 1947-82. (Sources listed below.)

	N.E. Atlantic[a]						N.W. Atlantic[b]			
Age	S. Barents Sea[d]	N.W. Norway[d]	E. Baltic Sea[e]	North Sea[c] South	North	Iceland[f]	Labrador[g]	S.W. Grand Bank[g]	Gulf of Maine[h]	Georges Bank[h]
(y)	(I) (1982)	(IIa) (1982)	(IIId) (1982)	(IVa) (1968-72)	(IVb,c)	(Va) (Jan-May 1982)	(2) (1947-50)	(3NO) (1947-50)	(5Y) (1970-74)	(5Z) (1970-74)
1	--	--	22.3	15.6	15.0	--	--	--	11.7	26.1
2	33.05	--	29.0	39.3	32.7	--	--	--	26.4	39.9
3	43.75	42.00	35.6	66.2	60.2	47.1	--	44.0	39.6	52.1
4	48.15	48.75	43.5	78.8	73.9	55.3	41.1	49.0	51.3	63.0
5	56.60	57.05	49.4	87.9	84.5	60.0	43.6	51.6	61.7	72.6
6	62.75	64.00	61.3	94.4	92.5	67.4	48.8	59.7	71.0	81.1
7	70.85	72.25	69.5	99.0	98.7	75.0	51.8	69.8	79.3	88.7
8	79.20	81.55	77.1	--	--	82.8	54.2	76.9	86.6	95.4
9	86.40	91.95	84.1	--	--	88.3	56.7	83.5	93.2	101.4
10	--	100.00	91.6	--	--	97.5	58.4	87.6	99.0	106.7
11	98.05	106.20	--	--	--	--	57.8	90.4	104.2	111.4
12	118.05	110.80	--	--	--	--	58.5	91.2	108.9	115.5
13	--	115.55	--	--	--	--	59.0	91.9	113.0	119.2
14	118.05	119.72	--	--	--	--	--	--	116.7	122.5
15	123.05	--	--	--	--	--	--	--	119.9	125.4

a. ICES Area. See Fig. 2.3.
b. ICNAF/NAFO Area. See Fig. 2.4.
c. Daan (1974, Tables III and VI)
d. Lebed and Ponomarenko (1985, Table 41); presumably only adults.
e. Aro and Sjoeblom (1985, Table 59); only spawners.
f. Schopka (1985, Table 34)
g. Fleming (1960, Table II)
h. Penttila & Gifford (1976)

Table 5.5.9. Mean length (L) and weight (W) at age, and inter-age weight increments (w), by location, for Pacific cod in the northeast Pacific[a].

Age (y)	Georgia Strait (4B)			Southwest Vancouver Island (3Cn)			Hecate Strait (5C+5D)			East Bering Sea		
	L (cm)	W (g)	w (g)	L (cm)	W (g)	w (g)	L (cm)	W (g)	w (g)	L (cm)	W (g)	w (g)
1	28.1	224		26.0	174		27.7	214		25.8	178	
			958			689			650			355
2	47.1	1182		42.7	863		42.8	865		36.5	532	
			1395			1087			1023			515
3	60.1	2577		55.1	1950		54.6	1888		45.2	1047	
			1419			1234			1226			614
4	68.9	3995		64.2	3184		63.7	3114		52.3	1661	
			1223			1193			1274			668
5	74.9	5218		70.9	4377		70.9	4389		58.2	2329	
			963			1052			1216			649
6	78.9	6181		75.8	5429		76.5	5605		62.9	2978	
			720			877			1098			624
7	81.7	6901		79.4	6306		80.9	6702		66.8	3602	
			521			704			954			556
8	83.5	7422		82.1	7011		84.4	7657		69.9	4158	
			369			551			808			509
9	84.8	7790		84.0	7562		87.0	8464		72.5	4667	
			257			424			670			
10	85.7	8048		85.5	7987		89.1	9135				
Parameters[a]:												
L_∞:	87.5			89.48 cm			96.58 cm			84.008 cm		
K:	0.387			0.307			0.247			0.203		
t_o:	no estimate			-0.116 y			-0.3685 y			-0.806 y		

$W = 0.004988\ L^{3.2117}$ (B.C.)
$W = 0.00608\ L^{3.1635}$ (E. Bering Sea)

a. B.C. parameters provided by R.P. Foucher (pers. comm.).
East Bering Sea parameters from Thompson and Shimada (1988).

Table 5.6.1. Criteria for maturity condition of Pacific cod gonads. (Source: Westrheim 1977, Table 12)

Condition	Testes	Ovaries
1. Immature	string-like, translucent	small, translucent
2. Maturing	small, some proportionally large convolutions, translucent to white	small, colouring
3. Mature	large, convolutions firm, whitening	large, opaque, creamy, blood vessels prominent
4. Mature	large, convoluted white	large, eggs visible, creamy yellow
5. Mature (ripe)	large, milt running, white	large, eggs translucent
6. Mature (spent)	medium, convolutions flaccid, bloodshot	medium, flaccid, bloodshot
7. Mature (resting)	small, convolutions firm, translucent red, or tan	small, firm, black or grey

Table 5.6.2. Incidence (%), among years within months, of gonad conditions[a] for mature male and female Pacific cod collected during December-May 1977-85 from Areas 4B, 3Cn, 5C, and 5D. (Source: Foucher and Westrheim 1990, Table 6).

		Males						Females					
Month	Year	3	4	5	6	7	N[b]	3	4	5	6	7	N[b]
						Area 4B							
Jan	78	14	84	0	0	1	206	34	57	0	0	9	120
	79	22	74	0	0	4	23	57	7	0	0	36	14
	80	12	52	0	0	35	113	40	14	0	0	45	99
	81	0	92	0	0	8	13	50	0	0	0	50	8
	82	5	81	0	0	15	108	76	20	1	0	3	71
	83	33	60	0	0	7	15	82	0	0	0	18	11
Feb	77	1	14	84	1	0	87	5	65	26	4	0	81
	78	5	74	10	5	6	132	12	70	2	3	13	162
	79	1	66	5	14	15	392	2	53	10	14	22	419
	80	0	82	7	5	5	112	11	66	9	5	10	128
	85	2	94	2	0	2	93	48	47	0	0	5	85
Nov	77	97	0	0	0	3	36	5	0	0	0	95	19
	78	81	6	0	0	13	48	7	0	0	0	93	74
	79	41	0	0	0	59	46	9	0	0	0	91	58
	81	50	8	0	0	42	12	0	0	0	0	100	7
	82	7	0	0	0	93	15	3	3	0	0	94	34
Dec	78	68	32	0	0	0	37	92	8	0	0	0	12
	79	34	0	0	0	66	50	4	0	0	0	96	46
	80	58	4	0	0	38	26	0	0	0	0	100	13
	81	91	0	0	0	9	23	40	0	0	0	60	5
	82	100	0	0	0	0	5	0	0	11	0	89	9
						Area 3Cn							
Feb	77	0	9	77	14	0	592	0	40	37	23	0	575
	78	0	28	49	20	2	967	0	35	41	16	8	675
	82	3	39	39	18	1	272	4	18	50	27	2	288
	83	10	41	29	19	2	281	3	43	33	18	3	98
	84	1	24	47	24	3	148	0	8	63	13	15	52
Apr	77	0	0	9	91	0	78	0	11	2	87	0	84
	78	0	0	0	16	84	58	0	0	0	0	100	47
	79	0	0	0	6	94	50	0	2	0	2	97	59
	80	0	9	2	0	89	47	0	0	14	0	86	28
	81	0	0	0	16	84	62	0	0	0	0	100	42
	82	0	1	4	3	92	119	0	1	2	0	97	106
	85	0	0	3	12	85	293	0	0	0	0	100	251

Table 5.6.2 (cont.)

Month	Year	Males 3	4	5	6	7	N[b]	Females 3	4	5	6	7	N[b]
						Area 5C							
Feb	78	19	16	35	28	1	99	5	20	37	24	15	117
	79	2	52	21	13	12	163	1	45	19	33	3	194
	80	1	58	19	8	15	113	3	49	14	5	29	116
	82	0	87	10	2	2	120	9	64	22	2	2	95
	83	2	45	1	30	22	168	8	16	22	17	38	212
Apr	77	0	0	15	85	0	59	0	13	9	79	0	56
	78	1	2	7	13	78	196	0	7	4	6	83	168
	80	0	4	2	14	80	373	0	4	2	19	74	337
	82	1	0	2	5	92	86	0	1	0	1	98	98
	83	0	12	0	12	76	90	0	3	9	0	88	110
						Area 5D							
Feb	78	4	56	15	20	4	91	31	30	14	18	7	102
	79	2	46	35	12	5	155	6	66	10	17	1	166
	80	1	76	14	5	5	371	3	79	7	6	6	348
	82	7	68	4	0	21	85	45	36	7	4	8	74
	83	1	80	3	11	5	298	14	13	50	15	9	364
	85	8	68	18	0	6	227	10	47	31	2	9	216
Apr	77	0	3	40	54	4	219	0	31	11	53	4	166
	78	0	6	6	31	57	202	2	8	3	19	69	178
	79	0	17	11	19	52	150	0	15	3	28	55	195
	80	0	1	11	5	82	74	0	10	5	5	80	99
	83	0	10	7	6	78	768	0	4	14	6	76	877
May	77	0	0	8	92	0	37	2	14	0	76	8	51
	78	0	2	2	19	77	115	0	2	2	27	69	130
	79	0	1	0	0	99	101	0	0	0	1	99	106
	80	0	1	0	12	87	132	0	1	0	26	73	89
	81	0	2	0	29	69	49	0	0	0	0	100	57

a. See Table 5.6.1. (3 & 4 = maturing; 5 = ripe; 6 = spent; 7 = resting)

b. N =numbers of specimens examined.

Table 5.6.3. Spawning times, by location and source, of Pacific cod.

Location	Time	Source
N.E. Pacific		
Juan de Fuca Strait (Area 4A)	Jan-Mar	Karp (1982)
Georgia Strait & Juan de Fuca Strait (Area 4B)	Feb-Mar[a]	Foucher & Westrheim (1990)
S.W. Vancouver Is. (Area 3Cn)	ca. Feb Feb-Mar[a]	Westrheim (1977) Foucher & Westrheim (1990)
Hecate Strait (Areas 5C+5D)	ca. Mar Feb-Mar[b]	Westrheim (1977) Foucher & Westrheim (1990)
Gulf of Alaska	Feb-Jul	Hirschberger & Smith (1983)
N. Bering Sea	Jan-Mar	Svetovidov 1949[b]
N.W. Pacific		
Gulf of Anadyr	? -Apr	Moiseev (1953)
Olyutorskii Bay	? -May	
Kronotskii Gulf	Jan-Mar	
Komandorski Islands	Jan-May	
S.E. Kamchatka	Mar-May	
W. Kamchatka	Mar-May	
Peter-the-Great Bay	Feb-Apr	
W. Sakhalin	Jan-Mar	
Japan[c]	Dec-Mar	Mishima (1984)
S.E. Korea	Dec-Jan	Moiseev (1953)

a. Principal time.
b. Cited by Musienko (1970).
c. Includes Hokkaido, and East and West Honshu, north of ~36 N lat.

Table 5.6.4. Spawning times, by location and source, for Atlantic cod.

Location	Time[a]	Source
N.E. Atlantic[b]		
Combined areas	Jan-Dec	Hardy (1978)
White Sea (1)	Apr *	Brander (1993)
N.W. Norway (IIa)	Feb-May	Pedersen (1984)
	Apr *	Brander (1993)
W. Baltic Sea & vicinity (IIIb,c)	Jan-Aug	Poulsen (1931)
Skagerrak-Kattegat (IIIa)	Feb-Mar *	Poulsen (1931)
Kattegat-Belt Sea (IIIb,c)	Mar-Apr *	
Bornholm (IIId)	Apr-Jun *	
	Mar *	Brander (1993)
E. Baltic (IIId)	Apr *	Brander (1993)
North Sea (IV)	Oct-Nov	Fulton (1904)
	Feb-Apr	Graham et al. (1924)
	Sep-Oct	Graham & Lumby (1929
	Autumn	Graham (1934)
	Jan-Feb*	Oosthuizen & Daan (1974)
North (IVa,b)	Mar *	Brander (1993)
South (IVc)	Feb *	
English Channel (VIId,e)	Feb *	Brander (1993)
Irish Sea (VIIa)	Feb-Apr	Johnstone et al. (1924)
	Mar *	Brander (1993)
Faroes (Vb)	Apr *	Brander (1993)
Iceland (Va)	Apr-Jun	Einarsson & Williams (1968)[c]
	Apr *	Brander (1993)
N.W. Atlantic[d]		
Combined areas	Jan-Dec	Hardy (1978)
W. Greenland (1)	<= Mar-Jul	Jensen & Hansen (1931)

Table 5.6.4 (cont.)

Location	Time[a]	Source
S.W. Greenland (1E)	May *	Brander (1993)
S. Greenland (1F)	Apr *	Brander (1993)
Canada	Feb-Dec	Scott & Scott (1988)
Labrador (2GHJ)	Mar-Aug	Hardy (1978)
2J	Mar-Apr *	Brander (1993)
Newfoundland (3KLNOP4R)	Mar-Oct	Hardy (1978)
3K	Apr *	Brander (1993)
3L	Apr-May *	
Grand Bank (3NO)	Apr-Aug	Hardy (1978)
Gulf of St. Lawrence (4RST)	Jan-May, Nov	Hardy (1978)
North (4R)	Apr-May *	Brander (1993)
South (4T)	Jun *	
Nova Scotia (4VWX)	Mar,Jun-Jul, Sep-Dec	Hardy (1978)
Scotian Shelf (4VnWX)	Jan-Dec[e]	Gagne & O'Boyle (1984)
4Vn	May *	Brander (1993)
4W	Apr *	
4X	Mar *	
Bay of Fundy (4X)	Jan-May, Nov	Hardy (1978)
Gulf of Maine (5Y)	Nov-Apr	Hardy (1978)
	Feb *	Brander (1993)
Browns Bank (4X)	Mar-Apr	Hardy (1978
Massachusetts (5Y)	Jan-Apr,Jun, Sep-Oct	
Georges Bank (5Z)	Jan	Hardy (1978)
Rhode Island (5Zw)	Jan-May	
North Carolina (6C)	Jan-Jun, Sep-Oct	Hardy (1978)

a. Principal time indicated by asterisk.
b. ICES Area. See Fig. 2.3.
c. Cited by Bagenal (1971).
d. ICNAF/NAFO Area. See Fig. 2.4.
e. Based on bimonthly egg and larvae surveys, 1978-82.

Table 5.6.5. Length (cm) at 50% maturity (L/50), by location, time, sex, and source, for Pacific cod, 1938-87.

Location	Time Month	Time Year	L/50 M	L/50 F	Source
N.E. Pacific					
Georgia Strait (4B)	---	<1961	48-49	55	Ketchen (1961)
	Jan-Mar	1973-85	46	47	Westrheim (1987)
S.W. Vancouver Is. (3Cn)	Feb	1976	50	53	Westrheim (1977)
	Jan-Mar	1973-85	41	48	Westrheim (1987)
Hecate Strait (5C+5D)	Jan-Feb	1960-61	50	55	Thomson (1962)
	Feb	1976	53	56	Westrheim (1977)
	Jan-Mar	1973-85	46	49	Westrheim (1987)
	Jan-Mar	1960-87	--	56	Welch & Foucher (1988)
E. Bering Sea	Jul-Dec	1981-82	60	62	Teshima (1985)
N.W. Pacific					
W. Kamchatka	Dec 1938-Mar 1939		--69[a]--		Moiseev (1953)

a. Interpolated from his Table 41. Sexes combined.

Table 5.6.6. Maximum-likelihood estimates of length (cm) at 50% maturity (L/50) for female Pacific cod from White Rocks Ground, Hecate Strait, January-March 1960-87. (Source: Welch and Foucher 1988, Table 3)

Year	Sample type[a]	Sample numbers	L/50 (cm)
1960	R	436	55.6
1961	R	357	55.4
1975	P	178	46.5
1976	R	115	55.6
1978	P	216	37.5
1979	P	452	49.7
1980	P	1113	52.3
1982	P	222	49.7
1983	P	858	49.4
1985	P	297	42.8
1986	P	348	52.1
1987	P + R	2622	55.1

a. P = port sample; R = research-vessel sample.

Table 5.6.7. Percent mature (%M), by length (cm), sex, and area, for Pacific cod, without parabranchial lesions, from Areas 4B, 3Cn, and 5D, January-March, 1973-85. (Source: PBS files[a])

Fork Length (cm)	4B Males %M	4B Males (N)[b]	4B Females %M	4B Females (N)[b]	3Cn Males %M	3Cn Males (N)[b]	3Cn Females %M	3Cn Females (N)[b]	5D Males %M	5D Males (N)[b]	5D Females %M	5D Females (N)[b]
23	--	(0)	--	(0)	--	(0)	--	(0)	0	(1)	0	(1)
26	--	(0)	--	(0)	--	(0)	--	(0)	0	(1)	0	(2)
29	--	(0)	--	(0)	--	(0)	--	(0)	0	(2)	0	(3)
32	--	(0)	--	(0)	--	(0)	--	(0)	33	(3)	--	(0)
35	0	(3)	0	(1)	--	(0)	0	(1)	25	(4)	14	(7)
38	11	(11)	0	(17)	75	(8)	0	(5)	13	(15)	11	(18)
41	21	(86)	4	(73)	38	(26)	19	(16)	13	(78)	14	(79)
44	41	(169)	23	(170)	56	(57)	21	(39)	27	(211)	14	(183)
47	65	(220)	48	(163)	73	(147)	33	(96)	43	(228)	25	(215)
50	83	(223)	71	(208)	95	(324)	74	(117)	59	(322)	43	(260)
53	93	(376)	83	(259)	99	(649)	97	(265)	80	(406)	65	(298)
56	98	(400)	90	(304)	99	(829)	99	(433)	88	(446)	74	(342)
59	98	(307)	96	(303)	100	(846)	100	(514)	93	(463)	90	(394)
62	99	(258)	97	(293)	100	(765)	100	(537)	99	(347)	97	(336)
65	100	(166)	97	(230)	100	(599)	100	(510)	99	(310)	99	(320)
>65	100	(190)	92-100	(492)	100	(775)	100	(1212)	100	(367)	100	(689)
Total		(2428)		(2513)		(5025)		(3745)		(3204)		(3147)
L/50[c]	45		47		43		48		48		51	

a. Groundfish data base, Pacific Biological Station, Nanaimo, B.C., Canada.
b. Numbers sampled.
c. Fork length at which 50% are mature. Estimated by linear interpolation.

Table 5.6.8. Percent mature (%M), by length (cm) and ground, for female Pacific cod landed from Hecate Strait, January-March 1980 and 1987. (Source: Foucher & Welch 1987)

Fork Length (cm)	Two Peaks 1980		White Rocks 1980		White Rocks 1987		Reef Island 1980	
	%M	(N)[a]	%M	(N)[a]	%M	(N)[a]	%M	(N)[a]
<40	0	(3)	0	(4)	0	(38)	--	(0)
41	0	(12)	7	(28)	1	(97)	--	(0)
44	0	(59)	6	(54)	6	(213)	60	(5)
47	2	(46)	16	(91)	5	(310)	67	(24)
50	11	(27)	39	(146)	7	(270)	94	(33)
53	28	(18)	58	(170)	22	(151)	92	(24)
56	34	(35)	67	(165)	60	(125)	93	(30)
59	62	(42)	88	(154)	86	(165)	100	(28)
62	87	(46)	97	(88)	97	(209)	100	(15)
65	100	(19)	95	(61)	98	(256)	100	(17)
>65	100	(84)	97	(152)	99	(789)	100	(57)
Total		(391)		(1113)		(2623)		(233)
FL @ 50%:								
Linear[b]	57.7		51.7		55.2		<47	
MaxLkl[c]	57.0[d]		52.3[d]		55.5[e]		43.1[d]	

a. N = numbers sampled.
b. Linear interpolation.
c. Maximum likelihood (Welch & Foucher 1988).
d. Table 2 in Welch & Foucher (1988).
e. Table 1 in Welch & Foucher (1988).

Table 5.6.9. Length (cm) at 50% maturity (L/50), by location, time, sex, and source, for Atlantic cod, <1893-1990.

Location	Time		L/50		Source
	Month	Year	M	F	
N.E. Atlantic[a]					
North Sea	---	<1893	72	74	Holt (1893)[b]
(IV)	Jan-Mar	1923	67	74	Graham et al. (1924)[b]
	---	1909-29[c]	57	66	Poulsen (1931)
	Jan-Feb	1968-72	53	60	Oosthuizen & Daan (1974)
W. Baltic Sea	---	1909-29	25	28	Poulsen
(IIIc,d/24)					(1931)
N.W. Atlantic[d]					
W. Greenland	---	<1931	64-66	72	Jensen &
(1A-D)					Hansen (1931)
Labrador	---	1947-50	--42[e]--		Fleming
(2J)					(1960)
	Fall	1978-90	--	46-56	Xu et al.
	Fall	1981-90	--	46-56	(1993)
E. Newfoundland	---	1947-50	-- 64[e]--		Fleming
(3KL)					(1960)
3K	Fall	1978-90	--	50-61	Xu et al.
	Fall	1981-90	--	50-56	(1993)
3L	Fall	1981-90	--	49-57	
W. Newfoundland	---	1953-65	46	50	Wiles & May
(4RS3Pn)					(1968)
S.W. Gulf of					
St. Lawrence	---	1955	53	57	Powles
(4TVn)	---	1956	50	52	(1958)
	---	1959-64	46	54	Beacham
	---	1975-79	39	40	(1983a)

Table 5.6.9 - (cont.)

Location	Time		L/50		Source
	Month	Year	M	F	
Scotian Shelf (4VsW)	---	1959-64	46-57 36-45	44-55 34-45	Beacham (1983b)
	---	1975-79			

a. ICES Area. See Fig. 2.3.
b. Cited by Oosthuizen & Daan (1974, Table X).
c. Includes Skagerrak & N. Kattegat.
d. ICNAF/NAFO Area. See Fig. 2.4.
e. Deduced from his Figure 5, presumably males + females.

Table 5.6.10. Estimated length (cm) at 50% maturity (L/50), by year and NAFO Division, of female cod collected in the Labrador-Newfoundland Region during autumn, 1978-90. (Source: Xu et al. 1993, Table 2).

	NAFO Division			
Year	2J	3K	3L	2J3KL
1978	53.71	60.64	--	--
1979	52.25	53.32	--	--
1980	53.01	55.06	--	--
1981	55.53	54.79	54.40	54.85
1982	54.25	55.89	57.23	55.97
1983	54.65	55.97	58.79	56.56
1984	49.41	52.89	58.85	52.17
1985	48.32	51.28	55.06	50.56
1986	48.09	50.45	57.52	52.04
1987	47.87	51.60	56.67	50.91
1988	48.39	49.57	50.22	49.25
1989	48.39	50.31	50.88	49.75
1990	45.87	49.75	55.02	49.72

Table 5.6.11. Estimated fecundities at selected lengths, by location, time, and source, for Pacific and Atlantic cod, 1939-90.

Location	Time	N[a]	Size range (cm)	Fecundity (x 1000) at: 60 cm	80 cm	100cm	Source
N.E. Pacific							
Juan de Fuca Strait (4A)	1977-78	43	40-78	2200	5100	9900	Karp (1982)
S.W. Vancouver Is. (3Cn)	1988,1990	83	47-80	1390	3233	6223	Foucher & Tyler (1990b)
Hecate Strait (5C+5D)	1961	46	40-88	1182	3375	7616	Thomson (1962)
	1986-89	266	44-89	1326	3663	8054	Foucher & Tyler (1990b)
S.W. Van. Is. + Hecate Strait	1986-89	349	44-89	1352	3580	7621	Foucher & Tyler (1990b)
N.W. Pacific							
W. Kamchatka	1939	10	68-100	1809	3055	5722	Moiseev (1953)
W. Sakhalin	1947	12	63-93.5	1986[b]	4745[c]	--	Moiseev (1953)
N.E. Atlantic[d]							
N. Norway--ANC[e] (I+II)	1986-87	100	50-135	489	1671	4334	Kjesbu (1988)
N. Norway--CC[e] (I+IIa)	1986-87	40	54-95	671	3789	--	Kjesbu (1988)
S. Norway--CC[e] (IIa+IVa+IIIa)	1959	NR[f]	NR	1452	3862	8250	Botros (1962)[g]
Baltic Sea (IIIc,d)	NR	191	NR	1741	4163	8186	Schopka & Hempel (1973)
W. Baltic Sea (IIIc,d/24)	1959	NR	NR	1453	4078	9079	Botros (1962)[g]
North Sea (IV)	NR	47	NR	1083	2409	4480	Schopka & Hempel (1973)
	1970-72	92	NR	913	2354	4904	Oosthuizen & Daan (1974)
Iceland (Va)	NR	103	NR	807	2183	4724	Schopka & Hempel (1973)
N.W. Atlantic[h]							
Labrador[i] (2GHJ)	1964	65	45-77	(532)	(991)	--	Postolakii (1967)
Labrador & Newfoundland (2J3KLNO)	1964-65	120	50-107	603	1613	3459	May (1967)
Newfoundland:	1966-70	398	51-128				Pinhorn (1984)
Bonavista Bay (3L)		58		593	1626	3614	
Trinity Bay (3L)		78		653	1607	3296	
St. John's (3L)		72		845	1268	1770	
Placentia Bay (3Ps)		96		1079	2164	3715	
St. Pierre Bank (3Ps)		104		409	1079	2291	
S.W. Gulf of St. Lawrence (4T):	1955-56	53	51-140	(No formula or data)			Powles (1958)

Table 5.6.11 (cont.)

Location	Time	N[a]	Size range (cm)	Fecundity (x 1000) at: 60 cm	80 cm	100cm	Source
		(39)[j]	NR	468	1779	5011	May (1967)
		(43)[k]	NR	636	1740	3800	Buzeta & Waiwood (1982)
	1981	30	48-103	748	1921	3994	Buzeta & Waiwood (1982)

a. N = number of specimens.
b. Actually 63-67 cm (N = 7).
c. Actually 82 cm (N = 1).
d. ICES Area. See Fig. 2.3.
e. ANC = Arcto-Norwegian (= Northeast Arctic) stock; CC = Coastal stock (formula not valid @ >95 cm;
f. NR = not reported.
g. Cited by Oosthuizen & Daan (1974).
h. ICNAF/NAFO Area. See Fig. 2.4.
i. Reported formula not used. See text.
j. Formula "estimated" from the log-log plot (39 points) in Fig. 5 of Powles (1958).
k. Calculated from data in Powles (1957). Not given by the latter two authors.

Table 5.7.1. Selected parameters for eggs and larvae of Pacific cod, by location. (Sources listed below.)

Parameter	British Columbia[a]	Washington State[b]	Northeast Pacific[c]	Asia[d]
Fertilized ova:				
a. Mean diameter (mm)	1.02	0.96	1.02	0.98
b. Condition	Adhesive & demersal	Adhesive & demersal	Demersal	Adhesive & demersal
Optimum incubation conditions:				
a. Temperature (C)	3-5	---	---	---
b. Salinity (ppm)	13-23	---	---	<30[e]
c. Dissolved oxygen (ppm)	2-3 to saturation +	---	---	---
Incubation time (d)[f]	15-17 @ 3-5 C[g]	12 @ 8-9	---	15-20 @ 5.5 C 9-14 @ 7-11 C[g]
Length (mm) at hatching:				
a. Standard length	---	---	3-4	3.45
b. Total length	4.1-4.5	3.2-3.5	---	3.6
Yolk-sac resorption:				
a. Days after hatching	10 @ 5 C	---	---	10 @ 5.5 C[h]
b. Length (mm) of larvae	---	---	---	4.0
Length (mm) at metamorphosis:	<40[i]	<33	25-35 (35)	>32 <40[j]

a. Alderdice and Forrester (1971); Forrester (1964); Forrester & Alderdice (1966).
b. Walters (1984).
c. Matarese et al. (1989); (Dunn & Matarese 1987)
d. Mukhacheva & Zviagina (1960), unless otherwise noted.
e. Yamamoto & Nishioka (1952).
f. To 50% hatching.
g. Optimum.
h. Mishima (1984).
i. This study, Fig. 5.1.1.
j. Moiseev (1953, Table 30).

Table 5.8.1. Principal invertebrate and fish components reported, by location, time, and source, in stomachs of Pacific cod caught off British Columbia, 1950-82.

Location	Time	No. of stomachs[a]	Invert.[b]	Fish[c]	Source
Coast-wide	Winter	491	"shrimp"	herring sandlance flatfish	Hart (1949)
3Cn	Feb 76	199	shrimp	herring poacher	Westrheim (1977)
	Apr 75	141	euphausiid	sandlance	
	Jul 75	324	euphausiid	flatfish herring	
	Oct 75	243	euphausiid	sandlance	
3Cn+3D	1950-80:				Westrheim &
	Jan-Mar	(25)	---	sandlance	Harling
	Apr-Jun	(39)	---	sandlance herring	(1983)
	Jul-Sep	(16)	"shrimp"	herring	
	Oct-Dec	(3)	---	herring	
5A+5B	1950-80:				Westrheim &
	Jan-Mar	(2)	---	herring	Harling
	Apr-Jun	(36)	---	sandlance	(1983)
	Jul-Sep	(27)	---	sandlance	
	Oct-Dec	(1)	"shrimp"	herring	
	Sep-Nov (1982)	303	pandalid	herring	Westrheim *et al.* (1989)
5C+5D	Feb 76	314	crangonid	herring	Westrheim
	Apr 75	324	euphausiid	sandlance	(1977)
	Jul 75	403	crangonid euphausiid	sandlance	
	Oct 75	377	crangonid euphausiid	herring flatfish	
	1950-80:				Westrheim
	Jan-Mar	(85)	---	herring sablefish	& Harling (1983)
	Apr-Jun	(109)	---	sandlance	
	Jul-Sep	(70)	"shrimp"	sandlance herring	
	Oct-Dec	(40)	---	herring sablefish	
	1979:				
	Jun-Jul	559	euphausiid shrimp	sandlance	Westrheim *et al.* (1980a)

Table 5.8.1 (cont.)

Location	Time	No. of stomachs[a]	Invert.[b]	Fish[c]	Source
	Sep	102	amphipod crab euphausiid shrimp	flatfish herring sandlance	Westrheim et al. (1980b)
	Sep-Oct (1982)	1074	crangonid	sandlance	Westrheim et al. (1989)
5E	Sep 82	18	pandalid	herring	Westrheim et al. (1989)

a. Values in parentheses = numbers of port samples (100-300 specimens per sample). See text.

b. Crab, Cancer sp.; "shrimp" = copepods, Crangonidae, and/or Pandalidae; shrimp = Pandalidae and/or Crangonidae.

c. Flatfish = Pleuronectidae or Bothidae; herring, Clupea harengus pallasi; poacher, Agonidae; sablefish, Anoplopoma fimbria; sandlance, Ammodytes hexapterus.

Table 5.8.2. Principal invertebrate and fish components reported, by location amd source, in stomachs of Pacific cod caught elsewhere than off British Columbia.

Location	Invertebrates[a]	Fish[b]	Source
N.E. Pacific			
Gulf of Alaska	pink shrimp	walleye pollock	Cobb (1927)
	snow crab	walleye pollock	Jewett (1978)
	snow crab Dungeness crab[c]	walleye pollock herring[c]	Clausen (1981)
	pink shrimp[d]	walleye pollock & capelin[d]	Albers & Anderson (1985)
East Bering Sea	crab shrimp	walleye pollock	Mito (1974)[e]
	pink shrimp Tanner crab snow crab	walleye pollock	Bakkala (1984)
	Tanner crab king crab	walleye pollock pleuronectids	Livingston et al. (1986)
	Chionoecetes	walleye pollock	Livingston (1991)
N.W. Pacific			
West Bering Sea	Chionoecetes	walleye pollock capelin, sand-lance, herring Atherinops	Moiseev (1953)
S.W. Bering Sea	Chionoecetes	walleye pollock	Tokranov & Vinnikov (1991)
E. & W. Kamchatka	Chionoecetes	walleye pollock	Tokranov & Vinnikov (1991)

Table 5.8.2. (cont.)

Location	Invertebrates[a]	Fish[b]	Source
Okhotsk Sea	Chionoecetes	walleye pollock sandlance herring salmon smolts	Moiseev (1953)
Kurile Islands	crustacea	sardine herring	Moiseev (1953)
Japan Sea	Chionoecetes	herring	Moiseev (1953)

a. Dungeness crab, Cancer magister; king crab, Paralithodes; pink shrimp, Pandalus borealis; snow crab, Chionoecetes opilio; Tanner crab, C. bairdi.

b. Capelin, Mallotus villosus; herring, Clupea; salmon smolts, Salmonidae; sandlance, Ammodytes; sardine, Sardinops melanosticta; walleye pollock, Theragra chalcogramma. c. Inside waters: Southeast Archipelago.

d. Inside waters: Pavlov Bay (West Gulf).

e. Cited by Livingston et al. (1986).

Table 5.8.3. Principal invertebrate and fish components reported, by location and source, in stomachs of Atlantic cod.

Location	Invert.[a]	Fish[b]	Source
N.E. Atlantic[c]			
Barents Sea (I+IIb)	euphausiid	herring capelin juv. cod	Brown & Cheng (1946)
	euphausiid amphipods	capelin juv. cod herring	Graham et al. (1954)
	amphipod ctenophore euphausiid pink shrimp polychaete pteropod	capelin herring polar cod redfish	Bergstad et al. (1987)
Baltic Sea (IIId)	Chiridotea	herring Ammodytes juv. cod	Poulsen (1931)
	Mesidotea Harmothoe	herring sprat	Ojaveer et al. (1981)
North Sea (IV)	Crangonidae Pandalidae Portunus	Ammodytes Limanda Clupea Gadidae haddock mackerel	Daan (1973)
Scotland (IVa,b;VIa)	Eupagurus Portunas Nephrops	Ammodytes	Rae (1967a)
Faroe Islands (Vb)	Pandalus	Ammodytes	Rae (1967b)
Iceland (Va)	Pandalus euphausiid	Ammodytes capelin	Rae (1968a)
N.W. Atlantic[d]			
W. Greenland (1) W. Atlantic (1-6)	Crangonidae pink shrimp brittle star lobster moon snail shrimp squid	capelin Ammodytes alewife capelin herring menhaden	Jensen & Hansen (1931) Jensen (1972)

Table 5.8.3. (cont.)

Location	Invert.[a]	Fish[b]	Source
Canada (2-4)	euphausiid mysid Pandalidae	Ammodytes capelin herring	Scott & Scott (1988)
S.W. Gulf of St. Lawrence (4T)	mysid euphausiid decapoda mollusca	Ammodytes herring capelin	Powles (1958)
	crustacea	herring	Kohler & Fitzgerald (1969)
	snow crab	American plaice	Waiwood & Majkowski (1984)
Nova Scotia Banks (4VWX)	crustacea	Ammodytes	Kohler & Fitzgerald (1969)
Nova Scotia to Cape Hatteras (4V-6C)	decapod crab	Clupeidae	Langton & Bowman (1980)

a. Invertebrates: Pink shrimp, Pandalus borealis; snow crab, Chionoecetes opilio.

b. Alewife, Alosa pseudoharengus; American plaice, Hippoglossoides platessoides; capelin, Mallotus villosus; haddock, Melanogrammus aeglefinis; herring Clupea harengus harengus; mackerel, Scomber scombrus; menhaden, Brevoortia tyrannus); polar cod, Boreogadus saida; redfish, Sebastes spp.; sprat, Sprattus sprattus.

c. ICES Area. See Fig. 2.3.

d. ICNAF/NAFO Area. See Fig. 2.4.

Table 5.9.1. Common and scientific names of reported predators, by ocean and source, of Pacific and Atlantic cod.

Common Name	Scientific Name	Ocean[a]	Source
	FISH		
Angel shark	Squatina dumeril	A	Merriman & Olsen (1949)
Atlantic cod	Gadus morhua	A	[b]
Atlantic halibut	Hippoglossus hippoglossus	A	McIntyre (1953)
Blue shark	Prionace glauca	A	Scott & Scott (1988)
Greenland shark	Somniosus microcephalus	A	Taning (1937)
Pacific cod	G. macrocephalus	P*	[c]
Pacific halibut	H. stenolepis	P*	[d]
Porbeagle	Lamna nasus	A	Scott & Scott (1988)
Round skate	Raja fyllae	A	Berestovskiy (1989)
Saithe	G. virens	A	Sars (1869)
Salmon shark	L. ditropis	P	Paust & Smith (1986)
Sculpins	Hemilepidotus jordani	P	Jewett & Powell (1979)
	Myoxocephalus spp.	P	Jewett & Powell (1979)
Spiny dogfish	Squalus acanthias	P*	Jones & Geen (1977)
Spurdog	S. acanthias	A	[e]
Thorny skate	Raja radiata	A	Berestovskiy (1989)
"Large sharks"	---	A	Bigelow & Schroeder (1953)
	BIRDS		
Cormorant	Phalacrocorax carbo	A	Rae (1969)
Rhinoceros auklet	Cerorhinca monocerata	P*	Vermeer & Westrheim (1984)
Shag	P. aristotelis	A	Rae (1969)
Tufted puffin	Fraturcula cirrhata	P	Sanger (1987)
	MAMMALS		
Seals:			
Grey	Halichoerus grypus	A	[f]
Harbour	Phoca vitulina	A	[g]
		P*	[h]
Harp	P. groenlandica	A	[i]
Hooded	Cystophora critata	A	Malouf (1986)
Northern fur	Callorhinus ursinus	P*	[j]
Ribbon	P. fasciatus	P	Kenyon & Scheffer (1953)

Table 5.9.1. (cont.)

Common Name	Scientific Name	Ocean[a]	Source
Ringed	P. hispida	A/P	Kenyon & Scheffer (1953)
Spotted	P. largha	P	Frost & Lowry (1987)
Sea lions:			
California	Zalophus californianus	P	Gearin et al. (1986)
Steller	Eumetopias jubatus	P	k
Whales:			
Killer	Orcinus orca	A	Bergstad et al. (1987)
Minke	Balaenoptera acutorostrata	A	Bergstad et al. (1987)
Sperm	Physeter catodon	A	Roe (1969)

a. A = Atlantic Ocean; P = Pacific Ocean, including Bering Sea and Okhotsk Sea, but not British Columbia waters; P* = including B.C. waters.

b. Bigelow & Schroeder (1953); Brown & Cheng (1946); Daan (1973); Graham et al. (1954); Ponomarenko (1965); Poulsen (1931); Powles (1958).

c. Allen (1987); Cobb (1927); Houghton (1987); Moiseev (1953); Westrheim et al. (1980b).

d. Best & St.-Pierre (1986); Moiseev (1953); Novikov (1964).

e. Holden (1966); Templeman (1944).

f. Hauksson (1984); Malouf (1986); Rae (1968b,1973)

g. Boulva & McLaren (1979); Hauksson (1984); Malouf (1986); Rae (1968b,1973).

h. Everitt et al. (1981), Frost & Lowry (1987); Imler & Sarber (1947); Karp (1982); Kenyon & Scheffer (1953); Olesiuk et al. (1990); Pitcher (1980); Scheffer & Slipp (1944).

i. Anon. (1981); Bergstad et al. (1987); Malouf (1986); Sergeant (1973).

j. Kenyon (1956); Milouf (1986); Perez & Bigg (1980); Spalding 964);

k. Frost and Lowry (1987); Imler & Sarber (1947); Kenyon & Scheffer (1953); Pitcher (1981); Spalding (1964).

Table 5.10.1. Parasites present (+) or absent (-) in Pacific cod (P), and Atlantic cod (A), from Canadian waters, by phylum, class, species, and body location. (Sources listed below.)

Phylum Class	Species[a]	Cod P	Cod A	Body location
Sarcomastigophora[b]				
Lobosea	Hartmannellidae[c]	++[d]	+	parabranchial X-cell lesions
Zoomastigophorea	Spironucleus torosa	-	+	rectal lumen
	Trypanosoma murmanensis	-	+	blood
Apicomplexa[b]				
Sporozoea	Goussia gadi[e] (once Eimeria gadi)	-	+	swim bladder
	G. spraguei	-	+	kidney
	G.sp.	-	+	kidney,liver
Microspora[b]				
Microsporea	Loma morhua	-	+	gill filament, pseudobranch, & viscera cysts
	Microsporida gen.sp.	++[d]	-	kidney & musculature cysts
	Pleistophora sp.	++[d]	+	probably musculature cysts
Myxozoa[b]				
Myxosporea	Kudoa sp.	++[d]	+	musculature cysts
	Myxidium gadi	-	+	gall bladder
	M. ochotense	+	-	gall bladder
	Zschokkella russelli	-	+	gall bladder
Ciliophora[b]				
Oligohymenophorea	Trichodina cooperi	-	+	skin,fins
	T. murmanica	+	+	gills
	T. sp.	-	+	skin,gills,fins
Platyhelminthes				
Monogenea	Gyrodactylus marinus	+	-	gills
	G. sp.	-	+	body surface,gills,fins
	Udonella caligorum	-	+	skin
Digenea	Brachyphallus crenatus	+	+	stomach
	Cryptocotyle lingua (metacercaria)	-	+	skin,gills,fins
	Derogenes varicus	+	+	stomach,intestine
	Fellodistomum furcigerum	-	+	pyloric caeca,intestime
	Gonocerca phycidis	-	+	stomach
	Hemiurus levinseni	+	+	stomach,pyloric caeca
	Lecithaster gibbosus	++[d]	+	stomach,pyloric caeca,intestime
	Lepidapedon elongatum	-	+	pyloric caeca,intestime
	L. gadi	+	-	intestine
	L. rachion	-	+	intestine
	Neophasis sp. (immature)	-	+	intestine
	Otodistomum sp. (metacercaria)	-	+	encrusted on viscera
	Parahemiurus merus	++[d]	-	stomach,pyloric caeca,intestime
	Podocotyle atomon	+	+	intestine
	P. reflexa	+	+	stomach,pyloric caeca,intestime
	Prosorhynchus crucibulum	+	-	intestine
	P. squamatus	-	+	pyloric caeca,intestime
	Pronoprymna petrowi[e] (once Pseudopentagramma petrowi)	+	-	intestine
	Steganoderma formosum	+	-	intestine
	Stenakron vetustum	+	-	intestine
	Stephanostomum baccatum	+	-	intestine
	Tubulovesicula lindbergi	+	-	stomach,intestine
Cestoidea	Abothrium gadi	++[d]	+	pyloric caeca,intestime
	Bothriocephalus sp.	+	-	pyloric caeca,intestime
	Ceratobothrium xanthocephalum (larva)	-	+	stomach,intestine
	Grillotia erinaceus (larva)	-	+	cysts on viscera & mesenteries

Table 5.10.1 (cont.)

Phylum Class	Species[a]	Cod P	Cod A	Body location
	Nybelinia surmenicola (larva)	+	-	viscera, mesenteries
	Phyllobothrium loliginus (larva)	-	+	stomach
	P. sp. (larva)	++[d]	-	pyloric caeca, intestine gall bladder, intestine
	Pseudophyllidea gen.sp. (larva)	-	+	intestine, viscera
	Scolex pleuronectis (larva)	+	+	intestine, gall bladder
	Spathebothrium simplex	-	+	stomach
	Tentacularia coryphaenae (larva)	-	+	cysts on viscera & mesenteries
Nemathelminthes				
Nematoda	Anisakis simplex (larva)[f]	++[d]	+	musculature, viscera
	A. sp. (larva)	++[d]	+	viscera, mesenteries, body cavity
	Ascarophis arctica	-	+	stomach
	A. extalicola	-	+	posterior intestine, rectum
	A. filiformis	+	+	stomach
	A. pacificus	+	-	stomach
	A. sp.	++[d]	-	stomach, intestine
	Capillaria sp.	-	+	intestine
	Contracaecum osculatum (larva)	-	+	viscera mesenteries
	C. sp. and/or Phocascaris sp. (larva)	+	+	intestine, liver, kidney, body cavity
	Cucullanus cirratus	-	+	stomach, intestine
	Hysterothylacium aduncum[e] (once Thynnascaris adunca)	-	+	stomach, intestine
	H. sp. (larva)	-	+	viscera, mesenteries
	Pseudoterranova decipiens (larva)[e] (once Phocanema decipiens, larva)	++[d]	+	musculature cyst
Acanthocephala				
Palaeacanthocephala	Corynosoma strumosum (larva)	+	-	intestine
	C. wegeneri (larva)	-	+	mesenteries, intestine
	C. sp. (larva)	-	+	mesenteries, intestine
	Echinorhynchus gadi	++[d]	+	intestine, mesenteries
	E. sp.	-	+	intestine
Annelida				
Hirudinea	Beringobdella rectangulata (once Levinsenia rectangulata)[e]	+	-	gills, gill cavity
	Johanssonia arctica	-	+	body surface
Arthropoda				
Copepoda	Caligus curtus	-	+	body surface
	C. elongatus	-	+	body surface
	C. sp.	-	+	body surface
	Chondracanthus palpifer	++[d]	-	gill cavity
	Clavella adunca	++[d]	+	gills, gill cavity, anal region
	C. irina	++[d]	+	gills
	Haemobaphes diceraus	++[d]	+	head in bulbus arteriosus, body protruding from gill arch
	Lepeophtheirus cuneifer	+	-	not listed
	L. hospitalis	++[d]	-	body surface
	L. parviventris	++[d]	-	body surface, fins
	L. sp.	++[d]	+	body surface
	Lernaeocera branchialis	-	+	gills, gill cavity
	Naobranchia occidentalis	+	-	gills
Amphipoda	Lafystius sturionis	-	+	body surface
Isopoda	Aega psora	-	+	gill cavity
	Rocinela belliceps	++[d]	+	gill cavity

Table 5.10.1 (cont.)

a. Sources: Appy & Burt (1982); Bousfield (1987); Dawe (1981); Kabata (1988); Khan et al. (1980,1983,1986); Ko (1986); Lee (1988); Love & Moser (1983); Meyer & Khan (1979); Margolis (1977); Margolis & Arthur (1979); McCain et al. (1979); McClelland et al. (1990); Morrison & Marryat (1990); Morrison & Poynton (1989); Morrison & Sprague (1980,1981); Munger (1983); Poynton & Lom (1989); Poynton & Morrison (1990); Rafi (1988); Tomasiewicz (1982); Wellings et al. (1977); Westrheim (1987).

b. Levine et al. (1980).
c. Tentative identification by Dawe (1981).
d. ++ = including B.C. waters.
e. Revised genera names provided by L. Margolis and T.E. McDonald (pers. comm.).

f. Noted in Pacific cod by Margolis (1977). Common, but not documented, in cod from B.C. waters (L. Margolis, pers. comm.).

Table 5.11.1. Reported effects of diseases and pathogenic parasites, by name, causative agent, and source, for juvenile and adult Pacific (P) and Atlantic (A) cod.

Name	Causative agent	Species	Effects	Source
	Virus			
Viral erythrocytic necrosis	(irido virus)[a]	A	reduced resistance to stress: fragility of erythrocytes	Munro et al. (1983) Reno et al. (1985, 1986)
Atlantic cod				
adenovirus	Adinoviridae	A	epidermal hyperplasia	Moeller & Anders (1986)
iridovirus	Iridinoviridae	A	dermal papules (ulcer disease)	
rhabdovirus	Rhabdoviridae	A	dermal papules	
Pacific cod				
herpesvirus	Herpesvirus (presumptive)	P	hypertrophied cells in skin epithelium	Moeller & Anders (1986)
	Fungi			
None	Ichthyophonus hoferi	A	debilitation	Neish & Hughes (1980)
None	Fungi imperfecti[b] (= anomorph)	A	not listed	Neish & Hughes (1980)
None	Cladosporum morhua	A	hypertrophy of epithelium	Sindermann (1990)
Systemic mycosis	Exophiala pisciphilus (= E. pisciphila)[c]	A	fungus cultured from kidneys, liver, heart, spleen, and swimbladder; internal gross lesions	Blazer & Wolke (1978)
None	Exophiala pisciphila	A	chronic inflamation	Neish & Hughes (1980)
	Bacteria			
Vibriosis	Vibrio spp.	P,A	hemorrhagic septicemia, anemia	Anderson & Conroy (1970) Egidius & Andersen (1984)
Tuberculosis	Mycobacterium sp.	A	infection of liver, kidney, spleen, & gonads; emaciation; lesions on skin, fins, caudal peduncle.	Conroy (1970)
None	Pseudomonas-like	P	epidermal ulcers	McCain et al. (1979)
None	Unknown	P	epidermal lesions (ringlike)	
	"Protozoa"			
None	Hartmannellidae	P	delayed maturity, inhibited growth, increased mortality rate (Z)	Westrheim (1987)
None	Hartmannellidae	A	retarded gonad development and high mortality due to bacterial infection for cod held in captivity	Morrison et al. (1982)
Whirling disease	Myxosoma cerebralis (now Myxobolus c.)[c]	A	destroys balance organs	Lee (1988)
None	Trichodina sp.	A	smothers gills	Egidius & Andersen (1984)

Table 5.11.1. (cont.)

Name	Causative agent	Species	Effects	Source
None	Trypanosoma murmanensis	A	lethargy in juveniles	Khan (1977)
None	Eimeria gadi (now Goussia g.)[c]	A	debilitation due to loss of air bladder function; attaches to air bladder connective tissue	Lom (1970)
None	Eimeria gadi (now Goussia g.)[c]	A	emaciation and skin abnormalities in heavy infections; possible mortalities during spawning migrations.	Munro et al. (1983)
None	Pleistophora gadi	A	marked changes in musculature, and open boils; thought to be highly pathogenic to fingerlings	Munro et al. (1983)
	Trematoda			
Black spot	Digenean; mostly Cryptocotyle lingua (metacercaria)	A	skin, eye; minimal effect on adults; fatal to larvae and juveniles if brain or heart is penetrated	Moeller & Anders (1986) Egidius & Andersen (1984)
	Nematoda			
Contracaeciasis	Contracaecum aduncum, larva (now C. osculatum, larva)[c] Anisakis sp. (larva)	A	debilitation; liver atrophy	Margolis (1970)
	Amphipoda			
None	Laphystius sturionis Copepoda	A	epidermal sores	Kabata (1970)
None	Clavella adunca	A A	minor gill tumors lower weight & condition at length (age > 6 y)	Kabata (1970) Janusz (1980)
None	Lernaeocera branchialis	A	debilitation due to blood loss and secondary bacterial infection; head in bulbus arteriosus	Kabata (1970)
	L. branchialis	A	20-30% weight loss in North Sea cod.	Mann (1970)[g]
None	L. branchialis	A	weight loss & lower K for Newfoundland farm cod, and post-capture stress	Lee (1988)
	Complexes[d]			
Fin rot	"pollution" + viruses + bacteria	A	fin destruction	Moeller & Anders (1986)
Lateral Line Necrosis	Unknown	A	complete destruction of tissue along lateral line; no apparent ill effects	Moeller & Anders (1986)
Ulcus syndrome	virus + "pollution" + bacteria (primarily	A	initially epidermal papules and vesicles, followed by	Jensen (1983); Larsen (1983);

Table 5.11.1. (cont.)

Name	Causative agent	Species	Effects	Source
	Vibrio anguillarum)		erosions and ulcers; mainly in 1.5- to 2.5-y cod in Baltic Sea	Munro et al. (1983)
Vibriosis	high cod abundance + low food abundance + bacteria (Aeromonas, Pseudomonas, Vibrio)	A	petechies on body surface & gill covers; epidermal ulcers; caudal fin necrosis	Ipatov (1989)

a. Tentative identification by Reno et al. (1986).
b. Asexual stage.
c. Revised species' names provided by L. Margolis and T.E. McDonald (pers. comm.).
d. Multiple causes acting synergistically.

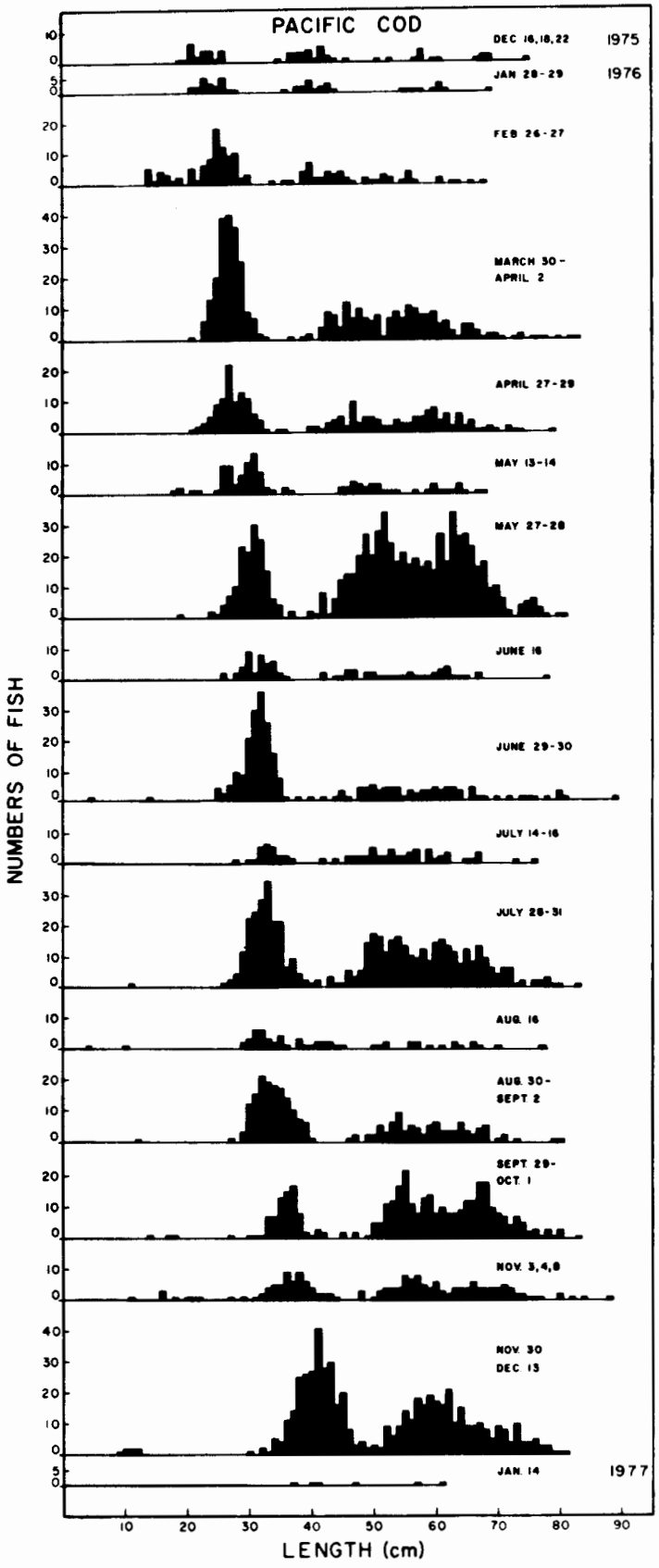


Fig. 5.1.1. Length-frequencies (nos. measured), by month, of Pacific cod from research-vessel catches in Georgia Strait (4B), December 1975-January 1977. (Fig. 10 in Beamish et al. 1978).

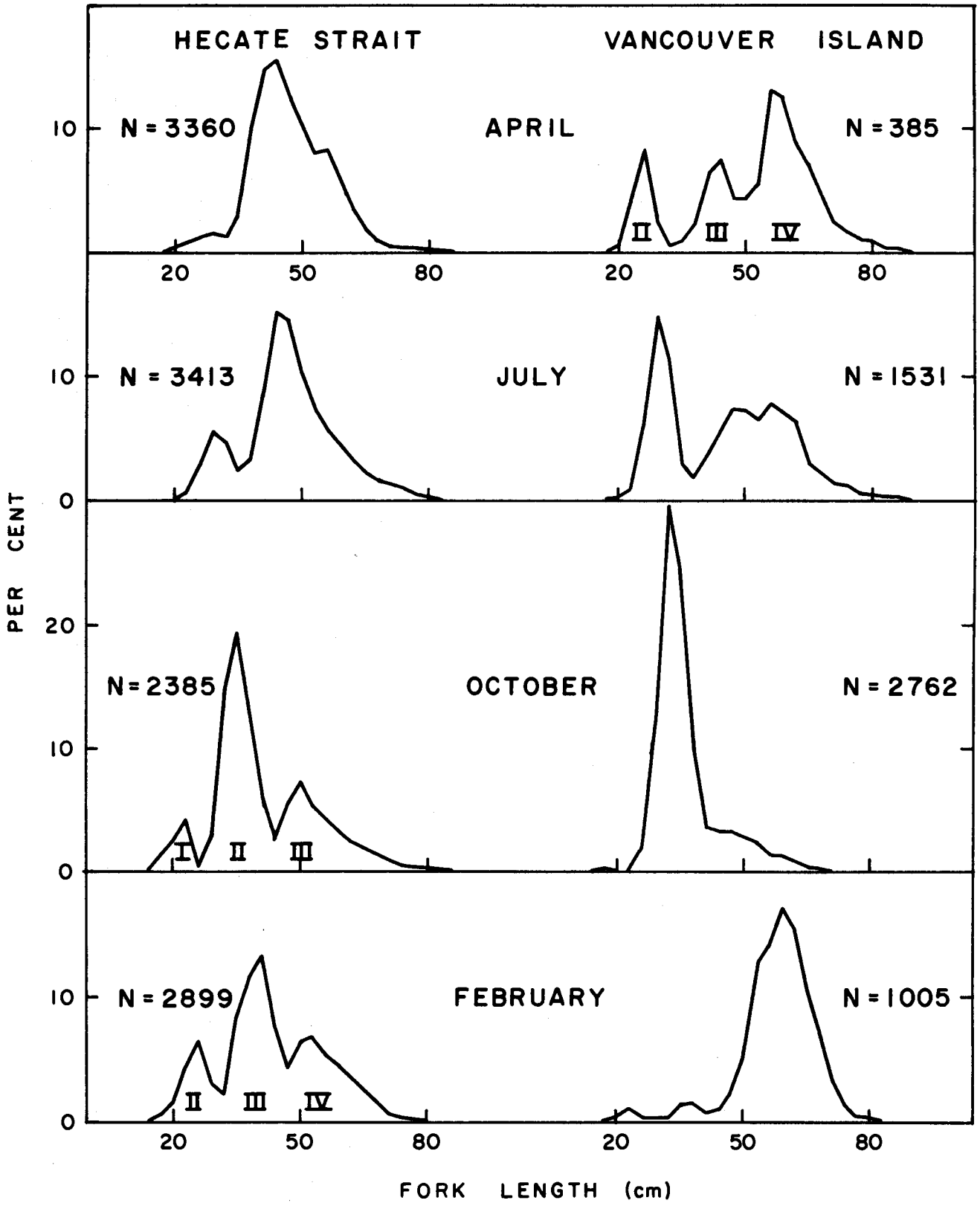


Fig. 5.1.2. Length-frequencies (%), by season, of Pacific cod from research-vessel catches off southwest Vancouver Island (3Cn) and in Hecate Strait (5C+5D), April 1975-February 1976. (Fig. 2 in Westrheim 1977)

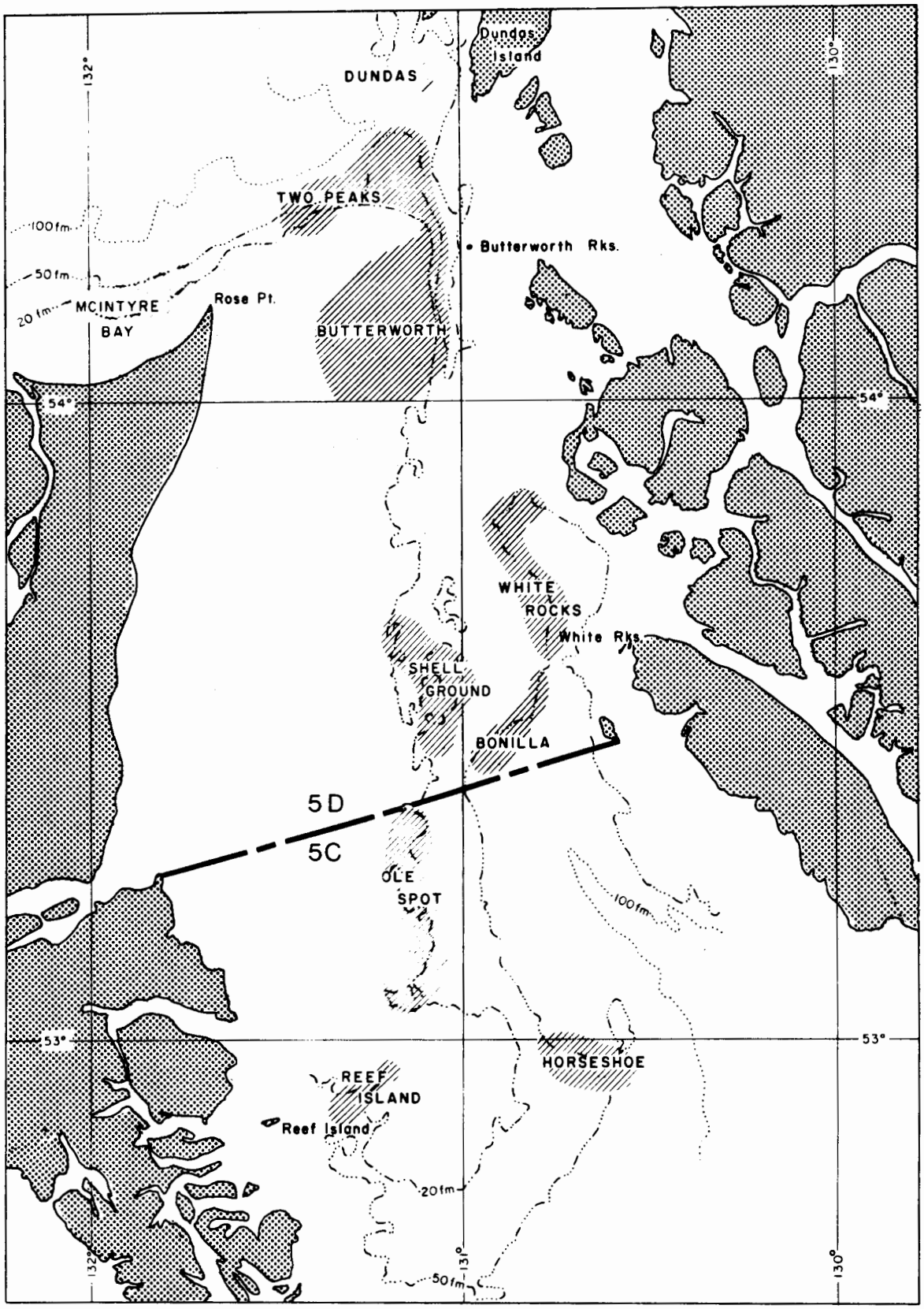


Fig. 5.1.3. Important trawling grounds in Hecate Strait (5C+5D).

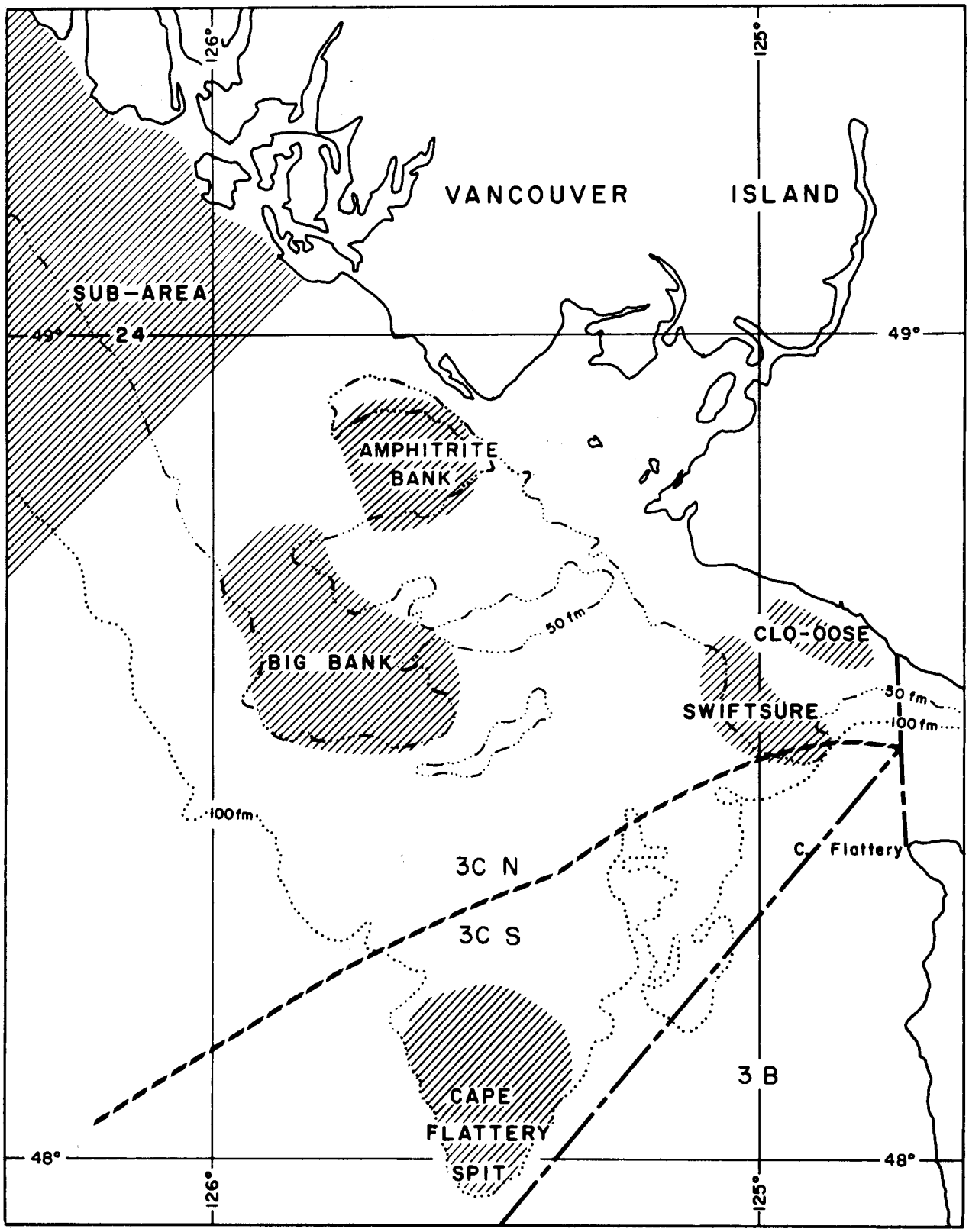


Fig. 5.1.4. Important trawling grounds off southwest Vancouver Island (3C).

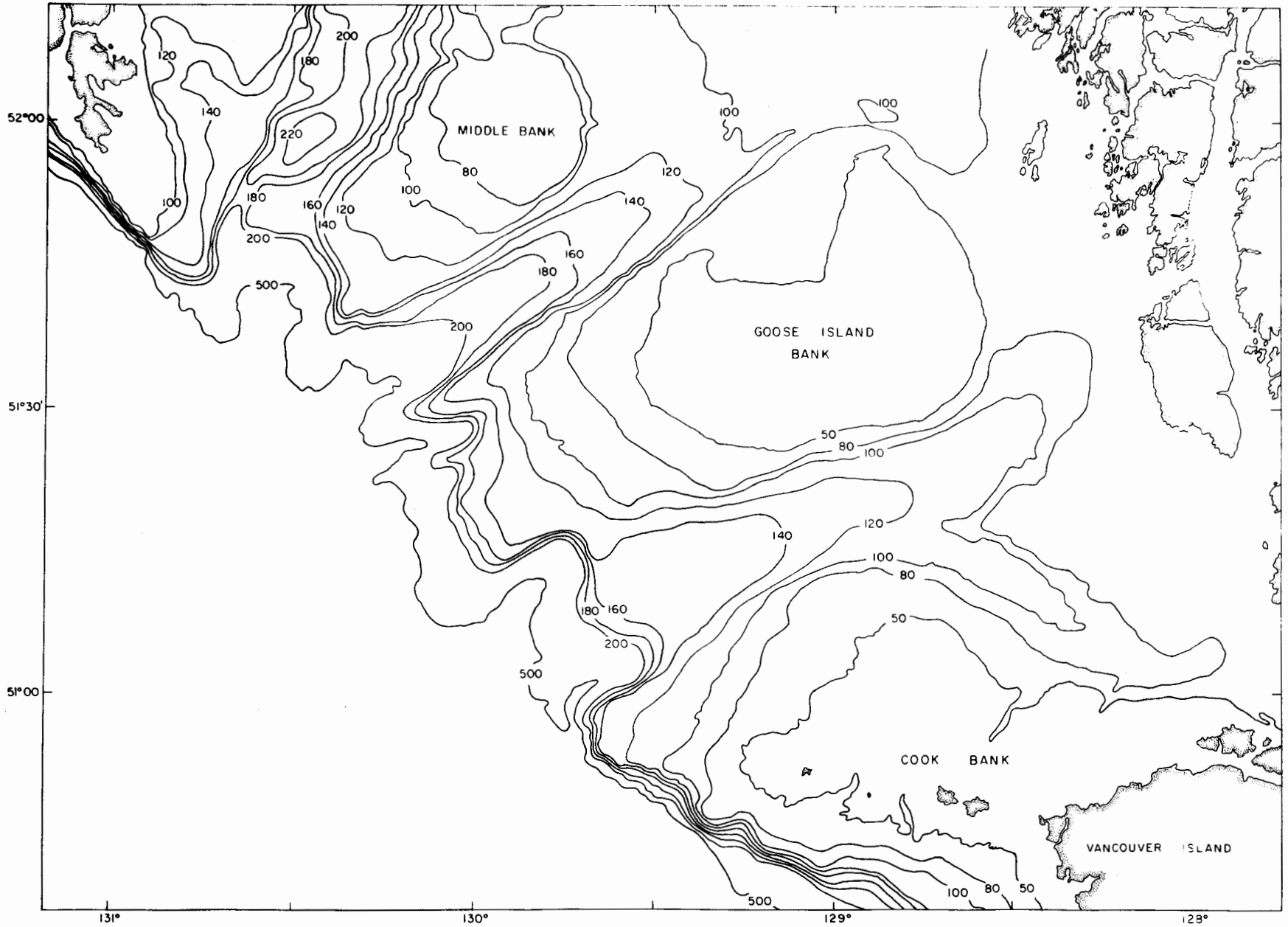


Fig. 5.1.5. Important trawling banks in Queen Charlotte Sound (5A+5B).

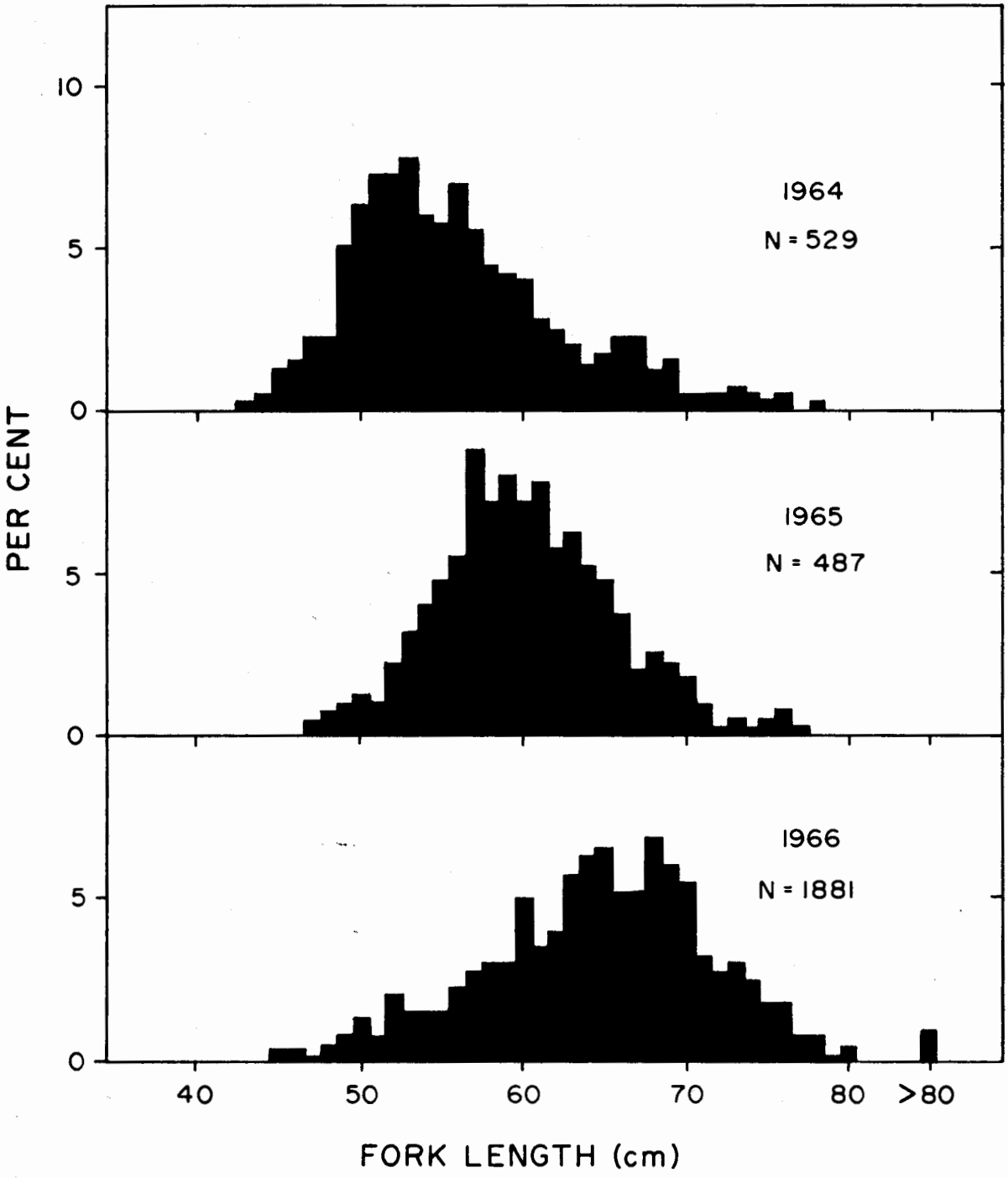


Fig. 5.1.6. Length-frequencies (%) of Pacific cod sampled from commercial landings in British Columbia, from Two Peaks Ground (5D), May-June 1964-66.

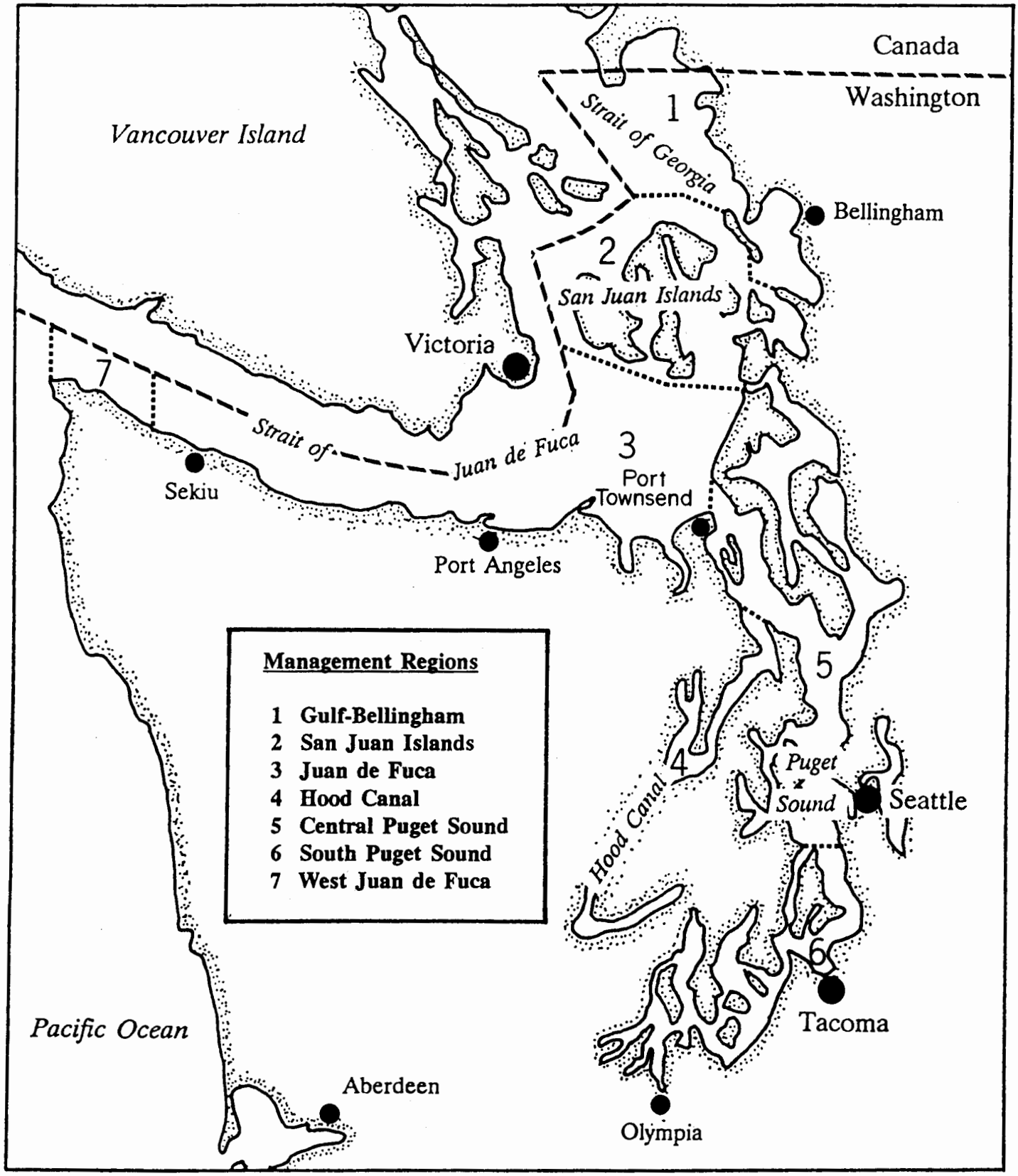


Fig. 5.1.7. Marine fish management regions of Puget Sound and vicinity (4A).

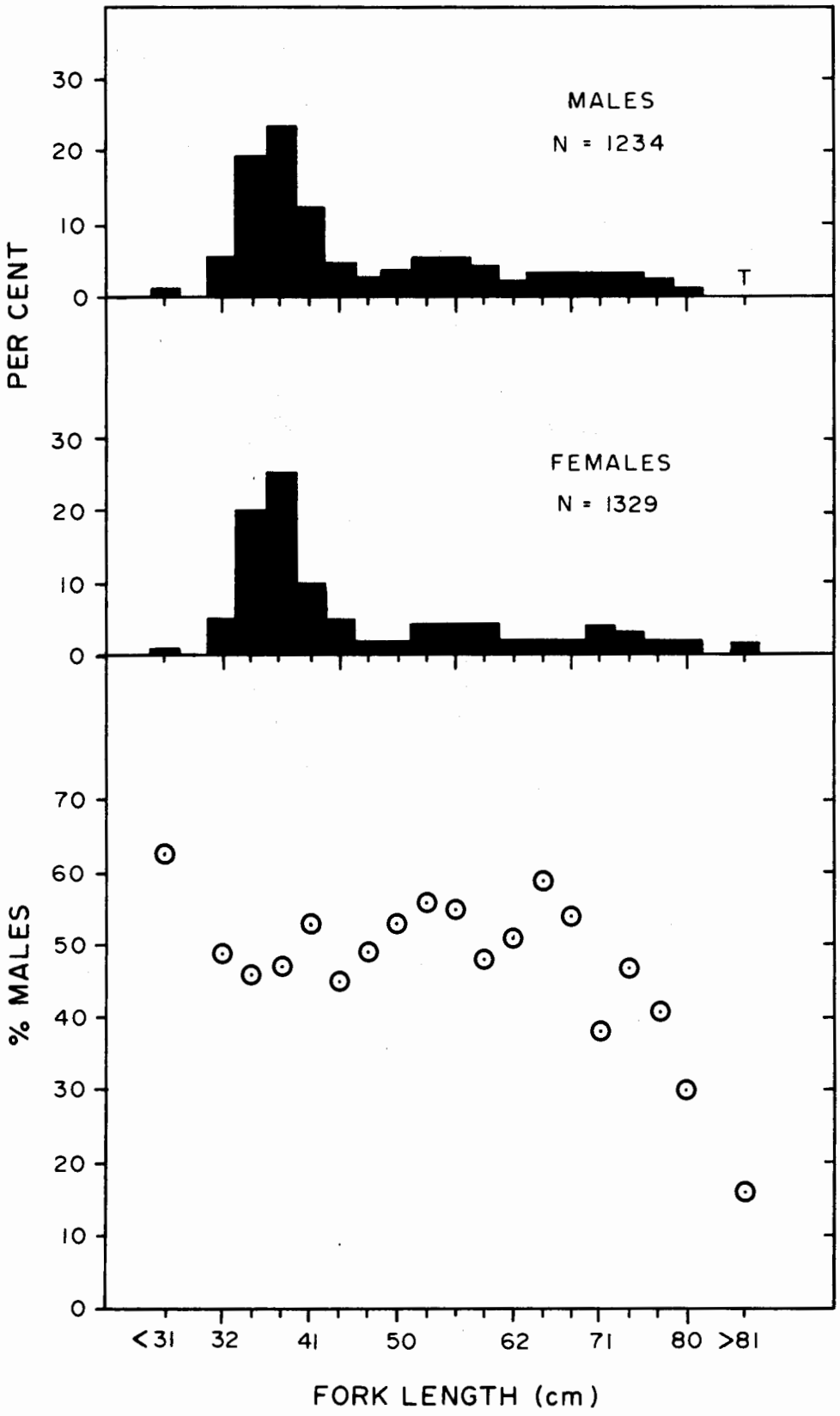


Fig. 5.2.1. Length-frequencies (%), by sex, and sex ratios (% males), by 3-cm length interval, of Pacific cod in research-vessel catches on Two Peaks Ground (5D), September 1979. (Source: Westrheim et al. 1980b)

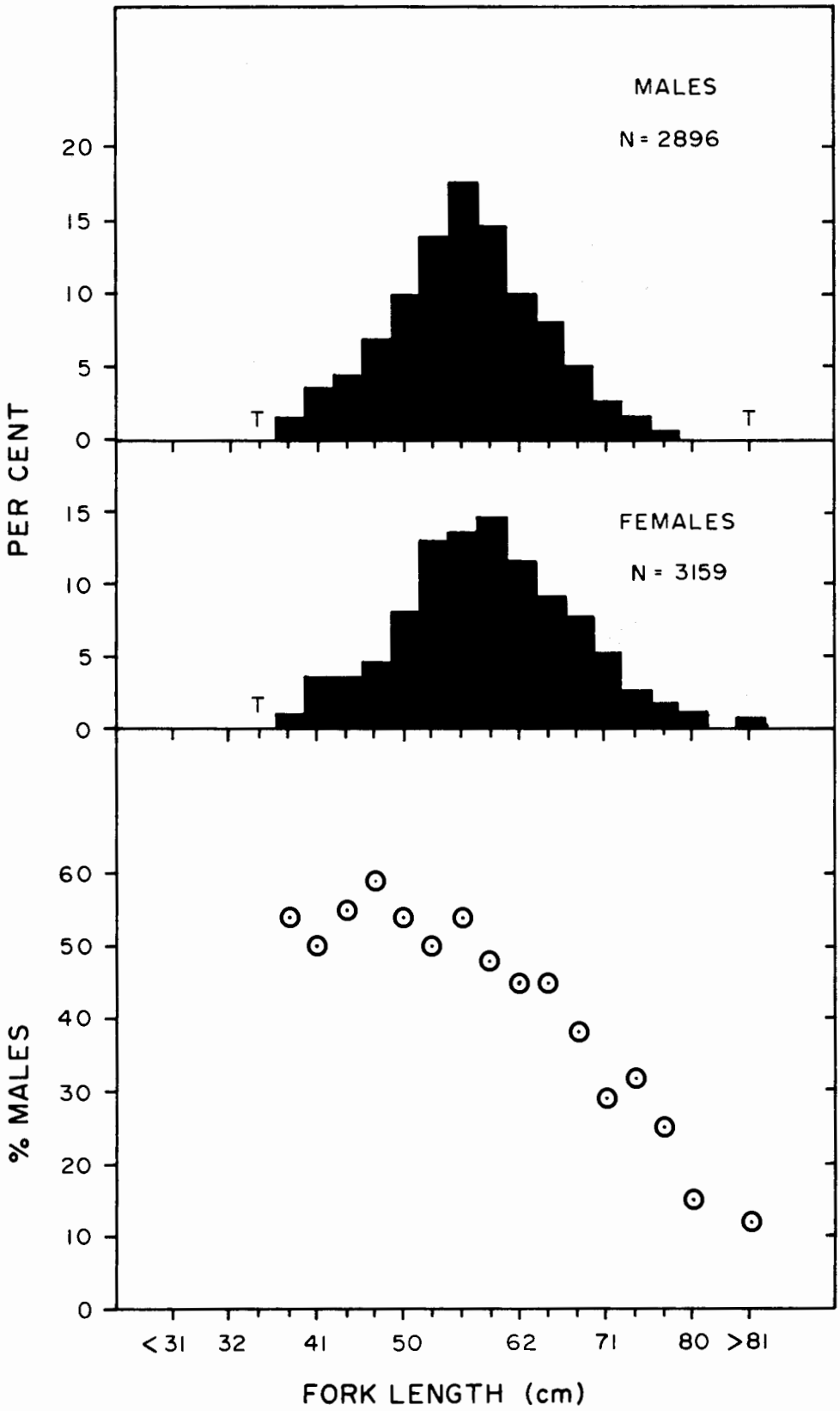


Fig. 5.2.2. Length-frequencies (%), by sex, and sex ratios (% males), by 3-cm length interval, of Pacific cod sampled from commercial landings in British Columbia (combined areas), 1982. (Source: PBS files)

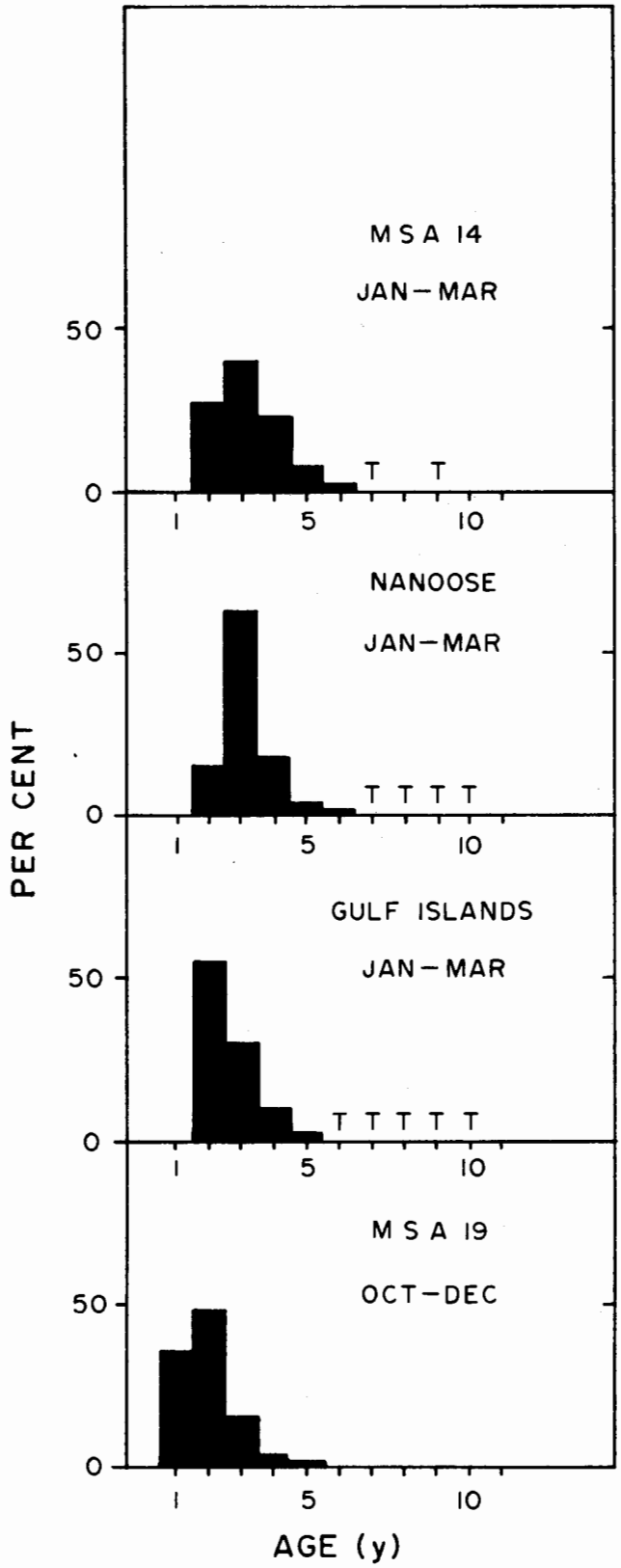


Fig. 5.4.1. Mean age-frequencies (%), by important area-time cells, of Pacific cod sampled from commercial landings in British Columbia, from Georgia Strait and vicinity (4B), January-March or October-December 1954-84. (Source: PBS files)

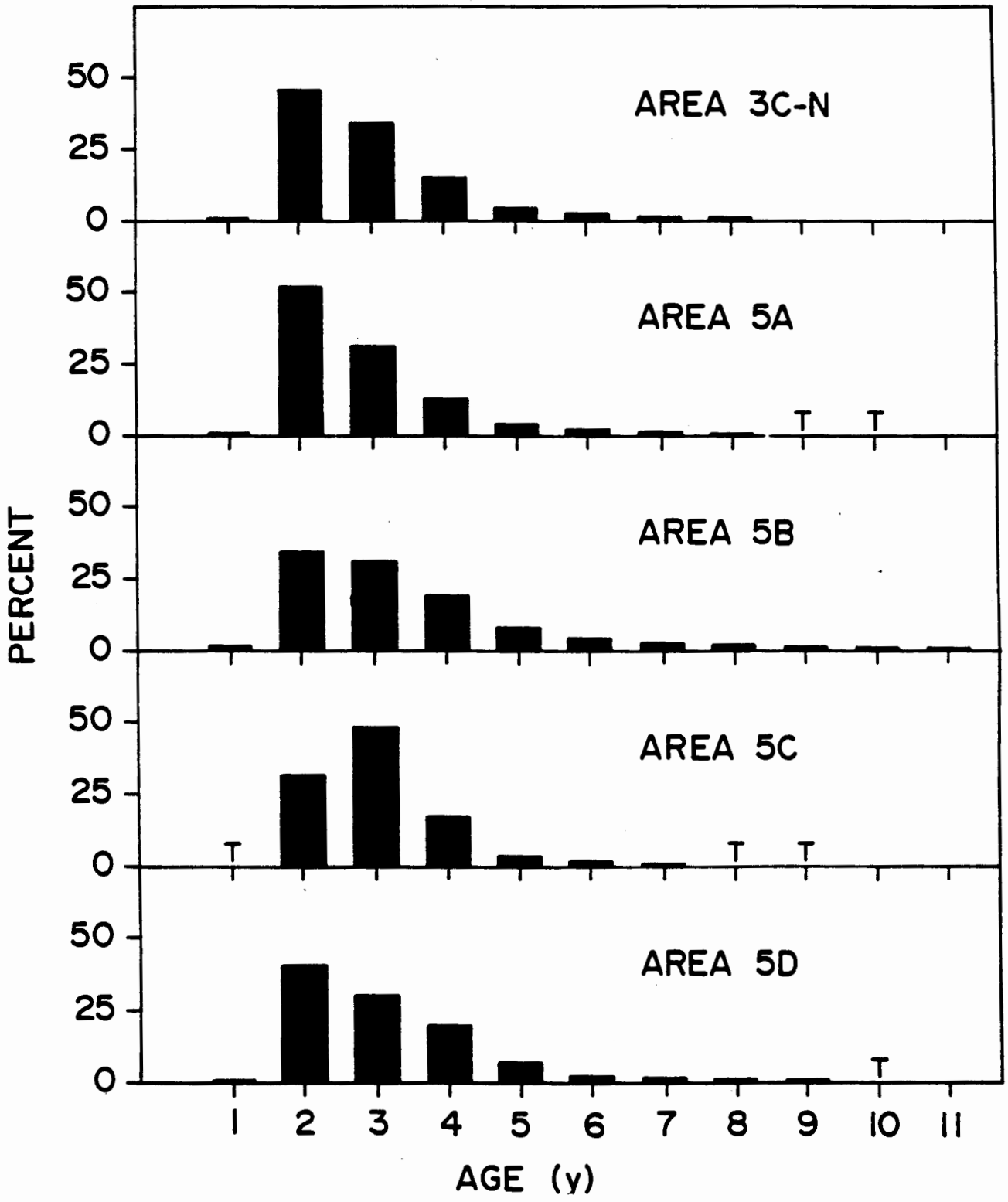


Fig. 5.4.2. Mean age-frequencies (%) of Pacific cod in commercial landings in British Columbia, from important offshore areas, April-June 1956-86. (Fig. 3 in Westrheim and Foucher 1986)

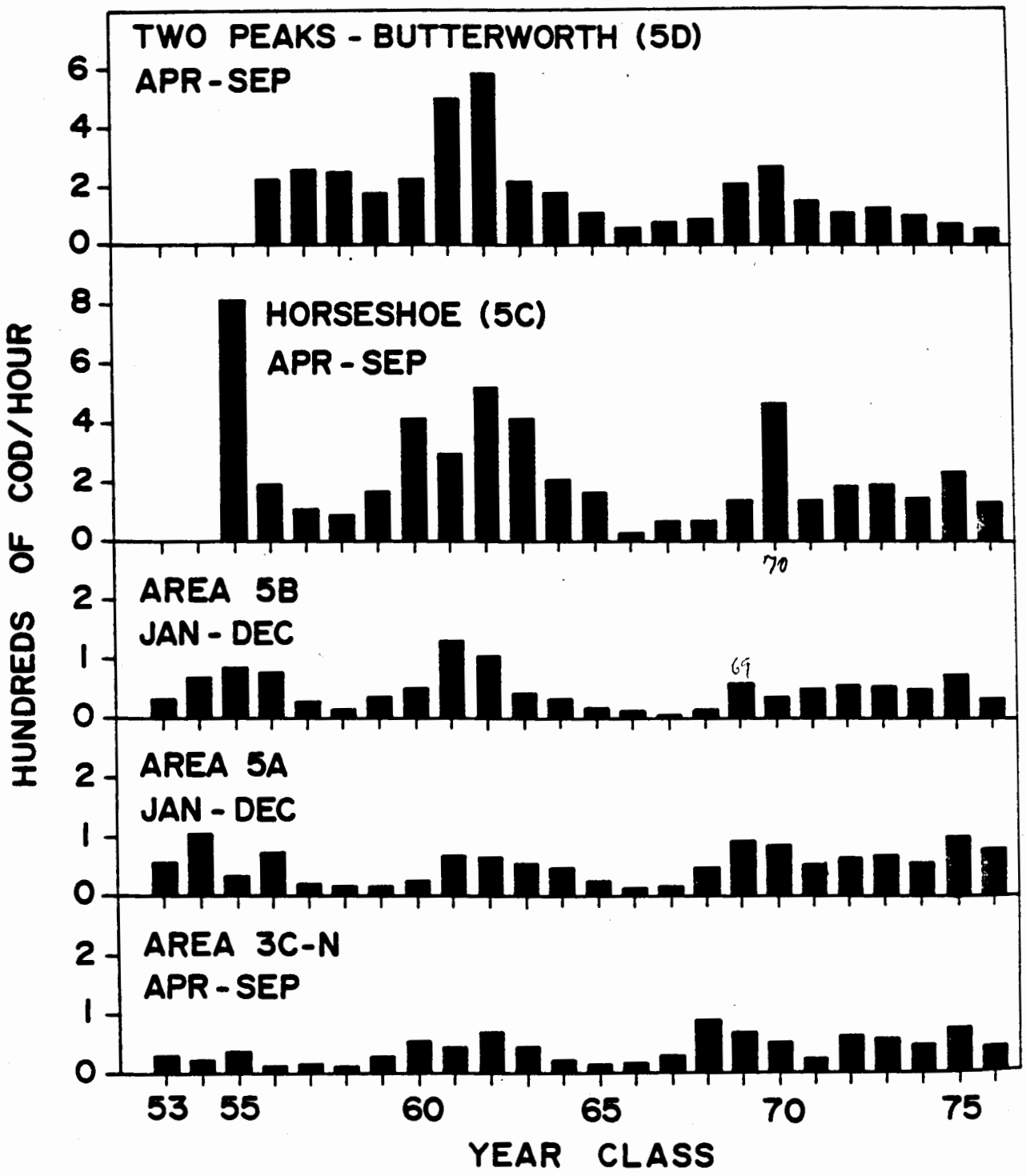


Fig. 5.4.3. Cumulative catch rates (N/h, ages 3-6), by important area-time cells off British Coumbia, for Pacific cod year-classes 1953-76. (Fig. 4 in Westrheim and Foucher 1986)

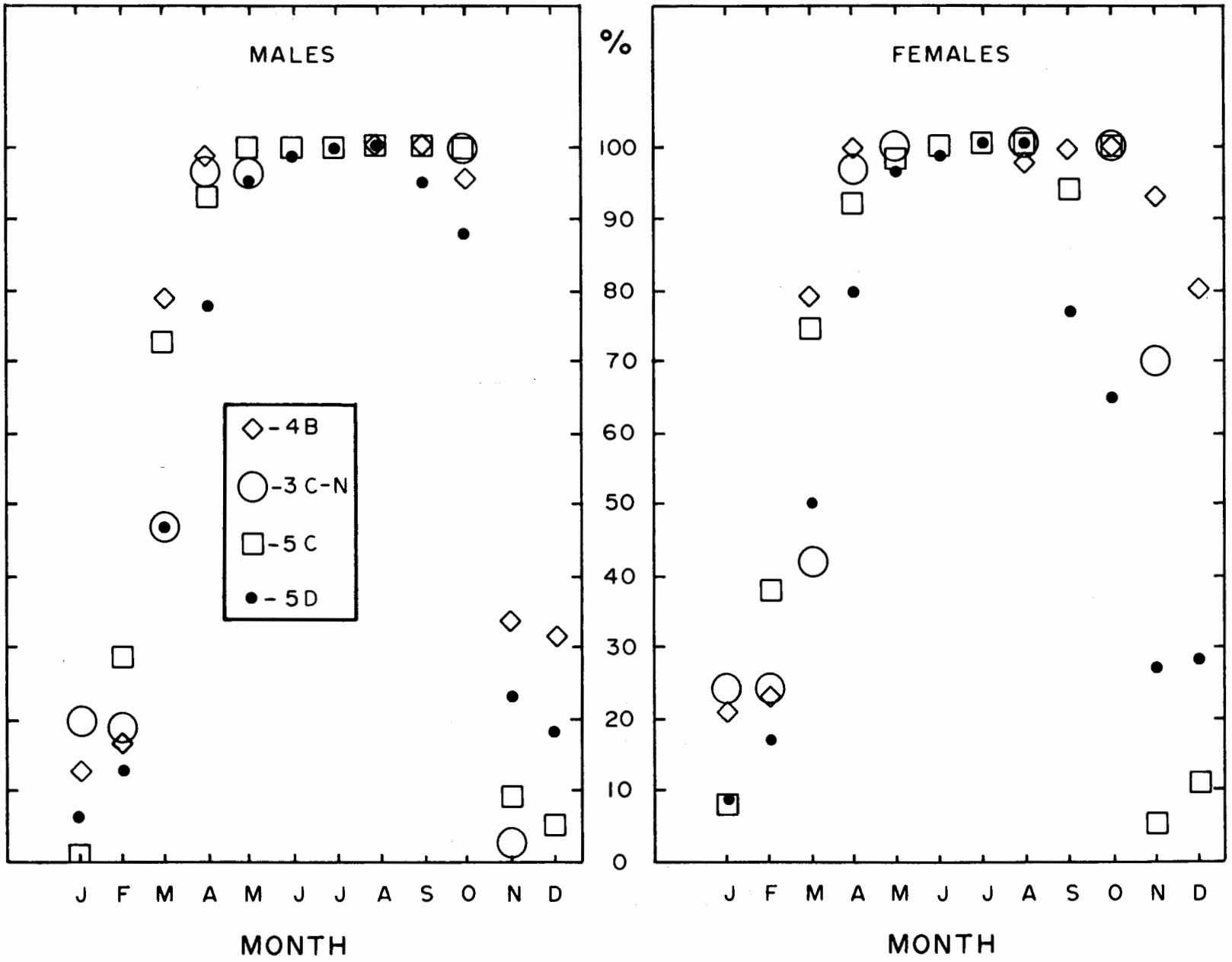


Fig. 5.6.1. Incidence (%), by month, sex, and area, of gonad conditions 6+7 for Pacific cod sampled from commercial landings in British Columbia, 1976-85. (Source: Westrheim and Foucher 1990, Table 3)

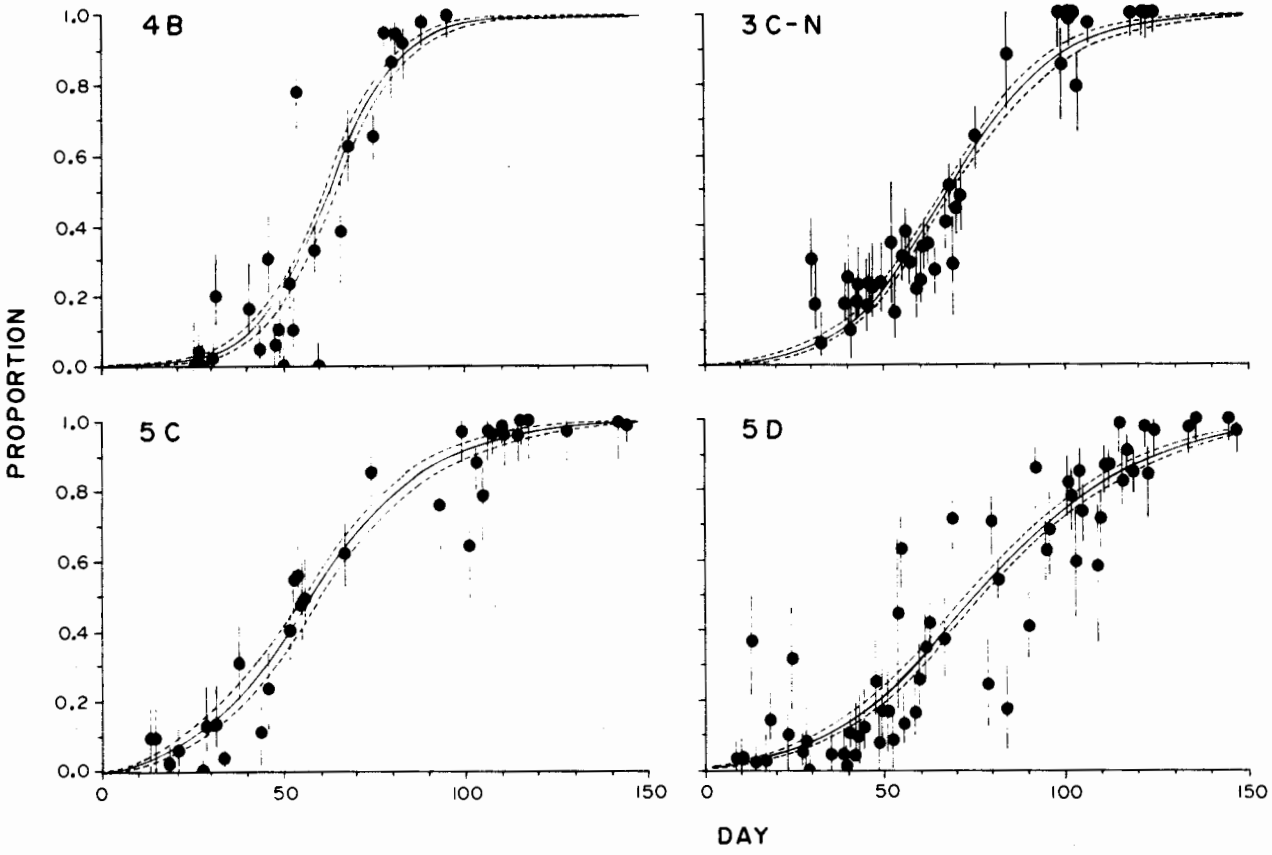


Fig. 5.6.2. Relationship between proportion of ovary conditions 6+7 and day-of-year, by area, for Pacific cod sampled from commercial landings in British Columbia, 1976-85. Vertical lines indicate the 95% confidence intervals around the mean proportions. Areas between dashed lines indicate the 5% plausibility regions, fitted by maximum likelihood around each curve. (Fig. 4 in Foucher and Westrheim 1990)

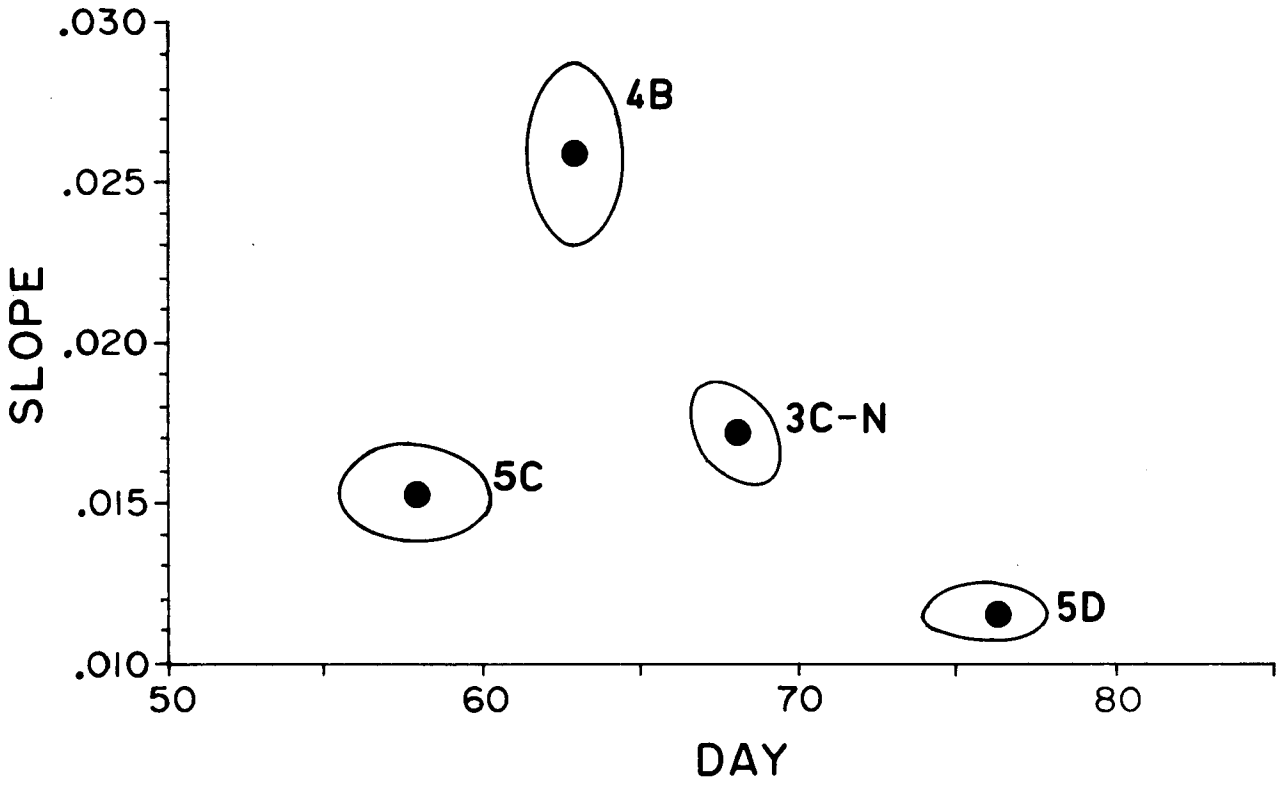


Fig. 5.6.3. Relationship between slope at D/50 and D/50, by area, for female Pacific cod sampled from commercial landings in British Columbia, 1976-85. Open ellipses around the black dots represent the 5% plausibility regions. (Fig. 5 in Foucher and Westrheim 1990)

6. FISHERIES

INTRODUCTION

This chapter will deal with aboriginal, commercial, and recreational fisheries for, and artificial propagation of, Pacific and Atlantic cod.

6.1. ABORIGINAL FISHERIES

PACIFIC COD

Pacific cod was at least a minor component of the aboriginal subsistence fisheries of western Canada (Stewart 1977) and Alaska (Cobb 1927) (Fig. 3.1). For British Columbia waters, records were difficult to assess, because the term "cod" was used for both Pacific cod and lingcod. No reports were located for aboriginal fisheries off Asia.

ATLANTIC COD

Atlantic cod served a similar role to inhabitants on the shores of the north Atlantic Ocean (Jensen 1972). Earliest record was ca. 8000 B.C., based on the contents of middens in Denmark (Fig. 3.2) (Cushing 1988).

Detailed information on later Danish middens was provided by Enghoff (1983), who examined the middens near Vedbaek (ICES III/23; Fig. 2.3), dated at ca. 4500-4000 B.C. Cod comprised ca. 75% of the fish bones. Most of the cod were small, based on vertebrae measurements. Two-thirds were 25-35 cm long (150-400 g). Capture was probably by trap, in shallow water during spring and summer, based on size of cod, and other species present in the midden. Traps, or remnants thereof, from the same era were found elsewhere along the Danish and Swedish coasts. The author noted that traps are still used in shallow water, and were of great importance in inner waters until the 19th Century, when industrialization of the cod fishery began (Cushing 1988).

6.2. COMMERCIAL FISHERIES

PACIFIC COD

History

The earliest historical record located was that of a line fishery in local waters of Japan, during the 17th Century (Forrester et al. 1978). No production[1] records were reported. In the mid-19th Century, U.S. schooners

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[1] Production, in this chapter, refers to nominal catches, or landings, and is not to be confused with the term productivity.

developed a line fishery, producing salt cod, in the Okhotsk Sea and off Alaska (Cobb 1927). Japanese began a line fishery in the Okhotsk Sea about 1900 (Moiseev 1953). Trawl and line fisheries, usually producing fresh and frozen cod, arose in the 20th Century--late 1920s off the U.S.S.R. (Moiseev op. cit.; 1950s off North America (Forrester et al., op. cit.).

The first commercial fishery for Pacific cod by North Americans was a line fishery in the Okhotsk Sea which produced salted or dried cod (Cobb 1927). The resource was discovered by Captain Matthew Turner, U.S. Brig TIMANDRA out of San Francisco, who discovered concentrations of cod, in 1857, in the Tatar Strait (W. Sakhalin Island) while waiting to discharge cargo at Nicolaevsk (Amur River). A return trip in 1859 yielded the same results. In 1963, he brought along fishing gear, and salt, and conducted some fishing in Tatar Strait and off south Kamchatka. Results were satisfactory, and he returned in 1864, equipped only as a fishing vessel, and made a financially successful trip. In 1865, six U.S. vessels fished in the Okhotsk Sea. Similar fisheries began in the Gulf of Alaska during 1865, and in the Bering Sea during 1882. One unsuccessful trip to the Bering Sea was made in 1864. The U.S. west coast market demand was soon satisfied, and additional markets were developed in Asia, Hawaii, Mexico, West Indies, and South America. Attempts to enter the U.S. market east of the Rocky Mountains were largely unsuccessful, due to transport problems (sometimes exacerbated by poor quality of fish) and strong resistance by the U.S. east coast industry.

Initially, fishing gear was handline, but later longlines were also used. The U.S. purchase of Alaska from Russia in October 1867 stimulated development of the Alaskan fishery. Processing plants were established in Alaska, and this led to the entry of smaller, shore-based vessels into the fishery. The U.S. fishery in the Okhotsk Sea terminated in 1909, in part due to harassment by Russian officials (Cobb op. cit.). The "harassment" may have been due to increased Russian patrols to reduce poaching of "sea-bears" (fur seals?) by the U.S. vessels (Moiseev 1953). The single U.S. vessel there, in 1909, reported "a considerable fleet of Japanese vessels fish there for cod" (Cobb op. cit., p. 412).

Early Line Fisheries

Production records for 1863-1925 were reported by Cobb (1927) in numbers of fish, and converted to tonnes, based on the mean round weight of 10 lb (4.5 kg) (Rigby 1984). Rigby's records for 1926-50 were reported in pounds (round weight), which were converted to tonnes by dividing by 2204.6.

Total annual production (Okhotsk Sea + Alaska) rose quickly to a peak of 6,602 t in 1870, then fluctuated around 5,000 t until 1898 (Fig. 6.2.1). Subsequently, major peaks occurred during 1904-08 (13,541-16,263 t), and 1914-20 (16,227-17,519 t). After a brief flurry during 1923-25 (12,533-13,302 t), production declined steadily to 235 t in 1950, when the fishery terminated. For the Okhotsk Sea, production rose quickly to a peak of 4,622 t in 1870; declined to 585 t in 1872; rose to a maximum of 4,522 t in 1884; peaked once more at 3,114 t in 1906; then terminated in 1909 (360 t). No records were available for 1867, 1869, 1874-75, and 1897-1902.

Both Cobb (1927) and Rigby (1984) reported intermittent economic problems afflicting the fishery. Among these were competition with "foreign" imports (including Atlantic cod from eastern United States), marketing, transportation, and poor quality.

Trawl/Line Fisheries

Records of production were reported by various agencies, but the only agency to report all-nation catch records for both the northeast and northwest Pacific was the United Nations' Food and Agricultural Organization (FAO). The

common boundary between the two regions was 175 W long. Records began with 1958, and included all commercial fish species and types of gear. For the northwest Pacific, only FAO reports all-nation fisheries statistics on a regular basis. For the northeast Pacific, two agencies provide partial records of groundfish catches--Pacific Marine Fisheries Commission (PMFC) and International North Pacific Fisheries Commission (INPFC). PMFC was founded in 1947 (PMFC 1988), and their reports of Canada-U.S. groundfish landings, excluding halibut, began with 1956. INPFC was founded in 1952 (Jackson and Royce 1986), and their reports of groundfish catches of Canada, Japan, and the United States, began with 1956. Records were not complete for other nations.

North Pacific. For 1929-38, Moiseev (1953, Table 76) reported the annual catches of cod by nation (Korea, Japan, U.S.S.R., and Canada-U.S). Mean annual all-nation catch was 203,300 t, of which 197,400 t was caught in the northwest Pacific (Table 6.2.1). Principal producer was Japan--93,200 t in local waters (principally Hokkaido), and 69,600 t from distant waters (principally Kurile Islands, Sakhalin Island, and Kamchatka). Other producers, in descending order of importance, were Korea (26,500 t), USSR (8,900 t), and Canada-U.S. (6,000 t).

For 1960-77, Bakkala et al. (1984, Table 1), reported annual catches by region. The mean annual catches were as follows:

Region	Catch (t)	%
Korea	1,690	1.3
Japan	40,700	31.9
USSR	18,667	14.6
Aleutian Island	1,485	1.2
E. Bering Sea	51,563	40.4
Gulf of Alaska	3,447	2.7
British Columbia	9,059	7.4
Washington-California	1,056	0.8
Total	127,667	100.0

During 1958-91, all-nation nominal catch (= round weight, excluding discards at sea) of Pacific cod rarely exceeded 200,000 t/y prior to 1982, but subsequently rose to a peak of 453,000 t in 1988, then declined to 420,000 t in 1991 (Fig. 6.2.2). In the northwest Pacific, catches peaked in 1985, at 272,000 t, then declined to 157,000 t in 1991. In the northeast Pacific, catches rose irregularly to 263,000 t in 1991. Trawls were the principal gear in all regions.

Northwest Pacific

A Russian line fishery developed following the success of the U.S. and Japanese line fisheries (Moiseev 1953). By 1927, Russian littoral catches reached 143 t/y, primarily off west Kamchatka.

The first trawl fishery took place during 1911-15, in Peter-The-Great Bay (E. Kamchatka) (Moiseev 1953). Principal species were flounders and walleye pollock. Cod was a minor component. This fishery was terminated due to the hostile attitude of industry and government officials, who claimed that trawl-caught fish "depreciated" the line-caught products brought to the Vladivostok markets from the Okhotsk-Kamchatka region.

The second trawl fishery, during 1929-33, was also government-sponsored, and was designed to delineate the cod resources off the USSR coast, from the Japan Sea to the Bering Sea (Moiseev 1953). Some 20 trawlers were deployed, and scientists were actively involved in the program. Total catch was 20,607 t, of which flounders comprised 92%, and cod only 3% (560 t). The project was terminated in 1934, and most of the trawlers were sent elsewhere. Subsequent analyses revealed that the apparent negative results were caused by improper survey techniques, improperly trained trawl crews, and long distances between the single base (Vladivostok) and the fishing grounds. Trawl fisheries resumed during World War II, and expanded rapidly thereafter. No records other than those of FAO were found.

Northeast Pacific

Production records for the Gulf of Alaska-California region (1956-86), and the eastern Bering Sea and Aleutian Islands (1959-86), were reported by Forrester et al. (1978, 1983) and subsequent INPFC Statistical Yearbooks, but did not always include records of all nations involved. All-nation catch records were available for the eastern Bering Sea, and the Aleutian Islands, during 1964-88 (Low and Narita 1990), and for the Gulf of Alaska, during 1977-87 (Wilderbuer 1989). Subsequent records through 1992, for both regions, were taken from unpublished stock assessment documents, prepared in 1993, kindly provided by Dr. G.G. Thompson (Alaska Fisheries Center, U.S. National Marine Fisheries Service, Seattle, Washington).

In the eastern Bering Sea, during 1964-88, Pacific cod was a minor component in the overall fishery--4.8% of the cumulative all-species catch during 1964-88, and 6.3% during 1977-88 (Table 6.2.2). Principal species was walleye pollock--77.3% of the cumulative all-species catch during 1964-88, and 75.9% during 1977-88. Pacific cod catches ranged from 13,000 t to 70,000 t during 1964-88, and 33,000-193,000 t during 1977-88. During the latter period, cod catches rose steadily from 33,000 t in 1977 to 193,000 t in 1988. Subsequently, catches declined to 163,000-167,000 t during 1989-90, and to 126,000 t in 1991.

In the Aleutian Islands, during 1964-88, cod was also a minor component in the fishery--6.3% of the cumulative catch during 1964-88, and 10.0% during 1977-88 (Table 6.2.2). Walleye pollock comprised 26.2% during 1964-88, and 45.4% during 1977-88. Annual catches of Pacific cod ranged from <1,000 t to 4,000 t during 1964-76, and 3,000-22,000 t during 1977-88. During the latter period, catches rose from 3,000 t in 1977 to a peak of 22,000 t in 1984, then declined to 5,000 t in 1988. Subsequently, catches remained low during 1989-91 (5,000-8,000 t/y), then rose abruptly to 38,000 t in 1992.

In the Gulf of Alaska, cod was also a minor component (10.6%) in the cumulative all-species catch during 1977-87, and probably also during 1971-76 (Table 6.2.3). Principal species during 1977-87 was walleye pollock (68.9%). Annual cod catches ranged from 1,000 t to 7,000 t during 1971-76, and 12,000-36,000 t during 1977-87. Catches rose to a peak of 36,000 t in 1981, then fluctuated at 14,000-36,000 t/y through 1987. Subsequently, catches increased sharply to 75,000 t in 1990, and remained at that level through 1992.

In the British Columbia-California region, Lynde (1986) compiled the 1956-79 Canada-U.S. trawl landings, by International Statistical Area (ISA) (Fig. 2.1), of Pacific cod and other species (Table 6.2.4). Cod was a minor component of the all-species landings south of Area 3C--8% in 3B, 2% in 2D/3A, and <1% in Areas 2C-1A. Principal production areas were off British Columbia--5D (25%), 3C

(20%), and 5C (12%). Among these ISAs, cod comprised 13-54% of the all-species landings. No other nation had a directed fishery for cod in the British-California region.

In British Columbia, the fishery for Pacific cod is relatively new, and has developed slowly (Forrester et al. 1978). The initial commercial fishery for marine fishes began about 1860 as a small-boat, handline fishery in the vicinity of Victoria (MSA 19; Fig. 4.2) (Lord 1866). Principal species sold were pleuronectids (including halibut), hexagrammids, and scorpaenids. Pacific cod was not offered for sale, although available on the local grounds. Anderson (1873) noted that Pacific cod were compared unfavorably with Atlantic cod.

The first commercial fishery for Pacific cod in British Columbia waters may have occurred in 1866, when two or three small schooners outfitted in Victoria, and fished on grounds north of the Nass River (northeast Hecate Strait; Area 5D) (Cobb 1927). However, the author noted that "it is a question whether this fish was the true cod or one of the several unrelated species which bear the common name of cod." (op. cit., p. 403).

During 1903-05 and 1913, Canadian vessels participated briefly, and unproductively, in the early line fishery in the Bering Sea (Cobb 1927).

During 1908-09, a trawl fishery developed in British Columbia waters, but Pacific cod was not a target species (Forrester et al. 1978). Pacific cod was not reported in the landings until 1927, when 10 t was reported, out of a total groundfish catch (including line-caught halibut) of 15,479 t (op. cit., Table 29).

During 1927-91, Canadian landings, from local waters, rose irregularly to a peak of 4,600 t in 1958; then fluctuated substantially thereafter, with peaks in 1966 (12,200 t), 1975 (10,300 t), and 1987 (13,900 t) (Fig. 6.2.3). The 1992 catch was 11,900 t. Virtually all Pacific cod from British Columbia waters are caught by demersal trawls, and the Canadian trawl fleet has, with rare exceptions, always operated within the current boundaries of the Canadian extended economic zone (EEZ). In 1977, Canada and the United Stated promulgated their respective EEZs. Thereafter, each national fleet was confined to its own EEZ after March of that year. However, U.S. vessels were permitted to trawl for selected species of rockfish (Sebastes spp.) in Canadian waters, under controlled conditions, until April 1981. During 1956-77, the Canada-U.S. trawl catch of cod ranged from 2,700 t (1961) to 14,800 t (1966). Peak years, in addition to 1966, were 1959 (8,000 t) and 1975 (12,500 t).

During 1950-91, Canada-U.S. cod landings from major regions off British Columbia fluctuated quasi-cyclically, but not always synchronously (Fig. 6.2.4). Mean annual landings among regions, in order of magnitude, were 3,624 t (S.D. = 2256; Hecate Strait), 1,766 t (1,183; W. Vancouver Island), 1,294 t (768; Queen Charlotte Sound), and 747 t (368; Georgia Strait). Years in which major zeniths (landing > mean + one S.D.) are listed below:

Region	Zeniths
Hecate Strait	1966,1987
W. Vancouver Island	1957,1972,1975,1989
Queen Charlotte Sound	1966,1972,1975,1987
Georgia Strait	1954,1981,1988

The 1991 landings were above average in all regions except Georgia Strait, but only in Hecate Strait was the landing greater than one S.D. above the mean.

While spatial and temporal variations in production within areas, or regions, are listed below, more detailed treatment is provided in Section 7.3 (Stock Assessment).

In Area 4B, there are 11 minor statistical areas (MSAs 12-20, 28, and 29), and all but MSAs 12 and 13 are shown in Fig. 4.2. During 1945-84. MSAs 14,

17, 18, and 19 contributed 86% of the cumulative landings (Table 6.2.5). Seasonally, 72-90% of the landings occurred during October-March. Seasonality of landings was due to substantial restrictions on trawling during April-September, and economics (Forrester and Ketchen 1963; Westrheim 1980). Offshore grounds yielded greater catches, but inclement weather during October-March precluded participation of the smaller trawlers in the offshore fishery at that time. MSA 20 contributed 9% of the cod landings from Area 4B, and exhibited no seasonal variation in production. There were no regulatory restrictions, but the exposed nature of the area precluded exploitation by relatively small trawlers. Foreign vessels have always been prohibited from fishing in Area 4B.

Off west Vancouver Island (3C+3D), Area 3C accounted for some 90% of the cod production during 1956-79 (Table 6.2.4). In 1977, Area 3C was divided into 3Cs (U.S.) and 3Cn (Canada) as a result of the promulgation of Canadian and U.S. 200-mile EEZs. Area 3Cn comprises approximately 80% of Area 3C, based on the provisional boundary (Fig. 6.2.5). In Area 3Cn, during 1956-82, Amphitrite Bank (spawning ground) and Big Bank (feeding ground) contributed 75% of the cod landings (Fig. 5.1.4; Table 6.2.5). As might be expected, principal production seasons were January-March (77%) on Amphitrite Bank, and April-September (80%) on Big Bank. The lack of production during October-December in Area 3Cn was perhaps due in part to inclement weather, availability of cod, and/or declining demand.

In Queen Charlotte Sound, during 1956-82, individual grounds were not well delineated within the major banks in each area--Scott Bank in Area 5A, and Goose Island Bank in Area 5B (Fig. 5.1.5). April-September was the important production season on Scott Bank (82%) and Goose Island Bank (91%)(Table 6.2.5). Inclement weather and the lack of nearby harbors severely inhibits trawling during October-March.

In Hecate Strait, during 1956-82, three grounds contributed 79% of the production--Horseshoe (5C; feeding; 22%), White Rocks (5D; spawning; 21%), and Two Peaks (5D; feeding; 36%) (Fig. 5.1.3; Table 6.2.5). Reef Island (5C; spawning; 5%) was recently discovered and exploited. Principal production season was January-March for Reef Island (64%) and White Rocks (55%), and April-September for Horseshoe (93%) and Two Peaks (85%). Some problems have arisen in separating catches from Horseshoe and nearby Reef Island grounds, and as a result, the proportions are somewhat overestimated for Horseshoe during January-March, and for Reef Island during April-June.

ATLANTIC COD

HISTORY

In contrast to Pacific cod, the documented history is long for the Atlantic cod commercial fishery. Instrumental in the early development was the concession of the Church, in the 8th Century, to permit the consumption of fish, in lieu of fasting, on Fridays and during Lent (Jensen 1972). Primary products to benefit were dried or salt cod and salt herring. The earliest important fishery for Atlantic cod was located off northern Norway, no later than the 11th Century, and the latest was located off west Greenland, in the early 20th Century.

The first formal indication of the early trade in cod was the designation of Bergen, Norway, as a market town in 1075 (Gade 1951). There, dried cod from northern Norway was traded primarily for grain with various countries in northern Europe. Initially, the principal nation was England, but by 1250, German traders, of the Hanseatic League, had supplanted the English. Principal reason was the latter's change in agriculture production from grain to sheep. Principal source of cod was Lofoten (spawners) and Finnmark (juveniles and adults). The Hanseatic League conducted trading throughout the Baltic Sea,

along the east coast of the North Sea, and in England, but only obtained cod (dried) from Norway and Iceland (Kjersgaard 1982). No explanation for this phenomenon was found. Possible reasons might be: (1) low abundance of cod in the Baltic and North seas; (2) unsatisfactory climate for drying cod; and (3) high cost of salt.

Formal collection of Norwegian catch statistics began in 1860 for Lofoten (Rollefsen 1954), and in 1866 for Finnmark (Hjort 1914). Recording of other nations' catches began in 1903, by the International Council for the Exploration of the Sea (ICES), formed in 1902 (Went 1972).

Iceland merged with Norway in 1264, and its cod products were shipped to Bergen for inclusion in the cod-grain trade with Europe (Gelsinger 1981). Exports of dried cod to Norway replaced woolens to England due to the aforementioned change in emphasis of English agriculture (Gade 1951). Formal collection of catch statistics by participating nations began in 1906 (Fridriksson and Taning 1948).

Cod fisheries elsewhere in Europe probably were underway by the 15th Century (Cushing 1988).

Off North America, Europeans discovered the great cod resource on the Grand Bank in the 16th century (de Loture 1949, Jensen 1972). The inshore fishery produced dried cod, while the offshore fishery produced salted cod. By the 18th Century, the fishery extended southward to Cape Breton, and U.S. vessels began fishing the Grand Bank (Garrod 1977). U.S. vessels began a line fishery on Georges Bank in the early 18th Century, but this fishery was eliminated during the Revolutionary War, due to hostile actions of the British fleet (German 1987). The postwar cod fishery did not resume until the 1850s, when the halibut fishery on the Bank declined in profitability.

North Atlantic

All-nation catch statistics for the north Atlantic Ocean are reported by FAO, and include the periods 1938 and 1948-date. Records by region (northeast and northwest) began with 1964. Detailed records for the northeast Atlantic (east of 42 W long) are reported by ICES. These records began with 1903, but did not initially include all participating nations. For example, for the North Sea, records began in 1909, but records for all nations were not included until 1931 (Holden 1978). The comparable agency in the northwest Atlantic (west of 42 W long) was the International Commission for the Northwest Atlantic Fisheries (ICNAF), founded in 1949 (Halliday and Pinhorn 1990). Catch-record collection encompassed 1951-78, but did not include all nations until 1955 (Clayden 1972). Its successor, in 1979, was the Northwest Atlantic Fisheries Organization (NAFO), which has maintained continuity of the reported catch statistics. Halliday and Pinhorn (op. cit.) provided a history of catch-statistics collections in the northwest Atlantic since the 1930s. Atlantic cod are caught with a variety of gear, including gillnets, handlines, longlines, seines, traps, and trawls. Processing includes drying, freezing, and salting.

In the north Atlantic as a whole, all-nation, nominal catches (round wet weight, excluding discards) of cod rose irregularly from 1.6 million tonnes in 1948 to a peak of 3.9 million tonnes in 1968 (Fig. 6.2.7). Subsequently, catches have declined irregularly to 1.3 million tonnes in 1991. Since 1968, the northeast Atlantic has consistently produced most of the cod--0.9-2.1 vs 0.4-1.8 million t/y. Catch trends were similar in both regions. In the northeast Atlantic, catches rose to a peak of 2,123,000 t in 1969; peaked again at 2,018,000 t in 1974; then declined irregularly to 916,000 t in 1991. In the northwest Atlantic, catches rose to a peak of 1,802,000 t in 1968; declined sharply to 469,000 t in 1977; rose slowly to 704,000 t in 1982; then gradually subsided to 423,000 t in 1991. See Section 7.3 (Stock Assessment) for analyses of production trends.

In both the northeast and northwest Atlantic, cod was the predominant demersal species caught for human consumption. For example, in 1987 it comprised 53.0 and 54.5%, respectively, of the catch of important demersal species (Table 6.2.6). Secondary species were saithe, Pollachius virens, (14.8%) and haddock Melanogrammus aeglefinus, (13.1%) in the northeast Atlantic; and redfish, Sebastes spp., (19.4%) and American plaice, Hippoglossoides platessoides, (7.7%) in the northwest Atlantic.

Northeast Atlantic

There are 14 ICES subareas (SAs I-XIV) (Fig. 2.3), but SAs I-V account for a substantial proportion of the total cod catch. For example, in 1987, the latter group accounted for 96% of the total cod production (1,468,000 t) in the ICES area (Table 6.2.7). Among SAs I-V, cod proportions, of important demersal species, ranged from 27% in SA IV to 91% in SA III.

Northwest Atlantic

There are seven NAFO subareas (0-6) (Fig. 2.4). SAs 1-5 account for a substantial proportion of the total cod catch. For example, in 1987, the latter group accounted for 99+ % of the total cod production (601,000 t) in the NAFO area (Table 6.2.7). Among SAs 1-5, cod proportions, of the all-species catch, ranged from 48% in SA 4 to 74% in SA 2.

6.3. RECREATIONAL FISHERIES

PACIFIC COD

No records were located of recreational fisheries in the northwest Pacific. In the northeast Pacific, recreational fisheries were reported for Alaska, British Columbia, and Washington State.

Alaska

Pacific cod is a component of the recreational fishery in three regions--southeastern, Prince William Sound, and the Kenai Peninsula (Squire and Smith 1977). No estimates of the catches were provided.

British Columbia

Recreational fisheries for marine non-salmonids are a recent development. Records are available for Georgia Strait (Area 4B), the principal site of the fishery, during 1983-90 (Shardlow et al. 1989; Shardlow and Collicutt 1989a-e; Collicutt and Shardlow 1990,1992). Pacific cod was a minor component. For example, in 1990, the reported catch of all species was 219,300 fish, which consisted of 71% rockfish, 15% lingcod, 1% spiny dogfish, and 13% other finfish (Collicutt and Shardlow 1992, p. 9). The latter category included, without quantitative assessment, bothids, embiotocids, hexagrammids, Pacific cod, Pacific hake, Pacific herring, Pacific tomcod, pleuronectids (including Pacific halibut), and walleye pollock.

Washington State

In Puget Sound and vicinity (Area 4A), angling for marine non-salmonids developed earlier, and is more important than in British Columbia. During 1970-85, annual catch of cod by all boat-based anglers ranged from 7,585 (1970) to 159,775 (1976) fish, out of an all-species annual catch of 97,667 (1970) to 917,940 (1980) fish (Palsson 1988, Table 3A). Corresponding values for anglers targeting only on marine non-salmonids were 1,273 (1970) to 114,165 (1976) fish out of 14,290 (1971) to 744,560 (1982) of all species. During 1978-87, the recreational fishery accounted for 17.1% of the total catch of cod in Area 4A (Palsson 1990, Table 10). One important angling area is located at Agate Passage (MR 5; across the Sound from Seattle) (Fig. 5.1.7), where cod concentrate for spawning (Palsson 1991). That fishery drew over 8,000 trips, and a catch of 32,800 cod in 1981 (Palsson 1990, Table 14).

ATLANTIC COD

Catch statistics for recreational fisheries are not reported by FAO, ICES, or NAFO.

Northeast Atlantic

Recreational fisheries for Atlantic cod have been reported to exist in some Norwegian fjords, around Great Britain, and in the Baltic Sea. Norwegian fisheries were mentioned in connection with evaluating releases of artificially reared juveniles (Kristiansen and Svasand 1990). Wheeler (1969) reported that cod was popular with British anglers, and that the record rod-caught specimen, taken in 1966, weighed 44.5 lb (20.18 kg). In the western Baltic, Moeller and Tiffert (1988) reported on the year-round angling fishery for cod aboard charter vessels in the Kiel Bight (III/24). Total catch was estimated at 1,100 t in 1985, some 22% of the commercial catch in that area by fishermen of the Federal Republic of Germany. In the eastern Baltic, Lehtonen et al. (1988) noted that cod was a component in the recreational and subsistence fisheries of Finland. No reports were found of recreational fisheries elsewhere in the northeast Atlantic.

Northwest Atlantic

The recreational fishery for cod is quite old, at least off the United States. Jensen (1972) reported the following information: (1) in July 1873, Miss Fannie Belis, of St. Louis, Missouri, landed a 130-lb (59 kg) cod off Gloucester, Massachusetts, aboard the yacht UNITED STATES; (2) the official International Game Fish Association record is 98 lb 12 oz (45 kg), and was caught by Alphonse Bielevich in June 1969, off Newburyport, Massachusetts; and (3) the world record for women anglers was 48.5 lb (22 kg), and was caught by Mrs. Estele Lindsay in January 1967, aboard the partyboat VIKING, out of Montauk, New York.

Serchuk and Wigley (1993) provided estimates, by number and weight, of cod catches off the United States for 1960, 1965, 1970, and 1979-90. Overall, annual catches ranged from 1.5 to 5.0 million cod (3,400-16.300 t); and during 1979-90, 1.5-4.9 million cod (3,800-9,000 t). Georges Bank (5Z) was the principal offshore fishing ground.

6.4. ARTIFICIAL PROPAGATION

INTRODUCTION

The principal purposes of artificial propagation are augmenting natural populations and rearing (farming) for direct commercial sale. Augmentation may involve rejuvenation of a depleted stock, increasing the abundance of a "healthy" stock, or moderating natural fluctuations in abundance. Shelbourne (1964) noted that in the case of a depleted stock, artificial propagation was often considered more palatable, politically, than fishery regulations. Rearing for direct commercial sale may involve the complete cycle, egg to marketable size, or simply rearing captured wild juveniles to marketable size.

PACIFIC COD

No reports were found on artificial propagation of Pacific cod.

ATLANTIC COD

Augmenting Natural Populations

The initial effort at artificial propagation of Atlantic cod began in North America, in part due to earlier successes in Canada with brook trout (Salvelinus fontinalis) and Atlantic salmon (Salmo salar) (Aiken 1993), and in the United States with freshwater trout (Salmo spp.), and anadromous shad (Alosa sapidissima) and striped bass (Roccus saxatilis) (Solemdal et al. 1984). Subsequently, hatcheries were operated in Canada, Scotland, and Norway. The announced purpose of all of these operations was to rejuvenate "depleted" stocks, and the universal method was to release yolk-sac larvae into nearby waters.

U.S. hatcheries were operated in Massachusetts, at Gloucester (1878-1953) and Woods Hole (1885-1943), and in Maine, at Boothbay Harbor (1905-50). Canadian hatcheries were established in Newfoundland, at Dildo (Trinity Bay) (Aiken 1993) in 1889, and in St. John's in 1891 (J.C. Rice, pers. comm., January 1993). The former lasted nine years. The latter lasted no more than 10 y (J.R. Rice, pers. comm., January 1993). Fisher (1988) reported that the St. John's hatchery was closed for lack of evidence that the operations were effective, and Aiken (op. cit.) implied the same for the Dildo hatchery. In Europe, hatcheries were established in southern Norway (Dannevig 1895), at Floedevigen (1884-1970), and Scotland (Sutherland 1898), at Dunbar (1894-96). The Norwegian effort may have been inspired by the results of the first scientific investigation of the Lofoten cod fishery during 1864-69 (Sars 1869). Sars successfully carried out fertilization and incubation to hatching of cod eggs collected there. He stated in his 1864 report that "the question might even be raised, if nature might not be assisted in this respect, so as to prevent the occurrence of unfavourable years ... . I here refer to the artificial hatching of fish." In Scotland, emphasis quickly shifted to propagation of plaice (Pleuronectes platessa), for reasons not discovered. In 1987, only Norway reported stocking cod in the northeast Atlantic--240,000 fish "to a controlled environment" (ICES 1990).

Annual releases from U.S. hatcheries reached approximately 1.3-2.6 billion larvae during 1921-50; were less than 200 million during 1871-1920; and were negligible after 1950 (Solemdal et al. 1984, Fig. 7). No records of releases were found for the Canadian hatcheries, but Aiken (1993) reported that

the Dildo hatchery was a multi-species unit, and the largest cod hatchery in the world. Norwegian releases were approximately 100-200 million per year during 1891-1970. Scottish releases were 0.5-2.8 million per year (Sutherland 1898). No evaluation reports were found for the Scottish or U.S. operations. Four substantive evaluations were reported for the Norwegian operations.

The first evaluation was conducted in Oslofjord (southern Norway), where a localized and heavily exploited wild stock existed (Dannevig 1963). There, 100-150 million yolk-sac larvae were released during February-March in alternate years. "Success" was measured by the abundance of age-0 and age-1 juveniles sampled, by seine, in the littoral zone during autumn of each year. Results from the 1950-62 experiment indicated that larvae releases did produce a measurable effect in the subsequent abundance of juveniles during autumn. Anecdotal corroborative evidence was provided from the commercial fishery, where cod recruit at age 2.

The second evaluation involved the results of beach seining for age-0 cod in 17 districts of southern Norway, including Floedevigen (Tveite 1971). Seining was conducted annually during September-October 1920-69, except 1940-44. Catch rates of age-0 cod correlated well with subsequent commercial catches of ages 1-4 of the same year-classes, but effects of cod liberations could not be statistically separated from random variations.

The third evaluation was conducted in the Austvoll area of southwestern Norway, and involved releases of juvenile cod, 4-6 months old, into a semi-enclosed fjord. During 1975-83, techniques were developed to mass-rear cod, from yolk-sac larvae to juveniles, in outdoor ponds on natural food (Kvenseth and Oiestad 1984; Oiestad et al. 1985), rather than in the laboratory on artificial food (Howell 1984). The stated purpose of the study was to determine the most appropriate way to produce juvenile marine fish for farming as well as restocking. Cod was selected for the initial study. During 1983-86, substantial numbers of age-0 cod were tagged and released, during autumn, into relatively confined areas where localized stocks existed (Svasand et al. 1990; Svasand and Kristiansen 1990a,b; Kristiansen and Svasand 1990), and their progress followed to spawning. Overall, the reared cod did not differ from the wild cod with respect to growth, migration, or spawning. They comprised 26 to 61% of each year-class, through first spawning.

The fourth study, at Floedevigen, involved the release of pond-reared age-2 cod (33-52 cm; 0.3-1.3 kg) (Moksness 1990). Dispersion was modest, but greater than that of age-0 cod (7-17 cm) released in previous studies. Although recapture rates were greater for the larger (older) cod, recoveries of commercially marketable cod (1.5+ kg) were not sufficient to justify artificial rearing to augment the commercial fishery

Ulltang (1984) estimated the potential effects of introducing artificially propagated cod into two wild stocks--Arcto-Norwegian (northwest Norway and Barents Sea) and North Sea. He concluded that theoretically a significant contribution could only be made to a stock subjected to severe recruitment-overfishing, and he knew of none at that time. Furthermore, he suggested that prior to large-scale releases, the following factors should be considered: (1) purpose (restock a defined natural population or release in a general area); (2) juvenile mortality, and causes; (3) yield curve and present value of the fishing mortality (F) for population to be restocked; and (4) effects on other species in an enclosed area.

Farming

Rearing for commercial sale is a relatively new enterprise, and modest operations have begun in northern Europe (Jobling 1988) and Canada (Lee 1988; Fisher 1988). No details were found on the European operations. In Canada, the Newfoundland operation rears juveniles, captured from traps or longlines, to marketable size. Aiken (1993) noted that there were technical and economic problems with the enterprise.

Jones (1984) reviewed the economics of the new industry in the United Kingdom, and concluded that cod farming was technically feasible, but current production costs exceeded quayside prices of commercially caught cod. He did note that small operations, such as those in Norway, with access to cheap food and specialty markets, could be viable. For the northeast Atlantic, in 1987, only Norway reported production (5 t) and sale of farm-reared cod (ICES 1990).

6.5. SUMMARY

Aboriginal Fisheries

Fisheries were documented for Pacific and Atlantic cod, but no quantitative data were found. Middens in Denmark revealed that cod was an important component in the aboriginals' diet as early as 8000 B.C. Traps were in use as early as 4500 B.C., and the catch consisted primarily of smaller (younger) cod.

Commercial Fisheries

For Pacific cod, the fishery is relatively new. In the northwest Pacific, a Japanese fishery was underway in the 17th Century, but in the northeast Pacific, the first fishery began in the 19th Century. U.S. fishermen established a line fishery for production of salted and dried fish in the Okhotsk Sea in 1863, which rapidly spread to Alaska. Production ranged from 9,000 to 16,000 t/y during 1902-25; then declined precipitously; and terminated in 1950. Trawl fisheries began modestly in the 1920s, and did not become important until after 1945. Trawling is the principal gear now in use in the cod fisheries.

During 1958-91, all-nation nominal catch rarely exceeded 200,000 t/y prior to 1982, but subsequently rose to a peak of 453,000 t in 1988 , then declined to 420,000 t in 1991. In the northwest Pacific, catches peaked in 1985, at 272,000 t, then declined to 157,000 t in 1991. In the northeast Pacific, catches rose irregularly to 263,000 t in 1991. In 1968, the catch in the northeast Pacific was only 17,000 t. The recent increase in the northeast Pacific was largely due to an increase in production off Alaska. Ironically, while the Alaska production now predominates in the northeast Pacific, cod occupies a minor position in the groundfish fishery there--*ca*. 6% of all-species production in the eastern Bering Sea, and 10% in the Gulf of Alaska. Walleye pollock was the principal component in the groundfish fisheries of the eastern Bering Sea (76%), and the Gulf of Alaska (68.9%). South of Alaska, 81% of the cod production was from Canadian waters, during 1956-79. Principal sources were off west Vancouver Island, and in Queen Charlotte Sound and Hecate Strait, where cod accounted for 13-54% of the groundfish trawl landings.

For Atlantic cod, the fisheries are much older than those for Pacific cod, based on available literature. In the northeast Atlantic, the fishery may well have begun off Norway about the 8th Century. In the 11th Century, a thriving trade in salted and dried cod was underway between Norway and Europe. A similar fishery for salted and dried cod began in the northwest Atlantic during the 16th Century, following discovery of the Grand Bank.

Atlantic cod is the single most important groundfish species in the northeast and northwest Atlantic. For example, in 1987, cod comprised 53 and 54%, respectively, of the nominal catches of important groundfish species in the northeast and northwest Atlantic. Production is greater in the northeast than in the northwest Atlantic--2,065,000 t *vs* 1,802,000 t in 1968; 900,000 t *vs* 400,000 t in 1991. In 1987, principal production areas in the northeast Atlantic were northwest Norway, the Barents Sea, Iceland, Baltic Sea, and North Sea--*ca*. 96%. In the northwest Atlantic, for the same year, principal production areas were Labrador, Newfoundland, and the Gulf of St. Lawrence--*ca*. 90%.

Production of Pacific cod is substantially less than that of Atlantic cod. During 1958-91, peak production of the combined species was 4.0 million tonnes in 1968--3,867,000 t of Atlantic cod, and 143,000 t of Pacific cod. Subsequently, production of Atlantic cod decreased to 1,339,000 t in 1991, while production of Pacific cod increased to 453,000 t in 1988, then declined to 420,000 t in 1991.

Recreational Fisheries

For Pacific cod, no records were found for recreational fisheries in the northwest Pacific. In the northeast Pacific, a substantial fishery exists in Puget Sound and vicinity (Washington State). During 1970-85, annual catches ranged from 7,600 to 159,800 fish. Minor fisheries were reported in Canadian waters of Georgia Strait, and in the Gulf of Alaska.

For Atlantic cod, recreational fisheries were reported in the Baltic Sea, Norway, England, and the United States. Off Europe, the only quantification was for the Baltic fishery in the Kiel Bight, where 1,100 t were caught in 1985. Largest cod caught by angling off Great Britain was reported to be 44.5 lb (20.18 kg). Off the United States, the fishery is both old and substantial. Largest cod reported weighed 130 lb (59 kg), and was caught in July 1873, off Gloucester, Massachusetts. During 1960-90, annual catches ranged from 1.5 to 5.0 million cod (3,800-9,000 t). Principal fishing ground was Georges Bank.

Artificial Propagation

No reports were found which dealt with artificial propagation of Pacific cod.

Artificial propagation of Atlantic cod began during the late 19th Century--1878 in the United States (Maine and Massachusetts); 1884 in Norway; 1889 in Canada (Newfoundland); and 1894 in Scotland. Original purpose, in all cases, was to rejuvenate "depleted" stocks. The universal method was to release prodigious quantities of yolk-sac fry--up to 2.6 billion/y in the United States; up to 200 million/y in Norway. U.S. operations did not terminate until 1953, and no published report was found which assessed their effectiveness. Canadian operations terminated after 9-10 y, when no benefit was evident. Norwegian operations received no formal assessment until the 1960s. The Scottish operation was brief, as attention turned to the rearing of plaice.

Initial Norwegian assessments indicated little effectiveness in the release of yolk-sac fry. Recent rearing procedures, involving pond-rearing on natural food and extended rearing for 4-6 and 24 months, showed more promise. Substantive evaluations revealed that cod so reared behaved like wild cod, with respect to growth, migration, and spawning. Survival rate was higher for the cod reared 24 months, but the contribution to the commercial fishery was not sufficient to justify the cost of rearing. One analysis indicated that augmentation of important stocks with reared cod was not likely to be of any benefit, unless the target stock was sustaining severe recruitment overfishing.

Farming of Atlantic cod for direct commercial sale is conducted on a small scale in Norway and Canada (Newfoundland). Norway reported the production of 5 t of farm-reared cod in 1987, but no report was found which described the operations. Apparently, current production costs preclude a substantial market for farm-reared cod. The Canadian program involves capture of wild juvenile cod, and rearing them to commercial size. Technological and economic problems persist. No information was found on the quantity produced or sold.

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Table 6.2.1. Nominal catches ($x10^3$ t), by nation, of Pacific cod in the north Pacific Ocean, 1929-38. (Source: Moiseev 1953, Table 76)

Year	Korea	Japan		USSR	Canada-U.S.	Total
		Home[a]	Other[b]			
1929	26.0	86.3	28.3	3.9	7.0	151.5
1930	30.3	83.0	37.8	16.8	6.8	174.7
1931	35.7	79.2	34.8	16.1	6.6	172.4
1932	36.3	84.5	51.4	9.4	6.4	188.0
1933	34.3	93.8	69.3	4.0	6.1	207.6
1934	32.6	99.6	76.2	4.8	6.0	210.2
1935	20.7	103.9	110.0	6.5	5.8	246.9
1936	14.9	108.7	108.8	6.7	5.5	244.6
1937	14.2	95.9	96.2	7.2	5.0	218.5
1938	19.7	98.0	82.8	13.7	4.7	218.9
Mean	26.5	93.2	69.6	8.9	6.0	203.3

a. Primarily Hokkaido.
b. Distant waters. Mainly Kurile Islands, Sakhalin Island, and Kamchatka.

Table 6.2.2. All-nation nominal catches ($x10^3$ t) of important groundfish species[a] in the eastern Bering Sea, and off the Aleutian Islands, 1964-88. (Source: Low & Narita 1990, Tables, 2 and 3).

	Eastern Bering Sea						Aleutian Islands					
Year	PC	WP	YF	TF	%PC	%WP	PC	WP	AM	TF	%PC	%WP
1964	13	175	111	394	3.3	44.4	T[b]	--	--	93	--	--
1965	15	231	54	344	4.4	67.2	T	--	--	112	--	--
1966	18	262	102	452	4.0	58.0	T	--	--	88	--	--
1967	32	550	162	836	3.8	65.8	T	--	--	68	--	--
1968	58	702	84	977	5.9	71.9	T	--	--	56	--	--
1969	50	863	167	1192	4.2	72.4	T	--	--	44	--	--
1970	70	1257	133	1594	3.3	78.9	T	--	1	81	--	--
1971	43	1744	160	2157	2.0	80.9	2	--	--	32	6.3	--
1972	43	1875	48	2249	1.9	83.4	T	--	6	80	--	--
1973	53	1759	78	2064	2.6	85.2	1	--	2	34	2.9	--
1974	62	1588	42	1900	3.3	83.6	1	--	1	49	2.0	--
1975	52	1357	65	1645	3.2	82.5	3	--	13	47	6.4	--
1976	50	1178	56	1424	3.5	82.7	4	--	13	43	9.3	--
1977	33	979	58	1161	2.8	84.3	3	8	21	67	4.5	11.9
1978	43	979	138	1299	3.3	75.4	3	6	23	61	4.9	9.8
1979	34	914	99	1155	2.9	79.1	6	10	21	75	8	13.3
1980	46	958	87	1218	3.8	78.7	6	58	16	108	5.6	53.7
1981	52	974	97	1256	4.1	77.5	10	56	17	104	9.6	53.8
1982	55	956	96	1209	4.5	79.1	12	58	20	109	11.0	53.2
1983	83	982	108	1278	6.5	76.8	10	59	12	95	10.5	62.1
1984	111	1099	160	1456	7.6	75.5	22	82	36	147	15.0	55.8
1985	133	1180	227	1648	8.1	71.6	13	59	38	113	11.5	52.2
1986	131	1188	209	1634	8.0	72.7	10	47	32	96	10.4	49.0
1987	145	1238	181	1640	8.8	75.5	13	29	30	82	15.9	35.4
1988	193	1228	223	1748	11.0	70.3	5	43	22	78	6.4	55.1
Total	1618	26216	2945	33930	4.8	77.3	124	515	324	1962	6.3	26.2
1977-88 Total	1059	12675	1683	16702	6.3	75.9	113	515	288	1135	10.0	45.4

a. AM = Atka mackerel (Pleurogrammus monopterygius); PC = Pacific cod; TF = total fish; WP = walleye pollock; YF = yellowfin sole (Limanda aspera).
b. T = < 500 t.

Table 6.2.3. All-nation nominal catches ($x10^3$ t) of Pacific cod, during 1971-87, and important groundfish species, during 1977-87, in the Gulf of Alaska. (Sources: 1971-76 from Table 1 in Zenger 1988; 1977-87 from Table A in Wilderbuer 1989)

	Species[a]					
Year	PC	WP	S	TF	%PC	%WP
1971	1					
1972	2					
1973	6					
1974	5					
1975	6					
1976	7					
1977	2	118	17	201	1.0	58.7
1978	12	97	9	174	6.9	55.7
1979	15	106	10	163	9.2	65.0
1980	35	115	9	207	16.9	55.6
1981	36	148	10	248	14.5	59.7
1982	32	169	9	237	13.5	71.3
1983	36	216	9	297	12.1	72.7
1984	24	307	10	355	6.8	86.5
1985	14	285	12	319	4.4	89.3
1986	25	73	21	126	19.8	57.9
1987	31	62	26	136	22.8	45.6
1977-87 Total	262	1696	142	2463	10.6	68.9

a. PC = Pacific cod; S = sablefish; TF = total fish; WP = walleye pollock.

Table 6.2.4. Mean Canada-U.S. trawl landings (t) of Pacific cod, by area of catch and 5-y period, in the California-British Columbia Region, 1956-79. (Source: Lynde 1986)

Area[a]	56-59 (t)	60-65 (t)	65-69 (t)	70-74 (t)	75-79 (t)	1956-79 Pacific cod (t)	1956-79 Pacific cod (%)	1956-79 All-Spp (t)	1956-79 % cod
1A-2C	4	3	9	2	19	7	<1	>20000	<1
2D/3A	149	42	100	161	531	222	2	7566	3
3B	1028	497	497	525	1164	730	8	4213	19
3C	1036	781	1796	2397	3284	1893	20	6824	28
3D	217	59	293	182	213	192	2	2455	8
4A	727	614	897	744	1250	860	9	5686	15
4B	708	608	398	596	1149	691	7	2464	28
5A	967	263	729	579	905	677	7	4385	15
5B	481	387	655	972	1075	784	8	5616	13
5C	692	645	1788	1033	1168	1081	12	2000	54
5D	2870	2190	1912	1826	2913	2220	25	5817	40
5E	--	--	--	--	3	1	<1	897	<1
Total						9398	100		

a. See Fig. 2.1

Table 6.2.5. Mean Canada-U.S. landings (%), by quarter-year, from important locations off British Columbia, 1945-84.

Area	Quarter-year I	II	III	IV	Total (%)	(t)	%
Georgia Strait[a] (4B)	48	12	10	30	100	723	100
MSA 14	49	15	9	27	100	86	12
MSA 17	77	9	1	13	100	116	16
MSA 18	60	11	3	26	100	243	33
MSA 19	19	6	22	53	100	177	25
MSA 20	28	25	25	22	100	62	9
S.W. Vancouver Island (3Cn)[b]	44	36	16	5	101	2108	100
Amphitrite Bank	77	20	2	<1	99	1039	49
Big Bank	8	39	41	12	100	541	26
Queen Charlotte Sound (5A+5B)[b]	4	49	38	10	101	1324	100
Scott Bank (5A)	5	48	34	14	101	581	44
Goose Is. Bank (5B)	3	50	41	7	101	743	56
Hecate Strait[b] (5C+5D)	24	36	31	8	99	3916	100
Horseshoe (5C)	6	60	33	2	101	867	22
Reef Island (5C)	64	31	1	4	100	177	5
White Rocks (5D)	55	9	10	25	99	807	21
Two Peaks (5D) 11	29	56	4	100	1410	36	

a. 1945-84. Foucher & Guidici (1985). Canada only. U.S. vessels prohibited from fishing in Area 4B.
b. 1956-82. Foucher & Westrheim (1984).

Table 6.2.6. Nominal catches ($x10^3$ t) of important demersal species from the northeast and northwest Atlantic, in 1987.

Species[a]	Catch ($X10^3$ t)	(%)	Species[a]	Catch ($X10^3$ t)	(%)
N.E. Atlantic[b]			N.W. Atlantic[c]		
Cod	1468	53.0	Cod	601	54.5
Saithe (= pollock)	409	14.8	Redfish	214	19.4
Haddock	363	13.1	American plaice	85	7.7
Redfish	227	8.2	Silver hake	78	7.1
European plaice	183	6.6	Pollock (= saithe)	73	6.6
Whiting	118	4.3	Greenalnd halibut	52	4.7
Total	2768	100.0		1103	100.0

a. American plaice (Hippoglossoides platessoides); European plaice (Pleuronectes platessa); Greenland halibut (Reinhardtius hippoglossoides); haddock (Melanogrammus aeglefinus); pollock (= saithe) (Pollachius virens); redfish (Sebastes spp.); saithe (= pollock); silver hake (Merluccius bilinearis); whiting (Merlangius merlangius).

b. ICES (1990).

c. NAFO (1990).

Table 6.2.7. Nominal catches (x10³ t), by principal ICES and NAFO Subareas, of Atlantic cod and other important demersal species, in 1987.

Species[a]	ICES[b] I	II	III	IV	V	Sub-total (I-V)	Grand total (I-XIV)	%[c]
Cod	156	396	270	166	416	1404	1468	96
Saithe (= pollock)	19	73	4	150	121	367	409	90
Haddock	110	45	4	109	56	324	363	89
Redfish	3	31	<1	1	106	141	227	62
Plaice	<1	<1	19	131	11	161	183	88
Whiting	-	<1	1	65	1	67	118	57
Total	288	545	298	622	711	2464	2768	
% cod	54	73	91	27	59	57	53	
			NAFO[d]					
	1	2	3	4	5	(1-5)	(0-6)	
Cod	19	59	310	174	38	600	601	99+
Redfish	1	3	151	57	2	214	214	100
American plaice	<1	<1	65	15	4	84	85	99
Silver hake	--	--	<1	62	12	74	78	95
Pollock (= saithe)	--	--	6	45	22	73	73	100
Greenland halibut	9	18	14	11	--	52	52	100
Total	29	80	546	364	78	1097	1103	
% cod	66	74	57	48	49	55	54	

a. American plaice (Hippoglossoides platessoides); European plaice (Pleuronectes platessa); Greenland halibut (Reinhardtius hippoglossoides); haddock (Melanogrammus aeglefinus); pollock (= saithe) (Pollachius virens); redfish (Sebastes spp.); saithe (= pollock); silver hake (Merluccius bilinearis); whiting (Merlangius merlangius).

b. ICES (1990). See Fig. 2.3.

c. Sub-total of Grand Total.

d. NAFO (1990). See Fig. 2.4.

Table 6.2.8. Five-year mean nominal catches ($x10^3$ t) of Atlantic cod in important ICES and NAFO Subareas or Divisions, 1966-85. (Sources listed below)

Subarea or Division	1966-70	1971-75	1976-80	1981-85	1966-1985
ICES[a]					
Barents Sea + N.W. Norway (I+II)	893	849	698	364	701
Iceland (Va)	392	396	364	353	376
North Sea (IV)	236	260	228	233	264
Baltic Sea[b] (IIId)	168	158	253	350	197
Sub-total	1689	1671	1543	1300	1538
% Total	93	92	92	89	91
Total[c] (I-IX)	1816	1799	1677	1466	1690
NAFO[d]					
W. Greenland (1)	304	78	41	43	117
Labrador (2)	352	120	38	47	139
E. Newfoundland[e] (3)	613	445	227	275	390
Gulf of St. Lawrence to U.S. border[e] (4)	225	189	176	237	207
Sub-total	1494	832	482	602	853
% Total	97	96	91	91	95
U.S. waters (5+6)	45	34	46	59	46
Total[c] (1-6)	1539	867	528	661	899

a. 1966-80 in ICES (1982); 1971-85 in ICES (1988).
b. Estimates based on proportions of IIIa-d noted in 1965 (ICES 1967), 1975 (ICES 1978), 1980 (ICES 1982), 1985 (ICES 1988), and 1987 (ICES 1990).
c. Excluding catches from unknown areas.
d. 1966-80 in NAFO (1984); 1971-85 in NAFO (1988).
e. Including Grand Bank (3NO) and Flemish Cap (3M).

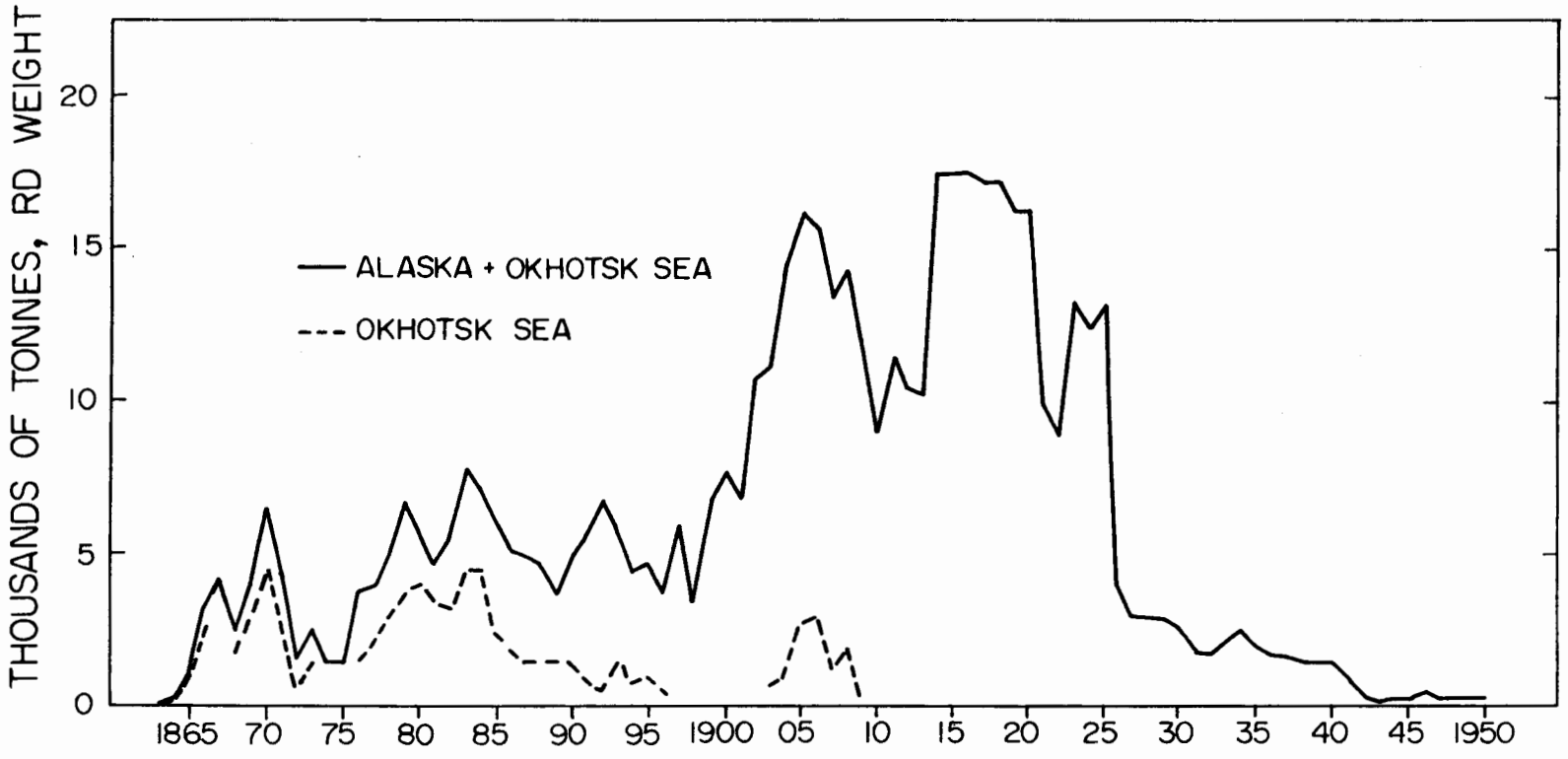


Fig. 6.2.1. Pacific cod catches ($X10^3$ t), by location, during the salt-cod fishery, 1853-1950. (Sources: Cobb 1927; Rigby 1984)

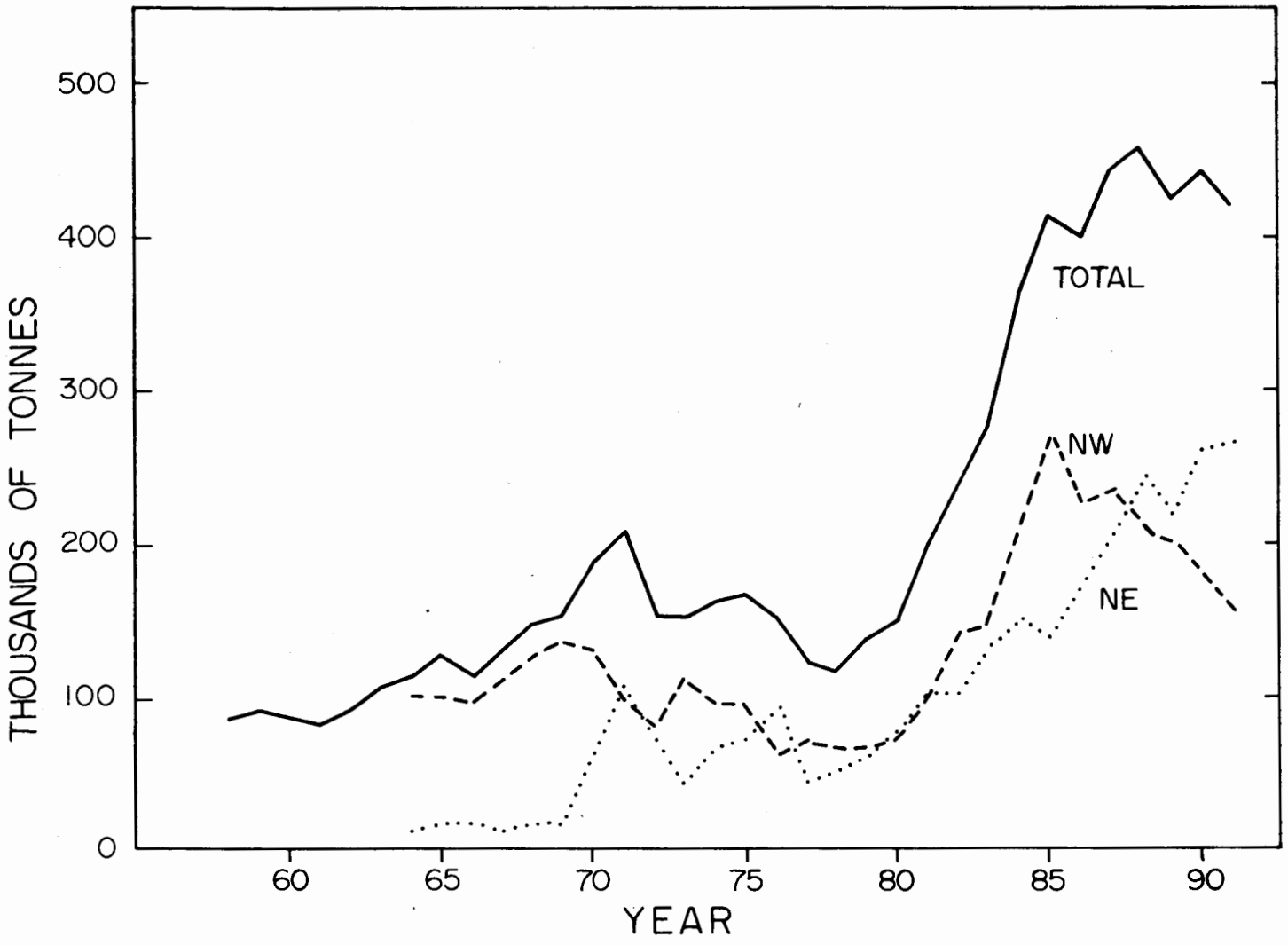


Fig. 6.2.2. **Nominal** catches ($X10^3$ t) of Pacific cod in the north Pacific Ocean during 1958-91, and for the northeast and northwest Pacific Ocean during 1964-91. (Sources: FAO 1964, 1971, 1976, 1981, 1989, 1993)

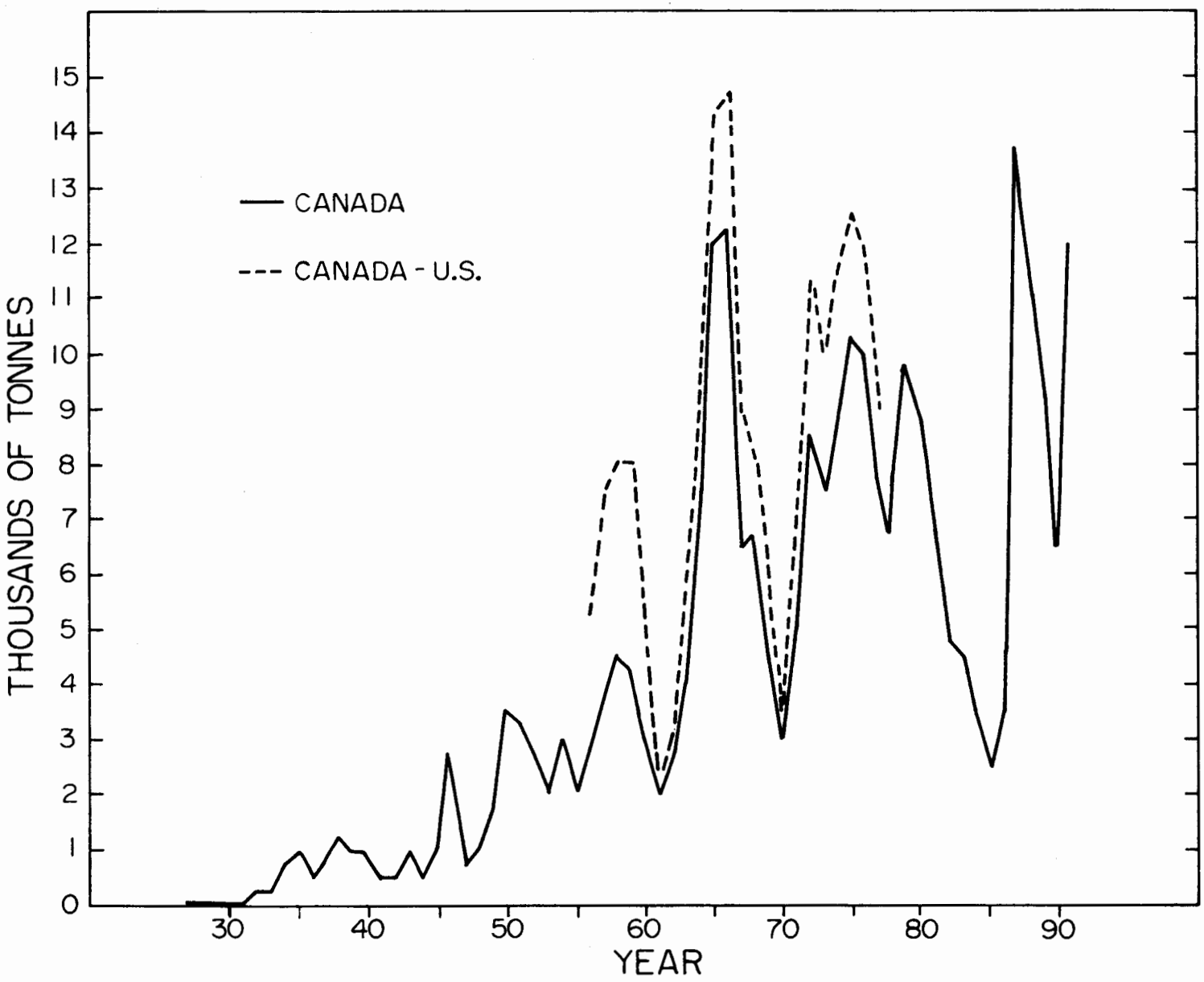


Fig. 6.2.3. Canadian (1927-89) and Canada-U.S. (1956-89) landings ($X10^3$ t) of Pacific cod from Canadian waters. (Sources: Forrester et al. 1978; PBS files)

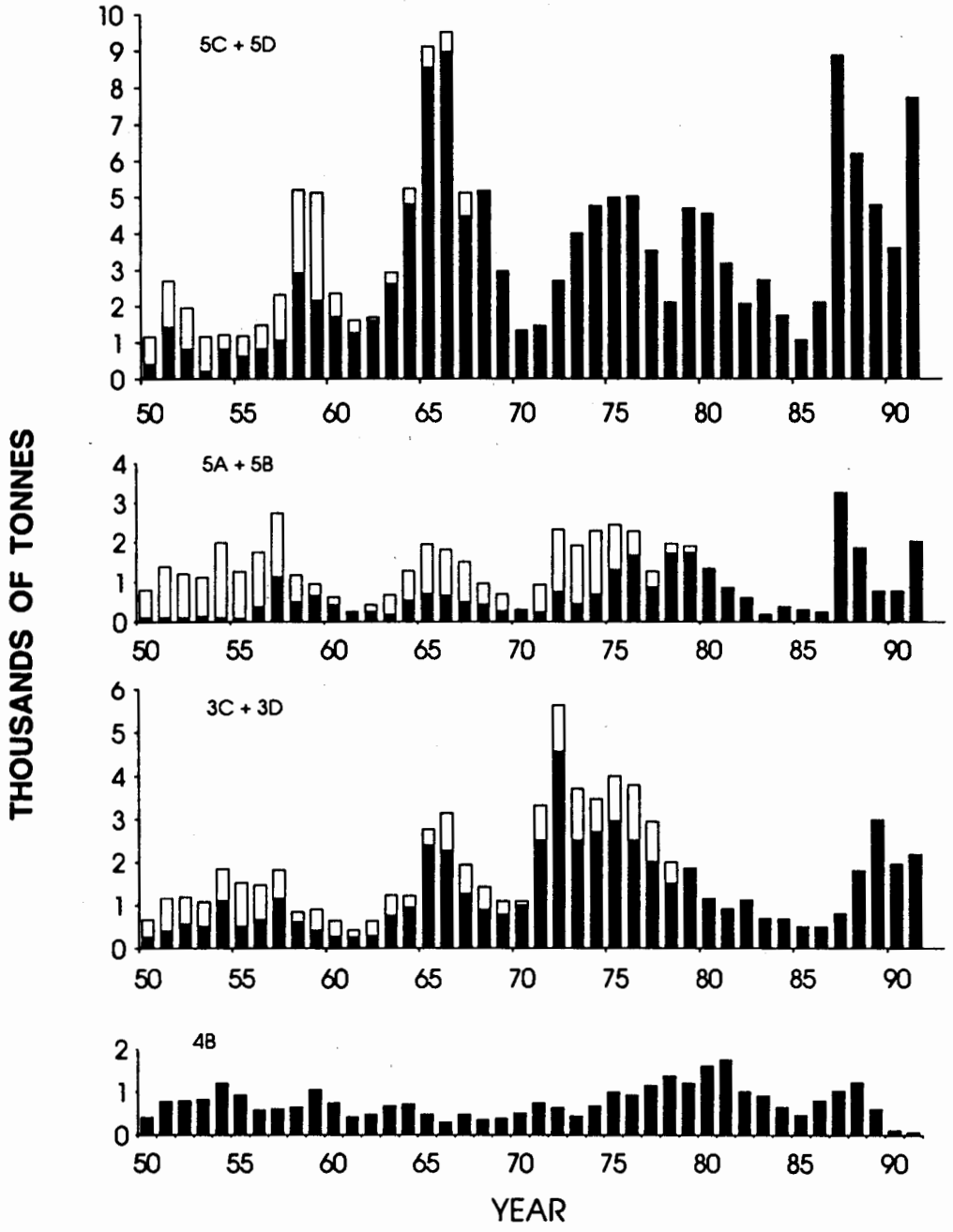


Fig. 6.2.4. Canada-U.S. landings (X10^3 t) of Pacific cod, by importent region, 1950-91. (Fig. 3.1 in Stocker and Hand 1993) (Solid bars = Canadian landings)

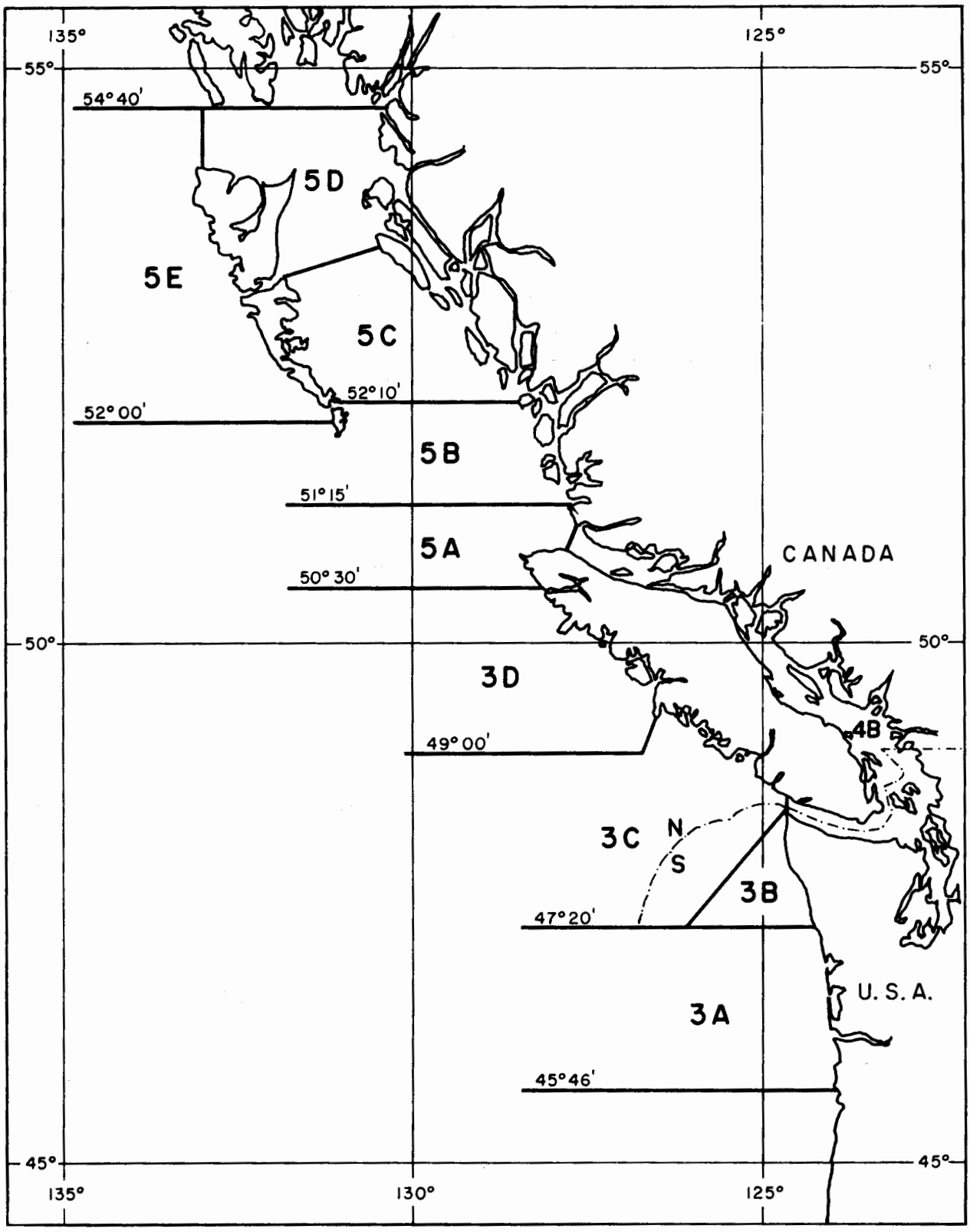


Fig. 6.2.5. PMFC groundfish statistical areas in the northwest Oregon-British Columbia Region.

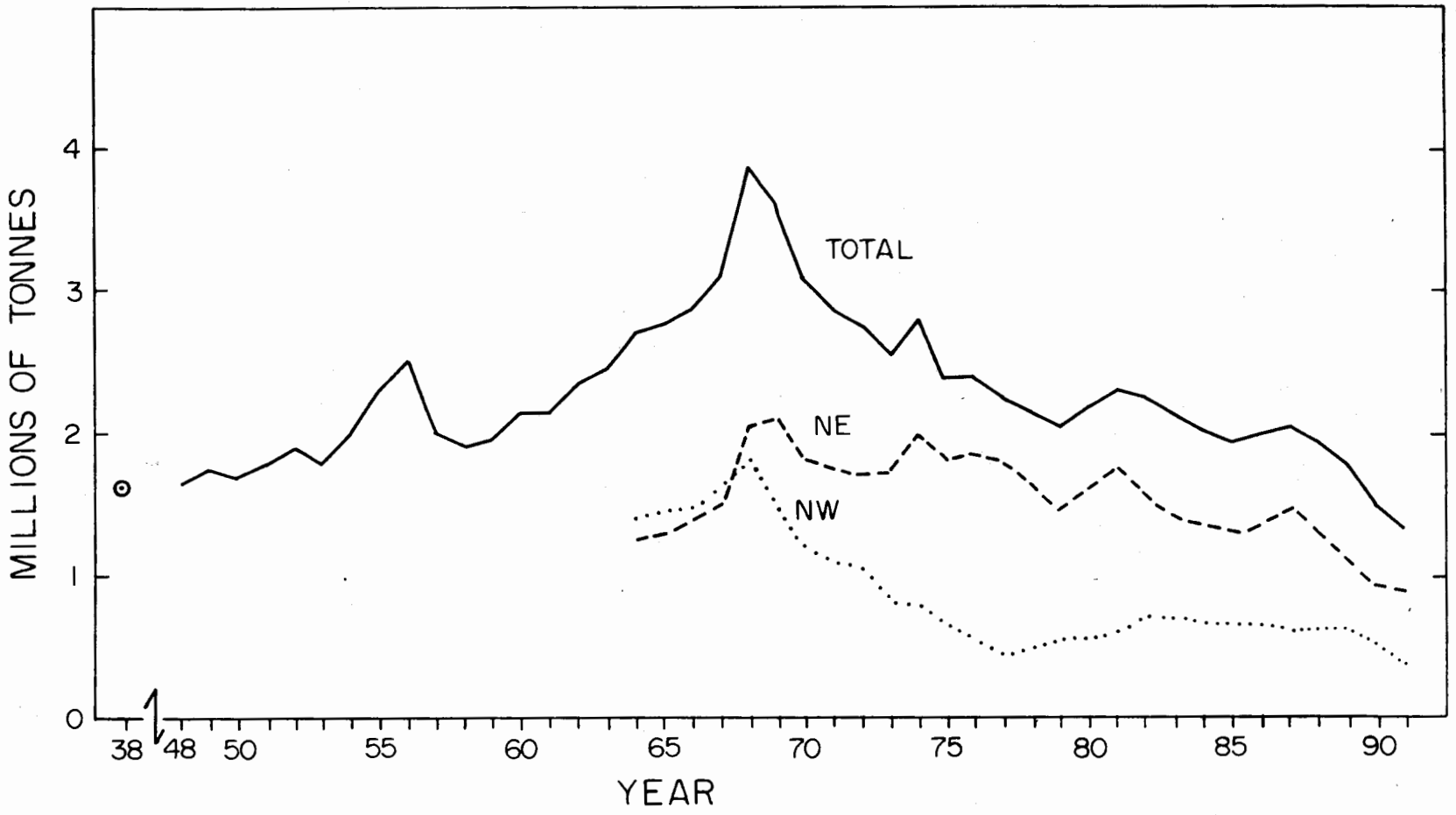


Fig. 6.2.6. Nominal catches ($X10^6$ t) of Atlantic cod in the north Atlantic Ocean during 1938 and 1948-91, and in the northeast and northwest Atlantic during 1964-91. (Sources: FAO 1964, 1971, 1976, 1981, 1989, 1993)

7. STOCK ASSESSMENT

INTRODUCTION

This chapter will deal with stock delineation, mortality and exploitation rates, and stock assessment for Pacific and Atlantic cod.

7.1. STOCK DELINEATION

INTRODUCTION

For this report, the term "stock" is used within the context of Templeman's (1962) definition, which is: "a recognizable unit in which most of the fish have a similar area-occupying and migratory pattern. Along with this partial isolation of a stock from neighboring stocks, there are often other physical differences such as growth, vertebral numbers, etc.". The "area occupying pattern" may well apply only to the spawning ground.

PACIFIC COD

North Pacific

Grant et al. (1987) investigated the ocean-wide genetic population structure of Pacific cod using tissue samples collected at 11 sites extending from southwest Korea to Puget Sound, Washington. Two major genetic groups were detected, based on electrophoretically detectable population markers at 41 loci. The groups were Asian (northwest Pacific), and American (northeast Pacific, including Bering Sea). Intra-group differences were minor, except for an anomalous stock off southwest Korea.

Northwest Pacific

Moiseev (1960) concluded that at least 10 localized cod stocks existed. Off Korea, east and west coast stocks appeared to be unique, based on the substantial difference in length frequencies (see Section 5.2). He considered that demersal egg deposition was instrumental in the creation of numerous localized stocks.

Northeast Pacific

Alaska

No reports were located which provided definitive stock delineations. For management purposes, two stocks were recognized--Gulf of Alaska (Thompson and Shimada 1990) and Aleutian Islands-East Bering Sea (Zenger and Thompson 1989). Both sources reported some inter-regional movement of tagged cod, but provided no details.

Alaska-British Columbia

Wilimovsky et al. (1967) analyzed morphometric ratios and meristic counts of 61 Pacific cod collected from British Columbia (N = 13), southeastern Alaska (6), eastern Bering Sea (14), and the Aleutian Islands (28). Morphometric ratios provided no evidence of stock delineation. Meristic counts (fin rays, gill rakers) suggested four identifiable stocks--western Aleutian Islands, eastern Aleutian Islands + Bering Sea, southeastern Alaska + northern British Columbia, and southern British Columbia. They noted that small sample sizes precluded precise delimitation of the individual "stocks". No records were found of tagged cod crossing the Alaska-British Columbia border.

British Columbia-Washington State

Pacific cod exhibited little intermingling among or within areas or regions, based on tagging and biological studies in British Columbia and Washington State. This phenomenon may be related to reproduction, i.e., laying of demersal eggs. Presumably, both eggs and larvae will develop in the area of spawning, which is nearby to the feeding area of juveniles and adults (who laid and fertilized the eggs).

Among Areas (Regions). Ketchen (1967) initiated investigations into coastwide stock delineation in British Columbia waters, based on the results of Canadian tagging of some 16,000 cod. Tagging locations were Georgia Strait, west coast of Vancouver Island, and Hecate Strait. The author reported little intermingling among the three tagging areas. Subsequently, three analyses of Canadian and U.S. tagging studies have corroborated the negligible inter-area mingling of cod in the B.C.-Washington State region. During 1954-68, 34,218 cod were tagged and released in the B.C.-Washington State region (Table 7.1.1). Of the 7,511 usable recoveries, 86-99+ % were reported from the respective areas of tagging (4A, 4B, 3A, 3B, 3C, and 5C+5D)--except 3A, 57% (4 of 7 recaptures). No tagging occurred in areas 5A or 5B, but negligible recoveries (0-0.9%) were reported there from taggings elsewhere. During 1978-79, 2,083 cod (mostly juveniles) were tagged and released in Area 4B, and 1,297 (mostly juveniles) in Area 3Cn (Table 7.1.2). Of the 457 usable recoveries, 83-94% were reported from the respective tagging areas. Palsson (1990) re-analyzed the results of U.S. tagging studies of 1955-79 (Areas 4A, 3A, and 3B), and the Canadian taggings at Nanoose (4B/17n) after excluding all recoveries in the season of tagging (Table 7.1.3). Of the 501 usable recoveries from the Area-4A tagging, 83-95% were reported from their respective tagging areas. Comparable value was 51.3% for the 107 usable recoveries from taggings at Nanoose. The re-analysis yielded different results from those of Westrheim (1982)--23.0% in 4A, and 73.3% in 4B. Some inter-area intermingling was also suggested by the results of taggings in Area 3B. In that case, the 18 usable recoveries were primarily divided between the "northwest coast" of Washington State (probably 3B and 3Cs; 61%), Area 4A (22%), and Area 3Cn (17%).

Other evidence of stock delineation among major areas included non-synchronous fluctuations in commercial landings (Fig. 6.2.4) and year-class abundance (Fig. 5.4.3), length at 50% maturity (Table 5.6.6; Section 5.6.2), spawning season (Table 5.6.3; Fig. 5.6.3), and incidence of parabranchial lesions (Table 7.1.4). Length at 50% maturity increased northward (Table 5.6.5). Spawning season occurred later northward, except for Area 5C. Lesion incidence in standard samples, during 1968-85, ranged from 0.7% (4B) to 11.0% (5A); increased northward to 5A; then decreased sharply for Areas 5B (3.0%), 5C (1.5%), and 5D (1.9%). The pattern was similar among sexes in the special and research-vessel samples. Higher incidences in research-vessel samples were attributed to more small cod in those samples. Additional information on parabranchial lesions was recently reported for cod in Washington State waters (Palsson 1990). For 1987-88, the incidence was 0.2% for 4,313 cod sampled from Area 4A, and 0% for 600 cod sampled from the "N.W. coast" (probably Areas 3B and 3Cs).

Within Areas (Regions). Evidence for stock delineation within areas or regions was reported for Areas 4A and 4B, Queen Charlotte Sound (5A+5B), and Hecate Strait (5C+5D). For Area 3Cn, results of limited tagging studies provided little evidence of intra-area stock delineation (Westrheim 1982,1984,1985).

In Area 4B, early studies, based on results of tagging studies, delineated two stocks--North (MSA 14) and South (MSAs 17-20) (Forrester and Ketchen 1963; Ketchen 1967), but now four stocks are recognized--MSA 14 (resident), Nanoose (17n; itinerant), Gulf Islands (17s+18; resident), and MSA 19 (Juan de Fuca Strait; itinerant) (Westrheim and Foucher 1987a). The fishery in MSA 19 was negligible prior to 1974 (Westrheim and Pedersen 1986). The recent stock delineation was based primarily on results of Canadian tagging during 1954-62 (Westrheim 1982) and 1978-79 (Westrheim 1985), and U.S. tagging during 1955-70 (Gosho 1976) and 1977 (Bargmann 1980). Additional evidence included differential estimates of instantaneous total mortality rate (Z)--higher for itinerant stocks. For the MSA-19 stock, diet, gonad condition, and herring behaviour were also utilized (Westrheim and Pedersen op. cit.). For the taggings in MSA 14 and the Gulf Islands, 92-93% of cod were recovered in the tagging area (Table 7.1.5). Taggings at Nanoose yielded only 45% of the recoveries in the tagging area. Taggings in MSA 19 were too few to yield credible results. As with area 4A, intermingling with offshore stocks was noted in the results of tagging studies and in the cline in parabranchial lesion incidence. In the latter case, during 1969-85, incidences were 0.1% in MSAs 14 and 17, 0.5% in MSA 18, and 1.7% in MSA 19; and offshore, 5.4% in Area 3Cn and 9.3% in Area 3D (Westrheim 1987, Table 6).

In Queen Charlotte Sound, incidence of parabranchial X-cell lesions, and their effects, differentiated cod in Areas 5A and 5B. Lesion incidence in standard samples was 11.0% in Area 5A, and 3.0% in Area 5B (Table 7.1.4). Associated with the higher incidence in Area 5A cod was slower growth (49.8 cm vs 51.4 cm @ age 2, and 57.7 cm vs 60.7 cm @ age 3 during April-June) and higher values of Z (1.33 vs 0.98 during 1968-84; 1.47 vs 1.07 for year-classes 1966-74) (Westrheim 1987).

In Hecate Strait, Ketchen (1967) suggested that there might be two stocks (North and South), based on results of tagging studies. Since then, a spawning ground was discovered, and exploited, off Reef Island, the first in Area 5C. These 5C cod may well be different from those spawning on the White Rocks ground. Recent analyses of all past tagging studies yielded inconclusive evidence of stock delineation (Westrheim 1982, 1984). However, the female members of the two spawning groups varied in size at 50% maturity and spawning time. Reef Island cod were smaller at 50% maturity (43.1 cm vs 52.3 cm; Welch and Foucher 1988, Table 2b); and spawned earlier, over a shorter time period (Fig. 5.6.3).

Washington State

Detailed stock delineation was only reported for Puget Sound and vicinity (Area 4A).

Three stocks (North, West, and South) were delineated, based on tagging studies and locations of spawning grounds (Palsson 1990). The North stock included cod in the Gulf-Bellingham and San Juan Management Regions (Fig. 5.1.7). Some of these cod spawned at Nanoose Bay (Area 4B/17n). The West stock comprised cod in the West Juan de Fuca and Juan de Fuca Management Regions (including Port Townsend). The South stock comprised cod in the central Puget Sound (south of Admiralty Inlet), Hood Canal, and South Sound Management Regions. Incidence of parabranchial lesions was 0% in all management regions except San Juan (0.04%; numbers sampled = 2,374) and Juan de Fuca (0.86%; N = 700). The positive westward cline in incidence suggests some intermingling with offshore stocks, as did the results of the tagging studies.

ATLANTIC COD

North Atlantic

A genetic (electrophoretic) study indicated little variation among areas, based on analysis of tissues collected from Atlantic cod throughout its range (Mork et al. 1985). A dendogram of genetic distances indicated that: Baltic Sea cod were different from all other Atlantic cod; west Greenland and Gulf of Maine cod differed from cod off Iceland and Europe; and Iceland and Barents Sea cod differed from the Norwegian Coastal and North Sea cod. Smith et al. (1990) reviewed electrophoretic studies on 20 marine teleosts, including Atlantic cod, and reported that the majority of the genetic variation detected by gel-electrophoresis lay within, rather than between, spawning groups. They suggested that future management decisions on fish resources should take account of the high genetic variability within areas and the low genetic differentiation between areas.

Garrod (1977) listed 19 cod stocks which supported major international fisheries--9 in the northeast, and 10 in the northwest. He noted that a number of smaller stocks, usually fjord-coastal, were also recognized, as well as sub-stocks within the major stocks.

In contrast to Pacific cod, some Atlantic cod undertake substantial migrations, both as groups and as individuals. Group migrations usually involve adult cod moving between feeding and spawning grounds, and the larvae drifting "downstream" to the feeding grounds. For example, Atlantic cod migrate from the feeding areas in the Barents Sea, and off Newfoundland, to the spawning grounds near the Lofoten Islands, and off Labrador, respectively (Garrod 1977). In only one case was extensive movement documented across stock boundaries, viz. Iceland-Greenland (Parrish 1956). This involved eggs and larvae drifting to east and west Greenland, and mature cod migrating from Greenland to Iceland, and, to a lesser extent, from Iceland to Greenland. However, the author noted that "no substantial interchange with any other area separated by deep water has been established for the North Sea, the Faroe Plateau, the waters eastwards from the Skagerrak, the Newfoundland and Labrador areas, and the North American coast" (op. cit., p. 280).

Some individual tagged Atlantic cod travelled far. A summary by Graham (1956, Figure I.2) included journeys from: Massachusetts to Maryland and Nova Scotia; Gulf of Maine to Gulf of St. Lawrence and Newfoundland; east and west Greenland to Iceland; Jan Mayen Island to Barents Sea, northwest Norway, Faroe Islands, Iceland, west Greenland, and Newfoundland; and Faroes to North Sea. Gulland and Williamson (1962) reported a cod recovered on the Grand Bank (NAFO SA 3), in December 1961, which had been tagged and released in the North Sea (ICES SA IV) in January 1957. This was the first reported transit of the Atlantic Ocean from east to west. Templeman (1979) reported 27 "distant recaptures" among 15,500 recoveries from 47,560 Atlantic cod tagged during 1962-66 off Labrador, Newfoundland, and the north shore of the Gulf of St. Lawrence. One was recovered southward on Georges Bank, and the remainder eastward, off west Greenland (28), east Greenland (3), Iceland (3), and in the Barents Sea (2). Most of these cod were tagged and released off Labrador.

Northeast Atlantic

Four of the stocks listed by Garrod (1977) accounted for 89.3% of the cod catch in the ICES Area during 1956-90 (Table 7.1.6). In order of importance, these were: Arcto-Norwegian (ICES SAs I + II; 39.1%), Iceland (Va: 24.5%), Baltic Sea (III/22,24-32; 14.3%), and North Sea (IV; 11.4%) (Fig. 2.3). A brief description of each stock follows.

Arcto-Norwegian (I+II)

This stock, more recently referred as Northeast Arctic cod, utilizes the Barents Sea (I and IIb) as a feeding area, and the northwest Norwegian coast (IIa; ca. 62 to 71 N lat) as a spawning ground (Bergstad et al. 1987). Three sub-stocks are recognized on the feeding grounds--Bear Island (IIb), and the west and east Barents Sea. The spawning grounds, primarily near the Lofoten Islands, are shared with a portion of the small Norwegian Coastal cod stock, which remains year-round on coastal grounds and in fjords along the entire coast of Norway (Jakobsen 1987). The Arcto-Norwegian and Coastal cod stocks were found to be differentiated by environmental rather than genetic factors, based on laboratory studies (Godoe 1987).

Iceland (Va)

This stock utilizes the coastal banks completely around Iceland as a feeding ground. Spawning grounds are located off the southwest coast, and are shared on an irregular basis with cod from east Greenland (XIVb) and west Greenland (NAFO SA 1; Fig. 2.4) (Garrod 1977). Under favorable oceanographic conditions, considerable quantities of eggs and larvae drift on the Irminger Current to east and west Greenland, and some of the maturing adults return to Iceland to spawn.

Baltic Sea (III/22,24-32)

ICES Subarea III contains four divisions--IIIa (Kattegat and Skagerrak), IIIb,c (The Sound, Belt Sea, and west Baltic Sea), and IIId (east Baltic Sea). Cod catches are relatively large only in IIId. For example, in 1987, they were 32,368 t in IIIa, 14,013 t in IIIb,c, and 223,704 t in IIId (ICESa 1990). Cod in Divisions IIIa-c were deemed distinct from those in IIId, and closely related to North Sea cod (Poulsen 1931). West Baltic (IIIc/22 + IIId/24) and East Baltic (IIId/25-32) stocks are now recognized, based on meristics, morphometrics, electrophoresis, otoliths, and tagging (Bagge and Steffensen 1989; Bagge et al. 1993). The West Baltic stock is relatively unimportant--mean annual catch during 1970-87 was 41,000 t vs 234,000 t for the East Baltic stock (ICESb 1991b). However, for management purposes they are treated as a single stock (ICESb 1993).

North Sea (IV)

Three substocks are recognized--North (ICES IVa) and South (IVc) by Garrod (1977), and West-Central (IVb) by Houghton and Flatman (1981). The West-Central stock is semi-artificial in that it consists primarily of young (age 1-3) cod, which by nature are relatively non-migratory. Their age-length relationship occupies an intermediate position between those of the other two stocks.

Northwest Atlantic

Templeman (1962) listed, without quantification, 27 stocks, plus two probables--7 off south and west Greenland; 15 (+2?) off Canada (SAs 3 + 4); and 5 off the United States (SAs 5 + 6), the latter largely based on unpublished data from the Woods Hole Laboratory, Massachusetts (Fig. 2.4). Wise (1963) reviewed all available stock delineation data for NAFO SAs 5 and 6, and concluded that four "groups" of cod were identifiable: (1) offshore banks (Browns, 4X; Georges, 5Z); Gulf of Maine (5Y); (3) southern New England and the South Channel (5Y); and (4) New Jersey coastal (6A). Recent otolith-growth studies suggest that Browns

and Georges Banks are separate stocks (Pentilla 1988). Diagnostic data used by one or more of the authors included: vertebral numbers; migration; growth; year-class strength; and time and location of spawning, and other concentrations.

Eight stocks accounted for 90.5% of the cod catch in the NAFO Area, during 1960-89 (Table 7.1.6). Only two of these were deemed important--Labrador-East Newfoundland (2J3KL; 38.9%) and West Greenland (1; 16.1%). The remaining six stocks contributed 3.4-8.6% each. Recent modifications to the six stocks resulted in the following list, for management purposes: 3NO, 3Ps, 3Pn4RS, 4TVn (January-April), 4Vn (May-December); 4VsW; 4X (south Scotian Shelf), and 5Zjm (Canadian portion of Georges Bank (CAFSAC 1992); and 5Z6 (less 5Zjm).

Labrador-East Newfoundland (2J3KL)

The complex of cod stocks occupying this region is treated as a unit for management purposes, and commonly called the Northern Cod stock. NAFOb (1986) provided a review of past studies on delineation of the stock components in 2J3KL. Spawning occurs in deep water, during April-June, in the northern portion, after which some of the stock move inshore and southward (Templeman 1962). The remainder occupies the northern portion of the Grand Bank. Cod occupying the northeast coast of Labrador (2GH) are considered separately due to the severe effect of the new offshore trawl fishery during 1965-69 (op. cit., 1962).

During 1959-91, annual catches ranged from 139,000 t (1978) to 810,000 t (1968) (CAFSAC 1992). The inshore portion of the catch ranged from 30,000 t (1975) to 160,000 t (1959).

West Greenland (1)

Three substocks were recognized (fjord, inshore, and offshore), of which the offshore is most important, based on historical catch records (Hovgard and Christensen 1980). The offshore cod occupying Divisions 1A-D were originally recognized as a unit for stock assessment purposes (Templeman 1962). However, recent analyses have included Divisions 1E and 1F in the offshore stock, although these cod have closer ties with the East Greenland and Iceland stocks (Hovgard 1993).

During 1940-90, annual catches ranged from 7,000 t (1986) to 460,000 t (1962) (NAFOa 1984,1991; NAFOb 1991). The offshore stock provided the bulk of the catch until its collapse in the 1980s.

St. Pierre Bank (3Ps)

This stock occupies the western and southern slopes of the bank during winter-early spring, and shifts to the shallower portions during the remainder of the year. Spawning occurs primarily in May-June (Pinhorn and Wells 1976, Fig. 9).

During 1959-91, annual catches ranged from 27,000 t (1975) to 84,000 t (1961) (CAFSAC 1992).

South Grand Bank (3NO)

This stock occupies the south slopes during winter; disperses northward across the surface of the bank in summer; and exhibits little movement inshore. Spawning occurs in April-May (Templeman 1962).

During 1952-91, annual catches ranged from 15,000 t (1978) to 225,000 t (1967) (NAFOb 1992).

South Gulf of St. Lawrence (4TVn)

This stock occupies the Magdalen Shallows region (4T) during summer, and overwinters in deep water off Cape Breton (4Vn and southeast 4T) (Halliday 1972a). Spawning occurs during June-July (Templeman 1962).

During 1950-90, annual catches ranged from ca. 22,000 t (1977) to ca. 106,000 t (1957) (CAFSAC 1991, text figure, p. 8).

In 1992, the stock was subdivided into 4TVn(January-April) and 4Vn(May-December).

For the 4TVn(Jan-Apr) stock, during 1950-91, annual catch ranged from 72,000 t (1977) to 104,000 t (1958) (CAFSAC 1992). However, significant quantities have been caught in 4Vs, at least since 1986.

For the 4Vn(May-Dec) stock, during 1970-91, catches ranged from 4,600 t (1991) to 12,650 t (1981) (CAFSAC 1992).

Scotian Shelf (4VsW;4X)

A complex of stocks occupies this region which intermingle as adults, and possibly as pelagic eggs and larvae (Halliday 1972b). Spawning season is variable among stocks, including spring and autumn by one stock. The 4VsW stock is treated as a unit for management purposes. Assessment of the 4X stock was first reported in 1992.

During 1958-91, annual catches in 4VsW ranged from 10,000 t (1977) to "more than" 80,000 t (1968) (CAFSAC 1992).

For the 4X stock, during 1948-91, annual catches ranged from 12,000 t (1958) to 35,500 t (1968) (CAFSAC 1992).

North Gulf of St. Lawrence (3Pn4RS)

This stock, also referred to as West Newfoundland, occupies the west coast of Newfoundland (4R) and the south coast of Quebec (4S) during summer, and the southwest coast of Newfoundland (3Pn) during winter (Wiles and May 1968). CAFSAC (1978) reviewed the information and problems with delineating this stock. Spawning occurs principally during April-June (Templeman 1962).

During 1964-91, annual catches ranged from 32,000 t (1991) to 106,000 t (1983) (CAFSAC 1992).

Georges Bank (5Z6)

Cod on Georges Bank have exhibited minimal interchange with those in the Gulf of Maine (5Y) and on Browns Bank (4X), but substantial interchange with those from the southern New England-Middle Atlantic region (6), based on tagging studies, parasite infestation, spawning time, and growth rate (Serchuk and Wigley 1993). Since 1977, U.S. scientists have identified 'Georges Bank' cod as those occupying Division 5Z and Subarea 6. In 1985, the boundary between the Canadian and U.S. fishery zones was resolved, and the eastern portion of Georges Bank was

placed in the Canadian zone (5Zjm). Currently, cod in the Canadian zone are treated as a separate stock by Canadian scientists.

During 1960-90, annual catches of the entire stock ranged from 10,800 t (1960) to 57,200 t (1982) (Serchuk and Wigley 1993, Table 1). For the Canadian portion (5Zjm), during 1978-91, annual catches ranged from 12,400 t (1979) to 26,400 t (1982) (CAFSAC 1992).

SUMMARY

Pacific Cod

Trans-Pacific genetic studies detected only two major cod groups--northwest and northeast Pacific. In the northwest Pacific, other studies noted, but did not identify, 10 stocks. In the northeast Pacific, at least 14 stocks exist, based primarily on tagging studies--two off Alaska, nine off British Columbia, and three in Puget Sound and vicinity (Washington State). A limited study of cod meristics in the Alaska-British Columbia region suggested four stocks--western and eastern Aleutian Islands + Bering Sea, southeastern Alaska + northern British Columbia, and southern British Columbia. The nine stocks identified off British Columbia were located in Hecate Strait (2) and Queen Charlotte Sound (2), off west Vancouver Island (1), and in Georgia Strait and vicinity (4). Delineation of major stocks is probably complete off British Columbia and Washington State, but not off Alaska.

Atlantic Cod

Trans-Atlantic genetic studies indicated little variation among areas, although Baltic Sea cod were different from all other Atlantic cod. One study suggested that the majority of the variation detected by gel-electrophoresis lay within, rather than between, spawning groups. Major stocks in the northeast Atlantic, in order of importance, were the Arcto-Norwegian (or Northeast Arctic), Iceland, Baltic Sea, and North Sea. Together, they accounted for 89.3% of the total cod catch in the ICES Area during 1956-90. At least 27 stocks were identified in the northwest Atlantic. Eight stocks accounted for 90.5% of the 1960-89 cod catch, but only two of these were deemed important--Labrador-East Newfoundland (2J3KL) and West Greenland (SA 1). The remaining six stocks accounted for 3-9% each.

7.2. MORTALITY AND EXPLOITATION RATES

PACIFIC COD

Northwest Pacific

No reports dealing with mortality or exploitation rates were found for cod in the northwest Pacific Ocean.

Northeast Pacific

British Columbia

Three sources of data were employed to estimate the various rates: (1) length-frequency/von Bertalanffy growth parameters; (2) tagging studies; and (3) age-frequencies, derived from scale readings or length-frequencies. Spatially, estimates were obtained for Areas 4B (Georgia and Juan de Fuca straits), 3C+3D (west Vancouver Island), 5A+5B (Queen Charlotte Sound), 5C+5D (Hecate Strait), and some sub-divisions thereof.

Methods employed to estimate the instantaneous total mortality rate (Z) are listed in Table 7.2.1. In all but one case, the instantaneous natural mortality rate (M) was estimated by regressing Z values on corresponding values of effort. The y-intercept provided an estimate of M, and the slope of the regression was an estimate of the catchability coefficient (q). The single exception applied the length-frequency/von Bertalanffy (L-F/vB) method to length-frequency samples collected during the early stages of the fishery in Hecate Strait. The instantaneous fishing mortality rate (F) was estimated by subtraction (Z - M) or multiplication (qE). Estimates of F-at-age were derived from virtual population analysis (VPA) (Gulland 1969,1983) or cohort analysis (Pope 1972).

Estimates of the exploitation rate (U) were derived by two conventional methods: (1) $U = AF/Z$, where $A = 1 - e^{-Z}$ (Ricker 1975); and (2) U = (numbers landed)/(numbers present in the fishable stock). In the latter case, numbers landed were estimated by converting weight landed to numbers landed by means of length-frequency samples and a length-weight relationship. Numbers present in the fishable stock were estimated by sequential population analysis (SPA)--virtual population analysis (VPA) or cohort analysis (CA). Spatially, estimates were obtained for Areas 3Cn+3D, 5A+5B, and 5C+5D.

General results are discussed below, by region. Mortality rates are shown in Table 7.2.2, and exploitation rates in Table 7.2.3.

Georgia Strait and Vicinity (Area 4B). Among methods, ranges of estimates were: Z = 1.03-1.77; M = 0.59 and <1.39; and F = 0.44-0.75 (Table 7.2.2). Ketchen (1961) provided the first estimates of mortality rates, specifically the Nanoose stock (MSA 17n)--Z = 1.27-1.77; M = <1.39; and F = 0.27. He opined that his methods (Tag-1,2; L-F/vB) probably produced overestimates of the rates. He also noted that estimates of Z based on tagging data increased with age, perhaps due to emigration from the fishing area, and that M increased with age.

Results of the L-F/vB method, using various estimates of K and L_{∞} (Table 7.2.4), were compared with the conventional regression of $\log_e$ age-frequencies on age for the data in Table X of Ketchen (1961). These data consisted of the mean length-frequencies of cod landed from Nanoose Bay during 1956-60. Ketchen smoothed the length-frequencies by threes, and then estimated $l' = 60.0$ cm, and $\bar{l} = 64.6$ cm. In his text table (p. 544), the four estimates of Z, together with estimates of K and L_{∞}, were as follows:

Z	K	L_{∞}
1.27	0.56	75.0
1.27	0.71	72.8
1.53	0.67	75.1
1.62	0.58	77.4

The Foucher-Fournier method was used to derive age-frequencies from the unsmoothed length-frequencies (Claudia M. Hand, Pacific Biological Station,

pers. comm.). For ages 2-7, derived frequencies (%) were 13.15, 57.52, 22.46, 6.49, 0.22, and 0.25, respectively (K = 0.214; L_{oo} = 95.6). For ages 3-6, Z = 1.79.

The results suggest that the L-F/vB method produces smaller estimates of Z. However, Ketchen noted the sensitivity of the L-F/vB method to estimates of K and L_{oo}. The relatively low estimate of K, and high value of L_{oo}, derived in the Foucher-Fournier method makes comparisons difficult.

Westrheim and Foucher (1987a) estimated Z for cod in four MSAs, based on various arrays of age-frequency data. Their estimates were Z = 1.03-1.63; M = 0.59; and F = 0.44-0.75. No "best" estimates were indicated. The single estimate of M was for MSA 14. They noted that estimates of Z were smaller for the two "resident" stocks (MSAs 14 and 17s + 18; 1.03-1.41) than for the two "itinerant" stocks (Nanoose & MSA 19; 1.26-1.63). Resident stocks were lightly exploited during April-September each year due to regulations and economics, but the itinerant stocks were exploited elsewhere at other times of the year on grounds outside Area 4B--Area 4A for Nanoose cod, and Area 3Cn for MSA 19 cod.

No estimates of exploitation rate were found.

West Vancouver Island (3Cn+3D). The first estimates of Z were reported in Ketchen (1980), and were based on regressions of age-frequencies (derived from scale readings) in landings from Amphitrite Bank (spawning ground) and Big Bank (feeding ground), in Area 3Cn: Z = 1.38 and 1.11, respectively. These two banks produce most of the cod landed from Areas 3Cn+3D. All subsequent estimates were based on age-frequencies derived from length-frequencies by the Foucher-Fournier computer method.

Westrheim and Foucher (1985a) applied two age-frequency regression methods to estimate Z, based on age-frequencies for Big Bank, considered to be representative of cod in Areas 3Cn+3D, during April-September. Their "best" estimates were Z = 1.11, M = 0.58, and F = 0.53, based on "corrected" age-frequencies (age-classes 3-6) of seven strong year-classes (1961, 1963-64, 1969-70, and 1972-73). The need for "correcting" age-frequencies arose when an investigation revealed probable errors in age-determination, beginning at age 3. That is, strong year-classes (large N/h at age 2) tended to lose their relative dominance as early as age 3. For example, in the following text table (op. cit., p. 62), the 1961 year-class was more than twice as abundant at age 2 as the 1960 year-class, and more than three times as abundant as the 1962 year-class. By age

	Year-class (N/h)		
Age-class	1960	1961	1962
2	11.7	27.8	8.9
3	11.4	55.4	41.6
4	31.9	16.0	21.6
5	4.5	4.9	2.2
6	2.9	0.9	1.4
7	0.3	0.3	0.3

4, abundance of the 1961 year-class was only half that of the 1960 year-class, and 74% of that for the 1962 year-class. Accordingly, a second method was developed which utilized only strong year-classes whose CPUEs (N/h) were "corrected" for the apparent age-determination errors. The "correction" involved adjusting subsequent CPUEs to maintain the relative position at age 2. In the above case, the ratio of 1961 vs 1960+1961+1962 (= 0.574) was used to estimate the "corrected" CPUEs for the 1961 year-class at ages 3-7. These corrected CPUEs were 62.2, 39.9, 6.7, 3.0, and 0.5, respectively. All seven strong year-classes were treated in this manner. This "correction" may have overcompensated for the likely ageing errors, if fishing mortality varied directly with year-class

abundance, as with Atlantic cod (Houghton and Flatman 1981). The explanation for this phenomenon was that cod tended to school by size, and that trawlers "hunted" them with echo sounders. Thus the largest schools would receive more attention.

Foucher and Tyler (1988) employed different methods to estimate Z, to avoid reliance on only strong year-classes, and "because of possible variation in mortality rates with age and the possibility of ageing error, especially in the older age groups" (op. cit., p. 47). Furthermore, they returned to the calendar year, and did not address the problem of "slopover" noted by Westrheim and Foucher (1985a). M and F were estimated in the conventional manner. Both the Paloheimo (A-F/P) and Ricker (A-F/S) methods were used to calculate Z, between adjacent age-classes 3-7 (Table 7.2.5). They reported their "best" estimates were derived from the Ricker method, and involved the rate between age-classes 4 and 5, where Z = 1.19; M = 0.69; and F = 0.50. They concluded that: (1) age-3 cod were not fully recruited, based on estimates of F-at-age; (2) Z and M increased with age; and (3) Z was positively related to year-class strength.

Estimates of the mean exploitation rate, based on VPA, were 0.27 and 0.31, and by the AF/Z method, 0.32 and 0.29 (Foucher and Tyler 1988).

Queen Charlotte Sound (5A+5B). Westrheim and Foucher (1985a) provided the first estimates of mortality rates for Pacific cod in Queen Charlotte Sound. Their "best" estimates were: Z = 1.22; M = 0.61; and F = 0.61, and were based on age-classes 4-7 of four strong year-classes (1955, 1962, 1970, and 1973), as shown below:

Parameters	Age-class 3-6	3-7	4-7
Z	1.14	1.14	1.22
M	0.85	0.90	0.61
F	0.29	0.24	0.61
q' [a]	-1.11	7.41	1.32
r [b]	0.857	0.918	0.928

[a] x 0.00001 = catchability coefficient (q).
[b] for regression of Z on effort.

Of some interest was the reciprocal relationship between M and F for the four strong year-classes, as shown below (from op. cit., Table 3.4.5):

Year-class	cum. E[a]	Age-classes 4-7 Z	F[b]	M[c]
1955	13,900	1.01	0.18	0.80
1962	28,500	1.22	0.38	0.84
1970	35,300	1.04	0.47	0.79
1973	26,900	1.04	0.36	0.68

[a] cumulative standardized effort.
[b] F = qE
[c] M = Z - F

Westrheim (1987) used two methods to compute individual estimates of Z for areas 5A and 5B--age-classes 3-6 in each case. Both methods produced larger estimates for area 5A than for Area 5B--1.33 and 1.46 vs 0.98 and 1.07, respectively. He attributed the higher values in Area 5A to the substantially greater incidence of parabranchial lesions in cod from that area--10.0-11.3% vs 2.2-3.7%.

Estimates of the mean exploitation rate were 0.13 (VPA) and 0.21 (AF/Z) (Westrheim and Foucher 1985a).

Hecate Strait (5C+5D). Ketchen (1964a) provided the first estimates (L-F/vB) of mortality rates of Pacific cod in Hecate Strait, actually for cod on Two Peaks and White Rocks grounds (Area 5D)--Z = 1.05-1.53; M = 0.83-0.99. His Z estimates were based on assumed minimum and maximum values of length at full recruitment (l' = 55 and 60 cm), and mean length-frequencies for two or three time periods. The results from his Table IV are shown below:

Time	Two Peaks 55 cm	Two Peaks 60 cm	White Rocks 50 cm	White Rocks 60 cm
1950-52	0.83	0.99	--	--
1954-58	1.23	1.53	1.12	1.29
1959-63	1.05	1.26	1.19	1.37

His estimates of M were based on the length-frequencies collected from Two Peaks Ground during 1950-52, when the fishery was beginning, and F would be close to zero. As with Georgia Strait, he considered the estimates to be high. He also noted that if the low estimates of Z during 1950-52 were due to chance alone, then "we are left with the interesting speculation that natural mortality rate is density-dependent" (op. cit., p. 1966).

The first estimates of mortality rates for Hecate Strait as a whole appeared in Stocker (1981). "Best" estimates were: Z = 1.05; M = 0.38; and F = 0.67. The correlation (r = 0.595) between Z and effort (for calculating M) was considered weak.

Fournier (1983) employed an age-structured model, including stock-recruitment and environmental factors, which provided an estimate of M = 0.65. He noted that "the function was still very insensitive to changes in the value of M, however, indicating that this parameter is not well determined by the data as the following table demonstrates." (op. cit. , p. 1240). In the table referred to, the value of the objective function (to be minimized) was 447.6 at M = 0.65, and 447.9 at M = 0.8 (maximum value listed). He noted evidence of a density-dependent trend in natural mortality which may have been caused by: (1) "some form of interaction between the fishing fleet behavior and stock biomass" or (2) "presence of systematic errors in the age structure estimates produced by the length-frequency analysis because of density-dependent changes in growth of the fish" (op. cit., p. 1243). Other plausible explanations were his use of nominal, rather than standardized, effort, and absolute errors in age determination. No evidence of age-dependent natural mortality was reported.

Westrheim and Foucher (1985a) reported their "best" estimates were: Z = 1.27; M = 0.65 (r = 0.435); and F = 0.62, based on age-classes 3-7, for strong year-classes, with "corrected" CPUEs.

Foucher and Tyler (1988) used the same procedures as they had for the west Vancouver Island region. Their "best" estimates were: Z = 1.13; M = 0.61; and F = 0.52. These values were also used in all subsequent assessments until that for 1992 (Stocker and Hand 1993).

Stocker and Hand (1993) estimated mean F, for 1971-91, by multiplication (qE), where q was estimated, for two arbitrary values of M (0.45,0.55), by the Paloheimo (1980) method, and E was the mean annual nominal effort during 1971-91. Their estimates (1.13,1.03) appear to be anomalous which may be due to the method of estimating q.

Estimates of the mean exploitation rate were: 0.27 and 0.32 (VPA); 0.31 and 0.35 (AF/Z); and 0.40 and 0.45 (CA) (Stocker and Hand 1993).

Puget Sound and Vicinity (Area 4A)

The first report of mortality rates was that of Karp (1982), for cod spawning near Port Townsend, Washington, (opposite MSA 19) in Juan de Fuca Strait. He estimated Z = 1.5-1.7; and M = 0.7-0.8; and F = 0.7-1.0 (Table 7.2.6). Two methods were employed to estimate Z, both based on tagging data: (1) regression (Beverton and Holt 1956, as modified by Paulik 1963), Z = 1.63 and 1.71; and (2) maximum likelihood, developed for catch curve analysis by Robson and Chapman (1961), and modified for tagging data analysis by Paulik (op. cit.) and Ricker (1975), Z = 1.45 and 1.65. M (= 0.7-0.8) was estimated by the method of Alverson and Carney (1975). Thus, by subtraction, F = 0.7-1.0.

Palsson (1990) employed the L-F/vB method (Table 7.2.1) to 5-y mean length-frequencies, from landings during 1970-89, to estimate Z for the three designated stocks in Area 4A. The results were 1.35-1.85 for the North stock, 1.45-1.79 for the West stock, and 1.01 for the South stock (Table 7.2.6).

Exploitation rate for the spawning stock near Port Townsend, Washington, was estimated to be 0.10-0.11, based on the AF/Z method (Karp 1982).

Alaska

Gulf of Alaska. Past estimates of Z, M, and F were deemed unsatisfactory, according to the latest published stock assessment report (Zenger and Thompson 1989). The authors used mortality rates (and other parameters) of cod in the eastern Bering Sea. They remarked that parameters specific to cod in the Gulf of Alaska "will be estimated as age-at-length data become available" (op. cit., p. 66). Zenger and Thompson (MS 1993)[1] provided estimates of F by Stock Reduction Analysis (SRA) of Kimura (1985) and the length-based Synthesis method (LBSM) of Methot (1990). For both analyses, age compositions were derived from length-at-age data from the 1990 and 1992 domestic fisheries, and length-frequencies from catches of commercial and research vessels. During 1978-92, SRA estimates of F ranged from 0.02 to 0.21--0.17-0.22 during 1990-92 (Table 7.2.6). LBSM estimates were similar--0.05-0.22 during 1978-89, and 0.19-0.30 during 1990-92.

M was estimated in the SRA by the wet gonad-somatic index (WGSI), for female cod, of Gunderson and Dygert (1988)--M = 0.27 (Table 7.2.6). The authors noted that the estimate seemed low, based on the shape of the length-frequencies. In the LBSM, the LBSM-based estimate for the easterm Bering Sea was used--M = 0.35. The WGSI estimate for M was 0.27, based on the WSGI (0.141) of female cod collected in the Aleutian Islands during February 1982.

Z was estimated by addition (M + F). Estimates ranged from 0.29 to 0.48 by SRA, and 0.38 to 0.57 by the LBSM (Table 7.2.6).

Estimated mean exploitation rate, based on the catch/biomass method, was 1.7% during 1973-78, and 9.0% (4.4-18.7%) during 1981-90 (Table 7.2.7). Peak value occurred in 1990. Exploitable biomass was estimated by resource assessment trawl survey. Zenger and Thompson (MS 1993) provided annual estimates, based on SRA, of U' (numbers caught/stock size in January) for 1978-93 which increased from 2% in 1978 to 21% in 1991; then declined to 18% in 1992.

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[1] Zenger, H. H. and G. G. Thompson. MS 1993. Pacific cod. In: Plan Team for the Groundfish Fisheries of the Gulf of Alaska [ed.]. Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 1994. Chapt. 2. North Pacific Fishery Management Council; P.O. Box 103136; Anchorage, AK, 99510; U.S.A.

Eastern Bering Sea. Only two estimates of F were found--0.16 (1973-85) and 0.03-0.31 (1978-92) (Table 7.2.6). The latter estimates were from the LBSM, with length-frequency progressions providing estimates of length-at-age (Thompson and Methot MS 1993)[2].

Estimates of M ranged from 0.22 to 0.70 (Table 7.2.6). Low (1974) estimated M to be 0.7 before, and 0.5 after, maturity. Thompson and Methot (MS 1993) reported that their current LBSM was configured "to estimate M by constraining the commercial selectivities to remain approximately asymptotic, as they had shown to be previously" (op. cit., p. 2-5). The value of M which maximized total likelihood was 0.35.

Z was estimated by addition (M + F). Estimates were 0.60 for 1973-85, and 0.38-0.66 (LBSM) for 1978-93 (Table 7.2.6).

Estimated mean exploitation rate, during 1978-92, based on the catch/biomass method, was 12.6% (4.3-31.3%)--23.0% in 1992 (Table 7.2.8). Peak year was 1991. Total biomass was estimated by resource assessment trawl survey.

Aleutian Islands. No estimates of Z, M, or F were reported, but there were four estimates of exploitation rate, all based on the catch/biomass method. These were 7.6% (1980), 8.8% (1983), 7.1% (1986), and 4.7% (1991), with a mean of 7.0% (Table 7.2.8). Total biomass was estimated by resource assessment trawl survey.

ATLANTIC COD

Northeast Atlantic

Estimates of mortality rates, by stock, time, and source, are listed in Table 7.2.9. No estimates of exploitation rates were found.

Recent estimates of Z for major stocks were derived by adding "accepted" estimates of M to those of F, if direct estimates were not reported. Through 1991, maximum Z values ranged from 1.35 (0.33 + 1.02; Arcto-Norwegian) to 1.67 (East Baltic). Substantial temporal increases in Z were reported for the Baltic Sea, North Sea, and Iceland stocks. For example, Z estimates for the East Baltic stock increased from 0.35 during 1919-21 to 1.67 during 1968-71, and were 0.73-1.36 during 1970-91.

Estimates of M, for fully recruited cod, generally varied narrowly around 0.2 or 0.3, in sharp contrast to the higher estimates (0.59-0.69) reported for Pacific cod stocks in British Columbia waters (Table 7.2.2). Notable exception was the estimate of 0.40 for the East Baltic stock (IIId), for 1919-68. This estimate may not be unreasonable, since the Baltic Sea stocks are characterized by few age-classes and rapid growth, as are the Pacific cod stocks in British Columbia waters. Furthermore, pollution is a serious problem in the Baltic Sea. However, Sparholt (1990) cited two smaller, unpublished estimates--0.17 and 0.19 for 1965-77, and 0.12-0.18 for 1973-85, and Bagge et al. (1993) reported 0.2. Svasand and Kristiansen (1990) estimated M = 0.22 for fully recruited, reared, wild cod (>30 cm; age =>2) in a nearly enclosed fjord in southwestern Norway (see Section 6.4 for details). Their estimate of

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[2] Thompson, G.G. and R.D. Methot. MS 1993. Pacific cod. In: Plan Team for the Groundfish Fisheries of the Bering Sea and Aleutian Islands [ed.]. Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions as projected for 1994. Chapt. 2. North Pacific Fishery Management Council; P.O. Box 103136; Anchorage, AK, 99510; U.S.A.

pre-recruitment Z (largely M) was 1.57. They noted that similar results were obtained for North Sea cod, and cited the unpublished 1988 report of the North Sea Roundfish Working Group, whose estimates of M, by age, were: 0-group, 2.7; 1-group, 0.8; 2-group, 0.35; 3-group, 0.25; and 4-group and older, 0.2.

Maximum estimates of F for the major stocks ranged from 1.0 (Iceland) to 1.16 (East Baltic). Svasand and Kristensen (1990) estimated F = 0.61 for cod in the aforementioned fjord in southwest Norway.

Northwest Atlantic

Estimates of mortality rates, by stock, time, and source, are listed in Table 7.2.10. Recent assessments have estimated U rather than F (CAFSAC 1992).

Maximum estimates of F were 1.4 for the 2J3KL stock, 1.05 for West Greenland (SA 1), and 1.31 (3NO) among the remaining six stocks. After 1990, CAFSAC began estimating exploitation rate (U) in lieu of F. No estimates of F for the West Greenland stock were reported after 1989 due to the substantial emigration of mature cod to Iceland.

Estimates of M generally ranged narrowly around 0.2, for the period 1959-76. Two divergent estimates were 0.1 and 0.35, for cod in NAFO Division 4RS.

Estimates of Z were derived in the same manner as for the northeast Atlantic. Maximum estimates for the two major stocks were >1.6 (>0.2 + 1.4) for Labrador-East Newfoundland, and 1.25 (0.2 + 1.05) for West Greenland. For the other stocks, maximum estimates ranged from 0.99 (5Z6) to 1.51 (0.2 + 1.31; 3NO).

Estimates of exploitation rate for the 2J3KL stock ranged from ca. 0.2 to ca. 0.6, during 1962-90 (CAFSAC 1992, text figure, p. 3). In 1991, estimates were ca. 0.45, based on ADAPT, and ca. 0.68, based on the Laurec-Shepherd method--both tuned VPAs (see Section 7.3). For the other Canadian stocks, maximum range was ca. 0.18 to ca. 0.66, for the 4VsW stock. No reports of exploitation rate were found for the West Greenland stock, or for stocks in the U.S. EEZ.

SUMMARY

Pacific Cod

For the northwest Pacific, no reports on mortality or exploitation rates were found.

For the northeast Pacific, methods of estimating mortality and exploitation rates varied among and within regions. Z was usually estimated from age-frequencies or tagging results; M from regression (Z on effort); and F by subtraction (Z - M) or multiplication (qE). F-at-age and U-at-age were estimated by virtual population analysis (VPA). Estimates of exploitation rate were derived from catch/biomass ratios or mortality rates (AF/Z). Biomass was estimated from trawl surveys or VPA. All estimates based on age readings were subject to question, because no validated method of age determination has been reported for Pacific cod (see Section 5.3, Age Determination).

British Columbia. "Best" estimates of mortality rates were not reported for Area 4B, but the latest estimates, among the four stocks, were: Z = 1.03-1.63; M = 0.59; and F = 0.44-0.75. Estimates were higher for the two itinerant stocks than for the two resident stocks. "Best" estimates among the offshore regions were: Z = 1.11-1.27; M = 0.58-0.69; and F = 0.50-0.62. Of some interest was the apparent reciprocal relationship of M and F in Queen Charlotte Sound, with little temporal variation in Z. Distributions of F-at-age and U-at-age were usually dome-shaped, and often skewed left. "Best" estimates of mean exploitation rate among offshore regions were 0.13-0.45. No estimates were found for Area 4B.

Washington State. Mortality-rate estimates for Port Townsend were Z = 1.45-1.79, and M = 0.7-0.8, hence F = 0.7-1.0. For Puget Sound and vicinity (4A), estimates, among stocks, were Z = 1.01-1.85. Estimated exploitation rate for the Port Townsend stock was 0.10-0.11.

Gulf of Alaska. SRA-based estimates of F, during 1978-93, exhibited an increasing temporal trend--0.02-0.09 during 1978-89; 0.16-0.22 during 1990-93. WGSI-based estimate of M was 0.27. Thus the range of Z was 0.29-0.49. Estimated mean exploitation rate, based on the catch/biomass method, during 1981-90 was 8.9% (4.4-18.2%), and the 1990 estimate was the largest.

Eastern Bering Sea. LBMS-based estimates of F, during 1978-93, exhibited an increasing temporal trend--0.02-0.09 during 1978-89; 0.19-0.30 during 1990-93. Estimates of M ranged from 0.2 to 0.7. The recent LBSM-based estimate was 0.37. Thus, the range of Z was 0.39-0.67. Estimated mean exploitation rate, based on the catch/biomass method, during 1979-92 was 12.2% (4.5-39.0%). Peak year was 1991, the 1992 estimate was 29.6%.

Aleutian Islands. No estimates were found for Z, M, or F. The four estimates, based on the catch/biomass method, of the exploitation rate ranged from 4.7% (1991) to 8.8% (1983), and the mean was 7.5%.

Atlantic Cod

Northeast Atlantic. Recent estimates of Z for major stocks were derived by adding "accepted" estimates of M to those of F, if direct estimates were not reported. Through 1991, maximum Z values ranged, among stocks, from 1.35 (Arcto-Norwegian) to 1.67 (East Baltic). Substantial increases in Z were reported for the Baltic Sea, North Sea, and Iceland stocks. Estimates of M for fully recruited cod generally varied narrowly around 0.2 or 0.3. Notable exception was the estimate of 0.40, during 1919-68, for the East Baltic stock (IIId). Maximum estimates of F ranged from 1.0 (Iceland) to 1.16 (East Baltic).

Northwest Atlantic. Estimates of Z were derived in the same manner as for the northeast Atlantic. Maximum estimates were >1,6 for the Labrador-East Newfoundland (2J3KL) stock, 1.25 for the West Greenland (SA 1) stock, and 1.51 (3NO) for the other six stocks. Maximum estimates of F were 1.4 for the 2J3KL stock, 1.05 for the SA 1 stock, and 1.31 (3NO), among the remaining six stocks. Recently, estimates of exploitation rate (U) replaced those for F. Estimates of U, for the 2J3KL stock, ranged from ~0.2-~0.6 during 1962-90. Maximum range for other Canadian stocks was ~0.18-~0.66 (4VsW). No estimates of U were found for the West Greenland stock or those off the United States. Estimates of M generally ranged narrowly around 0.2.

7.3. STOCK ASSESSMENT

7.3.1. PACIFIC COD

INTRODUCTION

Published stock assessment reports were found for cod in the northeast Pacific Ocean (British Columbia, Washington State, and Alaska), but not in the northwest Pacific.

7.3.1.1. British Columbia

Materials and Methods

Basic data available for analysis were landing statistics (catch, effort, CPUE), length-frequency samples from landings, and age-frequencies based on scale readings or length-frequencies. Trawl captains were interviewed, when they landed their catches, as to species caught, location and depth of catches, and trawling hours expended. These "interviewed" landing records were used to compute CPUE and total effort, and usually comprised at least 70% of the total weight of important groundfish species landed each year.

The fishing "year" has varied among areas and investigators. In Area 4B, it was October-September in all reports published prior to 1988. The three reasons for this arrangement were: (1) Area 4B provided relatively sheltered waters during autumn-winter for the smaller trawlers which could not cope with the heavy seas on the offshore grounds; (2) catch rates were seasonally higher, because cod and other species were more congregated prior to and during spawning; and (3) numerous regulations inhibited trawling during April-September. Forrester and Ketchen (1963) and Westrheim (1980a) provided chronologies and descriptions of these regulations. Reports published after 1987 used January-December as the fishing year, but retained October-March as the source of CPUE data, for the year containing January-March. For Areas 3Cn+3D, 5A+5B, and 5C+5D, the fishing year was January-December, until Westrheim and Foucher (1985a) changed it to April-March, because recruitment of each year-class generally began in April, at age 2, and concluded the following January-March, at age 3, when most members spawned for the first time. Foucher and Tyler (1988) returned to the January-December fishing year. Their reasons for changing were: "1) calling all fish of a year-class caught in a calendar year the same age follows the adopted convention of a January 1 birthday for all fish aged at the Pacific Biological Station (Chilton and Beamish 1982); 2) cod may be recruiting earlier now than in the past. In the port samples taken from White Rocks during January-March 1987, 32% of the fish were 50 cm or less in length. The majority of these were likely age 2. This is biased by the strong 1985 year-class, however, the willingness of fish plants to take fish as small as 40 cm has been demonstrated; and (3) the bookkeeping for biological studies is greatly simplified. With either method, fish caught in January-March are attributed to the same year-class so differences in virtual population analysis (VPA) results will be minimal. Abundance estimated from LPUE (sic) uses data from April-September only, and so is not affected by the change." (op. cit., p. 46) The term LPUE (landings per unit effort) has been replaced, at the Pacific Biological Station, with CPUE (= nominal catch per unit nominal or standardized effort). The January-December year has been retained through the 1992 assessment.

Procedures for analyzing catch statistics have gradually become more sophisticated for the generally cod-dominated, mixed-species, trawl fisheries on the continental shelf off British Columbia. Time-space restraints, improved method of effort allocation, and effort standardization were developed, hopefully to improve the quality of CPUE as a relative index of abundance. However, all of these were modified or abandoned in the assessment for 1992 (see Recent Procedures, below).

Time-space restraints. These were designed to focus analysis on representative area-time cells for each region. For Area 4B, area restraints varied--nil (Ketchen 1967); major grounds (Forrester and Ketchen 1963); four important stocks (Westrheim and Foucher 1987a). All analyses used October-March, or January-March, as the time for calculating CPUE.

For the offshore grounds (3Cn-D, 5A-D), area-time restraints were initiated by Foucher and Westrheim (1984). They established four criteria for selecting representative area-time cells, as follows: "(1) account for a substantial proportion of the annual landings; (2) these should be distributed throughout the study period; (3) its LPUEs should reflect fluctuations in landings from its major area; and (4) no regulations should be in effect which affect quantities landed" (op. cit., p. 2). The representative "areas" in each region were: Big Bank (3Cn+3D); 5A (south Queen Charlotte Sound); 5B (north Queen Charlotte Sound); Horseshoe Ground (5C); and Two Peaks Ground (5D). April-September was selected as the representative time for all areas. January-March was rejected because of regulations affecting catches (3Cn), small catches (5A+5B; 4% of annual catch), and CPUEs unresponsive to fluctuations in catch (5C+5D). October-December was rejected because of small catches in all areas (4-10% of annual catch), primarily due to decreasing market demand.

Effort allocation. Initially, effort was determined, for all regions, by the conventional qualification method, which allocates all effort to those species which comprise at least a pre-determined percentage of the mixed-species landing. Ketchen (1964b) demonstrated the weakness of this system, at least for secondary species in the landings. For the offshore fisheries, the Option-2 method was developed to better cope with mixed-species catches (Westrheim 1983). Briefly, for each representative area-time cell, each species is allotted the all-species effort expended in the depth intervals containing the rank-1 (most) and rank-2 (next most) weight landed of that species. The author listed three advantages of the Option-2 method: (1) effort allotment is appropriate to all species which were equally available to the fishing gear; (2) estimates of effort, but not CPUE, are independent of intermittent market quotas imposed by processors on one or more of the available species; and (3) bathymetric arrays of effort and catch expand the conception of fishing activities, and may provide new insights into stock dynamics.

Effort standardization. This involved determining the relationship between CPUE and various attributes of vessel classes. The itinerant behaviour of Canadian trawlers precluded dealing with individual vessels. Ketchen and Thomson (1958) initiated effort-standardization studies for the British Columbia trawl fishery, and calculated relative fishing power (RFP) for trawlers landing all-species groundfish during 1955-57. Subsequently, four studies were undertaken which dealt primarily with Pacific cod, and were used in stock assessments.

Ketchen (1967) standardized CPUEs to Class 3 and 4 trawlers (25-49 and 50-74 gross registered tons (GRT)) equipped with double gear (two trawl warps), prior to assessing, for 1954-66, cod stocks in areas 4B, 3C+3D, 5A+5B, and 5C+5D. No details of the computations, or RFP values of individual vessel classes, were published.

Ketchen (1979) standardized CPUEs of all-species landings, exclusive of walleye pollock and spiny dogfish, for human consumption in Area 4B during 1954-78. RFP values were calculated for six tonnage classes (<15, 15-24, ..., 75-99, >99) and two gear types, single and "double" (double and double + net drum). Class 3 (25-49 t)-double-gear vessels were selected as the standard. The two predominant vessel types were Class 3-"double" (3d) and Class 3-single (3s),

and the 3d/3s ratio was 1.40.

Westrheim and Foucher (1985b) dealt with species groups (Pacific cod + its important shelf co-habitants) landed for human consumption from four offshore areas (3Cn, 5A+5B, 5C, and 5D), during April-September 1960-81. Nominal effort was calculated using the Option-2 method (Westrheim 1983). Twelve variables were considered, but only one (horsepower) was selected. Most were rejected because of incomplete or unavailable data. Tonnage classes were abandoned, because horsepower increased within tonnage classes during the study period. Gear type was abandoned, because one type predominated (double + net drum). Ten horsepower classes (<100, 100-199, ..., 800-899, >899) were created, and a linear relationship was demonstrated between nominal CPUE and horsepower class in each area. Horsepower-class 4 (300-399 hp) was selected as the standard for all four areas. RFP values varied among regions--0.23-0.63 for Hp-class 1 (<100 hp), and 1.74-2.53 for Hp-class 10 (>899 hp).

Westrheim and Foucher (1985c) standardized CPUEs of Canadian trawlers landing Pacific cod from Georgia and Juan de Fuca straits (MSAs 14 and 17-20) during October-March, 1954-84. They used the same 10 horsepower classes created in their previous study (Westrheim and Foucher 1985b), together with three gear types (1 = single; 2 = double; 3 = double + net drum). Nominal effort for cod was calculated at the 40% qualification level, which was determined empirically to retain the most data on cod while retaining the least data on Pacific hake and spiny dogfish. The Option-2 method was deemed inappropriate, because Pacific cod dominated the landings, the individual grounds were small and poorly delineated, and the relatively low percentage interview coverage in some important MSAs. For Gear-type 3, a linear relationship was demonstrated between nominal CPUE and horsepower class for the combined data from the five MSAs. CPUE was standardized with respect to Hp-class 2 (100-199) and Gear-type 3 (double + drum). Single- and double-gear types were minor components after 1960-64. RFP values ranged from 0.64 for Hp-class 1 to 2.25 for Hp-class 10. The authors noted that RFP values for Gear-class 3 vessels in Area 4B were similar, among horsepower classes, to those for vessels on the offshore grounds, if they were calibrated to Hp-class 3.

In all four studies, the authors stressed that their standardizations underestimated the upward trend in vessel efficiency, because of unquantifiable, but important, factors such as vessel captain, and the steady improvement in fish-finding and navigation equipment. Of particular importance were the introductions of LORAN C in the 1970s, and the LORAN C plotter in the 1980s.

Recent procedures. Substantial changes were introduced in the assessment for 1992 with respect to effort allocation, effort standardization, and CPUE (Stocker and Hand 1993). These were noted as interim measures until further analyses could be completed.

Time-space restraints for Area 4B, were the same as those initiated in the 1986 assessment (Foucher and Tyler 1988)--calendar-year catches and October-March CPUE. For the offshore regions, catches were also for the calendar year, and all grounds. CPUE was based on Canadian data: April-December for Areas 3Cn+3D; April-September for 5A+5B; and January-December for 5C+5D (C.M. Hand, pers. comm.). January-March data for Area 3Cn+3D were not used, because of intermittent regulations limiting the catch, and the potential influence of aggregations of spawning cod on the catch rate. October-March data for Area 5A+5B were not used, because inclement weather, and the lack of safe harbors nearby, inhibited trawling.

Effort allocation was changed from the Option-2 method to qualification levels, because the traditional CPUE did not reflect abundance well when the annual catch was small. In the case of 3Cn+3D, during 1981-87, 41% of the trip records failed the 10% qualification test (12% during 1973-80). Also, CPUE increased substantially without any other evidence of an increase in abundance. The qualification levels selected were 10% for 3Cn+3D, and 25% for 5A+5B and 5C+5D. For 5A+5B, an additional qualification was a minimum landing of 1,000 lb (454 kg) (C.M Hand, pers. comm.).

Effort standardization was abandoned, because scatter plots of log CPUE of cod against horsepower showed no strong relationship for the data from 3C+3D (1954-91) or 5C+5D (1961-91) (Stocker and Hand (1993, Fig. 3.2). The extreme scatter, and lack of a strong relationship, is difficult to explain since the authors provided no information on what data were used. The phenomenon might have been due, in part, to the limited temporal and spatial restraints applied to the data.

CPUE was defined as the qualified median, among C_i/E_i values. Median CPUE was shown to fall within the 95% confidence interval of the maximum likelihood estimate from the bivariate model recommended by Richards and Schnute (1992) for rockfish.

Stocks Assessed

In Area 4B, the number of stocks assessed varied from one (all 4B) to four--MSAs 14, 17n (Nanoose Bay), 17s (N. Gulf Islands) + 18 (S. Gulf Islands), and 19. Elsewhere, stocks, if more than one, were combined, for management purposes, in each of the important offshore regions.

During 1963-92, 22 reports were published which dealt with stock assessment of Pacific cod in one or more of the four important regions of British Columbia--Georgia Strait and vicinity (4B); west Vancouver Island (3Cn+3D), Queen Charlotte Sound (5A+5B), and Hecate Strait (5C+5D) (Table 7.3.1.1).

GEORGIA STRAIT AND VICINITY (4B)

Catch Records

During 1950-91, nominal catches ranged from 297 to 1,742 t/y, without evident trend (Fig. 6.2.4). Subsequently, annual catch declined sharply from 602 t in 1989 to 114 t in 1990, and 68 t in 1991. Foreign vessels have always been prohibited from fishing in Area 4B.

Stock Assessment

Seventeen reports were published, but only three involved analyses other than trends in catch statistics (Table 7.3.1.1). Those were mean length of landed cod, yield-per-recruit (YPR), and "catch profitablity" (YPR'/F).

Catch statistics. For Area 4B as a whole, during 1955-91, catch, effort, and CPUE generally fluctuated without trend, except for a precipitous decline after 1988 (Fig. 7.3.1.1). Mean annual catch was 749 t, and the range was 68 (1991) to 1,742 (1981) t (Table 7.3.1.2). Corresponding values for effort were 4,349 h--481 (1991) to 7,529 (1964) h; and for CPUE, 174 kg/h--88 (1968) to 304 (1979) kg/h. The 1991 values were 68 t, 481 h, and 141 kg/h, all below average. Recent estimates of CPUE probably represent cod abundance only in MSAs 19 and 20. While these two MSAs accounted for 34% of the cod landings from Area 4B during 1945-84 (Table 6.2.5), they accounted for 69% (56-82%/y) during 1985-91 (Leaman 1986; Leaman and Stanley 1987; Rutherford 1988, 1990, 1991a,b, 1993). MSA 19 has contributed a substantial portion of the total catch since 1975, and MSA 20 since 1978. The 1992 assessment attributed the substantial decline in catch and effort after 1988 to economic conditions, and the retirement of many of the original fishermen, who operated the smaller trawlers. However, the landings from MSAs 19+20 declined from 996 t in 1988 to 46 t in 1991; then rose to 221 t in 1992 (C.M Hand, pers. comm.), which suggests that another factor was

the variable immigration into these MSAs from offshore grounds (probably Area 3Cn; see Section 7.1 Stock Delineation).

Catch records, during 1954-84, for the four stocks delineated by Westrheim and Foucher (1987a) revealed a more complex situation. The authors reported that the two resident stocks (MSAs 14 and 17s+18) exhibited near-synchronous fluctuations, without trend, during 1954-79, and a sharp decline during 1980-84. Catch from the itinerant Nanoose (MSA 17n) stock declined steadily after 1971, and by 1984 the catch was negligible. The itinerant MSA 19 stock was of negligible importance until 1974, but was a significant component thereafter. It too suffered a sharp decline after 1980.

All analyses based on catch statistics concluded that there was no evidence of overfishing.

Mean lengths. Little relationship was evident between mean lengths and CPUE for cod landed from Area 4B as a whole, during 1953-66 (Ketchen 1967).

Yield-per-recruit (YPR). YPR analyses were utilized by Forrester and Ketchen (1963) and Westrheim and Foucher (1987a). The former employed growth and mortality rates from Ketchen (1961), and concluded that a decrease in age at recruitment from 2.5 to 2.0 y would increase yield substantially. Furthermore, monetary return would be maximal at recruitment age of 2.0, if M = 1.2, and F = 0.5-0.6. The latter suggested that achievement of maximum yield required excessive values of F (1.23) and mesh size (=> 165 mm), if M = 0.4 or 0.6, and the minimum commercial size (MCS) was 41 or 46 cm.

Catch-profitablity. Maximum "catch-profitability" indices (YPR'/F), based on maximum YPR values with respect to mesh size, were maximal at "practical" mesh sizes (102-114 mm) (Westrheim and Foucher 1987a). MCS of 41 cm was superior to 46 cm.

Summary. Westrheim and Foucher (1987a) concluded that the fishery had not adversely affected any of the four stocks, except possibly the MSA-14 stock during 1954-60. The uninterrupted decline of the Nanoose stock after 1971 was attributed to diversion of cod elsewhere, based on reciprocal catch histories with adjacent areas. Cause of the diversion was not determined. The sharp decline in abundance during 1980-84 of all stocks was also noted for British Columbia stocks elsewhere, and was attributed to natural factors. The sudden rise in cod catches in MSA 19 was attributed to cod being attracted there by the anomalous behaviour of herring enroute to spawning grounds in Area 4B (Westrheim and Pedersen 1986).

The differential exploitation history of the four stocks should preclude considering cod in area 4B as a unit stock, if the fishery returns to its former magnitude. Recently, the Georgia Strait cod fishery has received little attention, with respect to research or management, because of its relatively declining size.

WEST VANCOUVER ISLAND (3Cn+3D)

Catch Records

During 1950-91, nominal catches ranged from 420 (1961) to 5,629 (1972) t/y, without evident trend (Fig. 6.2.4). U.S. trawl catches generally predominated during 1950-65, but ceased after 1979. In 1977, Canada promulgated its 200-mile EEZ, and excluded all foreign fisheries after March 1977, except U.S. vessels fishing for selected rockfish species, during April 1979-April 1981.

Stock Assessment

Fourteen reports were published, and 10 of these utilized analyses other than trends in catch statistics (Table 7.3.1.1). They included mean lengths of landed cod, virtual population analysis (VPA), and yield-per-recruit (YPR). VPA provided estimates of recruitment, fishing mortality (F-at-age), and exploitation rate (U-at-age).

Catch statistics. During 1956-91, catch, effort, and CPUE generally fluctuated without trend, although since 1972, CPUE has gradually declined (Fig. 7.3.1.2). Mean annual catch was 1,852 t, and the range was 420 (1961) to 5,629 (1972) t (Table 7.3.1.2). Corresponding values for equivalent effort (catch/CPUE) were 10,154 h, and 2,432 (1985) to 23,277 (1976) h; and for CPUE, 178 kg/h, and 89 (1960) to 310 (1972) kg/h. The 1991 values were 2,188 t, 21,239 h, and 103 kg/h. Catch and effort were above average, but CPUE was below. All analyses based on catch statistics concluded that there was no evidence of overfishing.

In Ketchen (1980), concern was expressed over the new, intensive winter fishery on Amphitrite Bank (Fig. 5.1.4) for prespawning and spawning cod. This relatively small bank (ca. 220 km^2; Luternauer et al. 1986) is the principal spawning ground for cod in the region. Only limited portions (ca. 10-20%) of the bank contain "clean" substrate, on which cod were observed to congregate, presumably for spawning. The fishery had evolved temporally from spring (1960-64) on feeding cod to winter (1972-date) on spawning cod. Furthermore, improved navigation aids, and larger trawlers, led to a change in the winter fishery from interception on the bank's periphery, of cod moving on and off the bank, to "spot" trawling on shoals of spawning cod on the bank itself. Recruitment overfishing was considered to be possible, at least during periods of low stock abundance. Despite the lack of substantive proof of recruitment overfishing, restrictions were imposed on this fishery during winters when the stock was deemed to be at a low level of abundance, based on CPUE for the preceding April-September. Table 7.3.1.3 lists the restrictions imposed on the winter fishery in Area 3Cn during 1978-89. The fishery was not restricted during 1990-92 (C.M. Hand, pers. comm.).

Mean lengths. Ketchen (1967) noted that mean lengths of cod landed in British Columbia from Areas 3C+3D varied inversely with standardized Canadian CPUE, during 1954-66. The inverse relationship was explained as the passage of strong year-classes through the fishery. That is, small (young) fish/high abundance, and large (old) fish/low abundance. The author concluded that the fluctuations in abundance were not caused by the fishery, and that there was no evidence of overfishing, during the study period.

Recruitment. For 1956-90, VPA-based estimates of annual recruitment at age 2 ranged, without trend, from 0.8 million cod in 1982 to 9.1 million in 1971 (Table 7.3.1.4). The mean was 2.7 million; the coefficient of variation (CV) was 61%; and the 1990 estimate was 1.3 million. Prominent year-classes (>1 S.D. above the mean) were 1962-63 (4.9 & 4.4 million), 1967-73 (4.6-9.1) and 1984-85 (5.1 & 7.7). Recruitment at age 3 ranged, without trend, from 0.3 million in 1983 to 4.0 million in 1972. The mean was 1.7 million (CV = 59%), and the 1990 estimate was 0.5 million. Prominent year-classes (>1 S.D. above the mean) were 1968-72 (3.0-4.0 million) and 1985 (3.6).

The interim report for 1992 did not include a VPA, but did include CPUEs (N/h) at age, for 1956-91 (Stocker and Hand 1993, Table 3.2). CPUEs at age-2 ranged, without trend, from 0.6 cod/h (1960) to 73.8 cod/h (1971). The mean was 20.0 cod/h (CV = 53%), and the 1991 value was 4.3 cod/h. Prominent year-classes (>1 S.D. above the mean) were 1960-61 (38.7 & 50.8 cod/h), 1969-70 (73.8 & 67.8), 1972 (36.5), 1977 (33.1), 1981 (36.2), and 1987 (66.2). CPUEs at age-3 ranged, without trend, from 6.6 (1987) to 71.8 (1985) cod/h. Mean CPUE was 30.7 cod/h (CV = 62%), and the 1991 estimate was 12.7 cod/h. Prominent year-classes (>1 S.D. above the mean) were 1955 (55.1), 1963 (53.4), 1968-69 (50.5 & 51.9), 1972 (53.3), 1978 (59.3), and 1982 (71.8). The authors noted that length-frequencies indicated above-average abundance for the 1989 year-class, but this was not corroborated by the CPUE at age 2 in 1991 (4.3 cod/h).

Fishing mortality (F). Distribution of mean annual F-at-age was dome-shaped, but skewed (Table 7.3.1.5). For 1956-90, values rose from 0.08 at age 2 to a peak of 0.72 at age 6, then declined to 0.50 at age 7.

Exploitation rate (U). Annual estimates of U (ages 3-7) during April-March 1961-79 ranged from 0.10 (1963) to 0.43 (1966), and generally increased after the inception of the winter fishery (Westrheim and Foucher 1985a, Table 3.3.9). Distributions of U-at-age were generally dome-shaped, but skewed (Table 7.3.1.5). For the 1956-89 array, U rose from 0.05 at age 2 to a peak of 0.34 at age 6, then declined to 0.28 at age 7.

Yield-per-recruit (YPR). YPR analyses began with the 1954-85 data (Westrheim and Foucher 1987b). The authors reported that growth overfishing would occur with "current parameters". No data were provided, but parameters and results were reported to be similar to those for Hecate Strait. For the 1954-86 data, results indicated little variation in yield beyond F = 0.6 ($F_{current}$ = 0.5), but with rapidly decreasing yield as F decreased, if mean mesh size = 135 mm, and M = 0.7 (Foucher and Tyler 1988). YPR analysis of the 1954-87 data involved a minimum commercial size (MCS = 41 cm), mean mesh size = 135 mm, and M = 0.6, 0.7, and 0.8. Optimal F = 0.6, if M = 0.6 or 0.7, but ca. 1.5, if M = 0.8. Subsequent analyses yielded no new information.

Summary. All assessments concluded that the stock was not overfished. Possibly the winter closures may have prevented recruitment overfishing. The 1992 assessment expressed concern over the 1972-91 decline of CPUE, and noted that further decline would warrant resumption of restrictions on the winter fishery.

QUEEN CHARLOTTE SOUND (5A+5B)

Catch Records

During 1950-91, nominal catches ranged from 240 (1961) to 3,242 (1987) t/y, without evident trend (Fig. 6.2.4). U.S. trawl catches generally predominated during 1950-74, but ceased after 1979, due to the aforentioned restrictions, and eventual exclusion from the Canadian EEZ.

Stock Assessment

Twelve reports were published, but only two utilized analyses other than trends in catch statistics (Table 7.3.1.1). These were mean lengths of landed cod and virtual population analysis, which provided estimates of recruitment, fishing mortality rates (F), and exploitation rates (U).

Catch statistics. During 1956-91, catch, effort, and CPUE fluctuated moderately, without apparent trend (Fig. 7.3.1.3). Mean annual catch was 1,303 t, and the range was 240 (1961) to 3,242 (1987) t (Table 7.3.1.2). Corresponding values for effort were 4,129 h, and 882 (1962) to 7,518 (1974) h; and for CPUE, 302 kg/h, and 137 (1969) to 560 (1957) kg/h. The 1991 values were 2,008 t, 7,016 h, and 286 kg/h. Catch and effort were above average, and CPUE was below. All analyses based on catch statistics concluded that there was no evidence of overfishing.

Mean lengths. For cod landed in British Columbia during 1954-66, mean lengths varied inversely with standardized Canadian CPUE (Ketchen 1967). The inverse relationship was explained as the passage of strong year-classes through the fishery. That is, small (young) fish/high abundance, and large (old) fish/low abundance. The author concluded that the fluctuations were not caused

by the fishery, and that there was no evidence of overfishing, during the study period.

Recruitment. For 1956-78, VPA-based estimates of annual recruitment at age 2 ranged, without trend, from 1.5 million cod in 1969 to 5.8 million in 1971 (Table 7.3.1.4). The mean was 3.6 million (CV = 36%), and the 1978 estimate was 1.8 million. Prominent year-classes (>1 S.D. above mean), at age 2, were 1962 (5.2 million), 1964 (5.0), 1966 (5.3), and 1969 (5.8). For 1957-79, recruitment at age 3 ranged, without trend, from 0.6 million in 1970 to 2.5 million in 1972. The mean was 1.5 million (CV = 37%), and the 1979 estimate was 0.7 million. Prominent year-classes (>1 S.D. above the mean) were 1960 (2.2 million), 1962 (2.2), 1966 (2.3), and 1969 (2.5).

The interim report for 1992 did not include a VPA, but did include CPUEs (N/h) at age, for 1956-91 (Stocker and Hand 1993, Table 3.3). CPUEs at age-2 ranged, without trend, from 4.9 (1960) to 262.4 (1987) cod/h. The mean was 58.4 cod/h (CV = 28%), and the 1991 value was 122.0 cod/h. Prominent year-classes (>1 S.D. above the mean) were 1955 (142.3 million), 1964 (85.2), 1970 (99.4), 1973-75 (86.1, 77.6, 102.6), 1977-78 (112.4, 85.8), 1985 (262.4), and 1989 (122.0). CPUEs at age-3, ranged, without trend, from 3.5 (1964) to 90.1 (1978) cod/h. Mean CPUE was 36.2 cod/h (CV = 135%), and the 1991 value was 26.6 cod/h. Only one prominent year-class was noted--1975 (90.1 cod/h).

Mortality rates. For 1956-83, the relatively low value of F (0.35) with respect to that of Z (1.13) (Table 7.2.2) was considered as evidence of underfishing by Westrheim and Foucher (1985a). Distribution of mean annual F-at-age, was bimodal--0.10 at age 2; peaks at age 4 (0.32) and 6 (0.42); and 0.35 at age 7 (Table 7.3.1.5).

Exploitation rate (U). During 1961-78, exploitation rate for age-classes 2-7, based on a constant-F VPA, ranged from 0.03 (1962, 1970) to 0.33 (1978), and exhibited an irregular upward trend (Westrheim and Foucher 1985a, Table 3.4.10). Similar results were obtained using a constant F (op. cit., Table 3.4.11).

Summary. All assessments concluded that fluctuations in cod abundance were independent of the fishery. Westrheim and Foucher (1985a) noted two ameliorating factors which precluded concern at that time. First, extensive echo-sounder and trawl surveys of Cook and Scott banks during 1982-83 revealed extensive areas of "untrawlable" ground which provided refuges for cod and its shelf co-habitants. Second, no winter fishery had developed in the region, in part due to inclement weather and the lack of nearby safe anchorages or harbours. Improvements in navigational aids have likely enabled trawlers to operate to some extent in the "refuges", but to date (1991) production has been minor during October-March (Rutherford 1993).

HECATE STRAIT (5C+5D)

Catch Records

During 1950-91, nominal catches ranged from 1,064 to 9,519 t/y, without evident trend (Fig. 6.2.4). U.S. trawl catches generally predominated during 1950-59, but ceased after 1968. The early departure of the U.S. fleet probably was due to their shift to the more productive Pacific ocean perch fishery developing in Queen Charlotte Sound and off west Vancouver Island.

Stock Assessment

Sixteen reports were published, through 1993, and 11 involved analyses other than trends in catch statistics (Table 7.3.1.1). "Others" were mean lengths of landed cod, recruitment, mortality rates, exploitation rates, yield-per-recruit, simulation analysis, graphical analysis, surplus production, and delay-difference. VPA and cohort analysis provided estimates of recruitment,

F-at-age, and U-at-age.

Catch statistics. During 1961-91, catch, effort, and CPUE fluctuated substantially, but without trend (Fig. 7.3.1.4). Mean annual catch was 4,088 t, and the range was 1,064 (1985) to 9,519 (1966) t (Table 7.3.1.2). Corresponding values for effort were 8,588 h, and 4,039 (1986) to 20,662 (1991) h; and for CPUE, 461 kg/h, and 256 (1985) to 905 (1987) kg/h. The 1991 values were 7,920 t, 20,662 h, and 383 kg/h. Catch and effort were above average, and CPUE was below. Analyses based on catch statistics concluded that there was no evidence of overfishing.

Mean lengths. For cod landed in British Columbia during 1954-66, means varied inversely with Canada-U.S. catches and standardized Canadian CPUE, for both Area 5C (April-June) and 5D (January-September), treated here as separate stocks (Ketchen 1967). The author noted that strong year-classes arose from low-abundance spawning stocks, and vice versa, and concluded that the fishery had no effect on the abundance of either cod stock, during the study period.

Recruitment. For 1961-90, VPA-based estimates of annual recruitment at age 2 ranged, without trend, from 2.1 million in 1989 to 15.9 million in 1964 (Table 7.3.1.4). Mean was 6.2 million (CV = 52%), and the 1990 estimate was 5.2 million. Prominent year-classes (>1 S.D. above the mean) were 1960-62 (9.8,11.4 & 15.9 million) and 1985 (13.2 million). For age-3 cod, annual recruitment ranged, without trend, from 0.9 million in 1990 to 7.7 million in 1965. Mean was 3.0 million (CV = 52%), and the 1990 estimate was 0.9 million. Prominent year-classes (>1 S.D. above the mean) were 1960-62 (5.2,5.8 & 7.7 million) and 1985 (4.9).

The 1992 interim report included VPA-based estimates of numbers caught, and numbers in the population (based on M = 0.45 and 0.55), for 1971-91 (Stocker and Hand 1993, Tables 3.5-3.7). At M = 0.45, estimated numbers of age-2 cod in the population ranged from 2.3 million (1985) to 13.6 million (1987). The 1991 estimate was 5.3 million. For age-3 cod, the range was 0.9 (1971) to 6.4 (1987) million. The 1991 estimate was 1.3 million. At M = 0.55, estimated numbers of age-2 cod were 2.3 (1990) to 16.0 (1987) million, and for age-3 cod, 0.9 (1971) to 3.3 (1988) million. The 1991 estimates were 2.7 and 1.0, respectively. Neither set of data exhibited any trend.

The 1992 interim report also included CPUEs at age for 1961-91 (Stocker and Hand 1993, Table 3.4). CPUEs at age-2, ranged, without trend, from 5.8 (1978) to 346.6 (1987) cod/h. The mean was 65.9 cod/h (CV = 108%), and the 1991 value was 66.0 cod/h. CPUEs at age-3 ranged, without trend, from 13.9 (1971) to 179.6 (1965) cod/h. The mean was 77.2 cod/h (CV = 60%), and the 1991 value was 31.3 cod/h. Prominent year-classes (>1 S.D. above the mean) were 1960 (160.6 cod/h), 1962 (179.6), 1965 (135.3), and 1985 (174.8).

Mortality rates. During 1960-84, M (0.65) was relatively large with respect to Z (1.27) (Table 7.2.2), and Westrheim and Foucher (1985a) concluded that the stock was not overfished. Estimates of F-at-age were generally dome-shaped (Table 7.3.1.5). Mean annual values for 1956-90 were 0.14 at age 2, 0.60 and ages 5 and 6, and 0.50 at age 7.

Exploitation rate (U). Distribution of U-at-age was also dome-shaped (Table 7.3.1.5). Mean annual values during 1956-90 rose from 0.10 at age 2 to a peak of 0.34 at age 5, then declined to 0.29 at age 7 (Table 7.3.1.5). A later analysis, for 1971-91, yielded higher estimates (0.12-0.48), which also peaked at age 5. The higher values may have reflected the more intense fishery in the last two decades.

Yield-per-recruit (YPR). YPR analysis began with the 1954-85 data, because the appearance in 1986 of the strong 1985 year-class created a severe discard problem (Westrheim and Foucher 1987b). The analysis was undertaken using the following parameters: MCS = 41, 46, and 51 cm; M = 0.4 and 0.6; F = 0.4-0.7. Results indicated that growth overfishing would occur at a mesh size of 102 mm (internal measure), the most common size in use at that time. Optimum mesh size

at MCS = 46 cm (the most common minimum) would have been 165 mm, much too large for the MCSs of Dover sole (Microstomus pacificus) and English sole, but not rock sole, the three important flatfish species in the region (Table 7.3.1.6). Furthermore, severe gilling problems were known to occur with the two other important residents--rockfish (Sebastes spp.), at mesh sizes >76 mm, in deep waters of Area 5C; and the ubiquitous spiny dogfish, at mesh sizes >102 mm. For these and other reasons, no mesh regulation was recommended to alleviate growth overfishing. It was decided that adequate mesh-selection information was available to the fishermen, the ultimate beneficiaries, so that they could select the appropriate mesh size for each targetted species. YPR analysis for the 1961-86 was based on current MCS = 41 cm; current mean mesh size = 135 mm; M = 0.4 and 0.6 (Foucher and Tyler 1988). Results indicated that F_{opt} = 0.5, compared to $F_{current}$ = 0.52. The authors concluded that the fishery was self-regulating with respect to YPR. Subsequent YPR analyses yielded no different conclusion.

Simulation analysis (SA). The first SA was applied to the data for 1960-80, and involved an age-structured model which included a stock-recruitment relationship and an environmental component (sea level at Prince Rupert, B.C.) (Fournier 1983). A number of variations were employed, viz., numbers of parameters, methods of using the data, and different uses of the parameters. The author concluded that the stock has usually been higher than its most productive level. He found little evidence for a time-dependent or density-dependent trend in catchability, but did find a strong indication of density-dependent natural mortality.

Tyler (1990) applied the age-structured Self-Generating Model of Tyler and Gallucci (1980) to the 1960-87 data, as a preliminary exercise. Subsequently, it was applied to the data for 1956-88 (Tyler and Foucher 1990) and 1956-89 (Foucher and Tyler 1991). Tyler and Crawford (1991) conducted a response-surface analysis of recruitment and associated factors. They found evidence for a Ricker stock-recruitment relationship and a dominating influence of northward transport following spawning. The analyses served two purposes: (1) established the "critical spawning biomass" (CSB) that would ensure successful reproduction; and (2) predicted potential yield two years in advance. CSB was estimated to be 4,000 t, $\pm$ 1,000 t. During 1972-87, spawning biomass fell slightly below CSB (>2,000 t) in 1981 and 1984, which indicated that the current fleet was capable of recruitment overfishing. The alleged stock-recruitment relationship may be illusory.

Stocker and Hand (1993) conducted a four-part analysis which consisted of: (1) exploratory data analysis; (2) biomass dynamic modeling; (3) delay-difference modeling; and (4) an age-structure model.

(1) Exploratory data analysis. The Biomass Index Model (BIM), of Schnute et al. (1989) was used to determine if sufficient information was available in catch and effort data for analysis, and if so, what was the mean relationship between recruitment, survival, and catchability. The analysis indicated that the data were adequate, and that the fishery may have had an effect on survival. BIM provided estimates of the overall constant level of recruitment ($A^{'}$ = 0.184 t/h), natural survival (sigma = Ricker's m = 0.600; M = 0.51), and the catchability coefficient ($q = 4.083 \times 10^{-5}$/h). These estimates were used as initial estimates in the subsequent analyses.

(2) Biomass dynamic modeling. A surplus-production model (Walters and Hilborn 1976) was used to describe the effect of effort on the population, in the long run. The questions of interest were: current stock size, and the short- and long-term consequences of current landings. Estimates of pertinent management parameters were as follows:

Parameter	Estimate
MSY	4,610 t
Biomass for MSY (B_{MSY})	13,800 t
Harvest rate for MSY (HR_{MSY})	0.33
Effort for MSY (E_{MSY})	8,350 h

Simulations indicated that continued high current values of harvest rate would reduce the stock to a record low level.

(3) Delay-difference model (DDM). The DDM (Deriso 1980; Schnute 1985) involves the biomass dynamics of the age-structured cod population with a delay-difference equation. The model incorporates growth, mortality, and a density-dependent Ricker stock-recruitment relationship. It was used to predict the observed cycles of abundance. Hypotheses of high and low survival rate provided equally good fits to the catch and CPUE data. Estimates of pertinent management parameters were as follows:

Parameter	Survival rate	
	0.589	0.468
MSY	10,700 t	10,300 t
B_{MSY}	13,400 t	12,900 t
HR_{MSY}	0.8	0.8

The plots of equilibrium stock and equilibrium catch on harvest rate, for both high and low survival, were strongly skewed left, which indicated considerable risk if harvest rate were permitted to approach 0.8. For 1992-2012, the model predicted continued cycles of cod abundance, and at $F_{0.1}$, mean annual catches would be 5,600 and 5,000 t, respectively, for the high and low survival rates.

(4) Age-structure model (ASM). The ASM involved the microcomputer program CATANAL (Walters MS 1987[3]), which provided a package consisting of Paloheimo's (1980) regression analysis (M,q, and recruitment), stock reconstruction by cohort analysis (Walters op. cit.; Hilborn and Walters 1992), stock-recruitment using stock reconstruction, and age-structure analysis of population response to alternative fisheries policies. Estimates of mean F (= qE) of 1.03 (M = 0.55) and 1.13 (M = 0.45) corresponded to harvest rates of 0.64 and 0.68, respectively. Cohort analysis was undertaken using two estimates of constant M (0.55 and 0.45). Mean 1971-91 harvest rates-at-age were similar for the two values of M--0.12-0.48 for M = 0.55; 0.13-0.46 for M = 0.45. In both cases, the 1991 estimates were substantially above average--0.50-0.87 at M = 0.55; 0.35-0.88 at M = 0.45. Stock recruitment analysis yielded a dome-shaped, but somewhat uncertain, stock-recruitment relationship. Age-structure analysis yielded the following management parameters, at M = 0.55: MSY = 3,600 t; B_{MSY} = 9,300 t; and U_{MSY} = 0.39.

Summary. Prior to 1986, all assessments concluded that fluctuations in abundance of Hecate Strait cod were independent of the fishery. Subsequently, the next set of analyses revealed that while a dominant factor was northward transport after spawning, there was a minimum spawning stock biomass (4,000 t $\pm$ 1,000 t), below which recruitment would be adversely affected. SSB had fallen slightly below this level twice in the 1980s. The interim analysis for 1992, oriented primarily to MSY, noted that fishing mortality and effort were at or above average, abundance was below average. and the status of recruitment was uncertain. The current situation posed a threat to the stock, and called for catch restrictions. Potential yield was 3,200-6,500 t/y, depending on type of

[3] Walters, C.J. MS 1987. Microcomputer catch-at-age analysis system. Univ. British Columbia, Vancouver.

model and stock-productivity option.

Species/Fishery Interactions

Potential species, or fishery, interactions were noted between Pacific cod and its principal shelf co-habitants off west Vancouver Island, and in Queen Charlotte Sound and Hecate Strait (Westrheim and Foucher 1985a). Off west Vancouver Island, reciprocal relationships were noted for nominal catches of cod and lingcod from Big Bank, the major source of both species, during April-September 1956-85, notably during 1957-59, 1969-71, 1981-85 (Fig. 7.3.1.5). Similar relationships were noted for the same two species in Queen Charlotte Sound, notably during 1957-61, 1965-68, and 1978-83 (Fig. 7.3.1.6). In Hecate Strait, interactions were only important on Two Peaks Ground, during April-September, where occasional reciprocal relationships were noted between the catches of cod and English and rock soles (Westrheim et al. 1990). However, both flatfish species were relatively minor components (Fig. 7.3.1.7). No reports were found which dealt with the cause(s) of the phenomenon.

SUMMARY

Analyses have increased in sophistication, but continue to yield, with one or two exceptions, the same conclusion first reached by Ketchen (1967). That is, cod abundance fluctuations were without trend, and merely reflected the passage of strong year-classes through the fishery. Explaining and predicting these fluctuations remain to be undertaken. Encouraging progress has been made with cod in Hecate Strait.

Georgia Strait and vicinity. The delineation of four important stocks, and their diverse exploitation histories suggested the cod should not be treated as a unit stock, if the fishery returns to a sufficient size to warrant such treatment. The fluctuations in all four stocks remain to be explained. The precipitous decline in total catch during 1988-91 was attributed to economic conditions and the retirement of older fishermen who operated the smaller trawlers which provided most of the catch. The current magnitude of the catch largely depends on the variable immigration of offshore cod into MSAs 19 and 20.

West Vancouver Island. The rise in importance of the winter fishery on Amphitrite Bank during the 1970s, created the possibility of recruitment overfishing. Although there was no proof of recruitment overfishing, restrictions were imposed, and that in 1985 may have contributed to the high abundance of the 1985 year-class. Unfortunately, no proof was provided nor was any possible under the circumstances. Growth overfishing was noted as a potential problem for the pre-recruits of the strong 1985 year-class, but no action was taken.

Queen Charlotte Sound. Large sections of "untrawlable" ground, and the lack of a winter fishery, have to date precluded concern over the possibility of recruitment overfishing. However, the substantial improvement in navigational and fish-finding equipment may soon create some concern. The potential problem of growth overfishing was not addressed for this region.

Hecate Strait. Prior to 1986, all assessments concluded that fluctuations in abundance of Hecate Strait cod were independent of the fishery. Subsequently, analyses based on an age-structured model, and an environmental factor (northward transport) revealed that there was a minimum spawning stock biomass (4,000 t $\pm$ 1,000 t), below which recruitment would be adversely affected. SSB had fallen slightly below this level twice in the 1980s. The interim analysis for 1992, oriented primarily to MSY, estimated that the potential yield was 3,200-6.500 t, depending on type of model and the stock-productivity option chosen. Fishing mortality and effort were at or above average, abundance was below average. and the status of recruitment was uncertain. The analysis concluded that the current situation posed a threat to the stock, and called for catch restrictions. Growth

overfishing was recognized as a problem with respect to pre-recruits of the large 1985 year-class, but minimum mesh-size restrictions were not imposed, because the preferred mesh size for cod was inappropriate for other important demersal species in the region.

Multi-species. The mixed-species nature of the cod fishery was noted in one report, and relatively important, but unexplained, reciprocal relationships were noted between catches of cod and lingcod off west Vancouver Island and in Queen Charlotte Sound. In Hecate Strait, species interactions were only important on one bank, and there the two co-habitant flatfish species were a minor component in the catch. No analysis of these phenomena was found.

General. Three other factors in stock assessments remain to be resolved, i.e., firmer estimate(s) of M, restandardization of effort to correct for recent substantial improvements in vessel efficiency, and investigation of the reciprocal relationship between the catches of lingcod and Pacific cod off west Vancouver Island and in Queen Charlotte Sound.

7.3.1.2. WASHINGTON STATE

Two stock-assessment reports were found which dealt with cod in the waters of Washington State. One dealt with spawning cod in the Port Townsend area of Juan de Fuca Strait (northwest 4A), and the other dealt with cod throughout Area 4A (Puget Sound, Georgia Strait, and Juan de Fuca Strait). No reports were found which dealt with cod in the offshore regions (3A,3B,3Cs).

PORT TOWNSEND

Catch Records

The fishery is seasonal (December-March), and is directed at cod entering Port Townsend Bay (Fig. 5.1.7) to spawn (Karp 1982). Both trawl and set gillnets are employed. The trawl fishery began "many years ago", but reliable catch records were first collected in 1967. Mean annual trawl landing during 1967-79 was 88 t (0.04-157 t). The setnet fishery began in 1975, with a catch of 55 t. Mean annual catch during 1976-79 was 108 t. During 1975-79, trawl landings generally decreased while setnet landings generally increased. No published records were found for production after 1979.

Stock Assessment

Karp (1982) applied a Beverton-Holt YPR analysis for 1977-78, and reported that for M = 0.5 and K = 0.33, age 3 was optimal, and maximum production would be achieved at F = 1.5.

PUGET SOUND AND VICINITY (4A)

Catch Records

Both commercial and recreational fisheries for Pacific cod were relatively important.

Commercial fishery. During 1921-34, annual catches were small, and relatively stable--23-79 t (Palsson 1990). Catches were not reported by species during 1935-41, and during 1942-87, catches fluctuated widely around ca. 700 t/y

(op. cit., Fig. 6). Mean annual all-gear catch in Area 4A during 1970-88 was 1,256 t, of which the Northern stock contributed 46% (581 t); the Western stock, 40% (499 t); and the Southern stock, 14% (176 t) (Table 7.3.1.7). After 1941, trawl catches predominated, and accounted for at least 77% of the annual catch. Trawls accounted for 99% of the cod catch from the Northern stock, 39% from the Western stock, and 73% from the Southern stock. Gillnets were an important gear exploiting the Western stock after 1973, primarily in the Port Townsend fishery.

Recreational fishery. During 1978-87, the mean annual catch was 115 t--1% (1 t) from the Northern stock, 11% (13 t) from the Western stock, and 88% (101 t) from the Southern stock (Palsson 1991, Table 10).

Stock Assessment

Palsson's (1990) assessments for the three important stocks were based primarily on catch statistics for both commercial and recreational fisheries, but also included mean lengths of landed cod, and total mortality rates (Z). No age-composition data were available.

Catch statistics. Long-term CPUE trends, during 1970-89, were "decreasing" for the Northern and Western stocks, and "stable" for the Southern stock (Table 7.3.1.8). Causes of the general decline in catch and CPUE, particularly after 1977, were not established.

Mean lengths. The author noted that mean lengths of trawl-caught cod varied inversely with CPUE, and attributed this phenomenon to the passage of strong year-classes. Notable were 1975-76, 1981, and 1984.

Mortality rates (Z). During 1970-89, five-year mean estimates of Z for the Northern stock ranged from 1.35 (1970-74) to 1.85 (1980-84) (Table 7.3.1.9). Comparable values for the Western stock were 1.45 (1975-79) to 1.79 (1985-89). The only estimate for the Southern stock was 1.01 (1980-84).

Summary. The author speculated that climatic conditions, biotic factors, and the fisheries were all potential factors affecting cod abundance. Short time series precluded a conclusion with respect to climate, and inadequate data with respect to biotic factors. The fishery factor was not evaluated, because no estimate of F was available, and no spawner-recruit relationship was identified.

7.3.1.3. ALASKA

Introduction

Since the 1960s, stock assessments have been undertaken on cod occupying two regions--Gulf of Alaska (GOA) and Eastern Bering Sea-Aleutian Islands (EBSAI). Stock-assessment reports were published through 1989 for the Gulf of Alaska, and through 1990 for the East Bering Sea-Aleutian Islands region. Subsequent reports, unpublished, were prepared as Stock Assessment and Fishery Evaluation (SAFE) reports, and submitted to the North Pacific Fishery Management Council (P.O. Box 103136; Anchorage AK, 99510) (H.H. Zenger, Jr., pers. comm., July 1992) for inclusion in their annual reports, whose distribution appears to be limited. Copies of the 1993 SAFE reports (see Footnotes 1 and 2, Section 7.2) were kindly provided by Dr. G.G. Thompson (Alaska Fisheries Science Center, Seattle, WA) to provide an update on assessment methods and results.

In 1977, the Magnuson Fishery Management and Conservation Act (MFMCA) was promulgated to deal with finfish and shellfish resources within the U.S. EEZ. In 1990, the MFMCA was amended to require, where feasible, a definition of recruitment overfishing in all Fisheries Management Plans (FMPs) (Goodyear 1993). Now most FMPs include the spawning stock per recruit (SPR) approach (Mace and Sissenwine 1993). Recruitment overfishing is defined as a selected ratio of

current SPR to pristine SPR--usually 0.2-0.3. The fishing mortality rate corresponding a SPR ratio is expressed as $F_{x\%}$, where x% is the ratio in percent. FMPs for both the Gulf of Alaska and the Eastern Bering Sea-Aleutian Islands regions now incorporate the SPR analysis in their FMPs.

GULF OF ALASKA

Catch Records

In the early phase of the post-war fishery, cod was not usually a target species (Zenger and Thompson 1989). All-nation catch records began in 1971. Principal participating nations were Japan (1971-86), USSR (1971-77), and USA (1986-date) (Zenger 1988, Table 1). All foreign fisheries were eliminated after 1986.

Under the MFMCA, regional regulatory bodies were established. For Alaska, this was the North Pacific Fishery Management Council (NPFMC). The NPFMC divided the Gulf of Alaska into three regulatory areas--Western (INPFC Shumagin Area), Central (Chirikof + Kodiak), and Eastern (Yakutat + Southeastern) (Fig. 2.2). During 1977-92, principal areas of cod catch were the Central (62.5%) and Western (35.2%), based on cumulative catch (Table 7.3.1.10). Various regulations were implemented which limited the quantities of cod caught. Primary purpose of these restrictions was to reduce the by-catch of Pacific halibut and sablefish.

During 1971-92, annual catches ranged from 1,000 t (1971) to 76,000 t (1992) (Table 7.3.1.10). They rose slowly from 1,000 t in 1971 to 35,000 t in 1980; ranged from 14,000 t to 42,000 t during 1981-1989; then rose sharply to 69,000-76,000 t during 1990-92. Records for 1981-92 were augmented with estimates of discards at sea, which increased catches by 0.1-1.6% during 1981-86, and 2.4-6.5% during 1987-92. The relatively small catch in 1985 marked the transition from foreign fishery to the domestic.

Stock Assessment

Nine reports were reviewed (Table 7.3.1.11). Eight were published, and one (Thompson and Zenger MS 1993; see Footnote 1, Section 7.2) was unpublished. Principal data sources were resource-assessment surveys (RAS), by trawl or longline, CPUEs from Japanese commercial longline fisheries, and length-frequency samples from catches of commercial and research vessels. Simulation analyses involved one multi-species model and four single-species models, usually to estimate MSY--the basis of management under the MFMCA.

Catch Statistics. Relative abundance generally increased from 1978 through 1985, then decreased slightly, as indicated by CPUEs in the Japan-U.S. longline surveys (1979-87) along the outer shelf and upper slope, and CPUEs from the Japanese commercial longline fishery in the Shumagin and Chirikof areas (Zenger and Thompson 1989).

Recruitment. Zenger and Thompson (1989) reported that no satisfactory method of age determination had been developed to date, and that length-frequencies were utilized to provide rough indices of year-class abundance. Analysis of length-frequency data collected during 1984-87, from catches of commercial and research vessels, suggested that no recent year-classes were equal in abundance to those of 1977 or 1978. Zenger and Thompson (MS 1993) estimated the annual recruitment at age 3 for 1978-93 with the length-based Synthesis model (LBSM; see Simulation analysis., below) of Methot (1990) (Table 7.3.1.12). Supporting material included length-at-age data from the 1990 and 1992 commercial fisheries, and length-frequency data from commercial and survey vessels. The mean was 94 million cod, and the range, 40-237 million. Above-average year-classes were 1977 (237 million), 1979-81 (107-134 million), and 1984 (143 million).

Fishing mortality (F). Computation methods and general results were discussed in Section 7.2, and shown in Table 7.2.6. For 1978-93, annual estimates of F followed a similar pattern, regardless of method of derivation (Table 7.3.1.12). Values were relatively low during 1978-89 (0.02-0.09 by SRA; 0.04-0.08 by LBSM), and relatively high during 1990-93 (0.16-0.18 vs 0.19-0.30). For both methods, peak value occurred in 1992.

Exploitable-stock biomass. Six estimates were reported, based on research-vessel surveys (Table 7.2.7). The mean estimate for 1960-64 was 80,000 t, and for 1973-78, 358,000 t. The remaining four estimates were 396,000 t (1981), 549,000+ t (1984), 482,000+ t (1987), and 379,000 t (1990). All estimates, except that for 1990, were deemed provisional, due to unresolved relative fishing powers of survey vessels and nets (H.H. Zenger, Jr., pers. comm., July 1992). In 1990, only one type of trawl was used, but by different vessels. Standardization studies are continuing (G.G. Thompson, pers. comm., November 1993).

For 1978-93, SRA- and LBSM-based annual estimates of age-3+ biomass varied in magnitude (320,000-658,000 t vs 395,000-838,000 t) and trend (Table 7.3.1.12). LBSM estimates may have been larger because a larger estimate of M (0.37 vs 0.27) was used. A second factor was the use of a selectivity function which allowed for decreasing selectivity at larger sizes. With respect to trend, SRA estimates declined steadily throughout the time series. LBSM estimates increased from 395,000 t in 1978 to 838,000 t in 1987, then declined to 482,000 t in 1993. SRA could not cope adequately with the variable recruitment of cod.

Exploitation rate (U). Computation methods and results were discussed in Section 7.2, and shown in Table 7.2.7. Briefly, the estimates were relatively low (1.7-9.1%), except for 1990, 18.2%.

Simulation analysis (SA). The multi-species PROBUB (Prognostic Bulk Biomass) model of Laevastu et al. (1982) was applied to the 1970-76 data for the western Gulf. Estimated minimum sustainable biomass was 101,000 t. Estimated minimum sustainable biomass was achieved by using the highest plausible growth rate and the lowest plausible food requirement. Comparable mean exploitable biomass, based on RAS data, was 112,000 t. The authors noted that the model was not suitable for prediction, because of the variable and unpredictable recruitment of the various species.

Two MSY estimates were based on the virgin-biomass method ($MSY = XMB_o$), where X = 0.4 (Gulland 1969) or 0.5 (Gulland 1975), M = natural mortality rate, and B_o = the biomass before exploitation began. The estimate by Zenger and Cummings (1983) (X = 0.4; M = 0.6, from Ketchen 1961) was 143,000 t (95,000-190,000). The estimates by Zenger and Blackburn (1986), based on X = 0.5; and M = 0.45 (Bakkala and Wespestad 1985) or 0.22 (Thompson and Shimada 1987) were 125,000 t and 59,000 t, respectively. The virgin-biomass method relies on the basic assumption that the virgin biomass was stable--a rather tenuous assumption for Pacific cod. Thompson (1992) provided a substantive criticism of two commonly accepted "rules-of-thumb", viz., $F_{MSY} = M$, and $B(F_{MSY}) = 0.5B_o$.

Two MSY estimates were based on the constant-parameter Beverton-Holt model, using parameters for cod in the eastern Bering Sea (Zenger 1988). Estimates were 296,000 t for 1984 and 246,000 t for 1987. The author rejected both as unrealistically high.

SRA has been was employed in all assessments since 1988 (Zenger and Thompson MS 1993). The 1992 assessment, with a creatively estimated Beverton-Holt stock-recruitment relationship, estimated MSY to be 34,190 t, based on survey results for 1984 and 1987, and parameters for cod in the eastern Bering Sea (Zenger and Thompson 1989). For 1993, results of the 1990 RAS were included, but no estimate of MSY was reported due to the difficulty in defining a stock-recruitment relationship (Zenger and Thompson MS 1993). They noted that SRA depends upon declining abundance (from the pristine level), and a strong stock-recruitment relationship. Since neither of these conditions was

necessarily relevant for Pacific cod in the Gulf, they deemed it "unwise" to select a single MSY estimate.

For the 1993 assessment, results are summarized in Table 7.3.1.13. Inadequacies of SRA, and age-frequency data, led to the supplementary application of the LBSM, now used for cod in the eastern Bering Sea, on a provisional basis. LBSM differs from SRA in that it allows the modeler to weight the individual components in the parameter estimation process, viz., size compositions, survey biomass, and stock-recruitment.

The overfishing level for 1994 was defined by SRA as $F_{30\%}$ = 0.24 (catch = 71,100 t), and by LBSM, $F_{30\%}$ = 0.41 (79,400 t) (Table 7.3.1.13). During 1978-93, the maximum value of F_{SRA} was 0.22, and for F_{LBSM}, 0.30 (Table 7.3.1.12). Interestingly, by definition, overfishing would allegedly occur at F = M, based on SRA.

Summary. The 1993 SRA-based, and the provisional LBSM-based, assessment, suggests that Pacific cod are not threatened by overfishing. Current estimates of F are less than $F_{30\%}$, the defined level of overfishing. Although estimates of MSY are required under the MFMCA, recent reports have noted that the MSY concept might not be appropriate for cod, whose recruitment is so variable (Zenger 1988; Zenger and Thompson 1989; Thompson and Zenger MS 1993).

EASTERN BERING SEA/ALEUTIAN ISLANDS

Catch Records

Thompson and Shimada (1990) provided the latest published review of the modern line/trawl fishery. During the early 1960s, cod was a target species for a Japanese longline fishery. In 1964, the Japanese trawl fishery for walleye pollock began to expand, and cod became an important incidental catch, and an occasional target species. During 1964-86, the principal nations reporting cod catches were Japan, Republic of Korea, U.S.A. (1981-date), and the USSR. By 1987, the U.S. fishery accounted for 65% of the total catch. All foreign fisheries were eliminated in the Aleutian Islands in 1986, and in the eastern Bering Sea in 1988. During 1977-92, eastern Bering Sea was the predominant cod-producing region, with a cumulative catch of 1,874,000 t (92.7%), compared to 147,000 t (7.3%) from the Aleutian Islands (Table 7.3.1.10).

During 1964-92, catches from the eastern Bering Sea ranged from 13,000 t (1964) to 208,000 t (1991), and from the Aleutian Islands region, 200 t (1964-65,1969) to 43,000 t (1992) (Table 7.3.1.10). In the EBSAI region annual catch ranged from 14,000-32,000 t during 1964-67, 36,000-103,000 t during 1968-83 t, and 133,000-218,000 t during 1984-92. Records for 1981-92 included estimates of discards at sea for all segments of the fishery.

Stock Assessment

Eleven reports were reviewed (Table 7.3.1.11). Ten were published, and one (Thompson and Methot MS 1993; see Footnote 2, Section 7.2, p. 213) was unpublished. Primary data sources were the RASs (trawl). Yields for the Eastern Bering Sea-Aleutian Island region were obtained by extrapolating EBS estimates--regression for 1986, and multiplication (1.1735 x EBS estimate) for 1987-92.

Catch statistics. Relative abundance of cod in the eastern Bering Sea, based on RAS CPUEs, increased from 2.7 kg/ha in 1975 to 24.8 kg/ha in 1983, and remained high through 1988 (20.9 kg/ha) (Thompson and Shimada 1990). Of some interest were the personal observations of Fadeev (1990), who compared, qualitatively, the USSR groundfish survey results in 1957-59 with those in 1988. He noted that Pacific cod occurrence in catches had increased from 47.5 to 88.7%;

its geographical range had expanded widely; and biomass had increased sevenfold. For other species, walleye pollock also increased in importance; Pacific halibut decreased; and flounders (including yellowfin sole) exhibited no change. He attributed the fluctuations to selective fishing or natural causes.

Recruitment. Irregularity has characterized cod recruitment. Recent sustained high production has been attributed to the strong year-classes of 1976-77, 1982, and 1984 (Thompson and Shimada 1990; Thompson and Bakkala 1990). Thompson and Methot (MS 1993) estimated the annual recruitment at age 3 for 1978-93 with the LBSM (Table 7.3.1.14). The mean was 168 million cod, and the range, 34-531 million. Above-average year-classes were 1977 (531 million), 1978 (230 million), 1979 (177 million), 1982 (338 million), 1984 (242 million), 1989 (216 million), and 1990 (212 million).

Fishing mortality (F). Computation methods and general results were discussed in Section 7.2, and shown in Table 7.2.6. Annual LBSM estimates for the eastern Bering Sea during 1978-93 declined from 0.31 in 1978 to 0.07 in 1982; rose to 0.25 in 1990; then rose more sharply to 0.40-0.47 during 1991-93 (Table 7.3.1.14).

Stock biomass. Absolute abundance of cod has been estimated by exploratory fishing, RAS surveys, the multi-species PROBUB model, and LBSM. Estimated total biomass in the southeastern Bering Sea during 1948-49 was 140,000 t, based on exploratory fishing (Table 7.2.8). Mean annual estimate, based on RAS data, for all of the eastern Bering Sea was 917,000 t during 1979-92, and ranged from 533,000 t (1991) to 1,176,000 t (1983). Total biomass remained above average during 1981-1989 (905,000-1.176,000 t); declined to 533,000 t in 1991; then rose slightly to 547,000 t in 1992. For 1970-76, the PROBUB model (Laevastu et al. 1982) estimated the mean equilibrium exploitable biomass to be 706,000 t, while the corresponding RAS-based estimate was 233,000 t. No explanation was offered for the difference between estimates. LBSM-based estimates of age-3+ biomass followed a similar pattern to that of total biomass. During 1978-93, annual estimates ranged from 247,000 t (1978) to 1,492,000 t (1983); were above average during 1981-1989 (1,103,000-1,492,000 t); then declined to 678,000 t in 1992, and 716,000 t in 1993--mean was 1,025,000 t (Table 7.3.1.14).

For the Aleutian Islands, the four RAS-based estimates of total biomass were 79,000 t (1980), 137,000 t (1983), 182,000 t (1986), and 170,000 t (1991) (Table 7.2.8). Their mean was 142,000 t.

Exploitation rate (U). Computation methods and results were discussed in Section 7.2 (Table 7.2.8). Briefly, for the eastern Bering Sea, mean estimate for 1979-92, was 12.2%. Annual estimates increased irregularly from 4.3% in 1979 to 39.0% in 1991, then decreased to 29.6% in 1992. For the Aleutian Islands, the four estimates were 7.6% (1980), 5.8% (1983), 3.8% (1986), and 5.9% (1991). Their mean was 5.6%.

Simulation analysis (SA). Seven single-species models and one multi-species (PROBUB) model were employed (Table 7.3.1.11). The single-species models were SRA (Kimura 1985), Beverton-Holt; EBSM-1,2a,2b,3 (named here) (Thompson and Shimada 1987,1988,1990; Thompson and Bakkala 1990), and the LBSM (Methot 1990). The "family" of EBSMs, in their various forms, were defined as numbers-based, which projected the population and fishery on a gear-, year-, age-, and month-specific basis (Thompson and Shimada 1990). Assumed were a January-December harvest year, a March-February recruitment year, and a July-June survey year.

For 1975-76, the PROBUB model revealed that food consumption by marine mammals was substantially more important than the fishery in affecting the state of the multi-species resource. Furthermore, the authors suggested that "components of the marine ecosystem have long-term fluctuations which are not necessarily caused by the fishery" (Laevastu et al. 1982, p. 74).

For 1986, EBSM-1 was employed to estimate equilibrium yield (EY)

rather than MSY. EY was defined as "the annual yield which allows a stock to finish the year at the same level of abundance found at the start of the year" (Thompson and Shimada 1987, p. 51). EY was estimated to be 375,000 t, while the catch was 131,000 t. The authors chose not to estimate MSY, because of the current dynamic state of abundance, and the absence of a spawner-recruit relationship.

For 1987, four models were employed to estimate MSY--SRA, Beverton-Holt (constant recruitment), EBSM-2a (with B-H stock-recruitment), and EBSM-2b (constant recruitment) (Table 7.3.1.11). Results were similar among estimates--176,000 t (EBSM-2a) to 242,000 t (EBSM-2b). The 1987 catch was 150,000 t (Table 7.2.8). The EBSM-2a estimate was deemed the best. SRA (224,000 t) was abandoned, because it assumed a strong stock-recruitment relationship, not evident for EBS cod. B-H (201,660 t) and EBSM-2b, assuming constant recruitment, were likewise rejected, because recruitment was evidently not constant. Thompson and Shimada (1988) acknowledged the aforementioned problems with MSY, but noted that "the federal guidelines for fishery management plans define MSY relative to 'prevailing ecological and environmental conditions'" (op. cit., p. 45). The current high stock abundance and estimates of MSY were not expected to continue indefinitely.

For 1988, EBSM-3, an improved version of EBSM-2a, estimated equilibrium harvest strategies for EBS at $F_{0.1}$, F_{MSY}, F_{max}, and F = M. Relatively substantial variations among strategies were noted for estimates of F, exploitation rate, biomasses, but not catch (273,000-213,000 t) (Thompson and Shimada 1990). Estimated 1989 catches ranged from 286,000 t ($F_{0.1}$) to 460,000 t (F= M). The actual 1989 catch was 178,000 t. The authors urged caution in accepting these estimates, but concluded that the cod stock appeared to be capable of withstanding a wide range of harvests without damage to its long-term viability.

For 1990, Thompson and Bakkala (1990) used updated EBSM-3 data to predict the 1990 catch, by strategy. Results ranged from 355,000 t ($F_{0.1a}$) to 523,000 t (F = M). $F_{0.1a}$ was derived from the sustainable yield curve generated by the Beverton-Holt S/R relationship. Estimated catch at $F_{0.1b}$, derived from the yield-per-recruit curve, was 378,000 t. Actual 1990 EBS catch was 172,000 t. The authors also considered the estimates "optimistic", because the stock-recruitment relationship had a "large stochastic component", and tuning data were collected from 1981-87, when the stock was at a relatively high level. Environmental factors were not considered in the model.

For 1993, the LBSM was applied by Thompson and Methot (MS 1993). Table 7.3.1.13 contains a summary of the results for the EBSAI region. Estimated overfishing levels for 1994 were $F_{30\%}$ = 0.43, and catch = 228,000 t. Past values of F only exceeded 0.43 in 1993 (0.47) (Table 7.3.1.14). Past catches never exceeded 228,000 t (Table 7.3.1.10). The estimated 1993 catch was 114,200 t.

Summary. The 1993 LBSM-based assessment suggests that the cod stock in the EBSAI region may be approaching recruitment overfishing, if the current rate of fishing continues. The 1993 estimate of F exceeds that of $F_{30\%}$, the defined level of recruitment overfishing. No estimate of MSY was included in the 1993 assessment, because of the difficulty in defining a stock-recruitment relationship.

7.3.2. ATLANTIC COD

Introduction

In the northeast Atlantic, the ICES Advisory Committee on Fishery Management (ACFM) provides technical advice, with respect to management and conservation of groundfish resources, to the North-East Atlantic Fisheries Commission, International Baltic Sea Fisheries Commission, and the European

Economic Commission (ICESb 1991a,b). Their reports are published in the ICES Cooperative Research Report series. Reports on Icelandic cod were not included after the survey report for 1970 (ICESb 1974) until the report for 1992 (ICESb 1993b).

In the northwest Atlantic, four agencies have provided stock-assessment reports for cod, and other species, in the ICNAF/NAFO area--ICNAF, CAFSAC (Canadian Atlantic Fisheries Stock Assessment Committee), NAFO, and the New England Fishery Mangement Council (NEFMC). ICNAF was founded in 1950 (Halliday and Pinhorn 1990), and was replaced after the promulgation of EEZs in 1977. Its successors were CAFSAC (1978) and NEFMC (Serchuk and Wigley 1993) in 1977, and NAFO in 1979 (NAFOc 1980). CAFSAC was disbanded in December 1992, and, pending its replacement, an ad hoc group of Canadian scientists prepared the groundfish assessment reports for 1992 (Sinclair 1993). NEFMC deals with assessment and management of groundfish stocks in the U.S. EEZ.

For 1959-77, stock assessment reports were provided by ICNAF, and published in its Redbook series. CAFSAC assessments were produced in its Advisory Document series. This series is not formally published, but is available to the public without restriction. Assessment reports to NEFMC are not published. NAFO assessments are published in its Scientific Council Reports series. After 1977, NAFO dealt primarily with assessments in Subarea 1 and Subdivisions 3M and 3NO. It shared with CAFSAC the responsibility for other cod-stock assessments in Subareas 2-4, but with a gradual shift to CAFSAC.

This Section will deal primarily with the more recent stock assessments, and will not provide a detailed history of the various procedures followed.

MATERIALS AND METHODS

ICESb (1988,1993a) provided useful references to assessment methods employed by the various working groups in the northeast Atlantic. A comparable report was prepared for the northwest Atlantic, but not published[4].

In both the ICES and NAFO areas, stock assessments now include biological reference points, with respect to the instantaneous fishing mortality rate (F).

For the northeast Atlantic, ICESb (1991a, p. 5) provided the following definitions:

F_{max} is the level of fishing mortality at which the maximum long-term average annual catch can be taken under the present exploitation pattern. It is based on the relationship between the yield per recruit and fishing mortality.

$F_{0.1}$ is the level of fishing mortality at which the slope of the yield-per-recruit curve is one tenth of its slope at the origin (Gulland and Boerema 1973). $F_{0.1}$ is always less than F_{max}; the catch is only slightly less than F_{max}, but the implied reduction in fishing mortality is much greater and so the catch per unit effort is higher with consequent economic benefits. $F_{0.1}$ is therefore, essentially an economic concept.

F_{high} corresponds to a level of F at which survival is so low that recruitment (per unit biomass) is insufficient to maintain the stock in about nine years in ten. Whilst it cannot necessarily be taken as an estimate of the

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[4] Rivard, D. [ed.]. MS 1988. Collected papers on stock assessment methods. Res. Doc. Can. Atl. Fish. Sci. Advis. Committee 88/61: 167 p.

F at which collapse will occur, it is a level for which the available data provide very little evidence that it could be maintained indefinitely. It is, therefore, not a target or option level of F, but, on the contrary a level which is probably dangerous to approach or maintain.

F_{med} is a level for which there is sufficient evidence that it should be sustainable (assuming, of course, that the underlying environmental or ecological conditions to which the data relate are maintained). Below or in the vicinity of F_{med}, there should, therefore, be no undue cause for concern about sustainability, and F_{med} could, therefore, in some circumstances, serve as a target for management, though many other factors (yield, exploitable biomass, etc.) are, of course, also relevant.

F_{low} corresponds to a level for which there is plenty of evidence that the stock is sustainable, subject to the same qualifications as for F_{med}.

A further caveat was that biological reference points were intended to provide guidance concerning management options, and that no single reference point could possibly serve as a universal target for management.

F_{med} and F_{high} are calculated from stock and recruitment scatter diagrams and plots of biomass per recruit. Lines are drawn through the origin of the scatter plot which leave about 10% (F_{high}) and 50% (F_{med}) of the points above the line. The slopes of these lines correspond to values of recruitment per unit biomass, and the reciprocals of these values are estimates of the spawning biomass per recruit (an estimate of survival) which must be maintained for the stock to be sustainable. The fishing mortalities (conditional on the assumed exploitation pattern) to which these biomass-per-recruit values correspond may be determined from the relationship between these quantities, and the yield estimates of F_{high} and F_{med}.

For the northwest Atlantic, CAFSAC (1978, p. 150) provided the following definitions:

F_{max} is the instantaneous rate of fishing mortality which maximizes the yield-per-recruit (dynamic pool model).

F_{msy} is the instantaneous rate of fishing mortality generated by the fishing effort which gives the maximum sustainable yield (general production model).

F_{opt} is a general term meaning an optimal level of instantaneous fishing mortality. Originally this term was used to mean $F_{0.1}$, but present usage is restricted to specific cases where "optimum" is defined in some way other than $F_{0.1}$.

$F_{0.1}$ is the instantaneous rate of fishing mortality (calculated from a yield-per-recruit curve) at which a unit increase in fishing effort (proportional to fishing mortality) will give an increase in yield 1/10th that of a unit of effort on the virgin stock (dynamic pool model).

7.3.2.1 Northeast Atlantic

Introduction

Table 7.3.2.1 lists the assessment reports selected for review with respect to the important stocks delineated in Section 7.1.

ICESa (1990, p. 11) reported the following caveat concerning national catch records reported to ICES: "During recent years, there has been an increasing concern with respect to the unreliability of the reported catch data". Alternate sources were recommended, such as the ICES Cooperative Research Report series, or unpublished reports of the relevant assessment working groups. For

recent stock assessments, national catch records used in stock assessments were adjusted, by appropriate members of working groups, for unreported landings, misallocation of catches by area or species, slipped catches, discards at sea, and by-catches from industrial fisheries. There, informal "corrections" were made to the catch statistics. Cushing (1990) noted the problem, and attributed the cause to the pressures of national catch quotas. He remarked that improved "policing" under the European Economic Council would alleviate the problem. However, Parsons (1993) reported that in 1990, the Netherlands' Fisheries and Agriculture Minister resigned, because his staff had submitted falsified landing records of cod and plaice to the EEC, in order to conceal the attainment of catch quotas, and prevent fisheries closures. Furthermore, the author quoted the Eurofish Report of January 31, 1991, as stating that fishery inspection facilities in EEC member states were "woefully inadequate", based on a survey conducted during 1990. Numbers of port inspectors was no more than half of the number required, and aerial surveillance was either inadequate or absent in most member countries.

ARCTO-NORWEGIAN (I+II)

Catch Records

Prior to 1920, the fishery was primarily based on spawning cod (skrei) in Division IIa (Fig. 2.3) (Saetersdal and Hylen 1964). Principal gears were line and gillnet. After 1920, trawling, by other national fleets, developed for feeding cod in the Barents Sea (Subarea I), and the Bear Island-Spitzbergen Shelf (Division IIb).

Annual catches in the skrei fishery, during 1866-1957, fluctuated substantially (14.3-65.4 million cod), but generally declined after 1947 (Saetersdal and Hylen 1964). During 1960-91, annual catches (mostly skrei) in Division IIa ranged from 99,000 t (1990) to 335,000 t (1972) (ICESb 1993b, Table 2.1.2.1). Other relatively important peaks occurred in 1969 (256,000 t), 1978 (263,000 t), and 1987 (245,000 t). The provisional estimate for 1991 was 155,000 t.

Catch records for the entire stock were first collected in 1903 (Table 7.3.2.2). Five-year mean annual catches rose irregularly from ca. 220,000 t for 1906-10 to ca. 510,000 t for 1936-40. After 1945, catches peaked at 936,000 t for 1956-60, and at 893,000 t for 1966-70; declined to 364,000 t for 1981-85; then rose slightly to 381,000 t for 1986-90. During 1950-91, mean annual catch, as used by the working group, was 691,000 t (187,000-1,343,000 t) (Table 7.3.2.3). During 1983-91, annual catches rose from 278,000 t in 1984 to 523,000 t in 1987, then declined to 187,000 t in 1990. The 1991 catch was 258,000 t. During 1961-90, nominal catches ranged from 187,000 t (1990) to 1,197,000 t (1969), with other peaks in 1962 (909,000 t), 1974 (1,102,000 t), 1977 (905,000 5), and 1987 (523,000 t) (ICESb 1993b, Table 2.1.2.1).

Stock Assessment

Fifteen reports were reviewed (Table 7.3.2.1). Principal analyses dealt with catch statistics, spawning stock biomass, recruitment, fishing mortality, yield-per-recruit, stock-recruitment relationship, replacement ratios, and simulations analyses.

Catch statistics. Analysis of the 1866-1957 data revealed that after 1947, the Barents Sea trawl fishery had substantially reduced the numbers of spawning cod, independent of the natural fluctuations (Saetersdal and Hylen 1964). During 1946-63, total catch remained relatively stable at 800,000 t/y, but effort increased steadily while CPUE declined 80% (Garrod 1967). No subsequent CPUE records were found.

Spawning stock biomass (SSB). During 1950-91, mean SSB was 513,000 t, and the range was 149,000-1,526,000 t (Table 7.3.2.3). During 1983-91, SSB declined from 326,000 t in 1983 to 149,000 t in 1987; then rose to 680,000 t in 1990, and to a provisional 1,056,000 t in 1992 (ICESb 1993b). The recent increase was attributed to reduced fishing mortality, early maturation (especially the 1983 year-class), and improved growth. In 1993, the 1983 year-class is expected to comprise 34% of the SSB.

Recruitment. During 1902-83, year-class abundance varied by at least a factor of 10 (Saetersdal and Loeng 1987). "High abundance" year-classes were 1904, 1918-19, 1937, 1950, 1963-64, 1970, and 1983. Similar results were reported by Bergstad et al. (1987) for 1946-83. During 1950-91, mean annual recruitment was 604 million (112-1,819 million) age-3 cod (Table 7.3.2.3). During 1983-91, recruitment peaked at 894 million in 1986; declined to 140 million in 1990; then rose to 227 million in 1991. The provisional estimate for 1992 was 370 million (ICESb 1993b). However, year-classes 1984-88 were rated poor, and the 1989-91 year-classes as below average. Decadal mean annual recruitment at age 3, during 1957-83, declined from 813 million during the 1950s to 475 million during the 1980s (Table 7.3.2.4).

Fishing mortality (F). Mean annual F (ages 5-10,u) during 1950-91 was 0.64 (0.19-1.02) (Table 7.3.2.3). During 1983-91, values peaked at 1.02 in 1987, then declined to 0.19 in 1991. Provisional value for 1992 is 0.31 (ICESb 1993b). Both 1.02 (1987) and 0.19 were record values.

Yield-per-recruit (YPR). Four analyses were reviewed, and all indicated that overfishing was evident. Clayden (1972) investigated the effects of the new, mobile trawl fleets on 10 stocks, or substocks, in the north Atlantic. His Beverton-Holt YPR analysis, for 1946-66, involved only the two feeder substocks (I and IIb). He concluded that both were overexploited. The 1966 yield was 32% of the theoretical maximum for the Barents Sea (I), and 68% for Bear Island (IIb). Garrod's (1977) analysis (using data from ICESb 1970) indicated that for the entire Arcto-Norwegian stock, in 1965-66, maximum YPR would be achieved with one third less effort. Ulltang (1987), using data for 1970-83, estimated an increase in yield of ca. 250,000 t/y, if mesh size was increased from 120 mm to 150 mm, and F was reduced to F_{max} for the exploitation pattern for the new mesh size. The general conclusion had been reported earlier (Ulltang 1984), but details were not included. Current long-term estimates for F_{max} and $F_{0.1}$ are 0.25 and ca. 0.14, respectively, and are both below the estimate of $F_{current}$ (0.31) (ICESb 1993b).

Stock-recruitment (S/R). Results of the two S/R analyses were contradictory. Garrod and Jones (1974) fitted a Ricker stock-recruitment curve to the data for 1942-68. Saetersdal and Loeng (1987), using data for 1902-83, reported that a S/R relationship did not seem to exist, "except at extremely low levels of spawning stock size" (op. cit., p. 267).

Replacement ratio (RR). Garrod (1973) investigated the RRs with respect to F for two clupeid stocks, three Atlantic cod stocks (Arcto-Norwegian, Iceland, and West Greenland), three stocks of haddock, and Pacific halibut. Replacement was defined as the ratio of numbers in a filial year-class, at age of recruitment (age x), to the mean numbers of each year-class contributing to the parental generation in the same year (x). Fishing mortality was the mean F on each year-class in the spawning stock in year x, up to and including x-1, except to year x if the fishery was based on the spawning stock. For the Arcto-Norwegian cod, during 1945-67, recruitment failure was evident after 1964.

Simulation analysis (SA). Three analyses were reviewed. Garrod (1969) employed the Schaefer general production model to assess seven cod stocks, or substocks, in the north Atlantic. For the Arcto-Norwegian feeder substocks (ICES I+IIb), he concluded that current effort assured maximum yield, but cautioned that excluding the skrei fishery (ICES IIa) led to overestimating the effort necessary to achieve maximum yield. Garrod and Jones (1974) linked their Ricker S/R curve with the annual value of F required to harvest surplus production (assuming M = 0.3). They noted that SSB was currently substantially below the

optimum level, last seen in the early 1950s. Optimum equilibrium SSB would provide an annual equilibrium yield of about 800,000 t with the current mesh size of 130 mm, at F = 0.26. At F >0.43, SSB would decline. A 25-y projection of a computer simulation suggested that equilibrium yields would be larger at mesh sizes of 145 and 160 mm. Corresponding optimum values of F were 0.4 at 145 mm, and 0.5 at 160 mm. Ulltang (1987) conducted simulation analyses, starting with the VPA-estimated stock size at the beginning of 1970, and ending at the end of 1982, for different exploitation patterns and rates. All options involving lower values of F and larger mesh sizes yielded substantial increases in net production.

Summary. The ACFM concluded that severe management measures have reduced fishing mortality substantially, and the stock has responded by increasing rapidly (ICESb 1993b). Continued fishing at current fishing mortalities would help maintain the spawning stock biomass at a healthy level and stabilize the fishery by providing a buffer for recurring periods when recruitment is reduced as a result of adverse environmental conditions. However, uncertainties in the assessment were noted, viz., problems with age readings and survey methods, and the expected decline in the capelin stock. Effects of the latter might be alleviated by the increase in the herring stock.

ICELAND (Va)

Catch Records

Formal collection of catch statistics, by participating nations, began in 1906 (Fridriksson and Taning 1948). During 1906-90, five-year mean annual catches rose irregularly from 120,000 t, for 1906-10, to 415,000 t for 1931-35; declined to 192,000 t for 1941-45 (restricted fishing due to the war); rose again to a peak of 500,000 t for 1961-65; then levelled off at 353,000-396,000 t for 1966-90 (Table 7.3.2.2). Mean annual catch (used by the working group), during 1955-91, was 394,000 t (284,000-538,000 t) (Table 7.3.2.3). During 1985-91, catch rose from 325,000 t in 1985 to 392,000 t in 1987, then declined to 313,000 t in 1991. The provisional estimate for 1992 was 250,000 t (ICESb 1993b).

Stock Assessment

Thirteen reports were reviewed (Table 7.3.2.1). Principal analyses involved catch statistics, total stock biomass, stock-recruitment, fishing mortality, yield-per-recruit, and the general production model.

Catch statistics. Analytical problems arose due to immigration and year-class abundance. Immigration of spawning cod from Greenland was intermittent, at times substantial, and difficult to quantify (Palsson et al. 1989; Schopka, 1993). Catches during 1906-66 were found to be largely dependent on the abundance of individual year-classes (Jonsson 1954; ICESb 1969b). ICESb (1969b) reported that abundant year-classes were 1922, 1924, 1931-36, 1942-45, and 1949-56. Gulland's (1961) analysis of catch statistics (CPUE/E) for 1906-57 suggested that MSY would be achieved by doubling effort, however he noted that his analysis did not include an unpublished YPR relationship of J. Jonsson, the effects of long-term environmental trends, or immigration from Greenland.

Total-stock biomass (TSB). TSB, corrected or uncorrected for immigration, declined irregularly, from ca. 2-3 million tonnes during 1941-55 to ca. 1.0-1.5 million tonnes during 1969-90 (Schopka 1993, Fig. 3).

Spawning-stock biomass (SSB). During 1955-91, mean SSB was 556,000 t (194,000-1,428,000 t) (Table 7.3.2.3). SSB has shown a declining trend since 1955, and since 1985 has been close to the lowest level on record (ICESb 1993b). During 1985-91, SSB declined from 272,000 t in 1986 to 194,000 t in 1988; rose

to 352,000 t in 1991. The provisional estimate for 1992 was 211,000 t (ICESb 1993b).

Recruitment. During 1955-91, mean annual recruitment was 210 million age-3 cod, with a range of 86 million to 432 million (Table 7.3.2.3). During 1985-91, annual recruitment oscillated between 86 million (1989) and 343 million (1987). The provisional estimate for 1992 was 150 million (ICESb 1993b). ICESb (1993) reported that year-classes 1985-89 were all poor. During 1952-83, decadal means were relatively stable, at 196 million to 227 million (Table 7.3.2.4).

Recruitment assessment was complicated by the intermittent, and at times substantial, emigration of eggs and larvae to east and west Greenland, and their return as spawners. The problem was sufficiently serious in 1980 and 1981, that trawl surveys were introduced to provide additional information to supplement or replace VPA (Palsson et al. 1989). Schopka (1993) noted that trawl surveys for juveniles would underestimate year-class abundance when appreciable emigration to Greenland occurred. Apparently the returning adults remain in Icelandic waters. Schopka (op. cit.) investigated the impact of immigration, during 1941-90, and developed a method for correcting stock estimates. He found that without a correction, stock size was overestimated and F was underestimated. The year-classes containing detectable quantities of immigrants were: 1936-38, 1942, 1945, 1950, 1953, 1961-63, 1973, and 1984. One example of the impact was the 1945 year-class--very large in Greenland, but only average in Iceland. Beginning in 1953 the Greenland immigrants appeared on the Iceland spawning grounds, and comprised some two thirds of the total year-class on Iceland grounds. VPA estimated stock biomass to be 900,000 t with immigrants, and 200,000 t without immigrants. A more serious problem arose when the strong 1973 year-class immigrated in 1980 and 1981. The apparent increased biomass, and decreased F, were incorrectly attributed to the reduction of foreign fishing effort in 1977 and 1978 resulting from the extension of Iceland's fishery jurisdiction. An optimistic, but incorrect, TAC was imposed in 1982.

Replacement ratio (RR). Garrod's (1973) analysis indicated no recruitment failure during 1936-59.

SSB-Recruitment. Cushing (1982a) reviewed this relationship for the 1920-67 year-classes. A relatively flat curve described the relationship, with optimum SSB = ca. 600,000 t. Year-class abundance fluctuated substantially. Ocean warming began in the 1920s, and the most abundant year-classes were 1931-35. The author suggested that the onset of the Russell Cycle (Cushing and Dickson 1976) presaged a decline in cod production in the north Atlantic Ocean.

Fishing mortality (F). Estimates of F (5-10,u) rose steadily from ca. 0.1 in 1941 to 0.6-0.8 in 1970, then fluctuated at 0.4-0.9 through 1990 (Schopka 1993, Fig. 4). During 1955-91, mean F-at-age (5-10,u) was 0.58, with a range of 0.30 to 0.99 (Table 7.3.2.3). Since 1985, F ranged from 0.66 (1985) to 0.99 (1988), and was 0.80 in 1991.

Yield-per-recruit (YPR). For 1946-66, Clayden (1972) reported that the stock was slightly overexploited (F_{max} = 0.3), and current yield was ca. 78% of the theoretical maximum. The spawner fishery was not included in his analysis. ICESb (1969b) provided estimates of maximum yield, based on four options of altering effort (spawning/non-spawning fisheries and domestic/foreign vessels), four options of mesh size (increasing current mesh size from 100 mm to 110, 120, 130, and 140 mm), and three estimates of M (0.05, 0.15, and 0.30). They assumed complete mixing of the exploited and non-exploited portions of the immature stock. In all cases, increasing effort would reduce CPUE, and the catch would contain more younger fish and less older fish. Based on a "long-term" S/R relationship (through 1991), $F_{current}$ is close to F_{high} (ca. 0.82) and far above F_{med} (ca. 0.43) (ICESb 1993b, Fig. 2.6.2).

Simulation analysis (SA). The single Schaefer-type analysis, for 1946-66, indicated that the stock was slightly overexploited (Garrod 1969). Actual fishing intensity was to the right of the value producing the maximum yield in weight. However, the author noted that the spawner fishery was not included in

the analysis.

Summary. For 1992, ACFM concluded that the stock had reached a level of exploitation which will bring it below the minimum biologically acceptable level. SSB has been generally declining since 1955. Fishing rate is excessive, and must be reduced substantially in order to reduce the declining trend in SSB. Climate may also be a factor in the decline. Cushing (1982a) attributed the initial increase in Iceland stocks since the 1920s to a favorable, but temporary, change in climate.

BALTIC SEA (III/22,24-32)

Catch Records

Formal collection of catch statistics, by participating nations, began in 1911 (Thurow 1974). During 1911-90, five-year mean annual catches for the Baltic Sea proper (Subdivisions 22, 24-32) were negligible through 1935 (2,000-7,000 t); rose sharply to 163,000 t for 1956-60; dipped to 128,000 t for 1961-65; resumed the rise to 422,000 t for 1981-85; then declined sharply to 220,000 t for 1986-90 (Table 7.3.2.2).

For the West Baltic stock (SDs 22 and 24), during 1965-91, mean annual catch (used by the working group) was 40,000 t (15,000-54,000 t) (Table 7.3.2.3). During 1983-91, catches declined steadily from 48,000 t in 1984 to 15,000 t in 1991. Catches peaked in 1968 (51,900 t), 1973 (54,400 t), and 1981 (51,300 t), but declined thereafter (ICESb 1993c, Table 3.1.3).

For the East Baltic stock (SDs 25-32), during 1970-91, mean annual catch (used by the working group) was 218,000 t (122,000-391,000 t) (Table 7.3.2.3). During 1983-91, catch declined from 391,000 t in 1984 to 122,000 t in 1991. During 1965-91, catches peaked in 1969 (170,000 t), 1976 (203,000 t), 1980 (348,000 t), and 1984 (391,000 t) (ICESb 1993c, Table 3.1.4).

Stock Assessment

Six stock assessment reports were selected for review (Table 7.3.2.1). Principal analyses involved catch statistics, spawning stock biomass, recruitment, fishing mortality, yield-per-recruit, and recruitment variability factors. One report provided an evaluation of ICES stock assessments.

Catch statistics. Thurow (1974) summarized available catch statistics for 1911-69, and noted that a directed trawl fishery for cod in the open Baltic Sea began in the 1920s, "when the flatfish stocks were depleted" (op. cit., p. 87). Estimated fishing effort, during 1931-53, appeared to increase 2.5 to 7.0 times after the early 1930s. Estimates were derived by dividing appropriate annual catches by intermittent records of research- and commercial-vessel CPUEs. Bagge et al. (1993) reviewed the catch statistics, primarily of the East Baltic stock, for 1911-90, and the intermittent CPUE data from research and commercial vessels. They discounted the value of research-vessel CPUEs. Their preferred source was the mean daily catch by USSR trawlers during 1948-56 (120-hp vessels) and 1974-88 (150-hp vessels) which operated in eastern Gothland Deep (SD 28). CPUE declined from 1.82 t/d in 1948 to 1.14 t/d in 1953, then rose to 1.66 t/d in 1956. In the latter period, CPUE rose irregularly from 2.5 t/d in 1974 to 5.00 t/d in 1980, then declined to 1.24 t/d in 1988.

Spawning-stock biomass (SSB). For the West Baltic stock, during 1965-91, mean annual SSB was 35,000 t (14,000-49,000 t) (Table 7.3.2.3). During 1983-91, SSB declined irregularly from 40,000 t in 1985 to 14,000 t in 1991. The provisional estimate for 1992 was 14,000 (ICESb 1993c). For the East Baltic, during 1970-91, mean annual SSB was 461,000 t (178,000-811,000 t). During 1983-91, SSB declined steadily from 775,000 t in 1983 to 170,000 t in 1991 (Table

7.3.2.3). The provisional estimate for 1992 was 115,000 t (ICESb 1993c). Bagge et al. (1993, Fig. 2) reported, for 1966-90, that SSB rose irregularly from ca. 200,000 t in 1966 to ca. 800,000 t in 1980, then declined to ca. 210,000 t in 1990, based on tuned VPA (Laurec-Shepherd method; E. Steffensen, Inst. Fish. Mar. Inst., Copenhagen, Denmark, pers. comm. November 1992).

Recruitment. Cushing (1982b) used YPR and catches to estimate the change in recruitment in the Baltic Sea during 1925-57. His estimates of mean annual recruitment, at age 1, increased from 210 million cod during 1925-28 to 3,740 million cod during 1951-57.

For the West Baltic stock, mean annual recruitment of age-1 cod, during 1965-91, was 70 million cod (11-145 million) (Table 7.3.2.3). During 1983-91, recruitment declined irregularly from 93 million in 1983 to 14 million in 1990, then rose to 24 million in 1991. The provisional estimate for 1992 was 51 million (ICESb 1993c). Estimated decadal mean annual recruitment at age 1, during 1969-85, declined from 107 million cod in the 1960s to 54 million in the 1990s (Table 7.3.2.4).

For the East Baltic stock, mean annual recruitment of age-2 cod, during 1970-91 was 347 million cod (54-773 million) (Table 7.3.2.3). During 1983-91, recruitment declined irregularly from 427 million in 1983 to 54 million in 1991. The provisional estimate for 1992 was 57 million for 1992 (ICESb 1993c). The 1985 year-class was the last strong year-class. The 1989 year-class was the poorest on record, and the 1990 and 1991 year-classes appear to be very poor. Estimated decadal mean annual recruitment at age 1, during 1966-85, was 316 million cod in the 1960s, 554 million in the 1970s, and 477 million in the 1980s (Table 7.3.2.4). Bagge et al. (1993, Fig. 2) reported the annual age-2 recruitment for 1966-90, which peaked in 1972 (ca. 450 million cod), 1976 (ca. 790 million), 1979-80 (ca. 650 million), and 1985 (ca. 300 million). Their estimates were based on a tuned VPA, assuming M = 0.2.

Fishing mortality (F). Mean F-at-age (3-7,u) for the West Baltic stock, during 1965-91, was 0.98 (0.73-1.56) (Table 7.3.2.3). During 1983-91, values peaked at 1.56 (1986), and ranged from 0.85 to 0.98 during 1987-90. The 1991 value was 0.73. For the East Baltic stock, mean F-at-age (4-7,u), during 1970-91 was 0.83 (0.51-1.16). During 1983-91, values peaked at 1.16 in 1986, then declined slightly to 0.82-0.95 during 1987-91. The 1991 value was 0.95. Bagge et al. (1993, Fig. 2) reported mean F (4-7,u), during 1966-90, ranged from ca. 0.48 (1980) to ca. 1.1 (1986,1990). Trend was downward during 1966-80, and upward thereafter. They used a tuned VPA, assuming M = 0.2.

Yield-per-recruit (YPR). For the West Baltic stock, ICESb (1993) reported F_{max} to be 0.27, far below F_{91} (0.73), which was in turn less than F_{87-90} (0.85-0.98) (Table 7.3.2.3). $F_{0.1}$ was ca. 0.14 (ICESb 1991b, Fig. 4.1.2). For the East Baltic stock, ICESb (1993) reported F_{max} to be 0.28, far below F_{91} (0.95) and F_{87-90} (0.83-0.96). $F_{0.1}$ was ca. 0.18 (ICESb 1991b, Fig. 4.1.3).

Recruitment variability factors. The unique environment of the Baltic Sea is generally recognized as an important factor determining the abundance of fish stocks therein. The Sea is strongly stratified (Kullenberg 1986), and variable interannual inflow of saline water from the North Sea, at intermediate depth, is a major factor in the successful incubation of the cod eggs. A recent negative factor is eutrophication (Nehring et al. 1989). Details of these and other physical factors will be dealt with in Chapter 8.

Evaluation of assessments. Weber (1988) reviewed the assessments provided by the ICES Working Group on Assessment of Demersal Stocks in the Baltic for 1973-88. He reported that the initial F-estimate in most years was too high, and recruitment was often underestimated, particularly for rich year-classes. These biases were usually eliminated in one or two years for the West Baltic stock, but up to three years were required for the East Baltic stock. He evaluated the quality of the major assessment components as follows: (1) recruitment indices--good for the West Baltic stock; bad, but improved somewhat, for the East

Baltic stock; and (2) estimates of F, CPUE, and effort--bad for both stocks; biased due to shoaling behaviour and ice. He also noted that management was bad for both stocks, and was the cause of depletion of the West Baltic stock.

Summary. In its 1992 assessment, the ACFM expressed concern over both stocks. They noted that the West Baltic stock continues to decline with respect to SSB and recruitment, while F remains high. SSB is currently the lowest on record. No improvement is likely unless F is reduced. For the East Baltic stock, both SSB and recruitment were at record low levels, and the ACFM concluded that the stock was in a depleted state. They recommended no fishing be allowed in 1993. The ACFM further recommended that West Baltic and East Baltic stocks be managed as separate units.

The initial rise in abundance of the two stocks was attributed to strong inflow of high-saline water, and resulting strong year-classes. Catches were further increased by increased effort. Inflows have been relatively weak in recent years; eutrophication has increased substantially; and effort has not decreased in proportion to stock decrease. If inflow were the only factor initiating stock increase, one wonders why there were no records of substantial fisheries in past centuries. Unless, of course, inadequate fishing gear, inadequate climate for drying cod, or the lack of an inexpensive source of salt were inhibiting factors.

NORTH SEA (IV)

Catch Records

Records of Atlantic cod catches in the North Sea began with 1906, but did not include all participating nations until about 1931 (Holden 1978). However, the records are virtually complete, except for 1939-45, for the principal participants--England, Germany, Netherlands, Norway, and Scotland. During 1906-90, five-year mean annual catches were generally stable (81,000-129,000 t) for 1906-65, except 1936-40 (61,000 t); rose dramatically to 228,000-260,000 t for 1966-85; then declined to 142,000 t for 1986-90 (Table 7.3.2.2). During 1963-91, mean annual catch, as used by the working group, was 207,000 t (86,000-341,000 t) (Table 7.3.2.3). During 1983-91, annual catches declined steadily from 234,000 t in 1983 to 86,000 t in 1991.

Stock Assessment

Twelve published reports were selected for review (Table 7.3.2.1). Principal analyses involved catch statistics, spawning stock biomass, recruitment, fishing mortality rate, and yield-per-recruit. Three evaluations of stock assessment procedures were reviewed.

Catch statistics. ICESb (1969a) examined records for 1906-66, and noted that CPUE generally followed the trend of catch. Holden (1978) examined catch records for 1909-73, and perceived four recent phases--decline, 1920-38; postwar recovery and subsequent decline, 1946-51; relative stability 1952-62; and a substantial increase during 1963-73. He noted that the latter increase also occurred in the catches of plaice, sole, haddock, and whiting, and attributed the increases to recruitment, but found no explanatory factor(s). Daan (1986) reviewed the catch records for 1903-83, and found yield relatively stable throughout the century, until catches doubled in the 1960s, and the amplitude of fluctuations increased. He opined that the increase during the 1960s was not due to the fishery, and considered the cause unknown.

Spawning-stock biomass (SSB). Mean annual SSB was 160,000 t (56,000-263,000 t) during 1963-91 (Table 7.3.2.3). During 1983-91, recruitment declined from 135,000 t in 1983 to a record low of 56,000 t in 1991. The provisional estimate

for 1992 was 51,000 t (ICESb 1993b). The "critical level" was considered to be 150,000 t, and the "safe" level, 280,000 t (ICESb 1991a; 1993). Daan (1986) noted that SSB increased sharply during the 1960s, but he could find no relationship between SSB and recruitment of age-2 cod, during 1954-83.

Recruitment. Mean annual recruitment during 1963-91 was 373 million (108-847 million) age-1 cod, and annual estimates, during 1983-91, ranged from 137 million to 581 million, without trend (Table 7.3.2.3). The provisional estimate for 1992 was 342 million (ICESb 1993b). During 1960-85, decadal mean annual recruitment at age 1 was 337 million in the 1960s, 456 million in the 1970s, and 386 million in the 1980s (Table 7.3.2.4). With respect to the substantial increase in cod recruitment after the 1950s, Cushing (1984) hypothesized that the primary cause may have been an anomalous inflow of Arctic Intermediate Water (AIM) through the Faroe-Shetland Channel, larger than any since 1927. AIM originates from the Norwegian Sea and the East Icelandic Current which contain the highest abundances of Calanus in the northeast Atlantic. This inflow, sustained through 1959, coincided with a three-fold increase in abundance of C. finmarchicus, and a one-month delay in peak abundance which favored the feeding of cod larvae. The author noted that this was possibly the first corroboration of his match/mismatch hypothesis (op. cit., 1975). Brander (1992) examined Continuous Plankton Recorder (CPR) records for 1958-90, but could find no marked trends in timing and abundance of C. finmarchicus. However, he conceded that the smaller sizes were not retained by the CPR. He concluded that "Cushing's multiple regression model resolves the time scale by including the timing of peak abundance of Calanus, but it ignores spatial heterogeneity." (op. cit., p. 401)

Fishing mortality (F). Mean annual F-at-age (2-8,u) was 0.73 (0.47-1.00) during 1963-91, and was relatively stable during 1983-88 (0.82-0.89), but less so during 1989-91 (0.78-1.00) (Table 7.3.2.3). F_{max} was estimated to be 0.25 (ICESb 1991a), far below F_{91}. Cook (1984) found that for both cod and haddock, F-at-age varied directly with age-class abundance, but the problem was less serious for cod, because recruitment was less variable.

Yield-per-recruit (YPR). Five single-species YPR analyses were reviewed (Table 7.3.2.1). All indicated that yield could be increased substantially by reducing F. ICESb (1969a) encountered problems with adequately estimating effort, but concluded that some decrease in F would result in increased yield. Ursin (1982) compared results of single- and multi-species YPR analyses. Single-species analysis (taken from an unpublished report of the North Sea Roundfish Working Group) indicated that YPR would be maximized if $F_{current}$ (0.75) was reduced 30%. Yield would increase 43%, and biomass, 5.9 times.

The only multi-species analysis reviewed (Anderson and Ursin 1977, modified), indicated that a 53% reduction in F (to 0.40) would result in a 31% increase in yield, and a 2.9-fold increase in total stock biomass. The relatively low increase in biomass was attributed to an increase in cannibalism. Furthermore, the increase in cod biomass would cause a reduction in the biomass of the other important "large" species, due to cod predation. Cod prey size varies directly with cod size, and a larger biomass implies more large cod.

Evaluation of assessments. Three reports evaluated various aspects of past assessments of the North Sea cod stock.

(1) Pope and Gray (1983). They investigated the relationship between the precision of assessment data (fishing effort, catch-at-age, and recruitment) and the resulting catch projections for cod, plaice, and sprat. Results from the Monte Carlo simulations suggested that TACs set to maintain status quo were less affected by variability of fishing effort and possibly catch-at-age, than if TACs were set to achieve any other value of F. For example, if for cod, CVs were 15% for fishing effort and recruitment, and 10% for catch-at-age, the CV for projected status-quo F was 18%, and for F_{max} and $F_{0.1}$, 26%. Comparable values if parameter CVs were 30% and 20%, were 27% and 51%, respectively. They noted that a CV for projected F as large as 20% was unsatisfactory for management purposes.

(2) Brander (1987). He compared actual catches to status-quo projections for nine stocks in the ICES area, including North Sea cod (1977-84). Mean prediction error was 17% for "year ahead" (the current source of prediction) and 11% for "current year". Furthermore there was no evidence of improvement in the forecasts over time. He considered the overall mean error of 21%, for all stocks, unsatisfactory, and questioned the procedure of using TACs to alter F. He recommended conducting the assessments later in the year to take advantage of the "current year" data.

(3) Cook et al. (1991). They fitted statistical models to commercial catch-at-age and recruitment data to provide estimates of the variance of forecasted catches (at t+2). Sensitivity analysis indicated that recruitment was one of the most critical ingredients in the yield forecast for North Sea cod. Estimates of SSB were insensitive to poor estimates of recruitment, but TSB was the most sensitive quantity to recruitment. Forecasts of F which would reduce yield by a small amount, say 10%, were unlikely to be accurate. The authors noted that "There is a tendency for assessment working groups to devote considerable effort to the estimation of fishing mortality (F) in year T. While there is no harm in doing this it can direct attention from the important task of obtaining a satisfactory forecast where great care is needed in estimating recruitment." (op. cit., p. 129)

Summary. ACFM's 1992 assessment noted the record-low level of SSB, its expected further decline, and the continuing high fishing mortality rate; and concluded that the cod stock was outside safe biological limits. Substantial reduction in fishing mortality would be necessary to arrest the decline, and return the stock to safe biological limits. The three evaluations of past assessments generally concurred on an unsatisfactory grade. One evaluation suggested that more attention be directed to predicting recruitment.

7.3.2.2. Northwest Atlantic

Introduction

For the eleven important cod stocks identified in Section 7.1, Table 7.3.2.5 contains the list of stock assessment reports selected for review. Principal stocks, based on historical catch records, were Labrador-East Newfoundland (2J3KL) and West Greenland (SA 1) (Fig. 2.4). Their 1960-89 mean annual landings were 374,000 t and 155,000 t, respectively--39 and 16% of the total cod catch in SAs 1-6 (Table 7.3.2.6). Comparable values for the remaining stocks were no more than 33,000-83,000 t-- 3-9%. Accordingly, the former two received individual attention, while the other six were discussed as a group.

NAFOb (1991) also reported problems with catch statistics and sampling data in its Regulatory Area, These included unreported catches, and corresponding lack of sampling data, from non-member nations, as well as, for the first time, underreported catches from member nations.

LABRADOR-EAST NEWFOUNDLAND (2J3KL)

Catch Records

The modern fishery consists of an inshore component using mixed gear (gillnet, line, and trap), and an offshore component using primarily demersal trawls (Harris 1990; Baird et al. 1991). The inshore fishery takes place primarily during summer, and the offshore fishery during winter, on pre-spawning and spawning concentrations. Harris (op. cit.) noted that offshore trawling began in the 1950s, and since 1978, the inshore fishery has expanded offshore as much as 60 miles, with gillnets and longlines.

Historical catch records of 2J3KL cod during 1850-1987 were presented by Harris (1990, Fig. 1). Catches up to 1958 were estimated by various means, and regular reporting began with 1959. For 1850-1958, Harris (op. cit.) estimated the mean annual catch was ca. 250,000 t, and the range was ca. 138,000 t (1854) to ca. 338,000 t (1908). After 1958, catches rose dramatically to a peak of ca. 810,000 t in 1968; declined equally dramatically to ca. 140,000 t in 1978; then rose irregularly to ca. 255,000 in 1987. During 1959-92, mean annual catch was ca. 363,000 t, and the range was 49,000 to 810,000 t (Table 7.3.2.7). During 1988-92, catches declined from 269,000 t, in 1988, to 171,000 t in 1991, and 44,000 t in 1992 (Sinclair 1993, Table 9.1), when the moratorium was imposed in mid-year.

Canadian catches during 1959-89 rarely exceeded 200,000 t/y (Baird et al. 1991). Inshore catches (all Canadian) declined from 160,000 t in 1959 to 34,000 t in 1978; increased to 72,000- 112,000 t/y during 1984-89; then declined to ca. 60,000 t in 1991 (CAFSAC 1992, text figure, p. 3). They comprised 10-30% of the all-nation catch during the 1959-77, and 30-60% thereafter.

Stock Assessment

Stock assessments were prepared by ICNAF prior to 1977. NAFO prepared them for 1977-86; NAFO and CAFSAC for 1987; and CAFSAC for 1988-91. The 1992 assessments were completed by both NAFO (NAFOb 1993) and an ad hoc group, in lieu of CAFSAC, which had been disbanded (Sinclair 1993). Early assessments dealt primarily with reducing growth overfishing, by means of regulating trawl mesh sizes, and hook sizes. TACs, to control catch and optimize yield, were first employed in 1973.

Fifteen published reports were selected for review (Table 7.3.2.5). Assessments involved catch statistics, trawl-net mesh size, total stock biomass, recruitment, fishing mortality, exploitation rate, yield-per-recruit, simulation analysis, biological factors, and environmental factors. Six reports were found which reviewed past methods of stock assessment, and four reviewed the biological and environmental factors which might have contributed to the recent substantial reduction in cod abundance.

Catch statistics. Hodder (1965) noted that for 1954-63, the increase in offshore trawl effort corresponded with decreases in offshore trawl CPUE, inshore catches, and size and age of cod in both fisheries. Pinhorn and Wells (1970) noted that for Subarea 2, and Division 3KL, catch, effort, and CPUE increased during 1959-68. NAFOb (1982) reported that after 1962, relative CPUE (indexed to 1962) declined irregularly to 0.268 in 1977, then increased steadily to 0.780 in 1982.

Mesh size. Beverton and Hodder (1962) reported that overall cod yield, for 3KLM, would be maximized with a minimum mesh size of 127 mm (5"), and that for trawl only, 114 mm (4.5"). They emphasized that their conclusions were valid only if the amount and composition of the fishing activity did not change from that in 1955-58. Subsequently, a minimum mesh size of 130 mm was imposed in the early 1980s (CAFSAC 1990).

Total-stock biomass (TSB). During 1962-91, mean TSB for age 3+ cod, based on sequential population analysis (SPA), was 900,000 t, and ranged from ca. 500,000 t (1976) to ca. 3,000,000 t (1962) (CAFSAC 1992, text figure, p. 5). The estimates for 1992 were 210,000 t, based on a Laurec-Shepherd(L/S)-tuned SPA, and 108,000 t, based on an ADAPT-tuned SPA (Table 7.3.2.7). However, no estimate was made in Sinclair (1993), because of reservations about the possible effects of biological and environmental factors on the estimate of M. SPA was based on the assumption that M was constant, and equal to 0.2 in this case.

Spawning-stock biomass (SSB). During 1962-91, mean SSB for age 7+ cod was 290,000 t, with a range of ca. 80,000 t (1977) to ca. 1,600,000 t (1962) (CAFSAC

1992, text figure, p. 5). The estimates for 1992, based on tuned SPAs, were 15,000 t (L/S) and 22,000 t (ADAPT) (Table 7.3.2.7). No estimate was made in Sinclair (1993), for the reasons cited above.

Resource-assessment surveys (RAS). Canadian surveys during 1986-91 revealed differing trends in catch rates for younger (age 1-5) and older (age 6+) cod. For the younger cod, catch rates declined from ca. 60 cod/tow in 1986 to ca. 19/tow in 1988; then increased to ca. 30-37/tow during 1989-91 (NAFOb 1992, Fig. 8). For the older cod, catch rates declined irregularly from ca. 40/tow in 1986 to ca. 5/tow in 1991. The catch rates for 1992 were the lowest on record for all three divisions (Sinclair 1993).

Recruitment. During 1959-85, decadal mean annual recruitment at age 3 was 726 million cod in "1950s", 760 million in the 1960s, 260 million in the 1970s. and 376 million in the 1980s (Table 7.3.2.4). During 1962-90, mean annual recruitment was ~300 million age-3 cod; range was 150 million (1973-74) to 1,200 million (1966) (CAFSAC 1991; Table 7.3.2.7). Subsequently, estimates of recruitment based on Laurec-Shepherd-tuned SPAs were 64 million in 1991, and 68 million in 1992 (NAFOb 1993; Table 7.3.2.7). Comparable estimates based on ADAPT-tuned SPAs were 101 and 79 million. For 1986-92, L/S-tuned SPA estimates ranged from 64 to 185 million cod, with relatively high values in 1988 (165) and 1989 (185) (NAFOb 1993, text table, p. 6). For the ADAPT-tuned SPA, estimates ranged from 79 to 238 million cod, with relatively high values in 1989 (223) and 1990 (1990). At least the 1986 year-class was the strongest recent year-class. CAFSAC (1991) noted that an investigation was underway to determine if the large year-classes in the 1960s were an artifact produced by SPA. No further references to this investigation were found.

Fishing mortality (F). During 1962-90, mean F was 0.50, and range was 0.25-1.23, based on ADAPT-tuned SPA (Table 7.3.2.7; CAFSAC 1991). Since 1980, F increased sharply to ca. 0.42 in 1985, then fluctuated between ca. 0.40 and 0.54. The 1990 value was ca. 0.40. CAFSAC (1992) provided no estimates of F, but NAFOb (1992,1993) did. The estimates for 1985-91 (NAFOb 1992, text table, p. 26) and 1986-92 (NAFOb 1993, text table, p. 6) were based on ADAPT- and L/S-tuned SPAs. For 1986-92, ADAPT-tuned SPA estimates rose from 0.52 in 1986 to 2.23 in 1991, then declined to 1.17 in 1992. L/S-tuned SPA estimates rose steadily from 0.53 in 1986 to 2.86 in 1992. The recent substantial increase in total mortality rate (Z), was acknowledged in NAFOb (1992,1993) and Sinclair (1993). And it was noted by all that fishing effort had not increased sufficiently to account for all of the apparent increase in F. Hence, M may have increased due to biological and/or environmental conditions.

Exploitation rate (U). During 1962-91, mean U was 0.35, and the range was ca. 0.2-0.6 (Table 7.3.2.7). Values increased irregularly to a peak in 1976, then declined to the minimum in 1980 (CAFSAC 1992, text fig., p. 3). Since 1983, U has fluctuated narrowly around the mean, except in 1991. In that year divergent estimates were ~0.45 (ADAPT) and ~0.67 (L/S). These larger estimates were attributed to an increase in M, due to biological and/or environmental factors, because fishing effort had decreased from 63,000 h in 1988 to 43,500 h in 1991. CAFSAC concluded that the increase in "total mortality" in 1991 could not be explained by fishing alone.

Yield-per-recruit (YPR). All three YPR analyses reviewed used the Beverton-Holt constant-parameter model. Beverton (1965) and Clayden (1972) concluded that current yield was at or near optimum. Pinhorn and Wells (1970) concluded that current effort was "very close to" that necessary to generate MSY in Division 2J, but 30-50% above for Division 3KL. They further noted that no correction had been made for secular changes in fishing power or fleet mobility. Hence, upward trends in CPUE were probably overestimated, and effort was underestimated. Also, the constant-parameter model was only applicable if indeed all relevant parameters were constant. CAFSAC (1990) estimated $F_{0.1}$ = 0.20, and the 1990 estimate of F was ca. 0.40 (Table 7.3.2.7). After 1977, F_{max} was replaced with $F_{0.1}$, as the concept of MSY fell into disfavor. For example, see Larkin (1977).

Simulation analysis (SA). Schaefer-type general production models were employed by Garrod (1969) and Pope (1976). The former concluded that for 1954-66, the yield was at or near MSY, while the latter concluded that for 1959-73, the stock was very seriously overfished.

Biological factors. Suggested factors were emigration to other locations or deeper water, trophic relationships with capelin, and/or predation or competition by seals (CAFSAC 1992; NAFO 1992,1993; Sinclair 1993). Evidence of emigration, particularly to deeper water, was presented. In the 1990s, capelin biomass had declined, based on offshore acoustic surveys, or had remained normal or above normal, based on inshore indices. No decision was reached on the trophic relationship with capelin. Seal predation was not clearly documented. High incidence of cod in seal stomachs was only reported for seals caught in trawls, and the predated cod were largely undersized (<41 cm), and probably were those discarded from the trawl catches. Discussion of competition was limited to speculation.

Environmental factors. Principal factor suggested was a substantial change in the Labrador Current--increased volume, and decreased temperature and salinity (CAFSAC 1992; NAFOb 1992,1993; Sinclair 1993). Suggested consequences were increased mortality, inhibited reproduction, and an alteration of the cod distribution which might be inimical to its survival. Woodhead and Woodhead (1965) cited a number of examples where substantial cod mortalities in the northeast and northwest Atlantic were attributed to anomalously low water temperatures. Curiously, the adult cod appeared to be more sensitive than juveniles, but the sensitivity was least during the summer feeding period. The decline in water temperatures began in the 1980s. Other records linked the local anomalous conditions with those off Iceland and west Greenland, particularly the location and strength of the Iceland Low (see Chapter 8). It was acknowledged that no method was available for incorporating environmental factors in the stock assessment models.

Evaluations of Assessments. By 1987, considerable concern had arisen with respect to the status of the inshore and offshore segments of the 2J3KL cod stock. Following are brief summaries of the six aforementioned stock-assessment evaluations.

(1) Alverson (1987). In August 1987, the Canadian Minister of Fisheries appointed a five-member Task Group on Newfoundland Inshore Fisheries (TGNIF) to "provide an independent analysis of the factors which have influenced the recent (1982-87) declines in the catches of certain inshore fisheries" (op. cit., p. 1). The completed report was submitted in November 1987. With respect to cod stock assessments, TGNIF reached the following conclusions:

1. Stock condition was considered "good", and slowly increasing after 1977, based on a modified SPA. The slow recovery was attributed to past overestimates of stock size and poor recruitment since 1968, perhaps related to excessive removals.

2. The decline of inshore catches was attributed to a complex of factors: (1) changes of availability resulting from predator-prey and/or environmental relationships; (2) slower rebuilding of the major sub-stocks; (3) differential fishing mortalities on offshore sub-stocks prior to inshore migration; (4) potential overfishing on resident inshore sub-stocks; (5) redeployment of effort to other target species; (6) possible effects of fishing on recruitment; and (7) changes in the size at age of cod.

(2) Rivard and Foy (1987). They identified and evaluated the components of error inherent in the catch projection method used in assessment of 18 Canadian Atlantic fish stocks (including 2J3KL cod), and made recommendations for improving catch projections. The first method, retrospective analysis, compared the immediate projection with that obtained some years later by back-calculation. Relative errors in projection of 2J3KL cod catch, at $F_{0.1}$, were +46.9% for 1980 (made in 1979 with 1978 data) and +30.2% for 1982 (made in

1980 with 1979 data). Principal sources of error were estimates of stock size, partial recruitment coefficient, and F. The second method determined the precision of the projections, by calculating the variance of the projections from the variances of the input variables. For cod, variance, as measured by coefficients of variation, was 15-20%, and the principal sources of error were estimates of stock size, partial recruitment coefficient, and $F_{0.1}$. The authors emphasized the need for separate estimates of variance for partially and fully recruited segments of the stock. Partial recruitment could be significantly affected by changes in fleet behaviour and fishing pattern. For example, fleets commonly targetted on large cohorts as soon as they reached marketable size.

(3) Harris (1989,1990). By early 1989, concern over the status of the 2J3KL cod stock caused the Canadian Minister of Fisheries to appoint, in February 1989, a seven-member Northern Cod Review Panel. An interim report was completed in May 1989, and the final report in February 1990. Terms of reference were: "The panel will consider the scientific advice provided by the Department of Fisheries and Oceans on the northern cod stock since 1977 and make recommendations regarding stock assessment methods and means with a view to better forecasting the size, growth potential and behaviour of the stock in the future" (Harris 1990, p. 11).

With respect to stock assessment, the Panel concluded that "the population, the biomass, the spawning population, and the spawning biomass of northern cod are all currently in decline, and that the fishing mortality rate is currently at the level of 0.45 or higher" (Harris 1990, p. 5). In contrast, $F_{0.1} = 0.18$. The leveling off and subsequent decline in the stock after 1984 was attributed to incorrect analyses, which in turn were essentially caused by inadequacies in data series and analytical methods. Catch records were inaccurate (misreporting, high-grading, non-reporting of by-catches); offshore trawl CPUEs overestimating abundance, and inshore CPUEs not available; and research vessel survey data with a relatively large variability. Analytical methods relied on SPA, using bulk biomass, and yielded divergent results with commercial (optimistic) and research (pessimistic) data. The Panel expressed confidence in the new SPA, which employed ADAPT[5], modified to include mortality at age, rather than bulk biomass. Three other tuning methods were also employed--L/S (Laurec and Shepherd 1983), XSA (Doubleday 1981), and CAGEAN (Deriso et al. 1985). All produced results which bracketed those of ADAPT.

The Panel suggested that less reliance be placed on mathematical models based on convenient assumptions, and that future models incorporate more data on the biology of cod and its physical environment. Furthermore, more attention should be paid to qualitative and anecdotal information.

(4) Baird et al. (1991). They reviewed the history of the fishery, stock-assessment procedures, and management goals, and noted that during the 1988 autumn assessment, it became evident that previous assessments had substantially overestimated TSB. The new estimate of $F_{0.1}$ catch for 1989 was 125,000 t, less than half the previous estimate. They offered four reasons for the overestimations. First, a review of data quality since 1962 revealed that data collected prior to 1978 were inadequate, and had to be discarded. Second, the tripling of commercial catch rates during 1978-85 was partly due to changes in fleet efficiency, rather than simply an increase in stock size. Third, the new calibration time series (1978-date) was short, and was vulnerable to unique single-year values e.g., the anomalously high 1986 research-vessel index. Four, the tuning methods used prior to 1988 were too subjective. The introduction, for the 1989 assessment, of ADAPT reduced the subjectivity; provided new insights into the process; and reduced, but did not eliminate, the difference between stock-size estimates based on commercial catch rates and research-vessel data. A further refinement in the 1990 assessment was computation of CPUE by age, from both sources.

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[5] Gavaris, S. MS 1988. An adaptive framework for the estimation of population size. CAFSAC Res. Doc. No. 29: 12 p. See also Sinclair et al. (1991) or Mohn and Cook (1993).

(5) Sinclair et al. (1991). They investigated the consistency of population estimates for four stocks of cod (including 2J3KL) and three of haddock, using case studies and simulation analysis. For each stock, assessments, based on ADAPT-tuned SPAs, were undertaken using progressively shorter time series. Results were compared with those utilizing the longest series (reference assessment). For the 2J3KL stock, annual assessments consistently underestimated F, and overestimated recruitment and stock size. Furthermore, SPAs tuned only with research-vessel data produced higher estimates of F, and lower estimates of stock size, than those tuned only with commercial-vessel CPUEs. They noted that even estimates of stock size based on the converged portion of SPAs did not necessarily produce "true" values of stock size, unless catches were not misreported. Simulation studies demonstrated the need for improved precision in abundance estimates and for some measure of the accuracy of catch records.

Summary. The substantial decline in abundance of the 2J3KL cod stock appears to have been attributed entirely to the fishery, based on reports published through 1991. During 1959-76, overfishing was caused by the increase in foreign fleet activities. The evidence for strong year-classes during this period was based on SPAs, now in question. After 1976, foreign fleet activity was substantially reduced, and the stock began to recover. However, domestic fleet activity increased, and recent analyses disclosed that TSB and recruitment were consistently overestimated during 1977-88, while F was underestimated. Inadequate and inaccurate data were also factors. The report for 1992 suggested that a recent change in the Labrador Current (increased flow; decreased temperature and salinity) may have also been a factor in the sharp decline in stock size and recruitment. Anomalous conditions persisted at least through 1991. Drinkwater and Trites (1993) reported that 1990 was the eighth consecutive year of anomalously cold near-bottom (150-175 m) temperatures, but anomalies were decreasing during the last two years.

The continuing decline in abundance of the 2J3KL stock caused the Minister of Fisheries to initially close the Canadian fishery in May 1992 (Sinclair 1993). Subsequently, he declared a two-year moratorium on all cod fishing within the Canadian EEZ in the Labrador-East Newfoundland region (23KLNO) beginning July 3, 1992 (Fedarko 1993; Lear and Parsons 1993). Fedarko (op. cit.) reported that non-biological, as well as biological and oceanographic, factors were attributed to be contributors to the current crisis. Detailed corroboration was provided by the Lear and Parsons (op. cit.) and Sinclair (op. cit.). Lear and Parsons noted additional factors were inadequacies in the data base and the large variances around research-vessel estimates, arising from environmental factors and the behaviour of the cod. Both reports noted that SSB has continued to decline, and the estimate for 1993 was only 20,000 t--the lowest level in the 20th Century.

WEST GREENLAND (1)

Catch Records

Historically, cod occurrence off west (and east) Greenland was described as "periodic" by Hansen (1949). The fishery consists of an inshore/fjord fishery with mixed gear (except trawl), and an offshore fishery by line and trawl.

Qualitative records indicated that substantial quantities of cod were present off west Greenland in the 1820s and 1840s, but not for the remainder of the 19th Century (Hansen 1949). For example, a well-documented, and substantial, fishery took place during the 1840s, throughout what is now NAFO Subarea 1. Meager catches were reported in 1850, and practically none in 1851, or for the remainder of the 19th Century. During the early 20th Century, experimental fisheries and/or scientific expeditions reported that cod were scarce in 1906, 1908-09, and 1911-16. Abundance began to rise in 1917, together with a geographical expansion northward. By 1931 the fishery extended to the northern limit of ICNAF Subarea 1.

Published records of all-nation catches began with 1900 (Hovgard 1993). Five-year mean annual catches were negligible during 1900-29 (op. cit. Fig. 2); relatively stable at ca. 50,000-65,000 t during 1930-49; rose abruptly to 279,000-359,000 t during 1954-69; declined equally abruptly to 91,000 t during 1970-74; and continued to decline to 24,000 t for 1985-89 (Table 7.3.2.6). The sudden increase after 1945-49 was due in part to expansion of the trawl fishery which increased its share of the catch to approximately 50%. Recently, annual catches were relatively stable at 53,000-58,000 t during 1980-83; declined to 7,000 t in 1986; rose to 112,000 t in 1989; and declined to 20,000 t in 1991 (NAFOb 1990, 1991; ICESb 1993b). Coincident with the decline in production was the geographical contraction of fishery to the southernmost divisions of Subarea 1.

Stock Assessment

Eighteen published reports were selected for review (Table 7.3.2.5). Principal analyses involved catch statistics, total biomass, recruitment, trawl-net mesh size, yield-per-recruit, replacement ratio, and simulation analysis.

Catch statistics. CPUEs of six "sister" Greenland trawlers (500-999 GRT), accounting for 90% of the Greenland trawl effort, were utilized to assess abundance during 1975-89 (NAFOb 1990). They were indexed to 1989 (= 100%), and exhibited zeniths in 1978 (ca. 62%) and 1981-82 (ca. 60-61%) (op. cit., Fig. 1). Nadirs occurred in 1975 (ca. 12 %), 1980 (ca. 35 %), and 1985 (ca. 14%). For 1990, the index was probably no more than 40% (NAFOb 1991, text table, p. 47). TACs were first imposed in 1974.

Mesh size. Early assessments were concerned with optimizing mesh size to reduce growth overfishing. Beverton and Hodder (1962) reported the optimum mesh size for cod in Subarea 1 was 5.0-5.5" (127-140 mm). Further studies led ICNAF to recommend a minimum mesh-size of 130 mm, which went into force in 1968 (Horsted 1969).

Total-stock biomass (TSB). Estimates for 1982-90 ranged from 24,900 t (1984) to 547,600 t (1988) (Table 7.3.2.7), based on SPA and autumn trawl surveys (NAFOb 1990, Table 3). The sharp reduction to 40,000 t in 1990 was attributed to emigration of the 1984 and 1985 year-classes to east Greenland and Iceland (NAFOb 1991). For 1985-91, ICESb (1993, Table 2.6.1) provided a survey-based "stock biomass index". Values rose from 65,000 t in 1985 to 678,000 and 648,000 t in 1987 and 1988, respectively; then declined to 49,000 t in 1991.

Recruitment. Substantial fluctuations in recruitment have been the norm since the current fishery began in the 1920s (Hansen 1954). Important, but unquantified, early year-classes were 1917, 1922, 1924, and 1926, followed by 1934, 1936, 1942, and 1945, the latter two the strongest of all. Subsequent strong year-classes were 1956, 1961, 1969, 1968, 1973, and 1984 (Cushing 1982b; Stein and Mestorff 1990). During 1953-84, recruitment, at age 3, ranged from ca. 10 million (1978,1982) to ca. 530 million (Hovgard 1993, Fig. 2). During 1953-86, decadal mean annual recruitment, at age 3, declined from 235 million in the 1950s to 62 million in the 1970s, and 100 million in the 1980s (Table 7.3.2.4). However, these data concealed the fact that only one year-class dominated the recruitment in each of the latter two decades--1973 (220 million) and 1984 (500 million) (Hovgard op. cit., Fig. 2). Both year-classes originated in Iceland, and a substantial portion of each emigrated to Iceland when they reached maturity. The latest strong year-class is 1984 (Table 7.3.2.7). Subsequent surveys have revealed that the 1985-90 year-classes are all weak (NAFOb 1991).

Recruitment to the inshore stocks has remained relatively stable, with modest fluctuations in year-class strength. These stocks are apparently not affected by immigration or emigration. Hovgard (1993) acknowledged that climate variability was an important factor in the recruitment of West Greenland cod. A detailed treatment of this factor appears in Chapter 8.

Fishing mortality (F). The most recent estimate was ~0.40, for 1989 (Table 7.3.2.7). No recent estimates have been reported because of the substantial emigration of the 1984 and 1985 year-classes (NAFOb 1991; ICESb 1993).

Yield-per-recruit. Gulland (1968) and Horsted (1969) used the FAO Yield Tables (Beverton and Holt 1964) to compute yield curves. Gulland (op. cit.) concluded that the 1965 effort was 35% greater than that providing maximum yield. Horsted (op. cit.) concluded that either the present effort was too high, the mesh size was too small, or both. The recent imposition of the minimum mesh size of 130 mm would produce a 10-35% increase in yield, and an additional 6-10% in yield, if effort was reduced by 39-63%. Clayden (1972) applied a modified, fixed-parameter Beverton-Holt analysis, and concluded that the 1966 values for northwest and southwest Greenland were 109% and 85% of their respective maxima. For 1975-89, NAFOb (1990) estimated $F_{0.1}$ = 0.409, F_{max} = 1.363 ("not well defined"), and $F_{current}$ = 0.49, via tuned SPA. NAFOb (1991) employed the same technique, and estimated $F_{0.1}$ = 0.43, for 1991, but did not estimate F_{max}. The latter two analyses included an exponent for emigration, as a source of "mortality"--0.25 for the 1984 and 1985 year-classes, and 0.15 for the others. M was assumed to be 0.2.

Replacement ratio. Garrod (1973) calculated the replacement ratio (F/RR) and reported no recruitment failure during 1948-63.

Simulation analysis. Gulland (1968) and Garrod (1969) utilized the Schaefer general production model for data from 1959-64 and 1954-66, respectively. Both concluded that "current" fishing effort was not far from the optimum to achieve MSY.

Other. Stein and Mestorff (1990) concluded that extremely high fishing pressure during the 1960s and recruitment failure during the climatic cooling period in the early 1970s resulted in a considerable reduction in stock size.

Summary. The current decline in cod abundance off west Greenland, primarily the offshore segment, has been attributed to adverse climate, emigration, and excessive fishing effort, but no quantitative evaluation of these factors was found. The current situation is analogous to that of the Baltic Sea stock.

OTHER (3NO,3Ps,3Pn4RS,4TVn/J-A,4Vn/M-D,4VsW,4X,5Zjm,5Z6)

Catch Records

Long-term, tabular data were found for six stocks (3NO,3Ps,3PnRS,4TVn,4VsW,5Z6) (Table 7.3.2.6). Five-year mean annual catches generally fluctuated without trend during 1950-89, except for 3NO, where catches were substantially smaller after 1970-74. Zeniths occurred in 1965-69 for 3NO, 3Ps, and 5Z6, and 1980-84 for 3Pn4RS, 4TVn, 4VsW, and 5Z6. Mean annual landings for 4TVn(Jan-Apr), 4Vn(May-Dec), 4X, and 5Zj, respectively, were 67,200 t (1950-91), 8,500 t (1970-91), 22,000 t (1948-91), and 17,400 t (1978-91) (CAFSAC 1992).

Stock Assessment

Table 7.3.2.5 lists the reports reviewed for the "Other" stocks, and Table 7.3.2.7 and 7.3.2.8 lists the most recent information available. Pertinent information was not uniformly available for all stocks.

Mesh size. Early assessments were concerned with optimizing mesh size to reduce growth overfishing. In 1955, ICNAF recommended a minimum mesh size of 4.5" (114 mm) (Martin (1957). Martin considered that a good first step, and suggested that a mesh size of 5.5-6.0" (140-152 mm) was "practicable" to optimize yield in NAFO Divisions 4TVWX, together with equivalent hook sizes. Beverton and

Hodder (1962) reported the optimum mesh size for cod to be 5.5" (140 mm) in NAFO Divisions 3NOP and Subarea 4, and 6" (152 mm) in Subarea 5, based on the effort expended during 1957-58. Minet (1978) recommended 155 mm for cod in 3Pn4RS, based on data for 1973-76. However, the increased fishing effort, and catch, in the 1960s and 1970s clearly indicated that mesh-size regulations alone would not be satisfactory as a conservation measure.

Total-stock biomass (TSB). Among stocks, estimates of mean TSB ranged from ~62,000 t (5Zjm; 1978-92) to 329,000 t (3Pn4RS; 1974-92)(Table 7.3.2.7 and 7.3.2.8). No estimates were found for 4Vn(May-Dec) or 5Z6. All 1992 TSB estimates were below average.

Spawning-stock biomass (SSB). Among stocks, estimates of mean SSB ranged from 41,000 t (5Zjm; 1978-92) to 161,000 t (4TVn/Jan-Apr; 1950-93)(Table 7.3.2.7 and 7.3.2.8). No estimates were found for 4Vn(May-Dec). All estimates were below average.

Recruitment. During 1950-89, decadal trends in recruitment were positive for the 3Pn4RS and 4TVn stocks; negative for 3NO and 4VsW, and stable for 3Ps (Table 7.3.2.4). Among stocks, mean annual recruitment ranged from 9 million cod (5Zjm; 1978-92) to 114 million cod (3Pn4RS; 1959-91)(Table 7.3.2.7 and 7.3.2.8). No estimates were found for 3Ps, 4TVn(Jan-Apr), and 5Z6. Current recruitment is below average for all stocks, except 3NO (35 million) and 5Zjm (~12 million). Among stocks, the most recent strong year-class ranged from 1980 (4TVn/Jan-Apr) to 1987,1989 (3Ps).

Fishing mortality (F). Mean values ranged from ca. 0.4 (3NO; 1959-92) to ca. 0.54 (4TVn/Jan-Apr; 1950-92)(Table 7.3.2.7 and 7.3.2.8). No estimates were found for 4Vn(May-Dec). Current estimates were above average for all stocks, except 3Pn4RS. $F_{current}$ was greater than $F_{0.1}$ in all cases where comparisons were possible--3NO, 3Ps, 3Pn4RS, 4TVn(Jan-Apr), 4VsW, 4X, and 5Z6.

Exploitation rate (U). Estimates of U first appeared for 1991 (CAFSAC 1992), in place of estimates of F. Mean values ranged from 0.34 (4X) to 0.38 (4TVn)(Tables 7.3.2.7 and 7.3.2.8). No estimates were found for 3NO, 3Ps, 4Vn(May-Dec), and 5Z6. Estimates for 1991 were below average for 3Pn4RS, and 4TVn, but above average for 4VsW, 4X, and 5Zjm.

Evaluations of assessments. Two reports were found which dealt with stock assessment evaluation for the "other" stocks in the northwest Atlantic.

(1) Rivard and Foy (1987). They identified and evaluated the components of error inherent in the catch projection method used for four "other" cod stocks--3NO, 3Ps, 4TVn, and 4VsW (see 2J3KL section for details). Relative errors in projection of cod catch, at $F_{0.1}$, ranged from -27.5% (3NO) to 204.4% (4TVn) for 1980 (made in 1979 with 1978 data) and -16.2 % (3NO) to 124.5% (4VsW) for 1982 (made in 1980 with 1979 data)(op. cit. Table 2). Principal sources of error were estimates of stock size, partial recruitment coefficient, and F.

(2) Frechet (1991). He reported that 3Pn4RS TSB estimates, for t+1, were initially overestimated by ADAPT-tuned SPA, but steadily improved for that year, with each subsequent annual estimate. The initial error was at least 50%.

Summary. All "other" stocks in the Canadian EEZ appear to be in serious condition, based on the stock assessments for 1992. TSBs and SSBs are declining, and some are currently at record low levels. Recruitment is below average for four of the six stocks for which that information was found. Recent assessments were handicapped by anomalous behaviour of the cod, such as moving to deeper water or a pronounced southward shift onto grounds occupied by other stocks. In the U.S. EEZ, the 5Z6 cod, to 1989, was deemed to be growth overfished, and in danger of recruitment overfishing. Evaluation of assessment methods revealed that "projections" are prone to serious errors.

7.3.2.3. North Atlantic

Three studies dealt with groups of Atlantic cod stocks (Table 7.3.2.9), and two studies provided overviews of the north Atlantic cod stocks (Jakobsson 1992; Parsons 1993).

Garrod (1969) applied a modified Schaefer model to the catch statistics of seven important "stocks"--four in the northeast Atlantic (1946-66), and three in the northwest Atlantic (1954-66). He acknowledged the approximate nature of this form of analysis, but concluded that the northeast Atlantic stocks were fully exploited, and the northwest Atlantic stocks were nearing, or at, that level.

Clayden (1972) noted the technological changes in the north Atlantic trawling fleets, during the 1960s and 1970s. The most important change appeared to be the increase in numbers of large vessels (>900 GRT) capable of fishing anywhere in the north Atlantic. He stated the problem as follows:

> "It is therefore possible to visualize the north Atlantic fish/fishery interaction as a dynamic situation held in its state of balance or imbalance by the distribution of fishing effort between stocks. The basic biological characteristics of the different stocks are the weighting factors affecting the distribution and spread of the different fishing fleets." (op. cit. p. 1)

He created Beverton-Holt models for each of the 10 selected stocks--five each in the northeast (1946-66) and northwest (1955-66) Atlantic. A comprehensive model was created to simulate the fleet reactions to predicted abundances in the individual stocks. The simulation explained satisfactorily the changes in abundance of the northeast Atlantic stocks. Results were not as satisfactory for the northwest Atlantic stocks, perhaps due to insufficient data.

ICESb (1973) reported the results of a joint ICES/ICNAF study of interstock exploitation of north Atlantic cod. Ten stocks were selected for analysis--five each in the northeast and northwest Atlantic (1960-70). The results, with respect to fleet efficiency and mobility, corroborated those of Clayden (1972). For stocks supporting interacting fisheries, 30% of the all-nation catch was taken by vessels of >900 GRT which were capable of working any fishing ground in the north Atlantic. A summary of all past stock assessments led to the conclusion that all stocks considered, except those in the Gulf of St. Lawrence, were fully exploited, and that 95% of the potential yield-per-recruit could be realized with a substantial reduction in effort. They employed the Clayden model to explore the results of alternative management strategies.

Promulgation of 200-mile economic zones in 1977 by the major fishing nations largely eliminated the potential danger of this "pulse" fishing by the mobile fleets.

Jakobsson (1992) reviewed fisheries trends during the 1980s for a number of species in six key areas of the north Atlantic--Barents Sea, Baltic Sea, North Sea, Iceland-Greenland, Canadian coast, and the United States coast. For cod, yields were generally declining in all areas, coincident with excessive fishing mortalities (F substantially greater than $F_{0.1}$). However, environmental factors were considered to be predominant in most cases. Notable were the ecosystem collapse in the Barents Sea, and the weakened or failed recruitments (West Greenland, 2J3KL, and Barents Sea) which coincided with the passage around the north Atlantic, during 1969-82, of the "Great Salinity Anomaly" (Dickson et al., 1988; see Section 8.1.4 for description) For 2J3KL cod, he noted that Koslow et. al. (1987) attributed recruitment variation to large-scale meteorological events rather than spawning stock abundance. Furthermore, the stock collapse occurred during a period of high fishing mortality coincident with a sharp decrease in recruitment. The above-normal recruitment during the 1960s may have been an anomaly, based on historic yield records. Georges Bank was the

only area where fishing rather than environmental events was the predominant factor in the decline in yield of cod and other species. He further noted an interesting event of the 1980s was the appearance of strong 1983 year-classes among several fish stocks off Norway (cod, saithe, and herring) and Iceland (cod, saithe, herring, and capelin). and attributed the event to ocean warming.

Parsons (1993) reviewed scientific assessments and management decisions within the jurisdictions of Norway (Barents Sea), the European Economic Community (North Sea), Iceland, Canada, and the United States. For cod, he noted that incorrect scientific assessments and management decisions (such as ignoring scientific advice) contributed to the general decline in stocks throughout the region, but also acknowledged that recruitment variability due to environmental factors was also a factor. He noted that one handicap in stock assessments was inaccurate catch records, due to "cheating" by fishermen, fish plants, and even fisheries agencies.

7.4. SUMMARY

Stock Delineation

Pacific cod. Ocean-wide genetic studies detected two major groups--Asian and American. Intra-group differences were minor, except for the anomalous stock off west Korea. Detailed reports on stock delineation primarily dealt with cod off British Columbia and northern Washington State. In British Columbia waters, eight (nine ?) important stocks were provisionally identified--four in Georgia Strait, one off the west coast of Vancouver Island, two in Queen Charlotte Sound, and possibly two in Hecate Strait. Delineation was based on tagging studies, parasites, size at maturity, and/or time of spawning. Intermixing was relatively light, except for cod in Georgia Strait which intermingled with those in adjacent waters. In Washington State waters, three stocks were identified in the waters of Puget Sound and Georgia Strait, based on tagging studies and locations of spawning grounds. Elsewhere, no stock delineation reports were found for Alaska, although two stocks were informally acknowledged; ten stocks were identified in the northwest Pacific, but no details were provided; and off Korea, East and West Coast stocks were delineated by length-frequencies.

Atlantic cod. Ocean-wide genetic studies indicated little variation among areas. Baltic Sea cod were different from all other Atlantic cod, West Greenland and Gulf of Maine cod differed from cod off Iceland and Europe, and Iceland and Barents Sea cod differed from Norwegian Coastal and North Sea cod. One study noted the high genetic variability within areas and the low genetic differentiation between areas. Numerous stocks are recognized. Some stocks undertook substantial migrations between feeding grounds and spawning grounds, and some individual tagged cod wandered widely. In the northeast Atlantic, four stocks accounted for 89% of the mean annual catch during 1956-90. In order of importance, these were the Arcto-Norwegian (Northeast Arctic), Iceland, Baltic Sea, and North Sea stocks. In the northwest Atlantic, eight stocks accounted for 91% of the mean annual catch during 1960-89. The Labrador-East Newfoundland (Northern) and West Greenland stocks accounted for 55%, and the remaining six accounted for 3-9% each.

For most important stocks of Pacific and Atlantic cod, sub-stocks were acknowledged, but not incorporated in assessments for management purposes.

Mortality and Exploitation Rates

Pacific cod. No reports were found on mortality or exploitation rates in the northwest Pacific. In the northeast Pacific, various methods were employed for estimating Z, M, and F, and although all produced relatively high values,

overfishing has not ensued to date--a testimony to the rapid growth and short lifespan. "Best" estimates, among regions off British Columbia were: Z = 1.01-1.63; M = 0.58-0.78; and F = 0.35-0.75. Of some interest was the apparent reciprocal relationship between M and F in Queen Charlotte Sound. For the three stocks in Puget Sound and vicinity (Washington State), estimates of Z ranged from 1.01 to 1.85, and for the small fishery on spawning cod at Port Townsend, 1.45-1.71. For the Gulf of Alaska, efforts to estimate mortality rates were postponed, pending solution of the age-determination problem. However, renewed effort in 1993 produced annual estimates of F for 1978-93, and a single estimate of M (0.27). For the eastern Bering Sea, only one report provided estimates of all three parameters--Z = 0.60; M = 0.44; and F = 0.16. More recent estimates of M in the latter region were 0.22 and 0.29.

VPA-based estimates of exploitation rates in British Columbia waters were 0.27 for west Vancouver Island, 0.13 for Queen Charlotte Sound, and 0.27 for Hecate Strait. Comparable values based on mortality rates ($U = (1 - e^{-z})F/Z$) were 0.32, 0.21, and 0.35. The only estimate for cod in Washington State waters was that for the Port Townsend fishery--0.10-0.11, based on the aforementioned mortality-rate method. In Alaskan waters, mean estimates, based on catch/biomass proportions, were 0.054 (0.017-0.091) in the Gulf of Alaska, 0.106 (0.054-0.201) in the eastern Bering Sea, and 0.075 (0.071-0.086) in the Aleutian Islands.

Atlantic cod. In the northeast Atlantic, maximum estimates of Z ranged from 1.20 (North Sea) to 1.67 (East Baltic Sea). Substantial temporal increases in Z were reported for the Iceland, Baltic Sea, and North Sea stocks. Estimates of M, for fully recruited cod, generally varied narrowly around 0.2 or 0.3, in sharp contrast to the higher estimates (0.59-0.69) reported for Pacific cod in British Columbia waters. Notable exception was the estimate of 0.40 for the Baltic Sea stock, which is characterized by few age-classes and rapid growth. Maximum estimates of F for the major stocks ranged from 1.0 (Iceland) to 1.16 (East Baltic). Only for the Arcto-Norwegian stock has F been substantially reduced recently. No estimates of exploitation rate were found.

In the northwest Atlantic, maximum estimates of Z for the two major stocks were >1.40 (Labrador-East Newfoundland), and 1.25 (West Greenland). Among the other six stocks, maximum estimates ranged from 0.51 (3NO) to 1.15 (3Pn4RS). Estimates of M generally ranged narrowly around 0.2. Maximum estimates of F were 1.2 for Labrador-East Newfoundland, 1.05 for West Greenland, and 1.18 (4TVn/Jan-Apr) for the remaining six stocks. For most stocks, F has been reduced recently. Estimates of exploitation rate for the Labrador-East Newfoundland stock ranged from ca. 0.2 to ca. 0.6, during 1962-91, based on tuned VPAs. For the other Canadian stocks, maximum range was ca. 0.18-0.66, for the 4VsW stock. No reports of exploitation rate were found for the West Greenland stock, or for stocks in the U.S. EEZ.

Stock Assessments

Pacific cod. Analyses have increased in sophistication, but continue to yield, with one or two exceptions, the conclusion that cod abundance fluctuations are without trend, and merely reflect the passage of strong year-classes through the fishery. Explaining and predicting these fluctuations remain to be achieved. Encouraging progress has been made with cod in Hecate Strait.

In British Columbia, the virtual collapse of the fishery in Georgia Strait and vicinity was attributed to economics, and the retirement of the older fishermen. Off west Vancouver Island, the rise in importance of a fishery on the small, and only important, spawning ground has created the possibility of recruitment overfishing. To date, intermittent regulations may have forestalled overfishing. In Queen Charlotte Sound, large sections of "untrawlable" ground, and the lack of a winter fishery, have to date precluded concern over the possibility of recruitment overfishing. However, recent substantial improvements in navigational and fish-finding equipment may soon create some concern. In Hecate Strait, recruitment overfishing may have occurred twice, to a small

extent, and a spawning biomass of 4,000 t (± 1,000 t) was estimated to be the minimum necessary to preclude recruitment overfishing. The 1992 assessment, oriented to MSY, concluded that recruitment overfishing was a current threat, and recommended catch restrictions. Growth overfishing was recognized as a problem with respect to pre-recruits of large year-classes, but minimum mesh-size restrictions were deemed impractical, because the preferred mesh size for cod was inappropriate for the other important demersal species in the region. The mixed-species nature of the cod fishery was noted in one report, and relatively important, but unexplained, reciprocal relationships were noted between catches of cod and lingcod, off west Vancouver Island and in Queen Charlotte Sound. Three other factors in stock assessments remain to be resolved, i.e., firmer estimates of M, restandardization of effort to correct for recent substantial improvements in vessel efficiency, and investigation of the reciprocal relationship between the catches of lingcod and Pacific cod off west Vancouver Island and in Queen Charlotte Sound.

In Puget Sound and vicinity, all cod stocks exhibited sharp declines in recent years. Available, but inconclusive, evidence suggested that climate, predation, and fisheries could be factors.

In Alaskan waters, the 1993 assessments suggested that the Gulf of Alaska "stock" was underexploited, but not the Eastern Bering Sea-Aleutian Islands stock. The latter stock appeared to be approaching recruitment overfishing, as defined by the NPFMC--$F_{current} > F_{30\%}$.

Atlantic cod. In the northeast Atlantic, recent assessments of three of the four important stocks have indicated continued high fishing mortality rates and severe decreases in abundance. Only for the Arcto-Norwegian stock has this trend been reversed, as a result of management measures which severely reduced the fishing mortality rate. The Iceland stock is currently sustaining an exploitation level which will bring it below the minimum biologically acceptable level. The environment, as well as fishing, might be a factor in the stock's decline. The decline of the Baltic Sea stock may be due to fishing as well as environmental factors. Although its initial rise in importance was attributed largely to fortuitous environmental conditions, its decline might have been accelerated by excessive fishing effort, as well as adverse environmental conditions. The North Sea stock continues to decline steadily, and is currently considered to be below safe biological limits. Excessive fishing appears to be the only factor in its decline. In all cases, declines have been attributed to inaccurate assessments and to management-set quotas in excess of those recommended by scientists. In some cases, scientific assessments have been adversely affected by "cheating" (falsifying catch records) by fishermen, fishing companies, and even fisheries agencies.

In the northwest Atlantic, all but two of the eleven "important" stocks were in serious condition. The exceptions, deemed in satisfactory condition, were North Gulf of St. Lawrence, and South Scotian Shelf. Excessive fishing was the accepted explanation for the decline of the other stocks. The Labrador-East Newfoundland stock is currently at such a low level, that a two-year ban on all fishing was imposed in 1992, for that portion of the Canadian EEZ occupied by the stock. A contributory cause may have been adverse environmental conditions, at least since 1989. The history of the West Greenland stock is analogous to that of the Baltic Sea stock. Its rise to importance was also attributed to fortuitous favorable environmental conditions, and its current decline to unfavorable environmental conditions, and perhaps excessive fishing. Of the remaining four, Georges Bank appeared to be in the worst shape--growth overfished, and in danger of recruitment overfishing. Here too, "cheating" has been a problem.

General. The widespread use of stock-recruitment relationships has recently come into question, for high-fecundity teleosts. Empirical evidence of their limitations was provided by Koslow (1992), and corroborative mathematical evidence by Power and Power (1993). Essentially, the weakness of the method lies in the variability in M during the pre-recruitment stage. If the variability is more than slight, small changes in M will result in substantial changes in

survivorship, hence the "noise" in most such data. Thus the credibility is questioned of those models which rely on a stock-recruitment relationship.

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Table 7.1.1. Distribution (%) of recovered Pacific cod tagged by Canada (C) and the United States (U), by area of tagging and recovery, 1954-68. (Source: Westrheim 1984, Tables 1 and 4)

	Tagging Area						
	4A (U)	4B (C)	3A (U)	3B (U)	3Cs (U)	3Cn (C)	5C+5D (C)
Nos. tagged:	10749	6859	30	1716	92	1686	13086
Usable recoveries:[a]	2500	1017	7	109	7	283	3588
Recovery Area							
4A	97.7	8.5	0	4.6	0	0	0
4B	1.9	90.8	0	0	14	1.8	0
3A	0	0	57	0	0	0	0
3B	0.2	0.2	14	88.1	0	0.1	0
3C[b]	0.4	0.6	29	5.5	86	97.7	0
3D	0	0	0	0.9[c]	0	0	0.1
5A+5B	0.3	0	0	0.9[b]	0	0	0.1
5C+5D	0.2	0	0	0	0	0.4	99.7

a. Recovery area known; N = 7511.
b. Not separated by subarea.
c. Recovery area unverified.

Table 7.1.2. Distribution (%), by area, of recovered Pacific cod tagged and released in Areas 4B and 3Cn, January-March 1978-79. (Source: Westrheim 1985, Tables 1 and 22)

Recovery Area	Tagging Area		
	4B		3Cn
	1978	1979	1979
4A	6	8	1
4B	94	86	8
3Cn	0	7	83
3Cs	0	0	1
3B	0	0	2
3A & 3B	0	0	1
3A	0	0	2
3D	0	0	1
Total	100	101	99
Usable recoveries[a]	221	90	146
Nos. tagged	974[b]	1109[b]	1297[c]

a. Recovery area known.
b. Principally ages 1 & 2.
c. Principally ages 2 & 3

Table 7.1.3. Distribution (%) of recovered Pacific cod tagged by United States in Areas 3A, 3B, and 4A, and by Canada at Nanoose (4B/17n), by area of recovery, 1955-79. (Source: Palsson 1990, Table 4)

Tagging			Nos. recovered		% Recovered				
Location	Time	Nos.	Total	Usable	4A	4B	3A-3Cs	3Cn	Other[b]
4A:									
Agate Pass	Winter 77	643	121	60	91.6	6.7	0	1.7	0
Port Townsend	Winter 79	2456	769	78	91.0	5.1	1.3	0	2.6
Bellingham Bay	Apr 68	1318	242	86	94.3	4.7	0	1.2	0
Gulf of Georgia	Jan 67	113	67	23	82.7	13.0	4.3	0	0
Gulf of Georgia	Spring 67	2474	1604	180	94.9	4.5	0.6	0	0
Gulf of Georgia	Jun 70	306	88	74	91.8	8.2	0	0	0
4B:									
Nanoose[c]	Winter 55-59	1975	255	107	42.0 (23.0)	51.3 (73.3)	2.8 (1.6)	3.7 (2.1)	0 (0)
3A:									
Destruction Is.	Jun 67	531	72	18	5.6	0	94.4	0	0
3B:									
Cape Flattery	May 57	215	39	18	22.2	0	61.1	16.7	0

a. Recovery location known. Excluding recoveries in season of tagging.
b. Not explained by author.
c. Values in parentheses calculated from Table 11 in Westrheim (1982).

Table 7.1.4. Incidence (%) of X-cell parabranchial lesions in Pacific cod from British Columbia waters, by area of catch and sampling method, 1968-85. (Source: Westrheim 1987, Table 3)

Area	Sample Type						
	Standard[a]	Special[b]			Research Vessel[c]		
	M + F	M	F	T	M	F	T
4B	0.7	2.2	1.7	1.9	--	--	--
(N)[d]	(43976)	(4377)	(4507)	(8884)			
3Cn	5.2	5.0	2.9	4.1	17.8	18.3	18.1
(N)	(72946)	6459)	(4932)	(11391)	(330)	(520)	(908)
3D	8.4	--	--	--	--	--	--
(N)	(6178)						
5A	11.0	13.2	10.6	11.8	--	--	--
(N)	(15750)	(652)	(761)	(1414)			
5B	3.0	3.5	3.5	3.6	--	--	--
(N)	(7880)	(595)	(664)	(1259)			
5C	1.5	1.2	1.1	1.1	--	--	--
(N)	(33673)	(3033)	(3080)	(6113)			
5D	1.9	1.2	1.0	1.1	--	--	--
(N)	(55942)	(8141)	(8098)	(16239)			
5C + 5D	--	--	--	--	1.6	2.0	1.8
(N)					(687)	(749)	(1436)
Total	3.5	2.8	2.0	2.4	7.4	8.7	8.1
(N)	(236.345)	(23257)	(22042)	(45300)	(1075)	(1269)	(2344)

[a] Conventional dockside sample for length-and age-frequencies.
[b] Sub-samples of Standard samples, to collect suplementary data on gonad maturity and, usually, parabranchial lesions.
[c] Stratified samples collected during April, July, October 1975, and February 1976. See Section 5.5.1 for details.
[d] N = numbers sampled.

Table 7.1.5. Distribution (%), by recovery area, of Pacific cod tagged and released in Georgia and Juan de Fuca straits (Area 4B), 1954-62. (Source: Westrheim 1984, Table 5)

Recovery Area		Tagging Area			
MSA	Location	North of Nanoose (14)	Nanoose (17n)	Gulf Islands (17s + 18)	Juan de Fuca (19)
14	N. of Nanoose	93	7	1	0
17n	Nanoose	5	45	1	0
17s+18	Gulf Islands	0	13	92	4
29+80+ 82+83[a]	S.E. Strait	0	5	2	2
19+20+86[a]	Juan de Fuca	2	26	4	81
3B	N.W. Washington	0	2	0	0
3Cn	S.W. Vancouver Is.	0	2	<1	13
Total		100	100	100	100
Usable Recoveries[b]		61	193	626	48
Nos.Tagged		414	1994	3843	528

a. MSAs 80-86 were subdivisions of Area 4A at the time of analysis, and now are included in the San Juan and Juan de Fuca Management Regions.

b. Recovery area known; N = 928.

Table 7.1.6. Mean annual catches ($x10^3$ t), and percentage of total catch, for principal stocks of Atlantic cod in the ICES (1956-90) and NAFO (1960-89) areas. (Sources: Tables 7.3.2.2 and 7.3.2.6, this study)

Stock	Location	Mean Catch ($x10^3$ t)	%
N.E. Atlantic (ICES)		1956-90	
Arcto-Norwegian	I+II	649	39.1
Iceland	Va	406	24.5
Baltic Sea	IIId	237	14.3
North Sea	IV	189	11.4
Subtotal		1481	89.3
Total	I-XIV	1658	
N.W. Atlantic (NAFO)		1960-89	
Labrador-E. Newfoundland	2J3KL	374	38.9
W. Greenland	1	155	16.1
N. Gulf of St. Lawrence	3Pn4RS	83	8.6
S. Grand Bank	3NO	64	6.7
S. Gulf of St. Lawrence	4TVn	61	6.4
Scotian Shelf	4VsW	51	5.3
St. Pierre Bank	3Ps	49	5.1
Georges Bank	5Z6	33	3.4
Subtotal		870	90.5
Total	1-6	961	

Table 7.2.1. Codes for, and descriptions of, methods used to estimate Z for Pacific cod in British Columbia and nearby waters.

Code[a]	Description
A-F/F	Age-structured model, including environmental factor. (Fournier 1983)
A-F/P	Relates decline in CPUE-at-age to cohort age and cumulative effort. (Paloheimo 1980)
A-F/R-1	Regression of ln N/h-at-age on age, using selected year-classes. Age determined by scales. Slope is an estimate of Z. (Ricker 1975)
A-F/R-2	Regression of ln N/h-at-age on age, using mean A-F among years for selected age-classes. Age determined by Foucher-Fournier computer method. Slope is an estimate of Z. (Ricker 1975)
A-F/R-3	Regression of ln N/h-at-age on age, using mean A-F among selected age-classes within individual year-classes. Age determined by Foucher-Fournier computer method. Slope is an estimate of Z. (Ricker 1975)
A-F/R-4	Regression of ln N/h-at-age on age, usng selected age-classes within individual year-classes. Age determined by Foucher-Fournier computer method. Slope is an estimate of Z. (Ricker 1975)
A-F/R-5	Regression of ln N/h-at-age on age, using selected age-classes (with adjusted N/h) within strong year-classes. Age determined by Foucher-Fournier computer method. Slope is an estimate of Z. (Ricker 1975)
A-F/S	Subtraction. Z = (ln N/h at age i) - (ln N/h at age i+1), for selected age-classes. (Ricker 1975)
A-F/Z	Mean Z for selected age-classes within individual year-classes. Individual Z values estimated by regression. (Ricker 1975)
F + M'	F = qE, where q is estimated by regression (Paloheimo 1980) and E = effort. M' is arbitrarily selected as an estimate of natural mortality.
L-F/vB	$Z = K(L_{\infty} - \bar{l})/(\bar{l} - l')$, where K and L_{∞} are von Bertalanffy growth parameters; $\bar{l}$ = mean length of fish in the catch as long or longer than the length (l') at full recruitment. (Beverton & Holt 1956)
Tag-1	Tagging. Z = -ln [(recaptures in year i+1)/(recaptures in year i)]; where recaptures are corrected for fishing effort and tag loss. (Ketchen 1961)
Tag-2	Tagging. Interrelationship of M, F, effort, and returned tags. Select values of M and F which produce actual number of tags returned. M + F = Z. (Ketchen 1961)

a. Used in Table 7.2.2.

Table 7.2.2. Mortality rates (Z,M,F) for Pacific cod in British Columbia waters, by location, method of estimation, and source. (Asterisks indicate authors' "best" estimates.)

Location[a]			Method[b] (for Z)			Rate	Source
Area	MSA	Grnd		Z	M[c]	F[d]	
Georgia Strait:							
4B	14	--	A-F/R-2	1.03-1.34	0.59	0.44-0.75	Westrheim & Foucher (1987a)
	17n	Nan	L-F/vB	1.27-1.62	--	--	Ketchen (1961)
			Tag-1	1.46 & 1.77	--	--	
			Tag-2	1.68	<1.39	0.27	
			A-F/R-2,3,Z	1.35-1.50	--	--	Westrheim & Foucher (1987a)
	17s+18	GI	A-F/R-2,3,Z	1.11-1.41	--	--	Westrheim & Foucher (1987a)
	19	--	A-F/R-2,3,Z	1.26-1.63	--	--	Westrheim & Foucher (1987a)
	20	--	A-F/Z	1.16 & 1.32	--	--	Westrheim & Foucher (1987a)
West Vancouver Island:							
3Cn+3D	--	--	A-F/R-4	1.08-1.12	0.25-1.12	0.07-0.83	Westrheim & Foucher (1985a)
			A-F/R-5	1.11*	0.58*	0.53*	
	--	--	A-F/P[e]	1.19	0.67	0.52	Foucher & Tyler (1988)
			A-F/S[e]	1.19*	0.69*	0.50*	
3Cn	--	AB	A-F/R-1	1.38	--	--	Ketchen (1980)
		BB	A-F/R-1	1.11	--	--	

Table 7.2.2 (cont.)

Location[a]			Method[b] (for Z)			Rate	Source
Area	MSA	Grnd		Z	M[c]	F[d]	
Queen Charlotte Sound:							
5A+5B	--	--	A-F/R-4	1.06-1.09	1.63-2.05	-0.56--0.96	Westrheim & Foucher (1985a)
			A-F/R-5	1.13*	0.78*	0.35*	
5A	--	--	A-F/R-2	1.33	--	--	Westrheim (1987)
			A-F/R-3	1.47	--	--	
5B	--	--	A-F/R-2	0.98	--	--	Westrheim (1987)
			A-F/R-3	1.07	--	--	
Hecate Strait:							
5C+5D	--	--	A-F/Z	1.05*	0.38*	0.67*	Stocker (1981)
	--	--	A-F/F	--	0.65	--	Fournier (1983)
	--	--	A-F/R-5	1.27*	0.65*	0.62*	Westrheim & Foucher (1985a)
	--	--	A-F/P[e]	1.13	0.67	0.46	Foucher & Tyler (1988)
			A-F/S[e]	1.13*	0.61*	0.52*	
	--	--	F + M'	1.58	0.55, 0.45	1.03, 1.13	Stocker & Hand (1993)
5C	--	HS	A-F/R-1	1.29	--	--	Ketchen (1980)
			A-F/R-4	0.66-1.93	--	--	Stocker (1981)
5D	--	TP	L-F/vB	1.05-1.53	0.83-0.99[f]	--	Ketchen (1964a)
			A-F/R-1	0.02-1.16	--	--	Ketchen (1980)
			A-F/R-4	0.76-2.57	--	--	Ketchen (1980)
			A-F/R-4	0.67-1.35	--	--	Stocker (1981)
		WR	L-F/vB	0.83-1.53	--	--	Ketchen (1964a)
			A-F/R-1	1.11 & 1.17	--	--	Ketchen (1980)

Table 7.2.2 (cont.)

a. MSA = minor statistical area. Grnd = ground: AB = Amphitrite Bank; BB = Big Bank; GI = Gulf Islands; HS = Horseshoe; Nan = Nanoose; TP = Two Peaks; WR = White Rocks.
b. See Table 7.2.1 for details.
c. Unless otherwise noted, M is estimated by regressing Z on effort. The y-intercept is an estimate of M.
d. Unless otherwise noted, F = Z - M.
e. Ages 4-5.
f. For 1950-52, during the early fishery when F was small.

Table 7.2.3. Estimates of exploitation rate (U), by method, area, and source, for Pacific cod in British Columbia waters.

Method[a]	Exploitation rate		Source
	Mean	Range	
Areas 3Cn+3D			
AF/Z	0.32	--	Westrheim &
VPA[b]	0.27	0.10-0.43[c]	Foucher (1985a)
AF/Z	0.29	--	Tyler & Hand
VPA[d]	0.31	0.29-0.34[e]	(1992)
Areas 5A+5B			
AF/Z	0.21	--	Westrheim &
VPA[b]	0.13	0.03-0.33[c]	Foucher (1985a)
Areas 5C+5D			
AF/Z	0.35	--	Westrheim &
VPA[f]	0.27	0.08-0.41[c]	Foucher (1985a)
AF/Z	0.31	--	Tyler & Hand
VPA[g]	0.32	0.29-0.34[e]	(1992)
CA[h]	0.40 (M = 0.45)	0.33-0.46	Stocker & Hand (1993)
	0.45 (M = 0.55)	0.41-0.48	

a. AF/Z = U, where A = 1 - e^{-Z} (Ricker 1975); CA = cohort analysis (Hilborn & Walters 1992)--U = nos. caught/CA-based estimate of nos. in stock; VPA = virtual population analysis (Gulland 1969,1989)--U = nos. caught/VPA-based estimate of nos. in stock.

b. Nos. landed (age 3-7)/Nos. in stock (age 3-7), April-March 1961-62 to 1978-79. Not reported by age-class.

c. Among years.

d. Nos. landed (age 4-7)/Nos. in stock (age 4-7), January-December 1956-90.

e. Among age-classes. See Table 7.3.1.5.

f. Nos. landed (age 3-7)/Nos. in stock (age 3-7), April-March 1965-66 to 1978-79. Not reported by age-class.

g. Nos. landed (age 4-7)/Nos. in stock (age 4-7), January-December 1961-90.

h. Nos. landed (ages 4,5,6+)/Nos. in stock (ages 4,5,6+), January-December 1971-91.

Table 7.2.4. Estimates of Z, by the Beverton-Holt (1956) method (L-F/vB), from the mean length-frequency[a] of Pacific cod landed from Nancose (4B/17n), 1956-60.

Parameters			Z[b]			
		K:	0.21[c]	0.39[d]	0.56[e]	0.71[e]
l'	$\bar{l}$	L_{oo}:	95.6	87.5	77.4	72.8
59	64.02		1.32	1.82	1.49	1.24
60	64.66		1.39	1.91	1.53	1.24
61	65.40		1.44	1.96	1.53	1.19
62	66.15		1.49	2.00	1.52	1.14
63	66.90		1.54	2.06	1.51	1.07
64	67.80		1.54	2.02	1.42	0.94
65	68.52		1.61	2.10	1.41	0.86
66	69.31		1.67	2.15	1.37	0.75

a. Table X in Ketchen (1961).
b. $Z = K(L_{oo} - \bar{l})/(\bar{l} - l')$. See Table 7.2.1 for definitions of terms.
c. Source of K & L_{oo}: C.M. Hand (pers. comm.).
d. Source of K & L_{oo}: Westrheim & Foucher (1987a, Table 3).
e. Source of K & L_{oo}: Ketchen (1961).

Table 7.2.5. Estimates of mortality rates (Z,M,F) and catchability coefficient (q) for Pacific cod landed from Areas 3Cn+3D and 5C+5D, based on the Paloheimo (A-F/P) and Ricker (A-F/S) methods. (Source: Foucher & Tyler 1988)

Method[a]	Age classes	Rates				
		Z	M	F	q'[b]	r[c]
Areas 3Cn+3D						
A-F/P	3-4	0.69	0.19	0.50	3.03	--
	4-5	1.19	0.67	0.52	2.95	--
	5-6	1.46	0.85	0.15	2.33	--
	6-7	1.36	0.22	-0.73	6.85	--
A-F/S	3-4	0.69	0.35	0.34	1.10	0.164
	4-5	1.19	0.69	0.50	1.57	0.205
	5-6	1.46	1.15	0.31	1.00	0.096
	6-7	1.36	0.73	0.63	1.99	0.216
Areas 5C+5D						
A-F/P	3-4	0.63	0.19	0.44	3.03	--
	4-5	1.13	0.67	0.46	2.95	--
	5-6	1.22	0.85	0.37	2.33	--
	6-7	1.16	0.22	0.94	6.85	--
A-F/S	3-4	0.63	0.24	0.39	2.71	0.257
	4-5	1.13	0.61	0.52	3.54	0.352
	5-6	1.22	0.69	0.53	3.65	0.344
	6-7	1.16	0.98	0.18	1.22	0.082

a. See Table 7.2.1 for descriptions.
b. 0.00001q' = catchability coefficient (q).
c. Correlation coefficient for regression of Z on effort.

Table 7.2.6. Estimates of mortality rates (Z,M,F), by location and source, for Pacific cod elsewhere than British Columbia.

Location	Rate			Source
	Z	M	F	
Port Townsend	1.5-1.7	0.7-0.8	0.7-1.0	Karp (1982)
Puget Sound & vicinity:				Palsson (1990)
Overall	1.85	--	--	
North stock	1.35-1.85	--	--	
West stock	1.45-1.79	--	--	
South stock	1.01	--	--	
Gulf of Alaska	0.29-0.48	0.27[a]	0.02-0.21[b]	Zenger & Thompson (MS 1993)[c]
	0.38-0.57[d]	0.35[d]	0.03-0.22[e]	
E. Bering Sea	--	0.30-0.50[f]	--	Low (1974)
	--	0.70	--	Wespestad et al. (1982)
	0.60	0.44	0.16	Bakkala et al. (1986)
	--	0.5	--	Wespestad et al. (1986)
	--	0.22	--	Thompson & Shimada (1987,1988)
	--	0.29	--	Thompson & Shimada (1990); Thompson & Bakkala (1990)
	0.38-0.66	0.35[d]	0.03-0.31[g]	Thompson & Methot (MS 1993)[h]

a. WGSI method.
b. SRA estimates for 1978-93: 0.02-0.09 (1978-89); 0.17-0.21 (1990-93).
c. Reference listed in Footnote 1, Section 7.2, p. 212.
d. LBSM estimates for 1978-93: 0.02-0.09 (1978-89); 0.17-0.22 (1990-93).
e. LBSM estimates for 1978-93: 0.02-0.09 (1978-89); 0.19-0.30 (1990-93).
f. 0.30-0.50 cited by Thompson & Shimada (1990); 0.30-0.45 cited by Thompson & Bakkala (1990).
g. LBSM estimates for 1978-93: 0.31 (1978); 0.03-0.16 (1979-87); 0.23-0.31 (1988-93).
h. Reference listed in Footnote 2, Section 7.2, p. 213.

Table 7.2.7. Estimated exploitation rate (U), by year and source, for Pacific cod in the Gulf of Alaska, 1960-90.

Year	Source	Total catch[a] (10^3 t)	Biomass (10^3 t)				U (%)
			West	Cent	East	Total	
1960-64 Mean	Alverson (1968)	NK[b]	NK[b]	NK[b]	NK[b]	80[c]	--
1973-78 Mean	Zenger & Cummings (1983)	6	40	304	24	358	1.7
1981	Zenger & Cummings (1983)	36	235	152	8	396	9.1
1984	Zenger (1988)	24	170	345	34+[d]	549+	4.4
1987	Zenger (1988)	30+	94	354	34+[d]	482+	6.2
1990	Zenger & Thompson (MS 1993)[e]	75	132	248	22	402	18.7
1981-90 Mean		41	158	275	25	457	9.0

a. Sources: 1973-87, Table 6.2.3, this study.
b. NK = not known. Regulatory areas created in 1978.
c. Excluding INPFC Southeastern Area.
d. Incomplete. Survey limited to western portion of Yakutat Area (144-147 W long).
e. Reference listed in Footnote 1, Section 7.2, p. 212.

Table 7.2.8. Estimated exploitation rate (U), by year, for Pacific cod in the eastern Bering Sea and Aleutian Islands, 1948-49 and 1970-92. (Sources listed below.)

	East Bering Sea				Aleutian Islands		
		Biomass(10^3 t)					
Year	Catch (10^3 t)	Est.	95% CF[b]	U[a] (%)	Catch (10^3 t)	Biomass (10^3 t)	U[a] (%)
1948-49	--	140[c]	---	--	--	--	--
1978	43	312	87-537	13.8	--	--	--
1979	34	792	603-981	4.3	--	--	--
1980	46	913	736-1031	5.0	6	79	7.6
1981	52	840	692-988	6.2	--	--	--
1982	55	1014	875-1153	5.4	--	--	--
1983	83	1126	904-1349	7.4	12	137	8.8
1984	111	1000	873-1127	11.1	--	--	--
1985	133	950	856-1060	13.9	--	--	--
1986	131	1134	993-1275	11.6	12	182	7.1
1987	145	1147	1002-1283	12.7	--	--	--
1988	193	960	810-1109	20.1	--	--	--
1989	165	963	827-1098	17.1	--	--	--
1990	163	709	603-814	23.0	--	--	--
1991	167	533	451-614	31.3	8	170	4.7
1992	126	547	457-636	23.0	--	--	--
1978-92 Mean	189	863		12.6	10	142	7.0

*Sources: 1948-49 (Alverson et al. 1964); 1978-92 (Thompson & Methot MS 1993; Footnote 2, Section 7.2, p. 213)

a. U = annual catch/summer biomass.
b. CF = confidence interval.
c. Data base was 235 trawl hauls at 2-90 m in southeastern Bering Sea (Alverson et al. 1964).

Table 7.2.9. Estimates of mortality rates (Z,M,F), by time and source, for important stocks and substocks of cod in the northeast Atlantic. (ICES statistical units in parentheses.)

Stock	Time	Rate Z	M	F	Source
Arcto-Norwegian (I+II)	"recent"	0.93	0.33	0.6	Garrod (1977)
	1970-89	--	--	0.36-0.97	ICESb (1991a)
	1989	--	--	0.67	
	1950-91	--	--	0.19-1.02	ICESb (1993b)
	1991	--	--	0.19	
Barents Sea (I)	1946-66	0.86	0.29[a]	0.59	Clayden (1972)
	1950-63	--	0.34[a]	--	Garrod (1967)
	1950-63	--	0.10[a]	--	Ricker (1975)[b]
Bear Island (IIb)	1946-66	1.17	--	--	Clayden (1972)
Iceland (Va)	1932-33	0.46	--	--	Jonsson (1954)
	1942-43	0.54	--	--	
	1952-53	0.89	--	--	
	1955-65	0.75	0.32	0.43	Clayden (1972)
	1960-66	--	--	0.16-1.0	ICESb (1969b)
	"recent"	--	--	0.8 & 1.0	Garrod (1977)
	1941-90	--	--	0.1-0.9	Schopka (1993)
	1955-91	--	--	0.30-0.99	ICESb (1993b)
	1991	--	--	0.80	
Baltic Sea (IIId)	1919-68	--	0.40[a]	--	Thurow (1974)
	"recent"	--	--	0.9	Garrod (1977)
W. Baltic Sea (22 & 24)	1965-70	1.34	--	--	Bagge (1974)
	1970-89	--	--	0.68-1.52	ICESb (1991b)
	1989	--	--	0.68	
	1965-91	--	--	0.73-1.56	ICESb (1993c)
	1991	--	--	0.73	

Table 7.2.9. (cont.)

Stock	Time	Rate Z	M	F	Source
E. Baltic Sea (25-32)	1919-21	0.35	--	--	
		0.43-			
	1925-44	0.77	--	--	
	1939-44	0.77	--	--	
		1.12-			
	1948-56	1.39	--	--	
		1.10-			
	1951-68	1.56	--	--	
	1962-66	1.05	--	--	
	1965-69	1.24	--	--	
	1968-71	1.67	--	--	
				0.51-	
	1970-89	--	--	1.16	ICESb (1991b)
	1989	--	--	1.00	
				0.48-	
	1966-90	--	0.2	1.1	Bagge et al. (1993)
				0.53-	
	1970-91	--	--	1.16	ICESb (1993c)
	1993	--	--	0.95	
C. Baltic Sea: (22 & 25)	1925-28	0.80	--	--	Jensen (1959)
	1931-35	0.43	--	--	
	1935-39	1.43	--	--	
	1951-57	1.51	--	--	
			0.17 &		
(26)	1965-77	--	0.19	--	Sparholt (1990)
			0.12-		
		--	0.18	--	
North Sea (IV)	1931-36	0.76	~0.1	0.66	Beverton & Holt (1957)
	NR[c]	--	~0.2[a]	--	Beverton & Holt (1959)
				0.5-	
	1963-83	--	--	1.2	Daan (1986)
	NR	--	~0.2	--	Sparholt (1990)
				0.77-	
	1970-89	--	--	0.90	ICESb (1991b)
	1989	--	--	0.86	
				0.47-	
	1963-91	--	--	1.00	ICESb (1991b)
	1991	--	--	0.93	

Table 7.2.9. (cont.)

Stock	Time	Rate Z	M	F	Source
North (IVa)	1946-66	0.88 & <1.30	--	--	Raitt & Symonds (1967)
North-Central (IVa,b)	"recent"	--	--	0.3	Garrod (1977)
West-Central (IVb)	1959-77	0.76-1.90	0.2	0.56-1.70	Houghton & Flatman (1981)
South	"recent"	--	--	0.5	Garrod (1977)

a. Cited by Sparholt (1990, Table 7).
b. Data from Garrod (1977, Table 3).
c. NR = not reported.

Table 7.2.10. Estimates of mortality rates (Z,M,F), by time and source, for important stocks and substocks of cod in the northwest Atlantic. (NAFO statistical units in parentheses.)

Stock	Time	Rate			Source
		Z	M	F	
Labrador-E. Newfoundland (2J3KL)	1955-66	0.45	--	--	Clayden (1972)
	1959-70	--	0.18[a]	--	Pinhorn (1975)
	"recent"	--	--	0.60 0.28-1.2	Garrod (1977)
	1962-90	--	0.2	0.4	CAFSAC (1991)[b]
	1990	--	--	--	
	1992	--	>0.2		CAFSAC (1992)
West Greenland (1)	1949-50	0.34 & 0.57	~0.20	0.14 & 0.37	Horsted (1969)
	1954-55	0.55 & 0.52	~0.20	0.35 & 0.32	
	1959-60	0.68 & 0.78	~0.20	0.48 & 0.58	
	1960	--	0.15-0.20	0.30-0.50	Gulland (1968)
	1963-64	0.73 & 0.85	~0.20	0.53 & 0.65	Horsted (1969)
	1983-89	--	~0.20	0.13-1.05	NAFOb (1990)[b]
	1989	--	--	0.40	
	1990	--	--	IND[c]	NAFOb (1991)
	1991	--	--	IND[c]	NAFOb (1992)
(1A-D)	1956-65	0.57	--	--	Clayden (1972)
	"recent"	--	--	0.50	Garrod (1977)
N. Gulf of St. Lawrence (3Pn4RS)	1973-76	0.57	0.15-0.20	0.37-0.42	Minet (1978)
	1974-90	--	--	0.37-0.95	CAFSAC (1991)[b]
	1990	--	--	0.5	
N.E. Gulf of St. Lawrence (4RS)	1957-59	0.60 & 0.95	0.20 & 0.35	0.40	Dickie (1963)
	1947-61	--	0.10[c]	--	
	1962-66	0.39[d]	--	--	Wiles & May
		0.65[d]	--	--	(1968)
W. Newfoundland (4R?)	"recent"	--	--	0.3	Garrod (1977)
S. Grand Bank (3NO)	1959-66	0.51	--	--	Clayden (1972)
	"recent"	--	--	0.6	Garrod (1977)
	1959-91	--	--	0.43-1.31	NAFOb(1992)[b]
	1991	--	--	0.42	

Table 7.2.10. (cont.)

Stock	Time	Rate			Source
		Z	M	F	
S. Gulf of St. Lawrence (4TVn)	1960-68	--	--	0.43	Halliday (1972a)
(4TVn,Jan-Apr)	1950-90	--	--	0.28-1.18	CAFSAC (1991)[b]
	1990	--	--	0.28	
Scotian Shelf (4VsW)	1960-69	--	--	0.49	Halliday (1972b)
	1960-69	--	--	0.29-0.57	Halliday (1976)
	1970-74	--	--	0.37-0.67	
	1958-89	--	--	0.3-1.2	CAFSAC (1990)[b]
	1989	--	--	0.38	
S. Scotian Shelf (4X)	1948-90	--	--	0.28-0.88	CAFSAC (1991)[b]
	1990	--	--	0.48	
St.Pierre Bank (3Ps)	1959-68	--	--	0.54	Pinhorn (1972)
	"recent"	--	--	0.5	Garrod (1977)
	1978-89	--	--	0.42-0.96	Moquedet (1993)
	1959-90	--	--	0.33-1.19	CAFSAC (1991)[b]
	1990	--	--	0.3	
Georges Bank:					
$5Z_{j,m}$ (Can.)	1978-90	--	--	0.27-0.58	CAFSAC (1991)[b]
	1990	--	--	0.40	
5Z6 (U.S.)	1964-89[e]	0.41-0.99	0.2	0.21-0.79	Serchuk & Wigley (1993)
	1987-89[f]	0.50	0.2	0.30	

a. Cited by Sparholt (1990, Table 7)
b. F values estimated from text figures.
c. IND = indeterminate due to excessive emigration.
d. Small-mesh trawl survey.
e. Seven time periods; M assumed to be 0.2.
f. Latest time period.

Table 7.3.1.1. List of reviewed assessment reports, by source, time, area, and method[a], for Pacific cod in British Columbia waters, 1963-91.

Source	Time	Area			
		4B	3Cn+3D	5A+5B	5C+5D
Forrester & Ketchen (1963)	1945-60	C',YPR	--	--	--
Ketchen (1967)	1954-66	C",L	C",L	C",L	C",L
Forrester & Smith (1974)	1960-72	C'	--	--	--
Westrheim (1977)	1950-74	--	C	--	C
Ketchen (1979)	1951-78	C"	--	--	--
Ketchen (1980)	1956-76	C'	C",MR	C"[b]	C'
Westrheim (1980a)	1945-77	C'	--	--	--
Westrheim (1980b)	1956-78	C	C'	C'	C'
Stocker (1981)	1956-80	C	C'	C'	C'
Ketchen et al. (1983)	1951-81	C"	--	--	--
Westrheim & Foucher (1985a)	1956-83	C	C",VPA	C",MR, VPA	C",MR, VPA
Tyler et al. (1986)	1956-86	--	C"	--	C"
Westrheim & Foucher (1987a)	1954-84	C",YPR, YPR'/F	--	--	--
Westrheim & Foucher (1987b)	1954-85	--	C",YPR	C	C",YPR
Foucher & Tyler (1988)	1954-86	C"	C",VPA, YPR	C	C",VPA, YPR
Tyler & Foucher (1989)	1956-87	C"	C",VPA, YPR	C"	C",VPA, YPR
Tyler (1990)	1960-87	--	--	--	SA
Tyler & Foucher (1990)	1956-88	C"	C",VPA, YPR	C"	C,SA, VPA

Table 7.3.1.1. - (cont.)

Source	Time	Area 4B	3Cn+3D	5A+5B	5C+5D
Foucher & Tyler (1990)	1956-89	C"	C",VPA	C"	C",SA, VPA
Tyler & Crawford (1991)	1962-81	--	--	--	SA
Tyler & Hand (1992)	1956-90	C"	C",VPA	C	C",VPA
Stocker & Hand (1993)	1955-91	C'	--	--	--
	1956-91	--	C'	C'	C',BIM, BDM,DDM, ASM

a. ASM = age-structured model (Walters MS 1987); BDM = biomass dynamic model (Hilborn & Walters 1992); BIM = biomass index model (Schnute et al. 1989); C = nominal catch only; C' = nominal catch, nominal effort, CPUE; C" nominal catch, standardized effort, CPUE; DDM = delay-difference model (Schnute 1985); L = mean length of landed cod; MR = mortality rates (excluding data cited in previous analyses); SA = simulation analysis; VPA = virtual population analysis (Gulland 1969,1989); YPR = yield-per-recruit; YPR'/F = "catch profitability" (see text).

Table 7.3.1.2. Canadian or Canada-U.S. annual nominal catch (t), equivalent nominal effort (h), and median CPUE (kg/h), by region, for Pacific cod in British Columbia waters, 1955-91. (Source: Stocker and Hand 1993, Tables 3.1-3.4)

Year	Georgia Strait (4B)			W. Vancouver Island (3Cn+3D)			Queen Charlotte Sound (5A+5B)			Hecate Strait (5C+5D)		
	Canada			Canada-U.S.			Canada-U.S.			Canada-U.S.		
	Cat. (t)	Eff. (h)	CPUE[a] (kg/h)	Cat. (t)	Eff. (h)	CPUE[b] (kg/h)	Cat. (t)	Eff. (h)	CPUE[c] (kg/h)	Cat. (t)	Eff. (h)	CPUE[d] (kg/h)
1955	967	9546	101	--	--	--	--	--	--	--	--	--
1956	578	5050	114	1468	7012	209	1753	6001	292	--	--	--
1957	607	4161	146	1814	12061	150	2744	4902	560	--	--	--
1958	650	5277	123	850	4827	176	1178	4682	252	--	--	--
1959	1047	6364	165	907	6784	135	946	3367	281	--	--	--
1960	744	5652	132	635	7099	89	618	2988	207	--	--	--
1961	415	3468	120	420	4198	100	240	882	272	1616	5317	304
1962	479	4870	98	633	5815	109	422	1389	304	1690	6440	262
1963	677	5311	127	1231	6522	189	677	3583	189	2927	7443	393
1964	713	7529	95	1221	5813	210	1275	3059	417	5228	8022	651
1965	484	3185	152	2768	12780	217	1940	5049	384	9119	13022	700
1966	297	2798	106	3136	12212	257	1811	3545	511	9519	12635	753
1967	475	2511	189	1941	11486	169	1501	3144	477	5112	10526	486
1968	349	3974	88	1425	14261	100	960	3043	315	5165	11378	454
1969	388	3280	118	1092	9011	121	699	5095	137	2959	9404	315
1970	502	4089	123	1095	8838	124	299	1467	204	1339	4518	296
1071	740	4766	155	3328	11290	295	928	4664	199	1474	5241	281
1972	630	3504	180	5629	18136	310	2320	8382	277	2694	6160	437
1973	441	2453	180	3712	15883	234	1914	6289	304	4003	6608	606
1974	681	3305	206	3474	13481	258	2292	7518	305	4764	6195	769
1975	991	5165	192	4000	16901	237	2444	6682	366	4982	9020	552
1976	927	3966	234	3797	23277	163	2271	7040	323	5016	11578	433
1977	1148	5183	221	2948	16047	184	1268	5198	244	3523	9293	379
1978	1373	5656	243	1998	10198	196	1959	5430	361	2102	6388	329
1979	1192	3939	304	1861	6690	278	1904	5167	368	4695	10671	440

Table 7.3.1.2 (cont.)

Year	Georgia Strait (4B) Canada			W. Vancouver Island (3Cn+3D) Canada-U.S.			Queen Charlotte Sound (5A+5B) Canada-U.S.			Hecate Strait (5C+5D) Canada-U.S.		
	Cat. (t)	Eff. (h)	CPUE[a] (kg/h)	Cat. (t)	Eff. (h)	CPUE[b] (kg/h)	Cat. (t)	Eff. (h)	CPUE[c] (kg/h)	Cat. (t)	Eff. (h)	CPUE[d] (kg/h)
1980	1606	7143	225	1152	7732	149	1335	4440	301	4540	12998	349
1981	1742	7110	245	918	4999	184	858	2721	315	3182	10157	313
1982	1011	3882	260	1123	7000	160	603	2525	239	2077	5735	362
1983	907	4106	221	694	4745	146	183	783	234	2717	6598	412
1984	652	4103	159	675	3759	180	382	2045	187	1748	5096	343
1985	463	1661	279	493	2432	203	299	1619	185	1064	4162	256
1996	803	4116	195	498	2524	197	241	1110	217	2099	4039	520
1987	1015	4768	213	809	6187	131	3242	7173	452	8870	9801	905
1988	1223	4585	267	1807	11162	162	1849	4749	389	6198	9751	636
1989	604	3055	198	2994	20588	145	765	2488	307	4789	9103	526
1990	114	906	126	1955	12592	155	773	3420	226	3611	8264	437
1991	68	481	141	2188	21239	103	2008	7016	286	7920	20662	383
Mean	749	4349	174	1852	10154	178	1303	4129	302	4088	8588	461

a. October (preceding year)-March (current year); 40% qualification levels; all grounds.
b. Canada; April-December; 10% qualification level; all grounds.
c. Canada; April-September; 25% qualfiication level; minimum landing, 1,000 lb (454 kg). (C.M. Hand, pers. comm.)
d. Canada; January-December; 25% qualification level; all grounds. (C.M. Hand, pers. comm.)

7.3.1.3. List of fishery closures in Area 3Cn, 1978-88. (Source: Tyler and Foucher 1990, text table, p. 63)

Year	Closed period(s)	No. of days open	Area 3Cn catch (t)	
			Jan-Mar[a]	Jan-Dec
1978	Feb 22-Apr 3	53	895	1878
1979	Feb 1-Mar 31	31	303	1677
1980	Jan 1-Mar 31	0	1	977
1981	Jan 1-Mar 31	0	5	856
1982	Jan 1-31	59[b]	624	1086
1983	Jan 1-20, Feb 6-17	58	113	674
1984	No closure	91	290	643
1985	Jan 1-Mar 31	0	124	449
1986	Jan 1-Mar 31	0	44	424
1987	Jan 1-Mar 31	0	18	747
1988	Jan 1-15, Feb 15-29, Mar 15-31	42	561	1652
1989	No closure	90	1880	2754[c]

a. In some years, the closure did not include all of Area 3Cn.
b. During February and March 1982, vessels were limited to 50,000 lb (22.7 t) per trip, and a maximum of two trips per month.
c. Rutherford (1991).

Table 7.3.1.4. VPA estimates, by area, of annual recruitment (millions) of age-2 and age-3 Pacific cod in British Columbia waters, 1956-90. (Sources listed below.)

	Age 2			Age 3		
Year	3Cn+3D	5A+5B	5C+5D	3Cn+3D	5A+5B	5C+5D
1956	1.6	3.4	--	0.8	--	--
1957	2.0	4.7	--	0.7	1.2	--
1958	1.5	2.0	--	0.8	1.7	--
1959	2.5	1.7	--	0.7	0.9	--
1960	1.7	2.7	--	1.2	0.8	--
1961	2.6	3.0	6.7	0.8	1.2	2.6
1962	3.2	4.9	9.8	1.3	1.4	3.6
1963	4.3	3.9	11.4	1.4	2.2	5.2
1964	4.9	5.2	15.9	1.9	1.7	5.8
1965	4.4	2.6	8.1	2.4	2.2	7.7
1966	4.0	5.0	5.7	2.1	1.1	4.2
1967	3.0	1.9	7.9	1.8	2.1	2.8
1968	2.6	5.3	2.8	1.5	0.8	3.6
1969	4.6	1.5	3.5	1.2	2.3	1.5
1970	6.3	4.8	4.8	2.2	0.6	1.6
1971	9.1	5.8	5.0	3.0	2.1	2.4
1972	8.1	4.2	7.6	4.0	2.5	2.4
1973	6.2	3.5	5.5	3.2	1.6	3.4
1974	8.0	3.5	5.8	3.0	1.5	2.5
1975	5.5	4.2	6.2	3.7	1.4	2.4
1976	4.2	3.5	4.8	2.5	1.6	3.0
1977	3.5	3.1	5.7	2.0	1.3	2.2
1978	1.9	1.8	4.3	1.6	1.1	2.4
1979	1.8	--	6.8	0.9	0.7	2.3
1980	2.0	--	3.9	0.7	--	2.7
1981	1.5	--	3.6	0.9	--	1.6
1982	0.8	--	2.7	0.7	--	1.7
1983	2.3	--	2.9	0.3	--	1.3
1984	1.8	--	4.4	1.0	--	1.4
1985	1.1	--	4.7	0.8	--	2.2
1986	5.1	--	8.2	0.5	--	2.5
1987	7.7	--	13.2	2.5	--	4.5
1988	2.9	--	3.8	3.6	--	4.9
1989	1.5	--	2.1	1.4	--	1.7
1990	1.3	--	5.2	0.5	--	0.9
Mean	2.7	3.6	6.2	1.7	1.5	3.0
C.V.(%)	61	36	52	59	37	52

Sources:

3Cn+3D: Tyler & Hand (1992, Table 3.4). F varies with effort. Terminal F at age 7 = 0.5; M = 0.7

5A+5B: Westrheim & Foucher (1985a, Table 3.4.6). Constant F. Terminal F at age 7 = 0.35; M = 0.78.

5C+5D: Tyler & Hand (1992, Table 3.10). F varies with effort. Terminal F at age 7 = 0.5; M = 0.6.

Table 7.3.1.5. Mean F-at-age and U-at-age, by source, area, and time, for Pacific cod in British Columbia waters, 1956-91.

Source	Time	Age					
		2	3	4	5	6	7
Areas 3Cn+3D				**Mean F-at-age**			
Westrheim & Foucher (1985a)	1956-83	0.09	0.41	0.58	0.70	0.59	0.53
Foucher & Tyler (1988)	1956-86	0.09	0.36	0.56	0.66	0.65	0.50
Foucher & Tyler (1989)	1956-87	0.08	0.35	0.55	0.66	0.68	0.50
Tyler & Foucher (1990)	1956-88	0.08	0.33	0.54	0.64	0.65	0.50
Foucher & Tyler (1991)	1956-89	0.08	0.32	0.53	0.64	0.69	0.50
Tyler & Hand (1992)	1956-90	0.08	0.32	0.53	0.65	0.72	0.50
Areas 5A+5B							
Westrheim & Foucher (1985a)	1956-83	0.10	0.21	0.32	0.29	0.42	0.35
Areas 5C+5D							
Westrheim & Foucher (1985a)	1956-83	0.11	0.37	0.55	0.62	0.61	0.62
Foucher & Tyler (1988)	1956-86	0.13	0.39	0.57	0.61	0.58	0.52
Foucher & Tyler (1989)	1956-87	0.13	0.38	0.57	0.60	0.62	0.50
Tyler & Foucher (1990)	1956-88	0.14	0.38	0.58	0.62	0.63	0.50
Foucher & Tyler (1991)	1956-89	0.14	0.37	0.57	0.61	0.61	0.70
Tyler & Hand (1992)	1956-90	0.14	0.38	0.58	0.60	0.60	0.50
				Mean U-at-age			
Areas 3Cn+3D							
Foucher & Tyler (1988)	1956-86	0.06	0.21	0.30	0.34	0.29	0.28
Foucher & Tyler (1989)	1956-87	0.06	0.21	0.30	0.34	0.33	0.28
Tyler & Foucher (1990)	1956-88	0.05	0.20	0.29	0.33	0.33	0.28
Foucher & Tyler (1991)	1956-89	0.05	0.19	0.29	0.33	0.34	0.28

Table 7.3.1.5 (cont.)

Source	Time	Age					
		2	3	4	5	6	7
Areas 5C+5D							
Foucher & Tyler (1988)[a]	1956-86	0.09	0.24	0.33	0.34	0.32	0.30
Foucher & Tyler (1989)	1956-87	0.09	0.23	0.33	0.34	0.33	0.29
Tyler & Foucher (1990)	1956-88	0.09	0.23	0.33	0.34	0.34	0.29
Foucher & Tyler (1991)	1956-89	0.09	0.23	0.32	0.34	0.33	0.29
Tyler & Hand (1992)	1956-90	0.10	0.23	0.33	0.34	0.32	0.29
Stocker & Hand (1992)	1971-91[b]	0.12	0.22	0.41	0.48	0.46[c]	
	1971-91[d]	0.13	0.23	0.42	0.46	0.33[c]	

a. Values computed from their Table 3.10. Values listed in their test were only for 1986.
b. M = 0.55.
c. Age 6+.
d. M = 0.45.

Table 7.3.1.6. Fork length (cm) at 50% retention, by mesh size (mm), for Pacific cod, Dover sole, English sole, rock sole, and lingcod. (Source: Westrheim and Foucher 1987b, Table 3.12)

Mesh size[a] (mm)	Pacific cod		Dover sole	English sole	Rock sole	Lingcod[b]
	FL (cm)	Age[c] (y)	FL (cm)	FL (cm)	FL (cm)	FL (cm)
76	24.4	0.8	24.1	21.6	18.4	28.5/28.9
89	27.6	1.0	28.2	24.8	21.0	32.4/32.9
102	30.9	1.2	32.3	27.9	23.5	36.3/36.8
114	34.9	1.4	36.3	31.8	26.7	39.9/40.5
127	37.2	1.6	40.4	34.3	29.2	43.8/44.4
140	40.5	1.8	44.2	38.1	31.8	47.7/48.3
152	43.6	2.0	48.3	41.3	34.3	51.3/52.0
165	46.8	2.3	52.3	44.5	37.5	55.2/55.9
178	50.0	2.5	56.4	--	--	59.1/59.9
MCS[d]	46/51		38	35	35[e]	58[f]

a. Internal measure. Original measurements in inches.
b. Males/Females. Source: Rogers & Pikitch (1987, Table 6).
c. Age 1.0 on March 1.
d. MCS = minimum commercial size, imposed by processors.
e. Source: Westrheim & Foucher (1987b, text table, p. 28).
f. Richards & Hand (1991).

Table 7.3.1.7. All-gear catch (t) and CPUE (kg/h), and mean demersal-trawl catch (t), by stock, for Pacific cod in Puget Sound and vicinity (4A), 1970-88. (Sources listed below. Original data in pounds.)

Year	Total Catch (t)	Stock: Northern (t)	Northern (kg/h)[a]	Western (t)	Western (kg/h)[b]	Southern (t)	Southern (kg/h)[c]
			All-gear				
1970	711	492	46	154	74	65	5
1971	745	472	61	161	60	112	8
1972	871	481	81	233	100	157	7
1973	559	293	44	115	60	151	11
1974	969	370	42	372	124	227	12
1975	1333	725	72	344	81	264	17
1976	1687	715	64	566	95	406	30
1977	1708	752	56	617	87	339	18
1978	2001	716	36	1010	79	275	26
1979	2224	611	36	1273	80	340	13
1980	2194	716	43	1264	98	214	8
1981	1614	797	41	629	68	188	15
1982	1096	526	32	451	69	119	12
1983	986	510	27	361	87	115	11
1984	1399	864	45	430	76	105	24
1985	1065	628	40	344	87	93	14
1986	795	443	30	271	24	81	10
1987	994	578	39	374	81	42	9
1988	915	351	27	508	49	56	50
Mean	1256	581	45	499	78	176	16
%	100	46		40		14	
			Demersal-trawl				
Mean	904	578		197		129	
%	100	64		22		14	
% All-gear	72	99		39		73	

Sources: catch from Schmitt et al. (1991); CPUE from Palsson (1990).

a. Gulf-Bellingham Management Region--92% of catch from Northern stock.
b. Juan de Fuca Management Region--99+% of catch from Western stock.
c. Central Sound Management Region--85% of catch from Southern stock.

Table 7.3.1.8. Catch and CPUE trends, by stock and region, for Pacific cod in Area 4A. (Source: Palsson 1990, Table 22)

Stock	Region	Catch	CPUE (1970-89)	
			Long-term	Short-term
Northern	Gulf-Bellingham	Stable	Decreasing	Stable
	San Juan	Decreasing	Decreasing	Decreasing
Western	Juan de Fuca	Stable	Decresing	Stable
	W. Juan de Fuca	Erratic	Erratic	Erratic
Southern	Hood Canal	Decreasing	Stable	Decreasing
	Central Sound	Stable	Stable	Decreasing
	South Sound	Stable	Stable	Decreasing

Table 7.3.1.9. Estimates of Z, by five-year periods, for the Northern, Western, and Southern stocks of Pacific cod in Area 4A, 1970-89. (Source: Palsson 1990, Table 20)

Period	Stock		
	Northern	Western	Southern
1970-74	1.35	1.57	--
1975-79	--	1.45	--
1980-84	1.85	1.60	1.01
1985-89	1.53	1.79	--

Table 7.3.1.10. All-nation catches ($x10^3$ t), of Pacific cod in the Gulf of Alaska (GOA), by Regulatory Area[a], 1971-92, and in the eastern Bering Sea (EBS) and Aleutian Islands (AI), 1964-92. (Sources listed below.)

	Regulatory Area[a]							
Year	West	Cent	East	Total		EBS[c]	Ai[c]	EBS+AI[c]
1964	--	--	--	--		13	0.2	14
1965	--	--	--	--		15	0.5	15
1966	--	--	--	--		18	0.2	18
1967	--	--	--	--		32	0.3	32
1968	--	--	--	--		58	0.3	58
1969	--	--	--	--		50	0.2	51
1970	--	--	--	--		70	0.3	70
1971	--	--	--	1		43	2	45
1972	--	--	--	4		43	0.4	43
1973	--	--	--	6		53	1	54
1974	--	--	--	5		62	1	64
1975	--	--	--	6		52	3	54
1976	--	--	--	7		50	4	55
1977	1	1	0.3	2		33	3	36
1978	6	6	0.4	12		43	3	46
1979	4	10	0.5	15		34	6	40
1980	9	24	2.1	35		46	6	52
1981	12	22	2.4	36	(36)	57	7	64
1982	7	20	2.1	29	(29)	89	8	97
1983	9	25	2.0	36	(37)	95	8	103
1984	12	12	<0.1	24	(24)	125	8	133
1985	8	6	0.1	14	(14)	143	7	150
1986	13	11	0.4	25	(25)	136	7	143
1987	2	28	0.4	31	(33)	150	13	163
1988	6	27	0.3	33	(34)	203	5	208
1989	14	28	0.2	42	(43)	178	5	183
1990	33	42	0.2	69	(73)	172	8	180
1991	28	47	0.3	74	(77)	208	10	218
1992	33	42	0.8	76	(80)	162	43	205
1977-92 Total	197	350	13	560		1874	147	2021
%	35.2	62.5	2.3	100.0		92.7	7.3	100.0

Sources:

GOA: 1971-76 from Zenger (1985, Table 1); 1977-92 from Zenger and Thompson (MS 1993, Tables 2.1 & 2.3); reference listed in Footnote 1, Section 7.2).

EBS/AI: 1964-76 from Thompson & Shimada (1988, Table 1); 1977-92 from Thompson & Methot (MS 1993, Table 2.1); reference listed in Footnote 2, Section 7.2).

a. Cent = Central; East = Eastern; West = Western
b. Numbers in parentheses include estimated discards.
c. Estimated discards included for 1981-92.

Table 7.3.1.11. List of reviewed assessment reports, by source, time, and method, for Pacific cod in Alaskan waters, 1970-89.

Source	Time	Method[a]
Gulf of Alaska		
Alverson (1968)	NR[b]	RAS
Laevastu et al. (1982)	1970-76	PROBUB
Zenger & Cummings (1983)	1973-81	RAS;JLLCPUE;MSY_a
Zenger (1985)	1977-83	RAS;JLLCPUE
Zenger & Blackburn (1986)	1977-84	RAS;JLLCPUE;MSY_b
Zenger & Blackburn (1987)	1977-85	RAS;JLLCPUE
Zenger (1988)	1977-87	RAS;JLLCPUE;BHM-1,2
Zenger & Thompson (1989)	1977-88	RAS;R;SRA
E. Bering Sea + Aleutian Islands		
Alverson (1969)[c]	NR[b]	RAS
Laevastu et al. (1982)	1975-76	PROBUB
Bakkala et al. (1983)	1973-82	RAS;JLLCPUE
Bakkala & Wespestad (1984)	1973-83	RAS;JLLCPUE
Bakkals & Wespestad (1985)	1973-84	RAS
Bakkala et al. (1986)	1973-85	RAS
Thompson & Shimada (1987)	1973-86	RAS;EBSM-1
Thompson & Shimada (1988)	1973-87	RAS;SRA;BHM;EBSM-2a,b
Thompson & Shimada (1990)	1973-88	RAS;EBSM-3
Thompson & Bakkala (1990)	1978-89	EBSM-3

a. BHM = Beverton-Holt model (1957); EBSM = E. Bering Sea model; JLLCPUE = Japanese longline fishery CPUE; $MSY_a = 0.4MB_o$ (Gulland (1969), M = 0.6 (Ketchen 1961); $MSY_b = 0.5MB_o$ (Gulland 1975), M = 0.6 (Bakkala & Wespestad 1985); PROBUB = prognostic bulk biomass model (Laevastu et al. 1982); R = recruitment; RAS = resource assessment survey (trawl or longline); SRA = stock reduction analysis (Kimura 1985). See text for explanations of models.

b. NR = not reported.

c. Excluding Aleutian Islands and north Bering Sea.

Table 7.3.1.12. Annual estimates of recruitment (age 3). fishing mortality rate (F), and age-3+ biomass ($x10^3$ t), by method, for Pacific cod in the Gulf of Alaska, 1978-93. (Source: Zenger and Thompson MS 1993)[a]

Year	Recruit. @ age 3 ($x10^6$ cod)	Fishing mortality rate (F)		Age-3+ biomass ($x10^3$ t)		
Method[b]:	LBSM	SRA	LBSM	SRA	RAS	LBSM
1978	40	0.02	0.04	658	--	395
1979	69	0.02	0.04	647	--	434
1980	237	0.06	0.09	635	--	579
1981	90	0.06	0.07	604	--[c]	642
1982	134	0.05	0.05	575	--	717
1983	111	0.07	0.06	555	--	772
1984	107	0.05	0.04	531	571[d]	803
1985	90	-.03	0.02	522	--	821
1986	70	0.05	0.04	523	--	817
1987	143	0.06	0.06	515	559[d]	838
1988	89	0.07	0.06	500	--	828
1989	68	0.09	0.08	485	--	799
1990	78	0.16	0.19	463	379	751
1991	49	0.19	0.23	415	--	658
1992	58	0.22	0.30	367	--	565
1993	63	0.18	0.25	320	--	482
Mean	94	0.08	0.10	520	503	681

a. Reference in Footnote 1, Section 7.2, p. 212.
b. LBSM = Length-based Synthesis Model (Methot 1990); RAS = Resource Assessment Survey (trawl); SRA = Stock Reduction Analysis (Kimura 1985).
c. 1981 estimate excluded--not comparable (G.G. Thompson, pers. comm., January, 1994).
d. Revised estimates (G.G. Thompson, pers. comm., January 1994).

Table 7.3.1.13. Selected results of 1993 stock assessments, by method, for Pacific cod in the Gulf of Alaska (GOA) and the Eastern Bering Sea-Aleutian Islands (EBSAI) Region. (Sources listed below.)

Factor	Gulf of Alaska		E. Bering Sea-Aleutian Is.
Method[a]:	SRA	LBSM	LBSM
M	0.27	0.37	0.37
Age at full selection:			
Trawl	3	3	5
Longline	NR[b]	NR	5
Pot	NR	NR	7
Reference F[c]:			
$F_{30\%}$	0.24	0.41	0.43
$F_{35\%}$[d]	0.20	0.34	0.35
$F_{0.1}$	0.17	0.29	0.54
F_{msy}	n/a[e]	n/a	n/a
Estimated 1993 values:			
F	0.18	0.25	0.47
Catch (t)	50,900	50,900	141,200
Estimated 1994 overfishing levels:			
F	0.24	0.41	0.43
Catch (t)	71,100	79,400	228,000

Sources:

GOA: Zenger and Thompson (MS 1993), listed in Footnote 1, Section 7.2, p. 213.

EBSAI: Thompson & Methot (MS 1993), listed in Footnote 2, Section 7.2.

a. LBSM = Length-based Synthesis Model (Methot 1990); SRA = Stock Reduction Model (Kimura 1985).

b. NR = not reported.

c. $F_{x\%}$ = the fishing mortality rate at which the current SPR is x% of the pristine SPR. See text for details. For definitions of $F_{0.1}$ and F_{msy}, see Section 7.3.2.

d. $F_{0.1} = F_{40\%}$.

e. n/a = not available due to difficulties in defining stock-recruitment relationship.

Table 7.3.1.14. Annual LBSM[a] estimates of recruitment (age 3), fishing mortality rate (F), and age-3+ biomass ($x10^3$ t) for Pacific cod in the eastern Bering Sea, 1978-93. (Source: Thompson and Mehtot MS 1993[b])

Year	Recruit. @ age 3 ($x10^6$ cod)	Fishing mortality rate (F)	Age-3+ biomass ($x10^3$ t)
1978	84	0.31	247
1979	53	0.17	292
1980	531	0.11	737
1981	230	0.09	1103
1982	177	0.07	1355
1983	154	0.09	1492
1984	67	0.11	1442
1985	338	0.13	1460
1986	53	0.15	1355
1987	242	0.17	1357
1988	131	0.24	1301
1989	87	0.23	1148
1990	34	0.25	949
1991	74	0.40	769
1992	216	0.42	678
1993	212	0.47	716
Mean	168	0.21	1025

a. LBSM = Length-based Synthesis Model (Methot 1990).

b. Reference in Footnote 2, Section 7.2, p. 213.

Table 7.3.2.1. List of reviewed stock assessment reports, by source, time, and method, for important stocks of Atlantic cod in the northeast Atlantic.

Source	Time	Method[a]	Source	Time	Method[a]
Arcto-Norwegian (I+II)			Iceland (Va)		
Saetersdal & Hylen (1964)	1866-1957	C,E,CPUE	Jonsson (1954)	1928-53	C,E,CPUE,AF,M
Garrod (1973)	1936-59	F/RR	Gulland (1961)	1906-57	C,CPUE,MR
Garrod (1973)	1946-63	C,CPUE,VPA	Garrod (1973)	1936-59	F/RR
Garrod (1969)	1946-66	CPUE/E	ICESb (1969b)	1923-66	SA
Clayden (1972)[b]	1946-66	YPR	Garrod (1969)	1946-66	CPUE/E
Garrod & Jones (1974)	1942-68	S/R,SA	Clayden (1972)	1946-66	YPR
Hylen & Dragesund (1973)	1963-69	S/R	Cushing (1982a)	1928-70	I,S/R
Bergstad et al. (1987)	1903-83	C,R	Cushing (1982b)	1920-70	R
Saetersdal & Loeng (1987)	1903-83	R,S/R,AB	Myers et al. (1990)	1952-83	R
Ulltang (1987)	1970-83	YPR,VPA,SA	Palsson et al. (1989)	1985-86	RAS
Myers et al. (1990)	1957-83	R	Borovkov & Serebryakov (1993)	1959-84	R/SSB
Serebryakov (1990)	1946-84	R/PF/SR	Schopka (1993)	1941-90	B,F,F/A,I,R
Borovkov & Serebryakov (1993)	1959-84	R/SSB	ICESb (1993)	1955-91	C,F,R,SSB, YPR
ICESb (1991a)	1970-89	C,F,R,SSB, AF,VPA'			
ICESb (1993)	1950-91	C,F,R,SSB, YPR,VPA'			
Baltic Sea (III/22,24-32)			North Sea (IV)		
Thurow (1974)	1911-69	C,E,CPUE, AB,RAS,Z/Y	ICESb (1969a)	1906-66	C,CPUE,YPR
Cushing (1982b)	1921-76	C,R,YPR, AB,R	Ursin & Andersen(1978)	1959-71	MSYPR
Myers et al. (1990)	1960-89	R	Daan (1978)	1920-73	PT
ICESb (1991b)		C,F,R,SSB, VPA',YPR	Holden (1978)	1903-73	C,CPUE,R
			Ursin (1982)	NR	MSYPR,YPR
			Ulltang (1984)	NR	YPR
			Daan (1986)	1903-83	C,F,R,SSB

Table 7.3.2.1. (cont.)

		C,E,CPUE,	Daan (1987)	1974-83	MSVPA,P
Bagge et al. (1993)	1970-89	MR,VPA C,F,R,SSB,	Macer & Shepherd (1987)	NR	MSVPA,P
ICESb (1993)	1911-90	VPA',YPR	Myers et al. (1990)	1960-85	R
	1970-91		ICESb (1991a)	1970-89	C,F,R,SSB, YPR,SA
			ICESb (1993)	1963-91	C,F,R,SSB, VPA',YPR

a. Codes:

AB = abiotic factors.
AF = age frequency.
B = biomass.
C = catch.
CPUE = catch per unit effort.
CPUE/E = CPUE vs effort.
E = effort.
F = instantaneous rate of fishing mortality.
F/A = F at age.
F/RR = F vs replacement ratio.
I = immigration.
M = instantaneous rate of natural mortality.
MR = mortality rates.
MSVPA = multispecies VPA.
MSYPR = multispecies YPR.
P = predation.
PF = population fecundity.
PT = parameter trends.
R = recruitment and/or year-class abundance.
RAS = resosurce assessment survey.
R/PF/SR = recruitment vs population fecundity vs survival rate.
R/SSB = recruitment vs spawning stock biomass.
SA = simulation analysis.
S/R = stock-recruitment relationship.
SR = survival rate.
SSB = spawning stock biomass.
VPA = virtual population analysis (single species).
VPA' = tuned VPA (method not specified).
YPR = yield per recruit.
Z = instantaneous rate of total mortality.
Z/Y = Z vs yield.

b. Excluding the skrei fishery (ICES IIa).

Table 7.3.2.2. Five-year mean annual catches ($x10^3$ t) from important stocks of Atlantic cod in the northeast Atlantic, 1903-90. (Sources listed below.)

Years	Arcto-Norwegian (I+II)	Iceland (Va)	Baltic Sea (III)[a]	North Sea (IV)	Total (I-XIV)
1903-05	E200	--	--	--	--
1906-10	E220	120	--	98	--
1911-15	E350	159	2	129	--
1916-20	E150	113	3	94	--
1921-25	E230	251	6	105	--
1926-30	E330	382	6	87	--
1931-35	E310	415	7	81	--
1936-40	E510	244	30	62	--
1941-45	--	192	65	--	--
1946-50	779	283	101	101	--
1951-55	875	463	137	81	--
1956-60	936	473	163	104	2142
1961-65	629	500	128	120	1451
1966-70	893	392	202	236	1816
1971-75	649	396	216	260	1799
1976-80	693	364	305	228	1677
1981-85	364	353	422	233	1468
1986-90	381	366	220	142	1253
1956-90	649	406	237	189	1658
%	39.1	24.5	14.3	11.4	89.3
Sources:					
Bergstad et al. (1987, Fig. 2)	1903-39	---	---	---	---
Fridrilksson & Taning (1948)	---	1906-38	---	---	---
ICESb (1969b)	---	---	---	1906-39 1946-55	---
Thurow (1974)	---	---	1911-65	---	---
ICESb (1970)	1946-55	---	---	---	---
Gulland (1961)	---	1939-55	---	---	---
ICESa (1958-65)	1956-63	1956-63	---	1956-63	1956-63
ICESa (1966-67)	1964-65	1964-65	---	1964-65	1964-65
ICESa (1987)	1966-80	1966-80	1966-80	1966-80	1966-80
ICESa (1989)	1981-85	1981-85	---	1981-85	1981-85
ICESb (1993b)	1986-90	1986-90	---	1986-90	---
ICESb (1993c)	---	---	1981-90	---	---
FAO (1993)	---	---	---	---	1986-90

a. Subdivisions 22 and 24-32.

Table 7.3.2.3. Information used for assessment of important stocks of Atlantic cod in the northeast Atlantic in 1990 and 1992. (Catch and biomass in 10^3 t; recruitment in 10^6 cod.) (Sources: ICESb 1991a,b;1993b,c)

Information[a]	1983	84	85	86	87	88	89	90	91	Mean	Range
Arcto-Norwegian (I+II)[b]										1950-91	
Nominal catch	328	315	336	454	552	459	343[c]	207[c]	--	--	--
Catch used by WG[d]	290	278	308	430	523	435	322	187	258	--	187-1343
SSB[e]	326	281	199	171	149	156	170	349	680	513	143-1526
Recruitment (age 3)	169	384	508	894	282	230	216	140	227	604	112-1819
Mean F (5-10,u)	.74	.89	.80	.92	1.02	.91	.63	.24	.19	.64	.19-1.02
Iceland (Va)[f]										1955-91	
Catch used by WG[d]	--	--	325	369	392	378	356	335	313	394	284-538
SSB[e]	--	--	271	272	256	194	273	348	352	556	194-1428
Recruitment (age 3)	--	--	145	336	343	175	86	133	123	210	36-432
Mean F (5-10,u)	--	--	.66	.78	.83	.99	.68	.73	.80	.58	.30-.99
West Baltic (III/22,24)[g]										1965-91	
Catch used by WG[d]	47	48	39	26	27	28	18	17	15	40	15[b]-54
SSB[e]	40	38	40	24	18	25	23	16	14	35	14-49
Recruitment (age 1)	93	30	24	68	39	14	20	14	24	70	14-145
Mean F (3-7,u)	.90	.85	1.28	1.56	.90	.85	.92	.98	.73	.98	.73-1.56
East Baltic (III/25-32)[h]										1970-91	
Catch used by WG[d]	332	391	315	252	207	194	179	153	122	218	122-391
SSB[e]	775	768	612	418	375	363	297	240	170	461	178-811
Recruitment (age 2)	427	276	229	244	329	209	120	118	54	347	54-773
Mean F (4-7,u)	.72	.89	.75	1.16	.95	.83	.96	.96	.95	.83	.53-1.16
										1963-91	
North Sea (IV)[i]											
Nominal catch	237	197	188	157	167	142	111	105	84	--	--
Catch used by WG[d]	234	205	193	163	175	150	116	105	86	207	86-341

Table 7.3.2.3. (cont.)

Information[a]	1983	84	85	86	87	88	89	90	91	Mean	Range
SSB[e]	135	116	107	95	86	79	73	62	56	160	56-263
Recruitment (age 2)	269	534	109	568	238	143	246	137	155	373	109-847
Mean F (4-7,u)	.89	.85	.83	.88	.89	.89	1.00	.78	.93	.73	.47-1.00

a. Catch and SSB in 10^3 t; recruitment in 10^6 cod.
b. 1983-84 in ICESb (1991); 1985-91 in ICESb (1993b).
c. Preliminary.
d. "Adjusted" values provided informally to the Working Group (WG). See text.
e. SSB = spawning stock biomass.
f. ICESb (1993b, Table 2.6.2)
g. 1983-84 in ICESb (1991b, Table 4.1.2); 1985-91 in ECESb (1993c, Table 3.1.3).
h. 1983-84 in ICESb (1991b, Table 4.1.3); 1985-91 in ICESb (1993c, Table 3.1.4).
i. 1983-84 in ICESb (1991a, Table 3.5.2); 1985-91 in ICESb (1993b, Table 3.5.7).

Table 7.3.2.4. Decadal mean estimates of annual recruitment (10^6 cod at age i) for important stocks of Atlantic cod, 1940-89. (Source: Myers et al. 1990).

Stock	Loc.[a]	Time	Age i	Decade				
			(y)	40-49	50-59	60-69	70-79	80-89
N.E. Atlantic (ICES Area)								
Arcto-Norwegian	I+II	1957-83	3	--	813	630	533	475
Iceland	Va	1952-83	3	--	196	227	220	213
Baltic Sea	III							
West	22,24	1969-85	1	--	--	107	89	54
East	25-32	1966-85	1	--	--	316	554	477
North Sea	IV	1960-85	1	--	--	337	456	386
N.W. Atlantic (NAFO Area)								
Labrador-E. Newfoundland	2J3KL	1959-85	3	--	726	760	260	376
W. Greenland	1A-D	1953-86	3	--	235	176	62	100
N. Gulf of St. Lawrence	3Pn4RS	1970-82	4	--	--	--	121	148
S. Grand Bank	3NO	1956-84	2	--	74	120	33	35
S. Gulf of St. Lawrence	4TVn	1947-83	3	107	62	93	117	174
Scotian Shelf	4VsW	1957-84	1	--	102	129	88	77
St. Pierre Bank	3Ps	1956-84	3	--	55	64	46	73

a. Location: subarea, division, or subdivision.

Table 7.3.2.5. List of reviewed stock assessment reports, by source, time, and method, for important stocks of Atlantic cod in the northwest Atlantic.

Source	Time	Method[a]	Source	Time	Method[a]
Labrador -E. Newfoundland (2J3KL)			W. Greenland (1)		
Beverton & Hodder (1962)[b]	1955-58	MS	Hansen (1954)	1924-52	C,YC
Beverton (1965)	NR[c]	YPR,C,E,CPUE',LF,AF	Hermann et al. (1965)	1932-52	YC/AB
Hodder (1965)	1954-63	C,E,CPUE'	Beverton & Hodder (1962)	1957-58	MS
Garrod (1969)[d]	1954-66	CPUE/E	Beverton (1965)	NR	YPR
Clayden (1972)[d]	1955-65	YPR	Garrod (1973)	1948-63	F/RR
Pinhorn & Wells (1970)	1964-68	E,CPUE,YPR	Horsted (1969)	1945-65	YPR
Pope (1976)	1959-73	CPUE/E	Clayden (1972)[d]	1956-65	YPR
NAFOb (1982)	1962-82	C,CPUE',RAS,SPA'	Gulland (1968)	1959-65	YPR
Borovkov & Serebryakov (1993)	1959-84	R/SSB	Garrod (1969)[d]	1954-66	CPUE/E
Myers et al. (1990)	1953-86	R	Cushing (1982b)	1920-67	R
CAFSAC (1991)	1959-90	C,CPUE,RAS,SPA"	Hansen & Buch (1986)	1956-84	YC
CAFSAC (1992)	1959-91	C,CPUE,RAS,SPA",BIOL,ENV	Borokov & Serebryakov (1993)	1959-84	R/SSB
NAFOb (1992)	1959-91	C,CPUE',RAS,AF	Myers et al. (1990)	1953-86	R
		W/A,ISPA',BIOL,ENV	Stein & Mestorff (1990)	1982-87	YC/AB
NAFOb (1993)	1959-92	C,AF,W/A,RAS,SPA",	Hovgard (1993)	1900-88	C,RAS,SPA
		ISPA',R/SSB	NAFOb (1990)	1955-89	C,CPUE,RAS,SPA
		BIOL,ENV	NAFOb (1991)	1940-90	C,CPU,RAS,YPR
Sinclair (1993)	1960-92	C,W/A,RAS,ISPA',BIOL,ENV	ICESb (1993b)	1981-91	C,RAS
N. Gulf of St. Lawrence (3Pn4RS)			S. Grand Bank (3NO)		
Beverton & Hodder (1962)	1957-58	MS	Beverton & Hodder (1962)	1955-58	MS
Beverton (1965)	NR	YPR	Beverton (1965)	NR	YPR
Wiles & May (1968)	1947-66	C,CPUE	Clayden (1972)[d]	1959-66	YPR
Pinhorn & Wells (1970)	1964-68	E,CPUE,YPR	Pinhorn & Wells (1970)	1964-68	E,CPUE,YPR
Minet (1978)	1972-75	C,YPR,MS	Myers et al. (1990)	1953-86	R
Myers et al. (1990)	1970-82	R	NAFOb (1991)	1959-90	C,CPUE,RAS,SPA'
CAFSAC (1990)	1961-89	C,CPUE,RAS,SPA'	Borovkov & Serebryakov (1993)	1959-84	R/SSB

Table 7.3.2.5 (cont'd)

Source	Time	Method[a]
N. Gulf of St. Lawrence (3Pn4RS)		
Frechet (1990)	1974-89	SA,SPA',S/R
CAFSAC (1991)	1964-90	C,RAS,SPA'
CAFSAC (1992)	1964-91	C,RAS,SPA'
Sinclair (1993)	1960-92	C,RAS,W/A SPA",BIOL ENV
S. Gulf of St. Lawrence (4tvn)		
Martin (1957)[e]	1938-55	C,YPR,MS
Beverton & Hodder (1962)	1957-58	MS
Beverton (1965)	NR	YPR
Paloheimo & Kohler (1968)	1949-65	MS
Halliday (1972a)	1960-70	C,CPUE,SPA
Lett et al. (1975)	1965-74	S/R
Lett (1980)	1950-77	MSSA
Myers et al. (1990)	1947-83	R
CAFSAC (1992)[f]	1950-91	C,CPUE,RAS
CAFSAC (1992)[g]	1970-91	C,RAS
Sinclair (1993)[f]	1960-92	C,CPUE'W/A, RAS,SPA""
St. Pierre Bank (3Ps)		
Beverton & Hodder (1962)[c]	1955-58	MS
Pinhorn & Wells (1970)	1964-68	E,CPUE,YPR
Pinhorn (1972)	1959-68	RAS,SPA,YPR
Borovkov & Serebryakov (1993)	1959-84	R/SSB
NAFOb (1988)	1959-87	C,E,CPUE,RAS, YPR,SPA
CAFSAC (1991)	1959-90	C,CPUE,
Moquedet (1993)	1978-90	RAS,SPA" RAS,SPA'
CAFSAC (1992)	1959-91	C,CPUE,RAS
Sinclair (1993)	1960-92	C,W/A,RAS, ISPA"
S. Grand Bank (3NO)		
NAFOb (1992)	1959-91	C,CPUE,RAS, SPA"
NAFOb (1993)	1959-92	C,RAS,C/A,W/ A,SPA"
Scotian Shelf (4VsW)		
Beverton & Hodder (1962)	1957-58	MS
Beverton (1965)	NR	YPR
Halliday (1972b)	1960-71	C,YPR,CPUE, SPA
Halliday (1976)	1958-74	C,CPUE,RAS, SPA,YPR
CAFSAC (1990)	1958-89	C,CPUE', RAS
CAFSAC (1992)	1958-91	C,RAS,SA
Sinclair (1993)	1960-92	C,CPUE', RAS,W/A, R/SSB,BIOL, ENV
S. Scotian Shelf (4X)		
CAFSAC (1992)	1948-91	C,RAS,SPA"
Sinclair (1993)	1960-92	C,CPUE,W/A, RAS,SPA"
Georges Bank (5Z6)		
Beverton & Hodder (1962)[c]	1955-58	MS
Beverton (1965)	NR	YPR
Serchuk & Wigley (1993)	1893-1990	C,CPUE,RAS, Z,F,SPA'

Table 7.3.2.5 (cont'd)

Source	Time	Method[a]	Source	Time	Method[a]
			Georges Bank ($5Z_{j,m}$)[h]		
			CAFSAC (1991)	1978-90	C,RAS,SPA'
			CAFSAC (1992)	1978-91	C,RAS,SPA'
			Sinclair (1993)	1960-92	C,RAS,W/A, CPUE',ISPA', YPR

a. Codes:
AF = age-frequency.
BIOL = biological factors (see text).
C = catch.
CPUE = catch per unit effort.
CPUE' = standardized CPUE.
CPUE/E = CPUE vs effort (general production model).
E = effort
ENV = environmental factors (see text).
F = instantaneous rate of fishing mortality.
F/RR = Fishing mortality vs replacement ratio.
ISPA' = illustrative SPA' (assuming M >0.2).
LF = length-frequency.
MS = mesh-size analysis.
MSSA = multi-species simulation analysis.
R = recruitment.
R/SSB = recruitment vs spawning stock biomass.
RAS = resource assessment survey.
SA = simulation analysis.
SPA = sequential population analysis = virtual population analysis or cohort analysis.
SPA' = tuned SPA (method not reported).
SPA" = SPA tuned with ADAPT.
SPA"' = SPA tuned with ADAPT and Laurec-Shepherd.
SPA"" = SPA tuned by HYBRID (Mohn & Cook 1993).
S/R = stock recruitment relationship.
W/A = mean weight at age.
YC = year-class abundance.
YC/AB = year-class abundance vs abiotic factors.
YPR = yield per recruit.

b. 2J & 3KL treated separately.
c. NR = not reported.
d. Primarily prepared for inter-stock assessments. See Section 7.3.2.3 (North Atlantic).
e. Primarily 4T and 4X.
f. 4TVn (Jan-Apr).
g. 4Vn (May-Dec).
h. Canadian sector.
e. Primarily 4T & 4X.
f. 4TVn (Jan-Apr).
g. 4Vn (May-Dec).
h. Canadian sector.

Table 7.3.2.6. Five-year mean catches (10^3 t) from important stocks of Atlantic cod in the northwest Atlantic, 1885-1989. (Sources listed below.)

Years	Stocks[a]								
	1	2J3KL	3NO	3Ps	3Pn4RS	4TVn	4VsW	5Z6	1-6
1885-89	--	--	--	--	--	--	--	82	
1890-94	--	--	--	--	--	--	--	62	--
1895-99	--	--	--	--	--	--	--	58	--
1900-04	--	--	--	--	--	--	--	48	--
1905-09	--	--	--	--	--	--	--	43	--
1910-14	--	--	--	--	--	--	--	37	--
1915-19	--	--	--	--	--	--	--	31	--
1920-24	--	--	--	--	--	--	--	32	--
1925-29	--	--	--	--	--	--	--	40	--
1930-34	E65	--	--	--	--	--	--	--	--
1935-39	E65	--	--	--	--	--	--	--	--
1940-44	E50	--	--	--	--	--	--	--	--
1945-49	E60	--	--	--	--	--	--	--	--
1950-54	279	--	--	--	--	--	--	--	--
1955-59	282	279	74	--	--	--	83	--	--
1960-64	359	514	58	54	106	66	66	20	1404
1965-69	348	649	138	65	71	51	51	42	1560
1970-74	91	429	96	57	73	66	58	27	989
1975-79	41	196	26	33	75	45	27	29	536
1980-84	49	208	27	37	102	70	53	47	643
1985-89	42	248	41	53	71[b]	69[b]	49[b]	33	633

Table 7.3.2.6. (cont.)

Years	Stocks[a]								
	1	2J3KL	3NO	3Ps	3Pn4RS	4TVn	4VsW	5Z6	1-6
1960-89 Mean	155	374	64	49	83	61	51	33	961
% 1-6	16	39	7	5	9	6	5	3	91

Sources:	1	2J3KL	3NO	3Ps	3Pn4RS	4TVn	4VsW	5Z6	1-6
Sette (1928)	--	--	--	--	--	--	--	1885-1926	--
Beverton & Hodder (1962)[c]	1930-49	--	--	--	--	--	--	--	--
Lett (1980)	--	--	--	--	--	--	1950-74	--	--
Hodder (1965)	--	1955-59	--	--	--	--	--	--	--
Halliday (1972a)	--	--	--	--	--	1960-69	--	--	--
Minet (1978)	--	--	--	--	1965-74	--	--	--	--
ICNAF (1957-80)	1952-78	1960-78	1955-78	--	1975-78	1970-78	--	--	--
NAFOa (1984-91)	1979-84	1979-88	1979-84	--	1979-88	1979-88	1979-88	--	--
ICESb (1993)	1985-89	--	--	--	--	--	--	--	--
NAFOb (1992)	--	1985-89	1985-89	--	--	--	--	--	--
Moquedet (1993)	--	--	--	1960-89	--	--	--	--	--
Serchuk & Wigley (1993)	--	--	--	--	--	--	--	1960-89	--

Table 7.3.2.6. (cont.)

Years	Stocks[a]								
	1	2J3KL	3NO	3Ps	3Pn4RS	4TVn	4VsW	5Z6	1-6
FAO (1964,1971 1976,1981, 1989,1993)	--	--	--	--	--	--	--	--	1963-89

a. 1 = W. Greenland; 2J3KL = Labrador-E. Newfoundland; 3NO = S. Grand Bank; 3Ps = St. Pierre Bank; 3Pn4RS = N. Gulf of St. Lawrence; 4TVn = S. Gulf of St. Lawrence; 4VsW = Scotian Shelf; 5Z6 = Georges Bank & south.

b. 1985-88.

c. Fig. 4.1.

Table 7.3.2.7. Selected assessment parameters for important stocks of Atlantic cod in the northwest Atlantic--W. Greenland to Gulf of St. Lawrence.

Parameter	Stock[a]					
	1[bc]	2J3KL[dfg]	3NO[ef]	3Ps[dg]	3Pn4RS[dg]	4TVn[deg] (J-A)
	1940-90	1959-92[dg]	1952-92[ef]	1959-92[dg]	1960-91[d]	1950-92[dg]
Catch (10^3 t):						
Mean	~140	~363	~70	~49	77	57
Range	7-450	49-810	13-227	27-84	32-106	22-105
1991	42	171	29	43	~32	47
(1992)	(--)	(44)	(13)	(32)	(29)	(39)
First TAC	1974	1973	1973	1973	1977	1974
Total Biomass: (10^3 t)	1982-90	1962-92[f]	1959-92[f]	1959-92[g]	1974-92[dg]	1960-90[d]
Mean	~200	--	~180	~168	329	235
Range	25-548	~500-3000	68-450	80-293	162-444	~110-330
(Age)	(3+)	(3+)	(3+)	(3+)	(3+)	(3+)
Current	40	210/108[fh]	~68[f]	81	172	119[g]
(year)	(1990)	(1992)	(1992)	(1992)	(1992)	(1992)
Spawning Biomass: (10^3 t)	1982-90	1962-92[f]	1952-92[f]	1952-92[f]	1974-92[dg]	1960-93[dg]
Mean	--	--	~100	~50	108	161[d]
Range		~80-1600	~20-200	18-122	29-182	65-260[d]
(Age)	--	(7+)	(NR)[j]	(6+)	(7+)	(5+)
Current	--	22/15[fl]	59	24	29	63[g]
(year)		(1992)	(1992)	(1992)	(1992)	(1993)

Table 7.3.2.7. (cont.)

Parameter	Stock[a]					
	1[bc]	2J3KL[dfg]	3NO[ef]	3Ps[dg]	3Pn4RS[dg]	4TVn[deg] (J-A)
	1940-90	1959-92[dg]	1952-92[ef]	1959-92[dg]	1960-91[d]	1950-92[dg]
Recruitment: (10^6 cod)	NR[j]	1962-92[dfh]	1959-92[f]	NR[j]	1975-93[d]	1960-93[d]
Mean	--	300[h]	~20 (1977-93)	--	114	86
Range	--	~150-1200[h]	~6-210[ef]	--	~38-200	~30-210
(Age)	--	(3)	(3)	--	(3)	(3)
Current (year)	"poor" (1991)	79/68[fl] (1992)	35 (1992)	--	~38 (1992)	~70 (1993)
Recent strong year-classes:	1984[k]	1986	1989	1987, 1989[g]	1988	1980
Fishing mortality rate (F):	1949-89	1962-92[df]	1959-92[f]	1959-92[g]	1974-92[g]	1950-92[g]
Mean	--	0.50[d]	~0.4	~0.54	~0.51	~0.54
Recent (year)	~0.40 (1989)	1.17/2.86[fl] (1992)	0.47[f] (1992)	0.70 (1992)	0.51 (1992)	0.87 (1992)
$F_{0.1}$	0.43	0.25[d]	0.25	--	0.20	0.20
F_{max}	--	--	0.40	--	--	--
Exploitation rate (U):	NR[j]	1962-91[d]	NR[j]	NR[j]	1974-91[c]	1950-91[d]
Mean	--	0.35	--	--	0.36	0.38

Table 7.3.2.7. (cont.)

Parameter	Stock[a]					
	1[bc]	2J3KL[dfg]	3NO[ef]	3Ps[dg]	3Pn4RS[dg]	4TVn[deg] (J-A)
	1940-90	1959-92[dg]	1952-92[ef]	1959-92[dg]	1960-91[d]	1950-92[dg]
Range	--	⁻0.2-0.6	--	--	⁻0.26-0.52	⁻0.27-0.54
1991	--	⁻0.31/0.67[h]	--	--	⁻0.26	⁻0.26

a. 1 = W. Greenland; 2J3KL = Labrador-E. Newfoundland; 3NO = S. Grand Bank; 3Ps = St. Piere Bank; 3Pn4RS = N. Gulf of St. Lawrence; 4TVn(Jan-Apr) = S. Gulf of St. Lawrence.
b. NAFOb (1991).
c. ICESb (1993b).
d. CAFSAC (1992).
e. NAFOb (1992).
f. NAFOb (1993).
g. Sinclair (1993).
h. ADAPT/Laurec-Shepherd tuning.
i. NR = not reported.
j. CAFSAC (1991).
k. Mostly Icelandic origin.

Table 7.3.2.8. Selected assessment parameters for important stocks of Atlantic cod in the northwest Atlantic--Cape Breton to Georges Bank. (Sources listed below.)

Parameter	Stock[a]				
	4Vn[b]	4VsW[bc]	4X[bc]	$5Z_{j,m}$[bc]	5Z6[d]
	1970-91	1958-92[c]	1948-92[c]	1978-92[c]	1960-90[d]
Catch (10^3 t):					
Mean	9	~52	~21	~17	33
Range	5-13	10-80	~12-36	12-27	11-57
1991 (1992)	5 (--)	24 (25)	~28 (26)	20 17	43
First TAC	1974	1973	1982	NR[e]	1973
Total biomass: (10^3 t)	NR	1958-92[c]	1948-92[c]	1978-92[c]	NR
Mean	--	~151	~80	~62	--
Range	--	~27-243	58-113	29-75	--
Age	--	(1+)	(1+)	(1+)	--
Current (year)	--	50 (1992)	74 (1992)	41 (1992)	--
Spawning biomass: (10^3 t)	NR	1970-92[c]	1948-92[c]	1978-92[bc]	1978-89
Mean	--	~59	~62	42[b]	~70
Range	--	10-102	42-95	25-58[c]	--
(Age)	--	(6+)	(3+)	(3+)	--
Current (year)	--	18 (1992)	56 (1992)	25 (1992)	66 (1989)
Recruitment (10^6 cod)	NR	1970-90[c]	1948-92[c]	1978-92[c]	1960-90[d]
Mean	--	~60	~21	9	--
Range	--	~10-110	~12-36	12-27	11-57

Table 7.3.2.8. (cont.)

Parameter	Stock[a]				
	4Vn[b]	4VsW[bc]	4X[bc]	$5Z_{j,m}$[bc]	5Z6[d]
	1970-91	1958-92[c]	1948-92[c]	1978-92[c]	1960-90[d]
(Age)	--	(1)	(1)	(1)	--
Current (year)	--	~10 (1990)	~20 (1992)	~8 (1992)	--
Recent strong year-classes:	--	1987	1985,1987	1985,1987	1985,1988
Fishing mortality rate (F):	NR	1970-92[c]	1948-92[c]	1978-92[c]	1964-89[d]
	--	~0.46	0.50	~0.48	~0.43
Recent (year)	--	1.56 (1992)	0.60 (1992)	0.86 (1991)	0.5-0.6 (1989)
$F_{0.1}$	--	0.20	0.20	--	0.15
F_{max}	--	--	--	--	0.27
Exploitation rate (U):	NR	1970-91[b]	1948-91[b]	1978-91[b]	NR
Mean	--	0.37	0.34	0.35	--
Range	--	~0.19-0.65	~0.21-0.49	~0.22-0.57	--
1991	--	~0.58	~0.40	~0.57	--

a. 4Vn(May-Dec) = E. Cape Breton; 4VsW = N. Scotian Shelf; 4X = S. Scotian Shelf; 5Zo $5Z_{j,m}$ = Canadian portion of Georges Bank; 5Z6 = Georges Bank and south.
b. CAFSAC (1992).
c. Sinclair (1993).
d. Serchuk & Wigley (1993).
e. NR = not reported.

Table 7.3.2.9. List, by source, of simultaneous assessments of selected stocks, or sub-stocks, of Atlantic cod in the north Atlantic.

Stocks	Location[a]	Source		
		Garrod[b] (1969)	Clayden[c] (1972)	ICESb[d] (1973)
N.E. Atlantic (ICES Area)				
Barents Sea	1	+	+	-
Bear Island	IIb	+	+	-
Barents Sea/Bear Is.	I+IIb	-	-	+
Norway coast	IIa	-	+	+
Faroe	Vb	+	+	-
Iceland	Va	+	+	-
Non-spawning		-	-	+
Spawning		-	-	+
E. Greenland	XIV	-	+	-
E. & S.W. Greenland	XIV+1EF	-	-	+
N.W. Atlantic (ICNAF Area)				
W. Greenland	NR	+	-	-
N.W. Greenland	1A-D	-	+	+
S.W. Greenland	1EF	-	+	+
Labrador	NR	+	-	-
Newfoundland	NR	+	-	-
Labrador-Newfoundland	NR	-	+	-
Labrador-E. Newfoundland	2g-3l	-	-	+
S. Grand Bank	3NO	-	+	+
St. Pierre Bank	3Ps	-	-	+
Gulf of St. Lawrence	4TVn	-	-	+

a. ICES & ICNAF sub-areas, divisions, or subdivisions. NR = not reported.
b. 1946-66 for N.E. Atlantic; 1954-66 for N.W Atlantic.
c. 1946-66 for N.E. Atlantic; 1955-66 for N.W. Atlantic.
d. 1960-70 for N.E. & N.W. Atlantic.

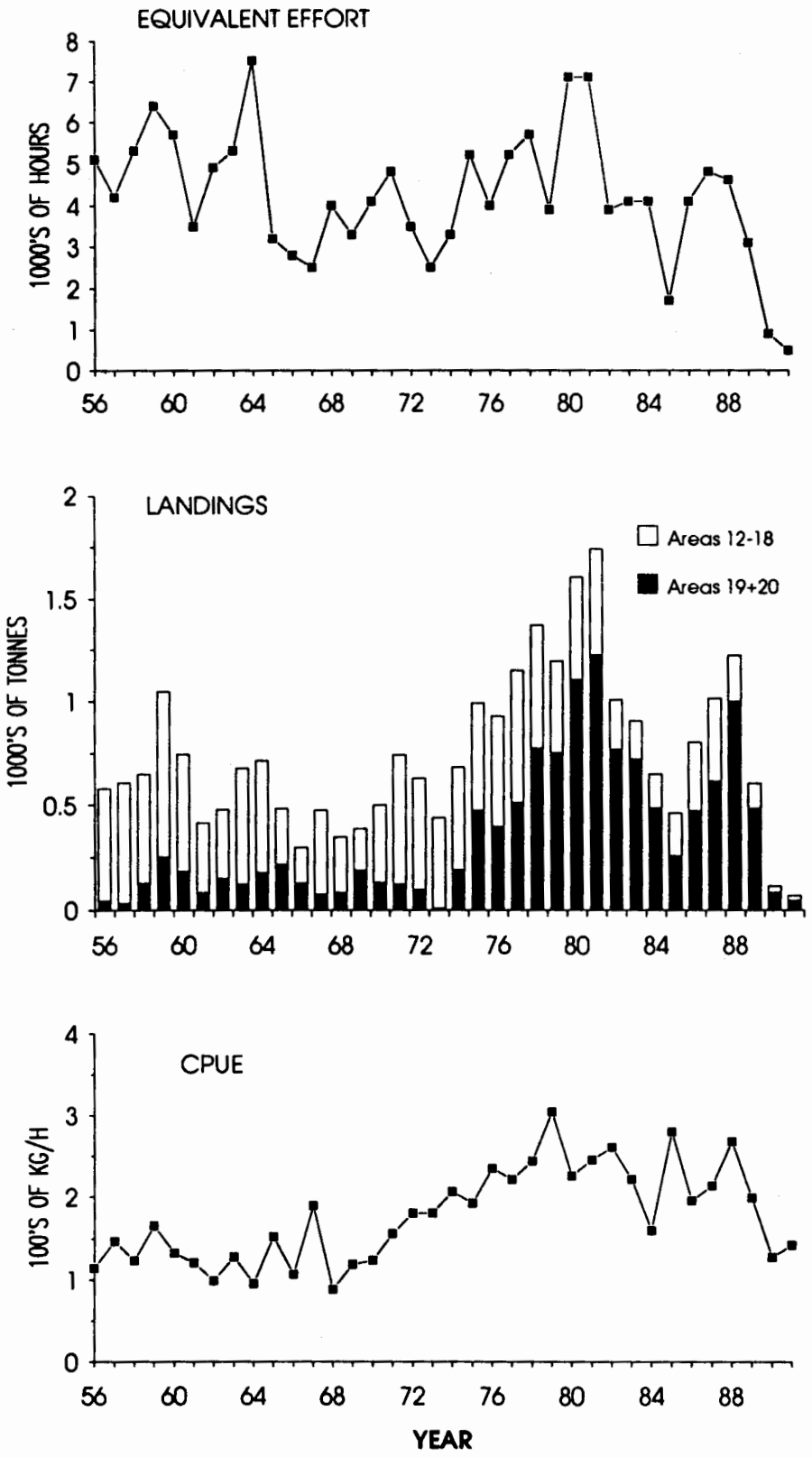


Fig. 7.3.1.1. Canadian annual landings ($x10^3$ t), equivalent effort ($x10^3$ h), and median CPUE ($x10^2$ kg/h) for Pacific cod from Georgia Strait (4B), 1955-91. (Sources: Table 3.1 in Stocker and Hand 1993; PBS files)

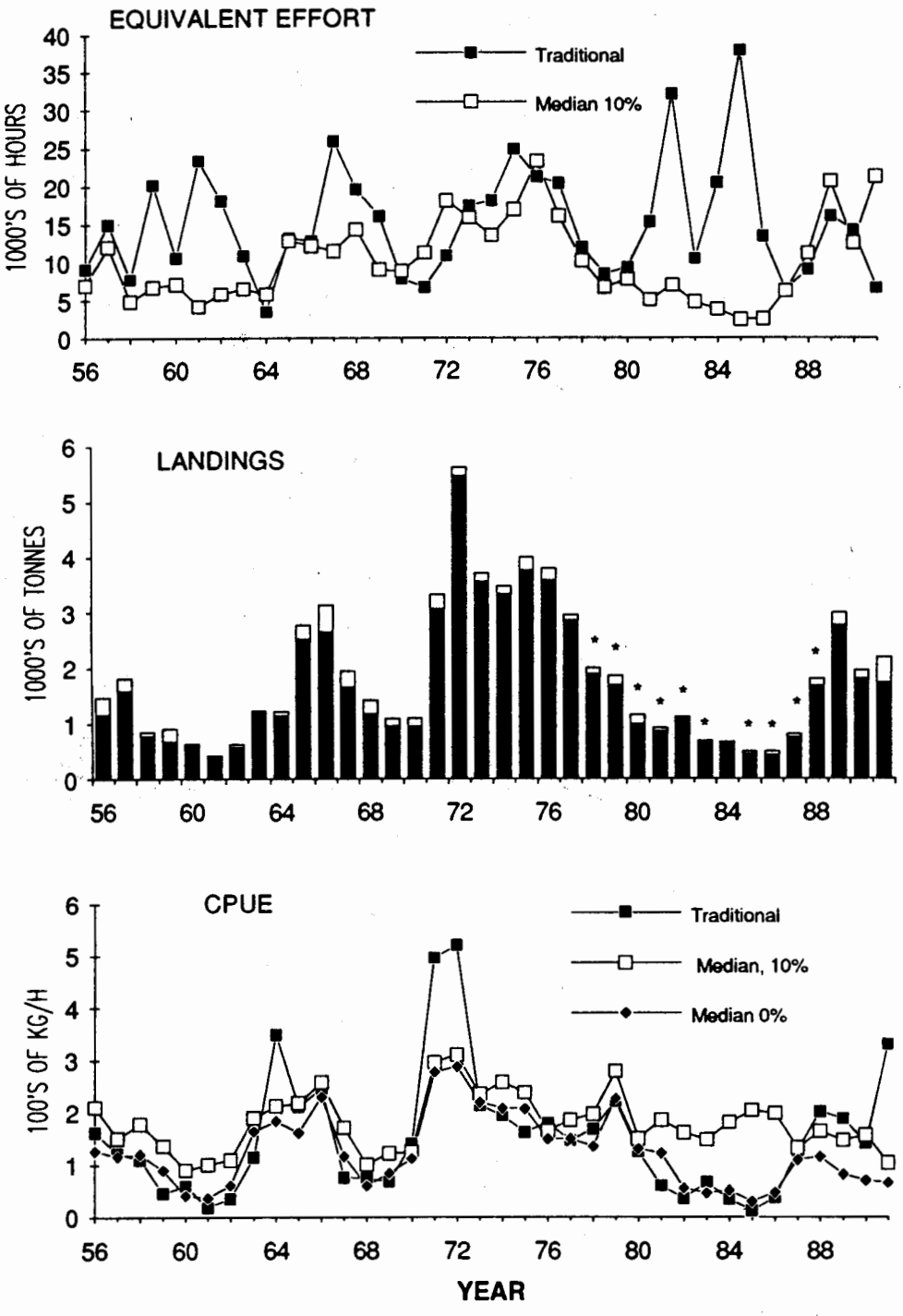


Fig. 7.3.1.2. Canada-U.S. annual landings ($x10^3$ t), equivalent effort ($x10^3$ h), and traditional (standardized) and median CPUE ($x10^2$ kg/h) for Pacific cod from off west Vancouver Island (3C+3D), 1956-91. (Clear areas represent Area 3D landings. Asterisks indicate years when Quarter I closures were in effect. (Source: Fig. 3.3 in Stocker and Hand 1993)

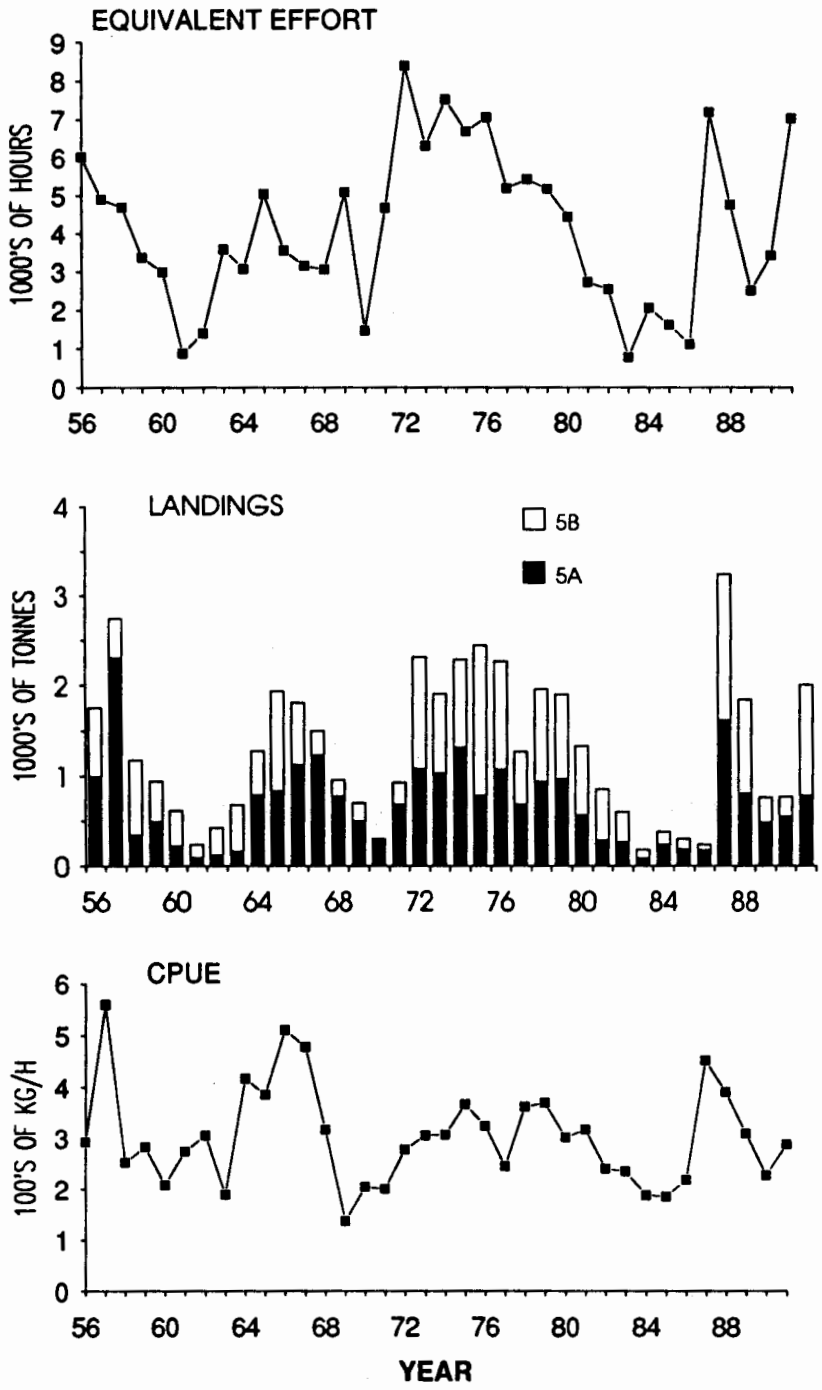


Fig. 7.3.1.3. Canada-U.S. annual landings ($x10^3$ t), equivalent effort ($x10^3$ h), and median CPUE ($x10^2$ kg/h) for Pacific cod from Queen Charlotte Sound (5A+5B), 1956-91. (Source: Table 3.3 in Stocker and Hand 1993)

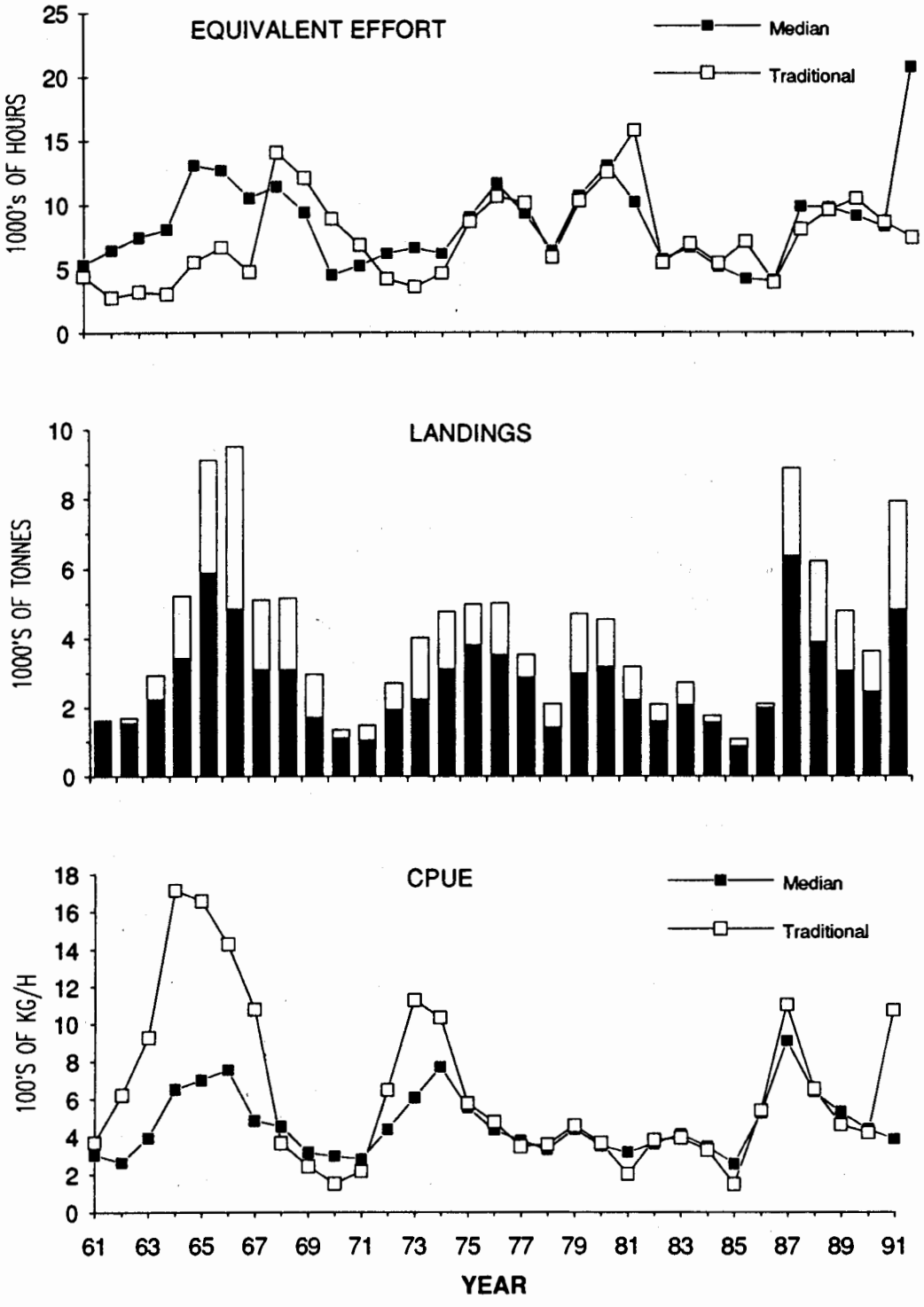


Fig. 7.3.1.4. Canada-U.S. annual landings (x10^3 t), equivalent effort (x10^3 h), and traditional (standardized) and median CPUE (x10^2 kg/h) for Pacific cod from Hecate Strait (5C+5D), 1961-91. Clear histograms indicate landings from Area 5C. (Fig. 3.6 in Stocker and Hand 1993)

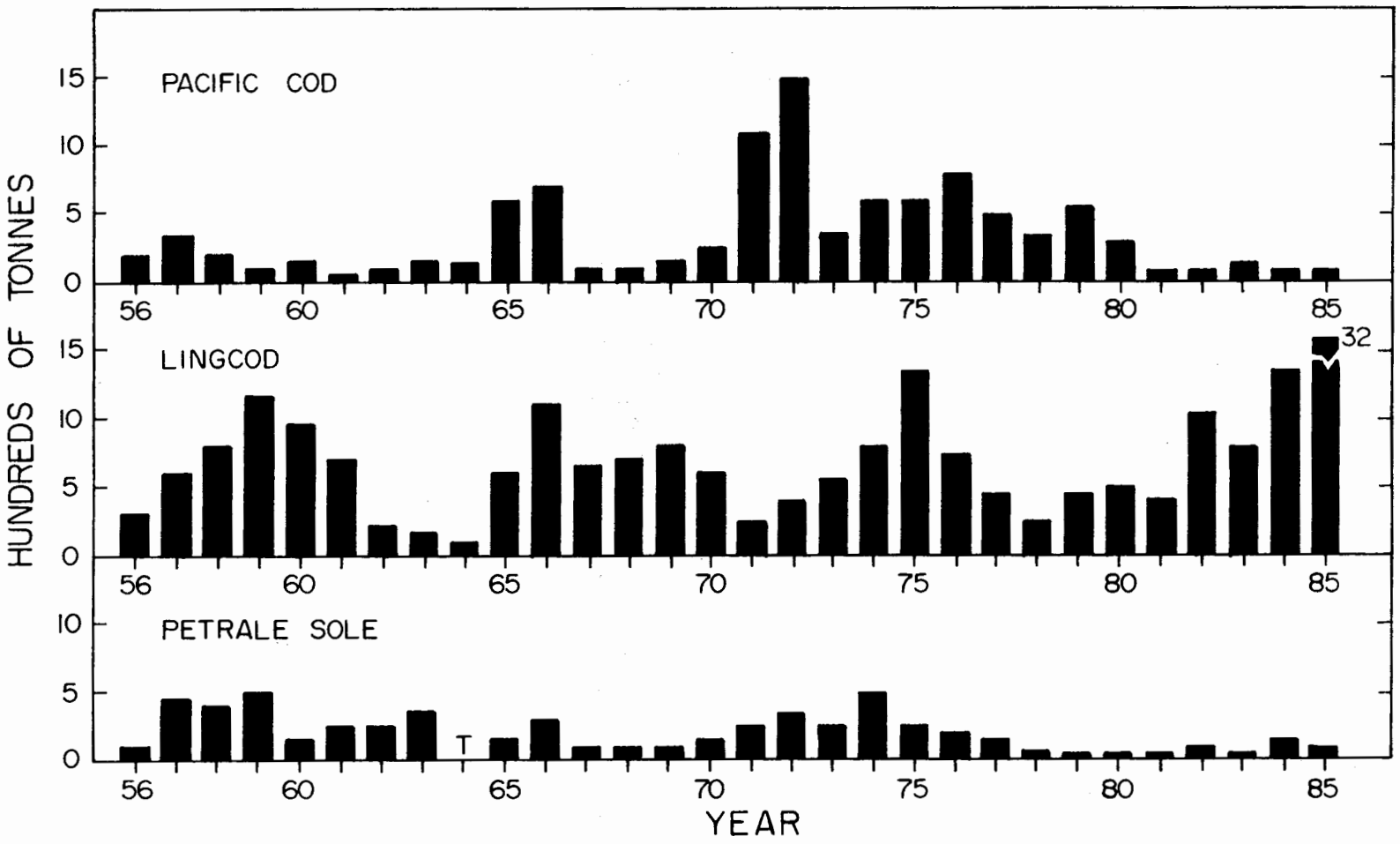


Fig. 7.3.1.5. Canada-U.S. annual landings ($x10^2$ t) of Pacific cod, lingcod, and petrale sole, from Big bank (3Cn), April-September 1956-85. (Source: Foucher 1987)

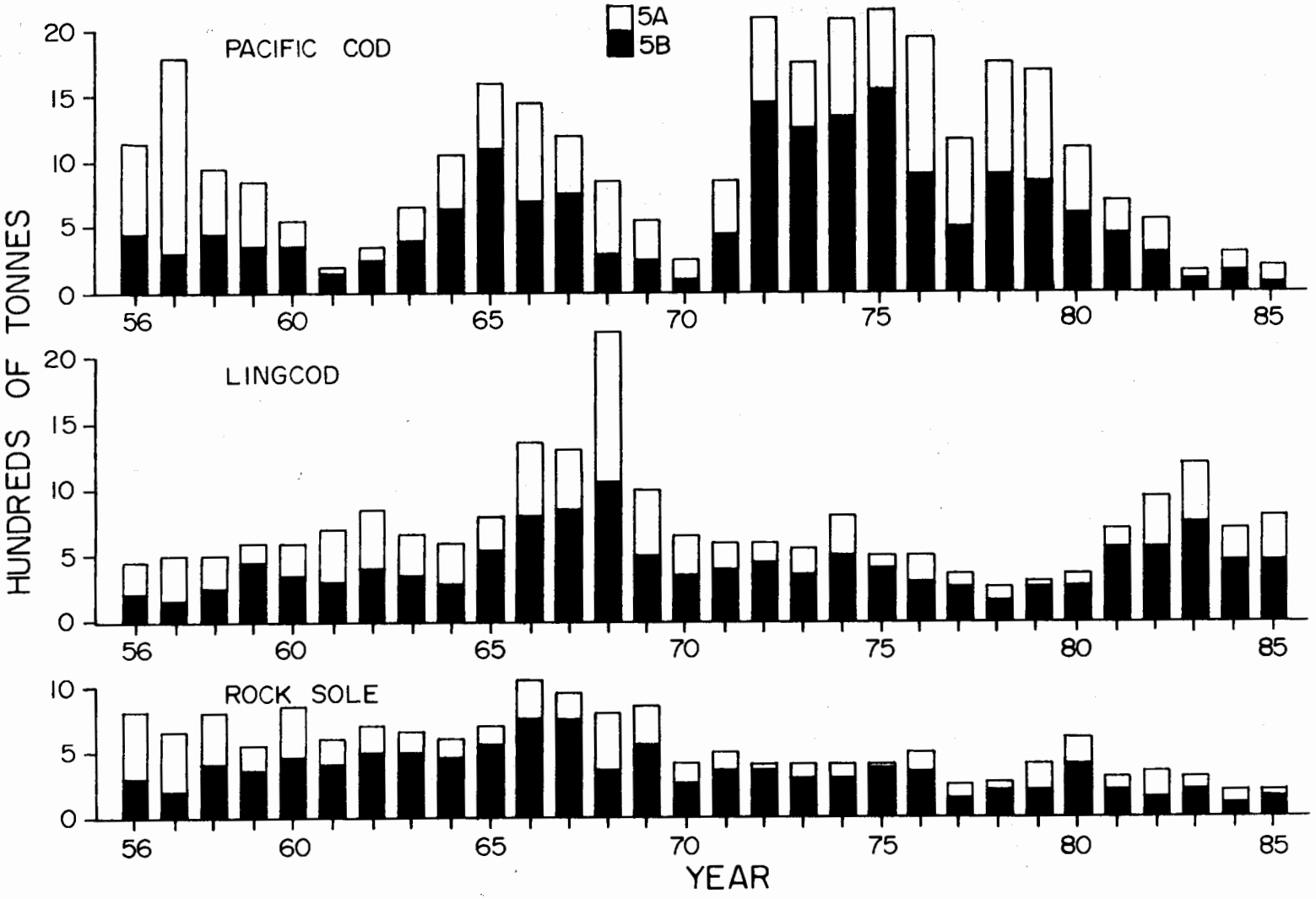


Fig. 7.3.1.6. Canada-U.S. landings ($x10^2$ t) of Pacific cod, lingcod, and rock sole, from Queen Charlotte Sound (5A+5B), April-September 1956-85. (Source: Foucher 1987)

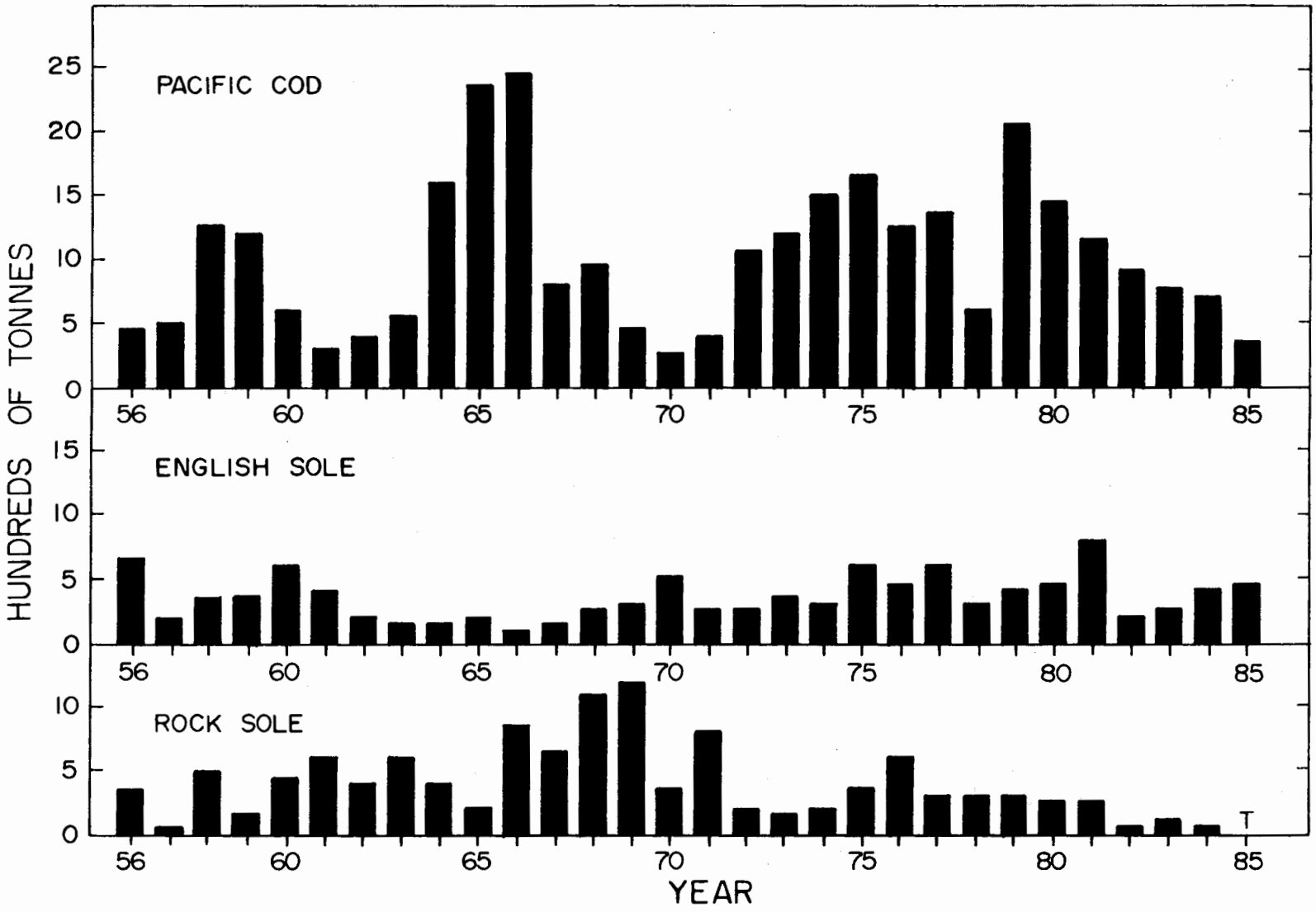


Fig. 7.3.1.7. **Canada**-U.S. landings ($x10^2$ t) of Pacific cod, English Sole, and rock sole, from Two Peaks Ground (5D), April-September 1956-85. (Source: Foucher 1987)

8. ABUNDANCE PREDICTION

INTRODUCTION

Physical environment is currently accepted as a factor in the recruitment variability of many important marine fish species. However, this was not always so. Solemdal and Sinclair (1989) noted that prior to Hjort's (1914) epic report, the "migration theory" was the accepted explanation for fluctuations in abundance. That is, environment affected the availability of a species, but recruitment was constant. Thus a decline in abundance merely indicated that the fish had "moved away", or failed to appear in their accustomed areas. The concept of stocks was absent or nebulous. Ironically, Hjort originally advocated the "migration theory", but abandoned it during his vigorous, but unsuccessful, opposition to the cod hatchery program of G.M. Dannevig. The latter, in turn, opposed the "migration theory", because it excluded the concept of local stocks, the basic justification for hatchery programs, whose purpose was the augmentation of "local" stocks. The hatchery controversy led to field studies on the early-life history of cod and other species. Hjort's studies yielded two conclusions which have prevailed to this day. First, year-class abundance was usually established in the first year of life. Second, there was a regional synchrony of recruitment among certain species which implied that some regional environmental factor was involved.

Once environment was accepted as a factor in recruitment variability, abundance prediction was considered possible. However, to date prediction of recruitment has proved to be an elusive goal. In part, this has been due to a slowly developing appreciation of the complexities in the lives of fishes, and their physical environment. The physical environment is but one factor, but an important one. Progress in relating the physical environment to recruitment followed the traditional path of the simple to the complex. Initial efforts involved relatively symptomatic phenomena such as temperature, for which records were generally plentiful. More fundamental factors such as oceanic circulation, atmospheric circulation, and their interactions are only recent subjects of study. Atmosphere-oceanic interactions were not generally acknowledged until the 1960s.

This chapter will reverse the process of investigations which began after 1914. The sub-chapters will deal in order with environment, recruitment vs environment, and abundance prediction, as they relate to Pacific and Atlantic cod. Undoubtedly, there are intermediate biological factors, such as plankton abundance, which mediate between the physical environment and cod abundance, but these are beyond the scope of the present study.

8.1 ENVIRONMENT

INTRODUCTION

The environment will be discussed on three scales--global, hemispheric, and oceanic. Emphasis will be placed on the Northern Hemisphere, and the northern sectors of the Pacific and Atlantic oceans.

8.1.1 Global

Energy Source. Solar energy is the driving force behind the circulation of the atmosphere and oceans (Tokioka 1983). Briefly stated, about 70% of the incoming solar energy is retained by absorption at the earth's surface. The

ocean occupies 70% of the earth's surface, and absorbs solar energy more efficiently than does the land.

The output of solar energy is not constant. One measure of its variability is solar activity, one measure of which is the sunspot (Wolf) number (Schove 1955). Annual Wolf numbers have been recorded since 1700. Records of maxima can be estimated back to at least 300 A.D., and minima to at least 200 B.C. A 78-y cycle appears to exist, together with an 11.1-y interval between maxima. The long-term net result of the variations is climate (see below).

Atmosphere. The atmosphere-ocean linkage is effected through energy transfer (evaporation and precipitation) and circulation (Tokioka 1983). Atmospheric circulation is initiated by non-uniform heating, from equator to the poles, while oceanic circulation is initiated by non-uniform heating, horizontally, and by wind stress.

Bjerknes (1972) provided a lucid explanation of the atmosphere-ocean linkage. In brief, the principal source of thermal energy, which drives the atmospheric circulation, is the ocean, primarily in the equatorial belt. Two reasons were offered to explain the location of the energy transfer. First, in the equatorial belt, the atmosphere in its average state, is close to the threshhold of vertical instability. Thus a small positive anomaly of heating and evaporation can release substantial quantities of atmospheric potential energy over the vast equatorial area. Second, air masses over the equatorial belt have the greatest angular momentum and thus export westerly angular momentum to extra-tropical air masses. Large-scale air exchange between the equatorial belt and extra-tropical latitudes is undertaken by Hadley circulations, centered near 30 N and S lat, at sea level. These are anti-cyclonic gyres with axis tilting westward and equatorward with height. The upward motion takes place along the westward fringe, and the downward motion on the eastern and central portions. The equatorial Pacific Ocean is the most important site of energy transfer, because of its extensive breadth, and the substantial differential of its surface temperature between the eastern and western sectors. The equatorial Atlantic is much narrower, and has a small temperature differential between its eastern and western sectors.

Prominent atmospheric features are the westerly winds, effects of volcanism, teleconnections, and the Southern Oscillation (SO).

Westerly Winds. The dominant atmospheric features are the bands of westerly winds which encircle both the Northern and Southern Hemispheres at mid-latitudes (Cushing 1982). These are produced by the pressure differential between the equator and the poles. The differential, and hence velocity, is greatest at high altitudes -- 16-17 km at low latitudes; 11 km at middle and high latitudes. The winds undulate horizontally (Rossby Waves); the undulations vary inversely with velocity; and the wave lengths are ca. 5,000 km. Surface weather is strongly affected by this upper-air flow, which causes the formation of pressure systems--lows on the cold side of the flow; highs on the warm side.

Volcanism. Volcanic eruptions inject ash and gas into the upper atmosphere which produce aerosol layers (Kelly and Sear 1984). If the eruptions are sufficiently violent, the aerosol layers can affect the global energy balance and climate. Acidity profiles from Greenland ice cores reflected large volcanic eruptions during the past 10,000 y (Hammer et al. 1980). Clusters of eruptions had a long-term cooling effect on climate, based on a comparison with temperature indices. Sear et al. (1987) noted that major eruptions in the Northern Hemisphere had little effect on surface temperatures in the Southern Hemisphere, but comparable eruptions in the Southern Hemisphere affected surface temperatures in both hemispheres.

Teleconnections. Wallace and Gutzler (1981, p. 784) defined teleconnections as "contemporary correlations between geopotential heights on a given pressure surface at widely separated points on earth". These are strongest

in winter. Effects in the Southern Hemisphere are not dealt with here, but see Horel and Wallace (1981) for references.

Southern Oscillation. Southern Oscillation (SO) is the seesaw variation in atmospheric pressure difference between the southeast Pacific Subtropical High and the Australian-Indonesian Low (Mysak 1986). The oscillation period is irregular--2-7 y. These oscillations produce corresponding oscillations in the thermocline across the Pacific south of the equator. When the thermocline is deepest off South America, a large-scale anomalous warming, called El Nino, occurs in the eastern tropical Pacific which can extend westward from South America to 180° longitude (Cane and Zebiak 1985; Mysak 1986; Mann and Lazier 1991). Advection poleward of the anomalously warm waters, and atmospheric teleconnections, can affect atmospheric and oceanic conditions in the extra-tropical latitudes.

Climate. Dunbar (1982) reviewed long-term, global temperature trends. Pleistocene temperature oscillations (reflecting glacial/interglacial periods) exhibited wave-lengths of ca. 50,000 y, for the past 400,000 y. Currently, the trend is downward towards the next glacial period, a few thousand years from now. In recent millenia, cycles of 200-250 y were evident. In the 20th Century, a distinct warming period began in the 1920s and may have terminated in the 1960s.

8.1.2 Northern Hemisphere

Atmospheric Circulation. Prominent zonal (east-west) features are the semi-permanent, alternating high- and low-pressure areas in the mid-latitudes (Mann and Lazier 1991). These vary in strength seasonally and interannually, and are interrelated to some extent. Ladurie's (1971) review noted that in the temperate zone of the Northern Hemisphere, during summer, there may be four or five cold troughs in the upper atmosphere. Four troughs (one each over the Bering Strait, Atlantic coast of the United States, over a line from Finland to the Adriatic, and Lake Baikal) are formed when the westerlies increase velocity, and move northward. The result speads apart the troughs. Five troughs (two over North America, and one each over England, the Aral Sea, and Manchuria) are formed when the westerlies decrease velocity, and are pushed southward. The four-trough pattern coincides with increased solar activity, and a general warming of the Northern Hemisphere. The five-trough system coincides with decreased solar activity, and a general cooling. Thus, the linkage between increased solar energy and hemispheric warming can be traced from the increased pressure differential between the equator and the North Pole, resulting in increased velocity, and a northward shift, of the westerlies.

Comparable meridional (north-south) features, are the low-pressure (high-pressure) systems at mid-latitude, and high-pressure (low-pressure) systems immediately northward and southward (Mann and Lazier 1991). At the surface of the Pacific Ocean, mid-latitude features are the Aleutian Low and Pacific High in the Pacific, and for the Atlantic, the Iceland Low and the Bermuda-Azores High (hereafter referred to as the Azores High).

Teleconnections. Wallace and Gutzler (1981) reviewed the literature on correlations between meteorological parameters at widely separated points, during winter, in the Northern Hemisphere. They found oscillation patterns unique to the north Pacific and to the north Atlantic, as well as a pattern which linked the two regions. Within the north Pacific, were the North Pacific Oscillation (NPO), and a zonally (east-west) symmetric see-saw of sea-level pressure (SLP) (described in Section 8.1.3). Within the north Atlantic, were the North Atlantic Oscillation (NAO) and a zonally symmetric see-saw of SLP (described in Section 8.1.4). The Pacific/North American (PNA) pattern provides a link between the Pacific and Atlantic. It links geopotential height anomalies in the mid-Pacific, near 45 N lat, with those over southeastern United States, which in turn are linked to the NAO. Furthermore, the pressure anomalies of the Aleutian and

Iceland lows are negatively correlated.

Wilson (1986) reported atmospheric teleconnections, during 1953-77, between sea-ice variability in the Greenland Sea and: (1) the Southern Oscillation Index (SOI); and (2) the North Atlantic Oscillation Index (NAOI). The sea-ice anomaly was negatively correlated with both--with the SOI anomaly when lagged 24-29 mos, and with NAOI anomaly when lagged 0-2 mos.

Atmosphere-Ocean. ENSO is generally accepted to be the "largest interannual climatic fluctuation in the atmosphere-ocean system" (Mysak 1986, p. 464). This is a two-part phenomenon consisting of the El Nino (EN) and the Southern Oscillation (SO). Mann and Lazier (1991) noted that the cause of ENSO has not been firmly established. It may or may not be self-sustaining. Interestingly, White and Burnett (1974) noted that discussion of the 1957-58 ENSO event, at the 1958 CALCOFI Symposium (Sette and Isaacs 1960), led to a consensus that ocean and atmospheric anomalies were somehow intimately coupled. Furthermore, it was acknowledged that little effort had been expended in the past to investigate the large-scale air-sea interaction problem, and steps were taken to correct this situation.

ENSO events probably began about 2.0-3.2 million years ago, when the Isthmus of Panama was formed (Colgan 1990). Flood-related geological evidence, in the Peruvian coastal plain, suggest that at least 15 very strong events occurred during the last 7500 years. ENSO events probably did not occur during glacial periods, when sea level was low. Recent chronology of the ENSO phenomenon was established for at least the last 500 y, based on a review of records from "natural systems" by Baumgartner et al. (1989) and historical written records by Quinn et al. 1987). The natural systems most sensitive to ENSO events were: processed widths of tree-rings (arid United States and Mexico), Cd/Ca ratios in coral bands (Galapagos Islands), and total diatom abundance in Gulf of California varves. Filtered ice accumulations (Quelccaya ice cap, Peru) were somewhat less sensitive, but potentially contained the longest time series--ca. 1,500 y. The historical records began in 1535, with the Spanish explorations, and consisted of diaries, mission records, ships' logs, etc.

Mean interval between ENSO events is generally 3-4 y, but aperiodic (Cane and Zebiak (1985). Quinn et al. (1987) reported the mean period between ENSO events was 3.8 y, based on all moderate, strong, and very strong events during 1803-1987. They noted a similar result from the theoretical studies of Cane and Zebiak (op. cit.).

Tree-ring records were used to reconstruct a 400-y record of ENSO events, during which cycles of 80-100 y were evident (Michaelsen 1989). ENSO exhibited consistent fluctuations in amplitude and frequency during each cycle. Progression of the predominant frequency increased from about 0.1 cpy (cycles/y; 10-y period) to 0.35 cpy (3 y). Amplitudes grew as events became more frequent; peaked when frequencies reached 0.15-0.25 cpy; then declined rapidly as frequencies approached 0.35 cpy. Intensity of ENSO events varied directly with amplitude. It was suggested that the long-term oscillation may represent a gradual increase in heat storage in the western Pacific, followed by a sharp depletion by one or more extreme events and several moderate ones.

Climate. Ladurie (1971) reviewed the reported effects of variations in the velocity of the westerly winds, and noted two major types of circulation which affected the climate of the temperate latitudes. Model I (five-trough pattern; see Atmosphere, above) tends to represent a pessimum climate, such as the Little Ice Age in the late-16th and 17th centuries. Conversely, Model II (four-trough pattern) tends to represent an optimum climate, such as that in the 11th and 20th centuries.

Beltrami and Mareschal (1993) examined ground temperature histories (GTHs) for central and eastern Canada for 1000-~1963. For records taken south

of 50 N lat, a warm period occurred around 1000 A.D. Subsequently, values declined steadily to a minimum in 1800; rose to a maximum in ~1940; then declined. The authors found similar trends in records of tree rings (since 1200 A.D.) in Quebec, atmospheric CO_2 concentrations (since ~1500 A.D.) from a Greenland ice core, and in oxygen isotope ratios ($^{18}O/^{16}O$; since ~1500 A.D.) in a Peruvian ice core (op. cit. Fig. 7). A similar pattern was noted for GTHs from northern Manitoba (north of 50 N lat), whose minimum occurred some 30 years later, and were correlated with tree-ring indices from northern North America, reported by Jacoby and D'Arrigo (1989). The authors concluded that climatic trends differed among regions.

Kelly (1984) reviewed the climatic variations in the Northern Hemisphere (air temperature) and the north Atlantic Ocean (air temperature and sea-level pressure) during 1881-1981. He noted the general, hemispheric, warming trend during the period, and attributed this to a combination of forcing by volcanic (and possibly solar) variations and increasing levels of atmospheric carbon dioxide (produced by burning fossil fuels, deforestations, and changing land use). With respect to forecasting climatic change, he rejected the use of "purely statistical" techniques, particularly because society itself may affect climate. Four mechanisms needed to be understood were: (1) rising levels of atmospheric CO_2; (2) large, explosive volcanic eruptions; (3) changes in degree of solar activity; and (4) "internal" mechanisms of ocean-atmosphere feedback such as ENSO. He considered that, for the present, "climate forecasts on decadal and longer time scales can only be phrased in terms of possibilities and, in some cases, probabilities." (op. cit., p. 232)

8.1.3 North Pacific Ocean

Atmospheric Circulation. Principal atmospheric features in the north Pacific are the Aleutian Low and the Pacific High (to the south) (Thomson 1981; Mann and Lazier 1991; Martyn 1992). The Aleutian Low dominates the region during October-March. With its counter-clockwise wind flow, it produces southerly winds on its eastern side, and northerly winds on its western side. During April-September, it subsides, and is replaced, from the south, by the Pacific High, which produces the opposite wind flow. Winter location of the Aleutian Low varies with its intensity--eastward with high intensity, and westward with low intensity. Favorite and Ingraham (1976) suggested that these movements were related to sunspot activity, but no corroborative reports were found. Davydov (1989) related the location of the Aleutian Low to that of the high-altitude ridge over the north Pacific.

The North Pacific Oscillation (NPO), and its Atlantic counterpart (NAO), were first described by Walker and Bliss (1932). Based on data for January, and December-February, 1906-78, Rogers (1981) defined NPO as a negative correlation between temperature anomalies of western Alaska-eastern Siberia (as represented by the stations at Dutch Harbor and St. Paul, Alaska) and western Canada (as represented by Edmonton, Alberta). The two oscillation nodes are associated with variations in the strength of the zonal westerlies over the Pacific and North America, which in turn are related to the longitudinal variations in the mean position of the Aleutian Low. Thus, the NPO reflects the location and intensity of the Aleutian Low--eastward and intense when the Canadian anomaly is negative.

Ocean Surface Circulation. Thomson (1981) provided a recent description of the general circulation of the north Pacific Ocean. Off Japan, the northward-flowing, warm Kuroshio Current meets the southward-flowing, cold Oyashio Current, at 35-40 N lat (Fig. 8.1.1). Most of the Kuroshio flows eastward as the North Pacific Current (part of the Central Pacific Gyre). The remainder mixes with the Oyashio to flow eastward as the Subarctic Current (originally called the West Wind Drift). The Subarctic Current bifurcates as it nears North America. The south segment flows southward off Washington, Oregon,

and California, as the California Current. The north segment flows into the Gulf of Alaska, as the Alaska Current. Subsequently, part turns southward to complete the Alaska Gyre. The remainder flows westward to Asia to form the Western Subarctic Gyre, or northward into the Bering Sea, between the Aleutian Islands.

The region landward of the Subarctic Current bifurcation in the eastern Pacific is termed the Transitional Domain, and its location varies seasonally and inter-annually (Fleming 1955). Fleming reported a seasonal shift in the location of the "split"--ca. 50 N lat (Vancouver Island; Area 3D) in summer, and 43 N lat (Oregon) in winter. Substantial interannual variations occur, based on oceanographic (Dodimead et al. 1963; Dodimead and Pickard 1967; Favorite et al. 1976) and plankton (Fulton and LeBrasseur 1985) data. A shift northward results in warm water conditions in the British Columbia-Washington region, and vice versa.

Short-term Phenomena. Two short-term phenomena were reported, which may be factors affecting Pacific cod abundance--ENSO and warm/cold water masses.

ENSO. These events were partially correlated with warming sea-surface temperatures (SSTs) in the northeastern Pacific, but the cause has not been well established (Mann and Lazier 1991). Direct advection of the warm tropical water to the mid-latitudes was not deemed feasible, but atmospheric teleconnections may be the prime cause. Thus, ENSO events may alter the behaviour of the westerlies, which in turn may alter the position and intensity of the Aleutian Low. Anomalous warming of waters off British Columbia and Alaska varies directly with the intensity of the Aleutian Low. Increasing intensity results in stronger, warm southerly winds which push warm, offshore surface waters onshore. Intense Aleutian Lows also occur when there is no ENSO event.

Warm/cold water masses. Eber (1971) analysed anomalies of monthly mean SSTs, for 1949-62, in the north Pacific Ocean. His data revealed a recurring pattern of quasi-stationary positive or negative anomalies located approximately between 30 N lat and 50 N lat, and surrounded on the east, north, and south by anomalies of opposite sign. He noted that this configuration suggested the presence of a standing wave, and that such a wave could affect the partitioning of the West Wind Drift as it approached North America, and the proportions of water diverted northward and southward. However, he conceded that no physical data were available for verification.

Favorite and McLain (1973) reviewed the explanations proposed for the anomalous warming of the northeast Pacific during 1957-58 (including air-sea interactions and standing waves), and suggested a different explanation, based on their analysis of anomalies of mean annual SSTs, during 1948-67, at 35-50 N lat. They reported that large areas of warm and cold water followed one another around the Pacific Gyre. The Asia-North America transit took 2-3 y, and the complete circuit encompassed 5-6 y. Cause of the phenomenon was not reported. The authors noted a positive correlation of herring year-class abundance in the southeastern Alaska commercial fishery with positive temperature anomalies in a nearby Marsden Square (No. 157, quadrant 1). Winstanley (1974) suggested that the cause was changes in the solar constant during the sunspot cycle.

Eber (1981) analysed anomalies of mean SSTs for January 1965-80, in the area encompassed by 30-45 N lat, west of 140 W long, and reached the same conclusion as in his 1971 report. There was no acknowledgment of the analysis of Favorite and McLain (1973). He speculated that the rapidity with which the anomalies could change sign, suggested that air-sea interaction processes may have played an active role in forming and maintaining these patterns. His speculations were at least partially confirmed by seasonal sea-level pressure charts of the north Pacific prepared by Hamilton (1984). SST anomalies tended to coincide with the interannual variations in the location and intensity of the Aleutian Low, during winter (December-February). Thus, negative (cold) anomalies coincided with deep lows, which were generally eastward of the mean position, and vice versa. For example, in January 1977, a large, negative (cold) anomaly (-2 F; Eber op. cit., Fig. 8) was centered at about 175 W long, and the anomalously

deep (<990 mb) Aleutian Low was centered at about 180 long (Hamilton op. cit., p. 154). In January 1962, the opposite situation occurred. The SST anomaly was positive (+1 F), and centered at about 150 W long (Eber 1971, Fig. 28), and the Aleutian Low was shallow (1010 mb) and centered at about 155 W long (Hamilton op. cit., p. 94).

Climate. Forester et al. (1989) noted the low-amplitude, climatic change during the last 2,700 y, based on ostracod sediments in Kepler Lake, south-central Alaska. In a 243-cm core, relative to the modern climate, the bottom layer (70-243 cm; pre-Little Ice Age) indicated a warmer and perhaps seasonally drier period, and the middle layer (67 cm to near surface; Little Ice Age), colder and probably drier. The low amplitude of change was implied due to the small change in pollen sediments in the same core.

Jacoby and Cook (1981) investigated ring widths from white spruce trees (Picea glauca) in the Yukon Territory, Canada. Ring-width indices during 1550-1975, reflecting summer temperatures, suggested warming periods around 1600 and 1660, intermittently during 1740-1810, and consistently during 1920-60 (op. cit., Figure 4). A declining trend began about 1960. Cold temperatures prevailed throughout virtually the entire 19th Century.

Roden (1989) investigated the recent climatic variability along the west coast of North America, based on instrumental oceanic and meteorological records collected during 1827-1985. Among his conclusions were the following: No secular trends in temperature were detected. Notable climatic events were: the unusual winter of 1862 (extreme cold in the Pacific Northwest; extreme floods in California); warm winters in 1926, 1931, 1941, 1958, and 1983; and cold winters in 1937, 1950, 1957, and 1969. Extended warm periods occurred during 1864-70, 1940-45, and 1977-84, and extended cold periods during 1857-63 and 1948-56. ENSO events, such as in 1926, 1931, 1941, 1958, and 1983, and coincident with intense Aleutian Lows in the Gulf of Alaska, tended to cause positive temperature anomalies along the west coast of North America and negative anomalies in the central and western Pacific. However, intense Aleutian Lows not associated with an ENSO event also produced the same effects. Polar-type disturbances of the atmospheric circulation, such as in 1937, 1950, 1957, and 1969, tended to cause negative temperature anomalies along the west coast of North America and positive anomalies in the subarctic regions of the central and western Pacific. In this case, a subarctic high-pressure system supplanted the Aleutian Low in the Gulf of Alaska.

Freeland (1990) examined 20th Century SST records (1921-89) from British Columbia lighthouses. He reported that a general warming trend was evident, and the variability showed remarkable similarity to the hemispheric variations in air temperature. However, neither the SSTs nor the Northern Hemisphere mean air temperatures showed coherence with ENSO events.

8.1.4 North Atlantic Ocean

Atmospheric Circulation. Principal atmospheric features are the Iceland Low (near 65 N lat), and the Azores High, at ca. 40 N lat (Mann and Lazier 1991). When the Iceland Low is intense, its counter-clockwise circulation produces warm temperatures off Europe, and cold temperatures off Greenland and northeast North America. When the Iceland Low is weak, the Azores High prevails, and the opposite situation occurs. These conditions occur at the extreme ends of the North Atlantic Oscillation (NAO).

The NAO is based on the differential atmospheric pressure between Iceland and the Azores (Mann and Lazier 1991). When the pressure differential is less than average (weak Iceland Low), the undulating westerly winds are shifted northward, which brings southerly winds and warmer temperatures to the northwest Atlantic, and northerly winds and colder temperatures to the northeast

Atlantic. When the pressure differential is greater than average (intense Iceland Low), the wind and temperature conditions are reversed. In the former case, the Azores High is located in mid-Atlantic at ca. 40-55 N lat, while in the latter case, the Iceland Low is located in mid-Atlantic at ca. 55-65 N lat. The NAO-ENSO linkage was reported by Rogers (1984). A variant is the "seesaw" of winter temperatures between Greenland and northern Europe (van Loon and Rogers 1978; Rogers and van Loon 1979; and Meehl and van Loon 1979). Van Loon and Rogers (op. cit.) found an early account of the phenomenon in the diary of a missionary in Greenland, for the period 1770-78. They quoted the diarist as stating: "In Greenland all winters are severe, yet they are not alike. The Danes have noticed that when the winter in Denmark was severe, as we perceive it, the winter in Greenland in its manner was mild, and conversely." (op. cit. p. 296)

Ocean Surface Circulation. Surface circulation is similar to that in the north Pacific. It begins in the western sector at the meeting of a southward-flowing, cold current and a northward-flowing, warm current. However, surface circulation is generally oriented on a southwest-northeast axis (Fig. 8.1.2), rather than west-east as in the north Pacific Ocean (Fig. 8.1.1). Off North America, the northward-flowing, warm Gulf Stream meets the southward-flowing, cold Labrador Current, at about 40 N lat. Most of the Gulf Stream flows eastward, as the north arm of the Subtropical Gyre. The remainder mixes with the Labrador Current, and flows northeastward towards Europe as the North Atlantic Current. Two major loops are formed. The first, which begins south of Iceland, comprises the Irminger, East Greenland, West Greenlsnd, and Labrador currents. The second loop comprises the Norwegian, Spitzbergen, East Greenland, West Greenland, and Labrador currents. Other diversions of the North Atlantic Current are those which flow around Iceland, into the North Sea and Skaggerak, and into the Barents Sea. The schematic diagram of Krauss (1986, Fig. 19) was used rather than that of Dietrich et al. (1980, Fig. 10.50). The former diagram is based on satellite-tracked buoys (90 during 1981-84) and hydrographic data, while the latter is based only on hydrographic data (mostly collected in 1957-58). Krauss (op. cit.) noted that the buoy data did not corroborate the circulation proposed by Dietrich et al. (op. cit.). For example, the westward-flowing branch of the Irminger Current did not appear in the Dietrich figure.

Climate

North Atlantic. Dunbar (1982) briefly reviewed reports involving SSTs collected during the ~1870s to the early 1970s.
A general warming began in 1920, and was preceded by a distinct cooling during the preceding 20 years. He noted that marine climate changes were not simple to explain, because of their non-uniformity within the region. Kelly (1984) reviewed the climatic variations, based on records of surface air temperature and sea-level pressure during 1881-1981. Air-temperature trends varied among seasons and between the northeast and Gulf Stream sectors. In the northeast sector, mean annual air temperatures exhibited a general decline after 1940, but seasonally, cooling did not begin until 1960 for autumn, and to some extent spring. In contrast, mean air temperatures in the Gulf Stream region exhibited no long-term trend, but did exhibit fairly regular 20- to 25-y cycles. Sea-level pressures reflected the intensity and movement of the Iceland Low and Azores High, and the westerly winds flowing between them. Limited data precluded discussing climatic trends.

Norwegian-Barents Seas. Loeng et al. (1992) analysed time series (35 to >100 y) from several hydrographic sections in the Norwegian and Barents seas, with respect to cyclic variations. They compared these variations to meteorological observations, and found that the variability in the Atlantic inflow is closely related to meteorological conditions. Warm periods are related to a stable low-pressure situation (cyclonic circulation) over the area, while cold periods are linked to a high-pressure situation (anti-cyclonic circulation). In the long-term the time series appeared to consist of several components, with periods varying from 2.5 to 17.5 y. During the 1980s, two large (warm) inflows

of Atlantic water entered the Barents Sea--1982-83 and 1989-90.

Baltic Sea. Fonselius et al. (1984) reported an unusually cold climate around 400 A.D. and 1220 A.D. Severe ice conditions occurred 11 times during the 14th and 15th centuries, but only 4 times during the 16th and 17th centuries. The last cold period occurred during the 18th Century, coincident with the largest extension of the glaciers. Kalejs and Ojaveer (1989) reported the relative severity of winters, as measured by ice cover (inverse relationship with winter air temperature), declined from the 1740s to the 1950s, then increased through the 1970s.

Northwest Atlantic. Ladurie (1971) described the climate of Greenland during ~350-1950 A.D., based on the concentration (o/oo) of the oxygen isotope (^{18}O) in ice-core samples. The isotope concentration varies directly with temperature at the time of precipitation as rain or snow. A prolonged warm period extended from ~610-1125 A.D., followed by mostly cold periods until ~1900, when the current warm period began. Dunbar (1982) reviewed the recorded changes in marine climate in Greenland, Iceland and the subarctic, and off eastern Canada, during the 20th Century. All regions exhibited a rise in temperature beginning in 1920. Peak temperature in eastern Canadian waters occurred about 1950, 10-20 y later than off Greenland and Iceland. A second peak occurred in the late 1950s to 1960 in Greenland and Iceland, but was less marked off Canada. One report noted that peaks in the northwestern and northeastern sectors were 180° out of phase with one another (also noted by Kelly 1984). Interestingly, Dunbar (op. cit.) noted that SSTs off Bermuda began declining in 1960.

Short-term Phenomena. Two short-term phenomena were reported which may be factors affecting recruitment of cod and other marine species--the Great Salinity Anomaly (GSA) and warm-core rings.

Great Salinity Anomaly. Dooley et al. (1984) noted the anomalously low salinities in the Faroe-Shetland Channel during 1908-09 and 1976, and considered that distant, and large-scale, climatic factors were responsible. The immediate cause for the 1976 anomaly was attributed to a 250-nm eastward shift of the Oceanic Polar Front (the southern and eastern boundary of the subpolar gyre). They speculated that causes of the eastward shift could have been due to "a combination of a persistently weak Gulf Stream, regular renewal of Labrador Sea water, and a very strong Labrador Current".

Dickson et al. (1988) hypothesized that advection was the principal cause of what they called the "Great Salinity Anomaly"--the widespread freshening of the upper 500-800 m of the northern North Atlantic. Their hypothesis was based on new evidence of a broader distribution of the anomaly than was known at the time of the Dooley et al. (1984) report. They proposed that two major hydrographic changes occurred in the late 1960s, north of Iceland, which produced a large ("several hundred kilometers across"; Cushing 1990, p. 276) and deep (ca. 600-800 m) water mass of low temperature and salinity. First, a prolonged high-pressure anomaly over Greenland produced strong northerly winds which brought an abnormal amount of polar water into the Greenland Sea which resulted in sharp reductions in water temperature and salinity. Second, the salinity was reduced to a critical 34.7 o/oo, which prevented the normal overturn in the Greenland Sea. Thus a large, traceable water mass (low salinity and temperature) was created which departed by way of the enhanced East Greenland and East Iceland currents. It was subsequently tracked around the Atlantic subpolar gyre for the next 14 y (op. cit. Fig. 7; Cushing 1988, Fig. 1). It passed west Greenland during 1969-70; Labrador-East Newfoundland in 1971-72; mid-Atlantic in 1974-76; and bifurcated in mid-Atlantic. The southern portion was detected in the Celtic Sea, English Channel, and off Portugal during 1977, and one sub-portion entered the Mediterranean Sea. The northern portion passed through the Faroe-Shetland Channel in 1976; passed along the Norwegian coast during 1977-78 (a sub-portion was detected in the North Sea and Skagerrak in 1977-79). Off northern Norway, another bifurcation, in 1978-79, sent one portion eastward into the Barents Sea, and the other northward along the west coast of Spitzbergen, in 1979. It returned to its origin in 1981-82. The authors also noted that a salinity

anomaly was detected passing through the Faroe-Shetland Channel during 1908-09, and suggested that similar salinity anomalies had occurred in the past.

Warm-core Rings. Large eddies are generated by the unstable meanders of the Gulf Stream (Stommel 1965). Those on the seaward side are cold, and those on the landward side are warm. The warm eddies can entrain large volumes of water from the continental shelf of the northwest Atlantic, and advect them offshore (Myers and Drinkwater 1989). The eddies are called warm-core rings, because they consist of warm Sargasso Sea water surrounded by cooler water of shelf-slope origin.

8.2 RECRUITMENT vs ENVIRONMENT

INTRODUCTION

Recruitment data are collected for short-term abundance prediction for management decisions, or for long-term studies to explain abundance fluctuations. The long-term studies will be addressed here.

8.2.1 Recruitment Synchronies

The case for environment as a factor in recruitment was initially made from observed synchronies of recruitment among stocks and/or species, often over large geographical areas of the Pacific and Atlantic oceans.

Pacific. Hollowed et al. (1987) examined quantitative and qualitative indices of abundance, primarily during 1946-78, for 28 species (59 stocks) in five geographic regions, from California to the Bering Sea. Pacific cod was poorly represented. They reported four major features in recruitment patterns: (1) synchrony of extreme year-classes throughout the region; (2) within region-species groups, significant correlations were usually positive; (3) among region-species groups, pairwise correlations were usually negative, and extreme year-classes were usually of opposite sign; and (4) many stocks exhibited recruitment trends, usually negative. The authors concluded that recruitment was influenced by environmental conditions.

A literature survey revealed that during 1975-78, strong year-classes appeared in several species, from California to the Okhotsk Sea (Table 8.2.1). The 1975-77 year-classes were strong for lingcod in Georgia Strait (4B), and the 1977-78 year-classes off west Vancouver Island (3Cn+3D) and in Queen Charlotte Sound (5A+5B). The 1976 year-class was strong for Pacific ocean perch off British Columbia and in the Gulf of Alaska. The 1977 year-class was strong for cod (British Columbia to the east Bering Sea), sablefish (British Columbia to the Gulf of Alaska), Pacific hake (California to British Columbia), and chub mackerel, Scomber japonicus (California). The 1978 year-class of walleye pollock was strong from the Gulf of Alaska to the Okhotsk Sea.

Atlantic. Studies of recruitment synchronies in the Atlantic Ocean have a long history, which began with Hjort (1914). Subsequent examples are Taning (1936), Templeman (1965,1972), Dragesund (1971), Garrod and Colebrook (1978), Koslow (1984), Shepherd et al. (1984), Koslow et al. (1987), Kalejs and Ojaveer (1989), and Thompson and Page (1989).

Hjort (1914) reported the coincident high abundance of the 1904 year-classes of cod (Norway and North Sea), haddock (North Sea), and Norwegian spring-spawning herring. Taning (1936) reported that the 1912, 1917, and 1922 year-classes of cod were dominant off Norway, Iceland, and Greenland. Templeman (1965) reported recruitment synchrony in the same areas for cod, haddock, and herring.

Dragesund (1971) reported little or no synchrony for capelin, cod, haddock, herring, redfish, and saithe among five regions from the Barents Sea to the U.S. coast. However, Garrod and Colebrook (1978) reported strong correlations among 18 stocks of cod, haddock, herring, plaice, and sole, if they were grouped by common environmental influences--oceanic, shelf, transitional, and range extremities. Templeman (1972) reported a loose relationship, within and among regions, between 18 stocks of cod and haddock, from Georges Bank to the Barents Sea. He noted that commonly there was a one- to two-year lag between western and eastern Atlantic regions.

Koslow (1984) investigated 14 stocks of cod, haddock, herring, mackerel, and redfish, in the northwest Atlantic (west Greenland-Scotian Shelf region), principally during 1960-75. He reported mostly positive correlations of recruitment among demersal (43 of 45) and pelagic (5 of 6) stocks, but mostly negative correlations between demersal and pelagic (32 of 40) stocks. He concluded that large-scale physical forcing was the predominant regulator of recruitment in the region. Koslow et al. (1987) reported the same results, with a longer time series (mostly 1956-80), for cod and haddock in the same region.

Shepherd et al. (1984) reached the same conclusion for the northeast Atlantic, after reviewing synchronies reported for flatfish, gadoids, and herring. However, their results, using the Bartlett Sphericity test, contradicted those of Garrod and Colebrook (1978), based on correlations and principal component analysis. Kalejs and Ojaveer (1989) reported the general synchrony of strong year-classes of cod, herring, and sprat in the Baltic Sea during 1948-85.

Thompson and Page (1989) noted that recruitment-synchrony studies have recently advanced to quantitative analyses, but problems persist. Contradictory results were occasionally reported among independent analyses of the same data, and some techniques were challenged. In the latter case, they cited a 1986 unpublished report which suggested that Koslow's (1984) patterns were due to his methods rather than large-scale correlations. The authors noted that two problems with delineating environment-recruitment relationships were autocorrelation and the relatively short (~20 y) time series currently available. For their own analysis, the authors selected time series, of varied lengths (~1950-82), for six cod stocks (1,2J3KL,3NO,3Ps,4TVn,4VsW) and three haddock stocks (4VW,4X,5Z) in the northwest Atlantic. After log transformations and first-differencing (correction for autocorrelation), the data were tested for recruitment dependence, within and among species, by the Bartlett's statistic, proportion of standardised variance accounted for by the first principal component, and inter-stock recruitment correlations. They found synchrony among cod stocks, but none between cod and haddock, the latter a contradiction to the results of Koslow (1984) and Koslow et al. (1987). They conceded that their method of correcting for autocorrelation may have eliminated low-frequency correlations, but also noted that VPA can cause recruitment trends, according to Bradford and Peterman (1989) (see also Bradford (1991). They decided that since spurious correlations cannot be separated from real low-frequency variations, it was perhaps better to remove them both by first-differencing.

8.2.2 Pacific Cod

Introduction

The substantial variations in recruitment of Pacific cod appeared to be largely independent of the fishery, based on the evidence provided in Chapter 7. The inevitable question arose as to the possible effect of environmental factors--atmospheric, hydrographic, or biotic. Seven reports were reviewed which dealt directly or indirectly with one or more of these factors in the northeast Pacific (Table 8.2.2). No reports were found which dealt with Pacific cod in the northwest Pacific.

Alaska

Ketchen (1956) examined selected data on air and water temperatures in the northeast Pacific Ocean, and noted evidence of long-term fluctuations in the marine climate. Some trends were parallel to those in the north Atlantic Ocean, e.g., the general warming during 1920-40. He noted negative or positive relationships between temperature and abundance of some marine fishes off British Columbia (English, petrale, and rock soles; sablefish) and Alaska (Pacific halibut). He suggested that "the relation of trends is too suggestive to be ignored, and points to the need for more trenchant investigation of variations in the marine environment and its effects on abundance" (op. cit., p. 370). He examined the CPUE data for line-caught cod off Alaska, during 1900-24; noted the substantial fluctuations (ca. 100-180 cod/trip); but found no close relationship with temperature (op. cit., Fig. 9)

Bell and Pruter (1958) undertook a more exhaustive investigation, apparently to refute Ketchen's (1956) positive relationship between halibut abundance and air temperature. They calculated a new cod CPUE (fish/vessel-ton/vessel-day's-absence) for the periods 1883-86 and 1891-1931. The increase in CPUE after 1919, was attributed to increased efficiency (introduction of powered dories). The authors did not relate these data to temperature, and generally discounted the possible relationship between climate and abundance of marine fishes in both the Pacific and Atlantic oceans. With respect to halibut, see Parker (1989) for an alternative hypothesis on environment versus recruitment.

Hecate Strait

Fournier (1983) incorporated mean annual sea level at Prince Rupert, B.C., as the environmental factor in his model of Pacific cod stock dynamics in Hecate Strait for 1960-80. He concluded that mean annual sea level was a "significant" factor in the dynamics of that stock. Significance was based on the reduction of the model's function (see Section 7.2) from 447.6 to 444.0, and that the percentage of the variance of the recruitment explained increased from 12 to 38%. Although he did not note the actual relationship between recruitment and sea level, recruitment appeared to vary inversely with mean annual sea level, based on the data in his Table 5.

Tyler and Westrheim (1986) investigated the relationship between cod recruitment (at age-3), with water transport (January-March), ambient water temperature (February), and relative size of the exploitable stock (kg/h; ages 2-7), during 1958-80. Linear analysis was unsatisfactory, but a multi-variate, second-order analysis (Schnute and McKinnell 1984) accounted for 67% of the variance. The principal factor was transport (northward advection). Relationship with recruitment of each factor varied with the values of the other two. For example, if stock size was held constant at 800 kg/h, recruitment varied inversely with transport, and directly with temperature, providing transport was not too strong.

Walters et al. (1986) considered the predator-prey relationship between cod and herring, during 1955-75, using linearizations of the Ricker stock-recruitment function, with a predation term added. They concluded that historic, reciprocal fluctuations in abundance of the two species could be accounted for with the predator-prey hypothesis. Anecdotal evidence by commercial fishermen suggested that a second prey species, Pacific sandlance, was also involved.

Tyler and Crawford (1991) combined the transport and predator-prey hypotheses, and used a different set of SSTs (this one from a lighthouse adjacent to the major spawning ground), and transport (based on current-meter data). They fitted a response surface with age-3 cod abundance as the independent variable, for the 1962-81 data. The 1982-85 data were reserved for prediction tests. Five

hypotheses were tested: (1) recruitment varied inversely with transport; (2) recruitment was related to a dome-shaped hatching success/temperature relationship; (3) recruitment positively related to abundance of age-0 herring hatched in the same year; (4) recruitment positively related to abundance of age-0 and age-1 herring in the year prior to cod spawning; and (5) recruitment/adult-stock-size relationship was dome-shaped. Only hypotheses (1) and (5) were supported by both the response-surface fit and prediction tests.

In summary, among the four analyses, cod recruitment was variously reported to vary directly with spawning season SSTs (if transport was not too strong), and inversely with mean annual sea level at Prince Rupert, northward transport during the spawning season, perhaps stock size, and juvenile herring abundance. Sea level at Prince Rupert and northward transport are positively correlated. However, the latest report suggests that only the inverse relationship with northward transport and the dome-shaped relationship with adult stock size are real.

Puget Sound and Vicinity

Palsson (1990) investigated potential climatic and biotic factors which might affect cod abundance. With respect to climate, he noted that during 1964-87, climate underwent one "cold" cycle before 1977, and one "warm" cycle after 1976, the period of declining cod abundance. The "cold" cycle was characterized by cool SST, high runoff, many storms, and low inputs of oceanic water. The "warm" cycle was characterized by warm SST, low runoff, few storms, and a great influx of oceanic water at depth replacing the colder regime. These climatic cycles had been recorded since 1924, well before cod indices of abundance were established (Ebbesmeyer et al. 1989). Unfortunately, only one "cold" and one "warm" cycle has occurred during the period when cod-abundance indices were reported.

Biotic factors considered were displacement and predators. Displacement involved the possible attraction of offshore cod to the Gulf-Bellingham region, where the abundance of spawning herring was high prior to 1977, but low thereafter. However, the decline in cod abundance elsewhere in Area 4A could not be explained by this factor. Predation was considered, because of the dramatic increase in abundance, after 1978, of seals and sealions. The author noted that further information was needed on the co-occurrence of cod and pinnipeds before this factor could be evaluated.

8.2.3 Atlantic Cod

Introduction

Twenty-eight reports were reviewed which dealt directly or indirectly with recruitment vs environment--six for the north Atlantic, 11 for the northeast Atlantic; and 12 for the northwest Atlantic (Table 8.2.3). One report dealt individually with single stocks in the northeast and northwest Atlantic (Cushing 1982).

North Atlantic

Templeman (1965) speculated that the recruitment synchonies of cod, haddock, and herring, in the Greenland-Norway region might be related to variations of the Gulf Stream. No other report was found which considered this factor, perhaps due to the lack of data. Stommel (1965) reported that insufficient data were available, because early measurements were made without a knowledge of the existence of meanders and eddies.

Templeman (1972) reviewed recruitment-fluctuation studies conducted during 1941-70. Principal factors reported were water temperature (possibly a secondary cause), larval drift (to desirable or undesirable locations), water mixing by wind and currents (favorable or unfavorable to plankton abundance), predation and competition (from other species), spawning stock abundance, and food (size, abundance, and quality). All factors were deemed to be interrelated.

Garrod and Colebrook (1978) correlated recruitment of 18 stocks, and plankton abundance, with large-scale patterns of wind. They noted that the precise nature of the relationships was not clear, and furthermore, the relationships might not necessarily be linear. Hence conventional correlations might be inappropriate.

Shepherd et al. (1984) reviewed 35 past studies involving three pelagic (13+ stocks) and seven demersal (15+ stocks) species in the north Atlantic; and four pelagic (4+ stocks) and one demersal (Microstomus pacificus; 1+ stocks) species in the north Pacific. For Atlantic cod (8 stocks), they reported that the most common factor was temperature (9 examples), followed by wind/pressure gradients/upwelling (3), "miscellaneous" (2), and salinity (1) (Table 8.2.4). Arcto-Norwegian was the only stock for which information was found for both proposed mechanisms and hypothetical ultimate cause (subject to hypothesis testing). The ultimate causes were wind strength/direction, pressure over Europe, and snowfall. The authors found within-area, but not among-area, correlations of log recruitments among species. For nine stocks in the North Sea/West of Scotland area, strong correlations were obtained between the first three principal components of North Sea water temperature and log recruitment of several species, including cod. Based on their, and others', analyses, they concluded that "an important relationship must exist between recruitment and climate" (op. cit., p. 266).

Cushing (1988) investigated the effect of the Great Salinity Anomaly (GSA) on the recruitment of 15 deep-water stocks in the north Atlantic, including six cod stocks--Faroe Plateau (Vb_1), Arcto-Norwegian, East Greenland, West Greenland, 2J3KL, and 3NO. Recruitment was significantly reduced for 11 of the deep-water stocks, and four of the six cod stocks (Arcto-Norwegian, East Greenland, West Greenland, and 3NO), during passage of the GSA through their respective areas. The 2J3KL cod year-classes were weak in 1969-71, rather than 1971-72, and the Faroe Plateau cod exhibited no weak year-classes immediately before, during, or immediately after passage of the GSA. The author noted that the GSA reduced primary and secondary production, and suggested that reduced recruitment was linked to reduced food for larvae.

Dickson and Brander (1993) reviewed the impacts of climatic change, during the 20th Century, on six Atlantic cod stocks--Baltic Sea, Faroe Islands, Barents Sea, and Iceland, West Greenland, and Labrador. The long-term, slow shift in the pan-Atlantic windfield was the overriding factor, but its effects varied among stocks. The authors emphasized the role of the windfield, because "it is the nearest point at which we can offer a unifying context for the very different cases we describe." (op. cit., p. 147). During "warm" periods, such as 1930s-early 1960s, the strong westerly winds, associated with a deep Iceland Low, produced favorable conditions for all six cod stocks by increasing advection of warmer water. The enhanced Irminger Current transported more eggs and larvae from Iceland to west Greenland which led to a substantial increase in the West Greenland stock. Furthermore, West Greenland eggs and larvae may have drifted to Labrador, particularly in 1957. Strong westerlies also enhanced the saline inflow into the Baltic Sea, which resulted in improved survival of eggs and larvae. Negative conditions prevailed when the westerlies subsided, after the early 1960s, and cold, northerly winds, associated with a strong Greenland High, prevailed in the region. All stocks were adversely affected by the cold water regime; egg-larvae transport from Iceland to Greenland virtually ceased; and saline inflows into the Baltic Sea ceased. The prolonged, strong Greenland High led to the development of the Great Salinity Anomaly (see Section 8.1.4), which produced secondary cooling effects during its 14-y cycle of the sub-polar gyre. The Barents Sea cod stock was particularly affected. No direct wind effects on the Faroe cod stock were noted.

Northeast Atlantic

N.W. Norway-Barents Sea. Hjort (1914) established that fluctuations in the cod stocks reflected variable survival of individual year-classes, a revolutionary concept at that time. He declined to suggest which factors caused the fluctuations, because information at that time was inadequate. Ottestad (1942,1960) discovered a relationship between the periodicity of ring-widths of the Scots pine (Pinus silvestria), near Lofoten, and the catch of skrei off Lofoten, during 1885-1939, and concluded that a common environmental factor (climate?) was operating. Ponomarenko (1973) compared the abundance of age-0 cod in the Barents Sea in 1948-51 with that during 1954-64, and concluded that survival varied directly with nutritional condition and temperature. Loeng (1989) noted that among the 1902-87 year-classes, strong ones only appeared during warm years, but not in all warm years. He concluded that the temperature effects on plankton were as important as those directly on cod.

Baltic Sea. The unique environment of the Baltic Sea is generally recognized as an important factor determining the abundance of fish stocks therein. A brief description follows, based on Cushing (1982) and Kullenberg (1986).

The Baltic Sea is a relatively shallow inland sea, whose connection with the North Sea and Atlantic Ocean is restricted by two shallow sills between Denmark and Sweden. Within the East Baltic, are three prominent deeps--Bornholm (SD 25), Gdansk (SD 26), and Godland (SD 28). Cod spawn at intermediate depths in each deep. Heavy freshwater runoff creates a permanent three-layer, vertical stratification. The surface layer has a low salinity. The bottom layer is very saline, but often anerobic in the major deeps. The middle layer is intermediate in salinity. Oxygen-rich, saline waters enter from the North Sea as a subsurface current, intermittently among years, and spread slowly throughout the Sea. This inflow tends to vary inversely with river discharge, perhaps a reflecting the overriding effect of meteorological phenomena over the eastern Atlantic Ocean and western Europe. The marine inflow increases salinity, which prevents the cod eggs from sinking into the anerobic depths, and also raises the level of the halocline, which places the larvae closer to their food supply.

Numerous investigations have correlated environmental factors with abundance of cod, and other species, in the Baltic Sea. Grauman (1973) conducted a census of eggs and larvae on the three spawning grounds (Bornholm, Gdansk, and Godland), during 1954-68. Results varied among grounds, but in all cases, embryo survival was the critical stage. He reported that the key environmental factor for egg survival was the thickness of the spawning layer, and within the layer, a salinity of $\geq$ 10.5 o/oo and oxygen at $\geq$ 1 ml/l. For larvae, the key factors were oxygen concentration and numbers of surviving eggs. He noted that larvae length and growth varied directly with plankton abundance.

Table 8.2.5 lists the factors, by source, which were considered at a recent symposium (Bagge and Rechlin 1989). One or more investigations reported that cod abundance varied directly with thickness of the intermediate layer, oxygen concentration, salinity, temperature, and volume of ocean inflow, but inversely with eutrophication (larvae survival).

Of particular interest was the complex relationship reported by Kalejs and Ojavier (1989). From the 1870s through the 1980s, they noted 23-y periods of high (8 y) and low (15 y) river discharge, and near-corresponding periodicity of ice cover. Cod year-class abundance varied inversely with these factors, for the 1950-85 year-classes. These two "regime-forming" factors were in turn affected by the alternating dominance of two atmospheric systems whose mutual boundary lies over the Baltic Sea, viz., the Atlantic (oceanic) circulation (westerly winds, warm winters--favorable to cod), and the Euro-Asiatic (continental) circulation (northerly winds, cold--unfavorable to cod). This relationship might also be described as the waxing and waning of the Iceland Low. The shifts in dominance of the two atmospheric systems were in turn due to "higher" factors, one of which might be solar activity, as measured by

Wolf numbers, which exhibits relatively consistent periodicity. During 1950-85, strong cod year-classes only occurred at, or adjacent to, the three nadirs of Wolf numbers. The authors acknowledged that all environmental factors were interrelated, and other factors such as age composition of the spawning stock were intermittently significant.

North Sea. Holden (1972) noted that mean abundance of the 1954-59 year-classes was substantially less than that of the 1960-67 year-classes, for cod landed at Grimsby and North Shields. Recruitment, at age 2, was measured as numbers landed per 100 h fishing. During 1954-67, mean May SSTs varied inversely with year-class abundance, except for 1962. Mean June SSTs varied directly with year-class abundance, if the negative anomalies were greater than -0.5 C, except for 1965. No explanation was offered for the relationships.

Dickson et al. (1974) cited reports showing that recruitment varied directly with temperature poleward, but inversely equatorward. Hence, an inverse temperature-recruitment relationship was expected in the North Sea. For the 1954-68 year-classes, they concluded that low SST during spawning (January) and larval drift (April) maximizes hatching success, by enhancing the chance of a match between hatching and food production, and by optimizing the metabolic range of the species. Mean annual landings nearly doubled between 1950-63 and 1965-71, which coincided with a decline in SST.

Cushing (1984) reviewed the 1954-77 fisheries, and described the "gadoid outburst", which began in 1962, and involved five gadoids, including cod (see Section 7.3.2.1). He attributed the phenomenon to three changes in the North Sea ecosystem: (1) increased abundance of Calanus in the northeast North Sea (and replacement of the smaller copepod species) which began in 1950; (2) delayed development of Calanus, after 1961, due to decreased SSTs; and (3) reduction of the herring and mackerel stocks, thus releasing food to gadoid recruits, other species, and invertebrate carnivores. The proportions allotted the three groups were unknown. The increase in abundance of Calanus was attributed to the influx of Atlantic Intermediate Water, during 1950-59, from the Norwegian Sea and the East Iceland Current, the regions where Calanus is most abundant in the northeast Atlantic. No explanation was offered for the external forces contributing to the gadoid outburst. However, his match/mismatch hypothesis appears to have been corroborated.

Pepin (1990) investigated the associations, for the 1960-80 year-classes, between biological variables and recruitment for several fish stocks. He found some strong relationships, such as abundance of Calanus. Nevertheless, he conceded, from a literature review, that environmental factors probably underly the relationship.

Northwest Atlantic

West Greenland. Hermann et al. (1965) found a linear relationship ($r = 0.85$) between abundance of the 1924-51 year-classes and mean water temperature (0-45 m) over Fylla Bank (SD 1B) in June. No correlation was found with currents or wind, with respect to survival of cod larvae. Cushing (1982) attributed the increased cod abundance, and northward shift of boreal species, to a relaxation of the westerlies which in turn allowed more heat to be retained in the sea. Stein and Mestorff (1990) noted that changes in tropical and polar regions, and teleconnections, affected the ocean climate off west Greenland. They reported that alternating 3-5 y periods of warm/saline and cold/dilute ocean climate coincided with similar periods of strong and weak year-classes, during the 45 y up to 1974. During 1974-83, there were no strong year-classes, but relatively strong year-classes appeared at 2-y intervals, when water temperatures were close to the long-term mean. Extreme cooling occurred during the early 1980s.

W. Greenland-Labrador-Newfoundland. Elizarov (1965) noted that water temperature not only affected living conditions for marine fishes, but was also

an indicator of oceanographic conditions. He found that during 1930-60, warm conditions in the West Greenland-Newfoundland Region generally enhanced cod recruitment and catch rates, and cold conditions produced the opposite effect. Warm periods coincided with a reduction in the polar outflow. Resulting oceanographic features were: (1) general increase of heat supply in the sea; (2) rise of near-bottom temperatures on the shelf; (3) increase in salinity, excluding coastal waters; (4) increase in river discharge and a corresponding increase in biogenic elements in the coastal zone; and (5) extension of the relatively warm Atlantic water, which increased the biogenic elements near the edge of the continental shelf.

W. Greenland-Scotian Shelf. Koslow (1984) investigated the potential factors underlying the correlations of cod-stock recruitments in the west Greenland-Scotian Shelf region. He discounted the freshwater outflow hypothesis of Sutcliffe et al (1983; see below), because: (1) correlation of the West Greenland stock with those south of Hudson Bay; (2) small contribution (~2%) of the Hudson Bay outflow to the Labrador Current; and (3) the high correlation, during 1964-74, of salinities in the Labrador Sea with those off Newfoundland. He attributed the declining salinity in the Labrador Sea during 1966-71 to an increased outflow of Arctic water into the north Atlantic, thence to the West Greenland Current, and finally to the Labrador Current. This event, in turn, was related to a shift in air pressure blocking over Greenland, and coincided with a period of mild winters in the Labrador Sea. The widespread nature of the climatic event is probably responsible for the apparent correlation between freshwater and Arctic outflows into the northwest Atlantic. However, he noted that the salinity in the northwest Atlantic is linked with a number of other factors, by which other processes may affect fish recruitment. The author also noted that the lack of recruitment correlations among cod stocks across the north Atlantic, reported by Garrod and Colebrook (1978), was apparently due to processes operating over distinct oceanographic or climatic regions. He recommended that "investigations of fishery dynamics and of marine communities generally should focus upon relationships on the ecosystem scale and should examine closely how large-scale oceanographic processes may influence fishery recruitment." (op. cit., p. 1729)

Koslow et al. (1987) updated the time-series of Koslow (1984), through 1980. They found no evidence of a stock-recruitment relationship. Their multivariate analysis led to rejection of previous hypotheses concerning the effect of single factors (run-off, salinity, and wind), all of which were inter-correlated. They did find, as did Koslow (op. cit.), a general coherence in recruitment among cod stocks, and between cod and haddock stocks, with apparent periodicities of 10-20 y. Several physical and biological variables in the region exhibited similar large-scale coherence and apparent periodicity. They concluded that recruitment was responding to large-scale environmental processes, most of which were not adequately represented in the local variables. Furthermore, statistical analyses were unlikely to explain the recruitment variability, because of widespread intercorrelations among environmental processes. Interestingly, they attributed the stock declines during the 1960s to adverse environmental conditions and heavy fishing, but also noted that during the same period stocks were improving in the northeast Atlantic under equally heavy fishing.

Labrador-E. Newfoundland. Sutcliffe et al. (1983) reported the strong multiple correlation (0.90) of abundance of age-4 cod, during 1958-76, with summer salinities off St. John's, Newfoundland, for each of the first three years of life of the cod. The salinities in turn were inversely correlated with river discharges into Hudson Bay, with a lag of four months. They hypothesised that heavy river discharge into the Bay tended to reduce mixing, and hence nutrient content of the outflow through Hudson Strait into the southward flowing Labrador Current. A strong stratification would also inhibit mixing with the nutrient-rich deep water. A corroboration of the effect of the Hudson Strait outflow was noted in the correlation (-0.71) of the St. Lawrence River discharge with the aforementioned summer salinities. The explanation for this was that most of the discharge into Hudson Bay comes from rivers south of the Bay whose headwaters lie near that of the St. Lawrence River.

Helbig et al. (1992) reviewed investigations aimed at correlating recruitment with climatic fluctuations for cod stocks occupying the Labrador-Newfoundland Shelf (2J3KL,3NO,3Ps). They concluded that those efforts were fruitless. They deplored the lack of data on distribution of eggs and larvae, but noted that simulations of drift patterns, currently under development, held some promise as a substitute.

Grand Bank-Georges Bank. Myers and Drinkwater (1989) tested the hypothesis that warm-core rings reduce recruitment of marine fish stocks through off-shore transport, using data collected during 1973-86. Study area extended from the New England Bight to the Grand Bank. Warm-core rings, large eddies generated by unstable meanders of the Gulf Stream, were counted and tracked from satellite images. Recruitment data were obtained for 17 groundfish stocks (5 species; 5 cod stocks--3NO,3Ps,4VsW,4X,5Ze), 7 pelagic fish stocks (5 species) and sea scallops (Placopecten magellanicus). Evidence was provided that increased warm-core ring activity did reduce recruitment of all groundfish stocks, except Georges Bank cod, but not the pelagic stocks and sea scallops. Auer (1987) tracked 115 warm-core rings during 1980-85, and reported the following gross statistics: mean surface diameter = 129 km (N = 905; S.D. = 42.7); mean scalar speed = 6.8 kg/d (N = 905; S.E. = 4.9); and mean lifespan = 19 wks.

S. Gulf of St. Lawrence. Lett et al. (1975) applied a multivariate analysis of cod year-class abundance which involved temperature and stock biomass, for the 1965-74 year-classes. They found that both were key factors in determining egg abundance and subsequently year-class abundance.

Scotian Shelf. Smith et al. (1991) provided qualitative evidence that environment affected estimates of cod recruitment in 4VsW, by altering the availability of cod. Catches of age-4 cod in research-vessel trawl surveys, during the March 1979-88, varied with depth, salinity, and temperature at the trawling sites. Large catches were associated with the intermediate, cold-water layer (32-33.5 o/oo; <5 C). Furthermore, interannual changes in the estimated abundance frequently coincided with changes in the proportion of bottom water composed of the intermediate, cold-water layer.

Subarea 5. Sutcliffe et al. (1977) found statistically significant correlations between temperature and catches for 10 of 17 species of commercial marine species of fish and shellfish in the Gulf of Maine. Study period for individual species was at least 40 y. From earlier studies (Sutcliffe et al. 1976) it was determined that the St. Lawrence River discharge was one important factor influencing the SST off Nova Scotia and in the Gulf of Maine. Temperature was acknowledged to be only a reflection of larger oceanic or atmospheric events. For cod, during 1893-1973, the correlation of Eastport, Maine, air temperatures with SA 5 catches was -0.661. For 1921-73[1], correlation was -0.833 for SA-5 catches and St. Andrews July-August SSTs, with a 4-y lag.

8.3. ABUNDANCE PREDICTION

INTRODUCTION

Only long-term abundance predictions will be discussed here. Short-term abundance predictions, for management purposes, were discussed in Chapter 7.

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[1] In text. 1925-73 in Table 3.

8.3.1 Pacific Cod

Introduction

Only two reports were found which dealt with "long-term" prediction of Pacific cod abundance, one each for British Columbia and Alaska (Table 8.3.1).

British Columbia

Tyler and Crawford (1991) achieved some success predicting abundance of age-3 cod in Hecate Strait using a two-factor (transport/adult stock size) model of conditions at spawning time (see Section 8.2.1 for details). They used data for 1962-81 to predict the results for 1982-85. Mean absolute difference between observed and predicted values was 55%. The prediction included the very large 1985 year-class.

Alaska

Wespestad et al. (1982) used a numerical population simulator to predict population size, in the eastern Bering Sea, during 1982-86, at various levels of constant catch. They assumed two levels of constant recruitment (low and high mean estimates from the 1977-81 trawl surveys), and M = 0.7. At their preferred low mean recruitment (221 million/y), fishable biomass declined from 494,000 t in 1982 to 231,000 t in 1986, if constant catch was 58,000 t. If constant catch was 120,000 t, fishable biomass declined to 120,000 t. Actual catches during 1982-86 ranged from 58,000 t (1984) to 133,000 t (1985), and biomasses, 958,000 t (1985) to 1,134,000 t (1986) (Thompson and Bakkala 1990, Tables 1,2). The latter authors estimated M = 0.29, and computed recruitment from a Beverton-Holt stock-recruitment relationship.

8.3.2 Atlantic Cod

INTRODUCTION

Ten reports were reviewed which dealt with predictions of cod abundance, four for the northeast Atlantic and six for the northwest Atlantic (Table 8.3.1).

Northeast Atlantic

Arcto-Norwegian. Ottestad (1960) predicted the yield of skrei at Lofoten during 1940-58, based on a projection of his 1885-1939 aggregate of sine functions of tree-ring widths (Ottestad 1942). For this prediction, he added the 8.5-y cycle to those of 11-, 17.5-, 23-. and 57-y in his initial analysis. The predicted catches exhibited the same trend (sharply downward after 1948) as the actual catches, but overestimated annual catches during 1941-45 and 1948-49. The former overestimates were attributed to World War II, and the latter to "uncommonly unfavourable" weather conditions. The underlying principle of this projection was the conservative nature of the skrei fishery. No allowance was made for the possible effect on the stock of fisheries elsewhere.

Serebryakov (1991) made no prediction, but proposed using long-term records of population fecundity, survival index (ratio of recruitment at age i to eggs laid, as a measure of environmental conditions), and year-class abundance to provide predictions of year-class abundance of capelin, cod (Arcto-Norwegian),

Greenland halibut, herring, and whiting. He proposed three categories of population fecundity--safe, medium required, and critical. For cod, the time series was 1946-84, and the fecundity values were 1,346 x 10^{12}, 570 x 10^{12}, and 175 x 10^{12} eggs, respectively. Once the population fecundity was established for a year-class, the survival conditions (biotic and abiotic, but unspecified) would determine the ultimate year-class abundance. Thus, for example, if the fecundity was at the critical level, an abundant year-class could only be expected under maximum survival conditions.

Baltic Sea. Kalejs and Ojaveer (1989) utilized the regularity of periodic changes in two "regime-forming" factors (river discharge and ice cover), during 1948-85, to predict future abundance of cod, and other important species, in the Baltic Sea. They predicted that the current cold-winter/high river runoff (adverse for cod) will end in 1992. The next 16-y period will be favorable to cod, and will feature fairly mild winters (with severe winters only in 1998/1999 to 2000/2001) and low river discharge. They expected that during 2009-2016, the average winter severity will increase and the river runoff will be particularly high, marking a return to unfavorable conditions for cod.

Lablaika et al. (1989) provided a series of formulae for predicting cod abundance in the Baltic Sea, based on a study of 20 generations (1966-85). Their factors were salinity, oxygen, thermal regime in the spawning zone of Gothland Deep, and abundance of the parent stock. However, they made no predictions.

Northwest Atlantic

West Greenland. Hansen and Buch (1986) reviewed the variables which were used, or suggested, to predict year-class strength of West Greenland cod, viz., temperature, density stratification, larval abundance, and spawning stock biomass. Temperature was the June mean at 0-40 m on Fylla Bank (64 N lat). Density stratification referred to the effectiveness of the vertical convection process during the previous winter which puts nutrients at the surface for the plankton bloom in the following year. The index was the mean stability of the upper 200 m of the water column on Fylla Bank in November--theoretically an inverse relationship with year-class abundance. Index of larval abundance was the July catch rate (nos./30-min haul) on Fylla and Store Hellefiske (67 N lat) banks. Only temperature and larval abundance were of some predictive value. Both exhibited a direct relationship with year-class abundance. The relationships were partially confounded by the intermittent immigration of eggs and larvae from east Greenland and Iceland. Warmer temperatures presumably favored survival of larvae from the West Greenland stock, but also reflected, to an unknown degree, the strength of the Irminger Current which transported immigrant larvae into the west Greenland area. Factors affecting the strength of the Irminger Current were not discussed. The authors concluded that no satisfactory method of predicting year-class abundance of West Greenland cod was possible with the data available at that time.

Stein (1991) investigated the potential effects of global warming on the stocks off Greenland. He concluded that the stocks would be adversely affected, because global warming would cool and freshen the surface waters in the north Atlantic.

W. Greenland/Newfoundland. Baidalinov (1992) examined the relationship between SST anomalies in the Irminger Sea (55-60 N lat; 30-35 W long) and: (1) biomass of West Greenland cod (1979-88); and (2) spawning biomass of 2J3KL cod (1962-88). These relationships were expressed by the following linear regressions:

$$B = 41.9\ SST + 249 \quad \text{(West Greenland), and}$$

$$B = -200\ SST + 1{,}700 \quad \text{(2J3KL),}$$

where B = biomass, and SST = summed SST anomalies lagged 2 y.

Labrador-Newfoundland. Myers et al. (1993) reported that the positive recruitment-salinity relationship for 2J3KL cod (1958-76), reported by Sutcliffe et al. (1983)(see Section 8.2.2), continued to hold, with respect to trend, when recent data (1977-87) were added. However, the recruitment estimates in recent years were larger than the "actual" values, in part because the 1980 assessment used by Sutcliffe et al. (op. cit.) had underestimated F. Myers et al. (op. cit.) found the most reliable prediction of absolute recruitment was achieved by including SSB estimates. This produced a significant increase in the percentage of the variation accounted for. The new formula predicted weak recruitment during 1989-91, and for 1991, the lowest on record. Two possible mechanisms were investigated which might explain the recruitment-salinity relationship, i.e., food-chain hypothesis of Sutcliffe et al. (op. cit.) and larval-freezing hypothesis. Neither could be validated, and the authors conceded that the underlying mechanism remains "elusive".

Labrador-Gulf of Maine. Frank et al. (1990) discussed the effect of changes in oceanographic conditions, induced by a global increase in CO_2, on invertebrate and fish stocks in the northwest Atlantic. They predicted a general warming and freshening of coastal waters. They did not deal directly with cod, but suggested that demersal stocks would tend to decrease while pelagic stocks would tend to increase.

Subarea 5. Drinkwater and Myers (1987) tested correlations (landings vs SST or river outflow) previously reported by Sutcliffe and co-workers for 13 stocks of marine species in the Gulf of St. Lawrence-New England region. Their test involved adding recent records and observing the change in correlation coefficients. The only example for Atlantic cod was St. Andrews, New Brunswick, SSTs versus cod landings from NAFO Subarea 5. For 1925-73, the original correlation was -0.83, but for the new (1974-85) data, only -0.31. The authors reported that after correcting for auto-correlation, none of the new correlations were significant. They attributed these results to large changes in fishing effort, and in the structure of the fisheries.

8.4 SUMMARY

This chapter dealt with environment, recruitment vs environment, and abundance prediction, of Pacific and Atlantic cod. Only physical environment (atmospheric and oceanographic) was considered.

Environment

Three scales were discussed (global, hemispheric, and oceanic), with emphasis on the Northern Hemisphere, and the Pacific and Atlantic oceans.

Global scale. Solar energy is the driving, but variable, force. A 78-y cycle appears to exist, together with 11.1-y intervals between maxima. However, peak values within each cycle vary substantially, as evidenced by the inter-millenium and inter-century variations in climate. Prominent atmospheric features are the westerly winds, volcanism effects, teleconnections, and ENSO (El Nino-Southern Oscillation).

Westerly winds encircle both the Northern and Southern hemispheres at mid-latitudes, in long (~5,000 km), horizontally undulating (Rossby) waves. Their velocity is greatest at high altitude (11-17 km), and varies directly with the amount of incoming solar energy. As velocity increases, the winds shift poleward and wave length increases. Atmospheric and oceanic conditions at the surface are strongly affected by this upper-air flow.

Volcanism of sufficient magnitude can affect the global energy balance by discharging gases and particles into the upper atmosphere which can

reduce the solar energy reaching the earth's surface. Clusters of eruptions produce a long-term cooling effect on climate. Northern Hemisphere eruptions do not affect surface temperatures in the Southern Hemisphere, but Southern Hemisphere eruptions do affect the Northern Hemisphere.

Teleconnections are mechanisms by which atmospheric-oceanic events in one region of the earth can affect a distant region. These mechanisms operate in the atmosphere, at the surface and/or at high altitude. They are strongest during winter.

ENSO is generally accepted to be a major factor in the atmosphere-ocean system. It is a complex phenomenon involving the Southern Oscillation (SO) and El Nino (EN). SO is a seesaw variation in atmospheric pressure difference between the southeast Pacific Subtropical High and Australian-Indonesian Low, which in turn produces corresponding oscillations in the ocean's thermocline across the Pacific, immediately south of the equator. El Nino occurs off South America when the thermocline there is deepest, and consists of a large-scale warming at the surface. The cause of ENSO has not been firmly established. It may or may not be self-sustaining. ENSO events probably began about 2.0-3.2 million years ago, when the Isthmus of Panama was formed, but probably did not occur during glacial periods, when sea level was low. Flood-related geological evidence, in the Peruvian coastal plain, suggests that at least 15 very strong events occurred during the last 7500 years. During the past 400-500 years, ENSO exhibited a long-term cycle of 80-100 y, with a mean interval of 3.8 y for maxima, based on records of natural systems (tree rings, Cd/Ca ratios, coral bands, and ice cores) and historical data (mission records, diaries, ships records, etc.). Within the each long-term cycle, amplitude and frequency of maxima increases. ENSO events can affect extra-tropical terrestrial and oceanic areas by advection or teleconnections. During 1900-83, strong events occurred in 1926, 1941, 1958, and 1983. The magnitude of ENSO events must vary substantially among centuries, based on the known variations in the incoming solar energy, which acts directly on the equatorial atmospheric circulation.

Global climate, as indicated by temperature, exhibited oscillations with wave-lengths of ca. 50,000 y, for the past 400,000 y. Current trend is downward towards the next glacial period, a few thousand years from now. Recent millenia have exhibited cycles of 200-250 y. A Little Ice Age has been variously reported as occurring in two or more of the 13th through the 19th centuries. In the 20th Century, a distinct warming period began in the 1920s. In general, climatic trends are similar in the Northern and Southern hemispheres, based on ice-core samples.

Hemispheric scale. In the Northern Hemisphere, prominent zonal (east-west) features of the atmospheric circulation are the alternating high- and low-pressure areas in the mid-latitudes. Comparable meridional (north-south) features are the low-pressure systems at mid-latitudes, and high-pressure systems immediately northward and southward. Teleconnections link many of these systems within and between oceans.

Oceanic. Principal atmospheric features in the north Pacific are the Aleutian Low and the Pacific High (to the south), and in the Atlantic, the Iceland Low and the Azores High (to the south). Low-pressure systems dominate during October-March, and the high-pressure systems during April-September. Winter locations of lows vary with their intensity--eastward with high intensity (low pressure); westward with low intensity. Winds rotate counter-clockwise in low-pressure systems, and hence intense lows produce warm temperatures in the northeast sectors of each ocean, and cold temperatures in the central and northwest sectors. Two factors reported to affect the location of the lows are the position of the high-altitude ridges, possibly sunspot activity, and sometimes ENSO events. Intensity of the Iceland Low generally varies inversely with that of the Aleutian Low.

Surface circulation is similar for the north Pacific and north Atlantic. It begins with a junction, off the continent in the west, of a southward-flowing, cold current and a northward-flowing, warm current, and a

resulting eastward flow to the opposite continent. There a bifurcation produces loops northward and southward. Each ultimately returns to the origin. Ancillary, shorter loops are also generated.

Two phenomena each were reported which might affect recruitment of cod in the north Pacific and north Atlantic. Pacific phenomena were ENSO events and warm/cold water masses, although the latter was not corroborated by other studies. The Atlantic phenomena were the Great Salinity Anomaly (GSA), and warm-core rings in the Gulf Stream. GSA was a large, cold, low-saline, water mass which cycled around the north Atlantic Gyre during ~1967-82. Another one may have occurred during ~1900-14. Warm-core rings are large eddies on the shoreside of the Gulf Stream which are generated by its unstable meanderings. Their centers are Sargasso Sea water. They entrain large volumes of surface water (containing eggs and larvae in season) and move them off the continental shelf.

Climate. In the northeast Pacific, a low-amplitude change was reported for the last 2,700 y, based on ostracod sediments collected from a lake in south-central Alaska. During the pre-Little Ice Age, the climate was warmer and perhaps seasonally drier. During 1550-1975, tree-ring data, collected from Yukon Territory, Canada, suggested warming periods around 1600 and 1660, intermittently during 1740-1810, and consistently during 1920-60. Cold temperatures prevailed throughout most of the 19th Century, and a cooling period began after 1960. During 1827-1985, no trend was reported by one author, but he noted extended warm periods during 1864-70, 1940-45, and 1977-84, and extended cold periods during 1857-63 and 1948-56. Another author detected a general warming trend, based on SSTs collected at British Columbia lighthouses during 1921-89.

In the northeast Atlantic, the longest records found concerned the Baltic Sea. Climate was unusually cold around 400 A.D. and 1220 A.D. Severe ice conditions occurred 11 times during the 14th and 15th centuries, but only 4 times during the 16th and 17th centuries. The last cold period occurred during the 18th Century, coincident with the largest extension of the glaciers. The relative severity of winters, as measured by ice cover, declined from the early 19th Century to the mid-20th; then increased through the 1970s. In the Norwegian-Barents Sea region, during the last 100 y, warm and cold cycles, of 2.5-17.5 y, followed one another. Warm cycles were associated with a stable low-pressure system over the area which created a strong inflow of Atlantic water. Evidently the Iceland Low was intense.

In the northwest Atlantic, climate in Greenland was reported for the period ~350-1950 A.D., based on oxygen isotope (^{18}O) concentrations (o/oo) in ice-core samples. A prolonged warm period occurred during ~610-1125 A.D., followed by mostly cold periods until ~1900, when the current warm period began. Temperature in the Iceland-Greenland-Canada region, began to rise in 1920. Peak temperature in eastern Canadian waters occurred about 1950, 10-20 y later than off Greenland and Iceland. Secondary peaks appeared afterwards, but temperatures began to decline after 1960. Interestingly, SSTs off Bermuda began declining in 1960.

In the north Atlantic, two reports noted that the warming trend which began in the 1920s was 180° out of phase between the northeast and northwest sectors.

General. The outstanding feature of the environment is its variability, on both spatial and temporal scales. The initial source of the variation is the incoming solar energy, which appears to be most influential in the tropical Pacific Ocean. The astronomical basis for the variations in the input of solar energy was not investigated in this report. Terrestrial factors which may inhibit input of solar input are volcanism, under certain circumstances, and possibly human activities, in the last two centuries. Major variations in global, hemispheric, and oceanic climate occur in scales of millions, thousands, hundreds, and tens of years, and all appear to be quasi-cyclic. The current period is inter-glacial, and the next glacial period is expected in a few thousands years. In the temperate zone of the Northern Hemisphere, variations

in the solar energy input affects the velocity and location of the high-altitude, westerly winds, which in turn affect the atmospheric and oceanic circulations at the surface. Currently, neither the atmospheric nor the oceanic dynamics appear to be well understood, nor their interactions. For example, atmospheric-oceanic interactions were not fully recognized until the 1960s.

Recruitment vs Environment

Recruitment synchronies. These provided the initial evidence that environmental factors operating over broad geographical regions affected recruitment of diverse marine fishes, including cod. The first comprehensive report for the Pacific (northeast only) appeared in 1987, and for the Atlantic, in 1914. No comparable report was found for the northwest Pacific. For the northeast Pacific (California-Bering Sea), synchrony of extreme year-classes was reported throughout the study area. Correlations were usually positive within region-species groups, and usually negative among region-species groups. Many stocks exhibited recruitment trends, usually negative. Pacific cod was poorly represented. A separate literature survey noted that during 1975-78, strong year-classes appeared in several species, from California to the Okhotsk Sea. For example, the 1977 year-class was strong for chub mackerel (California), lingcod (British Columbia), Pacific cod (British Columbia-Alaska), Pacific hake (California-British Columbia), and sablefish (British Columbia-Gulf of Alaska). No records were found for cod in the northwest Pacific.

In the Atlantic, the 1914 report noted the coincident high abundance of the 1904 year-classes of cod (Norway and North Sea), haddock (North Sea), and Norwegian spring-spawning herring. Subsequently, numerous reports appeared dealing with recruitment synchronies within and among the northeast and northwest sectors, and within and among species. Cod were well represented in the analyses. Recruitment synchronies were usually positive within sectors, and negative among sectors.

Pacific cod. Seven reports were found which dealt with recruitment versus environment--two for Alaska, four for Hecate Strait, British Columbia, and one for Puget Sound, Washington State. Both Alaska reports used air and sea temperatures. The first, using data for 1900-24, failed to find a relationship. The second, using data for 1883-86 and 1891-1931, found a direct relationship between temperature and abundance, using an improved CPUE, but considered it a coincidence, and attributed the rise in catch rate to increased efficiency of gear. Furthermore, they discounted the effect of climate on marine fishes of the Pacific and Atlantic oceans. The four Hecate Strait analyses dealt with (1) mean annual sea level pressure at Prince Rupert (1960-80), (2) SST/transport (1958-80), (3) cod/juvenile herring interaction (1955-75), and (4) SST/transport/cod-juvenile herring (1962-81). The Puget Sound study related the recent cyclical rise and fall of cod abundance to corresponding cycles in climate.

Overall, the temperature-recruitment relationship varied regionally--inversely in Puget Sound, and directly in Hecate Strait (if transport was not too strong) and the Gulf of Alaska. In Hecate Strait, results were sometimes contradictory among reports. Recruitment varied directly with mean annual sea level at Prince Rupert, but inversely with transport (which varies directly with mean sea level) during the spawning season. A predator-prey relationship with herring was demonstrated in one report, but not in the other. One analysis yielded a dome-shaped relationship with stock size.

No reports were found which related either ENSO events or warm/cold water masses to cod recruitment. Based on the temperature-recruitment relationship, ENSO should have a favorable effect off Alaska, and an unfavorable effect off British Columbia and Washington State.

Atlantic cod. Twenty-eight reports were reviewed--four (including one review) for the north Atlantic; 11 (including one review) for the northeast

Atlantic; and 12 for the northwest Atlantic. One report dealt individually with a single stock in each sector.

For the north Atlantic, proposed factors were wind, GSA, wind fields, and, more specifically, the relative intensity of the Iceland Low. One report noted that the precise nature of the relationship with wind was unclear, and might not even be linear. GSA was reported to adversely affect recruitment of some cod stocks. In the review, the most common factor reported for the eight cod stocks considered was temperature (all stocks), and the proposed mechanisms were larval drift, growth, and match-mismatch. ENSO, although not directly acknowledged, is probably a factor in cod recruitment, since via teleconnections, it was reported to affect the undulations of the westerly winds, and hence the position, and possibly intensity, of the Iceland Low.

For the northeast Atlantic, proposed factors were climate, temperature, and temperature/food off Norway; atmospheric circulation, salinity/temperature/spawning-layer thickness, subsurface inflow, and eutrophication in the Baltic Sea; and temperature and temperature/Calanus abundance in the North Sea. The review report dealt with the Baltic Sea, and noted that the most common factor reported was water chemistry (oxygen, salinity, temperature). Other factors were thickness of the halocline, ocean inflow, river discharge, ice cover, sun activity (Wolf number), atmosphere (air pressure, wind direction), and eutrophication. One report noted that generally, cod recruitment varied directly with temperature poleward, and inversely equatorward. Laboratory studies on Pacific cod suggested the same situation (see Section 5.7.1). Warm temperatures, during January-May, were favorable to cod from the Baltic Sea to Newfoundland, except the North Sea. In the latter case, colder temperature inhibited the growth of Calanus, and hence improved the match/mismatch relationship with larval cod.

For the northwest Atlantic, proposed factors were salinity/large-scale physical forcing and meteorological patterns/offshore winds for the entire region; temperature, atmosphere, and temperature/climate off west Greenland; temperature/salinity/river discharge, and transport in the W. Greenland-Newfoundland region; Gulf Stream warm-core rings in the Grand Bank-Georges Bank region; and temperature in the Gulf of St. Lawrence-New England region. In a 1965 report, the author speculated that variations in the strength of the Gulf Stream might be a factor, but no time series were, nor are, available which allow for the Stream's meanderings.

General. A good case has been made for the physical environment as a factor in the recruitment of Pacific and Atlantic cod, and other species. However, most reports reviewed here dealt with proxy factors, such as temperature and salinity, which merely reflect broader atmospheric and oceanic conditions. Exceptions were Cushing (1982) and Laevastu (1993), who dealt with climate and fisheries on a worldwide basis.

Only for Atlantic cod were reports found which considered the broader aspects of environment discussed in Section 8.1. Among these were atmospheric and oceanic circulations, and possibly solar activity. Few reports dealt directly with the vagaries of the westerly winds, or the Iceland Low, but some did refer to the results of such related factors as wind fields and (undefined) atmospheric systems. One report noted that the Greenland climate was affected by polar and tropical atmospheric conditions, a nod to teleconnections. One result of unusual atmospheric conditions adversely affecting some cod stocks was the Great Salinity Anomaly which resulted from a high-pressure system which remained over Greenland for an anomalously long time, during the 1960s. Furthermore, there is evidence to suggest that this anomalous behaviour has occurred in the past.

Some caveats were reported with respect to correlations of recruitment and environment, such as curvilinear rather than linear relationships, questionable relevance of statistical analyses, effects of salinity and temperature at survey sites on estimates of recruitment, and effects of errors in M used in VPA (Lapointe and Peterman 1991).

Abundance Prediction

Pacific cod. Two reports were found which dealt with long-term predictions of abundance--one each for British Columbia (Hecate Strait), and Alaska (eastern Bering Sea). The British Columbia report was fairly successful in predicting the abundance of age-3 cod during 1982-85 using a two-factor (transport/adult stock size) model of conditions at spawning time, based on data for 1962-81. Mean absolute difference between observed and predicted values was 55%. The Alaska report used a numerical population simulator to predict catch and population size (biomass) during 1982-86, at various levels of constant catch and two levels of constant recruitment. The low and high estimates of recruitment came from the 1977-81 trawl surveys. The predictions were not successful, since neither catch nor recruitment remained constant.

Atlantic cod. Ten reports dealt with long-term predictions of abundance--four for the northeast Atlantic, and six for the northwest Atlantic.

For the northeast Atlantic, two reports dealt with the Arcto-Norwegian stock and two with the Baltic Sea stock. In the first report for the Arcto-Norwegian stock, the yield of skrei at Lofoten, during 1940-58, was predicted reasonably well, or at least its trend, based on an aggregate of sine functions based on tree-ring data for 1885-1939. The second report made no prediction, but proposed using long-term records of population fecundity, survival index (ratio of recruitment at age i to eggs laid, as a measure of environmental conditions). In the first report on the Baltic Sea stock, "regime-forming" factors (river discharge, ice cover), predicted that the current, cold winter/high river runoff (adverse for cod) would end in 1992. The following 16-y period would be favorable to cod, but thereafter, adverse conditions would return. The second report offered no prediction, but provided a series of formulae for predicting cod abundance, based on a study of 20 generations (1966-85). Formula variables were salinity, oxygen, thermal regime in the spawning zone of Gothland Deep, and abundance of parent stock.

For the northwest Atlantic, six reports were found. Four dealt with predicting cod abundance in particular regions (west Greenland, west Greenland-Newfoundland, Labrador-Newfoundland, and NAFO Subarea 5), with respect to current environmental factors. Two dealt with the hypothetical effect of global warming on cod in two regions--Greenland and Labrador Shelf-Gulf of Maine. No predictions were made for the west Greenland and west Greenland-Newfoundland regions. The west Greenland report reviewed several environmental factors, but concluded that no prediction was possible, because of the lack of quantitative data on the immigration of eggs and larvae. The west Greenland-Newfoundland report presented formulae which related SST anomalies in the Irminger Sea to the biomasses of West Greenland and 2J3KL cod stocks. The Labrador-Newfoundland report noted that the recruitment-salinity relationship previously reported for 2J3KL cod (1958-76) continued to hold when 1977-87 data were added. The relationship was improved with the addition of spawning stock biomass, but the report conceded that the underlying mechanism remained "elusive". For Subarea 5 cod, the previously reported positive relationship between landings and SST at St. Andrews, New Brunswick, for 1925-73 did not hold with the additional 1974-85 data. This was attributed to large changes in fishing effort, and in the structure of the fisheries.

Predicted effects of global warming were the same, negative, for cod stocks off west Greenland and in the Labrador Shelf-Gulf of Maine region. Global warming would produce a substantial cooling of surface waters which would be detrimental to cod stocks.

General. Few reports were found which provided predictions of Pacific or Atlantic cod abundance, and fewer still which measured the accuracy of the predictions. In retrospect, this result is not unexpected. Time series of fisheries records are not only short, rarely as long as 100 y, but also limited with respect to general quality of data on abundance and/or recruitment and

biology. Substantial improvements in fishing efficiency have occurred since the 1920s, when trawling began to be important, Biology of cod, with respect to its environment, is still poorly understood. Environmental records, on the other hand, albeit limited in quality, span centuries and millenia, and indicate substantial environmental variation over short-term and long-term periods. A recent report expressed concern that prediction of weather or climate will become even more difficult unless the effects of human activity can be included.

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Table 8.2.1. Strong 1975-78 year-classes, by species, location, and source, of commercially important marine fishes in the north Pacific Ocean and adjacent seas.

Species	Location	Year class	Source
Chub mackerel	California	1977	McCall *et al.* (1985)[a]
Lingcod	British Columbia:		Cass *et al.* (1990)
	Georgia Strait	1975-77	
	Offshore (3CnD,5AB)	1977-78	
Pacific cod	E. Bering Sea & Gulf of Alaska	1977	Wespestad *et al.* (1986)
	British Columbia (3CnD,5A-5D)	1977	Foucher & Tyler (1991)
Pacific hake	Georgia Strait (4B)	1977	McFarlane & Beamish (1986a)
	W. Vancouver Is. (3CnD)	1977	Beamish & McFarlane (1986)
	Washington-California	1977	Bailey & Francis (1986)
Paciific ocean perch	Gulf of Alaska	1976	Clausen & Heifetz (1989)
	British Columbia (5A-5C)	1976[b]	Leaman (1991)
Sablefish	Gulf of Alaska	1977	Sigler & Fujioka (1988)
	British Columbia (3CnD,5A-5E	1977	McFarlane & Beamish (1986b)
Walleye pollock	Okhotsk Sea	1978	Zolotov & Antonov (1989)
	Aleutian Is., C. & E. Bering Sea	1978	Dawson (1989)
	E. Bering Sea	1978	Bakkala & Alton (1986)
	Gulf of Alaska	1978	Megrey (1989)

a. Suggested by R.J. Beamish.
b. 1977 in his Fig. 2.

Table 8.2.2. List of reports reviewed dealing with recruitment *vs* environment, by location, time, environmental factor(s), and source, for Pacific cod.

Location	Time	Factor(s)	Source
Alaska	1900-24	temperature	Ketchen (1956)
	1883-1931	"vessel efficiency"	Bell & Pruter (1958)
Hecate Strait	1960-80	sea level	Fournier (1983)
	1958-80	transport/ temperature	Tyler & Westrheim (1986)
	1955-75	herring abundance	Walters *et al.* (1986)
	1962-81	transport/ temperature/ herring abundance	Tyler & Crawford (1991)
Puget Sound	1964-87	climate	Palsson (1990)

Table 8.2.3. List of reports reviewed dealing with recruitment vs environment, by location, time, environmental factor(s), and source, for Atlantic cod.

Location	Time	Factor(s)	Source
N. Atlantic	1942-58	Gulf Stream[a]	Templeman (1965)
	1941-70	review: see text	Templeman (1972)
	1949-74	wind	Garrot & Colebrook (1978)
	1924-81	review: see Table 8.2.4	Shepherd et al. (1984)
	1962-82	Great Salinity Anomaly	Cushing (1988b)
	1870-1990	wind fields	Dickson & Brander (1993)
N.W. Norway-Barents Sea	1885-1939	climate	Ottestad (1942)
	1948-64	temperature	Ponomarenko (1973)
	1902-87[b]	temperature/food	Loeng (1989)
Baltic Sea	1954-65	salinity/temp./spawning layer thickness	Grauman (1973)
	----	review: see Table 8.2.5	Bagge & Rechlin (1989)
	1922-91	subsurface inflow/nutrients/eutrophication	Bagge et al. (1993)
North Sea	1954-67	temperature	Holden (1970)
	1950-71	temperature	Dickson et al. (1974)
	1954-71	temperature/Calanus abundance & timing	Cushing (1982)
	1954-77	Calanus timing	Cushing (1984)
	1960-80[b]	Calanus abundance/"environment"	Pepin (1990)
W. Greenland	1924-51[b]	temperature	Hermann et al. (1965)
	1920-67[b]	atmosphere	Cushing (1982)
	1929-73	temperature/climate	Stein & Mestorff (1990)
W. Greenland-Labrador-Newfoundland	1925-50	temperature/salinity/river discharge	Elizarov (1965)
W. Greenland-Scotian Shelf	1964-70	large-scale physical forcing	Koslow (1984)
	1956-80	large-scale physical forcing	Koslow et al. (1987)

Table 8.2.3 - (Con't)

Location	Time	Factor(s)	Source
Labrador-Newfoundland	1958-76	salinity/Hudson Bay outflow	Sutcliffe et al. (1983)
	1950-85	drift simulation	Helbig et al. (1992)
Grand Bank-Georges Bank	1973-86	warm-core rings	Myers & Drinkwater (1989)
S. Gulf of St. Lawrence	1965-74[b]	temperature	Lett et al. (1975)
Gulf of St. Lawrence-New England (SAs 4&5)	1921-62	temperature	Martin & Kohler (1965)
Scotian Shelf (4VsW)	1979-88	depth/salinity/temperature[c]	Smith et al. (1991)
Sub-Area 5	1893-1973	temperature	Sutcliffe et al. (1977)

a. Speculation.
b. Year-classes.
c. Factors which indirectly affect recruitment by affecting trawl-survey catch rates of age-4 cod.

Table 8.2.4. Environmental factors, by stock, in the recruitment of Atlantic cod. (Sources: Shepherd et al. 1984, Tables 1-4. Individual sources not listed here. --- = not reported.)

Stock	Related to:	Proposed mechanism	Hypothesized ultimate cause
Temperature			
Arcto-Norwegian	---	match/mismatch[a]	changes in wind
	---	larval drift & development time	---
North Sea	---	larval size, density dependence, ability to consume food, match/mismatch[a]	---
	---	---	---
Iceland & S. Newfoundland	---	---	---
W. Greenland[b]	---	---	---
Flemish Cap (3M)	---	---	---
S. ICNAF	---	larval transport	---
Wind/pressure gradient/upwelling			
Arcto-Norwegian	wind	turbulence	pressure over Europe
Bear Island	wind	water transport	---
North Sea	pressure gradients	---	---
Miscellaneous			
"Norwegian"	tree-ring widths	heavy spring floods drive larvae offshore, hence poor settlement	snowfall
Labrador	index of meridional atmospheric circulation	distance drifted by larvae	---

Table 8.2.4 - (cont.)

Stock	Related to:	Proposed mechanism	Hypothesized ultimate cause
<u>Salinity</u>			
Arcto-Norwegian	---	match/mismatch[a]	wind strength & direction

a. Cushing (1975,1990)
b. Only an indicator of onshore conditions--high/warm; low/cold; Elizarov (1965). Author also noted the offshore indicator was salinity--high/warm; low/cold. Author did not hypothesize on the ultimate cause.

Table 8.2.5. Environmental factors, by source and time, correlated with abundance of Atlantic cod in the Baltic Sea, at the symposium in Rostock, February 29-March 3, 1988 (Bagge and Rechlin 1989).

Source	Time	Environmental factor[a]							
		Thickn.	Water (O,S.T)	Inflow Ocean	Inflow River	Ice Cover	Sun Act.	Atmos.	Eutro.
Berner et al.	1969-83	-	+ (O,S)	-	-	-	-	-	-
Grauman & Yula	1954-86	-	+ (O,T)	+	-	-	+	-	+
Kalejs & Ojaveer	1950-85	+	+ (S,T)	+	+	+	+	+	-
Kosior & Netzel	1960-86	-	+ (O,S,T)	+	-	-	-	-	-
Lablaika et al.	1966-85[b]	+	+ (O,S,T)	-	+	-	-	-	-
Nehring et al.	1973-84	-	+ (O,S,T)	+	-	-	+	+	-

a. Factors: Atmos. = atmosphere (air pressure, wind direction); Eutro. = eutrophication; Ice cover = % of Baltic Sea covered; Inflow = surface from rivers/subsurface from North Sea; Sun act. = sun activity (Wolf number); Thickn. = thickness of intermediate, homohaline layer; Water = oxygen (O), salinity (S), temperature (T); + = yes; - = no.

b. Year-classes.

Table 8.3.1. List of reports reviewed dealing with abundance prediction, by location, time, source, and predictor, for Pacific and Atlantic cod.

Location	Time	Predictor	Source
		Pacific cod	
N.E. Pacific			
E. Bering Sea	1977-86	simulator	Wespestad et al. (1982)
Hecate Strait	1962-85	transport/SSB	Tyler & Crawford (1991)
		Atlantic cod	
N.E. Atlantic			
Lofoten (N.W. Norway)	1885-1958	tree rings	Ottestad (1960)
N.W. Norway	1946-84	fecundity/ survival conditions	Serebryakov (1991)
Baltic Sea	1950-2016	ice cover/ river runoff	Kalejs & Ojaveer (1989)
	1966-85	oxygen/sal./ temp./SSB	Lablaika et al. (1989)
N.W. Atlantic			
Greenland	1876-1990	global warming	Stein (1991)
W. Greenland	1953-78[a]	review	Hansen & Buch (1986)
W. Greenland-Newfoundland	1962-88	temperature	Baidalinov (1992)
Labrador-Newfoundland	1958-87	salinity/ Hudson Bay outflow/SSB	Myers et al. (1993)
Labrador-Gulf of Maine	---	global increase in CO_2	Frank et al. (1990)
NAFO SA5	1925-85	SST/salinity/ river discharge	Drinkwater & Myers (1987)

a. Year-class.

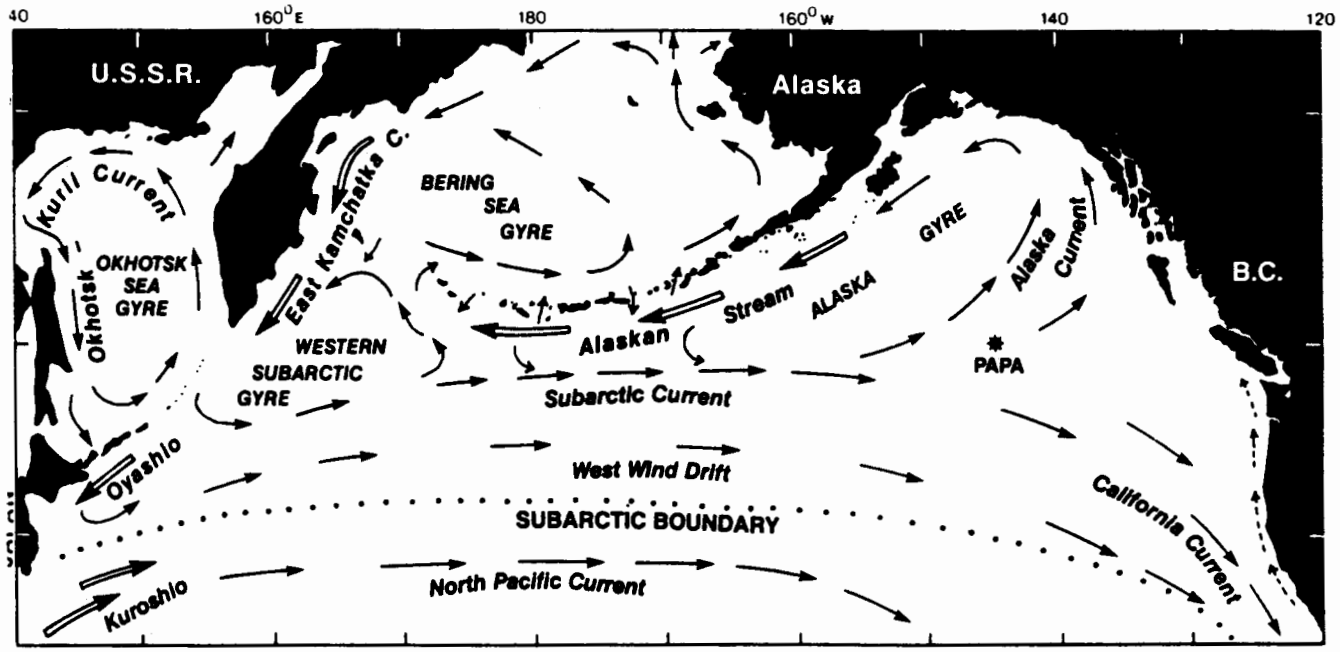


Fig. 8.1.1. Schematic diagram of prevailing surface currents in the north Pacific ocean. Double arows indicate intense boundary currents. Broken arrows indicate the Davidson Current off the Oregon-Washington coast. (Adapted from Fig. 13.17 in Thomson 1981)

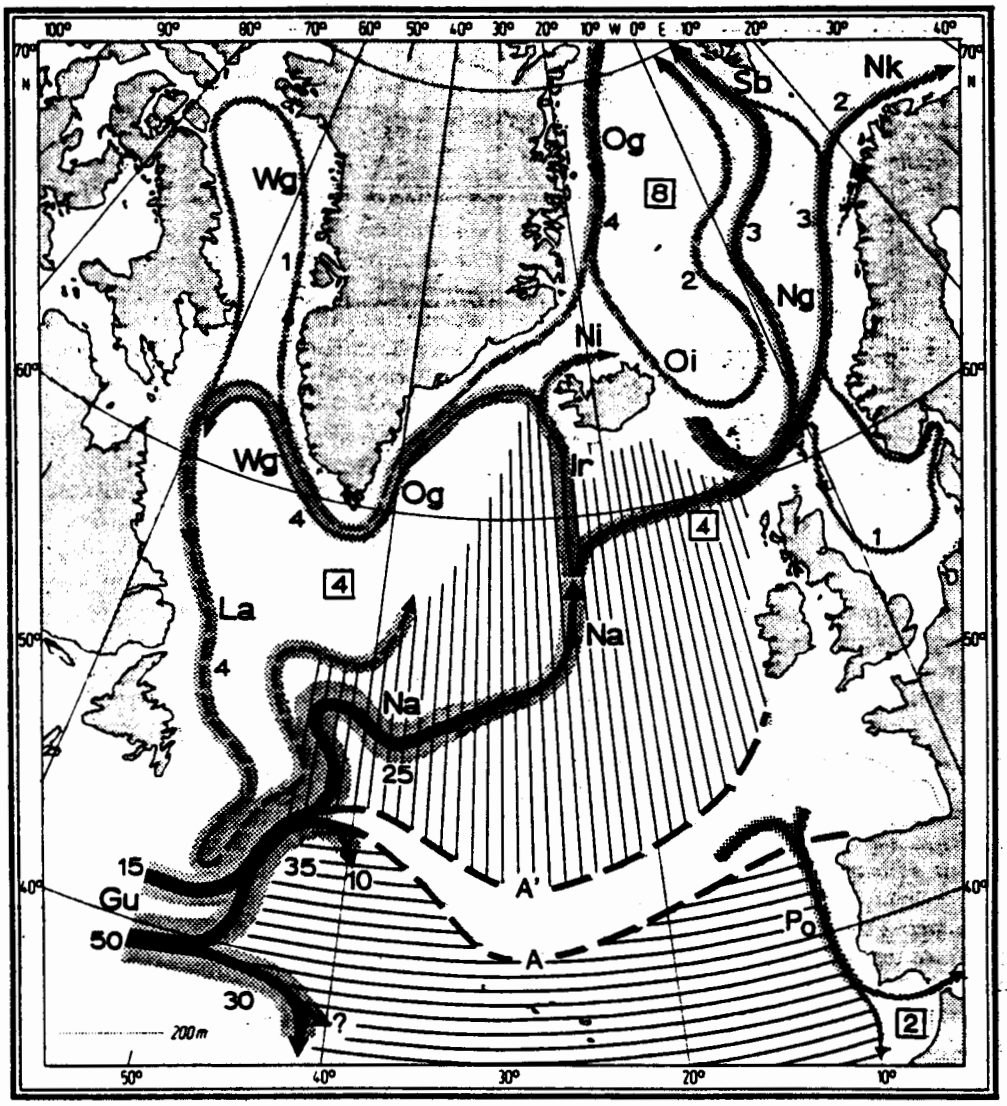


Fig. 8.1.2. Schematic diagram of prevailing surface currents in the north Atlantic Ocean. Vertical lines = northward flow associated with the North Atlantic Current. Horizontal lines = eastward/southward flow associated with the Subtropical Gyre. Area between A' and A belongs temporarily to the northern or southern area (Fig. 19 in Krauss 1986). Meanings of labels from Fig. 10.50 in Dietrich et al. (1980): Gu = Gulf Stream; Ir = Irminger Current; La = Labrador Current; Na = North Atlantic Current; Ng = Norweigian Current; Nk = North Cape Current; Ni = North Iceland Current; Og = East Greenland Current; Oi = East Iceland Current; Po = Portugal Current; Sb = Spitzbergen Current; Wg = West Greenland Current. Integers = volume of flow (10^6 m^3/sec). Squares = sinking water; volume in 10^6 m^3/sec. Solid arrows = relatively warm currents; broken arrows = relatively cold currents.

9. SUMMARY AND DISCUSSION

INTRODUCTION

The purpose of this report was twofold. First, to provide an overview, for the scientific community, of the information available on Pacific cod in the waters off British Columbia, Canada. Second, to compare this information with comparable information for Pacific cod elsewhere, Atlantic cod, and to a limited extent, Greenland cod. The general subjects dealt with (by chapter) were; nomenclature (3), distribution (4), biology (5), fishery (6), stock assessment(7), and abundance prediction (8). Since each chapter has its own summary, this chapter will only deal with relevant comparisons of Pacific cod off Canada with those elsewhere, Atlantic cod, and Greenland cod.

NOMENCLATURE

Pacific cod has been well differentiated from Atlantic cod, based on physical morphology, biochemical genetics, and karyological genetics. However, differentiation from Greenland cod is not well established at this time. Greenland cod may be a precursor to Pacific cod. However, should the two species be synonymized, the scientific name of Pacific cod would have priority. G. macrocephalus was described in 1810, while G. ogac was described in 1826. The range limits of the two species do not overlap at the present time.

DISTRIBUTION

Geographic

Distributions of Pacific and Atlantic cod are both transoceanic, in their respective namesake oceans. Southern limits are 34 N lat in the Pacific and northwest Atlantic, and 44 N lat in the northeast Atlantic. Northern limits are 63 N lat in the Pacific, and ~74 N lat in the Atlantic. Geographic range of Greenland cod is the northwest Atlantic, off Greenland and Canada (north of ~46 N lat), and in the Arctic Ocean, off Canada (east of ~131 W long).

Bathymetric

Ranges for Pacific and Atlantic cod are the same--shoreline to ~600 m. Greenland cod are mostly found inshore and in estuarine areas.

BIOLOGY

Comparable data were found for size composition, sex ratio, growth, reproduction, early life history, diet, predators, parasites, and diseases.

Size Composition

Maximum length of Pacific cod reported off Canada was 100 cm, and 114 cm elsewhere (Russia), compared to ~185 cm (U.S.A.) for Atlantic cod. Size range of Pacific cod landed at Canadian processing plants was ~41-80 cm, with one or two modes at 47-65 cm. Similar results were noted in samples from Washington State and Alaska. For Atlantic cod, modal lengths ranged from 65 to 110 cm in the Barents Sea, and 46 to 62 cm off Canada. Multimodality was common in samples of Pacific and Atlantic cod from research-vessel catches. Modal progressions were also common in length-frequency samples from commercial catches of both species, and were attributed to the passage of strong year-classes.

Sex Ratio

Pacific cod sex ratio, among length intervals in commercial landings and research-vessel catches, was approximately 50% males, to about 62-65 cm, then declined sharply to about 18% at 80 cm. Similar results were reported for Pacific cod elsewhere, and Atlantic cod.

Age Determination

To date (1993) no validated method has been reported for determining the age of Pacific cod, although numerous structures have been investigated. Currently, production ageing of Pacific cod from Canadian waters is undertaken with a computerized iterative method applied to length-frequencies, and elsewhere, otolith cross-sections (Alaska), scales (juveniles)/otoliths (adults) (Russia), and scales (Japan). For Atlantic cod, otolith cross-sections appear to be the established method, and some validations have been reported. However, workshop reports indicate regional, and perhaps national, interpretation problems still exist. The apparent low priority given to creating validated age-determination methods was surprising, since virtually all mathematical models applied in cod stock assessments were based on age compositions. Equally surprising, was the scarcity of reports which dealt with the effects of errors in age determination on these models.

Age Composition

Pacific cod off Canada comprise few age-classes, and the estimated maximum age is 11 y. Ages 2-4 comprise 84-95% of the commercial landings. Ratios of maximum/minimum year-class abundance ranged from 7.3 to 33.7, among areas. Similar results were reported for Alaska. In the northwest Pacific, modal age ranged from 4 to 7 y, and varied directly with latitude. Maximum age reported was 11 y. For Atlantic cod, catches contained numerous age-classes, except in the Baltic and North seas. Modal age ranged from 3 to 18 y, and varied directly with latitude. Maximum age reported was 23 y. Age-length keys (ALKs) were used to derive age-compositions of Pacific cod off Alaska, and commonly for Atlantic cod, but evaluations yielded mixed reviews, mostly negative. When tested, ALKs tended to produce their own age compositions when applied to length-frequencies of both Pacific and Atlantic cod.

Growth

Four aspects of growth were reviewed--length-weight, length-girth, age-length, and age-weight.

Length-weight. For round weights, Pacific cod off Canada were heavier per length interval than those off Washington State and in the Gulf of Alaska, and Atlantic cod off Canada, Norway, and in the North Sea. They were lighter per length interval than those in the eastern Bering Sea, off west Kamchatka, and in the Yellow Sea, as well as Atlantic cod in the New York Bight. For dressed weights, Pacific cod off Canada were heavier than those of Atlantic cod off Canada. Some corroboration of these relationships was provided by length-girth relationships. Girths of Pacific cod were greater than those of Atlantic cod off Canada and in the North Sea.

Age-length. Relationships of Pacific and Atlantic cod varied inversely with latitude. Mean lengths-at-age of Pacific cod were generally larger than those of Atlantic cod at comparable latitudes, perhaps because the water temperatures were greater in the Pacific. Atlantic cod exhibited, at times, substantial among-year variations in mean length-at-age--as much as 10 cm, but no such record was found for Pacific cod, perhaps due to limitations of the age-determination methods applied to the latter species.

Age-weight. Relationships were expectedly sigmoid for both Pacific and Atlantic cod. Weight-increment values of Pacific cod off Canada, peaked between ages 3 and 4 in the southern sector, and between ages 4 and 5 in the northern sector, and in the eastern Bering Sea. For Atlantic cod, weight-increment values

peaked between age 7 and 8 in the eastern Baltic Sea, and between 9 and 10 off Norway.

Reproduction

Four aspects of reproduction were reviewed--spawning, spawning season, length at maturity, and fecundity. Age at maturity could not be compared, because of the limited data available on Pacific cod.

Spawning. Type differs among the two species. Pacific cod are single-batch spawners, while Atlantic cod are multiple-batch spawners.

Spawning season. For Pacific cod, the season is January-April off Canada, and December-May elsewhere. In contrast, Atlantic cod spawning season is virtually year-round, albeit relatively short in individual areas. Perhaps this reflects the varied environments, and their effects on pelagic eggs and larvae.

Length at 50% maturity (L/50). L/50 values varied by sex, location, and year, for Pacific cod off Canada, and varied directly with latitude in the northeast Pacific. They were substantially larger in the northwest, off Kamchatka. Atlantic cod were similar to those off Kamchatka, with two exceptions. One exception was the Baltic Sea, where L/50 values were quite small. The other was the long-term decline in L/50 values in the North Sea, and in three areas in the northwest Atlantic.

Fecundity. Values, at length, for Pacific cod off Canada varied little with time (1961;1986-90) or area (W. Vancouver Island; Hecate Strait), and were similar to those off Russia (1939; 1947). In contrast, Atlantic cod fecundity varied among areas, and among years within some areas. Fecundities were relatively high for Norwegian Coastal and West Baltic Sea cod (both similar to Pacific cod off Canada); intermediate in the North Sea, off Iceland, and in the southeast Gulf of St. Lawrence; and low off Labrador and Newfoundland.

Early Life History

Few reports were found on the early life history of Pacific cod off Canada, or elsewhere. Laboratory studies indicated that Pacific cod eggs were demersal, slightly adhesive, and had a diameter of 1.02 mm. Atlantic cod eggs are pelagic, and have a diameter of 1.2-1.6 mm. Reports on the bathymetric distribution of Pacific cod larvae are contradictory--bathypelagic off Port Townsend (Washington); pelagic in the Gulf of Alaska. Atlantic cod larvae are pelagic. No report on the duration of the larval period was found for Pacific cod.

Diet

No information was found on the diet of Pacific cod larvae. Juvenile and adult Pacific and Atlantic cod have similar dietary habits. Both are omnivorous, opportunistic, and often cannibalistic (especially Atlantic cod). Diet varies with cod length--inversely with invertebrates, and directly with fish. For both species, the "boundary" size was usually ~50 cm. Miscellaneous stomach items included birds, algae, stones, and wood. Principal invertebrate and fish species varied among regions. For Pacific cod off Canada, these were crangonid and pandalid shrimp, Pacific herring, and Pacific sandlance. Elsewhere, north and west of Canada, principal species in one or more areas were crabs (Cancer, Chionoecetes, Paralithodes), pandalid shrimp, "atherina" (Atherinops?), capelin, herring, Pacific cod, salmon fry, sandlance, sardine, and walleye pollock. For Atlantic cod, the list was similar: euphausiids, crangonid and pandalid shrimp, decapod crabs, capelin, cod, flatfishes, herring, and sandlance. Pacific cod was reported to be a serious predator on pandalid shrimp and walleye pollock off Alaska. Atlantic cod was reported to be a serious predator on pandalid shrimp in the North Sea, and gadids in the Baltic, Barents, and North seas. One detrimental component in the diet of Atlantic cod (Norway, Greenland, and Newfoundland) was a pelagic pteropod (Limacina) which caused odoriferous flesh. One isolated incident was reported for Pacific cod, off

Canada.

Predators

No reports were found which listed predators on Pacific cod eggs, probably because no one has studied the eggs in situ. Hydrozoa and scyphozoa were reported as predators on larvae off Canada. For Atlantic cod, herring were reported as predators on eggs in the North Sea. Predators on larvae, based on laboratory studies, were copepods, euphausiids, and scyphozoa. The general list of predators on juvenile and adult Pacific and Atlantic cod were similar: several species of fish (including cod), birds, seals, sealions (Pacific cod), and whales (Atlantic cod). None of the predators on Pacific cod were listed as serious. For Atlantic cod, cannibalism was reported to be significant in the Barents, Baltic, and North seas.

Parasites

No reports were found which dealt with parasites on eggs or larvae of Pacific or Atlantic cod. For juvenile and adult Pacific cod, 46 parasite species were reported, of which 23 were found on cod in Canadian waters. For Atlantic cod, at least 66 species were reported in Canadian waters, of which 23 were also reported for Pacific cod. The sealworm (or codworm), was reported present in both Pacific and Atlantic cod, but was only sufficiently prevalent to be detrimental to the Atlantic cod industry. Its relatively large larvae encyst in the cod musculature, and must be removed at the processing plant. The sealworm is rarely harmful to humans.

Diseases and pathogenic parasites

A total of 34 ailments (14 unnamed) were reported--5 for Pacific cod, and 29 for Atlantic cod. Causative agents were viruses, fungi, bacteria, "protozoa", trematodes, nematodes, amphipods, copepods, and "complexes". None applied to eggs of either species. The only ailment reported for Pacific cod off Canada was parabranchial X-cell lesions, caused by a protistan amoeboid. The ailment was also reported elsewhere in the northeast Pacific Ocean, and in the Atlantic Ocean. Prevalence was relatively low, except in two areas off western Canada (W. Vancouver Island; S. Queen Charlotte Sound). There, the effects were retarded growth, delayed maturity, and increased mortality rate (Z). Afflicted, tank-held Atlantic cod exhibited retarded gonad development, and suffered a high mortality due to bacterial infections.

FISHERIES

Comparable data were found for aboriginal, commercial, and recreational fisheries. Records of artificial propagation were only found for Atlantic cod.

Aboriginal

Records were found for both Pacific and Atlantic cod, but none were quantitative. Data on Pacific cod off Canada were particularly difficult to evaluate, because the term cod was often applied to other species, such as lingcod.

Commercial

Commercial fisheries for Pacific cod are relatively new--17th Century in Japan; 19th Century for North America; mid-20th Century for Canada. In contrast, Atlantic cod fisheries began about the 8th Century off Europe, and the 16th Century off North America. Both Pacific and Atlantic cod were exploited primarily by line fisheries, until the introduction of otter trawls in the 1920s. FAO began reporting world fisheries statistics with 1958. During 1958-91, peak production for the combined species was 4.0 million tonnes in 1968--143,000 t of

Pacific cod, and 3,867,000 t of Atlantic cod. Subsequently, Pacific cod production increased (453,000 t in 1988; 420,000 t in 1991), and Atlantic cod production decreased (1,339,000 t in 1991). During 1985-91, annual catches in the northwest Pacific were 160,000-270,000 t (declining), and in the northeast Pacific, 140,000-260,000 t (increasing). Pacific cod is an important component in the trawl fishery off Canada. Annual catches rarely exceed 20,000 t, but account for some 80% of the production south of Alaska. Ironically, while the catch off Alaska was substantial, Pacific cod was a minor component in the line/trawl fisheries there.

Recreational

Off Canada, Pacific cod is a minor component in the marine recreational fisheries. Elsewhere in the Pacific, an important fishery (up to 160,000 cod/y) exists in Puget Sound (Washington State), and a minor fishery off Alaska. No records were found for the northwest Pacific. In contrast, Atlantic cod is a major component in the marine recreational fishery off the United States (1.5-5.0 million cod/y). Lesser fisheries were reported for the Baltic Sea, England, and Norway.

STOCK ASSESSMENT

Comparable data were found for stock delineation, mortality and exploitation rates, and stock assessment.

Stock Delineation

Criteria for stock delineation were similar for Pacific and Atlantic cod. Most common techniques were tagging studies, parasites, spawning-ground location, and such biological parameters as growth rate, size at maturity, and spawning time. Stock delineation appeared to be reasonably complete in most regions, except for Pacific cod in Alaska.

Mortality Rates

Estimates of Z were relatively high for Pacific cod stocks off Canada (1.01-1.63) and in Puget Sound (1.01-1.85), but not in the eastern Bering Sea (0.6). No estimates of mortality rates were found for cod in the northwest Pacific. Comparable estimates for Atlantic cod were also high for most important stocks (>1.15). Estimates of M were relatively high for Pacific cod off Canada (0.58-0.78), at Port Townsend, Washington (0.7-0.8), and at least initially in the eastern Bering Sea (0.70). In the latter case, recent estimates have been 0.22 and 0.29. Comparable estimates for important stocks of Atlantic cod were 0.2-0.3, except 0.4 in an early report on the Baltic Sea cod. Documentation for estimates of M were generally weak or absent, but the estimates for Pacific and Atlantic cod generally reflect the different lifespans--short for Pacific cod and long for Atlantic cod.

Exploitation Rates (U)

Estimates of U for Pacific cod off Canada were 0.13-0.35, and elsewhere, 0.10-0.11 in nearby Port Townsend, and 0.017-0.201 off Alaska. No estimates were found for cod in the northwest Pacific. Estimates for Atlantic cod were only found for stocks off Canada (0.18-0.66), and were a recent addition to stock assessment reports there.

Stock Assessment

All important cod stocks were not assessed separately in the Pacific or the Atlantic. For example, the eight (nine?) Pacific cod stocks off Canada were grouped, for various reasons, into four for assessment purposes. No assessment reports were found for cod in the northwest Pacific.

Off Canada, only three of the four Pacific cod "stocks" were subjected to foreign (U.S.A. only) fishing prior to establishment of the EEZ in

1977. South of Canada, the offshore cod stocks were too small to attract a directed foreign fishery. Off Alaska, there was virtually no domestic fishery until the 1980s, when the foreign fisheries were supplanted by domestic fisheries. Until recently, stock fluctuations throughout the northeast Pacific were attributed to natural causes. However, current analyses indicate that two stocks off Canada, and possibly the stock in the eastern Bering Sea, have become vulnerable to recruitment overfishing, due to increasing fishing effort.

In contrast, all important Atlantic cod stocks have sustained multi-national fisheries. Although some of these were reduced to single-nation fisheries with the advent of the EEZs, fishing effort declined only temporarily. All the important Atlantic cod stocks are currently assessed to be in critical condition. For some (Baltic Sea, West Greenland and Iceland), adverse environmental conditions may be fundamental, but all are suffering from very high fishing mortalities. Particularly acute is the condition of the stocks off Canada, where a moratorium on fishing was imposed in 1992. For most Atlantic cod stocks, estimates of F are two to five times $F_{0.1}$. One example of apparently successful remedial measures is that of the Arcto-Norwegian stock. F was substantially reduced after 1987, and spawning-stock biomass promptly rebounded equally substantially.

ABUNDANCE PREDICTION

This chapter dealt with the atmospheric and oceanic environment, environment versus recruitment, and long-term predictions of abundance.

Environment

The environment was discussed on three scales--global, hemispheric, and oceanic. Emphasis was placed on the Northern Hemisphere, and the northern sectors of the Pacific and Atlantic oceans.

Global. Solar energy is the driving force behind the circulation of the atmosphere and oceans, and is variable. A 78-y cycle appears to exist. The critical point of contact appears to be the tropical Pacific Ocean, where energy is transmitted by advection and teleconnections to extra-tropical regions, and where the anomalous ENSO events occur. Atmosphere circulation is initiated by unequal heating heating latitudinally, while ocean circulation is initiated by non-uniform heating horizontally, and by wind stress. Atmosphere-ocean linkage is effected through energy transfer (evaporation and precipitation) and circulation. Neither the variability nor interactions of atmosphere and ocean are understood at this time. Prominent atmospheric features are the high-altitude westerly winds which encircle the Northern and Southern hemispheres, volcanism, teleconnections, and the Southern Oscillation. Location and velocity of the westerly winds affect the surface atmosphere and ocean currents, and their variability is linked to the solar cycle. Volcanism can produce a cooling effect on surface weather. Teleconnections transmit atmospheric effects among regions. The Southern Oscillation is located in the tropical Pacific, and consists of a seesaw in pressure difference between the Southeast Pacific Subtropical High and the Australian-Indonesian Low. At one extreme of the cycle, the eastern tropical Pacific is anomalously warmed, and this is called the El Nino--thus the term ENSO. Advection poleward of the warm waters, and atmospheric teleconnections, can affect atmospheric and oceanic conditions in the extra-tropical latitudes. Long-term climatic trends were identified with cycles of tens of thousands, thousands, hundreds, and tens of years. In the 20th Century, a distinct warming period occurred during 1920-60.

Northern Hemisphere. Prominent zonal atmospheric features are the semi-permanent, alternating high- and low-pressure areas in the mid-latitudes. Their strengths vary seasonally and interannually, and are interrelated to some extent. Their variability is linked to the variability of the solar cycle. Comparable meridional features are the low-pressure (high-pressure) systems at mid-latitude, and high-pressure (low-pressure) systems immediately northward and southward.

Teleconnections among regions have been demonstrated by the linkage of pressure-oscillation patterns unique to the Pacific and Atlantic oceans. Atmosphere-ocean linkages are best demonstrated by the important ENSO events, which have broad repercussions in the Northern Hemisphere. These events exhibit a mean short-term cycle of 3.8 y, and a long-term cycle of 80-100 y.

North Pacific Ocean. Principal atmospheric features are the Aleutian Low and the Pacific High (to the south). The Low dominates during winter, and its location, then, varies with its intensity--eastward if intense, westward if not. An indicator of its position is the North Pacific Oscillation--a negative correlation between temperature anomalies of western Alaska-eastern Siberia and western Canada. The location of the Aleutian Low is eastward when the Canadian anomaly is negative, and vice versa. The surface circulation of the north Pacific, in brief, consists of conjoined flow eastward, from Japan, of the northward-flowing, warm, Oyashio Current and the southward-flowing, cold Kuroshio Current. Near North America, the northward portion of the flow bifurcates. One portion turns northward and cycles back westward to form the Alaska Current, while the other portion turns southward to form the California Current. The point of the westward bifurcation varies substantially, both seasonally and inter-annually. Two short-term phenomena are the ENSO events and the warm/cold water masses. ENSO events are associated with surface warming of the northeast Pacific. Warm/cold water masses are thought to affect the amount of water diverted northward and southward at the westward bifurcation, but no verification has been established.

North Atlantic Ocean. Principal atmospheric features are the Iceland Low and the Azores High (to the south). The Low dominates during winter, and its location, then, varies with its intensity--eastward if intense, westward if not. An indicator of its position is the North Atlantic Oscillation (NAO)--the differential pressure between Iceland and the Azores. The location of the Iceland Low is eastward when the differential is above average, and vice versa. An NAO-ENSO linkage was reported. The surface circulation of the north Atlantic is similar to that in the Pacific, except that the orientation is southwest-northeast, rather than west-east. In brief, off North America, the northward-flowing, warm, Gulf Stream joins the southward-flowing Labrador Current, and flows northeastward. Two northern loops are formed, one south of Iceland, and the other off Europe. Short-term factors are warm-core rings (Gulf Stream), the Great Salinity Anomaly, and probably ENSO events (by teleconnections). Warm-core rings, on the shoreside of the Gulf Stream, entrain shelf water and advect it offshore. The Great Salinity Anomaly, an infrequent phenomenon, consists of a vast water mass of low salinity and temperature which circulates around the North Atlantic Gyre. During the 20th Century, one occurred during 1969-82, and probably one early in the century which passed Norway about 1908-09. ENSO events appear to affect the circulation of the Atlantic Ocean via teleconnections, but few reports provided details. Climate effects appear to be generally hemispheric. The "warm" period of 1920-60 is a recent example.

Recruitment vs Environment

Recognition of environment as a factor in recruitment of Pacific cod occurred relatively late (1956) compared to that of Atlantic cod (1914). The case for environment was initially made from observed synchronies of recruitment among stocks and/or species, often over large geographical areas of the Pacific and Atlantic oceans. For both species, the most common environmental factor reported to affect recruitment was water temperature. In each case, recruitment varied directly with temperature poleward, and inversely equatorward. However, temperature was recognized as a proxy, not only for more fundamental environmental factors, but also for biological effects on cod. No reports were found which dealt with more fundamental factors, such as atmospheric systems, affecting Pacific cod recruitment and few for Atlantic cod. However, from the reports describing environmental factors, it is evident that intense Aleutian and Iceland lows produce favourable conditions for cod in the northeast sectors of each ocean, while the opposite condition favours cod in the northwest sectors. Similarly, ENSO events should favour cod off Alaska, but its effect on Atlantic cod is not clear. In theory, the warm/cold water masses would provide favourable

conditions for cod off British Columbia, if the bifurcation of the Subarctic Current (West Wind Drift) occurred southward. In the Atlantic, the warm-core rings and the Great Salinity Anomaly adversely affected cod.

No reports were found on the long-term effects of climate on the recruitment Pacific or Atlantic cod, primarily because of the relatively short recruitment time series (<100 y) for both species.

Abundance Prediction

Few reports were found which predicted abundance of Pacific or Atlantic cod. The single, fairly successful (55% accuracy), prediction for Pacific cod, in Hecate Strait (W. Canada), was based on transport/SSB during the spawning season. For Atlantic cod, tree-ring data were reasonably useful off Norway, and salinity/SSB off Labrador-Newfoundland. Global warming was predicted to produce adverse conditions (low temperature and salinity) for Atlantic cod in the West Greenland-Gulf of Maine Region. Presumably, this prediction would also apply to the Iceland-Norway Region, as well as for Pacific cod off Alaska and Siberia.

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