FISHERIES RESEARCH BOARD OF CANADA

UNDER THE CONTROL OF

THE HON. THE MINISTER OF FISHERIES

BULLETIN No. 88

EASTERN ARCTIC WATERS

By

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McGill University

OTTAWA

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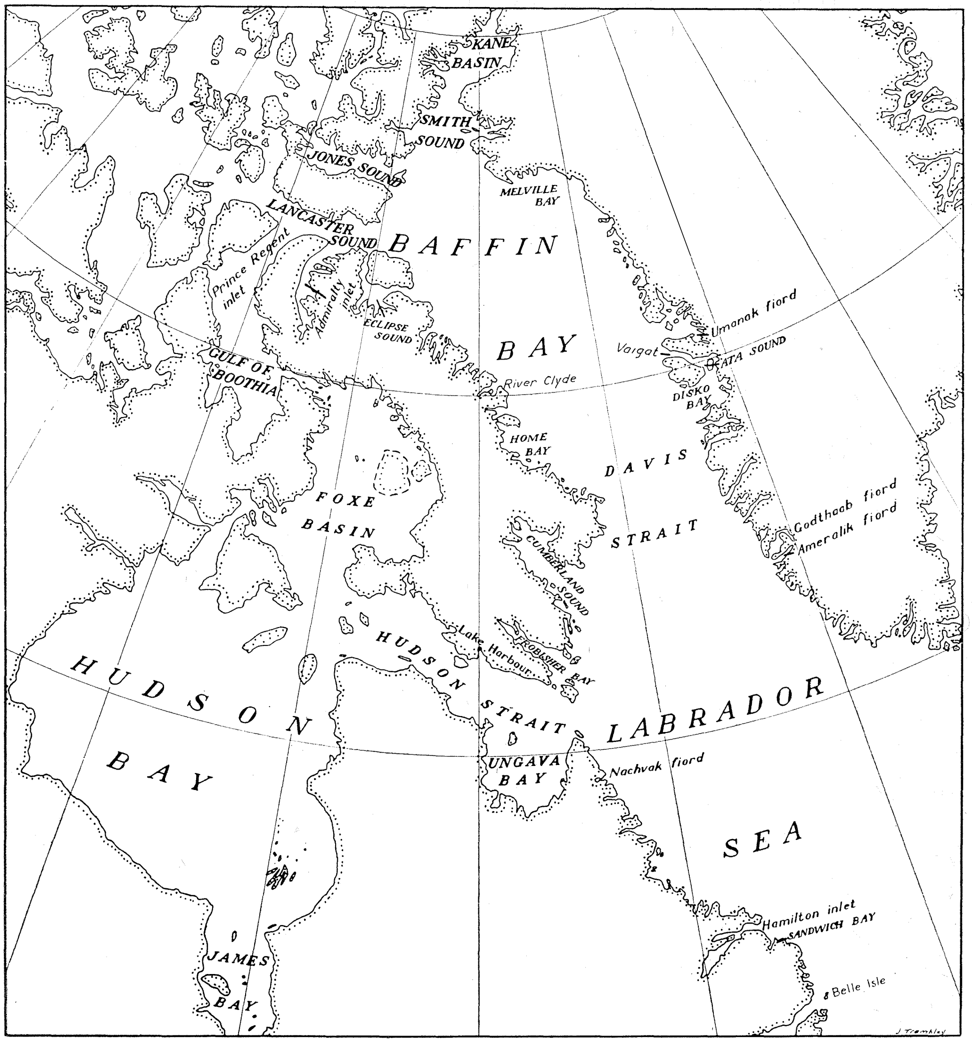

General Map of the Eastern Arctic Area

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A summary of our present knowledge of the physical oceanography of the eastern arctic area, from Hudson bay to cape Farewell and from Belle Isle to Smith sound

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EASTERN ARCTIC WATERS[1]

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INTRODUCTION

Deacon (1946), in discussing the state of the subject of oceanography, suggested that the systematic examination of the North Atlantic ocean as a whole was an outstanding need of the present time; it will be apparent from the material of this paper that the region covered here, being a part or an extension of the North Atlantic, is certainly in need of immediate attention. Deacon also pointed out that (in spite of recent mathematical methods which have not gone without serious criticism) our knowledge of the oceans and seas of the world is still qualitative rather than quantitative. It follows that the present work is largely descriptive, and only in small part analytic.

The purpose of the work is to bring together in one place all that has been done in the investigation of the physical oceanography of the Canadian eastern arctic region. Since the behaviour of the waters on the Canadian side of the Labrador sea, Davis strait, Baffin bay and northward is not intelligible without taking into account the waters of west Greenland, the eastern geographic limit has been put at cape Farewell. Thus the work of Danish oceanographers in Greenland is included. On the north American side, the southern limit of study is the strait of Belle Isle. Besides the bodies of water already mentioned, the area of reference includes Ungava bay, Hudson strait, Hudson bay, James bay, Foxe basin and channel; the gulf of Boothia and Prince Regent inlet; Lancaster and Jones sounds, and the narrow waters between northwest Greenland and Ellesmere island up to the Lincoln sea.

We are concerned here essentially with sea water in the fluid state; but since a large proportion of the area is frozen over during the winter, and since both sea ice and freshwater ice are elements of varying dominance also during the summer, ice conditions are included in so far as they affect the movement and behaviour of the water. But this is not in any way a study of ice conditions as such. The discussion of ice-forms at sea and along the coasts, the behaviour of the ice under the influence of wind and sun, and the relevance of such behaviour to the requirements of man in the north, are left to other students. This point is emphasized especially in view of the fact that there have been in the very recent past several studies of ice conditions for their own sake, to which reference is made in the text.

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It is not in any sense a coast pilot, nor are coastal conditions given special attention. The intention is to show, on the basis of our present knowledge, the oceanographic pattern in a section of the earth's surface which is not difficult to treat as a unit; and to show up in the process the places where our ignorance lies, so that steps may be taken to improve and complete the pattern. Where information from biological oceanography is helpful for this purpose, biological material is used. The specialized matter of tidal times and conditions is omitted.

HISTORY AND SOURCE MATERIAL

The work of the early explorers is necessarily of only very general value here. The technique of physical oceanography is of recent currency, and before the last twenty years of the nineteenth century comparatively few measurements of salinity or temperature were made, with the exception of temperature observations at the surface. Nevertheless much of the early observation is extremely valuable in estimating cyclical trends in aquatic and climatic conditions, for this can of course be done only by comparing earlier records with those of today. This applies in particular to variations in the extent of open water during the year, and to the behaviour of sea-ice and icebergs in the summer seasons.

The early history of the exploration of the waters of the eastern arctic is well known; many general histories of polar exploration have been published, including the recent studies of Breitfuss (1943) and Mirsky (1948). Some have been concerned more especially with marine exploration, as for instance the work of Alexander (1915). There is, however, no complete account of specifically oceanographic expeditions made during the past seventy years, during which period the science of oceanography has developed exceedingly. Such an account must include many small expeditions which escape the notice or the interest of the general historians, but whose work is of great importance. Indeed, it is perhaps not too much to say that the greater the strictly scientific contribution of an expedition, the less fuss is made over it and less it appears in the histories. Remarkable as it may seem, neither the "Godthaab" expedition of 1928 nor the "Marion" and "General Greene" expeditions of 1928-35 are mentioned by Mirsky; and yet it is to these expeditions that we owe most of our detailed knowledge of the waters of Davis strait and Baffin bay.

This neglect is the common fate of expeditions whose aims are mainly or wholly oceanographic. W. S. Bruce was the first explorer to bring out this fact; in his book "Polar Exploration" (1911) Bruce writes: ". . . if an expedition investigates 150 miles of unknown land it is said to have made 'important geographical discoveries,' whereas, if it investigates, with equal if not greater detail, 150 miles of unknown sea, it will be said that the expedition made 'no geographical studies' ".

The history of the study of the waters of the eastern arctic area begins no doubt with the famous voyage of Erik the Red from Iceland to west Greenland in the year 983 A.D. Two Portuguese, Caspar and Miguel Cortoreal, penetrated almost into our area when they sighted Greenland and made some survey of the Newfoundland fishing banks. This was in 1500, the first visit to Newfoundland since its discovery three years before by John Cabot. Not until the year 1576 were the voyages of the early Norsemen matched; in 1576, 1577 and 1578, Martin Frobisher made three voyages, touching the coast of southeastern Baffin island and exploring the bay which bears his name. These were the first of the northwest passage voyages which attempted the supposed arctic route.

The newly-formed Northwest Company sent John Davis to follow in Frobisher's track in 1585. In three voyages (1585, 1586 and 1587) Davis rediscovered Greenland and explored the coastal waters of the southern part, entered Cumberland sound in east Baffin island, sailed through the Davis strait named after him, and explored part of Baffin bay. Captain Weymouth sailed in 1602, in the "Discovery", into Hudson strait, to be followed in 1606 by Captain Knight. In 1603 and 1604, King Christian IV of the joint realms of Denmark and Norway sent out three Englishmen, James Cunningham, John Knight and James Hall, to visit the recently refound Greenland. They sailed up the west coast approximately as far as the present-day settlement of Holsteinsborg. In 1610, Henry Hudson's celebrated and disastrous journey in the "Discovery" through Hudson strait and into Hudson bay began the exploration of those areas which have since proved so important and so valuable, and started a series of expeditions in Hudson bay. Looking for a passage to the far east, instead they founded a fur trade. Button, with Bylot (one of Hudson's mutinous crew) as pilot, reached the west shore of Hudson bay in 1612. Baffin, also with Bylot, repeated this voyage in 1615. The next year Baffin sailed again, this time not into Hudson bay, which he considered unlikely to offer a northwest passage, but northward through Davis strait into Baffin bay.

It was the achievement of these pioneers to block out the coast-lines and the shapes of the water surfaces in these areas. The map of the eastern arctic was gradually taking shape—the process is not yet complete today. The early explorers, like their successors, also brought back information on currents and depths, and ice conditions.

To William Baffin we owe more than to most of them. Mirsky points out that his expedition followed the work of Davis to the north (of the Labrador sea) just as Hudson had followed it to the west. It was Baffin who sailed right through the "middle pack" of Baffin bay and finally found the "north water", the open water later to become famous in whaling operations. He reached as far north as Hakluyt island in latitude 77° 25′ before turning back. On the way south he sighted both Jones sound and Lancaster sound, both offering a passage to the west. No man was to reach farther north than this (in this region) until Inglefield in 1852.

Certain navigators apparently did not agree with Baffin that Hudson bay offered no opportunity to break through or around the North American continent; for in the next few years several expeditions attempted this route. Jens Munk, sent out by Christian IV, crossed Hudson bay with two ships, returning home the next year with only three men and one ship. In 1631 James wintered in the southern part of the bay, and in the same year Luke Foxe explored the waters round Southampton island and entered Foxe basin.

There followed a period of over a hundred years when interest in a northwest passage was allowed to subside. Instead, the economic exploitation of the north for its own sake was taken up with great energy. The Hudson's Bay Company established posts in our area and opened up parts of the interior, in the interests of the fur trade. These operations do not concern us directly here. The arctic whalers, on the other hand, were the direct legatees of the early navigators, and themselves added little by little to the knowledge of eastern arctic waters. Whaling in the eastern arctic began considerably later than in the waters east of Greenland, but early in the eighteenth century the Davis strait whale fishery was established, mainly by Dutch and Danish whalers. The story of the rise and fall of this industry is not relevant to this paper; suffice it to note that the whaling interests have always taken more out of the waters fished than they have added knowledge of them.

Exploratory voyages continued, but it was to be some time before the enterprise was resumed with the original strength. Various expeditions (apart from strictly commercial voyages) entered the eastern arctic sporadically during the period between 1650 and 1818. Middleton, in 1741, and Moore, in 1746, investigated the area west and north of Southampton island, including Roes Welcome, Wager bay, Repulse bay and Frozen strait. Hudson bay was still considered the most promising region. These expeditions were followed by a survey of Chesterfield inlet in 1761 by Christopher and by Norton in 1762.

Earlier than this, in 1721, the first missionary to Greenland, Hans Egede, landed at the mouth of Godthaab fjord in southwest Greenland and founded the Danish occupation and colonization which have developed both in science and humanity so much to the credit of Denmark. During the early days of this development the visits from Denmark were less frequent than they were to become as the enterprise grew, but nevertheless a steadily growing list of ships began to sail the coast of west Greenland out of Copenhagen. Here again, the details of this history do not merit inclusion here until the comparatively recent, scientific expeditions, but it should be remembered that just as the ships of the Hudson's Bay Company and other traders added their quota to the sum total of our present knowledge of Hudson strait and Hudson bay, so did the ships of the Danish Trading Company for the waters of west Greenland. Their story has been published recently by Tving (1944).

Nothing important happened in the exploration of eastern arctic waters until after the end of the Napoleonic wars, with the exception of a few recorded expeditions in Hudson's Bay Company ships, on which ice observations were made, such as those of Chappell (1817) and M'Keevor (1812). In 1818, Britain returned after so many fallow years to arctic voyages of discovery. It was in that year that the modern exploration of our area of reference begins. Hydrographic work formed an increasingly important part of the expedition programme, and new instruments began to be invented. Scientific oceanography was on the verge of being launched.

The expedition of 1818 contained such famous names as Ross (senior and junior), Sabine, Back, Parry and Franklin. In four ships, the expedition was to split into two, one company sailing northward, keeping east of Greenland, to attain the north pole, and the other rounding cape Farewell to recommence the search for a northwest passage. The first party, under Buchan, turned back west of Spitsbergen. The second, consisting of the ships "Alexander" and "Isabella", commanded by John Ross and including Parry, added considerably to the growing knowledge of the Baffin bay waters, and sailed a short distance into Lancaster sound. Here they turned back, because Ross thought he saw clearly that the sound was closed by land to the westward. Parry thought differently, and the next year (1819) a second expedition was dispatched with Parry in command. This memorable expedition, in the "Hecla" and "Griper", sailed through Lancaster sound, Barrow strait and Melville sound, to be stopped by the ice in the second summer season in McClure strait. This expedition was the first in our area to take subsurface temperatures and to take water samples from various depths (Prestwich, 1875).

Parry tried a more southerly route in 1821, this time in the "Hecla" and "Fury", sailing into Hudson bay and trying the coast west and north of Southampton island for a passage to the west. Repulse bay was explored thoroughly. Wintering on Melville peninsula, he sailed in the season of 1822 into Fury and Hecla strait, only to be stopped again by ice just as it had stopped him in McClure strait in 1820. Parry's third and last northwest passage expedition left England in 1824, this time to try Prince Regent inlet. In two severe ice seasons he managed to penetrate almost one hundred miles down this channel when the "Fury" had to be abandoned, battered by the ice. The expedition sailed home in the "Hecla".

Another Government expedition under Lyon had as little success in 1824 in an attempt to reach Repulse bay and cross overland to the waters reported to the northwest. The next effort (1829-33) was privately financed, and under the command of John Ross, with his nephew James Clark Ross among the officers. In the "Victory", the first power vessel (steam and paddle) to be used in this region, they sailed down Prince Regent inlet and into the gulf of Boothia (failing to observe that there was a strait between Somerset and Boothia peninsula). Altogether four winters were spent by this party in the north, and the scientific contributions were considerable, including the location of the magnetic pole. Oceanographic knowledge, however, was not greatly increased. After the Ross expedition, and one unsuccessful attempt by Back to carry out what Lyon had tried to do (to reach Committee bay), the exploration of arctic Canada was taken up by land, mainly in the central arctic area, and so for a time passes out of the focus of this paper. Ships continued, however, to enter Hudson bay for commercial purposes, and many of the voyages, such as those of Captain Coats between 1827 and 1851 (Barrow, 1852) added to the oceanographic knowledge of the region.

Navigation of the eastern arctic waters for scientific purposes began again with the last expedition of Sir John Franklin, which left England in 1845. Like other parties before them they waited on the west Greenland coast for a chance to cross through the ice of Baffin bay, sailed west along Lancaster sound and northward up Wellington channel, in the ships "Erebus" and "Terror", each with auxiliary screw power. After wintering at Beechey island, off the southwest coast of Devon island, the expedition made southward to the west of Somerset island, to King William island. The ships were abandoned in the ice northwest of King William island after two more winters. Franklin himself died in June, 1847; three men had died during the third winter. The remainder, 105 officers and men, died in an effort to reach the Back river overland.

Of the forty expeditions sent out in the ten years after 1847 to find Franklin's party, thirty-four were marine (Mirsky, 1948), and most of these travelled through eastern arctic waters. Most of them added something to the growing Admiralty Charts, but few of them will be mentioned here. The expedition of 1851-52, commanded by Kennedy and carrying Bellot as second-in-command, corrected the mistake made by the two Rosses in 1829 and showed that "North Somerset" was in fact an island. McClure, in 1851, by reaching Barrow strait by sledge, established the existence of a northwest passage, but was unable, due to ice conditions and finally to scurvy, to bring his ship, the "Investigator", farther than Mercy bay on Banks island. His party was rescued from the east by Kellet in the "Resolute", one of the ships of Belcher's expedition of 1852-4. McClure finally reached home in the "Phoenix" with Inglefield, the "Resolute" having been abandoned at Beechey island by orders from Belcher. The "Resolute", however, was not yet finished with her work; she was in good shape and drifted the following season, with no crew, out from Lancaster sound into Baffin bay. She was picked up in Davis strait and was finally sent back to England. She thus became, by no man's intention, probably the first current-indicator to be used in the eastern arctic.

The records of the Franklin expedition, left on King William island, were finally found by the McClintock expedition of 1857-9. Sir Allen Young made two attempts at the northwest passage in 1875 and 1876, failed in 1875 due to heavy ice in Bellot strait (Wordie, 1945), and was again stopped by ice (in Peel strait) in 1876 (Young, 1879). Soundings were made, and subsurface temperatures were measured with Casella's thermometer. The northwest passage was finally sailed for the first time by one ship when Amundsen, with the accumulated knowledge of many men and several centuries behind him, took the "Gjoa" through in 1903-6. Forty years elapsed before the passage was to be sailed in a single season, by Sergeant Larsen of the R.C.M.P., in the "St. Roch". Larsen sailed from east to west, via Lancaster sound, Barrow strait, Melville sound and

Prince of Wales strait, in the summer of 1944. He had already made the northwest passage from west to east, using the southern route round King William island, in 1940-2, wintering in Pasley bay on the west side of Boothia peninsula. Unfortunately, the "St. Roch" did not carry an oceanographer on either voyage, and made no measurements of water properties except surface temperatures.

The interesting waters to the north of Baffin bay, which had been seen by William Baffin in 1616, began to be investigated in 1852, when Inglefield entered Kane basin and returned home with the report that Smith sound led into still more northern waters. It was at this point that the United States entered the field of exploration in the eastern arctic. In the years 1853-55, Dr. Elisha Kane's expedition, having wintered at Rensellaer harbour, discovered the Humboldt glacier and the channel to the north of Kane basin, named Kennedy channel. In 1860, Dr. Hayes made soundings and ice observations in Smith sound and Baffin bay, in the "United States"; and again visited north Greenland in 1869 in the "Panther". Charles Francis Hall's famous "Polaris" expedition (1871-3) reached some two hundred miles farther north than Kane, up to latitude 82° 11′, almost into the Lincoln sea. Hall himself died on the expedition; the "Polaris", in Smith sound, lost company with part of the expedition, including the Greenlander Hans Hendrik and his family, during an attempt to land the ship's company and stores to an ice-floe. Both parties, however, survived; the group on the ice-floe had the astonishing experience of drifting, by floe and by open boat, from Smith sound to the coast of Labrador, a distance of 1,300 miles, before being picked up by Captain Bartlett in the "Tigress" (Mirsky, 1948).

One more British naval expedition added to oceanographic knowledge in this region. In 1875-6, Nares, with the "Alert" and "Discovery", wintered in northeast Ellesmere island and attempted to feel his way over the ice of the Lincoln sea. During this expedition, temperature and salinity observations were made at various depths. The first international Polar Year organization, in 1882-3, had three stations in the eastern arctic area which contributed tidal obervations. These were in Labrador (Koch), Cumberland sound, Baffin island (Giese), and Lady Franklin bay, Ellesmere island (Greely). On the Greely expedition, Lockwood added considerably to the outline of the Greenland shore of the Lincoln sea, penetrating as far to the northeast as Lockwood island, in longitude 40° W.

Oceanographic investigation of the Labrador sea, Davis strait, Baffin bay and Hudson bay had begun sometime before this. In the following chronological account of this work, certain annual or routine enterprises are not mentioned for each year. These include (1) ice records kept by the Danish Meteorological Office, which show the extent of the polar pack along the coasts of Greenland since the latter part of the nineteenth century. (2) The annual work of the United States Coast Guard in conjunction with the International Ice Patrol and Ice Observation Service along the northern sea-lanes, especially round Newfoundland. This work began in 1914 and has continued to the present date. (3) The expeditions of Commander Donald Macmillan in recent years, which have made soundings along the Labrador coast, and in Hudson strait and Baffin bay. (4) The various expeditions commanded by Captain Bob Bartlett in the same area and period, which almost every year brought back valuable reports of ice conditions, and occasionally made studies of bottom sediments and of benthonic and planktonic fauna. (5) The annual work of Dr. Adolf Jensen, and later of Dr. Poul Hansen, who have made most valuable contributions to the oceanography of the coastal waters of west Greenland during the course of their fishery investigations in that region. This work took its origin from the "Tjalfe" expeditions of 1908 and 1909, which are included in the account given below. (6) Surface temperatures and, in some cases, surface water samples, taken on routine voyages of the Danish Government vessels in the Greenland service, especially the M/S "Disko" (published in the "Bulletin Hydrographique" for the appropriate years), and by Canadian Government vessels and ships of the Hudson's Bay Company in Canadian arctic waters.

1860-1. Leopold McClintock and G. C. Wallich worked between Labrador and west Greenland in H.M.S. "Bulldog", making soundings of the sea floor. This work was followed up in 1868 by Captain Chimmo, in the H.M.S. "Gannet", in Labrador waters, and by the Swedish vessels "Gladan" and "Ingegerd", Captain von Otter, in west Greenland (Bencker, 1930), in 1871.

1874. Steenstrup and Johnstrup (Steenstrup, 1878), while on board the "Fox", then the property of the Cryolite Company, made a study of the temperature, salinity and colour of the surface water along the 59th parallel on the journey from Copenhagen to Ivigtut, in an attempt to discover whether there was any correlation between colour and other physical characteristics of the water. The observations were continued by the captain of the ship, Captain Olsen, in 1875, and again by Steenstrup in 1876. Since the study was extended up to the port of Ivigtut, part of it becomes included in our eastern arctic area.

1875. The Nares expedition to Smith sound has already been mentioned, also the "Pandora" expeditions of 1875 and 1876. Temperature observations on the Nares expedition were made by Dr. Moss, the ship's surgeon. In the same season, H.M.S. "Valorous" (Captain Carpenter) made three hydrographic stations in the Labrador sea, which included temperature measurements at intervals from the bottom to the surface (Carpenter, 1877).

1878. Under the auspices of the Administration of Greenland, in Copenhagen, a series of coastal studies of Greenland was undertaken, which studies have, in fact, continued to the present day. The first was in 1878, when J. A. D. Jensen made a report on the coast of southwest Greenland from the Frederikshaab "Iceblink", or glacier, north to Ameralik fjord in the Godthaab district. His field-work included temperature readings, both surface and subsurface, at various stations, and soundings (Jensen, 1879).

1879. Jensen continued his temperature observations in the coastal water farther north, from latitude 66° 55′ to 68° 30′ (Jensen, 1881), in west Greenland. The same year, and continuing into 1880, R. R. J. Hammer carried out a hydrographic programme in the Jakobshavn ice-fjord, making several temperature and salinity stations, the results of which, though not entirely dependable due to the faulty instruments of the time, nevertheless give data for comparison with later observations.

1882. International Polar Year Expeditions. Greely's expedition, and others in this series, have been mentioned above. The United States Army, besides sending Greely to Ellesmere island, sent L. M. Turner to Fort Chimo, on the Koksoak river at the head of Ungava bay. Turner's chief work consisted of meteorological observations; but his report also included notes on ice conditions which should not go unnoticed in this present account. Unfortunately, his narrative report appears to have been lost, in part. Part of it, the first few pages, is deposited in manuscript in the Smithsonian Institution, to which the present writer is indebted for the loan of this and other Turner material.

1883. The Swedish "Sofia" expedition of this year, led by Nordenskiold and with Dr. Axel Hamberg as oceanographer, was the most important oceanographic expedition up to that time in the eastern arctic area. Hamberg used reversing thermometers and water-samplers, and made observations along the Greenland coasts from Angmassalik in the east, round cape Farewell, and up the west coast of Thule. He described the west Greenland current, and the stratification of water in Baffin bay (Hamberg, 1884).

1884. The first Canadian Government eastern arctic expedition, in the "Neptune," commanded by Lieutenant Gordon, studied navigation conditions in Hudson strait, measuring surface temperatures and making tidal and ice observations. In the same year a Danish naval expedition worked in west Greenland waters, commanded by Captain Normann in the cruiser "Fylla". The "Fylla" was commissioned to make this expedition in connection with "repeated irregularities committed by the American fishermen who visit the Greenland fishing banks" (Wandel, 1891). Her programme included hydrographic stations and soundings in the west Greenland waters. At the same time J. A. D. Jensen was continuing his coastal survey in this region, from latitude 64° to 67°.

1885. The Canadian Government ship "Alert" continued the work of the "Neptune" in Hudson strait, Lieutenant Gordon again leading the expedition.

1886. The "Alert" was again in the field, on the same work and in much the same area, again with the same leader. On the Greenland side, Lieutenant C. H. Ryder examined and surveyed the coast in the Upernavik district, between latitudes 72° and 74° 35′, making soundings and temperature-salinity measurements in the Upernavik ice-fjord. This work was continued in 1887. The "Fylla" continued her hydrographic program in the waters off the coast, Captain Braem commanding.

1889. The "Fylla" survey was completed in this third season, this time with Captain Wandel in command. During her fisheries patrol work in the three seasons of 1884, 1886 and 1887, the "Fylla" made numerous soundings, and also six hydrographic sections from the coast across the shelf, varying in distance from 35 to 75 miles, along the stretch between Godthaab and the Svartenhuk peninsula (latitude 71° 10′). She had also crossed Davis strait to the Baffin island side. Her work had established the southward-flowing current down the coast of Baffin island, and into the Labrador sea; the mixture of Atlantic and east Greenland polar water to form the west Greenland current, and the branches of this west Greenland current which contributed to the Labrador sea; and the continuation northward of the remainder of the west Greenland current as far as the observations went (Wandel, 1891). Smith, Soule and Mosby (1937) comment on the accuracy of the observations and inferences made by the workers on the "Fylla" expedition.

1891. In the years between 1891 and 1895, ships used on the early Peary expeditions ("Kite", "Falcon" and "Miranda") made records of ice conditions in Baffin bay and northwest Greenland.

1893. Another expedition sent out by the Commission for the Scientific Investigation of Greenland (Copenhagen), under T. V. Garde, made a study of the Julianehaab district in the southwest, and included in its work observations on the sea-ice, a survey of the outlying skerries along that part of the coast, and soundings in the fjords (Garde, 1894, 1896).

1894. Garde's expedition of 1893 was followed by another survey expedition, under the leadership of Moltke. This expedition extended Garde's soundings in the fjords, and made hydrographic stations in some of them (Tasermiut, Nordre Sermilik, Ikersuak) with reversing samplers and thermometers (Woltke, 1896).

1895, 1896. The "Ingolf" expedition to the northwestern Atlantic spent two summers in the field, under the command of Captain (later Admiral) Wandel. Dr. Martin Knudsen was in charge of the hydrographic research. Of the numerous stations occupied between the Faeroe islands and Disko bay in west Greenland, many were complete hydrographic stations with serial temperature and salinity measurements at standard intervals from bottom to surface, and oxygen measurements were made in some instances. Bottom sediments were studied. Nineteen of the stations were in our area, west of cape Farewell. The findings of the "Fylla" expeditions were elaborated; the intermediate water of the Labrador sea was compared with the intermediate water farther east, in the Denmark sea, and found to be colder; and the source of this water in the Labrador sea was traced to the Irminger current, a branch of the North Atlantic Drift which strikes the coast of southeast Greenland and rounds cape Farewell. The Danish "Ingolf" expedition was a worthy successor to the "Fylla" work; it is one of the larger oceanographic expeditions which broke the ground for later and more intensive work in the eastern arctic area. The important papers which came out of it, for our present purposes, are those of Wandel (1899), Knudsen (1899) and Bøggild (1900).

1897. The Canadian Government Ship "Diana", under Captain Wakeham, made an inspection voyage in Hudson strait and into Hudson bay, with special reference to commercial whaling stations. A report on navigation conditions was printed, which contains information on ice, tides, and depths (Wakeham 1898). In this year also, Captain Wandel was instrumental in starting a co-operative effort between ships plying from Denmark to Greenland, such that temperatures at the surface were taken, and water samples brought home to Copenhagen. This was the beginning of the routine observations of this nature now made by the ships of the nations subscribing to the "Conseil Permanent" and published regularly in the "Bulletin Hydrographique" and "Bulletin Planktonique".

1898. Wandel's plan was continued and enlarged. Plankton samples were also taken from the surface. The combined efforts of several ships were published by Knudsen (1899b). In 1898 and 1899, the ship of the Peary expedition of 1898-1902 ("Windward") brought back information on ice and currents in northern Baffin bay; and the same years saw the arrival in Canadian arctic waters of the Second Norwegian Arctic Expedition in the "Fram". Most of the work of this expedition was done to the west of our eastern arctic area, among the islands of the arctic archipelago, but surface temperatures and the sediments of the bottom were investigated in Baffin bay and in Jones and Lancaster sounds. Full hydrographic equipment was not carried (Mohn, 1907).

1900. The Brown and Harvard Expedition to Nachvek, Labrador, in 1900, included oceanography in its programme, but no oceanographic results appear to have been published, with the exception of a little information on depths and temperatures in the general report (Delabarre, 1902). Temperatures and salinities were measured at different depths.

1903-4. The cruise of the "Neptune". This Canadian expedition, led by A. P. Low, wintered at Fullerton harbour north of Chesterfield inlet. The area covered was considerable, in mileage, from Hudson bay, through Hudson strait and up to Smith sound; into Lancaster and to Somerset island. It was, however, by no means an oceanographic expedition, and little valuable information about salt water was brought home, except for the usual reports and comments on ice conditions and surface temperatures. Canadian expeditions have, up until very recent years, been shy of spending much time at sea for working purposes as opposed to transportation. Had the "Neptune" expedition, and other Canadian expeditions in the decade after it, carried an oceanographer and proper hydrographic equipment, and had taken the time to make sections across the currents in various areas such as Hudson strait, Baffin bay, Hudson bay and the waters farther north, we would have been greatly enriched by that knowledge gained. As it is, the habit of oceanographic research is coming to us very gradually, from the Scandinavian countries, from the United Kingdom and from the United States, in that order.

1905. The Peary expedition of 1905 was carried north by the "Roosevelt", with Captain Bob Bartlett in command. The usual observations at the surface were made, in Baffin bay and the coastal waters of northwest Greenland.

1906. The visit of Napoleon Andreassen to southwest Greenland is worth mentioning here, not because he made any observations in physical oceanography which added much to the growing knowledge of that area, but because his was the first effort made by the Greenland Administration to find fishery resources for the Greenlanders. The fishing experiments of Andreassen, therefore, were the first of a series of researches in physical and biological oceanography, started and maintained by the Greenland Administration to the present day, which have considerably increased our understanding of the west Greenland coastal waters.

The first of Captain Bernier's three expeditions in the "Arctic", sent out by the Canadian Government, sailed in 1906, visiting the islands along Lancaster sound, Barrow strait and Melville sound, and wintering at Pond inlet. The work of the expedition was in the fields of surveying, geology and meteorology and in fishery patrol, and very little oceanographic observation was returned beyond the usual records of ice conditions along the route, and the taking of soundings.

1908. Bernier sailed again in 1908, wintering this time at Winter harbour on Melville island. The programme was much the same as the first of the "Arctic" expeditions; soundings, ice and tidal observations were made, and the geologist of the expedition, J. G. Macmillan, measured surface temperatures and salinities of surface water. On the way home, the navigation conditions in Hudson strait were examined.

The Danish "Tjalfe" expedition worked in west Greenland waters in 1908 and 1909. This was an expedition sent out by the Greenland Administration in order to find whether there were any fishery resources in west Greenland which could be developed to replace the seal, whose numbers were falling off in that area; it was the starting point of the considerable development in cod and halibut fishing of today. The physical results were published for the most part by Nielsen (1928), who did the field work. An interim report was published the year the field work was completed (Nielsen, 1909). Nielsen's 1928 paper summarized all information on the waters round Greenland at that time. His conclusions, with minor modifications, have been confirmed by later work. Those which affect the eastern arctic area are quoted here in summary from Smith, Soule and Mosby (1937):

"(*a*) The Labrador and Denmark seas, in mid-depths, are essentially of the same physical character; (*b*) the west Greenland current, with a velocity of approximately 8 miles per day, leaves the coast in the latitude of Godthaab to join the Labrador current; (*c*) the tidal flood current increases the velocity of the west Greenland current, the ebb decreases the same; (*d*) the velocity of the surface currents around Greenland are greatly affected by the winds; (*e*) the extension of the east Greenland current undergoes seasonal variation and along the southwest coast of Greenland disappears during autumn; (*f*) the effects of winter chilling of the surface layers of the Labrador sea probably extend all the way to the bottom, producing there the greater part of the bottom water of the north Atlantic; (*g*) the eastern part of Baffin bay, beneath the surface, is filled with warm water that has come across the Davis strait ridge from the Atlantic and this layer is thickest where it is pressed, by earth rotation, against the Greenland slope; (*h*) the surface layers of Davis strait are negative in temperature throughout the year, and the warm water underneath can have no direct effect, therefore, to melt the ice which is superficial in draft."

1910-11. The third Canadian expedition in the "Arctic", Captain Bernier, patrolled the waters of Baffin bay, Lancaster sound and west to Melville island.

Oceanographic work as such was not included in the instructions. The big "Michael Sars" north Atlantic expedition of 1910 skirted the eastern arctic area as defined here; since it did very useful work just on the southern periphery of our area it is mentioned in this historical review.

1913. The "Scotia" expedition, with Dr. D. J. Matthews in charge of the research, worked on the Newfoundland banks and made a section east from Labrador at the level of Hamilton inlet, extending out to the 44th meridian of longitude. This was the first section to be made across the Labrador current (Matthews, 1914).

1914. The Department of Naval Service, in Ottawa, sent the "Burleigh" into Hudson bay, to make fisheries investigations in Hudson and James bays, and Hudson strait. Tidal and ice observations were made (Melville and Lower, 1915; Comeau, 1920). 1914 was also the year in which the United States Coast Guard, in conjunction with its International Ice Patrol work, began to make oceanographic studies in the region of the Newfoundland banks, and between Labrador and Greenland. This programme has been continued with short interruptions during two world wars; several of its expeditions made major contributions to the eastern arctic oceanography, and are mentioned individually below.

1916. Dr. Thorild Wulff made hydrographic investigations, including full surface-to-bottom stations in west Greenland from Disko bay to Smith sound, during the Second Thule Expedition. Dr. Wulff died on the expedition, and his results were published by Knudsen (1923).

1920. Mr. Fritz Johansen, on the Hudson bay expedition of 1920, made coastal biological collections; it is understood that he also brought back records of ice conditions, etc., but these have apparently never been published.

1922. The first year of the Eastern Arctic Patrols sent out regularly by the Department of Mines and Resources (then the Department of the Interior). These expeditions made the usual records of ice, navigation conditions and surface temperatures; but unless they accomplished more than this in the line of physical oceanography, they are not mentioned for each year below. From 1922 to 1925, the patrol was carried in the "Arctic"; from 1926 to 1931 in the Hudson's Bay Company "Beothic", in 1932 in the "Ungava"; and from 1932 to 1947 in the "Nascopie". The "Ungava" and "Nascopie" were also ships of the Hudson's Bay Company. The patrols have been administrative rather than scientific. A new, and this time a Government, ship is at present under construction to serve the Government needs in the eastern arctic.

1923. The Biological Board of Canada (now the Fisheries Research Board) sent an expedition to the strait of Belle Isle in 1923, with the support of both the Canadian and Newfoundland Governments, in the ships "Arleaux" and "Prince". Dr. A. G. Huntsman was in charge of the field work and research. This expedition established the water exchange through the strait, in which the polar water flows in (to the Gulf of St. Lawrence) along the northwest side, and the Gulf water flows out along the southeast side (Huntsman, 1924).

1924. The Norwegian Government ship "Michael Sars" worked in the northwest Atlantic, and up to the Davis strait. Conclusions were drawn concerning the flow of water across the Davis strait ridge which are discussed in a later section. The expedition worked across the strait from Greenland to Baffin island (Martens, 1929).

1925. The Danish Commission for Fishery and Marine Investigation sent the "Dana" to west Greenland waters during June and July. The west Greenland current was studied in a series of stations from cape Farewell to Disko bay (Baggesgaard-Rasmussen and Jacobsen, 1930). The field work, besides the usual physical factors, included oxygen and hydrogen ion determinations.

In 1926, Iselin (Iselin 1927, 1930), in the schooner "Chance", worked in the waters of the northern Labrador shelf. This work, considered together with the earlier sections of the "Michael Sars" and the "Scotia", added considerably to the precision of our knowledge of the Labrador current and of its relation to the outlying water of the Labrador sea.

In 1927, the Putnam expedition studied and surveyed part of the coast of southwest Baffin island, using the schooner "Morrissey" with Captain Bob Bartlett as skipper. Tidal observations were made, and the soundings made by this expedition in Foxe basin comprise the bulk of our knowledge of the sea floor in that region (Putnam, 1928). In the same year, the Canadian Geological Survey worked in Cumberland sound, southeast Baffin island; and the Canadian Hudson Strait Expedition (Department of Marine) patrolled the waters of the strait making observations of the sea-floor, weather, and ice conditions. This expedition worked for two summers (1927 and 1928) in the ships "Stanley", "Larch" and "Montcalm". The work was related to the completion of the Churchill railway, and was consequently designed to explore navigation conditions. Some surface temperatures were taken, but no subsurface temperature or salinity observations were attempted, unfortunately (McLean, 1929). The Rawson-Macmillan subarctic expedition of 1927-8 worked in Frobisher bay and wintered in Labrador, making ice-observations and measuring surface temperatures.

Two important expeditions in 1928 are responsible for a large part of our present knowledge of the waters of the Labrador sea, Davis strait, and Baffin bay. The United States Coastguard expedition in the "Marion" made a series of sections along the Labrador coast and in west Greenland as far north as Disko island; also in the waters southeast of Baffin island. This work was continued later by the expeditions in the "General Greene" of 1931, 1933, 1934 and 1935. The results of this work were brought together by Smith, Soule and Mosby (1937), and are referred to frequently below. The Danish "Godthaab" expedition, commanded by Riis-Carstensen, did equally important work the same year in the Labrador sea and Baffin bay, going considerably farther north than the Coastguard expeditions (Riis-Carstensen, 1931).

The Wegener expeditions to west Greenland took place in the years 1929 and 1931-2. On both expeditions, oceanographical work was done in the waters of the Umanak district by Loewe. Such coastal studies over a small area are not so spectacular as the larger ocean-going expeditions, but they are of great interest and they are essential to a proper understanding of the water. Sometimes they bring to light phenomena of wide interest (Loewe 1933, 1934, 1935a, 1935b). Also in these years (1929, 1930 and 1931), the Canadian ship "Acadia", sent out by the Department of Marine and Fisheries, worked in Hudson strait and Hudson bay on an oceanographic and meteorological reconnaissance. These were the first Canadian expeditions to extend their oceanographic investigations below the surface. Besides charting the coasts, temperatures and densities were measured at all depths. Salinities as such were not measured, but were calculated (an inadvisable proceeding, as will appear below) from densities.

The German "Meteor" expeditions of 1928 to 1930, and 1933, worked just outside our present area, in the Denmark strait and Irminger sea, but since the published results included some treatment of relationships in the Labrador sea and Labrador current, they should be mentioned in this survey (Bohnecke, 1931; Bohnecke, Hentschel and Wattenberg, 1930). In 1929, 1930 and 1931, the French Office of Marine Fisheries made a study of the oceanographic conditions over the west Greenland fishing banks, extending work which had begun earlier on the Newfoundland banks. This study included full hydrographic stations including temperature and salinity measurements at all depths down to 200 metres, soundings and bottom sediments (Beaugé, 1931, 1932).

The Canadian Fisheries Expedition of 1930, to Hudson strait and Hudson bay, produced the first results in physical oceanography from those waters (with the exception of the temperatures recorded by the "Acadia" in 1929), from which any considerable knowledge of the waters could be obtained. The work in physical oceanography was done by H. B. Hachey; unfortunately the purpose of the expedition was somewhat narrowly defined, and the cruise was hurried, so that Hachey did not have the opportunity to make as complete a survey as he would no doubt have liked. The sections had to be made along the line of route, and hence in Hudson strait they were made parallel to the currents instead of across them. Nevertheless, the results (Hachey, 1931a, 1931b) are very important, supplying as they do the only information we now have for purposes of comparison with later work. Temperatures and salinities were measured at all depths, bottom samples taken, and drift bottles distributed. The drift-bottle results were published later (Hachey, 1935). The expedition ship was the trawler "Loubyrne".

In 1931, 1932 and 1933, the Newfoundland Government "Cape Agulhas" made a series of hydrographic stations round Newfoundland, in the strait of Belle Isle, and off southern Labrador, in connection with fishing operations and investigations (Wilson and Thompson, 1932, 1933, 1934). In northern Labrador, the Forbes Labrador expedition of 1931 and 1932 made a coastal survey, partly or mainly from the air, of the coast and outlying skerries, producing maps and sailing directions which have not yet been superseded for accuracy. Ice conditions in

Baffin bay were recorded by the Peary Memorial expedition (Captain Bartlett in the "Morrissey") in 1932, and in the same year the British H.M.S. "Challenger" began oceanographic work on the Labrador coast and shelf. In the first year two sections were made off Newfoundland and one out from cape Harrigan in central Labrador, to the deep water beyond the edge of the shelf (Wyatt, 1933). In the two following seasons the work was restricted to coastal survey and soundings between Indian harbour and cape Chidley. Wintering parties were landed in both seasons (Polar Record, 1935).

Also in 1932, Professor Loewe continued his studies of the waters of Umanak district in west Greenland, begun on the Wegener expeditions. In 1932 he was a member of the Fanck-Universal Greenland expedition, on which he managed to operate a reversing water bottle down to a depth of 100 metres from a folding canvas canoe in Umanak fjord; a motor boat was used for greater depths.

The 1932 cruises of the "Ocean Eagle", Captain W. A. Poole, should be included here. Captain Poole reported sighting land in Foxe basin not hitherto known. This report seems to have been forgotten, for the land, in the form of a large island, some 5000 square miles in area, was re-discovered in 1948 by an R.C.A.F. photographic aircraft. The "Ocean Eagle" made ice and tidal observations in the waters of Hudson strait and vicinity for several seasons.

1933. Besides expeditions already mentioned above, the Bartlett-Norcross expedition sailed in 1933 in an attempt to repeat the voyage made by Parry in 1821. Temporarily stopped by ice in Foxe channel, the expedition sailed round south and west of Southampton island and up the west side of Foxe basin. At Fury and Hecla strait they were turned back, like Parry, by adverse ice conditions (Polar Record, 1934). In the same year, and in the 1934 summer season following, the Canadian Hydrographic Service undertook a detailed coastal survey in southeast Baffin island from Frobisher bay to Lake harbour, in the "N.B. McLean", the survey party being under the command of F. C. G. Smith. Soundings, and tidal and ice observations were made (Polar Record, 1936a).

1934. The Cambridge expedition to Melville bay and Baffin island, in the "Heimen", under Professor J. M. Wordie, made soundings and recorded ice conditions, besides the main coastal survey work (Wordie, 1935, and personal communication). Captain Bartlett, in the "Morrissey", and Commander Macmillan, in the "Bowdoin", were again in Baffin bay waters. Both ships brought back hydrographic information (soundings) for incorporation in U.S. Hydrographic Office charts. The Danish cutter "Maagen" (fishery patrol boat in west Greenland) made hydrographic stations (temperature and salinity at all depths) in west Greenland (Conseil Permanent, 1935). Such work as these "Maagen" observations, unpublicized but to the point, are of greater value, in the opinion of the present writer, than the more spectacular efforts converted into heroics by the North American press.

1935. The "General Greene" expedition has already been recorded; Captain Bartlett's expedition of this year reached as far north as the Hakluyt islands at the entrance to Smith sound; the Canadian Eastern Arctic Patrol, in the Hudson's Bay Company's ship "Nascopie", carried Commander C. T. Beard, R.C.N., who obtained information on northern harbours for the Department of National Defence; and the Norwegian ship "Korsvik" carried a hydrographic party which studied the west Greenland fishing banks, and banks off the coast of Baffin island and Labrador (soundings, bottom sediments, fishing conditions) (Polar Record, 1936b). The "Korsvik" worked in the west Greenland area also in 1932, 1933, 1934, and again in 1936. The 1935 expedition was the most important.

1936. The Danish Naval patrol vessel "Heimdal", under Captain Riis-Carstensen, made hydrographic stations off the west Greenland coast (Conseil Permanent, 1938). C. H. Hartley and M. J. Dunbar, from Oxford University, made a study of the waters of the interior of Disko bay and Atâ sound (west Greenland), with particular reference to the stratification and behaviour of the fjord waters in the neighbourhood of active glaciers (Hartley and Dunbar, 1938). In northwest Greenland (Upernavik and Thule districts), the West Greenland Natural History expedition (Salomonsen) included the exploration of shallow water fauna and sediments, and temperatures, in its program (Vibe, 1939). The British Canadian Arctic expedition (Manning) began its survey work, which was to include tidal and ice observations in Foxe basin.

1937. T. H. Manning worked in the area of Southampton island, on coastal survey and surface observations. Captain Bartlett sailed into Kane basin, and investigated the seafloor with trawling gear down to sixty fathoms. J. M. Wordie, in the "Isbjørn", made a sketch survey of certain coastal parts of Baffin island, Greenland and Ellesmere island, and made observations of depths and ice conditions (Polar Record, 1938). Mr. H. M. Rogers, as a member of the Canadian eastern arctic patrol of 1937, measured surface temperatures and made dredgings at Lake harbour and other eastern arctic settlements. The Finland Labrador Expedition (Tanner, Kranck, Hustich) began their important studies on the Labrador. These were not oceanographic, but Tanner, in his final account resulting from this and another expedition in 1939, included an excellent description of the waters off the Labrador coast compiled from various sources (Tanner, 1947). The Danish naval vessel "Heimdal" was again in west Greenland waters, and did the only strictly oceanographic work of the year in the eastern arctic region (Conseil Permanent, 1939). In the polar basin, the Russian Papanin expedition landed on the ice at the pole; and the British Arctic Expedition (Haig-Thomas) established a base at Thule, where Hamilton made a month's tidal observations (Polar Record, 1939).

1938. The U.S. Coast Guard vessel "General Greene" made a "post-season" cruise (a cruise made after the ice patrol on the shipping lanes is ended) up the west Greenland coast, across Davis strait to cape Walsingham, and down the Labrador. This was a proper hydrographic cruise, including in its work full hydrographic stations (temperatures, salinities, oxygen concentrations). Captain Bartlett visited the coast of Ellesmere island, making the usual ice records en route. In the years 1938-40, T. H. Manning kept ice records and tidal observations in Foxe basin.

1939. The "General Greene" made a section from South Wolfe island, off southern Labrador, to cape Farewell, which is referred to below. M. J. Dunbar, on the Canadian eastern arctic patrol, began marine studies in the fjords of Baffin island, working mainly at Lake harbour (plankton and temperatures). The Van Hauen Expedition from Denmark established a base at Neqé, north of Thule; oceanography figured only slightly in the work of this expedition; Vibe made some bottom samples with the Petersen grab and a light dredge (Vibe, 1948).

1940. The Coast Guard cutter "Northland" repeated the section made by the "General Greene" in 1939, from South Wolfe island to cape Farewell (Smith, 1941). Captain Bartlett in the "Morrissey", with David Nutt in charge of scientific research, sailed up to latitude 80° 22′; as usual, drift-bottles were put overboard, surface temperatures recorded and ice conditions studied. The bottom was also examined by means of dredgings (Polar Record, 1941). M. J. Dunbar continued his coastal researches started in 1939 (plankton, temperatures and salinities at all depths) at Lake harbour, Frobisher bay, river Clyde and Pangnirtung (Dunbar, 1942). The R.C.M.P. patrol ship "St. Roch" started from the west on her two-winter voyage through the northwest passage.

During the years of the second world war, oceanographic research dwindled; routine observations on ice conditions, surface temperatures, etc., were not published until after the war, if at all. A useful summary of ice-patrol work from 1942 to 1946, including accounts of the conditions in the eastern arctic, has been published (Barnes, Challender, Soule and Read, 1947). While stationed at Godthaab in west Greenland, M. J. Dunbar continued his study of fjord oceanography and biology in west Greenland, only part of which has as yet been published (Dunbar, 1946). This included full hydrographic stations maintained in both summer and winter between the years 1942 and 1946. In 1944, the "St. Roch" repeated the northwest passage voyage, this time from east to west and in a single season, as already described above.

During the war, the Greenland Administration in Denmark built a new 50-foot research vessel, the "Adolf Jensen", for the fishery investigations in Greenland, which had been started almost forty years before. With the new boat, the researches have been expanded. She sailed to Greenland in 1946. In the same year, the Fisheries Research Board of Canada made plans to begin marine research in Canadian arctic waters; in 1947, M. J. Dunbar and Henry Hildebrand, from McGill University, worked in Ungava bay on a marine hydrographic and biological reconnaissance, and made a beginning in the physical oceanography of that area (temperatures, salinities and oxygen at all depths). In 1948, the work was continued by Hildebrand and Orkin, while a research vessel designed for arctic work was built in Nova Scotia to continue the long-term programme in the eastern arctic. The "Calanus", of dimensions similar to those of the "Adolf Jensen", was sailed to Fort Chimo in Ungava bay and beached for wintering.

The war had greatly stimulated arctic research in general. Immediately after the end of the war, the United States Navy undertook various exercises in arctic waters, and Canada and the United States together established new weather stations in the arctic islands. Some of these expeditions brought back oceanographic information. The bathythermograph, invented shortly before the war and developed during the war years, joined the army of oceanographic instruments. It offers an easy way of obtaining temperature-depth curves without stopping the ship, and moreover shows clearly where any sudden change in temperature occurs. It is not, however, anything like as accurate as the reversing thermometer, and it does not take water samples. In studying types of water, or water movement, it is a added help, but it does not replace the reversing bottle and thermometer.

In 1946, Operation "Nanook" explored the arctic archipelago as far west as Winter harbour, and established a meteorological station at Thule. Soundings were made along the route. The expedition included the icebreakers "Northwind" and "Whitewood", the seaplane tender "Norton Sound", and the supply ships "Alcona" and "Beltrami" (Polar Record, 1947). Other exercises and voyages in 1946 were either supply voyages (as the Canadian "Operation Packhorse") or strictly military (as the U.S. "Operation Frostbite").

The U.S.S. "Edisto", on Task Force 68 (1947), made extensive bathythermograph observations, and half-hour soundings, along the whole line of route from Belle Isle to Thule, and west through Lancaster sound; Jones sound was also visited. Nansen bottle samples were also taken, and temperatures with reversing thermometers, but these results have not been available to the present author at the time of writing.

In 1948, the U.S. Task Force 80, with the icebreakers "Edisto" and "Eastwind", sailed into Smith sound, and west through Lancaster sound. One ship went home for repairs while the other cruised farther west and in Prince Regent inlet. The two ships met again off northern Baffin island, and sailed down Prince Regent inlet and through Fury and Hecla strait; this strait being thus sailed for the first time in history. The return journey was continued through Foxe basin and Hudson strait. Soundings were recorded from the echo-sounders at 15-minute intervals. Neither the temperature observations of this expedition, nor the depths, were available for inclusion in this report.

A Canadian naval expedition in 1948 did some very useful oceanographical work off the Labrador coast, in Hudson strait and Hudson bay. The ships taking part were the aircraft-carrier "Magnificent", and the destroyers "Haida" and "Nootka"; the oceanographic work, consisting of a full hydrographic station (temperatures and salinities) every hundred miles along the route, and bathythermograph readings, were done on board the "Haida" by Lieutenant William Bailey.

The C.G.M.V. "Calanus", built for the Fisheries Research Board in 1948 did her first season's work in 1949, in Ungava bay, with M. J. Dunbar in charge.

Besides a variety of biological studies, hydrographic sections, consisting of a series of stations recording temperatures, salinities and oxygen concentrations, were made from port Burwell to Akpatok island, from Akpatok to Payne bay, and from Akpatok to the mouth of the Koksoak river. Other work in physical oceanography included scattered observations in connection with the biological programme, and the recording of depths.

Another vessel made her first working expedition in 1949. The schooner "Blue Dolphin", under Commander David Nutt, brought back valuable oceanographic information, including hydrographic sections across the strait of Belle Isle and in certain of the fjords of the Labrador (Hamilton inlet and Hebron fjord in particular). The "Blue Dolphin" was purchased by Commander Nutt in 1948 and made available to the Arctic Institute of North America for oceanographic research. Nutt intends to use her for a long-term project in the eastern arctic, and the "Blue Dolphin" now operates under the auspices of the Arctic Institute. The results of the 1949 season, and those of the "Calanus" in the same year, are not yet available for inclusion in this report.

In this long list of oceanographic work in the eastern arctic area, including the west Greenland coast, the contributions of many expeditions to oceanographic knowledge were quite small. The expeditions which contributed subsurface temperatures and salinities, and oxygen concentrations, are the most important, no matter how small the expedition may have been, for surface observations by themselves, being two-dimensional, are of little use in estimating the four-dimensional behaviour of water-masses. Especially interesting are the results of expeditions which have taken the time dimension into consideration, and maintained a station in the same position at intervals over a period of time. As will be emphasized below, there is a great need for work of this kind.

BATHYMETRY

The bathymetric map, fig. 1, has been prepared from various sources. Most important are the observations of the "Marion" in 1928 in Davis strait, Baffin bay and the Labrador sea (Smith, Soule and Mosby, 1937; Ricketts and Trask, 1932), and of the "Godthaab" expedition of 1928 (Riis-Carstensen, 1936). The soundings made and published by these two expeditions have been added to the soundings already available on British and American Admiralty charts. Two sections made by the "Northland" expedition of 1940 in Baffin bay (Hawley, Smith, Barnes and Soule, 1941) and a section made by the "Challenger" off northern Labrador in 1932 (unpublished data), have also been used, together with the soundings made by the United States' "Task Force 68" in 1947, and H.M.C.S. "Haida" in 1948 in the Labrador sea, Hudson strait and Hudson bay. The material collected by "Task Force 80" in 1948 was not available at the time of the preparation of the map; this would have been especially valuable for soundings in Foxe basin, Fury and Hecla strait, the gulf of Boothia and Prince Regent inlet, in all of which our knowledge is rudimentary. The only Foxe basin soundings used were the few published in nautical charts, and those made by the Putnam expedition of 1927 (Putnam, 1928).

The bottom contours of Hudson bay and Hudson strait are derived from a very detailed bathymetric map recently (1949) finished in manuscript at the

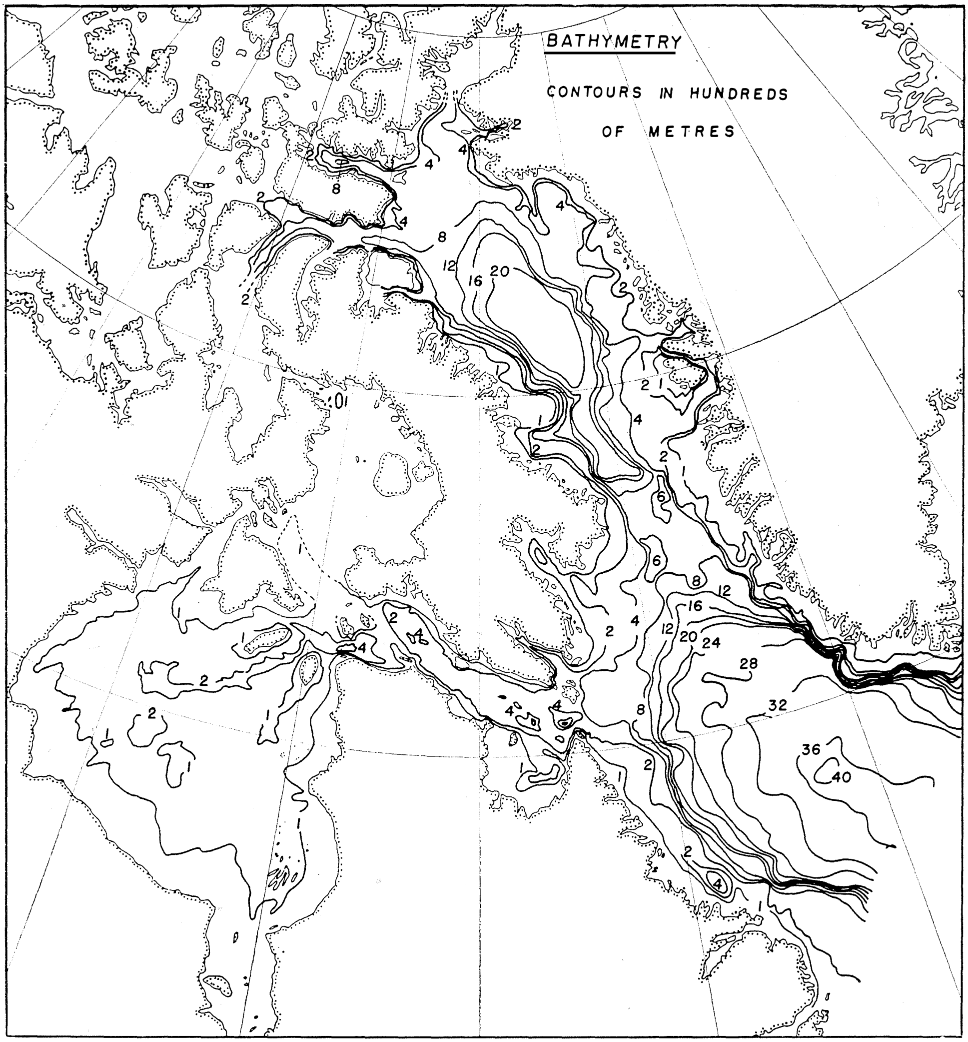


FIGURE 1. Bathymetric map of the eastern arctic area. Depths in metres; contours marked in hundreds of metres.

Geographical Bureau, Ottawa, and obtained through the courtesy of that organization. It is based upon the work of Dr. D. A. Nichols up to 1941, and with new material added up to the end of 1948, the whole thing being completed by Mrs. Morley.

Hudson bay is a shallow sea in which the 100-metre line lies at some distance from the shore, and in which most of the bottom is between 100 and 200 metres deep. At the entrance into Hudson strait there is a sudden depression of small area with a depth of over 400 metres. The Geographical Bureau map shows 475 metres here, south of Nottingham island. Foxe basin is still shallower than Hudson bay, almost the whole of the bottom lying above 100 metres. In the northwest corner, at the mouth of Fury and Hecla strait, the U.S. Hydrographic Office chart No. 6606 (1946) shows two soundings over 100 metres, one of 104 metres and one of 192 metres. For the rest, all available figures are less than 100 metres, varying from 90 to 13 metres in the central part of the basin. Foxe basin, like Hudson bay is enclosed by low-lying shores, with extensive tidal flats.

James bay, at the opposite end of Hudson bay, is even shallower than Foxe basin. The greater part of the bay is less than 50 metres in depth; there is a narrow trough, just over 50 metres, extending from a point southeast of Akimiski island northward to the mouth of the bay.

The 200-metre contour, extending along the former drainage trough of the Hudson bay region, stops south and east of Salisbury island at the west end of Hudson strait. Another 200-metre contour is met to the east of this, there being some 30 nautical miles between the two limits. Precisely in that gap we have at present apparently no soundings at all, to the east and north of Salisbury island. The map published here shows water between 100 and 200 metres deep in that region, but it is quite possible that it is shallower. From the general behaviour of the contours one would expect shallow water, perhaps a ridge across the strait of approximately 100 metres depth. The matter is of considerable importance to an understanding of the nature of the deeper water within Hudson strait, as will appear below.

East of the 76th meridian, the depths in Hudson strait lie for the most part between 200 and 400 metres. The shores of Hudson strait are considerably steeper than in Hudson bay, and the water consequently "bolder"; the 100-metre line lies fairly close in to shore, running, for instance, between Big island and the south shore of Baffin island. Northeast of Akpatok island, opposite the mouth of Ungava bay, there is a depression over 600 metres deep, and immediately to the east of this, just west of the Button islands, another depression going down to over 800 metres. Both these are very sudden; the southern slope of the easterly (deeper) one being apparently perpendicular for a vertical distance between 200 and 400 metres in extent.

Ungava bay, in its western and southern portions, is shallow, being well under 100 metres in depth. Approximately the shoreward half of this area is less than 50 metres deep. To the east and northeast, the bottom falls off below the 100-metre contour towards the 800-metre hole already described. There is a separate depression in the eastern part of the bay, dropping below the 200-metre line. As usual, the depths follow closely the outline of the shore; the western and southern coasts are low flat; only to the east does the shoreline rise to any height.

Here there is a coastal zone of skerries and rocky cliffs, leading back to hills generally 1,000 feet in height, which are in turn backed by the mountainous country of northern Labrador, rising to over 5,000 feet.

The whole of this subarctic mediterranean system, therefore, consisting of James and Hudson bays, Foxe basin, Hudson strait and Ungava bay, lies for the most part above slope levels; the edge of the shelf, marked by the 200-metre contour, appears in Hudson strait only, and its horizontal extent is not great. Along the Labrador coast the shelf is much wider, and is pitted in the southern portion by a small depression of over 400 metres depth. Beyond the 200-metre line the slope is steep as far down as the 2,400 metre level, beyond which there is a more easy gradient down to 4,000 metres approximately in the centre of the southern portion of the Labrador sea, on a line between Hamilton inlet and Julianehaab in southwest Greenland.

Along the western part of Davis strait and Baffin bay the shelf region is somewhat narrower than in the Labrador sea, with the exception of the extreme southeast of Baffin island and the region just north of Home bay, in which areas there are coastal banks similar to, though not as shallow as, the banks of the west Greenland coast. In the waters north of Baffin island, that is to say around Bylot island, in Admiralty inlet, Eclipse sound, Lancaster, Jones and Smith sounds, the shoreline becomes very steep and the shelf very narrow indeed; in this region the 100-metre contour has been omitted. The 800-metre contour penetrates only a small distance into Lancaster sound, and there is a very small area in the interior of Jones sound which lies below that depth.

Soundings in Smith sound are very few, and in the Gulf of Boothia the only reliable soundings so far made are those of the U.S. Navy "Task Force 80" (1948), which have not been available in the present study. "Task Force 80" also made a series of soundings in Smith sound. Smith sound is clearly very deep: measurements of 610, 650 and 672 metres have been recorded in the centre of the channel. Kane basin is somewhat shallower, with depths of 160, 220 and 250 appearing on the published nautical charts. Farther north, the waters of Kennedy and Robeson channels are deeper again, with published soundings down to 550 metres.

Along the northwest Greenland coast (north of Disko bay), the water is again deep, and here also the 100-metre contour has been omitted. In Melville bay, the drop over the continental edge from 200 to 400 metres is sudden. Disko island is surrounded on all sides by water deeper than 200 metres. From Disko bay southwards there extends a series of banks lying inside the 100-metre contour, which are of great importance economically in the Greenland fishery, and which have for years attracted the fishing vessels of many countries. The most northerly, and the largest, is the great Hellefiske bank ("Store Hellefiske Banke") between Egedesminde and Holsteinsborg (fig. 2). Next comes Helder's bank between Holsteinsborg and Sukkertoppen; the Lille Hellefiske bank southwest of Sukkertoppen; the Fylla bank off the mouth of Godthaab fjord; the Fiskenaes

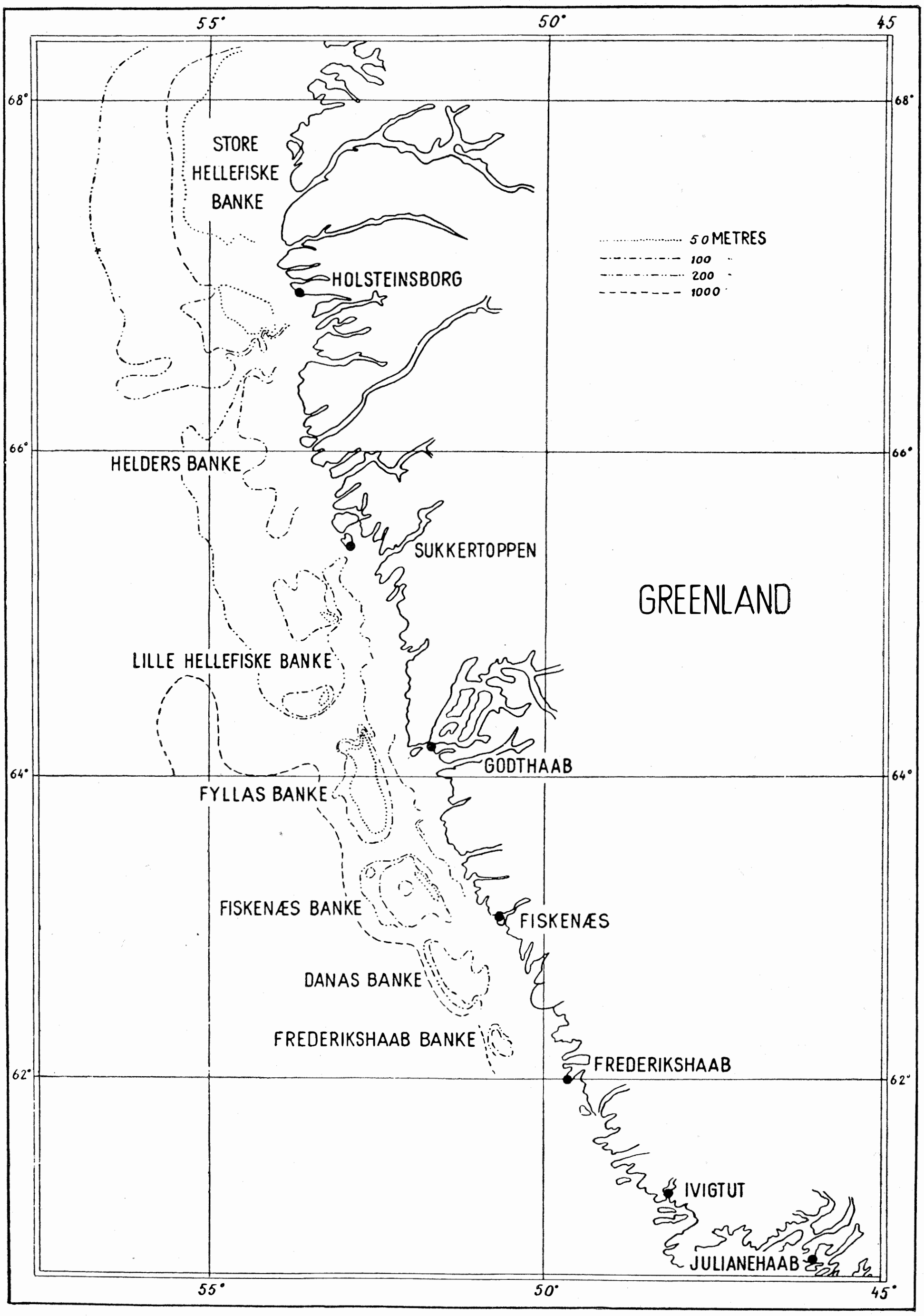


FIGURE 2. The west Greenland banks. From Kiilerich (1943).

bank off Fiskenaesset; the Dana bank, and finally the smallest of them all, the Frederikshaab bank off Frederikshaab. The inner part of the great Hellefiske bank, with depths of 24 and 25 metres, and the Fylla bank, which in its central part has depths of 29 and 33 metres, are the shallowest areas in this system.

The continental slope along the northeastern edge of the Labrador sea, off the coast of the extreme southwest of Greenland, is the steepest of all submarine gradients in the whole eastern arctic area, with the possible exception of the 800-metre depression at the mouth of Hudson strait. It is certainly the greatest in vertical height. From 200 to 2,800 metres in this region, the contour lines are so close together as to appear as a solid black band on the bathymetric map.

Baffin bay, in its central part, reaches depths of over 2,000 metres over a considerable area, this deep floor being somewhat closer to Baffin island than to Greenland. The bathymetric map of the Davis strait region, including the southernmost portion of Baffin bay, published by the U.S. Treasury Department on the basis of the survey made by the "Marion" (Ricketts and Trask, 1932), shows a separate small depression north of cape Dyer in eastern Baffin island, the position of the depression being approximately 67° 30′N; 61° 00′W. The depth reached is 1,000 fathoms (1,830 metres). This depth is allowed for in the present map, since the 1600-metre contour encloses this point; there is no evidence as yet that the depth here is greater than 2000 metres, however, and the soundings of "Task Force 78" in 1947 show that the 2000-metre contour is first met with just north of the 70th parallel, as shown in fig. 1. The depression figured by Ricketts and Trask does not appear as a separate deep in fig. 1, since the later observations of "Task Force 68" do not appear to be in accord with the Ricketts and Trask map.

There is a sounding which still appears on new editions of the nautical charts of Baffin bay, which is probably apocryphal. This is in 73° 15′N; 64° 25′W, and reads at 2870 fathoms (4,770 metres). None of the authorities agree with this sounding, and it would not be easy to fit the contours to it; pending more detailed sounding in this region, therefore, it has been treated as erroneous.

The waters of Davis strait, between Baffin bay and the Labrador sea, are much shallower than either of these basins. There is a broad ridge in this region, as shown in the bathymetric map, rising to depths just under 600 metres in two separate patches. This ridge may be considered as a continuation, on the west side of Greenland, of the Wyville Thompson ridge between Scotland and east Greenland. The two ridges, moreover, rise to similar heights and cause similar differences in the waters and faunas on their two sides.

The Canadian and Greenland coasts in the whole eastern arctic area differ considerably in type, in that the west Greenland coast (as the east Greenland coast) is a typical fjord region with a considerable development of local deep-water basins within the 100-metre contour. In some parts of the coast, the 100-metre contour should no doubt be drawn somewhat differently than appears in fig. 1, to show the existence of narrow channels in the continental shelf, leading out from some of the fjords. The details available, however, are not sufficiently fine to make this feasible, nor is the scale of the map large enough to allow it. The majority of the west Greenland fjords are of the typical bottom configuration with a well-developed threshold at the mouth, which normally rises to within 100 or 200 metres of the surface. In some instances the depth is much less than this. Some of the fjords, on the other hand, are considerably deeper than this at the mouth, a fact which is of great importance in determining the type of water found in the fjord basins. Such a fjord, of the so-called "Atlantic" type (allowing the invasion of Atlantic water) is Bredefjord in the Julianehaab district (Nielsen, 1928). On this fjord, and on the configuration of the mouths of fjords in general, Nielsen has this to say:

"Inside the Nunarssuit shoal the deep water sends off a bay in the direction of the mouth of Bredefjord, where the "Tjalfe" Expedition found a depth of 685m., and farther up the fjord still greater depths have been registered. It is, however, hardly probable that the 500 m. curve extends all the way up the fjord across the coast shoal, even though the hydrographical conditions, as will subsequently appear, favour the supposition that this fjord is being continued as a submarine fjord across the coast shoal, seeing that in the case of most fjords, even though they are continued across a depression in the coast shoal, there is as a rule a threshold with smaller depths than in the interior of the fjord. It must, however, be borne in mind that the sea bottom off most of the mouths of the fjords is very uneven, for which reason it is, as a rule, not possible to establish the maximum depths of the thresholds on the basis of the soundings at hand."

This matter is dealt with in greater detail below in the chapter on the hydrography of fjords. It is apparent, from the types of water which penetrate into many of the west Greenland fjords, that the thresholds at the mouths must be cut by deeper channels. This is well shown for instance in the differences between the deeper layers of Godthaab and Ameralik fjords; the threshold in Ameralik fjord appears to be intact; that in Godthaab fjord to be cut by a channel of considerable depth (see below).

The depths of the west Greenland fjords are nowhere, so far as is known, greater than 1,000 metres. Depths of from 400 to 700 metres are common. The "Godthaab" expedition measured 950 metres in Whale sound, at the approach to Inglefield fjord, in the Thule district, and over 800 metres in Melville bay. The Upernavik icefjord, north of Upernavik, appears to be deeper still, depths close to 1,000 metres having been recorded (Nielsen, 1928). Parts of Umanak fjord are over 700 metres in depth. The Vaigat, between Disko island and the Nugssuak peninsula, is between 300 and 600 metres deep; Disko bay, for the most of its extent, is 400 metres deep, with a deeper trough appearing on the southern side of its mouth, where the "Godthaab" expedition measured 685 metres. Godthaab fjord, according to measurements made by the writer, is over 500 metres deep in several parts, and possibly (this information was not obtainable by the writer due to lack of wire, but was supplied by local residents) over 600 metres in certain areas in the interior of the fjord. A depth of 600 metres was recorded by the "Tjalfe" expedition in this fjord, off the settlement of Kornok. In Ameralik fjord, immediately south of Godthaab fjord, soundings of 350 metres were made by the present writer; and in Fiskenaesfjord, further south, the "Tjalfe" expedition measured over 300 metres. Most of the larger fjords to the south appear to be between 400 and 800 metres deep.

Such depths as these have not been found at all in the inlets on the Canadian shores, with the exception of the great channels between the islands, already mentioned. The inlets of the Baffin island and Labrador coasts are much shallower, and the typical fjord contours are apparently absent. The only inlets known to approach the typical west Greenland pattern are Frobisher bay, where a sounding of 460 metres is marked on the most recent charts (see Canadian Hydrographic Chart No. 5000; 1948), fairly close to the head of the bay, and Sandwich bay, in southern Labrador, where Iselin (1932) measured 400 metres. In Cumberland sound, depths of 250 metres have been recorded. The remainder of the inlets on the Canadian shores in the eastern arctic area (among those so far charted) have been found to be less than 200 metres in depth. There is, however, still a great deal of work to be done in the sounding of these inlets; that depths comparable to those on the Greenland side will be found is improbable.

SEDIMENTS

Very few expeditions have made a special study of the bottom sediments of the eastern arctic seas. Many references to bottom sediments are scattered through the literature and most of them are not in sufficient number or in sufficient detail to be of value here. The "Marion" expedition of 1928 collected twenty-seven samples of deposits, most of them in Davis strait, and from single localities in Hudson strait, off cape Farewell and southern Labrador (Trask, 1932).

These samples were examined both for size and shape of particles and for chemical constitution. The particle-size was expressed in terms of the median size of the sample, with a "coefficient of sorting" which gave a measure of the homogeneity of each sample. Samples with median sizes between 50 and 1,000 microns were classed as sands; from 5 to 50 microns as silts; 1 to 5 microns as clays; and less than one micron, as colloids. Almost all of the samples contained a considerable amount of pebbles, ice-carried, and in fact most of the sedimentation must be ice-carried. Clays, silts and fine-grained sands were found at most stations, formed of the following rock types: granite, gneiss, quartzite, limestone, hornblendite, basalt. To quote from Trask's summary:

"The deposits contain much ice-borne detritus. Faceted, subrounded pebbles are fairly uniformly distributed in the sediments over the entire region. They constitute 14 per cent of the deposits. Gneiss, quartzite, and aphanatic limestone are the predominant rock types. The nearest source of the limestone seems to be in northern Greenland or the Arctic northwest 500 to 1,000 miles away, but the areal geology of northern Baffin island is imperfectly known, and the limestone may come from nearer regions not yet explored. The texture of the sediments varies with the configuration of the sea bottom and with the surface currents and tides. The deposits are relatively coarse on steep slopes and also in Hudson strait, off Cumberland bay, and on the transverse ridge that separates Davis strait from Baffin bay. The presence of 1 to 4 per cent of frosted, well-rounded sand grains suggest an eolian origin for some of the constituents. The fine sediments contain 20 to 40 per cent calcium carbonate, which is in a finely comminuted state. Its association with the limestone rock fragments in the deposit suggests that it derived from detritus carried by ice."

The "Godthaab" expedition kept records of bottom sediments at each sounding; no special study of them was made, nor were samples kept (Riis-Carstensen, 1931). Over the whole area of the expedition's work, in Baffin bay, Davis strait and the Labrador sea, gray clays predominated. Blue clays, fine and coarse sands, shells and pebbles were well represented. Similar deposits, labelled "gravel", "sand", "sandy clay" and "clay" were recorded by Vibe (1939) on inshore bottoms (8 to 64 metres) in the Upernavik and Prøven districts in northwest Greenland.

The Danish "Ingolf" expedition (1895 and 1896) collected bottom samples, and a very fine study of them was published by Bøggild (1900). The waters around Iceland, between Iceland and Greenland, and off west Greenland in the Labrador sea and Davis strait were covered, and ninety-one specimens were examined. In Davis strait and the Labrador sea, a zonation of bottom sediments was found, as follows (quotations are from Bøggild 1900):

The *shallow water deposits* are exclusively of terrigenous origin, and usually from the nearest coasts. These deposits surround the land down to the edge of the shelf, or roughly to the 200-metre line. "As no calcareous rocks are found in the territory surveyed by the Ingolf expedition, it follows from this that the percentage of carbonate of lime must be very small in these deposits; in three of the specimens where the percentage was measured, it varied from 0.11 to 0.35. . . . The four specimens taken immediately at the west coast of Greenland consist of common grayish arenaceous quartz, rather coarse, almost without finer particles, but also with rather few firm ingredients larger than 0.5 mm.". These deposits are thus to be classified as silts and sands.

The next zone found by Bøggild is that of the *gray deep-sea clay.* This corresponds to the sediment found abundantly by Trask in Davis strait, a little to the north of the Ingolf territory, but appears to differ in the smaller content of calcium carbonate, being in the Ingolf material 0.26% to 6.14%. Bøggild considers that the calcium carbonate in these deposits is of organic origin, and finds it more abundant as the gray clay merges with the transition clay (below). The size of particle in this clay is variable; particles over 500 microns are rare. Percentages of sizes below 500 microns are: 500-50 microns; 12-60%—50-20 microns; 2-25%—below 20 microns; 12-80%. It is immediately apparent that this is a mixed sediment, the particle-sizes falling into two groups. Although called a "clay", it is not for the most part as fine a sediment as is classed as clay by Trask.

According to Bøggild's map, the gray deep-sea clay covers a considerable area west of Greenland, most of Davis strait and the northern part of the Labrador sea. In vertical distribution, it lies usually between 200 and 900 metres, but is occasionally met at much greater depths. Bøggild considers that "probably the whole sea-bottom north of 63° Lat.N. between Greenland and Baffin Land opposite, consists of gray deep-sea clay".

The *transition clay* (continuing Bøggild's classification), covers the bottom between the gray deep-sea clay and the Globigerina ooze, covering a vertical distance normally from the 900-metre line down to 1800 metres (1000 fathoms). These limits, however, are variable. As its name implies, it is a mixture of the gray clay, of terrigenous origin, and Globigerina ooze, of pelagic origin. It is gray-brown, gray or brown in colour, and contains between 5% and 29% of calcium carbonate; again Bøggild implies here that the carbonate is of organic origin, whereas the calcium carbonate described by Trask (above) was of terrestrial origin. This discrepancy can only be resolved by further field-work, and the repetition of Bøggild's analysis. The particle-size in this deposit is predominantly less than 20 microns.

The *Globigerina ooze* was found by the Ingolf expedition to cover the deeper areas, and in the eastern arctic region is found in the southern portion of the Labrador sea. The upper limit of its appearance is normally at the 1,000-fathom line. It was found, however, at lesser depths than this, and it is very probable that were core-samplings to be made in shallower water, the Globigerina skeletons would be found underlying, or scattered through, the gray clay. The texture of this deposit was found by the Ingolf expedition to vary considerably, according to the size of the individual Foraminifera in the samples. The particles were distributed in size, on the average, in the frequency of: 0.90% over 500 microns; 6.49% between 500 and 50 microns; 4.38% between 50 and 20 microns; and 42.18% under 20 microns. The amount of calcium carbonate varied from 29.71% to 71.43%.

Bøggild gives an analysis of the chemical constituents of the sediments to which the reader is referred for further details.

No other detailed study of bottom sediments exists for the eastern arctic area, and in fact our knowledge of the distribution of the sediments is still rudimentary, in spite of the work of Bøggild, and of Trask; for even the collections of the "Ingolf" and the "Marion" were somewhat scattered. The "Valorous", returning home from northern Baffin bay in 1875, collected a very few samples of sediments (Markham 1875). In Davis strait and the northern part of the Labrador sea, four samples are recorded simply as "mud", "clayey mud", "clay and mud" and "soft mud". Peake (1901), reporting on the results of the deep sea sounding expedition in the north Atlantic in 1899, shows a distribution of Globigerina ooze in the Labrador sea which agrees with the "Ingolf" findings; he also shows in his sediment chart, which includes only the extreme southeast of our eastern arctic region, a broad band of "blue mud" (Murray's term) to the shoreward of the Globigerina ooze, which corresponds approximately to Bøggild's "gray deep-sea clay" and "transition clay" together. Knudsen (1923) describes two samples from Disko bay deep water as "clay" and "gray clay" without further analysis. A few samples brought back by the Second Norwegian Expedition in the "Fram" are described by Kiaer (1909); these are from very shallow water. One from 55 fathoms, north of Devon island, in 76° 41.5′ N, 93° W., is "gray mud", with a few Foraminiferan shells. Several samples from shallower water still (15 fathoms) in Goose fjord (Jones sound), are described as "soft brown clay", with pebbles, plant detritus, and molluscan shells.

There is even less information from Hudson bay and strait than from the regions already covered above. The samples collected by Johansen in 1920 in very shallow water along the eastern shores of James bay and Hudson bay are described by Cushman (1921) in a paper on the Foraminifera. These samples are recorded as "sand, gravel, stones", "sandy mud and algae", "stones, sand, algae", "clay with sand", and so on. They do not add very much to our knowledge of the sea-floor of Hudson bay. Hachey (1931a) gives the bottom types found at each of the stations made by the "Loubyrne" expedition of 1930 in Hudson bay and strait. Here again, samples were not kept, and the notes are of the kind normally kept in a ship's log, without any analysis: "mud and clay", "mud and stones", "gravel". Notes of bottom conditions in Ungava bay, by Dunbar (unpublished), are of the same order.

It is probable from these few data that the sediments over the whole area, with the exception of the southern half of the Labrador sea, are terrigenous, and carried by ice or by the effluxes of rivers (as in Hudson bay). As is thought to be the case over all the polar regions, the organic deposits, such as diatom oozes and Globigerina oozes, are masked entirely by the abundant clays and silts deposited by rivers and glaciers. In regions where active glaciers are abundant, as in the fjords of west Greenland, heavy glacial silts are found almost everywhere, only occasionally relieved by sands and gravels.

THE WATER MASSES

The water types found in the eastern arctic of North America are easily distinguishable. In fig. 3, this is done by means of the temperature-salinity diagram, the water masses being expressed as polygons whose sides enclose the temperatures and salinities measured in each type of water. The material from which the figure was drawn is taken from various expeditions, enumerated below. All depths below 50 metres are included; this avoids great expansion of the polygons and the confusion of the water masses due to surface heating and melting. The effects of surface heating, and of the melting of ice, no doubt extend farther down than 50 metres, and this may be especially true of the coastal water of the west Greenland current, but nevertheless the water masses, plotted in this manner, stand out distinctly and with remarkably compact distributions, on the T-S diagram. Fig. 3 is plotted for the months of August and September; only stations made in those two months have been used, with the exception of occasional records from the last three days of July. This is the period of the year when the water is at its warmest, for reasons of both surface heating and Atlantic influence. Five water masses are distinguished:

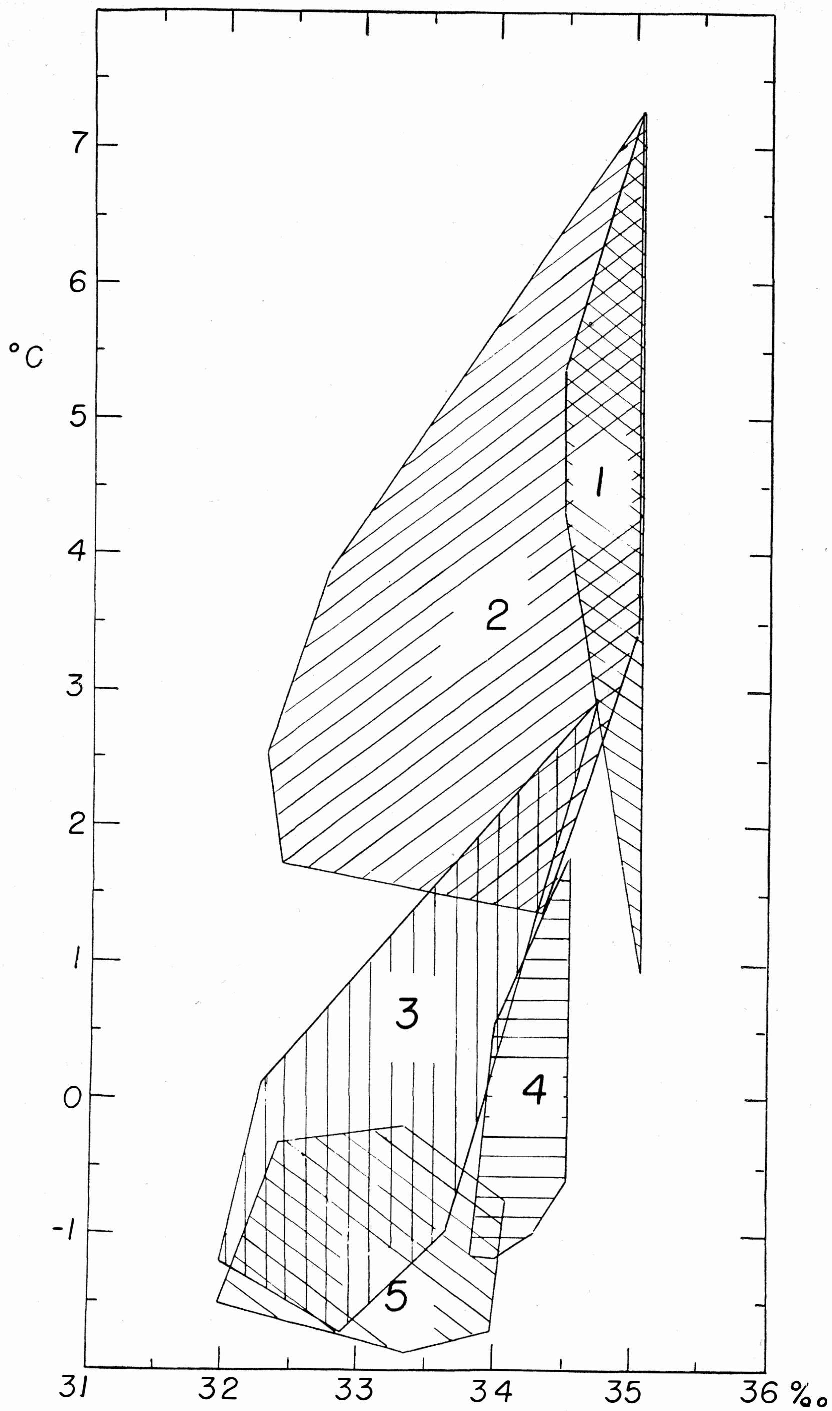


FIGURE 3. Temperature-salinity diagram showing the water masses of the eastern arctic. Water from the surface to 50 metres is omitted.

1. Labrador sea
2. West Greenland, Disko to cape Farewell
3. Labrador current
4. Deep Baffin bay water, from 300 metres to bottom
5. Polar water, from (*a*) Smith sound, Jones sound, Lancaster sound, from 200-250 metres to 50 metres. (*b*) Baffin bay, 250 metres to 50 metres, and all depths in the Canadian current. (*c*) Hudson bay (Haida stations, 1948).

THE WATER OF THE LABRADOR SEA (polygon no. 1 in fig. 3)

Compiled from "Godthaab", "Marion" and "General Greene" stations, all depths from 50 metres to the bottom included. This water is fairly homogeneous in salinity, varying only between 34.5 $^{o}/_{oo}$ and 35.05 $^{o}/_{oo}$. The range of salinity, and of temperature also, would have been considerably less had the upper limit of reference been lower, at 200 metres instead of 50 metres; for the coastal water, expanding out from the shores over Labrador sea, extends down to about 150 metres. Smith, Soule and Mosby (1937) describe four types of water found between southwest Greenland and the Labrador: coastal, arctic, atlantic and the water of the Labrador sea proper, the latter being formed of a mixture of the other three, and described by the authors as water which "with a remarkably small range of approximately 1° C. temperature and 0.06 $^{o}/_{oo}$ salinity, fills approximately 90 percent of the Labrador Basin". Such a remarkable homogeneity is in fact almost found in the water below 200 metres, and underlying the Labrador and west Greenland currents, and it might have been better to have excluded the upper layers from fig. 3. Coastal water, however, is not considered here as a separate water type, since it has always seemed to the present writer to be simply a modification of more permanent water masses in localized regions, and therefore (1) varying considerably according to the type of water modified, and (2) not properly separable from the origin mass.

Such a small range of temperature and salinity for the Labrador sea water is in point of fact not shown by the "Marion" results. Smith, Soule and Mosby (1937, fig. 146) publish a temperature-salinity diagram for the Labrador sea, showing a variation of almost 3° C., and 1.0 $^{o}/_{oo}$ salinity, which agrees better with fig. 3 here. In the "Marion" results, the Labrador sea water is further subdivided into Intermediate, Deep and Bottom water. The intermediate water lies between 500 and 2,000 metres, with a mean salinity of about 34.88 $^{o}/_{oo}$ and a temperature of 3.2° C. The deep water, according to this analysis, has a temperature range from 2.25° C. to 2.9° C., and a salinity range from 34.94 $^{o}/_{oo}$ to 34.97 $^{o}/_{oo}$, and extends down from 2,000 to approximately 3,500 metres, with considerable vertical variation. Below this comes the bottom water with salinity 34.91 $^{o}/_{oo}$ and temperature between 1.3° and 2.2° C.

Such a subdivision of the Labrador sea water is not followed by Kiilerich (1943) in his treatment of the "Godthaab" 1928 results; nor does he find evidence for such heterogeneity: "In the section which we from "Godthaab" laid from Cape Farewell to Labrador . . . it is, however, impossible to find such a border between heterogeneous water masses; temperature and salinity are very homogeneous throughout the greater part of the depth of the section".

The origin of the Labrador sea water is to be found in the mixture of west Greenland and Labrador current water, probably with the former predominating; Atlantic (drift) water also appears to play an important part. This matter is considered later in the discussion of the circulation of the eastern arctic water.

WEST GREENLAND WATER (polygon no. 2 in fig. 3)

Compiled from "Marion" and "Godthaab" stations, all south of Disko bay. The west Greenland water loses its identity to a large extent north of Disko bay. The temperature range of this water is approximately the same as in the water of the Labrador sea, but the salinity range is considerably greater. The expansion of the polygon to the left, showing lesser salinity, is of course due to the coastal water and to the presence of quantities of east Greenland polar water of low salinity. The polygon represents water not only of the continental shelf (which is very narrow in southwest Greenland), but also of the slope, down to a depth of 1500 metres. The relationship which exists between the Labrador sea water and the west Greenland water is well shown by the manner in which polygons 1 and 2 overlap. The west Greenland current consists of a mixture of polar, Atlantic (Irminger current), coastal and Labrador sea water; it is thus not surprising that the range of salinity and temperature is large. Had the water of the upper 50 metres been included in fig. 3, the range in both would have been larger still.

WATER OF THE LABRADOR CURRENT (polygon no. 3, fig. 3)

Compiled from "Marion" stations (1928), "Challenger" (1932), "Haida" (1948) and "Chance" (1926). This water is confined to the shelf and the upper reaches of the slope as a rule, though the "Marion" recorded Labrador current water as far down as 1,200 metres and perhaps lower, off Hamilton inlet. For the most part, the cold water of the Labrador current extends down to 500 metres.

The term "Labrador current" is used somewhat loosely in the literature; very often it includes the Canadian current running southward along the east coast of Baffin island. This latter current, however, is of a different and much more homogeneous sort than the Labrador current proper, and the water off the mouth of Hudson strait is in an area of eddies and mixing which obscures the current to some extent. "Labrador current" here, therefore, is used to apply only to the current running south along the Labrador shelf from cape Chidley to the Newfoundland banks, and this current which, as fig. 3 shows, is formed of mixed water. The waters which form it are the west Greenland current water itself, or its upper layers, and the polar water from the Canadian current and from Hudson bay. Thus the polygon overlaps both with the west Greenland water and with the polar water in polygon no. 5. It will be noticed that between the temperatures of 0° and −1° C., the water extends a little farther into the dilution range than does polygon no. 5; due, no doubt, to the continuation of the terrestrial drainage dilution, and of the solar warming, to which the polar water is subjected farther north.

DEEP WATER OF BAFFIN BAY (polygon no. 4, fig. 3)

Compiled from "Godthaab" stations, with small additions from the "Northland" sections in western Baffin bay waters made in 1940. The "Godthaab" stations extend into Smith sound, and include also two sections across the mouths of Jones and Lancaster sounds, which show clearly that the deep Baffin bay water invades all three areas to some extent, as is described below in the section on circulation.

This water is found from 300 metres down to the bottom in Baffin bay, sometimes lying even higher than this. In salinity it is almost as homogeneous as, and more dilute than, the water of the Labrador sea; in temperature it ranges from 1.8° to −1.2° C. This great mass of homogeneous water fills most of Baffin bay, and acts as the substrate over which the lighter polar water and the extension of the west Greenland current flow. The west Greenland current, continuing northward past Disko island in Melville bay, becomes diluted and cooled, so as to resemble, by independent evolution, the polar water from the north. There is considerable eddy formation in Melville bay, however, and some of the water of the upper 300 metres does not fit into the polar polygon (no. 5). This matter is dealt with separately below.

POLAR OR ARCTIC WATER (polygon no. 5, fig. 3)

This water is found over all the region north of Davis strait, and in Hudson bay. The polygon contains data from the following sources:

Baffin bay: "Godthaab" stations, 1928, and "Northland", 1940.

Smith sound, Jones sound and Lancaster sound: "Godthaab", 1928.

Hudson bay: "Haida", 1948.

For reasons which will be explained below, the 1930 data from Hudson bay, collected by Hachey (1931b), are not included in the figure. There are good reasons for supposing that there may have been significant changes in the hydrography of Hudson bay between 1930 and 1948, and that the 1930 results do not apply today.

This water lies generally above 300 metres in depth, and very often occupies a layer somewhat thinner than that. It is water of polar origin, which has entered the eastern arctic area through Smith sound, Jones sound, Lancaster sound, and Foxe channel. The T-S diagram presents a compact figure, with variation in salinity between 32 and 34.1 ‰, and in temperature between 1.8° and −1.8° C. In compiling the polygon, each sub-zone was first plotted by itself. Thus the water from the upper 300 metres in Baffin bay, and in Smith sound, is more saline than the Hudson bay water, and the coastal water along the east coast of Baffin island is less saline than the central Baffin bay water or the Smith sound water; there are also differences in the upper 200 metres in the northern and southern parts of the section across the mouth of Lancaster sound. These differences are discussed later. They are due to the effects of ice melting and land drainage, and do not obscure the clear relationship of the upper water from all areas covered.

In fig. 4, two more water types are added, superimposed upon three of the polygons from fig. 3. These are from Hudson strait and Ungava bay (solid lines) and from the mouth of Hudson strait and immediately outside. Both are clearly mixed waters.

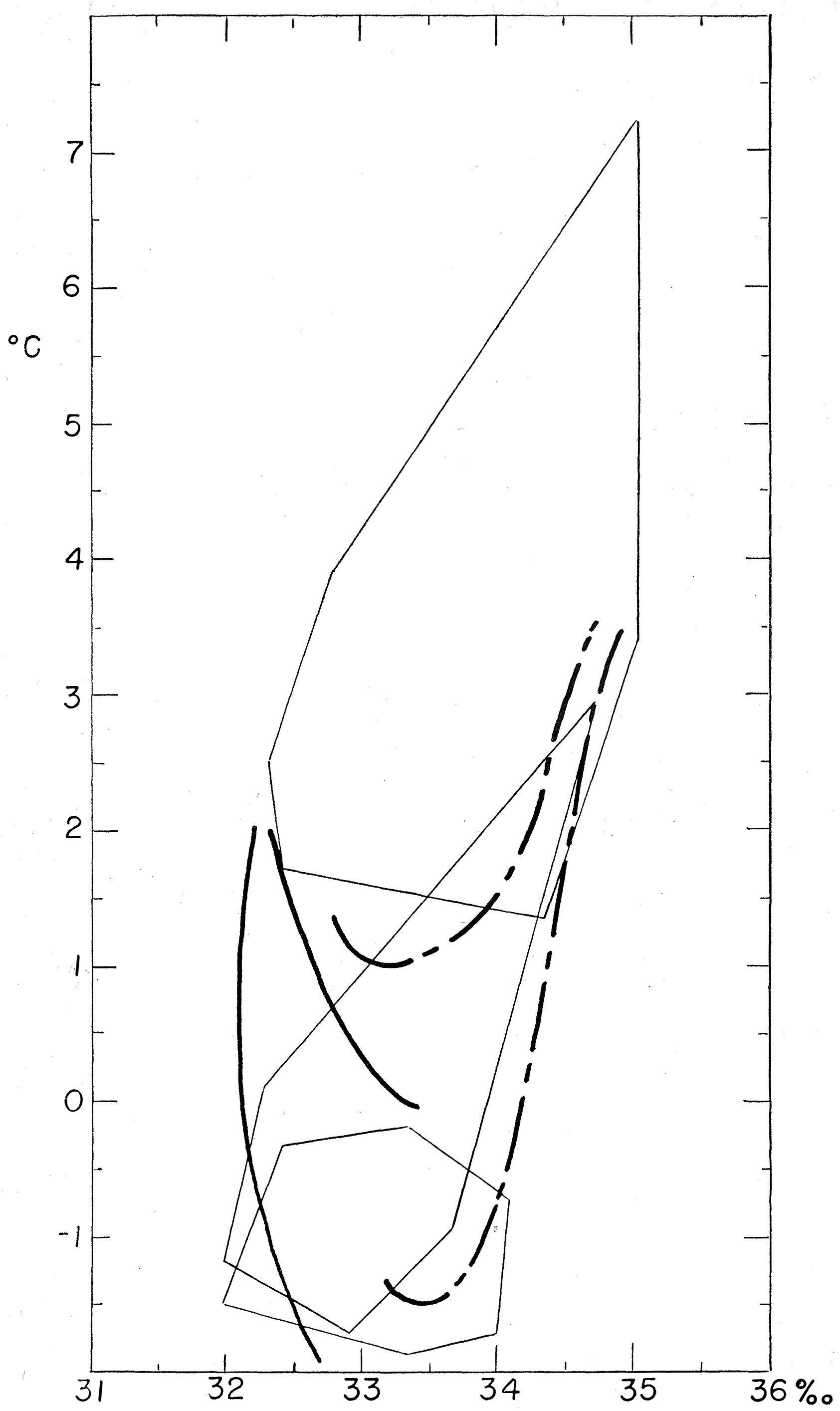


FIGURE 4. Temperature-salinity diagram showing water of Hudson strait and Ungava bay (solid heavy lines) and just outside the mouth of Hudson strait (broken heavy lines); superimposed upon the West Greenland, Labrador current and polar water polygons from fig. 3. For the stations used in the compilations, see text.

WATER OF HUDSON STRAIT AND UNGAVA BAY

Compiled from "Haida" stations 9, 10, 11, 25, 26 and 12 (see fig. 5), "Loubyrne" stations 57 and 58 (fig. 5), and from the author's own stations in Ungava bay in 1947 (fig. 6, stations 18 and 41). This water cannot be referred to any one of the polygons in fig. 3. When compared to the polar water of Hudson bay, there is clear evidence of warming; this warming may be, and probably is, due to surface heating and vertical mixing (see below). The low salinities do not suggest the invasion into Hudson strait and Ungava bay of west Greenland water (that is, of water containing an Atlantic element); but that such an invasion may occur nevertheless is strongly indicated by biological considerations discussed below.

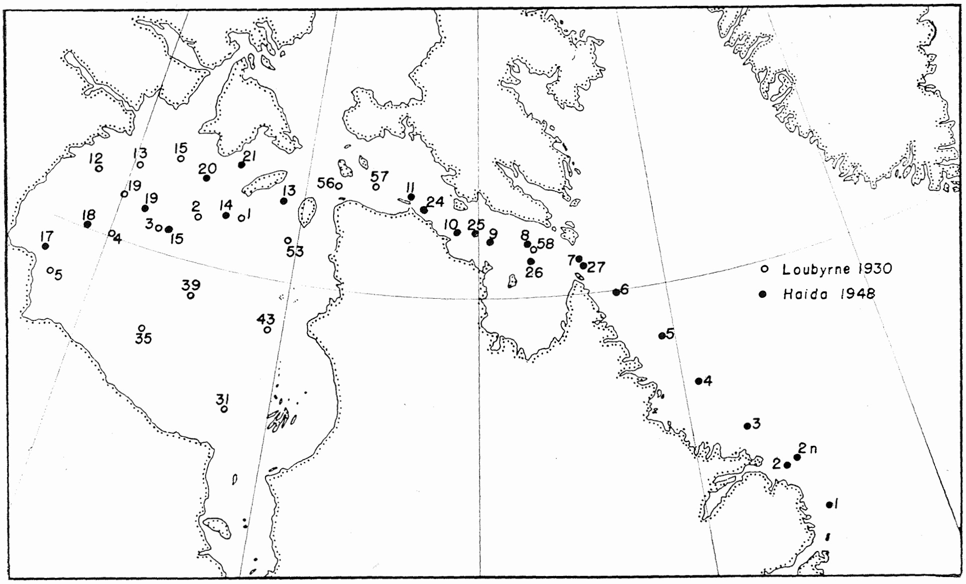


FIGURE 5. Stations occupied (reversing bottle) by the "Loubyrne" in 1930 and by the "Haida" in 1948. Open circles...."Loubyrne". Closed circles...."Haida".

The bulk of the Hudson strait water probably comes from Hudson bay. It will be observed that the boundaries of the T-S correlation area of this water enclose much of the polar water polygon, and that they just touch the corner of the west Greenland area.

WATER OFF THE MOUTH OF HUDSON STRAIT (interrupted lines in fig. 4)

This correlation is compiled from only five stations, all that are available in this area: "Godthaab" stations 18 and 19 (southeast and east of Resolution island), and "Marion" stations 1048, 1049 and 1050. All stations were made in the same year (1928), but the figure is open to the objection that the "Godthaab" stations were made on June 9 and 11 whereas the "Marion" stations are dated

August 21. In fact, however, the salinities and temperatures from the two expeditions fall close together, the data from June, as would be expected, being a little lower in temperature than the August data. The area off the mouth of Hudson

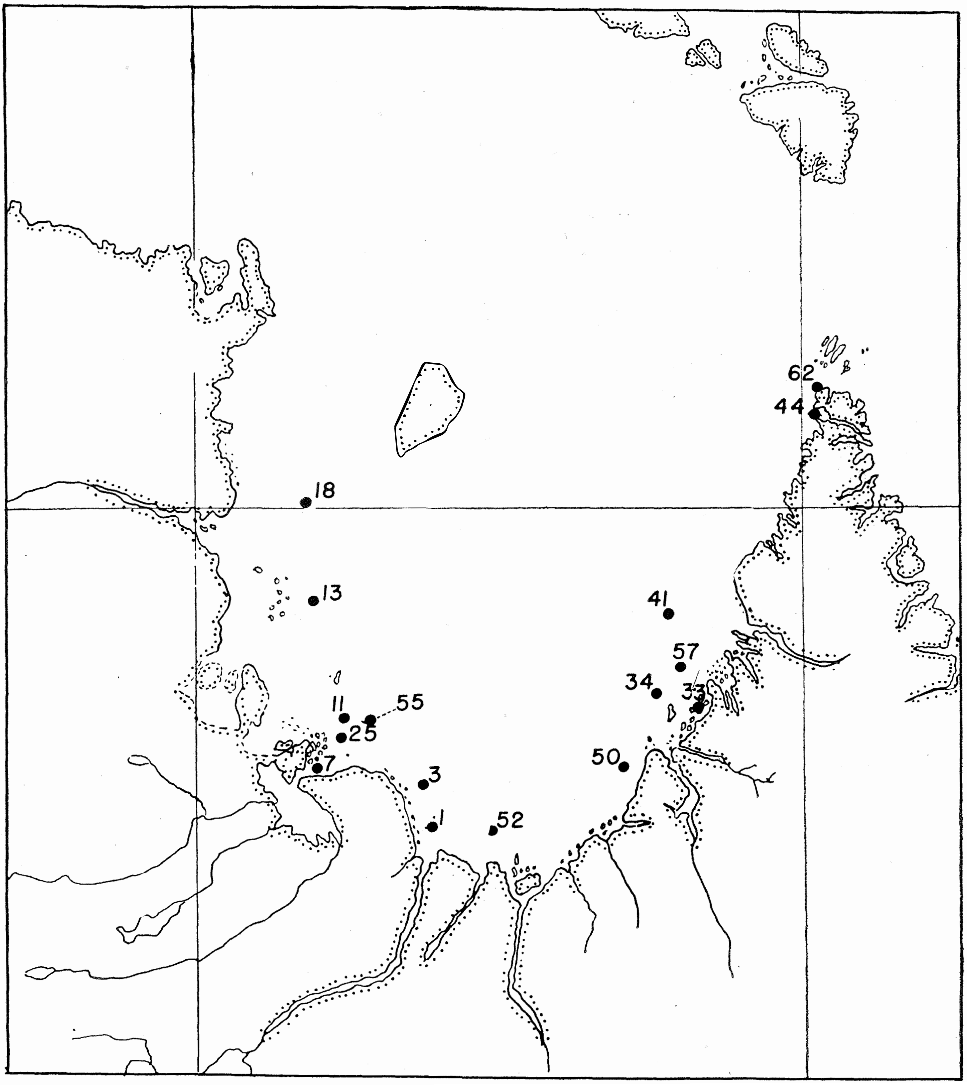


FIGURE 6. Ungava bay stations, 1947.

strait is the locus of origin of the Labrador current, where the Canadian current, the water from west Greenland and from Hudson strait converge; the T-S correlations of Hudson strait and the mouth area, shown in fig. 4, enclose between them almost the whole of the Labrador current polygon.

HORIZONTAL DISTRIBUTION OF TEMPERATURE AND SALINITY

In compiling the T-S correlations and the maps of temperature and salinity distribution, the reports of several expeditions have been used. As already mentioned, the figures published here represent the conditions during the months of August and September. Even that short period of two months can include considerable variation in physical conditions of the water, so that the figures are composite and approximate only. For the waters of Baffin bay, Davis strait and the Labrador sea, the "Godthaab" and "Marion" material has been drawn upon heavily, and in fact 1928 was the last year (with the exception of the "General Greene" work in succeeding years, which was done earlier in the season) in which extensive oceanographic work was carried out in that area. The information contained here, therefore, bears a strong 1928 stamp wherever the open and deep water of Baffin bay, Davis strait and the Labrador sea are concerned. It is thus important to know how typical a season was that of 1928.

During the past thirty years a remarkable warming of the hydrographic conditions west of Greenland has been observed, a so-called "amelioration" in marine (and atmospheric) climate which has had far-reaching effects upon the marine fauna. This is described in some detail in a later section. The warming seems to be due in great part to a general warming of the Atlantic drift water and hence of the Irminger current, and to an increase in the part played by the Irminger current in the formation of the west Greenland current. The process was first observed, by means of biological indicators rather than by physical measurements, in 1917, by Danish workers in Greenland waters. From that date it continued steadily and rapidly, apparently making a marked advance in the season of 1926 (Jensen, 1939).

The history of the waters over the Greenland banks from 1883 to 1938 has been followed by Kiilerich (1943). In that account Kiilerich has considered the conditions before the recent warming as "normal", so that the years following 1917 are for the most part described as being seasons of temperatures "above normal". Since we are concerned here for the moment with the present (1950) conditions in the eastern arctic area, it would be proper to interpret Kiilerich's "above normal" as "normal". The period of years in the 1920's and 1930's has, on this view, been thus one of higher temperatures compared to the years before, and there is as yet no indication that the cycle of warm marine climate is over; it may, however, have reached its peak in the middle of the decade of 1930-40 (see below). The year 1928 was in all respects typical of the warm period.

The figures of horizontal distribution of temperature and salinity (figs. 7 to 12 inclusive) are thus composite presentations of the probable conditions in normal years during the present warm period. Variations from them must of course be expected each year, especially at the surface, where local and seasonal differences in solar heating and ice-melting are important.

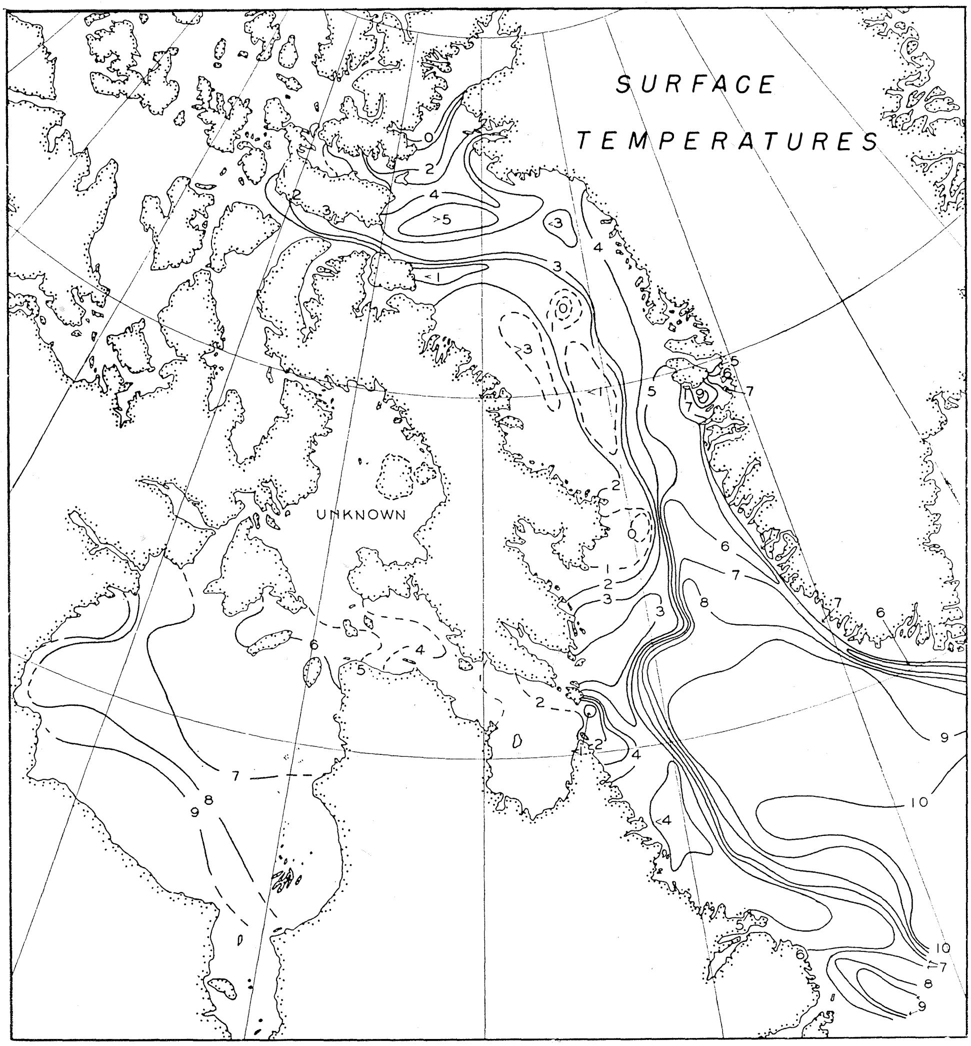


FIGURE 7. Surface temperatures, in degrees Centigrade, for the months of August and September. This is a composite figure, compiled from various expeditions of different years (see text), and shows the general temperature conditions to be expected in August and September during the present warm period.

SURFACE TEMPERATURES, AUGUST-SEPTEMBER (fig. 7).

Surface temperatures are compiled from the following sources:

"Marion" 1928; "Godthaab" 1928; "Loubyrne" 1930 (Hachey, 1931b, for Hudson bay and Hudson strait); Dunbar 1940 (Frobisher bay, Lake harbour, river Clyde); "Northland" 1940 (Smith 1941; western Baffin bay); "Challenger" 1932 (unpublished data, British Admiralty; Labrador section); U.S. Task Force 68 (unpublished data, Belle Isle to Devon island; "Haida" 1948 (unpublished data, Labrador, Hudson strait, Hudson bay); Dunbar 1947 and Hildebrand 1948 (unpublished data, Ungava bay).

The distribution of surface temperature clearly shows the warm Labrador sea "core" water, between the coastal currents of west Greenland and Labrador, which pushes the 9° isotherm up to the level of Hudson strait. The narrow west Greenland current off the extreme southwest of Greenland spreads out westward south of Davis strait, shown by the shape and spacing of the isotherms of 6°, 7° and 8° C. The surface waters of the Labrador current at this time of year have warmed up to 4°, helped considerably by west Greenland water. The surface of Hudson bay is warm, due to the influx of freshwater land drainage and solar heating; as this surface water flows round Hudson bay and out through Hudson strait, there is a progressive mixing with the cold sea-water, shown both by decreasing temperatures and increasing salinities. The water that finally flows out of Hudson strait is cold (there is still ice in Hudson strait in August) and contributes to the Labrador current. Another cold area is apparent in the western portions of Davis strait and Baffin bay, where ice-laden arctic water flows south, forming a cold front against the western Greenland water, which is particularly marked in Davis strait. The warmer temperatures off the Greenland coast in Baffin bay are of course due to the persistence of the west Greenland current.

The warm area in the northwest of Baffin bay, south of Smith sound, is of special interest, showing temperatures over 5° C. According to verbal reports made to the author by sea-captains, temperatures of 8° C. are sometimes recorded in this region. It is the area of the so-called "north water", which is normally free of ice for most if not all of the year, and a favourite haunt of the whalers in days of the Baffin bay whaling industry. The explanation of its existence, which remains today as puzzling as formerly, is discussed later.

SURFACE SALINITIES, AUGUST-SEPTEMBER (fig. 8)

Surface salinities are compiled from the same sources as contributed to fig. 7, with the exception of Task Force 68, which made no salinity measurements. Striking the eye at once is the direction of the isohalines in Hudson bay, which is approximately at right angles to the direction of the isotherms. This must be considered an indication of cyclonic circulation to Hudson bay, with an incoming supply from Foxe basin and possibly also from the north side of Hudson strait. Such a circulation within Hudson bay has long been known from ice movements, and was recently confirmed by Hachey (1931). The fact that the isotherms run at right angles to the isohalines indicates that solar heating *in situ* is of greater significance in heating the surface layer than the influx of warm land-drainage water. The patch of slightly higher salinity in the northwest of the bay, with values up to 31 $^{\circ}/_{oo}$, suggests at first sight a zone of upwelling; there is, however, no evidence beneath the surface for upwelling here. The salinity distribution must therefore be ascribed to the distribution of ice.

The differences between the west Greenland current and the Labrador current are again well demonstrated in the salinities, and the extension of the 33 $^{\circ}/_{oo}$ isohaline well up into Baffin bay illustrates the intrusion of west Greenland water right into Melville bay. Water of 32 $^{o}/_{oo}$ salinity and lower comes out of Smith sound, Jones and Lancaster sounds, and is soon diluted considerably by the ice of Baffin bay. In the extreme north of Baffin bay, salinities from 19 to 31 $^{o}/_{oo}$ were recorded by the "Godthaab" expedition, in the general area marked "varia-

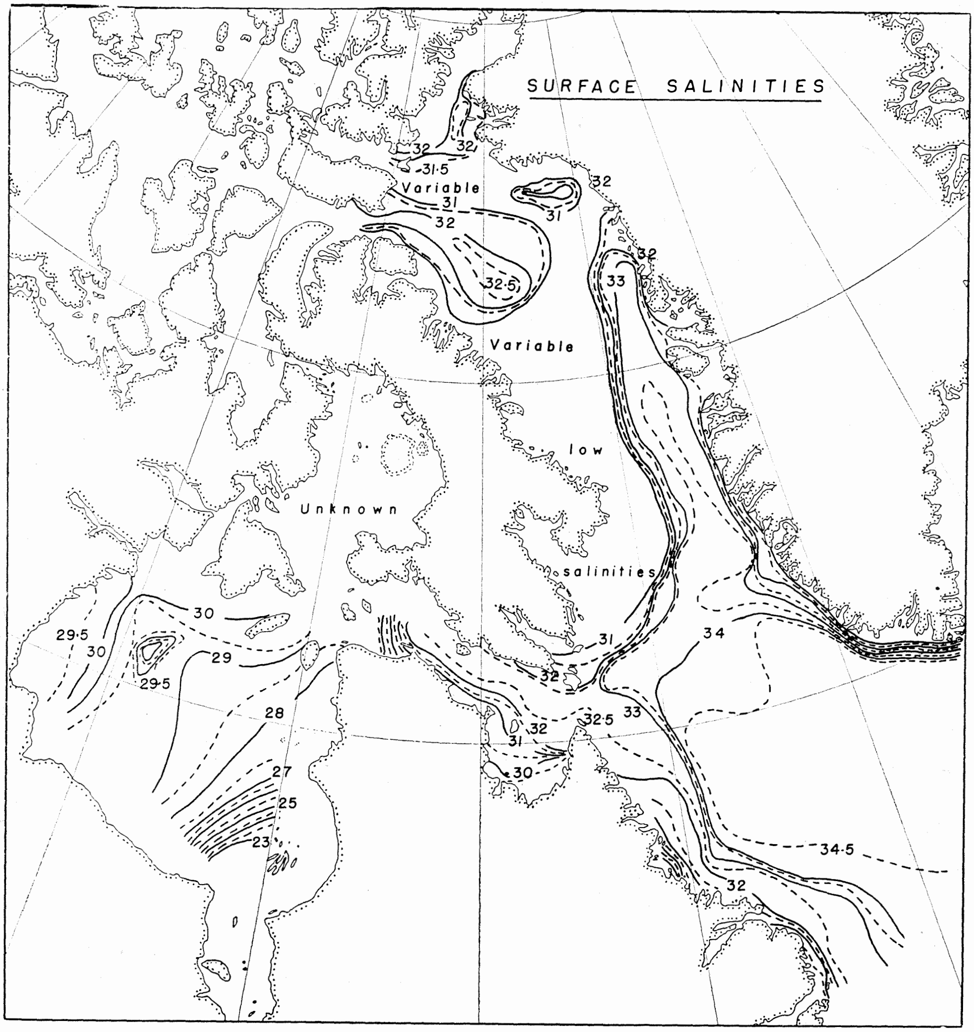


FIGURE 8. Surface salinities, August-September. Composite figure, from sources listed in the text.

ble" in fig. 8. Over the whole western portion of the bay, off the east coast of Baffin island, salinities from 24 to 31 $^{o}/_{oo}$ have been found by various expeditions. These variable salinities, which render the drawing of contours impossible, are of course due to the melting of ice. It will be noticed that there is no area of higher salinity in the "north water" area shown on fig. 7.

TEMPERATURES AT 100 METRES (fig. 9)

The closed -2°C. isotherm in Hudson bay is interesting. It is based on the observations of the "Loubyrne" expedition of 1930 (Hachey, 1931). The "Haida", in 1948, did not find temperatures as low as this, although some of the "Haida"

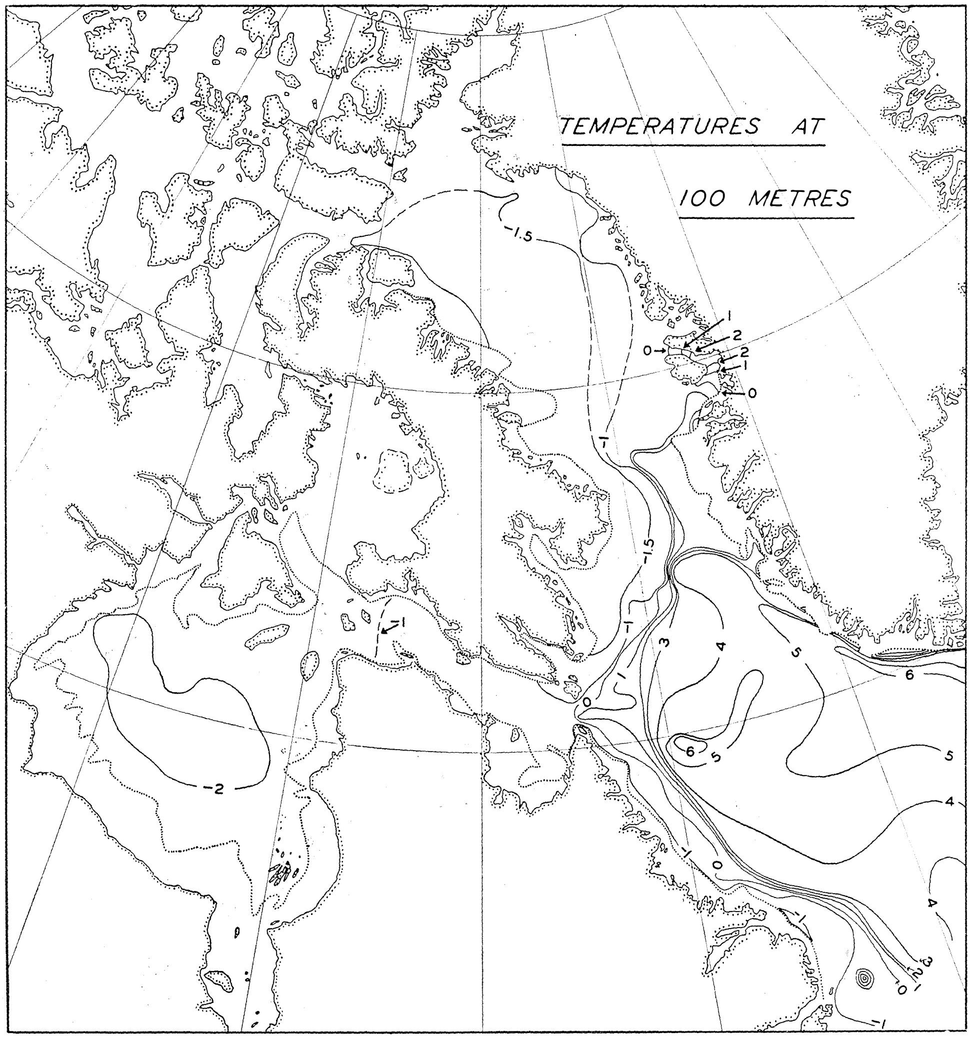


FIGURE 9. Temperatures at 100 metres, in degrees Centigrade, August-September. Composite figure from various sources. The -2° isotherm in Hudson bay is based on the "Loubyrne" 1930 observations, which may no longer apply today (see text).

stations were very close to the isotherm in fig. 9. It is possible that the measurements were inaccurate, and that the thermometers used were not trustworthy for the low extremes of temperature. Since, however, the deeper water of Hudson bay appears to be dynamically dead, there may be a constant loss of heat to the sea-floor or to the upper layers, or both, accounting for the very low temperature. Such temperatures could not exist at the surface, hence the cooling, assuming that the observations are correct, must have taken place *in situ*.

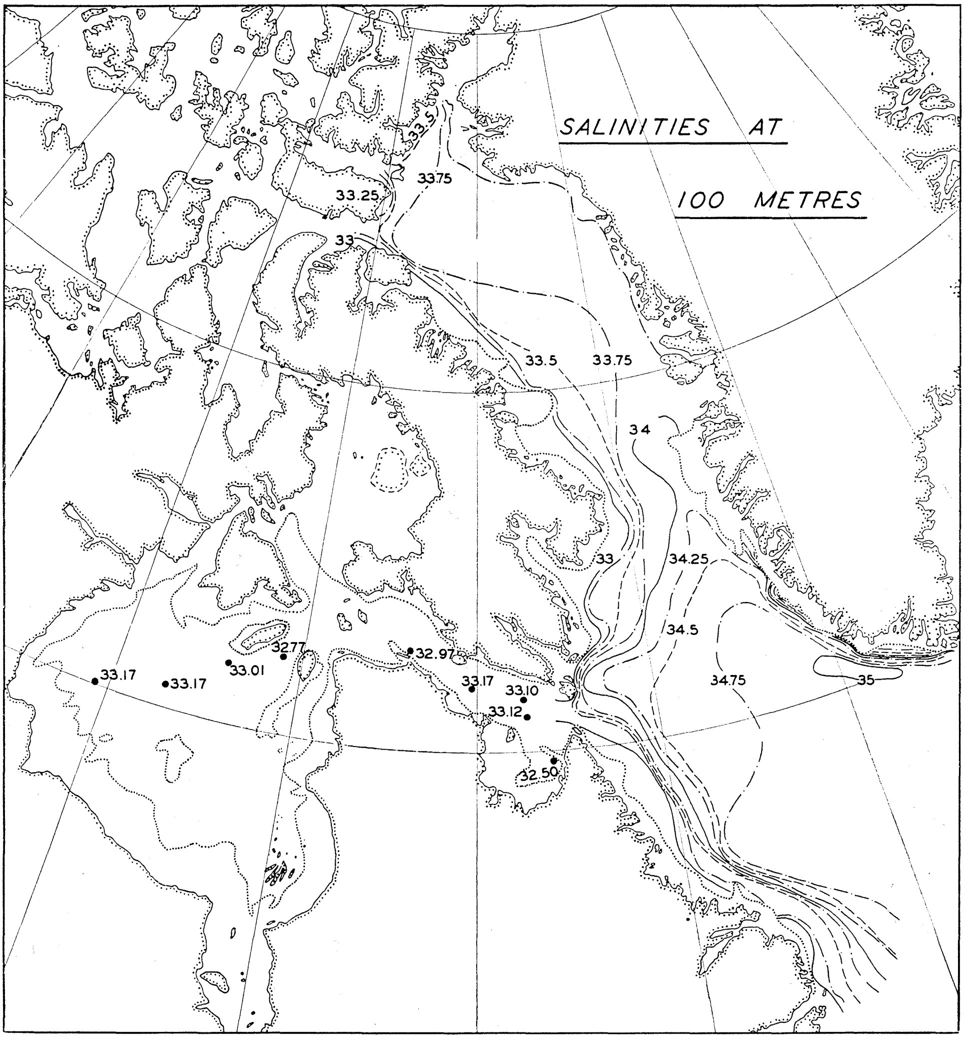


FIGURE 10. Salinities at 100 metres, August-September. Composite figure from various years (see text).

The effect of the west Greenland current over the Davis strait ridge and in southeast Baffin bay is still apparent at 100 metres, shown by the course of the 2° isotherm. All the patterns shown at surface are in fact still maintained at 100 metres, somewhat less emphasized. As will appear from the discussion of the water circulation, this similarity of the horizontal pattern at increasing vertical depths is found down to the depth of the Davis strait ridge (600-700 metres); the horizontal distributions of salinity and temperature below 100 metres are therefore

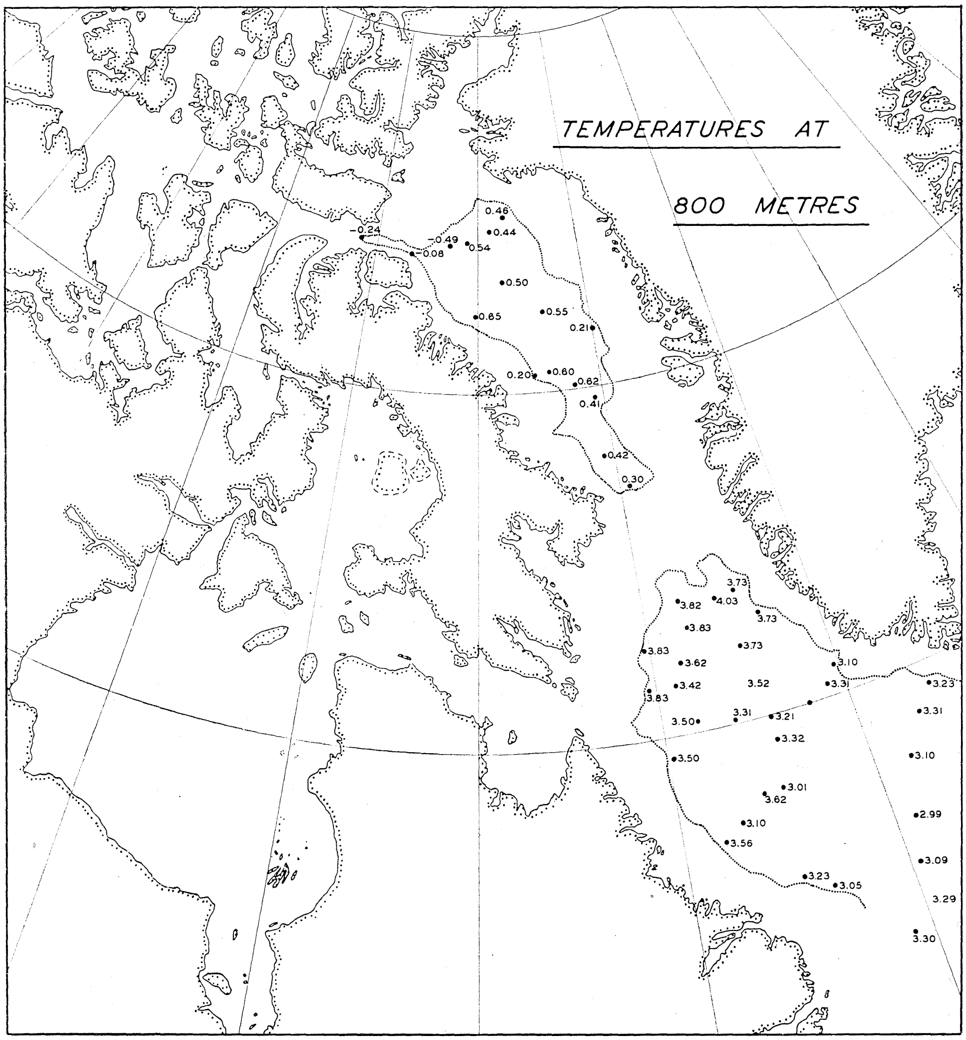


FIGURE 11. Temperatures at 800 metres, in degrees Centigrade, August-September. Composite figure from various sources (see text).

not included here, with the exception of one example of the pattern below the ridge depth, at 800 metres.

The very cold water of the Canadian current, much of which is enclosed by the $-1.5°$ isotherm at the 100 metre depth, is well shown in fig. 9. Since the temperatures at this level in Smith sound are above $-1.5°$, the low temperatures in Baffin bay are no doubt due to the effect of ice-melting. This is supported by the fact that the isotherm contains the cyclonic eddy of water observed in Baffin bay, which would tend to retain ice in that area.

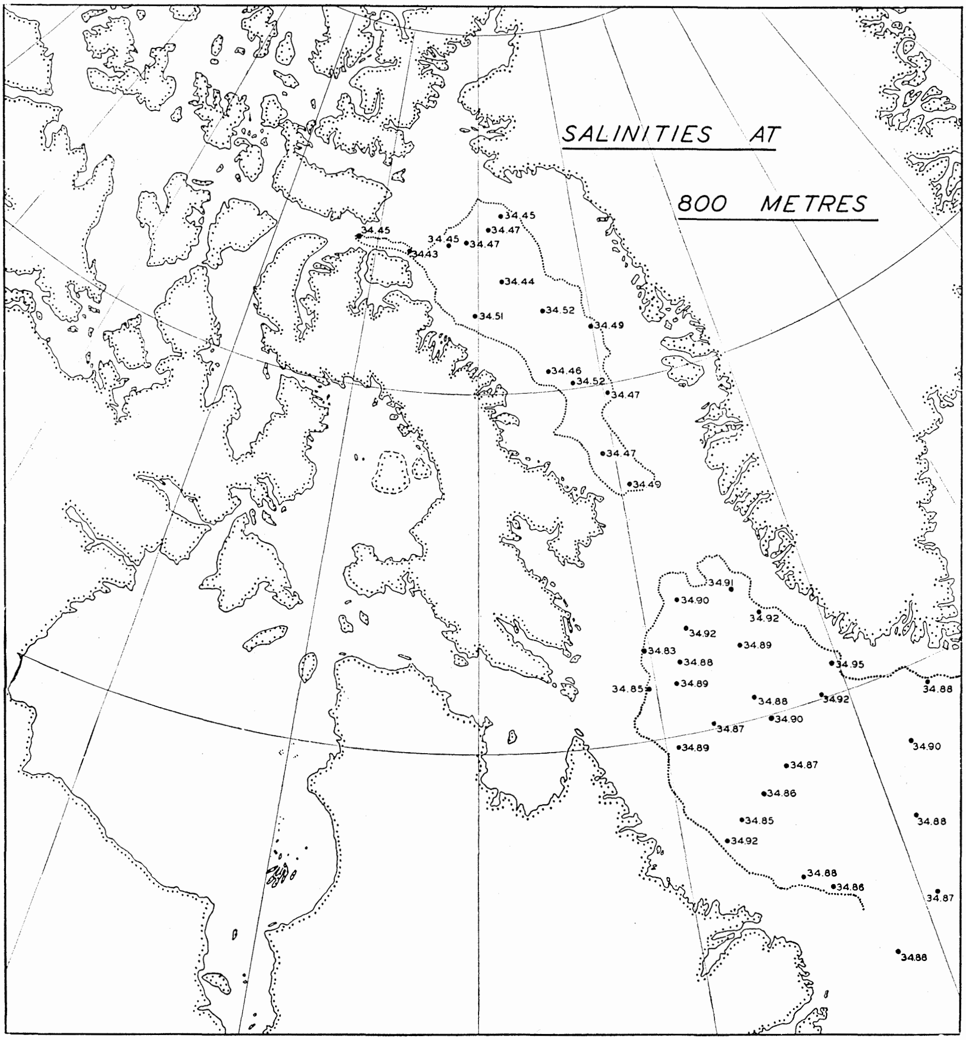


FIGURE 12. Salinities at 800 metres, August-September. Composite figure from various sources (see text).

SALINITIES AT 100 METRES (fig. 10)

Again the same pattern is apparent. The closed 35 $^{\circ}/_{oo}$ contour off south-west Greenland suggests a small area of upwelling water. The west Greenland current brings water of 34 $^{\circ}/_{oo}$ salinity up to the level of Disko bay, and the path of the 33.75 $^\circ/_{oo}$ isohaline follows closely the current computed for Baffin bay by Kiilerich (1943) and by Hawley, Smith, Barnes and Soule (1941).

The observations in Hudson strait and Hudson bay are too scattered to allow contours to be drawn. The salinities are all low, showing apparently no influence other than pure arctic water, unless any such influence which does exist has been obscured by dilution and mixing. The salinities of the "Loubyrne" 1930 expedition have not been included; those shown are "Haida" observations, with the exception of one reading for Ungava bay, supplied by the present writer. As already mentioned above, it is possible that hydrographic changes since 1930 have rendered the 1930 observations, especially of salinity, out of date and inapplicable. This objection applies also, it may be supposed, to the temperature observations expressed in the $-2°$ C. isotherm in fig. 9.

TEMPERATURES AND SALINITIES AT 800 METRES (figs. 11 and 12)

These figures, drawn from data of the "Marion", "Godthaab", "Northland" (1940) and "Challenger" (1932) expeditions, are included to show the hydrographic effects caused by the separation of the Baffin bay and Labrador sea basins by the Davis strait ridge. At 800 metres, below the level of the ridge, there is a temperature difference of some three degrees Centigrade and a salinity difference of approximately 0.4 $^\circ/_{oo}$. This scale of difference is found at all greater depths, and is expressed in the positions of the polygons on the T-S diagram (fig. 3). It is due, of course, to the prevention of the penetration of Labrador sea water into Baffin bay at these depths, and is comparable to the situation found on the two sides of the Wyville Thompson ridge between Scotland and Iceland, to which attention was drawn by the "Michael Sars" expedition of 1910, under Murray and Hjort.

CIRCULATION

The material of oceanographic field work is today worked out in terms of water movement by means of the prevailing orthodoxy, the dynamic topographic method. This method has certain limitations which might appear more vividly to the biologist than to the physical oceanographer, and the present author reserves the right to temper his admiration of the method with a little suspicion. Doubts of the complete validity of the dynamic treatment have already been expressed, as for instance by Parr (1938a, 1938b). It does not allow for, and therefore does not demonstrate, vertical movements in the water, and it depends for its accuracy on the supposition that the reference surface, from which the computations are made, is stationary. It is admitted, however, that in the matter of horizontal water movements the computed results agree closely with the results observed or inferred by more direct means (current meters, drift bottles, ice movement, etc.), provided that the calculations are made from a sufficiently large number of observations, and provided the field stations are sufficiently close together.

There is one more reservation to be made. The following account of the water circulation, being based on the work of expeditions in certain few years, must not be taken as correct for all years except in the broad outline. Variations in water transport, current velocities and other parameters, are considerable from year to year.

The pattern of circulation in all the major bodies of water in the eastern arctic is cyclonic, or anti-clockwise. In the Labrador sea, the west Greenland current and the Labrador current flow respectively northwest and southeast, and a large part of the west Greenland current turns west and southwest to join the Labrador current. In Baffin bay, the northward continuation of the west Greenland current flows north, turning northwest at the northern extremity of the bay, while the cold Canadian current, formed of polar water from Lancaster, Jones and Smith sounds, flows southward and southeast in the eastern half of Baffin bay. In Foxe basin, where our knowledge of the currents is derived entirely from ships' reports published in the "Arctic Pilot", the circulation is also cyclonic, and apparently not of any great intensity. Finally in Hudson bay, the water from Foxe basin flows southward into the bay along the western shore, and the outflow from the bay into Hudson strait moves up the eastern side. There is even an indication of a small cyclonic circulation within Hudson strait itself. Such anti-clockwise movement is of course to be expected from the geographic pattern of the region and positions of currents which enter the system; in the northern hemisphere all these entrant currents are forced to the right, along right-hand shores. See fig. 13, surface currents.

THE LABRADOR SEA

The *west Greenland current* is composed of water from four sources: (1) east Greenland current (polar water), (2) Irminger current (Atlantic drift water), (3) Labrador sea (mixed water), and (4) coastal drainage and melt water. The coastal contribution is not considerable in comparison with the others; it does, however, increase in volume during the summer and thereby raise the dynamic height of the coastal water, which in turn affects the velocity and direction of the current at the surface. The Irminger current, which is of much greater volume than the east Greenland polar current (see Kiilerich, 1943), flows west from the southwest shores of Iceland and comes to lie beneath and outside the east Greenland water. The east Greenland current holds close to the continental shelf, and gradually loses its polar characteristics as it rounds the southern tip of Greenland, due mainly to mixing with the Irminger water. According to Kiilerich, the greatest admixture takes place off cape Farewell, in the upper 100 to 200 metres. The consequence of this mixing is that the coldest water of the west Greenland current, in the extreme southwest of Greenland, lies close in to shore, where the remnant of the unmixed polar water usually persists for some distance in most years. This "arctic pocket" in the extreme southwest of the Julianehaab district has had certain effects upon the economy of the Greenlanders in that region. The arctic

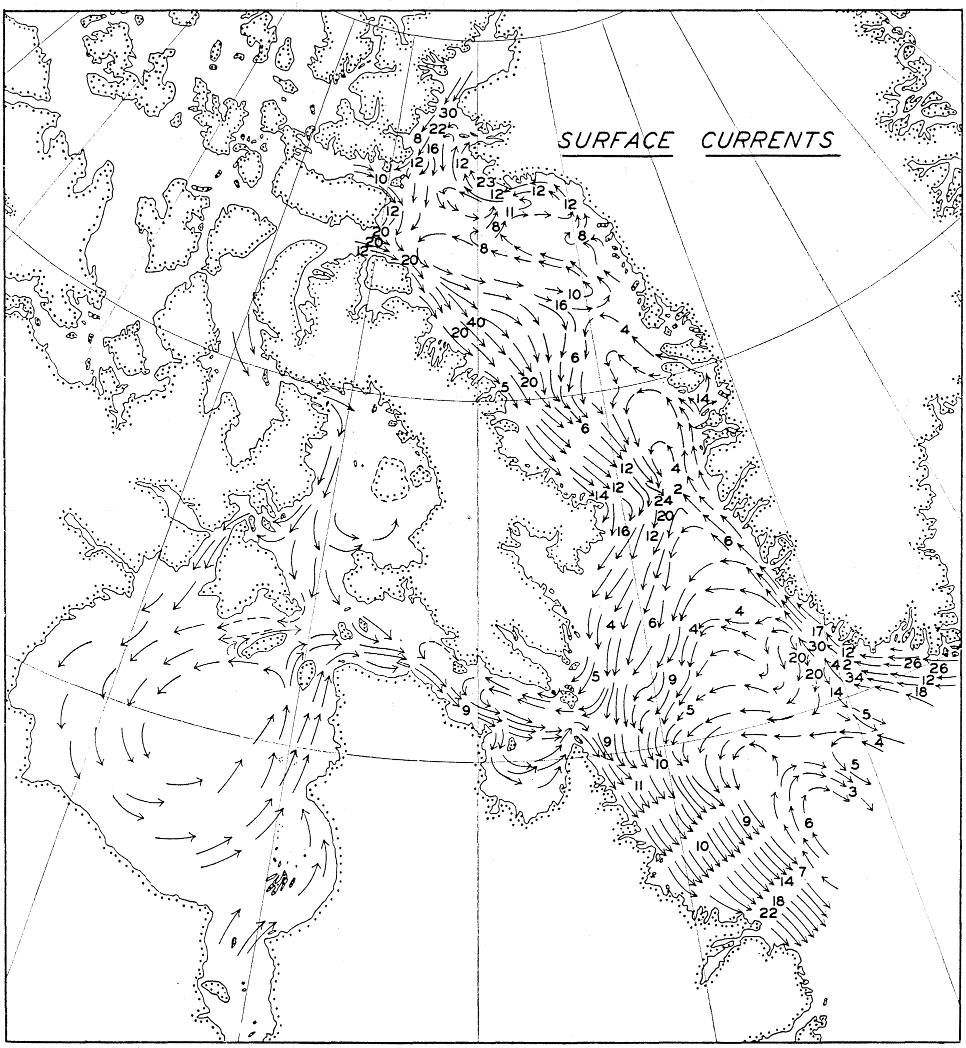


FIGURE 13. Surface currents, August-September. The circulation in Baffin bay, Davis strait and the Labrador sea (including the Labrador and west Greenland currents) is taken from Kiilerich (1939), based largely on the "Godthaab" expedition results of 1928. The course of the Canadian current along the northeast coast of Baffin island is plotted according to the "Northland" (1940) results (Hawley, Smith, Barnes and Soule, 1940). The Hudson bay and Hudson strait circulation is plotted from various sources, including Hachey (1931b, 1935). Ungava bay from the author's observations in 1947. *Figures are surface velocities in centimetres per second.*

halibut, for instance, has persisted here and affords a useful fishery, whereas it has disappeared from the remainder of the southwest coast, as far north as the Holsteinsborg or Egedesminde districts.

The west Greenland current lies over and somewhat beyond the narrow shelf in southwest Greenland, and thus comes to lie to some extent upon a substrate of Labrador sea "core" water, which fills most of the Labrador sea. Between cape Farewell and Ivigtut the current picks up more than twice its own volume of Labrador sea water, which further obscures the polar characteristics of the east Greenland water. Smith, Soule and Mosby (1937) give a résumé of the water transport of the west Greenland current, from cape Farewell to Disko island, based on the findings of the "Marion" expedition between July 29 and September 3, 1928, expressed in millions of cubic metres per second along the continental slope:

Cape Farewell	3.2 million cubic metres per second	
Ivigtut	7.4	
Fiskenaesset	6.6	
Godthaab	5.3	
Holsteinsborg	1.3	
Egedesminde	1.3	
Disko bay	0.4	(current through Disko bay)
Disko island	0.9	(current along western shore of Disko island)

It is apparent from these figures that most of the west Greenland current leaves the Greenland slope between Godthaab and Holsteinsborg. Working on the "Godthaab" results, Kiilerich (1939) found a depression in the Labrador sea immediately outside the west Greenland current in the region between cape Farewell and Fiskenaesset. Round this depression the water flows cyclonically, so that a considerable proportion of the west Greenland water turns southwest in this area and finally flows out of the Labrador sea in a southeasterly direction (see fig. 13). There is another depression immediately to the southeast, round which there is another cyclonic circulation. Some of the water thus deflected from the west Greenland current turns west, joining the bulk of the west Greenland water which crosses the northern part of the Labrador sea and finally forms part of the Labrador current. This westward turning of the west Greenland current continues up to the Davis strait ridge, in fact it is the presence of this ridge, and of the west Greenland banks, which causes the westward deflection. The westward course is of low velocity and therefore little affected by Coriolis force. Were a faster flow possible, this water might interfere considerably with the Canadian current off southeast Baffin island.

The *Labrador current* is formed of water from Hudson strait, from the Canadian current, and from the west Greenland current. The proportions are not known. The west Greenland water is of a very different type from the Hudson strait or Baffin island (Canadian current) water (see fig. 3), and it appears that the mixing of the two types of water is delayed greatly along the course of the Labrador current, so that a longitudinal banding of the Labrador current is found, with an inshore band of colder, more arctic water, and an outer band of warmer water, predominantly of west Greenland origin (Smith, 1931; Smith, Soule and Mosby, 1937). As already mentioned, the Labrador current holds fairly closely to the shelf, although downward extensions of the Labrador water have been recorded.

Small northward counter-currents were found by the "Marion" and "General Greene" workers along the outer margin of the Labrador current, which were not confirmed by the calculations of Kiilerich (1943). Smith, Soule and Mosby (1937) give the following account of the water transport of Labrador current in a south-easterly direction:

Off Nachvak fjord	1.9 million cubic metres per second
Off cape Harrigan	5.3
Off Hamilton inlet	4.7
Off Domino island	5.0
Off Belle isle	3.5

These figures are computed from the 1928 results.

The velocities of the west Greenland and Labrador currents shown on fig. 13 are those computed by Kiilerich (1939); they represent average velocities at the surface in the several areas marked. The values for the Labrador current are considerably lower, and those for the west Greenland current somewhat higher, than those computed by Smith, Soule and Mosby. This discrepancy may at least in part be due to the different methods of calculation. Smith, Soule and Mosby have used the 1500 decibar level as reference throughout, whereas Kiilerich has used various levels according to the depths available, using the deepest reference possible in each area of the total region covered. The much higher velocities set by Smith, Soule and Mosby for the Labrador current are furthermore partly due to their use of maximum velocities in the current axis rather than mean values spread over larger areas of the current surface. Thus the velocities in the axis of the current, computed by these workers, are 22 miles per day off Nachvak fjord, 38 miles per day off cape Harrigan, and 17 miles per day off Hamilton inlet. These values correspond to 47, 82 and 36.5 cm. per sec., and are thus of quite a different order from the calculations of Kiilerich. There is also some disagreement between the two authorities on the lateral extent of the Labrador current, Kiilerich showing somewhat wider current than do the American authors.

The velocity of these two currents is not constant throughout the year. Of the velocities during the winter we know nothing, but it is apparent that with the onset of the spring season the currents are of low velocity. As the ice melts, and as land drainage increases during the summer, the volume of the coastal water grows. The dynamic height of the currents, especially close in to shore, rises, and the velocity of the currents consequently increases. This increase in velocity does not follow the same pattern every year, and it has been pointed out by Kiilerich (1943) that the velocity of the west Greenland current in any given year and at any given season will determine the point at which it becomes deflected westward away from the Greenland coast. This follows from the fact that the greater the velocity, the greater will be the force of the earth's rotation forcing the current to the right, into the coast. This tendency has to be overcome by pressure from the north before the westward deflection will occur.

In the *Labrador sea deep circulation*, the direction of the current flow on both the Greenland and the Labrador sides remains the same, but the velocity decreases with the depth. The behaviour of the main body of the Labrador sea water, between the west Greenland and Labrador currents, is still in some doubt, for there is disagreement between the authorities on this point. The disagreement follows from the different choice of reference levels; there is some indication of movement in the water persisting down to the bottom, in which case it is impossible to find a stationary reference level. Both "Marion" and "Godthaab" authorities agree, however, on the broad outlines of the circulation of the Labrador sea water itself.

Smith, Soule and Mosby (1937) pay some attention to the question of the origin of the Labrador sea water, which it will be remembered these authors divide into three types: intermediate, deep and bottom water (see above). The west Greenland current plays the essential part in the formation of this water, and in the process the phenomenon of cabbeling appears to be demonstrated. The authors find an unbalanced excess of inflow over outflow of water into the Labrador sea, the excess being carried by the west Greenland current and amounting to about 1.9 million cubic metres per second during the summer. The following passages, which are quoted at length from Smith, Soule and Mosby, explain the conception held by these authors of the behaviour of the west Greenland water and of the formation of the Labrador sea water:

"The foregoing strongly suggests that about 1.9 million cubic metres per second of west Greenland current sink into depths below 1,500 metres (the reference surface of the dynamic computations) and eventually flows out of the Labrador sea at deeper levels into the north Atlantic, thus maintaining a quantitatively balanced system of circulation."

Concerning cabbeling:

"The indicated sinking of approximately 1.9 million cubic metres per second volume of current below the 1,500-metre level and also proportional quantities of heat, is substantiated by the position of the axis of saltest water along the southwest coast of Greenland for the summer of 1928. These data when plotted against depth show that the Irminger-Atlantic water sank from the 200-metre level off cape Farewell to about the 500-metre level off Godthaab. The temperature-salinity curves representative of the west Greenland current . . . , if interpreted in terms of density, also indicate the progressive increase of density along its course. This sinking of the Irminger-Atlantic water is verified by the observations of Baggesgaard-Rasmussen and Jacobsen (1930) and those of Riis-Carstensen (Conseil Permanent International, 1929). . . . The "Dana's" observations taken June to July, 1925, when plotted show that the core of warmest water (Irminger-Atlantic current) sank from a depth of about 200 metres to a depth of about 700 metres in transversing the west Greenland sector. Also the "Godthaab's" observations in the summer of 1928 reveal that the Irminger-Atlantic water sank along its pathway north of cape Farewell. Thus the observations of the "Dana", "Godthaab", and "Marion" all are in agreement in demonstrating the manner and rate of sinking of the Irminger-Atlantic water as it enters and pursues its course in the Labrador sea. This sinking of the water as it mixes in the west Greenland current is an illustration of what the authors consider to be cabbeling. . . . The idea of cabbeling was first published by Witte (1910) and depends upon the non-linear relation between the temperature and the density of sea water. Because of this non-linear relation and the practically linear salinity-density relation an adiabatic mixture of two waters of equal density but of differing temperature and salinity will have a greater density than its components. . . . The vertical component of motion as initiated by cabbeling is in many parts of the Labrador sea during the colder months of the year accelerated by convectional chilling, but the latter function is quite independent of the former."

Concerning the process of formation of the Labrador sea water, Smith, Soule and Mosby (1937) are somewhat diffident, and call attention to the hypothetical nature of the conclusions. Since, however, their account is the only suggested mechanism of the origin of this water, it is quoted here in full:

"The warm, salty west Greenland water progressively sinks as it proceeds northward and westward and bends southward, spreading as it goes to furnish the intermediate water of the Labrador sea between 500 and 2,000 metres.

"The most nearly motionless water, except perhaps that immediately adjacent to the bottom, occurs at about the 2,000-metre level below which lies the deep water and the bottom water.

"The deep water, according to the foregoing view, is formed during the colder part of the year largely by mixing of bottom water with water from the west Greenland current which has sunk to deep levels as it travels northward along the Greenland coast and westward near the head of the Labrador basin. The major flow of the deep water is southward along the American side where, off southern Labrador, there is probably some movement toward deeper levels along the bottom, the water flowing down the slope at levels of about 3,000 to 3,500 metres. This deep water is probably absorbed into the more central, north American basin, and thus compensates for the loss of water at higher levels to the northwestern north Atlantic from the northern branch of the Atlantic current.

"The bottom water, in our opinion, is formed by wintertime chilling of the surface, intermediate and deep waters in the northern part of the Labrador basin in the area off-shore from the rapid currents and roughly bounded on the south by a line from mid-Labrador to cape Farewell. It seems likely in this area that severe winter chilling produces vertical convection to bottom and results, with some mixture of Irminger-Atlantic water, in the coldest bottom water found in the deepest part of the basin and which in summertime is isolated from the cold surface currents by warmer water. The vertical convection which takes place in winter probably sets up steep horizontal density gradients to considerable depths, with a correspondingly increased cyclonic system of circulation. With the termination of vertical convection and its resulting heat losses the energizing force for maintaining this vigorous circulation is removed and the summertime equilibrium conditions are quickly restored as the marginal water of equal salinity and higher temperature is mixed in to destroy the temporary density gradients and raise the temperature of the intermediate water to the remarkably uniform value of about 3.2° C."

This ingenious interpretation of the Labrador sea water movement and evolution is well worth quoting here in full. There are objections to be raised to it, but failing more continuous field work and observations during the winter, they are of doubtful value. There seems to be little evidence for the division of the water into three distinct types; the effects of summer heating and mixing, and of winter chilling, might be thought to go remarkably far down in the water to achieve these results; and finally the supposed depression of the central water during the winter, a result of chilling and vertical convection, would surely be greatly off-set by similar depression of the surface in the marginal regions of the Labrador sea. This, however, can only be tested adequately by winter studies at sea.

It may be useful here to quote also the figures for inflow and outflow of water in the Labrador sea from which Smith, Soule and Mosby obtain their figure of excess inflow of 1.9 million cubic metres per second:

Exchange of water, Labrador sea.	
Inflow:	
West Greenland current (average cape Farewell)	5.0 $m^3/s \times 10^{-6}$.
Baffin land current (Canadian current)	2.0
Hudson bay discharge (net)	0.5
Total	7.5
Outflow:	
West Greenland current to Baffin bay	1.0 " "
Labrador current (average south Wolfe island)	4.6
Total	5.6

DAVIS STRAIT

Davis strait is one of the two "key" or strategic regions in the oceanography of the eastern arctic, being a region of shallower water between the two major basins. (The other key area, as will appear below, is Hudson strait.) The "Michael Sars" in 1924 (Martens, 1929); the "Dana" in 1925 (Baggesgaard-Rasmussen and Jacobsen, 1930); the "Marion" and the "General Greene" (1928 and following years); and the "Godthaab" in 1928, have all worked in Davis strait waters. The general pattern of circulation is simple—a strong southward flow along the west side (Canadian current) and a weaker northward flow along the east side (west Greenland remnant). There is also evidence for an eddy current set up on the outer edge of the Canadian current (Kiilerich, 1939). The Canadian current flows at velocities of from 10 to 24 cm. per second, according to all authorities, at the surface. The velocity as usual decreases inversely with depth. Smith, Soule and Mosby find a velocity of 6 cm./sec. at a depth of 500 metres. This is higher than the figures reached in the same region (off Exeter sound) by Kiilerich (1939), who records a velocity of between 1 and 2 cm./sec. at 400 metres. The Canadian current, as plotted by Kiilerich, extends downward to almost 500 metres at this point. Immediately to the east of the southward flow, he has calculated the presence of a small cyclonic eddy of Canadian current water, shown in fig. 13, and extending down to a depth of 400 metres. This eddy current touches the northward-flowing west Greenland current, which in September has a velocity in the axis of the current at the surface of 14-16 cm./sec., or about 7 nautical miles per day.

The west Greenland current in Davis strait, according to the "Godthaab" results, increases in velocity and transport considerably during the summer, being from two to three times stronger in September than in the early summer (June). In a later study of the west Greenland fishing banks, Kiilerich (1943) finds that the Canadian current also varies in lateral extent (though probably not in transport to any great degree) during the season:

"Normally it (the Canadian current) covers far more than half of the northern entrance of Davis strait, and, in the beginning of the summer, it often extends so far eastward, that, at a depth of 100-200 m, it washes the western slope of Store Hellefiske Bank with water at 0-1° C. with a salinity of about 34 $^{0}/_{00}$, or its somewhat higher layers (50-100 m) may spread over the deeper lying parts of the Bank and thus join the local cold water.... Off Helder's Bank too, the Canadian polar current in many cases occurs, but . . . its effect here will certainly be quite transitory. . . . It is not always the polar current itself which washes the Greenland Banks, but a branch or eddy from it." (Kiilerich, 1943)

The volume of flow of the two currents across the ridge is approximately in the ratio of 2:1, the Canadian current southward flow being calculated at 2.64 million cubic metres per second, and that of the west Greenland northward flow at 1.13 cubic metres per second (Smith, Soule and Mosby, 1937). These authors also show that the volume of the Canadian current flow a little to the north of the ridge (in latitude 67° 30′) is as high as 4.29 million cubic metres per second; they conclude therefore that "significant under portions of the Baffin land current on meeting the rise of the bottom, at the south end of the bay, are deflected to the left (east) following around the side of the basin". Such a blocking of a large part of the deeper water of the Canadian current would result, in other words, in a "feed-back" circulation in Baffin bay, some or most of which would return to the Davis region at later dates and cross over to the south.

The eastward deflection of this Canadian current water also appears to have the effect of blocking the passage into Baffin bay of much of the Labrador sea water to the south of the ridge, and also a large part of the west Greenland current water. Both Kiilerich (1939) and Smith *et al.* (1937), however, find the west Greenland current, hugging the coast, to extend down to at least 500 metres, and also the existence of a westerly tongue of west Greenland water which enters close to the Canadian current eddy already mentioned. The sections of temperature and salinity, however, published by Smith *et al.*, show that this latter tongue does not penetrate far into Baffin bay. Nevertheless, they consider it to be the source of the "well-known warm intermediate layer of Baffin bay", the existence of which as a separable body of water is doubted by the present writer.

From the information available, it appears that: (1) the outflow of the Canadian current across the Davis strait ridge exceeds the inflow of the west Greenland water by approximately 2 to 1; (2) there is a feed-back of Canadian current water which is stalled by the ridge, and which must play an important part in the formation of the Baffin bay water (below 300 metres, see fig. 3); (3) the inflow of west Greenland water increases considerably during the summer, and must account for the higher temperatures found along the east side of Baffin bay, in the upper layers, than on the west, and for the mixed condition of the water as far north as Melville bay (see below).

BAFFIN BAY

From the calculation of the current flow across the Davis strait ridge, it follows that Baffin bay receives its water in approximately equal quantities from the southeast (west Greenland water) and from the northwest (Lancaster, Jones and Smith sounds). The bulk of the Baffin bay water, from 300 metres to the bottom, is formed of the mixture of these two types of water. This is the water represented in fig. 3 by polygon no. 4. The division of this water into "intermediate" and "bottom" water, as is done by both Kiilerich (1939) and Smith *et al.* (1937) does not seem justified. In drawing the T-S correlations in fig. 3, the distinction between the water above and below the 300-metre level became at once apparent; but there was no similar difference within the water below 300 metres. There is rather a very gradual fall in temperature and rise in salinity, over a small range, from the 300-metre level to the bottom. The oxygen values also, recorded by the "Godthaab" expedition (Riis-Carstensen, 1936), fall gradually to a minimum value at the bottom. This suggests a gradual decrease in circulation downwards, a result which was found mathematically also; the water in the deepest layers of the Baffin bay basin seem in fact to be almost motionless.

It is clear that the upper water, resembling so closely the upper water of Lancaster sound and Smith sound, and the water of Hudson bay, is polar water originating in the polar basin itself. It is not possible as yet to know whether this polar influx includes a lower layer of water, below 250-300 metres, of more saline and warmer water, or whether the deeper water at the mouths of Lancaster and Jones sounds, and in Smith sound, which is very similar to the Baffin bay water, owes its existence entirely to intrusion from Baffin bay. Water of this general type is found, as is well known, in the polar basin, underlying the "arctic" water, so that the movement of such water southward and eastward through the arctic islands is not impossible. The analysis published by Kiilerich (1939), however, shows ingoing currents from Baffin bay entering all three areas: at the mouth of Lancaster sound, the ingoing current occupies the extreme northern side of the sound, and there is another current entering the central portion of the sound, just beneath the surface. In Jones sound, the current is shown as entering along both the north and south sides, and the outgoing current as occupying the central portion. Such an ingoing current along the south side is not confirmed by the experience of seamen, and moreover Kiilerich does not show it on his surface current map (see fig. 13). He points out that his calculations may have been seriously disturbed by tidal movements in the water. These ingoing currents are represented as extending down to 600 metres in Lancaster sound and 400 metres in Jones sound. In Smith sound, a similar current is shown entering the sound to the east, occupying more than half the sound and extending down to 400 metres. The surface velocities of these currents vary from 14 to 26 cm./sec. (Lancaster sound); 1 to 8 cm./sec. (Jones sound); and 4 to 24 cm./sec. (Smith sound).

That the ingoing current along the north side of Lancaster sound must penetrate in some volume to a point at least as far west as the entrance of Prince Regent inlet, is shown by the fairly common occurrence of large icebergs in Prince Regent inlet. Icebergs have also been reported from the gulf of Boothia, and there is even a record of an iceberg having been sighted in Foxe basin. These bergs can only have come from the west or northwest coasts of Greenland, or possibly from the glaciers of Devon and Ellesmere islands, and the only reasonable route by which they could have reached Prince Regent inlet is via Lancaster sound. Having been floated west in Lancaster sound, the icebergs must have drifted into the main eastbound current and been blown across it by northerly or north-westerly winds, so as to arrive at a point just west of the entrance of Prince Regent inlet, and close to the southern shore of Barrow strait.

There is no doubt that the greatest contribution of arctic water into Baffin bay is made through Lancaster sound, where the outgoing current greatly exceeds the ingoing current both in cross-sectional area and in velocity. Kiilerich estimates efflux as follows:

Lancaster sound	55 km^3/day		(0.65 million cubic metres per second)
Jones sound	25	" "	(0.29)
Smith sound	35	" "	(0.41)
Total			1.35 million cubic metres/sec.

This agrees closely with the surplus of southward flow over the Davis strait ridge, estimated by Smith *et al.* (1937), as 1.51 million cubic metres per second. The difference must represent the flow of water due to land drainage from the shores of Baffin bay itself, and from the melting of ice. These figures apply, of course, to the summer only.

As the surface current map shows, the remnant of the west Greenland current which flows over the Davis strait ridge and up the eastern side of Baffin bay is weak, especially in the early part of the summer. At that time (June and July) it appears to flow past the mouth of Disko bay without entering, which in itself is an indication of the weakness of the force of earth's rotation upon it. It continues at the same slow pace northward into Melville bay, a portion of it returning in an eddy to join the Canadian current. At the level of Upernavik the current divides, one branch continuing northward, the other striking west-north-west across Baffin bay towards Lancaster sound. Part of this latter branch turns back east to re-join the other branch, and the remainder forms an elongated eddy together with the outer edge of the Canadian current. In Melville bay the currents are wayward and uncertain, due perhaps to the configuration of the bottom (Kiilerich, 1939), but in the northern part of the bay the velocity increases, no doubt on account of the addition of coastal water and melt-water, with the accompanying raising of the surface. Surface velocities of from 20-25 cm./sec. have been calculated for the region close in to cape York. This water, circulating cyclonically in Smith sound, finally joins the polar water coming south along the west side of the sound.

The deeper water behaves in similar fashion, the velocities as usual being considerably lower. Kiilerich (1939) has found evidence for an entry of water at 500 metres into Lancaster sound, over the whole width of the strait, underneath the outgoing polar current. This inflow has a velocity of about 2 cm./sec.

The surface topography of Baffin bay resulting from the "Godthaab" observations showed the lowest part to be an oblong depression about 60 nautical miles west of the Greenland coast between latitudes 70° and 72° 50′, and it was therefore inferred that the Canadian current, on leaving Lancaster sound, flowed east-southeast across the bay and into its eastern half. The "Godthaab" made no measurements in the western part of the bay across the main stream of the Canadian current, so that this inference could not be confirmed. It was later confirmed by the "Northland" expedition of 1940 (Hawley, Smith, Barnes and Soule, 1941).

Ice had prevented the "Godthaab" from working this area in 1928. Since ice conditions in September, 1940, were very favourable, the "Northland" took the opportunity to fill in the empty area on the "Godthaab's" map. The Canadian current is shown by this work to extend out as far as demanded by Kiilerich, and to be bounded on its outer surface by a slow counter current setting northwest. A small eddy return current was also found within the Canadian current itself, formed of the same cold water as the Canadian current. This current has not been included in the present surface current map (fig. 13).

In the temperature sections published by Hawley *et al.*, a small intrusion into the Canadian current of warmer 1° water is shown at approximately the 500-metre level. This is assumed to be part of the tongue of west Greenland water found to cross the Davis strait ridge and lying outside the main west Greenland current, adjacent to the Canadian current. Its appearance as far west as this is surprising, and suggests that further field work is necessary before its identity can definitely be established.

The currents of Baffin bay are thus, at the present state of our knowledge, as shown on fig. 13. It has taken the combined work of several full-scale expeditions to produce this map. The final outcome does not differ greatly from the circulation pattern already worked out on the basis of ships' reports, drifts of ships, and above all ice-drift. In 1906, Mecking published a current map of the whole arctic area of Canada, with special attention to Baffin bay. Mecking's Baffin bay circulation differs from the present result only in one important characteristic, namely the course and extent of the Canadian current. Basing his opinions upon scattered reports of ice drift, and especially upon the drift of the "Fox" (McClintock) in 1857-8, and of part of the crew of the "Polaris" in

1872-3, Mecking (1906) drew a large current moving from Smith sound almost directly south across the middle of Baffin bay to Davis strait, joining the Canadian current in the strait. Much of this current has now been shown to be apocryphal, at least in its northern extent; but the southern portion of it is represented in Kiilerich's 1943 map, and in fig. 13, being that part of the Canadian current which bends sharply south (along the outer edge) in latitude 73° 30′.

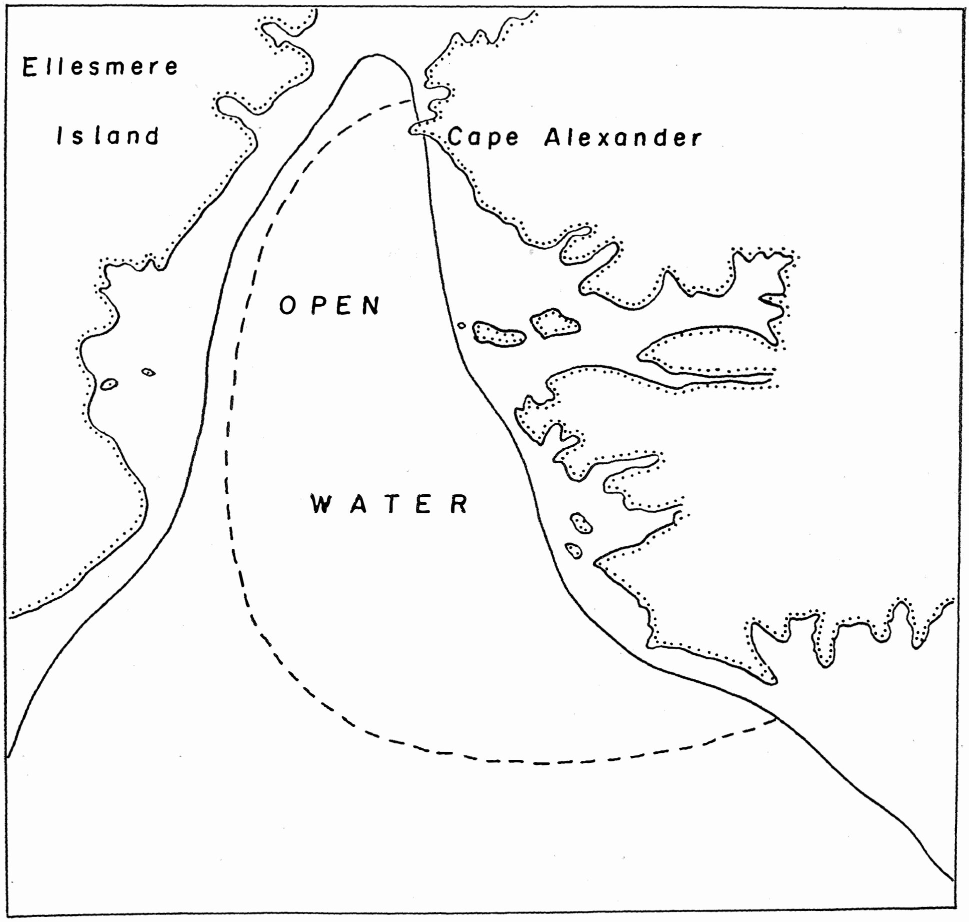


FIGURE 14. The "north water" in Smith sound and northern Baffin bay, as described by Kiilerich (1933). From Kiilerich (1933).

There remains to be discussed the problem of the "north water". The north water is an area of water in the northern part of Baffin bay, and in Smith sound, in which warm temperatures seem to be consistently found during the summer, and which is free of ice during all or most of the year. There is some disagreement as to the precise delimitations of this region, and also in the matter of the extent of the open water during the winter. The "Ice Atlas for the Northern Hemisphere" (U.S. Hydrographic Office, 1946) does not show the patch of open water to continue during the whole of the winter. The same doubt as to its persistence during the winter is implied in the description in the 1947 edition of the Arctic Pilot (British Admiralty, 1947), which reads as follows: "In April, May and June there is frequently a more or less open area of navigable water eastward of Lancaster sound, in the northern part of Baffin bay. This is called the "North Water", and has been known to explorers for two centuries. It was present during May in fifteen years out of the period 1920-1938. Its origin is not definitely known; more than one possible explanation has been suggested. In July, in an average year, the North Water is no longer isolated, being joined by a belt of more or less open water to the open water extending up the west coast of Greenland to the southward".

The account given by the Danish workers differs from this. The "north water" to Kiilerich (1933) is an area in Smith sound, extending from cape Alexander to a level a little south of cape York, as shown in fig. 14, and bounded approximately by the fast-ice, or shore-ice, of the winter. It is proposed that in the present paper the term "north water" be used to cover both of these areas, since they are contiguous. The area then stretches over the water shown in fig. 14 and south to include the 5° water shown in the surface temperature map (fig. 7), which is in the position described in the Arctic Pilot.

The northern part of this region, that area described by Kiilerich (1933) as "Nordvandet", appears to have remained open during the whole of the winter for many decades. Kiilerich, in fact, suggests that the only year in which this area was not free of ice was 1872-3, when part of Hall's expedition drifted on the ice through Smith sound and Baffin bay. Since Kiilerich's 1933 paper is in Danish, and since it is the only paper known to the present writer which is devoted entirely to this interesting matter, it is abstracted here in translation, to give an account of Kiilerich's views as to the possible mechanism by which the north water remains open during the winter. It should be remembered that in his paper he is talking throughout only of the Smith sound part of the north water, or "north north water".

"The precise area of the north water is uncertain, since few investigators have visited it in winter. It is well known among the Eskimos of the cape York district that there is open water in the region immediately north of Baffin bay. The reports of whalers and expeditions in former centuries confirm this information. Dr. Kane discussed it, and did not think that it ever froze in winter. Nares, Hayes, and Bessels, all mention open water in the vicinity of cape Alexander. Bessels is the only one to make an estimate of the area of the north water, but his estimate of 90,000 square miles is beyond all reason (Bessels, 1879).

"In the more recent literature the north water is often mentioned, but without any indication of its extent. Dr. Lauge Koch has on the other hand informed me that he thinks it probable that the north water not only remains ice-free during practically speaking every winter, but also that the extent of the open water is very great. Towards the north and west it is bounded by a line running from cape Alexander in an arc towards the southwest at some distance from Ellesmere island; to the east it is bounded by the winter ice, the edge of which normally reaches south from cape Alexander along the outlying portions of the coast. The boundary to the south is more difficult to define, since it is determined by the ice masses in Baffin bay.

"In past centuries it was supposed that the west Greenland current was responsible for the non-freezing of the north water; when this current passed Melville bay it was supposed to end at the entrance to Smith sound, and in these high latitudes it was looked upon as a relatively warm current, capable moreover of transporting so much heat as to be able to withstand the low winter temperatures. This interpretation was not opposed until Ludwig Mecking (1906) published a series of considerations which clearly showed it to be untenable. But the same considerations demonstrated the propriety of another interpretation, which Mecking himself originated, and which has not yet been refuted, although there are many who do not believe in it.

"Mecking's explanation was that the ice-free north water was due to the warm Atlantic (west Greenland) water which flowed north through Davis strait at a certain depth and which, meeting a shallower bottom at the entrance to Smith sound, was forced up through the upper layers to the surface. The warmer surface water (Nares measured 4.4° C. in 1876) is separated from the deeper and colder water by a sharp change in temperature at a depth of 40-50 metres. Mecking sees in this, correctly, evidence for the presence of water of a different kind, but that the upper layer should be of Atlantic origin is a somewhat rash conclusion."

Kiilerich goes on to show that the results of the "Godthaab" expedition of 1928 offer no evidence whatever of such an upwelling of water as was postulated by Mecking. The warmer water of the west Greenland current (by this time identified with the Baffin bay water, and lying below the upper polar water) is apparent in 74° to 75° N. latitude, at depths of 400-500 metres, and has a temperature of about 1° C. This water is moving west, not north, and appears again, for instance, at the entrance to Lancaster sound. But the highest temperature (at these depths) in the southern part of Smith sound is −0.5° approximately. There is thus no warm underlying layer in this region, and moreover no indication or possibility of an upwelling process either in Smith sound or in Baffin bay (in the north water area). The warm surface water, therefore, found in the north water region during the summer (5° C. and higher), must be due to solar heating, and upwelling of west Greenland water cannot be responsible for the open water during the winter.

Kiilerich instead puts forward another possible explanation of the north water which he emphasizes is largely hypothetical, and which requires hydrographic research in winter for its confirmation or refutation. He supposes that during the winter the density of the mass of water within Smith sound must be fairly uniform, and that therefore the vertical stability of the water is low. The summer stability is high, due to the melting of ice and the effects of land drainage. In winter, however, these effects are greatly reduced or absent, and the velocity and transport of the west Greenland water are very low. From all expedition accounts, however, the strength of the cold polar current southward through Smith sound is considerable during the whole of the winter. The salinity of the surface water of the polar basin is not low, certainly in comparison with the water of Baffin bay, a fact which has been established by several expeditions and which is no doubt partly due to the concentrating effects of the formation of salt-water ice. The probability is that in winter the surface layer of water in the polar sea has a salinity of about 34 $^{\circ}/_{oo}$. Water of this salinity, and of low temperature (down to $-1.7°$ C.), would have a fairly high density (about 27.38), and should sink beneath the Baffin bay water. Evidence for such vertical mixing in Smith sound is afforded by the known oxygen content of the deeper water in summer, which is considerably higher than in the water at similar depths farther south in Baffin bay.

Finally, Kiilerich shows that the open water during the winter cannot be due to any wind effect, since there is no correlation between the prevailing wind in any one winter with the extent or condition of the north water. The prevailing northerly winds in winter might perhaps determine the extent of the north water, but not its presence or absence. For the latter, some strictly hydrographic explanation is necessary.

The suggestion put forward by Kiilerich, therefore, to explain the persistence of the ice-free north water during the winter, is that there is a continuous, and presumably fairly rapid, vertical exchange of water throughout the winter, the supposed heavy polar surface water from the north being on this view heavier than the Baffin bay water and the west Greenland remnant which penetrates as far as Smith sound. The confirmation of this suggestion must await winter field work.

The theory would apply as well to Lancaster and Jones sounds as to Smith sound, since the type of water in all three is the same. Open water in the southern part of the "north water", in the area defined in the "Arctic Pilot" would be affected by the Lancaster and Jones sound polar water in the same way as Kiilerich's north water area is by the polar water from Smith sound. There is ample evidence from Eskimos and others resident in this area, that Lancaster sound does not freeze over completely during the winter. This has been put down in the past to the velocity of the Lancaster sound current, but it may as well be due to vertical interchange as suggested by Kiilerich.

Regarding the precise position of the north water, the recent researches of Hare and Montgomery (1949), on the atmospheric climate of the eastern arctic, are very useful. They have quoted the following mean monthly temperatures (°F) during the winter at Bache peninsula, Craig harbour and Dundas harbour:

	Bache peninsula	*Craig harbour*	*Dundas harbour*
Oct.	4.6° F.	12.2° F.	15.7° F.
Nov.	− 6.8	− 5.3	0.8
Dec.	− 23.5	− 18.1	− 11.4
Jan.	− 26.4	− 22.0	− 18.1
Feb.	− 26.1	− 23.4	− 21.6
March	− 23.2	− 14.8	− 10.3

Department of Transport, Ottawa

Differences of from 12 to 14 degrees Fahrenheit between Bache peninsula and Dundas harbour are interpreted as indicating open water somewhere east of

Dundas (the prevailing advection at Dundas is E.N.E.); this is emphasized by the fact that Dundas is also considerably warmer than either Arctic bay or Pond inlet, to the south. Although these figures are not incompatible with the persistence of open water in the Smith sound area, as in fig. 14, they strongly indicate the persistence of open water in the more southerly part of the north water, opposite Lancaster sound.

HUDSON BAY AND HUDSON STRAIT

No expedition has entered Hudson strait or Hudson bay for the primary purpose of studies in physical oceanography. The 1930 "Loubyrne" expedition

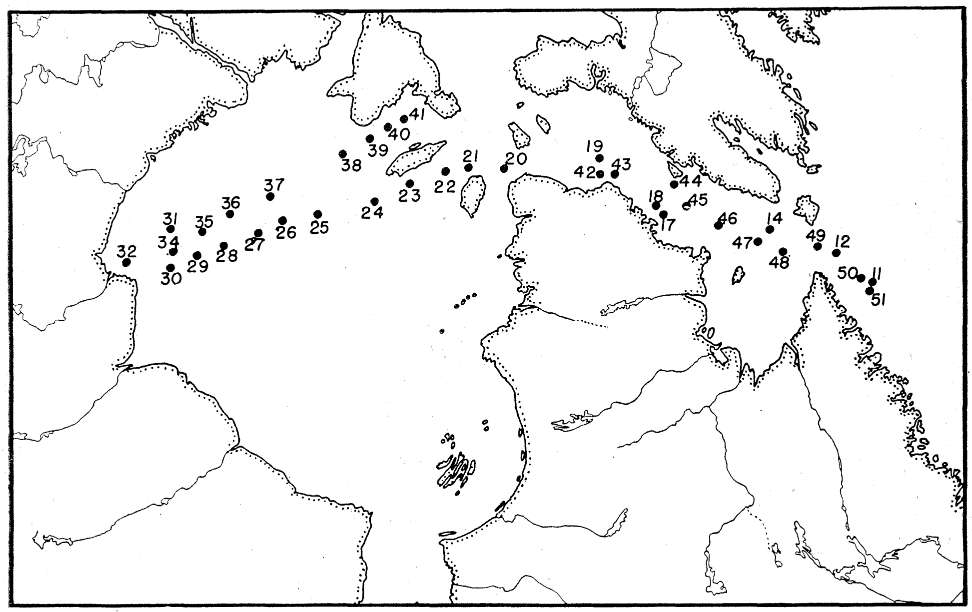


FIGURE 15. H. M. C. S. "Haida" bathythermograph stations, 1948.

had as its chief objective the exploration of the fishery resources of the waters of Hudson bay, and the temperature and salinity material collected was not designed for dynamic computation (Hachey 1931b). The H.M.C.S. "Haida", in 1948 made a hydrographic station, using Nansen bottles and reversing thermometers, at points along her route approximately one hundred miles apart, and established bathythermograph stations at more frequent intervals. The Nansen bottle stations across Hudson bay are no better spaced or planned for dynamic treatment than those of the "Loubyrne", and the information to be obtained from them, with respect to water movement, must necessarily be slight.

The results of the "Haida" work are shown in table I and fig. 5 (Nansen bottle results; fig. 5 includes also the "Loubyrne" hydrographic stations of 1930),

TABLE I. "Haida" reversing bottle observations.

Date	Station	Position	Depth (m)	T° C.	S°/oo
4. IX	1 300 m.	52° 53′ 30″ N. 54° 55′ W.	0	5.1	32.77
5. IX	2 522 m.	54° 17′ 30″ N. 56° 04′ W.	0	4.5	32.41
			10	3.84	32.47
			25	3.08	32.47
			50	0.06	32.72
			100	– 0.38	32.97
			200	– 0.43	33.51
			250	0.07	33.53
5. IX	3 198 m.	55° 39′ N. 57° 31′ W.	0	3.7	32.21
			10	3.27	32.25
			25	2.45	32.45
			50	1.61	32.56
			100	0.26	32.97
			150	– 0.22	33.98
5. IX	4 351 m.	57° 10′ N. 59° 25′ W.	0	4.3	32.03
			10	3.99	32.07
			25	2.13	32.45
			50	0.44	32.74
			70	0.67	32.94
			200	0.25	33.58
			250	1.08	34.07
6. IX	5 207 m.	58° 30′ N. 60° 50′ W.	0	4.2	31.94
			10	4.06	31.96
			25	0.14	34.05
			50	0.89	32.66
			100	0.89	32.97
			200	0.61	33.40
6. IX	6 195 m.	59° 55′ N. 62° 38′ W.	0	2.3	32.63
			10	2.05	32.65
			25	2.07	32.66
			50	1.46	32.72
			100	0.66	33.12
			150	0.66	33.39
6. IX	7 360 m.	61° (?) N. 64° 36′ W.	0	2.3	32.97
			10	1.49	33.06
			25	2.07	33.12
			50	1.64	33.17
			100	0.65	33.48
			200	0.57	33.57
			250	1.15	34.09

TABLE I. "Haida" reversing bottle observations (cont'd).

Date	Station	Position	Depth (m)	T° C.	S°/oo
6. IX	8	61° 31′ N.	0	1.7	32.81
	297 m.	67° 50′ W.	10	1.09	32.83
			25	1.09	32.88
			50	0.82	32.95
			100	– 0.16	33.10
			200	– 0.13	33.51
			250	– 0.15	33.71
7. IX	9	61° 40′ N.	0	3.1	31.87
	101 m.	69° 30′ W.	10	3.07	31.91
			25	2.81	32.05
			50	2.06	32.29
			70	1.95	32.30
8. IX	10	61° 53′ N.	0	3.7	31.60
	790 m.	71° 45′ W.	10	3.47	31.60
			30	2.86	31.74
			80	1.30	32.52
9. IX	11	62° 49′ N.	0	2.1	32.39
	200 m.	74° 05′ W.	10	1.99	32.21
			25	1.08	32.52
			50	0.55	32.77
			100	– 0.19	32.97
			150	– 0.27	33.01
9. IX	13	62° 19′ N.	0	6.8	29.94
	207 m.	81° 14′ W.	10	6.97	29.92
			25	5.01	30.52
			50	– 1.02	32.43
			100	– 1.31	32.77
			200	– 1.35	33.30
10. IX	14	61° 30′ N.	0	7.3	29.34
	185 m.	84° 12′ W.	10	7.41	29.27
			25	6.85	29.45
			50	– 1.48	32.01
			100	– 1.18	33.01
			150	– 1.40	33.40
10. IX	15	60° 45′ N.	0	7.2	29.36
	225 m.	87° 00′ W.	10	7.19	29.38
			25	– 0.64	31.58
			50	– 1.48	32.39
			100	– 1.15	33.17
			200	– 1.55	33.53

TABLE I. "Haida" reversing bottle observations (cont'd).

Date	Station	Position	Depth (m)	T° C.	S°/oo
15. IX	17	59° 01′ N.	0	8.0	29.43
	30 m.	93° 48′ W.	10	7.87	29.81
			20	4.88	31.53
16. IX	18	60° 06′ N.	0	7.8	30.95
	144 m.	91° 14′ W.	10	7.79	30.91
			25	7.77	30.91
			50	− 1.30	32.56
			100	− 1.39	33.17
			125	− 1.42	33.48
16. IX	19	61° 10′ N.	0	7.3	31.27
	156 m.	88° 43′ W.			
16. IX	20	62° 23′ N.	0	6.6	29.78
	135 m.	85° 55′ W.			
17. IX	21	63° 03′ N.	0	5.9	30.53
	108 m.	84° 04′ W.			
20. IX	24	62° 30′ N.	0	2.7	31.82
	213 m.	73° 20′ W.			
21. IX	25	61° 50′ N.	0	3.5	32.54
	324 m.	70° 15′ W.	10	3.35	32.52
			25	1.86	32.74
			50	0.02	32.97
			100	− 0.37	33.17
			200	− 0.56	33.57
			300	− 0.28	33.51
21. IX	26	61° 05′ N.	0	1.5	32.77
	684 m.	67° 21′ W.	10	1.17	32.77
			25	1.03	32.77
			50	0.05	32.97
			100	− 0.12	33.12
			200	− 0.01	33.40
			300	0.20	33.77
23. IX	27	60° 50′ N.	0	1.8	32.72
	342 m.	64° 27′ W.	10	1.59	32.72
			25	1.51	32.72
			50	1.47	32.75
			100	1.27	32.86
			200	1.11	32.94
			300	1.48	33.93

TABLE I. "Haida" reversing bottle observations (cont'd).

Date	Station	Position	Depth (m)	T° C.	S°/oo
23. IX	6	59°48′ N.	0	3.4	32.32
	155 m.	62° 40′ W.	10	3.33	32.32
			25	2.62	34.27
			50	1.45	32.72
			100	0.28	32.88
			150	0.30	32.97
24. IX	5	58° 26′ N.	0	3.2	32.36
	176 m.	60° 55′ W.	10	2.35	32.38
			25	2.08	32.74
			50	1.44	32.74
			100	0.99	32.97
			150	0.87	33.35
25. IX	3	55° 40′ N.	0	3.7	32.43
	216 m.	57° 22′ W.	10	3.47	32.38
			25	2.28	
25. IX	2N	54° 26′ N.	0	3.7	32.43
	234 m.	55° 50′ W.			

and in figs. 15 and 16 (bathythermograph stations and graphs). Table III shows the positions and dates of the bathythermograph stations.

The cyclonic circulation of the upper layer of water in Hudson bay, long known from observations of ice movements, was confirmed by Hachey (1931b, 1935) from the "Loubyrne" salinity and temperature observations and drift-bottle results. This is shown in the surface current map (fig. 13). In this map there is one departure from former current maps of Hudson bay (for instance, that published by Nichols (1940)), in the region between Southampton island and Coats island (Evans and Fisher straits). Hitherto current maps have shown the current through Fisher strait running northeast, out of the bay, and indeed such a current is implied by the description of the currents of Hudson bay in volume III of the Arctic Pilot (British Admiralty, 1947). The drift-bottle results of the "Loubyrne", however, (Hachey, 1935) indicate a southwesterly current from Coats island, travelling round the central part of Hudson bay, and it has seemed best to illustrate the possibility of a southwesterly set in Fisher strait, somewhat tentatively. The drift-bottle results may have been due largely to tidal currents; on the other hand, the same tidal currents certainly obscure the direction of set in Hudson bay.

Water from Foxe basin enters Hudson bay west of Southampton island, through Roes Welcome, and it is possible that Foxe basin water also enters through Evans and Fisher straits, as described. The drainage contribution to Hudson bay from its shores is very great indeed, but there are as yet no computations of the amount of water involved. Gans (1926) describes the Hudson bay drainage area as one of the largest in north America, but not even she, in her astonishingly wordy treatise on Hudson bay, makes any estimate of the volume

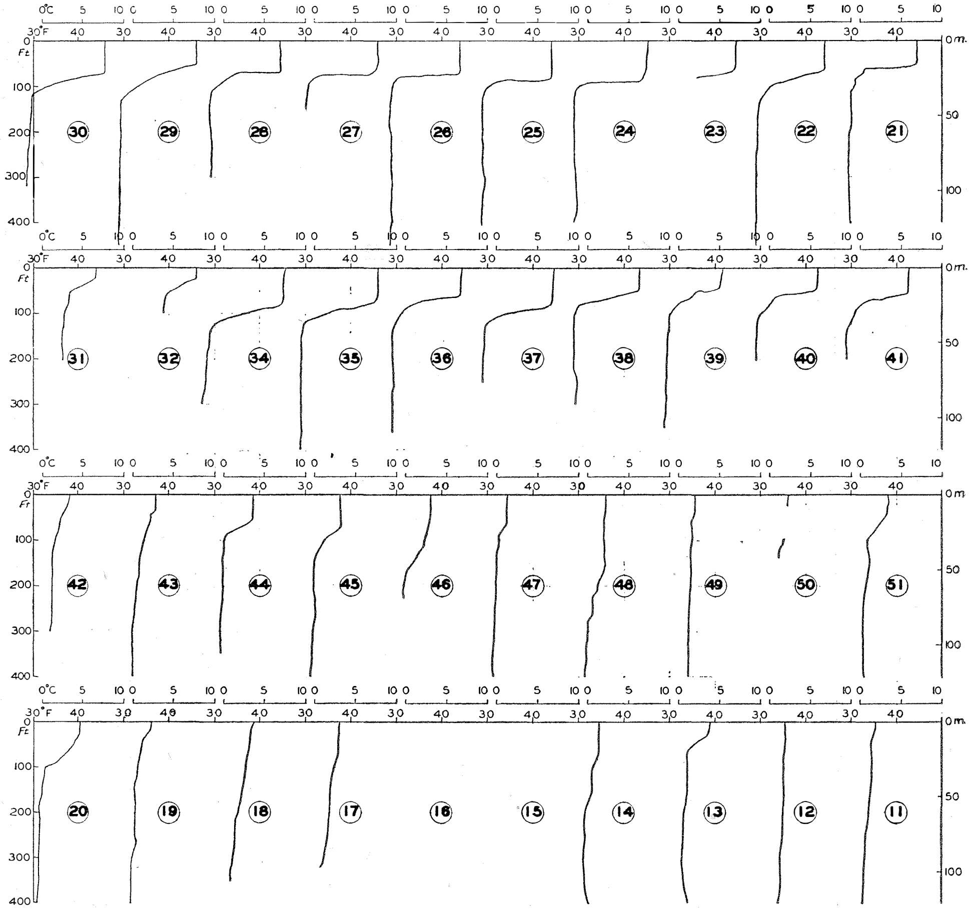


FIGURE 16. Bathythermograph temperature graphs, "Haida", 1948. For station positions see fig. 15 and table III.

of water contributed to the bay. As this water pours over the surface of the bay, it is deflected to the right and adds to the cyclonic circulation. In doing so, it raises the temperature and lowers the salinity, thus establishing an intense stratification of the upper waters of Hudson bay and an accompanying high stability. This great vertical stability, which probably continues to exist through the winter, is no doubt responsible for the somewhat low biological production of

Hudson bay. This point, however, cannot be made with certainty until proper field studies have been made.

In connection with the low salinity of the surface water of Hudson bay, and the great vertical stability, the recent work of Hare and Montgomery (1949) and of Burbidge (1949) is interesting. The U.S. Ice Atlas (U.S. Hydrographic Office, 1946) shows most of the water in Hudson bay to be open during the winter.

TABLE III. "Haida" Bathythermograph stations, 1948.

Date	Station	Latitude	Longitude
6. IX	11	59° 55′	62° 36′
6. IX	12	60° 42′	63° 35′
6. IX	13	61° ?	64° 36′
6. IX	14	61° 20′	66° 28′
7. IX	17	61° 40′	71° 31′
8. IX	18	61° 53′	71° 45′
9. IX	19	62° 49′	74° 05′
9. IX	20	62° 36′	78° 28′
9. IX	21	62° 27′	80° 08′
9. IX	22	62° 19′	81° 14′
10. IX	23	62° 00′	82° 40′
10. IX	24	61° 30′	84° 12′
10. IX	25	61° 00′	86° 14′
10. IX	26	60° 45′	87° 00′
10. IX	27	60° 18′	88° 33′
10. IX	28	59° 51′	90° 00′
11. IX	29	59° 32′	91° 06′
11. IX	30	59° 13′	92° 03′
11. IX	31	59° 57′	92° 31′
15. IX	32	59° 01′	93° 48′
15. IX	34	59° 33′	92° 24′
16. IX	35	60° 06′	91° 14′
16. IX	36	60° 39′	90° 06′
16. IX	37	61° 10′	88° 43′
16. IX	38	62° 23′	85° 55′
16. IX	39	62° 45′	84° 58′
17. IX	40	63° 03′	84° 04′
17. IX	41	63° 19′	83° 27′
20. IX	42	62° 30′	74° 03′
20. IX	43	62° 30′	73° 20′
20. IX	44	62° 21′	71° 40′
21. IX	45	61° 50′	70° 15′
21. IX	46	61° 28′	68° 45′
21. IX	47	61° 05′	67° 21′
21. IX	48	60° 44′	66° 04′
23. IX	49	60° 50′	64° 27′
23. IX	50	60° 01′	62° 58′
30. IX	51	59° 48′	62° 40′

Hare's approach to the study of the Hudson bay area, being that of the climatologist, cast serious doubt on the existence of open water in Hudson bay in winter; recent photographic surveys have shown that in fact Hudson bay does not remain open, although there is normally a strip of open water outside the shore ice, which varies in extent according to wind conditions during the winter. The calculated date of freezing (arrived at from a study of air temperature records) is in December, and the freezing is assumed to be effectively complete by the end of December. Such a result would be expected also on general oceanographic grounds; there is no violent circulation in Hudson bay which might be expected to delay or avoid freezing, and the high vertical stability, coupled with low surface salinity, would certainly encourage early freezing.

Arising in part out of the vertical stability, and also related in all probability to the biological status of Hudson bay, is the apparent stationary condition of the deeper water. According to Hachey (1931b), the waters of the bay, below fifty metres, are dynamically dead. Moreover, temperatures of − 1.9° and − 2° C., which could not exist at the surface, were found at 200, 100 and even 50 metres depth at certain of the stations (see fig. 10) occupied by the "Loubyrne". Assuming that there were no instrumental errors involved, it is very difficult to account for these low temperatures unless the waters at these depths are in fact stagnant or almost so, and are gradually losing heat to the solid material of the bottom, a contingency which itself might require some powers of credulity. Unfortunately, no oxygen measurements were made on the "Loubyrne" expedition; the oxygen content of the deep water would have been a valuable indication of stagnancy. It is of considerable interest, in this connection, to note that a temperature of − 1.92° C. was obtained by the writer in 1947 in Ungava bay, at 200 metres (see below), and that in that instance there could be no possibility of stagnant or dynamically dead water. The oxygen content of the sample was 7.12 cc./litre.

An important matter in the question of the possible stagnancy of the deep water of Hudson bay is the bathymetry at the entrance into Hudson strait from the west. It is precisely at that point on the bathymetric map that we find a blank spot, there being at present no information on the depths north and east of Salisbury island. If there is in fact a ridge in this region of approximately 100 metres depth, as is quite possible, then there is good reason for the apparent stationary condition of the Hudson bay deep water.

The "Haida" results of 1940 show no such low temperatures measured by the reversing thermometer, the lowest being − 1.55° C., at "Haida" station 15 (fig. 5), in the centre of Hudson bay. The bathythermograph results, however, show temperatures down to − 2° C. approximately at several stations (bathythermograph stations 26, 30, 34, as examples—fig. 15), in the central and western parts of the bay, at depths between 50 and 100 metres. As these stations are close to reversing-bottle stations where the temperatures were measured as considerably higher than this, it is doubtful whether these bathythermograph figures are reliable. For a comparison of the "Haida" (1948) and "Loubyrne" (1930) results, see below (long-term hydrographic change).

The marked differences between the surface layers and the lower water in Hudson bay, at least as regards temperatures, are well shown by the "Haida" bathythermograph slides (fig. 16—stations 21-30 and 31-41). It will be observed that the discontinuity layer is very well marked and occurs between 20 and 40 metres depth. The upper water, above the discontinuity layer, is of low salinity (shown by the Nansen bottle results), and of high temperature; it is the result of coastal drainage, ice melting, and solar heating. Below the discontinuity layer the water is of fairly uniform temperature. The Hudson bay stations are in marked contrast to the Hudson strait stations (stations 11-20 and 42-51), in which there is almost no discontinuity layer at all.

The Hudson strait deeper water (below 50 metres) is of the same nature as the Hudson bay water at similar depths, with the exception that the very low temperatures found by the "Loubyrne" expedition are not recorded from Hudson strait by either the "Loubyrne" or the "Haida". In the upper 50 metres, the flat discontinuity layer is absent, an indication of mixing. That vertical mixing occurs in Hudson strait to a considerable degree even during the summer is indicated by the stability calculation of Hachey (1931b), which showed very low vertical stability at "Loubyrne" station 58 (fig. 5) in September.

There is no information on the circulation of the deeper water in Hudson strait to be derived from physical observations. From direct observations of ice movements, it has long been known that surface water enters Hudson strait at its western entrance from Foxe basin and from Hudson bay, at its eastern entrance from Davis strait and the Labrador sea. The water from Foxe basin and Hudson bay is of course polar water; that which enters from the Labrador sea is apparently predominantly Canadian current water from Davis strait, but may contain some admixture of Atlantic (west Greenland) water. This contribution from the east into Hudson strait flows, (at least at the surface) westward along the north side of the strait, and is described as reaching as far into the strait as Big island where it turns south and joins the outgoing current along the southern side of the strait.

The velocity of these two currents, and their volumes of transport, are not known with certainty. The great tidal movements through Hudson strait, which is a bottleneck into Hudson bay, obscure the calculation of the "set" considerably. Hachey (1931b) records an outgoing current along Hudson strait of three knots, measured by dead reckoning. This presumably is an outgoing tidal current for the most part; a continual set outward of this velocity is out of the question. By dynamic calculation Hachey arrives at a velocity of 0.18 knots for the outgoing set (not 1.8 knots as misprinted in his paper).

That there is probably some admixture of west Greenland water entering Hudson strait from the east, and reaching at least as far into the strait as Lake harbour, is shown by the discovery in the Lake harbour summer plankton of large numbers of the hydromedusan *Hybocodon prolifer* L. Agassiz (Dunbar, 1942b). *Hybocodon prolifer* is a north Atlantic planktonic form, and is nowhere known from Arctic water. It is common in summer along the New England coast, in the waters of Newfoundland and west Greenland, off the south coast of Iceland, Norway and the British Isles, and from the north Pacific, but it is definitely not an arctic animal. Its presence in abundance at Lake harbour must be taken as good evidence for the penetration into Hudson strait of Atlantic water. That there is a possibility that Atlantic water penetrates farther than this, perhaps into Hudson bay itself, is pointed out below, in the discussion of hydrographic changes in Hudson bay during the past years.

The study of the waters of Ungava bay, from the hydrodynamic point of view, is not yet completed, although the field work for such a study was completed in 1949 by the Fisheries Research Board. From the behaviour of the ice in the summer, it is clear that there is a surface current which enters the bay in the northwest, between Diana bay and Akpatok island, and which crosses to the eastern side not very far south of Akpatok. No doubt the very shallow bottom at the head of Ungava bay deflects this set to the east; the current then leaves Ungava bay in the northeast, rejoining the outgoing current in Hudson strait.

This cyclonic set in Ungava bay is greatly obscured by the violent tidal currents. The tidal interval at the head of the bay, at the mouth of the Koksoak river, is 39 feet at springs. This great height, combined with the shallow bottom configuration, causes tidal currents of from 4-5 knots commonly in many parts of the bay. The "Arctic Pilot", volume III, 1947, describes 3-4 knot tidal streams at Akpatok island. The writer has himself estimated tidal currents in Keglo bay, on the eastern shore of Ungava bay, at 3 knots, and at Inuksulik island, north of Leaf bay, at from 4 to 5 knots, on the ebb tide at springs in July. With such tidal oscillating currents to deal with, it is difficult to estimate the strength or even the true direction of the constant "set" currents.

Temperature, salinity and oxygen measurements from the coastal waters of Ungava bay are given in table II. This material was obtained by the writer during the summer of 1947, at the stations shown in fig. 6. The boats available in that year did not permit the central and deeper waters of Ungava bay to be worked, and the results shown here clearly indicated the coastal nature of the water investigated. The salinities are everywhere, even at 200 metres at station 41, below 33 $^{\circ}/_{oo}$, and as such are lower than the salinities in Hudson strait and Hudson bay observed by the "Loubyrne" and the "Haida". No doubt the strong tidal currents moving over shallow bottoms are instrumental in mixing the coastal water to a great extent, causing the low salinity. The temperatures are a little higher than those recorded at similar depths by the "Haida" in 1948, with the single exception of the 200 metre reading at station 41 ($-1.92°$ C.) which, as already mentioned, is comparable to the very low temperatures recorded by Hachey in Hudson bay in 1930. In the Ungava bay instance, there is no possibility of this water being stagnant, since the oxygen content is 7.12 cc./litre.

TABLE II. Temperatures and salinities in Ungava bay, 1947.

Date	Station	Depth (m)	T° C.	S°/oo	O_2 cc/l.
24. VI	1	0	3.16	17.79	7.22
	18.3m	10	0.07		
29. VI	3	0	0.10	28.78	7.31
	28.5m	10	– 0.25	28.86	7.64
		23.5	– 0.06	29.88	7.99
3. VII	7	0	0.12	25.23	2.16
	10m	5	– 0.89	29.18	6.52
		8.5	– 0.90	29.40	7.06
12. VII	11	0	1.30	28.60	8.55
	46m	10	– 0.22	29.18	7.93
		25	– 1.00	30.82	8.00
		40	– 1.18	30.95	7.55
17. VII	18	0	2.55	30.88	8.55
	84m	10	1.10	31.04	9.26
		25	0.50	31.24	8.92
		50	– 0.91	31.83	8.25
		80	– 1.00	31.87	7.30
19. VII	25	0	0.80	30.10	
	35m	10	0.46	30.26	
		25	0.36	30.25	
8. VIII	33	0	2.61	28.49	7.44
	27m	10	2.35	28.98	5.81
		21.5	1.90	29.40	7.09
9. VIII	34	0			
	47.5m	10	2.22	29.81	7.35
		25	1.77	30.30	5.45
		44	1.54	30.53	7.70
17. VIII	41	0	2.30	32.01	8.15
	240m	10	2.33	32.00	8.05
		25	2.00	32.00	7.95
		50	0.54	32.27	7.17
		100	– 0.79	32.50	7.26
		150	– 0.95	32.77	6.95
		200	– 1.92	32.75	7.12
19. VIII	44	0	2.10	30.77	8.00
	79m	10	1.70	31.04	7.90
		25	1.35	31.15	7.71
		50	1.40		
		70	0.45	32.18	7.45

From these coastal results alone, which is all that we have at present, the presence of Atlantic (west Greenland) water in Ungava bay is not demonstrated. It is proposed during the 1949 season to make hydrographic sections across the deep waters in Ungava bay, from which definite results can be obtained. The plankton of Ungava bay, however, shows clear Atlantic influence, even as compared with the Lake harbour plankton. Thus, the arctic amphipod, *Themisto libellula* Mandt, is not the dominant species of macroplankton; *Themisto libellula* is normally dominant in arctic water. *Hybocodon prolifer* is again prevalent, and there are other non-arctic elements in the plankton. The presence of the Atlantic cod (*Gadus callarias* L.) in the northeast corner of the bay is another indication of Atlantic water, at least in the upper layers. Possibly the habit of the Atlantic salmon (*Salmo salar* L.) of ascending the major rivers of Ungava bay east of, and including, the Koksoak river, may also be taken as an indicator of Atlantic water.

Ungava bay, like Hudson bay, receives the drainage from a large area of land. Besides a number of smaller streams, the George, Whale, Koksoak, Leaf and Payne rivers all empty into Ungava bay. This considerable summer contribution accounts for the low salinities of the coastal water.

"FEED-BACK" CIRCULATION SYSTEMS

Reference was made in passing, above, in the description of the Baffin bay circulation, to the existence of what amounted to a "feed-back" path in Baffin bay, in the blocking of the deeper water of the Canadian current and its deflection to the left around Baffin bay (in cyclonic circulation). The whole of the eastern arctic circulation, in fact, might be interpreted as part of a large feed-back system, the eastern arctic area containing feed-back paths belonging to the main north-Atlantic-Arctic circulation. The total water circulation of the earth's surface is a system which is itself not closed, since it depends for its maintenance upon solar energy, and since there is a continual loss of energy by evaporation. It is thus a large open system, as most systems seem to be in nature. Inside this general circulation, several component circulations can be separated, of which one important example is the north Atlantic system, comprising the Gulf Stream — Atlantic drift — equatorial current circulation, and the Atlantic drift — arctic water circulation. The eastern arctic circulation belongs to both of these, is itself an open system (obtaining water from the east Greenland current, the Irminger current, the Labrador sea, and the polar basin, and losing water by way of the Labrador current), and contains feed-back paths along which water is returned temporarily to an earlier stage in the circulation.

Such feed-back paths are the deep Baffin bay circulation already mentioned, in which arctic water of the Canadian current is routed back round Baffin bay, and the Labrador sea circulation, in which Atlantic drift water is routed back from southern Iceland and into the west Greenland-Labrador system. Thus any fluctuations in the volume and transport of the north Atlantic drift will cause the deflection, in the region of the submarine ridge between Iceland and Greenland, of greater or lesser amounts of Atlantic drift water in the Irminger current. The Labrador sea circulation will then act to relieve the excess pressure at peaks in the Atlantic drift fluctuation. Similarly the Baffin bay circulation will absorb, for a period, excess pressure which may be delivered into the eastern arctic system from the polar basin. Since the arctic water in the polar basin is itself largely of

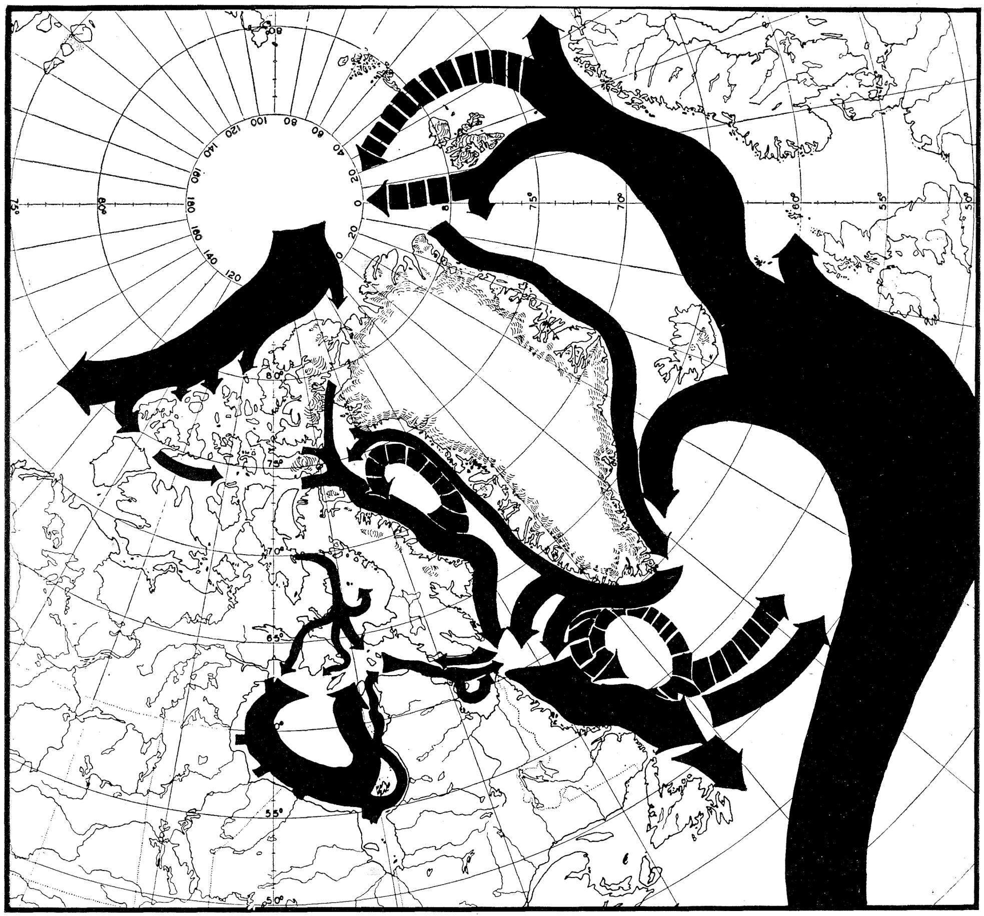


FIGURE 17. General circulation of water in the northern part of the north Atlantic and the eastern arctic, illustrating the feed-backs referred to in the text; a schematic diagram without attention to detail. The dotted portions represent sub-surface currents.

Atlantic origin (there may be a small contribution from the Pacific, and the waters of precipitation and of land drainage are not unimportant), the arctic and Irminger contributions to the eastern arctic area should be in equilibrium, and the system becomes to a large extent self-regulating. The whole Atlantic — Arctic circulation is itself a feed-back system (see fig. 17). The balance between arctic and Atlantic water in the whole system, moreover, is presumably ultimately a function of atmospheric conditions, and any cyclical or periodic phenomena in the latter will be reflected, no doubt with some time-lag, in the water circulation. This is an important consideration in estimating and understanding the changes in the circulation of the eastern arctic which have occurred in the past thirty years.

The concept of feed-back mechanisms, or servo-mechanisms, is perhaps peculiarly adaptable to oceanography, and might increase our understanding of water movements considerably, if applied. For an account of the application of the system in various fields of science, see Frank *et al.* (1948), and Wiener (1948).

FJORDS AND OTHER INLETS

"Fjords" are here defined as deep inlets in the coast, usually (but not always) with a threshold in the bottom configuration at the mouth, with steep sides, and formed either by the action of glacier ice or by movements of the earth-crust, according to the point of view taken. Shallower inlets, without the threshold and in different land-formations (such as Lake harbour inlet, Diana bay, and so on) do not come into this definition. The oceanographic differences between the two, largely due to the difference in depth, are considerable. The study of the waters of fjords and other inlets is of great importance in the economic biology of such areas, besides being decidedly rewarding in terms of general scientific interest.

Special studies of fjords have been made along the east and west coasts of Greenland, which are perhaps the most typical and the most famous fjord-coasts in the world. The early Danish workers in this field, around the turn of the century, made surveys of the fjord regions of west Greenland, including sub-surface temperatures and salinities, much of which work is summarized by Nielsen (1928). The "Tjalfe" expedition investigated certain fjords in the southwest. Loewe (1933, 1934, 1935a) studied Umanak fjord on two expeditions. During 1941-6, Dunbar (1946, and unpublished data) made observations of temperature, salinity and water movement in Godthaab and Ameralik fjords. Hartley and Dunbar, in 1936, worked in Atâ sound in the northeast corner of Disko bay, studying the water movements in the vicinity of active glaciers (Hartley and Dunbar, 1938). Dr. Poul Hansen, during the course of his extensive fishery investigations in west Greenland, has measured temperatures in several fjords (Hansen, 1939, 1940).

The north American side, as has already been mentioned (see above, bathymetry) does not show the fjord development to anything like the degree observed in Greenland. The Labrador coast, however, is greatly indented, and some of the inlets may be of the fjord configuration. This is shown clearly in the work of Iselin (1932), in the instances of Sandwich bay and Nachvak fjord, both of which exhibit the threshold across the mouth and the consequent special hydrographic conditions within the fjord basin. It is possible that some of the Baffin island inlets, when eventually investigated, may turn out to be fjords. The inlet of the river Clyde, for example, appears to show many of the typical physiographic characteristics of fjords; but the bathymetry and the hydrography are still unknown. Cumberland sound is deeper in the interior than at the mouth, and may possibly correctly be considered as a fjord.

Much of the work on the fjords of west Greenland must now be considered out of date, being seldom more recent than 1910. Such great changes in the west Greenland hydrography have taken place since that time that the older results cannot be considered to have any great relevance for today. As material for the study of cycles in the water temperatures and salinities they are valuable, and are analysed below; but as specific studies of fjord hydrography it is doubtful whether they should be included in a work of this nature. For the original material, therefore, the reader is referred to Nielsen (1928), Hamberg (1884), Garde (1896), Hammer (1883), Jensen (1881, 1889), Moltke (1896) and Ryder (1889).

The chief interest in the hydrography of these fjords is the extent to which the fjord waters are determined by the waters outside the fjords. In certain Norwegian fjords, the deep water inside is so isolated from the free water outside that it has become stagnant, with very low oxygen content and with the production of hydrogen sulphide (Strøm, 1939). Such extreme conditions of isolation have not so far been recorded in Greenland fjords, but unfortunately there have hitherto been very few measurements of oxygen content in the fjords. The determining factor in the isolation of the deep fjord water is of course the height of the threshold across the mouth of the fjord. The thresholds are however apparently frequently cut by deeper and narrow channels (Nielsen, 1928), and we do not yet have sufficiently detailed and accurate soundings of the fjord mouths to be certain of the greatest depth of water which has access to the fjord. In fact the minimum height of the threshold is not infrequently inferred from the type of water in the fjord, by a reversed process of reasoning; on this point there is some disagreement between the authors, and it seems very probable that errors have been made in the interpretation of the fjord conditions. Thus Hamberg (1884) in describing the conditions in Arsuk fjord, at Ivigtut, found an upper layer down to 100 metres with positive temperatures, a layer between 100 and 200 metres with negative temperatures, and a large mass of water from 200 metres to the bottom (550 metres) with temperatures as high as 1.8° C. and salinities of over 34 $^{\circ}/_{\circ\circ}$. It was assumed by both Hamberg and Nielsen (1928) that the threshold of the Arsuk fjord was high, in the region of 100 metres beneath the surface, and that therefore the presence of the warm bottom water in the fjord must be due to the thinning out of the cold water layer outside (of east Greenland origin) in the fall, allowing the warmer water to flood the banks and flush out the fjords. Hamberg's observations were made in August, not in the autumn, and moreover the supposed flushing out of the fjord by warm Atlantic water does not explain the layer of cold water with negative temperatures. It would be of great interest to carry out temperature, salinity and oxygen observations in this and other fjords today, and to include in the survey a detailed study of the thresholds by means of the echo-sounder.

Kvanefjord, in the Frederikshaab district, is of the same type as Arsuk fjord; the water measured in the deep layers here by the "Tjalfe" expedition was as warm as 3° C. at 500 metres. The same explanation postulating an autumnal invasion of west Greenland water was suggested here by Nielsen (1928).

Julianehaab fjord, and Bredefjord to the north of it, were found by several workers to have warm water, over 3° C., in the deeper layers, and clearly must have free access to the deeper water outside.

GREENLAND FJORDS

Only four fjord regions in west Greenland have been studied from the hydrographic point of view within the present warm period, that is to say since the early 1920's. These are Inglefield gulf, north of Thule, in which the "Godthaab" expedition occupied a few stations in 1928; Umanak fjord, studied both by the "Godthaab" expedition in 1928 and by Loewe in 1930-31 and 1932; the Vaigat and Disko bay regions in which the "Godthaab" expedition made observations in 1928, and Hartley and Dunbar in 1936; and the Godthaab-Ameralik fjord complex studied by Dunbar between 1941 and 1946. It is understood that Dr. Poul Hansen is in the present years undertaking such studies in various west Greenland fjords, but the results are not yet available.

Inglefield gulf is deep, soundings of 950 metres having been recorded by the "Godthaab" expedition (Riis-Carstensen, 1936). There is no evidence in the soundings of any threshold in this fjord, nor do the hydrographic conditions within the fjord suggest any isolation of fjord waters. "Godthaab" stations 106 (outside the fjord) and 92 (inside the fjord) are reproduced here from Riis-Carstensen's data:

	Station 106 August 11 Depth 858 m. 77° 00′ N; 71° 43′ W.			*Station 92* August 6 Depth 740 m. 77° 28′ N; 67° 30′ W.	
Depth	*T° C.*	*S °/oo*		*T° C.*	*S °/oo*
0	3.98	31.66		4.88	27.30
10	2.39	31.83		2.21	30.79
50	− 0.30	33.31		− 1.25	33.53
100	− 1.36	33.67		− 1.51	33.68
200	− 1.51	33.85		− 1.35	33.87
350	− 0.47	34.23		− 0.51	34.27
500	− 0.41	34.33		− 0.40	34.34
750	− 0.44	34.36	(720 m.)	− 0.42	34.36

It will be observed that both inside and outside Inglefield gulf the conditions are the same. At both stations the same distinction is apparent between the upper polar water (the 200 metre readings and above) and the lower Baffin bay water (350 metre readings and below); between 200 and 350 metres the temperatures at both stations rise from −1.51 and −1.35 to −0.47 and −0.51, and the salinities rise significantly.

The work of the "Godthaab" expedition, and of Dr. Fritz Loewe (Loewe, 1935a) in the Umanak fjord complex demonstrate a similar lack of isolation between inside and outside water, all stations showing the typical stratification of upper water, occupying two to three hundred metres, overlying the deep Baffin bay water. At the Umanak level, however, both bodies of water are warmer than at the level of Inglefield gulf, and show strong west Greenland influence. Oxygen concentrations measured by both Riis-Carstensen and Loewe agree with the interpretation of free access to the open water of Baffin bay, being generally high everywhere in Umanak fjord and of the same level as in Baffin bay. Loewe's stations 7, 14 and 20, however, show much lower oxygen values in the upper 100 metres, which obviously at these depths cannot be due to isolation of water, and must therefore be ascribed to specific and local biological conditions of which we have no information.

In the cases of Inglefield gulf and the Umanak fjord, there is little indication of the presence of a considerable threshold, either by hydrographic methods or by actual soundings. In most of the west Greenland fjords, however, such thresholds exist. Some of these fjords contain water which clearly originates outside the fjords, and often from deeper levels than the apparent tops of the thresholds. Such conditions exist in many of the southwest fjords, already described. It is still an open question, in many cases, whether the thresholds in such fjords are cut by narrow deep channels allowing the passage of the deeper outside water, as has been suggested above, or whether there is a periodic flushing-out, or "ventilation", to use Strøm's (1939) word, by the influx of water which is heavier than the water in the fjord basins. In his study of some thirty Norwegian fjords, Strøm has demonstrated the ventilation which occurs at uncertain intervals in Norway. One important result of his work was the finding of the rise in temperature which occurs in stagnant waters, and which decreases the density of the deep waters of the fjord, thus allowing the ventilation process to take place. He has also drawn attention to the importance of tidal currents in drawing in water from outside, and in favouring the process of the renewal of the bottom water inside the fjord. Both these effects may apply to the fjords of the eastern arctic, especially the latter. As already recorded, no instance of stagnant water in eastern arctic fjords has yet been found, and from the general high level of biological productivity in these fjords, it is very doubtful whether stagnation ever will be found. Strøm's results are, in passing, of some relevance to the problem of the cold deep water found in Hudson bay by Hachey (1931b). If those 100-200 metre waters in Hudson bay are in fact stagnant, there is certainly no rise in temperature accompanying the stagnancy.

EFFECTS OF GLACIERS

A common feature of fjords in Greenland is the presence of active, calving

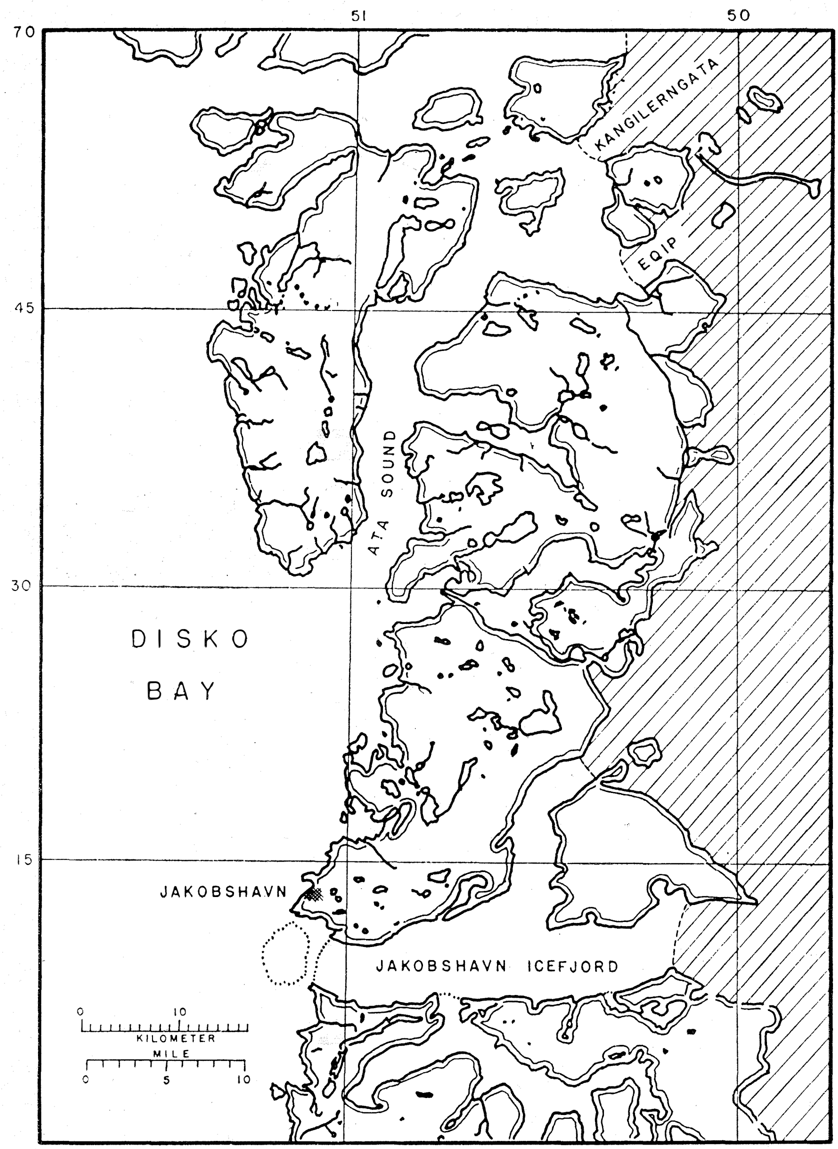


FIGURE 18. Map of the inner part of Disko bay, showing Ata sound and the Eqé and Kangilerngata glaciers. From Hartley and Dunbar (1938).

glaciers. Glaciers whose fronts debouch into water of considerable depth, and which produce large icebergs, might well, in fact, be considered a normal characteristic of Greenland fjords, where the ice-cap is still fully developed (in contrast with the conditions in Alaska and in the eastern arctic islands, where the glaciers have retreated from the salt water). Such glaciers have most interesting effects upon the movements of the water in their immediate vicinity. These effects appear to have been first noticed and recorded by the Oxford University expedition to Spitsbergen in 1933 (Stott, 1936), although somewhat similar phenomena, perhaps different in mechanism, have been observed in Alaska (Gilbert, 1910). I refer to the presence at the faces of such glaciers of localized zones of muddy, ice-free water, of the type shown in fig. 19. Such zones, known as "brown zones" or "feeding zones" (due to their great importance as feeding areas for sea-birds), are surrounded by the loose brash ice normally found at the face of tidal glaciers, and having a considerable surface current away from the ice face, of a speed of the order of half a knot.

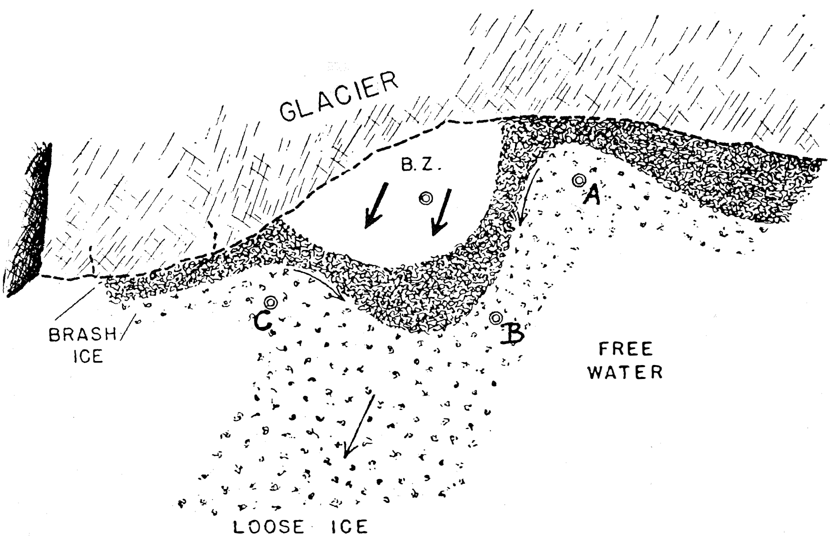


FIGURE 19. Sketch-map of the Eqé brown zone, August 22, 1936. Points of observation shown by double circles, surface movement of water by arrows. B.Z. is the brown zone. From Hartley and Dunbar, 1938.

Two such "brown zones", or ice-free zones, were studied by Hartley and Dunbar at the faces of two glaciers in Atâ sound, the names of the glaciers being Eqé and Kangilerngatâ (see map, fig. 18, Hartley and Dunbar, 1938). The technique involved the use of a small 25-foot motor boat which was pushed through the brash ice and into the brown zones themselves, so that hydrographic information from close to the ice-face was obtained. Unfortunately, it was not feasible to get closer to the glacier than about 100-150 yards, owing to the danger from falling pieces of ice. The Eqé glacier was especially chosen for its relatively harmless reputation; it produces small berg-pieces more or less continuously during the summer, and has never been known to calve a berg large enough to endanger a small motorboat reasonably close to the glacier face. The "Marion", in 1928, anchored some few hundred yards off the Eqê glacier and fired 3-inch shells into it, without any appreciable effect. The Kangilerngatâ glacier, on the other hand, does produce bergs of considerable size, and was therefore visited only once. Both glaciers possessed well developed brown zones.

The water at the surface of the brown zones is in strong contrast to the water surrounding them; not only is the surrounding water covered with brash ice, and the brown zone water free, but the brown zone water is of a thick coffee colour, and full of mud, whereas the surrounding surface water is the usual translucent green colour characteristic of such regions. The muddy water, on reaching the surrounding clear water, disappears under it, so that the edges of the brown zone are clearly marked. Planktonic crustacea, whose normal upper limit of vertical distribution is at a depth of between 15 and 25 metres, and sometimes much lower, are found at the surface in the brown zone in very large numbers, a condition which makes the zone an important feeding area for kittiwake, old squaw duck, eider duck, and murre. Upwelling water is thus suggested by zoological research alone, and from the fact that the birds are always crowded together immediately under the face of the glacier it is inferred that the upwelling is most marked at that point in the brown zone. The distance, at the Eqê glacier, from the ice cliff to the outer margin of the brown zone was about 250 yards in August, 1936.

Investigation of the hydrography of these areas was carried out on three separate days, on August 3 and 22 at Eqê, and on August 9 at Kangilerngatâ. The data are given here in table IV. From observations made at the Nordenskiold glacier in Spitsbergen, Stott (1936) was led to the belief that the brown zone there was due to a drainage stream at or near the surface, flowing away from the glacier face. Drainage streams of fresh water, heavily charged with mud, are an entirely normal feature of glaciers, but they usually appear close to the bottom of the ice, seldom at the surface of the water. Such drainage streams flowing out over the surface, and causing large broad patches of muddy water, are commonly seen in southern Alaska, where the glaciers today appear to be restricted to much shallower water than in Greenland. The existence of drainage streams associated with the brown zones is not excluded, in fact they may play an important part in the mechanism, but the data collected by Hartley and Dunbar definitely exclude the possibility of the effectiveness of a drainage stream in causing the upwelling. This is clearly shown in table IV, where it will be seen that the salinities at the surface in the brown zones are of the same order as the salinities at 25 and 50 metres both inside and outside the zones, whereas the surface salinities outside the zones are very much lower due to the melting of brash ice. Similarly the temperatures inside the zones are almost uniform up the column of water measured. The upwelling, then, which is clearly demonstrated by the figures, cannot be due to the rising of fresh water from a drainage stream; nor would such water contain the plankton found at the surface in the brown zones. The high surface salinities in the brown zones also exclude the possibility of a fresh drainage stream entering at the top. The existence of the brown zone cannot be dy-

TABLE IV. Eqé Glacier.

August 9, 1936

Depth (m)	Brown Zone			Outside; A		
	° C.	$S^{\circ}/_{oo}$	σ_t	° C.	$S^{\circ}/_{oo}$	σ_t
0	0.80	29.18	23.41	1.22	27.38	21.94
10	0.91	32.25	25.87	0.82	31.38	25.17
25	0.93	32.66	26.19	0.99	32.74	26.25
50	0.99	33.24	26.65	0.99	33.26	26.67
100	1.12	33.57	26.90	1.12	33.60	26.93

Eqé Glacier

August 22, 1936

Depth (m)	Brown Zone			Outside; A		
	° C.	$S^{\circ}/_{oo}$	σ_t	° C.	$S^{\circ}/_{oo}$	σ_t
0	0.80	32.16	25.80	1.86	22.11	17.71
10	0.81	32.28	25.895	0.80	32.41	26.00
25	0.73	32.92	26.41	0.89	32.95	26.42
50	0.90	33.22	26.63	0.90	33.21	26.63
Depth (m)	Outside; B			Outside; C		
	° C.	$S^{\circ}/_{oo}$	σ_t	° C.	$S^{\circ}/_{oo}$	σ_t
0	1.81	25.55	20.49	2.00	23.95	19.17
10	0.71	32.16	25.80	0.79	32.27	25.885
25	0.67	32.97	26.45	0.85	33.01	26.47
50	0.92	33.26	26.67	0.91	33.26	26.67

Kangilerngata Glacier

August 3, 1936

Depth (m)	Brown Zone			Outside;		
	° C.	$S^{\circ}/_{oo}$	σ_t	° C.	$S^{\circ}/_{oo}$	σ_t
0	1.35	32.14	25.74	3.85	26.13	20.79
10	0.96	32.09	25.735	1.22	31.44	25.19
25	1.05	32.36	25.94	1.13	32.56	26.09
50	0.87	33.12	26.56	1.01	33.19	26.61
100	0.99	33.51	26.87	1.00	33.49	26.85

namically dependent upon the presence of a glacier stream entering at any level. Such a drainage stream, however, may well be the source of the mud found in the brown zone waters.

The circulation found in the brown zones, derived from the data in table IV, is shown in fig. 20. It is obvious that the primary force responsible for the establishment of the brown zone must be sought outside of the zone itself. To quote from Hartley and Dunbar (1938): "Since the surface salinities observed immediately outside of the surrounding brash ice are in all instances much lower than the surface salinities within the brown zones, it is obvious that the actual freshening is mainly or entirely introduced in or via the brash ice belt. The primary cause for the maintenance of the brown zone phenomenon is therefore to

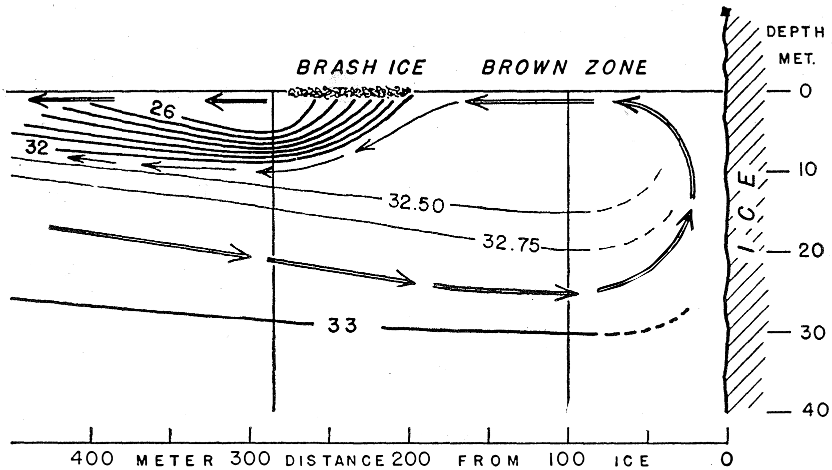


FIGURE 20. Salinity profile at Eqé brown zone, August 22, 1936, showing vertical circulation. Heavy isohaline for every 1 °/oo from 26 °/oo to 33 °/oo; light isohalines for 32.50 and 32.75°/oo. From Hartley and Dunbar, 1938.

be found in the movement away from the glacier of the fresh layer occurring in the brash ice belt, where it is probably mainly derived from the melting of the brash ice itself".

The outflow of surface water, then, which is a very common feature of fjords during the summer, causes a replacement current of heavier water from down below, which rises up the face of the glacier. This upwelling current, at the hypothetical beginnings of the brown zone formation in the early spring (assuming that the zone closes during the winter), might well be supposed to be originally in the form of a sheet spread all along the glacier face. The question arises, therefore, as to how the upwelling current comes to be so concentrated as to appear as a local zone only. Outside the zone, which occupies only a small portion of the glacier face, the brash ice holds close to the ice cliff. It is probable, on physical grounds alone, that such a rising sheet of water would soon take the line of least frictional resistance and form itself into a column. The presence of some centre of concentration, however, would greatly facilitate this process, and it is suggested that a freshwater drainage stream might well act as such a centre of concentration. There are, moreover, other good reasons for supposing that a glacial drainage is present in the brown zone complex. Quoting again from Hartley and Dunbar (1938), these reasons are as follows:

1. The normality of a drainage stream; most glaciers possess one at least (and none was visible elsewhere at the Eqé or Kangilerngatâ glaciers).

2. The presence of the mud. It has been suggested that the vibration caused by a moving glacier might keep the bottom sufficiently stirred up to supply the mud. The muddy water at Eqé, however, is found at the surface and at 10 metres depth only, in the brown zone, and at 10 metres depth outside the zone, in the direction of the brown zone current; it is not found at 25 metres or lower either in the zone or out of it. It seems, therefore, that the turbidity is not due to a general stirring up of the bottom by water movement or any other phenomenon, but to the presence of a localized source, such as a drainage stream emerging from the glacier. The supply of mud need not be very great, since (fig. 20) a large amount of it may be kept in circulation by means of its sinking from the outgoing flow at the surface to the incoming and ascending flow underneath.

3. The position of the brown zone. The Eqé brown zone is well toward the northeast end of the glacier. If there were no drainage stream to localize the zone, one would expect it to be found more nearly in the middle."

It was assumed in the above account, though the assumption does not greatly affect the theoretical method of the establishment of the brown zone, that the zone closed up during the winter. This may well not be so. The author has heard several accounts from native Greenlanders of patches of open water maintained at the faces of glaciers throughout the winter. Such open patches are moreover described as having strong currents in them, away from the ice face. Godthaab fjord, for instance, possesses two glaciers at its head, the more southerly of which is described by natives at Kapisigdlit as usually showing an open patch of water. This particular phenomenon was explained by the Greenlanders as being evidence for a continuous stream of water from Sermilik fjord, some 50 nautical miles to the south, to Godthaab fjord, underneath the permanent ice-cap! It is not improbable that there is a similar vertical circulation of water at this glacier as has been described for Eqé and Kangilerngatâ.

It is very probable that if the brown zones are maintained throughout the winter, they become considerably reduced in area. There seems indeed to be some variation in the extent of the brown zones from year to year, depending perhaps upon the extent of the glacier activity and the atmospheric climate, both of which would of course very largely determine the quantity of melting ice, and the speed of melting. The author visited the Eqé and Kangilerngatâ glaciers again in August, 1942, and although the great concentration of glacier ice prevented the boat from entering the brown zones, both were visible from the masthead, and both were clearly smaller than they had been in 1936.

Vertical circulations of such violent nature, and of so concentrated a plan, are very different from the supposed phenomena associated with melting ice.

Pettersson (1905) and Sandstrøm (1919) and others give accounts of the currents found, both experimentally and in the field, in the immediate vicinity of melting ice-bergs. According to their findings the sea-water immediately next the ice face is cooled and diluted, and, depending upon the extent of the dilution and the salinity of the surrounding water, either rises up the face of the ice to the surface, or sinks beneath the ice. Pettersson considers this process to be the source of both the arctic surface water (cold and of fairly low salinity), and the arctic bottom water (cold and of high salinity), with the intermediate warm Atlantic water acting as the origin of both.

The experiments and observations upon which this interpretation is based involved single isolated blocks of ice in water free of surface ice. The surface current away from the ice, engendered by the upward movement of the melt-water up the ice-face and the freshening of the surface water, is not, it seems, of sufficient magnitude to cause a vertical replacement of heavier water from below —the surface instead obtains a steady supply of dilute melt-water from the ice-face. In the phenomenon of the brown zone, however, the important agent appears to be not the melting of the ice-face itself but of the brash ice always found along the face of the glacier in summer; this great melting activity, and hence great dilution of the surface water, causes a surface current away from the glacier of such volume as to demand an actual upwelling of heavier water to replace it, a process which sets up the vertical circulation in the brown zone. It would be of great interest to study the water circulation in the vicinity of ice-bergs which are in the process of breaking up. It is not impossible that the amount of brash ice formed might be sufficient to induce localized zones of upwelling at the faces of the ice-bergs. The term "brown zone" would not, in point of fact, describe such upwelling circulations, since there would be no source of mud associated with ice-bergs; the principle, however, would be the same.

The principle of concentration, or localization, of vertical movement may be of fairly general application in the sea. The origin of the arctic bottom water in the polar basin, for instance, is thought by many to be found, not in the Pettersson effect just described, but in the increased salinity and density of the surface water caused by the freezing of the surface water during the winter, and the sinking of this cold heavy water to the bottom, through the warm Atlantic intermediate layer. Such a sinking process could not, obviously, occur over large areas of the polar basin simultaneously; rather it would be expected that the dense water would concentrate by lateral movement and sink in localized columns. Similarly the vertical interchange of water which occurs normally during the winter in the oceans generally, probably takes place in localized columns of sinking and rising water throughout the whole period of the process.

To return to the general study of fjord waters. During the years 1941 to 1946, the present writer made observations of temperature and salinity in the Godthaab-Ameralik fjord system, part of the results of which have already been published (Dunbar, 1946). Owing to wartime difficulties, the obtaining of equip-

TABLE V. Godthaab fjord, 1942.

Date	20. II		14. III		30. IV		19. VI	8. X	19. X	31. X	5. XI
Station	1		2		2		2	1	2	1	1
Depth (m)	T°C.	S°/oo	T°C.	S°/oo	T°C.	S°/oo	T°C.	T°C.	T°C.	T°C.	T°C.
0	0.76	33.03	0.89	33.01	1.46	33.26	5.90	0.68	0.10	2.10	1.90
10	0.90	33.08	1.00	33.08	1.70	33.26	3.57	1.68	1.00	2.18	1.91
25	1.00	33.08	1.06	33.06	1.64	33.31	3.35	2.88	1.83	2.19	1.97
50	0.90	33.10	1.17	33.12	1.61	33.32	2.50	3.04	2.42	2.21	1.90
75	1.00	33.09	1.21		1.61	33.32	2.41		2.57	2.21	

TABLE VI. Godthaab fjord, 1943.

Date	17. VI		30. VI		13. VII	21. VII		22. VII		23. VII	
Station	1		1		2	6		7		8	
Depth (m)	T°C.	S°/oo	T°C.	S°/oo	T°C.	T°C.	S°/oo	T°C.	S°/oo	T°C.	S°/oo
0	1.90		2.73	33.73	6.99	4.73	20.10	4.73	12.02	7.95	24.11
5								1.46		9.25	
10	1.90		2.50		5.18	0.16		0.86		2.65	
25	1.71		2.41		3.43	1.66	32.81	0.41	32.57	1.26	32.74
50	1.32		2.26		2.66			0.64		1.85	
70	1.32	33.75	2.45	33.75	2.65						
75						2.49		1.16	33.55	2.05	33.53

Date	24. VII		20. VIII	2. IX	20. X		28. X	2. XII	13. XII	
Station	2		9	2	1		1	12	1	
Depth (m)	T°C.	S°/oo	T°C.	T°C.	T°C.	S°/oo	T° C.	T° C.	T° C.	S°/oo
0	7.27	31.80	10.40	4.69	0.94		0.96	0.70	0.04	
5	5.82			3.84						
10	4.44		8.52	3.78	1.51	31.13	1.06			
25	3.05		3.75	3.60	2.05			1.16	1.06	
50	2.85			2.97	2.25		2.45		1.16	33.55
75	2.70	33.40	3.23	2.84	2.55	32.79				
100							2.75		1.26	
200									1.90	
300							3.25			

ment, especially of adequate winches and wires, was not always possible, hence the depths to which much of the investigation goes is not great. Towards the latter part of the period, however, equipment was available, and the observations extended down to 450 metres. The raw data are given here in tables V, VI, VII, VIII and IX, and the stations occupied are shown in fig. 21. Most of this material

TABLE VII. Godthaab fjord, 1944.

Date	21.IV		3.V		22.V		23.V		23.V		16.VII	
Station	2		1		7		7A		12		2	
Depth (m)	T° C.	S°/oo	T°C.	S°/oo	T° C.	S°/oo	T° C.	S°/oo	T° C.	S°/oo	T° C.	S°/oo
0	0.85	32.88	0.76		1.95	31.76	2.05		4.04	31.98	5.21	
10	0.75	32.99	0.52		0.46		0.06		1.60		3.35	
25	0.60	32.99	0.49	33.06	0.84	32.99	0.51		0.75	32.95	3.05	32.38
50	0.48	33.01	0.24		0.99		0.93		0.65		2.67	
75	0.46	33.24			1.01	33.31	1.21	33.21	0.30	33.12	2.30	32.92
100			0.31	32.24								
250			0.61	33.75								

Date	17.VII		18.VII		8.IX		10.IX		11.IX		30.IX	
Station	7B		12		12		7B		2		7C	
Depth (m)	T° C.	S°/oo	T° C.	S°/oo	T° C.	S°/oo	T° C.	S°/oo	T° C.	S°/oo	T° C.	S°/oo
0	3.15	11.40	4.70	19.94	3.84	19.56	2.35	8.48	4.68	24.98	0.20	
10	– 0.39		4.53		2.95		– 0.02		2.55		1.00	
25	– 0.34	30.91	3.55	31.96	2.42	31.29	0.62	31.27	2.45	31.55	1.20	
50	0.31		2.68		2.20		1.66		2.27		1.15	
75	0.76	32.81	1.84	32.95	2.05	32.36	1.85	32.48	1.90	32.48	1.85	32.57

TABLE VIII. Godthaab fjord, 1945-6.

Date	23. x. 45		14. xII. 45		8. I. 46		11. I. 46		12. I. 46		28. I. 46		1. II. 46	
Station	1		1		1		13		14		1		1	
Sounding	270m.						252m.		460m.					
Depth (m)	T°C.	S°/oo	T°C.	S°/oo	T° C.	S°/oo	T°C.	S°/oo	T° C.	S°/oo	T° C.	S°/oo	T° C.	S°/oo
0	2.00	30.53	0.56	32.20	0.22	32.74	– 0.04	32.95						
10	2.25	31.42	0.74	32.48	0.76	32.95	0.01	32.88						
25	2.30	32.34	0.99	32.54	0.71	33.03	0.96	33.04						
50	2.45	32.70	1.09	32.88	1.24	33.13	2.45	33.19						
100	2.45	32.83	1.85	33.28	1.64	33.24	2.27	33.28			1.66	33.68	2.10	
200	2.28	33.62	2.45	33.58	2.25	33.77	2.07	33.51			3.19	34.40	3.00	34.40
450									2.39	33.87				

TABLE IX. Ameralik fjord, 1945.

Date	9. X		10. X		10. X	
Station	Amer. 1		Amer. 2		Amer. 3	
Sounding	350m.		348m.		143m.	
Depth (m)	T° C.	S °/oo	T° C.	S °/oo	T° C.	S °/oo
0	3.74	31.15	4.01	29.79	3.64	23.37
10	3.35		3.72		3.91	
25	3.05	31.22	3.15	32.29	3.30	
50	2.65		2.80	32.54	3.12	
100	1.88	32.92	2.81	32.88	2.90	
150			0.96	33.51		
200	0.66	33.51	0.06	32.90		
300			– 0.24	33.77		

is used in the next section, on seasonal cycles in the eastern arctic. For the present the reader is referred to the temperature observations in October, 1943 (table VI) and during the fall and winter season of 1945-6 in Godthaab fjord and Ameralik fjord (tables VIII and IX). These data demonstrate the significant difference between Godthaab and Ameralik fjords, as representatives of the two main types of fjord found in west Greenland. Temperatures and salinities in both fjords are of the same order, subject to slight seasonal differential effects, down to and including 100 metres. Below 100 metres, however, there is a sudden drop in the temperatures in Ameralik fjord (Ameralik stations 1 and 2) of approximately 2° C., which is not shown in the Godthaab fjord stations. The salinities remain substantially the same in both fjords at these depths, with the exception of the somewhat lower salinity of 32.90 °/oo at 200 metres at Ameralik station 2. The proper interpretation of this lower salinity is not possible on the present data. The temperature differences between the deeper water of Godthaab and Ameralik fjords cannot be explained by supposing that there has been a vertical interchange of water between the dates of the Ameralik stations (October 9 and 10, 1945) and the first Godthaab station following (October 23, 1945), because of the similarity in salinities and because the salinities show no evidence of such vertical exchange. There remains only the explanation that the differences are due to the existence in Ameralik fjord of a threshold at the mouth which prevents the entry into the fjord of the warmer water outside lying deeper than some unknown depth between 100 and 150 metres. That the mouth of Godthaab fjord is in fact somewhat deeper than that of Ameralik fjord is shown by the charts available, although there are nowhere soundings published of the mouth of Godthaab fjord deep enough to meet the findings in that fjord. It will be observed (table VI) that a temperature of 3.25° C. was recorded at 300 metres in October, 1943, and that the temperature at Godthaab station 14 was 2.39° C. at 450 metres on January 12, 1946 (table VIII). Such depths are not recorded at the mouth of Godthaab fjord, but there may nevertheless exist a channel of this order of depth. On the other hand, it is possible that the great tidal currents engendered in this fjord, due to the considerable depths and surface area, and the narrow exit, may be sufficient to "ventilate" the deeper water frequently, as has been suggested (see above) by Strøm (1939)

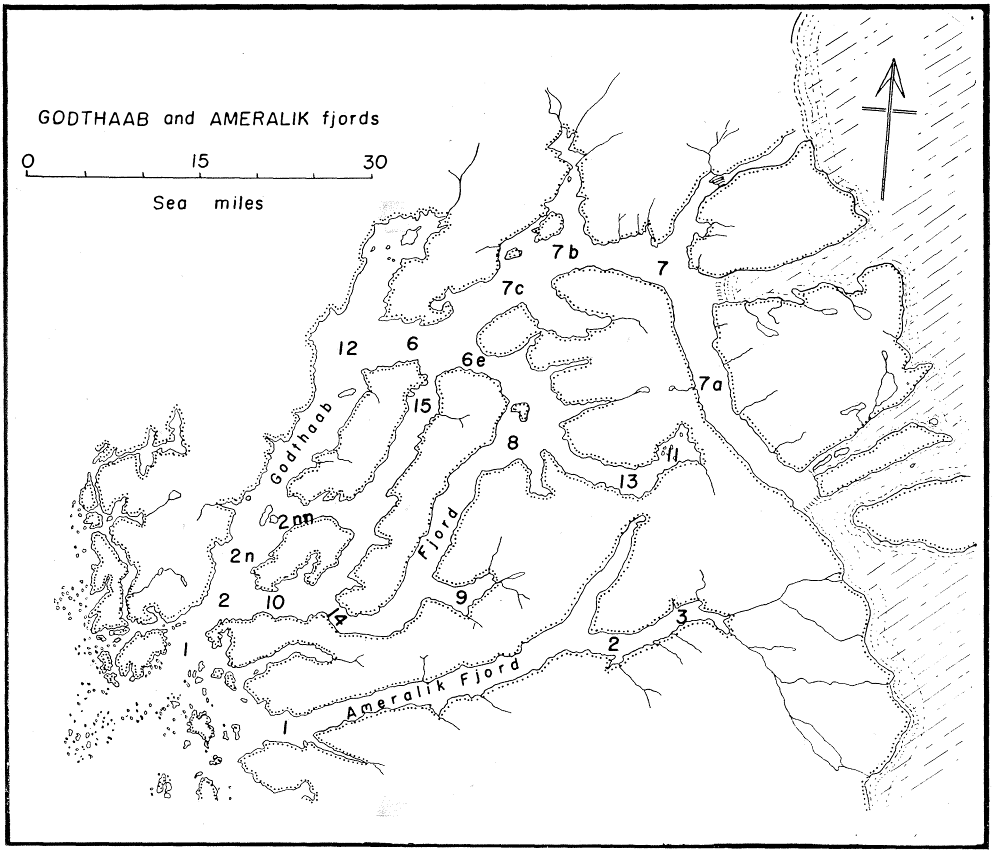


FIGURE 21. Stations in Godthaab and Ameralik fjords, west Greenland, occupied during 1941-6.

for the Norwegian fjords. Whatever the mechanism, it is clear that Godthaab and Ameralik fjords are of very different types.

CANADIAN FJORDS AND INLETS

On the Canadian side of the eastern arctic area, two fjords on the Labrador coast, Nachvak fjord in the north and Sandwich bay in the south, have been studied by Iselin (1932), by means of longitudinal sections.

The Sandwich bay section shows a small inner basin of 400 metres depth

TABLE X. Baffin island coastal data, 1940.

Date	Station	Depth (m)	T° C.	S°/oo
28. VII	Hudson Strait, 20 miles from land, south-east of Big Island	75	− 0.81	33.62
28. VII	Lake Harbour, station 1	0	1.56	30.31
		10	0.33	31.07
		25	− 0.13	31.65
		46	− 1.18	32.93
31. VII	Lake Harbour, station 4	0	3.68	30.74
		10	− 0.12	31.78
		25	− 0.54	32.28
		50	− 0.66	32.58
		75	− 0.72	32.62
6. VIII	Frobisher Bay, outside Ward Inlet	0	1.15	30.69
		10	0.10	32.34
		25	− 0.04	32.34
		50	− 0.06	32.24
		75	− 0.13	32.34
14. VIII	Lake Harbour, station 8	0	2.15	31.67
		10	0.21	32.28
23. VIII	Lake Harbour, station 4	0	0.85	32.50
		10	0.22	32.58
		25	0.38	32.60
		50	0.35	32.72
11. IX	Clyde River, mouth of fjord	50	− 1.39	...
17. IX	Clyde River, mouth of fjord	0	0.52	27.83
		10	0.60	28.04
		25	0.55	29.88
		50	− 1.32	32.50
22. IX	Pangnirtung anchorage	0	1.66	29.61
		10	1.09	31.41
		25	0.75	31.71
		50	0.62	32.03

separated from the main current along the shelf by a ridge of about 200 metres depth. The cold inner water of the Labrador current is pressed against the shore over the fjord basin, but nevertheless temperatures of 1° C. were recorded from the bottom of the basin, showing either that the threshold was channelled to allow the passage of water from outside at about 400 metres, or that tidal or other forces are capable of drawing this warm water in over the ridge. The small size of the basin does not favour the tidal theory.

In contrast to Sandwich bay, the basin of Nachvak fjord, which is even smaller than that of Sandwich bay and which is shown in Iselin's section to be

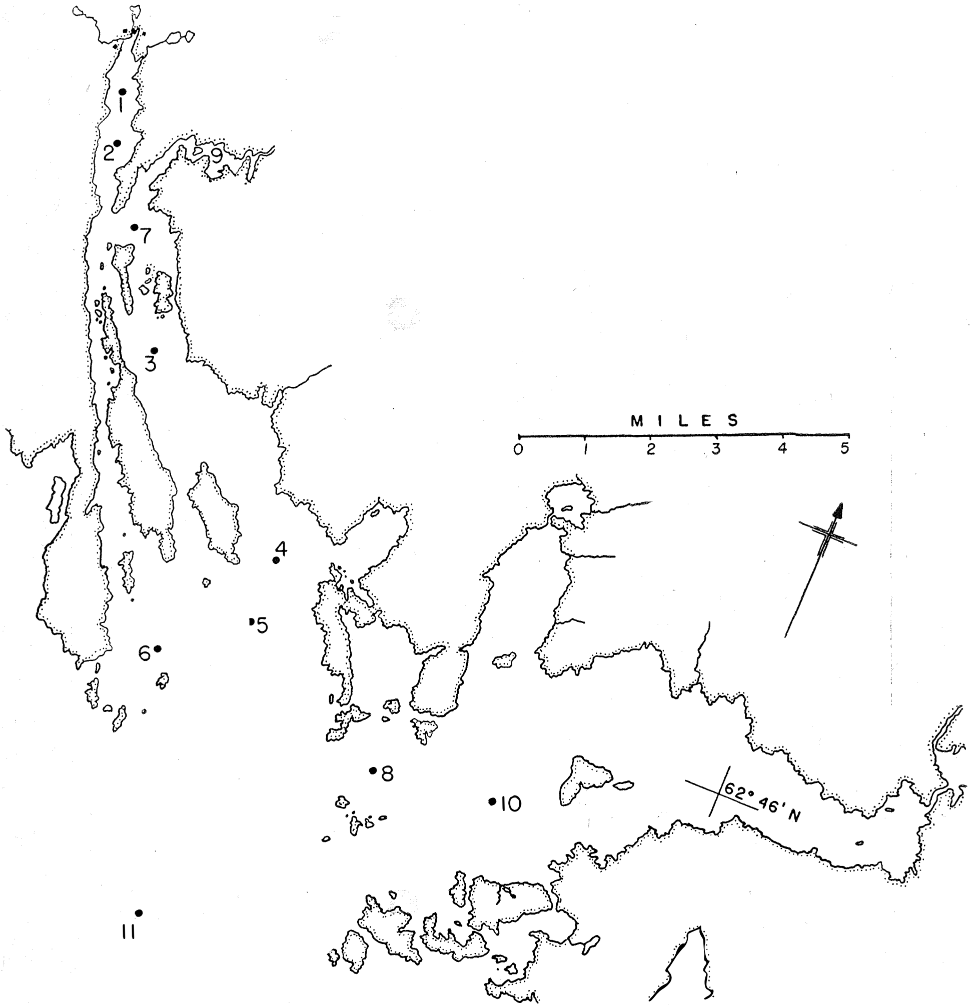


FIGURE 22. Lake harbour inlet, southern Baffin island, showing stations occupied in 1940. See table X.

about 200 metres deep with a threshold ridge of a little over 50 metres depth, contained water of $-1.83°$ C. in 1926. This water was approximately 1° C. colder than the water outside at similar depths, and more saline, which may be considered to be evidence of isolation of the deeper fjord water. Oxygen observations were not made.

The only remaining inlets of which we have any detailed oceanographic information at all are in Baffin island (Dunbar, 1942a). The temperatures and salinities measured in the upper layers in Lake harbour inlet, Frobisher bay, Clyde river and Pangnirtung fjord are given here in table X, and the map of the Lake harbour stations is given in fig. 22. The depths of Frobisher bay and Cumberland sound are shown in general outline in the bathymetric map (fig. 1). Cumberland sound has depths in the interior of over 200 metres, and a slight rise at the mouth of the sound to between 100 and 200 metres. Most of Frobisher bay appears to be about 200 metres deep, and there is as yet no evidence of a threshold at the mouth. The depths of the Clyde river fjord are not known; but

TABLE XI. Temperatures from Godhavn, Upernavik, and the Vaigat, 1942, 1943. Degrees centigrade.

Station	Two miles west of Godhavn, one miles from shore.	Four miles south of Upernavik, 72° 43′ N; 56° 11′ W. Approx.	Vaigat, approx. position 70° 00′ N; 52° 20′ W.
Date	31.VII.42	30.VIII.42	15.IX.43
Depth (m)			
0	6.83	3.50	3.65
10	5.93	2.92	3.47
25	2.03	1.67	2.85
50	1.93	1.30	3.25
75	1.43	1.01	2.43

the configuration of the shores suggests deep water. Lake harbour inlet lies entirely within the 100-metre contour, and so far as is known does not exceed 100 metres anywhere. The data in table X show typical arctic coastal water everywhere in the upper 75 metres, of low temperature and low salinity. A comparison of these figures with those at similar depths and dates from west Greenland, even as far north as Upernavik (table XI), emphasizes the differences between the west Greenland water and the water of the Canadian current.

SURFACE CURRENTS

It has already been mentioned that an outflowing surface current is a common feature of arctic and subarctic fjords and inlets. Indeed it is a common feature of all inlets in any part of the world, and is due to the fresh water collected from the drainage area of the inlet, which mixes with the salt water to produce a layer of low density. The depth of this outflowing layer, and the velocity and volume of the current, vary with the volume of drainage (or melting of ice), the turbulence of the surface (due to storms, tidal currents, and so on), and the solar heating.

It has been apparent in all the fjords in which the author has worked, and has already been described as the probable primary factor responsible for the establishment of the brown zones (above) at glacier faces. The current is most marked in Godthaab fjord in west Greenland, where the area drained (by Godthaab and Ameralik fjords together) is quite unusually large. This fjord system has been described by Birket-Smith (1928) as "in reality . . . at least four different fjords with a common outlet, but divided by peninsulas and islands with crosswise sounds". The drainage area extends back to the ice-cap, and over two degrees of latitude from north to south, or about 120 nautical miles. This large drainage, added to the presence of two active glaciers in Godthaab fjord with the consequent plentiful supply of melt-water, makes it not surprising that the outflowing surface current is well developed.

Observations of the actual depth of the outgoing surface layer were made in July, 1944, at Godthaab station 2 (fig. 21), by the use of a small plankton net from a motorboat drawing about five feet of water. The boat was drawn continually outward (towards the mouth of the fjord). On lowering the net to three metres depth, no pull on the net was observed; that is to say, boat and net were carried at the same speed in the outgoing current. At four metres depth, the net began to be pulled, relative to the boat, up-fjord; and at five metres the lower, more stationary water controlled the net completely, so that it was pulled strongly from the boat. The depth of the outflowing water was thus only about 3-4 metres. This was confirmed on numerous occasions.

The surface layer, moreover, appears to move independently of the underlying water at all times. On the flow tide the velocity of the outflowing current is lower, but it was observed to continue nevertheless on many occasions. The tidal inflow beneath the surface layer might take any of a number of horizontal directions depending on the part of the fjord and the state of the tide, but the surface layer continued, for the most part, to flow outward. The effect of this on ice-bergs in the fjord was observed at every opportunity. The direction taken by the ice-bergs depended not only on the state of the tide, but on the size of the berg. Thus small berg-chips, extending only a very few metres down into the water, were carried outward even when the tide was rising. Larger bergs were carried with the tide, and intermediate sizes were often seen to remain stationary at flow tide, with considerable current-ripples raised around them. The outflowing surface current was capable of carrying small bergs out of the fjord even against a considerable southwesterly wind.

The outflowing current appeared to be absent, or considerably weaker, along the southeastern shore of Godthaab fjord, during flow tide. This was due, no doubt, to the pressing of the incoming tidal stream to the right, forcing the surface layer away from the shore, with consequent upwelling of the incoming water. The effects of this process were quite apparent to the eye at the surface, and the phenomenon is well known to the native Greenlanders of the district, who sail up-fjord along the southeastern shore if possible.

The author is indebted to the late Canon Jack Turner, of the Anglican Mission in the Canadian Arctic, for an apparent exception to the rule of the outflowing surface current. While stationed at Moffett inlet, a tributary bay of Admiralty inlet in northern Baffin island, Canon Turner observed "a strong current setting toward the head of the inlet". To quote from a communication from Canon Turner to Dr. A. L. Washburn of the Arctic Institute: "Of course, this would mean a surface current as evidenced by the movement of the ice after 'break-up'. This ice moves up to the head of the inlet where it melts at a remarkable pace. That this movement is not entirely the result of winds is shown by the fact that it is during calm weather that the ice moves most rapidly. . . . In this connection it is interesting to note that quite large icebergs find their way up here very frequently and their movements seem to be quite unpredictable. We have two large bergs grounded less than three hundred yards off the north side of our point. One of these is about 100 feet high, so that even the "Queen Elizabeth" could pay us a visit!" This letter is dated August 4, 1947.

Such exceptions to the rule must in fact be fairly common, in inlets situated as Moffett inlet is. Moffett inlet is itself only a small bay in a larger fjord, and on the eastern, or "right bank" side. Any outflowing current in Admiralty inlet therefore would be expected to turn to the right into Moffett inlet, causing the phenomena described by Canon Turner.

SEASONAL CYCLES

There is a tendency to neglect the time-scale in oceanographic research, more especially in field work in the more inaccessible parts of the earth which have to be attacked by the expedition technique. Limited, therefore, though our knowledge is of the general oceanography of the eastern arctic, our understanding of seasonal changes in particular is less still, and water movements during the winter are almost completely unknown. It follows that a description of seasonal changes in these waters must be short. Only two sources of information over an appreciable period of time are in fact available—the "Godthaab" expedition of 1928, whose work extended from May 24 to October 10, and the observations of Dunbar in Godthaab fjord during 1941-6, a period which included one series of observations during the winter months of 1945-6. The "Marion" and "General Greene" between them, and over several seasons, covered the period from June to September, but seldom at the same or comparable stations. Neither the "Godthaab" workers nor the Coast Guard expeditions were primarily interested in seasonal succession; consequently no effort was made to repeat the same stations at different seasons, without which it is difficult to estimate the changes which take place.

The "Godthaab" work in this respect concerns only the west Greenland current. Seasonal changes occur both in the upper coastal water and in the deeper current water. The coastal water becomes more dilute, and warmer, due to drainage, melting, heating and mixing, and these effects may penetrate down to 100 metres, perhaps more, in inshore regions. The effect of these changes in increasing the velocity of the upper layers of the west Greenland current has already been mentioned. In the core of the current itself changes occur in the relative strength of the polar and Irminger water, such that the maximum influence of the Atlantic water is felt towards the latter half of the summer season (Kiilerich, 1939, 1943; also Loewe, 1935a). There is, however, considerable annual variation in this process, and in some years the strength of the polar element in the west Greenland current, and the velocity of the current as a whole, are such as to cause a cooling of the west Greenland area, especially over the banks, during the early part of the summer. To quote from Kiilerich (1943):

"On its course along west Greenland the polar current is forced towards the coast by the deflecting power of the rotation of the earth; the faster the current flows, the stronger is the influence of this power, and the closer is the current pressed towards the banks.

"In some years with a polar current of slight velocity it is able to leave the coast before it reaches the fish banks, and here temperature continues to rise fairly evenly during the summer.

"But in years where the velocity of the polar current is near normal, or stronger, the current is pressed by the rotation of the earth so strongly towards the outer slopes of the banks that it interferes with the heating of the water round the Fiskenaes banks, Fylla bank and the south point of Lille Hellefiske bank. The current attains its greatest cooling power at the end of June or sometime in July and in most years sometime about midsummer a more or less pronounced decline in temperature near the top of the banks can be found.

". . . As this advance of cold water off Fyllas bank normally takes place at 50-150 metres depth the surface temperature is less influenced by it. Here the increase of temperature generally continues throughout the summer, and, in warm years, it reaches from 6-9° C. in August and September. If the polar current does not spread itself over the top of the bank, the increase of temperature from above may continue somewhat, even as far as this depth (50 metres); but as the supply of warm water from below is stopped the temperature rises but slowly, and rarely more than 2° C. is found while the cold water lies outside. The strong (i.e. cold) advance of the polar current slows off usually before the middle of August and hereafter the warm water penetrates quickly both from above and below, so that 2-3° C. are reached at the top of the bank before the end of the summer. In years where the polar current is weak this temperature may be found as early as in June-July and after this the latter may rise further, up to 4-5° C. during the next months."

The "polar current" referred to here is the polar (east Greenland) element in the west Greenland current. It has already been observed that Kiilerich's use of the word "normal" refers to a condition found previously off west Greenland, but much more rarely during the present warm period. The most recent information available to Kiilerich when writing the paper quoted above seems to have been from 1938, which was a cold year (see below), and it must have seemed that the so-called "normal" conditions were returning. This did not occur, and at present the higher temperatures continue. The "Godthaab" results (Riis-Carstensen, 1936) being obtained in the warm year of 1928, show little if any sign of the cooling in June and July which Kiilerich describes.

Whatever the conditions in June, the warming of the west Greenland current during the later months of the summer is conspicuous. The increasing Atlantic influence at this season is moreover demonstrated (in the current water, not the inshore coastal water) by a slight rise in salinity.

The observations in Godthaab and Ameralik fjords between 1942 and 1946 were made by the writer in connection with biological studies. The salinity observations are not complete, and moreover a considerable number of the water samples were lost or broken in transit between Greenland and Canada under wartime conditions. Table V shows the observations in the upper 75 metres in Godthaab fjord in February, March, April, June, October and November, 1942. In the first three months the column of water is very uniform both in temperature and salinity from top to bottom and there is strong evidence for vertical interchange of water. Between March and April, the rise in temperature indicates either surface heating (which is not probable at that time of year) and further vertical mixing, or more probably, the arrival of warmer water in the west Greenland current. The increase in salinity also favours this latter view. Only temperatures are available in the remainder of the table, but these by themselves are enough to indicate the vertical interchange of water which occurred again in the autumn, between October 19 and October 31. Surface cooling was evidently well advanced by October 8; and heating at the surface is apparent in the figures for June.

The spring solar heating of the surface was somewhat retarded in 1943 (table VI), and the figures for June 17 and June 30 suggest that vertical interchange of water continued up to the end of June in that year. By July 13 the upper layers had become stabilized. Farther up the fjord (station 6 and more especially station 7), the upper layers are considerably colder, due to the chilling effect of the ice, and the surface is of very low salinity, due to melting in the ice-fjord. In contrast to this are the high temperatures at station 9 (Krokut bay) in August, when the surface was up to 10.4° C. Cooling of the water began at the mouth of the fjord in September.

In 1944 (table VII), the upper 75 metres were colder during April and May than in the two previous years, which must be considered as due to the retarded arrival of Atlantic water in the coastal current, for the early spring of 1944 was climatically warm; moreover, it is very doubtful if the sun is capable of any considerable heating effect in these latitudes before the month of June. There is evidence for greater cooling of the upper layers in September 1944 than in 1943 or 1942 (station 2, September 11, 1944).

During the fall and winter of 1945-46, observations were maintained from which a much fuller picture of the behaviour of the water can be obtained than from the earlier results (tables VIII and IX). These data have been plotted on a T-S diagram (fig. 23). It will be observed that in the upper 100-150 metres the water of both Godthaab and Ameralik fjords is of the same type, but that below this level the Ameralik water is much colder. The 200-metre points on the Godthaab fjord curves, moreover, are close together from October 23 to January 11. The T-S curves for the various stations rotate like the spokes of a wheel between October and January, and the rotation is a measure of the stability of the water; hence of the probability of vertical interchange. The hub of the rotation of Godthaab fjord curves is at 200 metres, from which it may be inferred that up to January 11 the vertical interchange was restricted to the water above 200 metres depth. The 400-metre reading on January 12, however, indicates that the differences between the water at 450 metres and at 200 metres were slight, so that a very little cooling of the 200-metre water would cause vertical movement between those two depths. That the vertical movement penetrated deeper late in January is shown by the position of the 200-metre water on January 28 and

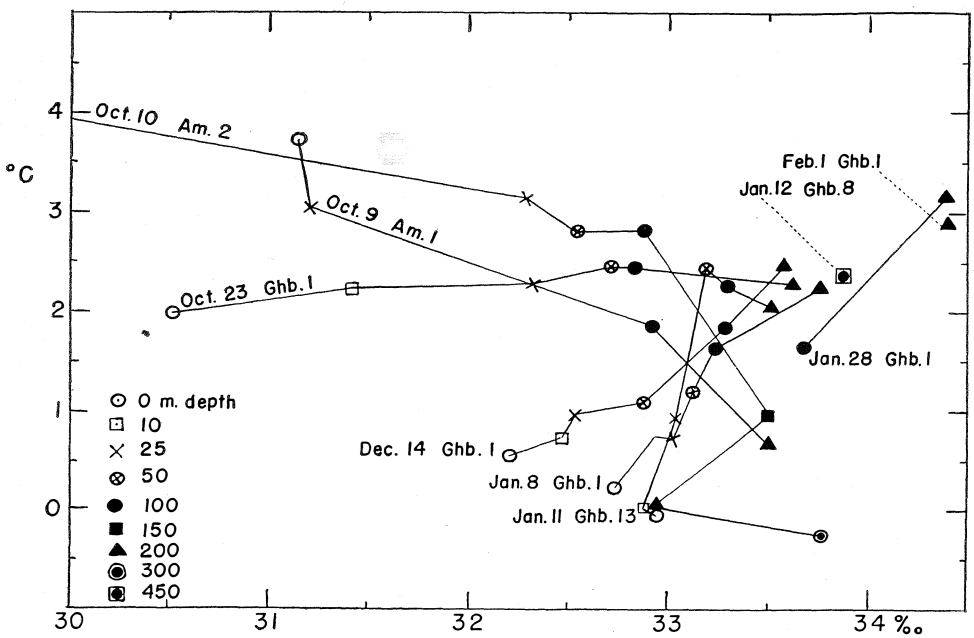


FIGURE 23. Temperature-salinity diagram based on observations in Godthaab and Ameralik fjords, 1945-6; showing the behaviour of the water during the winter. For explanation, see text (pp. 96-97). Raw data shown in tables VIII and IX.

February 1, when warmer and more saline water had invaded that depth. Furthermore, the low temperature of 0.61° C. at 250 metres on May 3, 1944 (table VII; and assuming that the two different years are comparable), suggests that the process of vertical interchange continues all through the winter and early part of the year, and that the degree of cooling of the whole water column is very great. This deep water must be replaced during the summer by new water in the west Greenland current.

It is seldom that opportunity occurs to study the waters of northern regions during the winter. Southwest Greenland is well adapted to such study, since the waters remain unfrozen south of Sukkertoppen. Unfortunately, the technical difficulties are still considerable and the work arduous, for the air temperature may be down to zero or a little below (Fahrenheit). The present material, however, shows that the results of such winter work may be of considerable interest, and could, if carried out in greater detail, greatly increase our understanding of the seasonal behaviour of such subarctic waters. In high arctic conditions the difficulties are greater by the degree of freezing of the surface water itself, but the winter study of deep fjord waters, through the ice, is nevertheless quite feasible.

Of the seasonal cycles in the Canadian waters of the eastern arctic we have no information, due to these difficulties of winter work. Indeed, the season in which it is possible to carry out oceanographic work in the Canadian waters is considerably shorter than in west Greenland, even in summer. The figures published here in table X show some warming, to no very great degree, in the upper layers between July and September in the coastal waters of Baffin island. The deeper core water of the Canadian current very probably changes very little during the season, except in so far as it is affected by west Greenland intrusion.

LONG-TERM CHANGES

Recent and secular changes in the climate, both atmospheric and marine, of the northern hemisphere and especially of the arctic regions have aroused great interest in several scientific fields. A bibliography of part of the work published on the subject has been circulated in mimeographed form by the International Council for the Exploration of the Sea (Conseil Permanent, 1948), and general reviews of the hydrographic change during the past thirty years in the eastern arctic area, especially in the west Greenland waters, have been published by Jensen (1939), Dunbar (1946, 1947) and Kiilerich (1943). The material collected by Dunbar (1946) is reproduced here as a guide to the temperature changes since the 1880's (figs. 24 to 29).

The change consists in a rise in sea and air temperatures and a retreat of the southern limit of sea-ice, and it affects the whole region from the eastern arctic of Canada eastwards over Greenland to the Siberian shores; recent climatic researches point to a complete circumpolar effect. In Spitsbergen, the average winter air temperature was 9° C. higher during 1931-5 than during 1911-15, and the southern limit of ice in the Spitsbergen-Jan Mayen area retreated 200-300 kilometres in the years between 1928 and 1936. The Gulf stream itself has increased about half a degree Centigrade, at its origin in the straits of Florida (Jensen, 1939). Scherhag (1937) ascribes the warming effect in the sea to an increase in the strength of atmospheric circulation between the tropics and the polar regions, and on the basis of an examination of Easton's (1928) coefficients for west European winters since the year 1235, concludes "that it appears to be a question of a secular period in the variation of atmospheric circulation of some 225 years duration, which seems at this juncture (1937) to have attained its maximum".

WEST GREENLAND WATERS

The result of the retreat of the influence of the polar water, and of the greater strength and temperature of the Atlantic drift water, has been the warming of the west Greenland current during the past few decades. This in turn has caused important and most striking changes in the marine fauna of that coast. The fauna of the arctic water has retreated steadily farther north, and has been replaced by Atlantic forms. Of first importance among the Atlantic animals are the cod (*Gadus callarias*) and the Atlantic halibut (*Hippoglossus vulgaris*), which have made possible the development of native and commercial fisheries in west Greenland. The transport of the arctic pack-ice (the Danish "storis") by the east Greenland current round to the west coast since 1820 has been reviewed by Speerschneider (1931), showing a marked decrease in the quantity of ice carried around since about 1910, and in the distance to which the ice reaches north along the west coast. The warming effect is now easily discernible in the water at least as far north as Upernavik, in latitude 73°, and possibly as far as Thule. A temporary return to colder conditions in 1937 in the southwest was recorded by Hansen (1939), and lower temperatures were repeated and accentuated all along the coast in 1938. Warmer ("normal") conditions returned in 1939 (Hansen, 1940).

The occurrence of the Atlantic cod in west Greenland is the simplest indicator of the strength of the Atlantic water, and the history of cod fishing in Greenland is thus the history of the water temperatures. Cod were fished on the west Greenland banks in the 1820's and again in the 1840's. By 1850 the cod had disappeared and more arctic conditions had returned to the banks. The more recent development of the native Greenland fishery is described in the following quotation from Dunbar (1947):

> "As early as 1906, the (then) Directorate of Greenland Trade sent Napoleon Andreassen to try for cod in west Greenland. He found a few in the fjords, and none on the banks. There seemed to be no possibility of the development of a sizeable fishery. However, in 1908 and 1909, the "Tjalfe" expedition was sent out, from whose pioneer work the present fishery has developed. This expedition extended its activities from cape Farewell to Umanak, and like Andreassen found cod in small numbers in certain fjords in the southwest. . . . In 1917 the constant vigilance of the Danes was rewarded by the appearance of Atlantic cod in some numbers in the Julianehaab and Frederikshaab districts. . . . The invasion spread north year by year. In 1919 the cod were found at Godthaab, in 1922 at Sukkertoppen, in 1927 at Holsteinsborg, and by 1928 they had reached the mouth of Disko bay. By 1931 the cod were well into the bay, being caught at Christianshaab and Ritenbenk, and had even penetrated round the Nugssuak peninsula to Umanak. In more recent years the codfish have appeared in small numbers at Upernavik."

Temperature curves, mostly of the upper 300 metres in the west Greenland current, from years back to 1883, are presented here in figs. 25 to 29, from Dunbar (1946). The material from which they are constructed is taken from all the available literature, both the reports of small individual expeditions and of larger undertakings such as the Swedish "Sofia" expedition of 1883 (Hamberg, 1884), and the Danish "Fylla", "Ingolf", "Tjalfe", "Dana" and "Godthaab" expe-

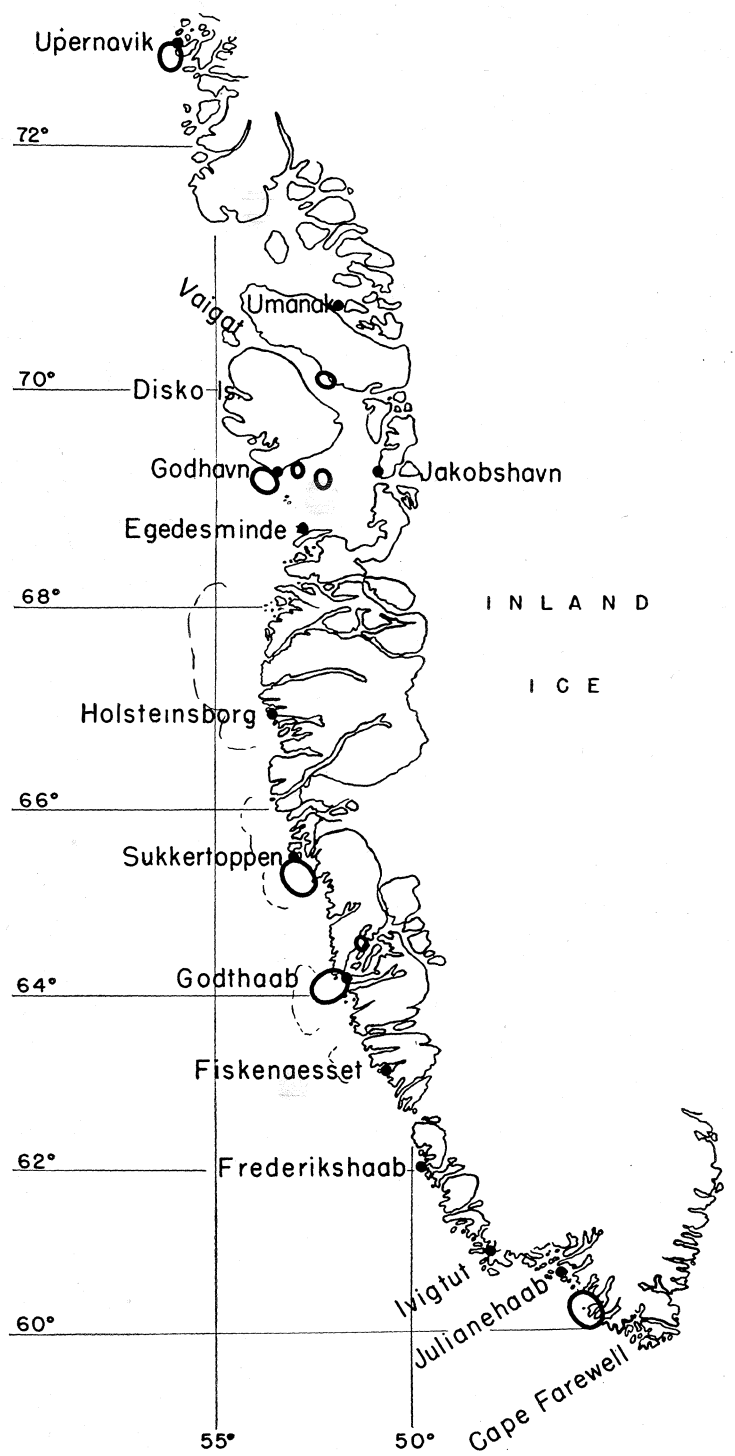


FIGURE 24. The west Greenland coast from cape Farewell to Upernavik. The heavy rings show the areas from which stations were taken for temperature comparisons shown in figs. 25 to 29 inclusive. From Dunbar (1946).

ditions (Wandel, 1891; Knudsen, 1898; Nielsen, 1928; Conseil Permanent, 1926 and Riis-Carstensen, 1936). Material is also taken from the results of the Norwegian "Michael Sars" expedition of 1924 (Martens, 1929), and the United States Coastguard "Marion" and "General Greene" investigations of 1928-35 (Smith, Soule and Mosby, 1937). The results of the smaller coastal expeditions have been published by Jensen (1881 and 1889), Hammer (1883), Ryder (1889), Moltke (1896), Garde (1896) and Knudsen (1923). The author's own records from west

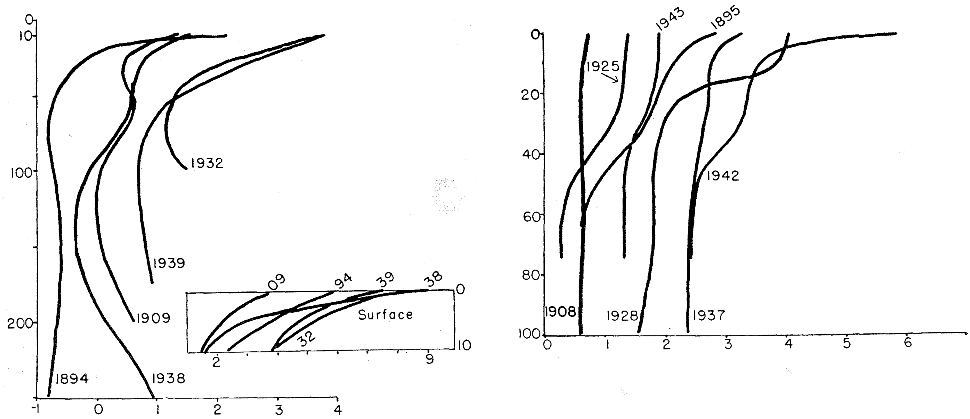


FIGURE 25. *Left:* Julianehaab district.

1894—Mouth of Tasermiut fjord, August 16, 1894; approximate position, 60° 08′ N, 45° 11′ W. (Moltke, 1896).

1909, 1932, 1938 and 1939—Lichtenaufjord, August 22, 1909; Aug. 15, 1932; Aug. 12, 1938; Aug. 18, 1939. (Hansen, 1940).

Right: Godthaab district.

1895—Off Godthaab fjord, June 25, 1895. 63° 57′ N, 52° 41′ W. (Knudsen, 1896).

1928—Off Godthaab fjord, June 18, 1928; 64° 02′ N, 52° 19′ W. (Riis-Carstensen, 1936).

1925—Off Godthaab fjord, June 19, 1925; 64° 11′ N, 52° 47′ W. (Conseil Permanent, 1926).

1908—Mouth of Godthaab fjord, June 20, 1908; "Tjalfe" expedition, quoted from Jensen (1939).

1937—Off Sardlok, just inside Godthaab fjord, June 26, 1937 (Jensen, 1939).

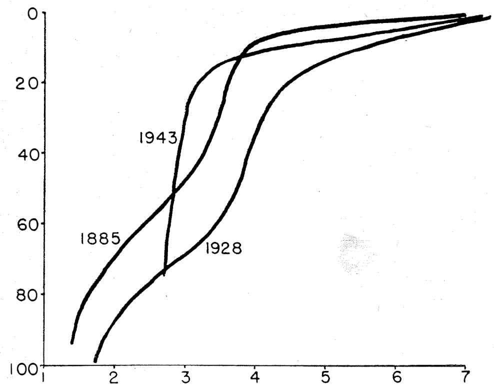
1942—Mouth of Godthaab fjord, June 19, 1942 (Dunbar).

1943—Mouth of Godthaab fjord, June 17, 1943 (Dunbar).

Ordinates: depth in metres. Abscissae: temperature centigrade. From Dunbar (1946).

Greenland have been used, and also temperature measurements made by Hansen during the course of his fishery investigations (Hansen, 1939, 1940).

The observations used were made at the stations shown in fig. 24. The records, for this purpose of comparison, had to be as closely as possible coincident both in place and in season. With two exceptions (fig. 28 left, and fig. 29 right) the seasonal range in any one figure does not exceed two weeks, and is usually less. Using this method, short-term fluctuations, and in the surface layers atmospheric



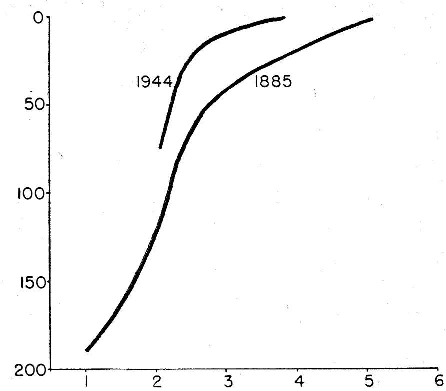


FIGURE 26. *Left:* Godthaab district.

1885—Mouth of Godthaab fjord, Aug. 7, 1885 (Jensen, 1889).

1928—Off Godthaab fjord, Aug. 1, 1928; 64° 01′ N, 52° 25′ W. (Smith, Soule and Mosby, 1937).

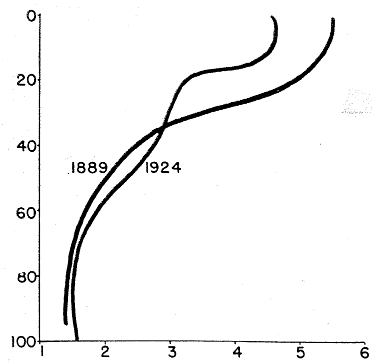
1943—Mouth of Godthaab fjord, July 24, 1943. (Dunbar).

Right: Godthaab district.

1885—Inside Godthaab fjord, about 27 miles north of Godthaab colony, Sept. 4, 1885 (Jensen, 1889).

1944—Same position (Station 12, fig. 21), Sept. 8, 1944. (Dunbar).

Coordinates as in fig. 25. After Dunbar (1946).



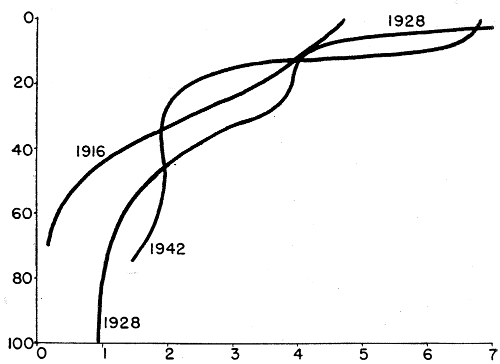


FIGURE 27. *Left:* Sukkertoppen district.

1889—Southwest of Sukkertoppen, July 29, 1889; 65° 18′ N., 53° 21′ W., (Wandel, 1891).

1924—South of Sukkertoppen, Aug. 6, 1924; 64° 53′ N., 52° 55′ W., (Martens, 1929).

Right: Disko bay area.

1916—West of Godhavn, Aug. 1, 1916; 69° 15′ N., 54° 00′ W., (Knudsen, 1923).

1928—Southwest of Godhavn, Aug. 7, 1928; 69° 09′ N., 53° 32′ W., (Smith, Soule and Mosby, 1937).

1942—Two miles west of Godhavn, July 31, 1942 (Dunbar, see table XI).

Coordinates as in fig. 25. From Dunbar (1946).

conditions, may be disturbing factors. It is, however, the only method which the data allow, and the pattern of the development of the present warm period, brought out at various points along the coast, is consistent. Temperatures used are typical for the time and place at which they were recorded, and observations derived from abnormal areas, as for instance the Jakobshavn ice-fjord, have been avoided.

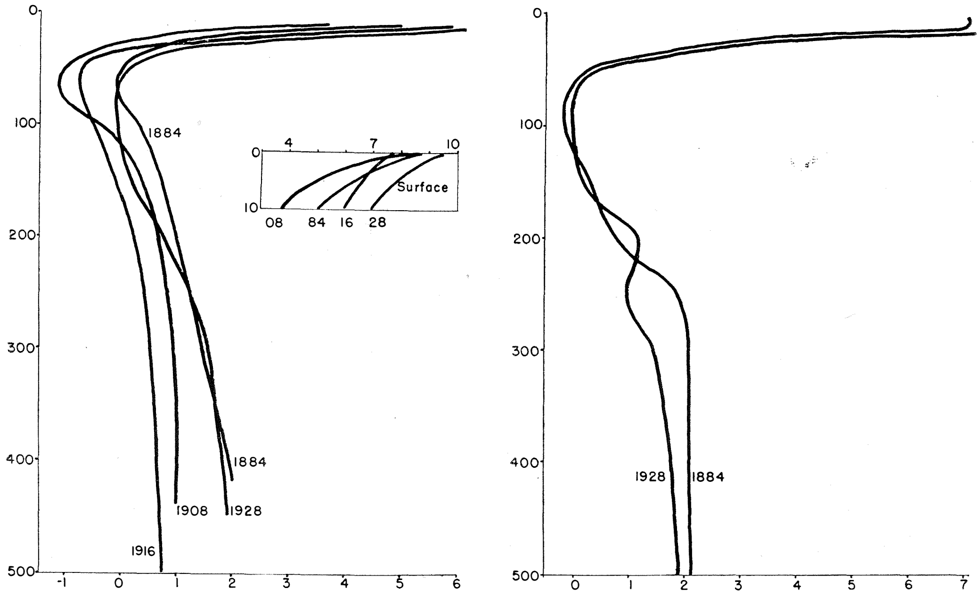


FIGURE 28. *Left:* Disko bay area, middle of bay.
1884—July 23, 1884; 69° 17′ N., 52° 15′ W., (Wandel, 1891).
1908—July 16, 1908; 69° 12′ N., 52° 08′ W., (Knudsen, 1923).
1916—July 22, 1916; 69° 13′ N., 52° 20′ W., (Knudsen, 1923).
1928—Aug. 8, 1928; 69° 12′ N., 52° 13′ W., (Smith, Soule and Mosby, 1937).
Right: Disko bay area.
1884—East of Godhavn, July 23, 1884; 69° 14′ N., 52° 54′ W., (Wandel, 1891).
1928—East of Godhavn, Aug. 8, 1928; 69° 12′ N., 52° 49′ W., (Smith, Soule and Mosby, 1937).
Coordinates as in figure 25. From Dunbar (1946).

The figures, with their legends, are self-explanatory, and very few notes are required. In fig. 25 left, the great difference in the deeper layers between the 1894 curve and the others is not due to an actual rise in temperature of this magnitude in the time interval concerned, but to the fact that the 1894 record comes from inside the mouth of a "threshold" fjord (Tasermiut fjord), into which the passage of the warm underlying water outside is prevented by the presence of the high threshold at the entrance, as described above. Fig. 29 left compares 1928 and 1943 temperatures from the eastern side of the Vaigat, in September.

The curves are in fairly close agreement, and have the wavy form often found in the vicinity of any considerable amount of berg-ice. The Vaigat, at that time of year, is the main outlet for icebergs from the Jakobshavn ice-fjord.

The curves in fig. 29 right are separated by so large a time interval that they are not properly comparable. They represent, however, the only material available from the vicinity of Upernavik, with the exception of temperatures from close to the inland ice in the same latitude as Upernavik, taken by Ryder in August 1886 (Ryder, 1889). Ryder's figures have not been included, as the distance

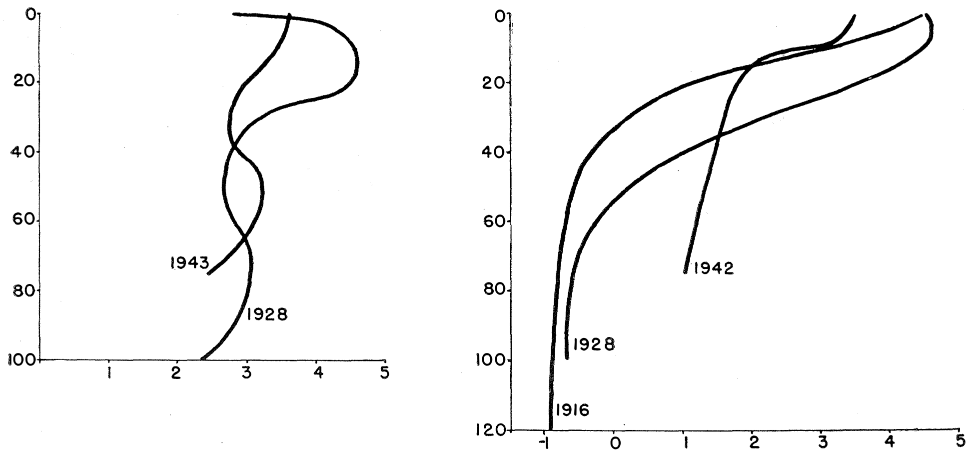


FIGURE 29. *Left:* The Vaigat.
1928—Sept. 6, 1928; 70° 07.5 N., 52° 33′ W., (Riis-Carstensen, 1936).
1943—Sept. 15, 1943; approximate position: 70° 00′ N., 52° 20′ W., (Dunbar, see table XI).
Right: Upernavik district.
1916—South of Upernavik, Aug. 3, 1916; 72° 30′ N., 56° 12′ W., (Knudsen, 1923).
1928—SSW of Upernavik, July 21, 1928; 72° 37′ N., 56° 31′ W., (Riis-Carstensen, 1936).
1942—Four miles south of Upernavik, Aug. 30, 1942; approximate position: 72° 43′ N., 56° 11′ W., (Dunbar, see table XI).
Coordinates as in fig. 25. From Dunbar (1946).

between his stations and those shown in the figure is some 35 miles, and the conditions are unlike. Ryder's observations show bottom temperatures of 2.0, 2.5 and 2.7° C. in depths of 114, 137 and 146 metres respectively. These are remarkably high temperatures, and can only be due to Atlantic influence. They are thus evidence of warmer water in the 1880's, in summer. In fig. 29 right, the 1928 temperatures are a little higher than those of 1916, and were taken two weeks earlier in the season. The seasonal interval between the 1928 and 1942 curves is 40 days, the 1942 observations being from August 30 and the 1928 observations from July 21. During such an interval the 1928 temperatures would be expected to have increased somewhat. All that can be inferred with certainty from the 1942 figures is that Atlantic influence is clearly discernible in August at Upernavik.

It stands out clearly from the temperature curves published here that the coldest period since 1883, in west Greenland, was approximately between 1900 and 1920. The figures from the 1880's, and even from the 1890's, are everywhere higher than from the ensuing period, and sometimes match the temperatures from the 1930-44 period. This is seen in fig. 25 right, and most conspicuously in fig. 26 right, from the interior of Godthaab fjord. The warm water found in 1884 is also well shown in figs. 28, left and right. The sudden cold season of 1938 is illustrated in the 1938 curve in fig. 25 left.

In constructing these figures, the warmer conditions found at the end of the last century came as a surprise, more especially since the ice records compiled by Speerschneider (1931) show that during the decade of 1880 the transport of ice up the coast was above normal. Speerschneider himself points out, however, that the amount of floe-ice in west Greenland is not necessarily a function of the quantity of arctic water in the west Greenland current, but is largely dependent on the agency of winds during the early part of the year. Kiilerich's study (1943), which was not available in Canada until 1946, agrees with the present findings; he describes the seasons between 1884 and 1895 inclusive (represented by 1884, 1886, 1889 and 1895) as being characterized by strong or fairly strong development of the Atlantic component of the west Greenland current. The 1883 season, on the other hand, was cold. Kiilerich summarizes his findings as follows:

"From this survey it appears that the hydrographic conditions off the western coast of Greenland have varied rather considerably during the last half century. Unfortunately years from which no hydrographic observations are available form the majority, and also observations from many of the expeditions are so scarce and scattered that it has been impossible to undertake dynamic computations or any other thorough investigation as to the character and movement of the volumes of water. Accordingly, no coherent view of the variations within this space of time is given, but we are able to say that apparently a relatively warm period sets in during the years of 1880, and was still (or again) present in 1895. Evidence is available of colder water in the first part of our century, until the year 1926 begins a new warm period with considerably warmer water than in the decade beginning 1880. This period culminated in 1934, 1936 was still very warm, 1937 fairly normal and 1938 very cold. The observations of the latter years, however, were made so close to the banks as to give us but little information about the currents out in the strait."

There is an apparent implication in this quotation that the present warm period is waning. More recent observations have not decided this point either way. The cold spell in 1938 was temporary only, and the warmer water returned in 1939. During the 1940's, temperatures measured in Godthaab fjord (see tables IV to VIII) show continued warm conditions. There is, on the other hand, no indication of the continued *increase* in temperature; the maximum, as Kiilerich points out, appears to have been reached in the middle 1930's. There are slight indications of a cooling during the years 1942-4 in the early spring, in Godthaab fjord; that is to say, a suggestion of a retardation in the effects of the Atlantic water in the west Greenland current, as already mentioned above. It is impossible to say at the moment whether these indications actually herald a return to colder water conditions. It may, however, be significant that in August, 1940, Godthaab was blocked to navigation by "storis" (from east Greenland) for the first time since 1898. No observations are at the moment available from west Greenland waters since 1946. The 1945-6 observations in Godthaab fjord did not indicate any further cooling.

The scale of the temperature changes involved is well shown by the following measurements made by Hansen (1939, 1940) illustrating the 1938 cold spell:

Julianehaab di.trict (Lichtenaufjord): (Degrees Centigrade)

YEAR	1909	1932	1938	1939
DATE	Aug. 22	Aug. 15	Aug. 12	Aug. 18
Depth (m.)				
0	3.85	9.35	9.50	7.60
10	1.45	3.85	1.56	3.85
25	0.52	2.49	0.87	2.87
50	0.62	1.35	0.63	1.38
100	0.07	1.53	−0.13	0.72
175				0.93
200	0.61	1.14	0.18	

Sukkertoppen district (Hamborgsund off Narssak):

YEAR	1934	1935	1936	1938
DATE	June 20	June 25	June 23	June 24
Depth (m.)				
0	6.70	3.60	4.00	5.60
10	3.42	3.12	2.83	2.20
25	2.40	1.48	2.41	0.88
50	1.64	0.80	2.04	0.42
100	1.08	0.02	1.43	0.03
200	1.23	0.26	1.04	−0.33
250	1.27		0.93	
300		0.38		−0.71

From these measurements it will be seen that the year 1935 was also a colder year than most, in the Sukkertoppen district.

The most recent information on the west Greenland current is somewhat disturbing, from the point of view of the Greenland economy. The early spring of 1949 (April-May) has been very cold in the marine environment. The quantity of east coast "storis" brought round to the west coast is reported as most exceptionally large for the present years, causing the blocking of southwest ports to navigation. More serious still, the water itself appears to have been very cold, and considerable numbers of Atlantic cod have appeared at the surface, dead, just as in 1938 (Einar Mikkelsen, personal communication). This is, in other words, a repetition of the cold spell of 1938. Whether it is nothing more than that, and is to be considered as a temporary reversal of the general warming, or whether it heralds the end of the warm period, cannot be decided now. In either case, the issue will probably not be clear for some few years yet.

CANADIAN WATERS

On the Canadian side of the eastern arctic area, the extreme sparseness of hydrographic observations during the past fifty years (or before) makes it impossible to form an opinion on any cyclical behaviour of the water temperatures. If any such change is occurring, or has occurred, it is probably due to the increased influence of Atlantic water, just as in west Greenland. Since the influence of Atlantic water is very much less in Canadian waters than in Greenland waters, such a change must of necessity be less in amplitude. That the Atlantic water of the west Greenland current, however, does penetrate some distance into Hudson strait (see above, on the plankton at Lake harbour), is already known, and it is therefore conceivable, if not also probable, that the Canadian waters of the eastern arctic are subject to similar fluctuations. It was in part to provide information on this point that the H.M.C.S. "Haida" included hydrographic measurements in her activities in 1948, and the results she obtained are interesting.

It will be remembered that the "Loubyrne" observations in Hudson bay, made in 1930, were not included in the T-S correlation diagrams used to show the various types of water present in the eastern arctic seas. When plotted on the diagram, the 1930 temperatures and salinities fell so far outside the polar water polygon (polygon no. 5, fig. 3—see above, page 31), and so far away from the "Haida" 1948 observations, that it was clear that some change had occurred between 1930 and 1948 in Hudson bay. The two sets of observations were made at similar seasons. The inclusion of the 1930 figures would, moreover, have enlarged and distorted the compact polar water polygon, so much that there would be little point in treating the Hudson bay water as of the same origin as the rest of the water represented in the polygon; and yet it is clear that the Hudson bay water must be derived very largely from the polar water entering through Foxe basin.

This anomalous situation is illustrated in fig. 30, in which the polar water of the eastern arctic (polygon no. 5), the water of the "Haida" 1948 observations in Hudson bay (polygon 6), and the "Loubyrne" 1930 Hudson bay observations (polygon 7), are shown together. (As before, the upper 50 metres of water have been omitted). It will be seen that the "Haida" 1930 water lies almost completely outside the polar water area, and that there is practically speaking no overlap between the 1930 and 1948 Hudson bay waters. The 1930 water is colder and less saline than the 1948 water. Only two possible explanations of this most interesting finding occur to the writer:

1. First possibility. Since 1930 there has been a progressive change in the water of Hudson bay, due to the increasing proportion of the Atlantic element in the water, which must enter through Hudson strait. This change has occurred during the peak of the warm period in west Greenland, and has effected an increase in both temperature and salinity in Hudson bay.

If this is a true interpretation, it must be admitted that the warming is slight, and that the 1948 water is still well inside the polar water area on the T-S diagram.

On the other hand, it might be reasoned that all the water inside polygon no. 5, the so-called polar water, is from areas where the possibility of Atlantic influence, via the west Greenland current is not completely excluded.

2. Second possibility. The change in the Hudson bay water occurred suddenly, at some time between 1930 and 1948. On this view the Hudson bay water, for the most part, is retained inside the bay by a threshold at the western end of Hudson strait, or by pressure from Foxe basin, or both, until critical conditions are built up, causing the flushing out, or ventilation, of Hudson bay. This might be a periodic phenomenon, and would depend on the decrease in density of the Hudson bay water, or increase in density of the Hudson strait water. Both might have occurred between 1930 and 1948, the former by a gradual process of dilution

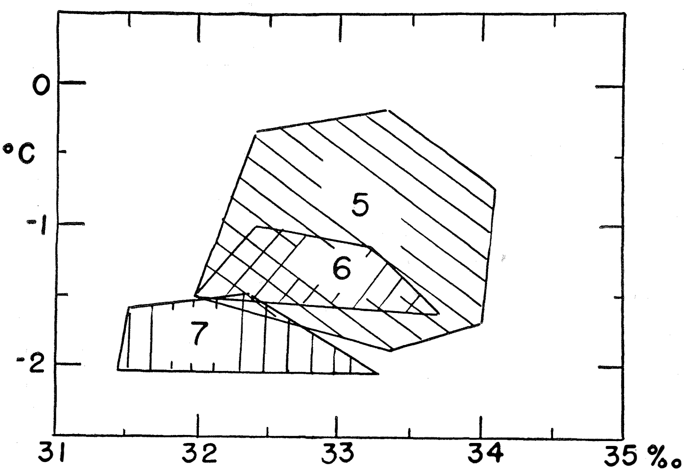


FIGURE 30. Temperature-salinity diagram showing the "Haida" observations of 1948, from Hudson bay, and the "Loubyrne" observations of 1930, superimposed upon the polar water polygon from fig. 3. 5. Polar water (from fig. 3). 6. "Haida" 1948. 7. "Loubyrne" 1930.

by mixing with the surface water of low salinity, the latter by an increase in the Atlantic, west Greenland, component. The excessive cooling of the Hudson bay water, found by the "Loubyrne" expedition, would of course increase the density, but it is by no means impossible that the processes operating would at some point decrease the density of the Hudson bay water to a figure below that of the Hudson strait water.

On the present data, which consist of a few observations made over a very small part of the season in two summers eighteen years apart, there is no value in further speculation. It will be necessary to study the waters of Hudson bay and Hudson strait from break-up to freeze-up for a period of years before the problem of the behaviour of the Hudson bay water can be solved. Both the explanations offered above are conceivably possible; and they are not incompatible the one with the other. It should be pointed out, finally, that if the first process has taken place, namely the gradual change in the water under increasing Atlantic influence, then it follows that the waters of Hudson bay, below 50 metres, are not dynamically dead as was calculated by Hachey (1931b). The second possibility, that of sudden ventilation, also requires a certain amount of movement in the deeper layers in order to allow for the dilution of the water. The present writer is inclined to favour this second explanation.

Since the preparation of the manuscript of this paper, the "Loubyrne" (1930) and "Haida" (1948) material has been independently studied by Bailey and Hachey (1949), who come to the same general conclusion concerning an increased Atlantic influence between 1930 and 1948. This study contains also a most useful analysis of the conditions in Hudson strait.

ARCTIC AND SUBARCTIC

The delimitation of the arctic from the subarctic has exercised scientific explorers for many years. The matter is of great interest, since a sound criterion of delimitation is a useful tool in geographic systematics, and moreover the resources and potentialities of subarctic regions are not the same as those of the arctic. In terrestrial environments, there are considerable difficulties involved in drawing a useful line between arctic and subarctic which is agreed upon by all concerned. Various criteria, such as the 50° F. July isotherm, the permafrost line, and the tree line, have been used, and a recent method developed by Baird (in press) defines the terrestrial arctic as the land area to the north of both of two lines, the one being the Nordenskiold line (based on a function of the highest and lowest temperatures during the year), and the other being the line of 500 mm. annual precipitation.

Whatever the most acceptable criterion to be used in the terrestrial environment, it has become clear that the terrestrial criterion cannot be imposed upon the marine environment, or *vice versa.* That there must be some relationship between the two, however, follows from the influence which the marine and the atmospheric climates exert upon each other. The discrepancy between the terrestrial and marine delimitations is due partly to causal lag in a changing system, and partly to the fact that in wintertime all of the arctic water, and part of the subarctic water, is frozen, with consequent winter climatic effects in the terrestrial environment which cannot be cancelled out by the short summer season. The marine and atmospheric climates are thus open systems which are in a condition of oscillating equilibrium and which together make up a larger (but still open) natural system.

It is simple, in the marine environment, to propose a criterion for the delimitation not only of the arctic from the subarctic, but also of the subarctic from the boreal or temperate. It is not always so simple to establish at any specific moment where the lines of delimitation lie. We can define arctic marine areas as composed of arctic water only, that is to say of water originating from the upper

200 metres of the polar basin; subarctic areas as composed of a mixture of arctic and non-arctic water (Atlantic or Pacific; coastal drainage water is ignored in this system); and boreal or temperate areas as bounded to the north by the line south of which there is no admixture of arctic water.

Arctic water is itself largely of Atlantic origin; but it has suffered a polar change such that it has lost in both salinity and temperature, and is recognizable as a quite distinct water mass. There is no doubt about the arctic nature of certain areas, for instance the shores of the polar sea itself, the northeast coast of Greenland, and the channels between the more northerly of the Canadian arctic islands (McClure strait, Melville sound, Barrow strait, Lancaster sound, and channels to the north). South of these regions, however, the arctic or subarctic nature of the water is not easy to establish, at least by physical methods. In Hudson bay, for example, it follows from material presented in this paper that there is a possibility of some admixture of Atlantic water, from the west Greenland current; yet the presence of this Atlantic water cannot (as yet) be demonstrated by the methods of physical oceanography. The circulation in Baffin bay, to take another example, brings a small amount of west Greenland water over to the west side of the bay; but it is not demonstrable in the upper layers. The west Greenland water clearly plays an important part in the formation of the deep Baffin bay water, but the subarctic or arctic nature of an area, for the purposes of the present discussion, is determined by the nature of the upper water.

Where physical methods fail, biological methods may be used instead. There are a number of biological indicators which can be used to delimit the arctic from the subarctic in the sea, which when used together, and with proper knowledge of their biology, are reliable. The most obvious is the Atlantic cod, *Gadus callarias* Linnaeus, which does not live or breed in pure arctic water, but which is very abundant immediately outside the arctic zone. The presence of this animal in northern waters is a sure sign of Atlantic admixture, and moreover it does not extend its range far beyond subarctic limits to the southward. In the eastern arctic area, then, the whole of the west coast of Greenland is subarctic, up to Upernavik (latitude 73° N) at least, on this criterion. Similarly the Labrador current is subarctic and the northeast part of Ungava bay, in the vicinity of Port Burwell, where Atlantic cod are numerous in the summer.

The hydromedusan *Hybocodon prolifer* L. Agassiz, as already mentioned (see section on circulation), extends the subarctic water into Hudson strait, at least along the north side, as far as Lake harbour (Dunbar, 1942b), and confirms the subarctic nature of the west Greenland water (Kramp, 1942). There are in fact many planktonic forms which may be used as indicators of Atlantic influence in these regions, some of which are discussed by Jensen (1939). So far, *Hybocodon* is the only one recorded from Hudson strait.

Madsen (1936, 1940) has shown that the distribution of three common intertidal littoral animals appears to be due to some factor other than atmospheric climate and winter ice, and suggests that the general productivity of the water may be the decisive factor. Dunbar (1947b) has suggested that the productivity may itself be due to the subarctic nature of the water, and that Madsen's littoral forms may in fact be useful indicators of the arctic-subarctic line of demarcation. The three animals quoted by Madsen are the common blue mussel (*Mytilus edulis* Linnaeus), the little gastropod *Littorina saxatilis* var. *groenlandica* Olivi, and the barnacle *Balanus balanoides* Linnaeus. Madsen found that a marked change took place in the intertidal fauna between latitude 66° and 67° on the east coast of Greenland, and at latitude 74° on the west coast, or a little north of Angmassalik and Upernavik respectively. The change consists in the sudden disappearance of the three "indicator" forms; and this disappearance is continued down into the sublittoral zone, below low water mark. The change is more noticeable in the case of *Littorina* and *Balanus* than for *Mytilus*, which continues farther north in the sublittoral, and which in fact has since been reported from as far north as Thule, in the littoral zone (Vibe, personal communication). On the east coast, the limit of distribution of these species coincides with a sharp drop in the production of fauna both above and below low water mark; information on this point from northwest Greenland is less clear.

Madsen points out that the atmospheric climate of Upernavik is considerably colder than that of Angmassalik, so that correlation of the climate with the littoral fauna is not possible, and he rejects the hypothesis that the temperature and salinity of the water are decisive factors for the littoral fauna. To quote from his 1940 paper: "It seems to me that other causes are decisive, causes which have some connection with the productivity of the sea, therefore also acting on the sublittoral". This greater productivity is thus, by implication, not demonstrable by the ordinary physical methods of oceanography. There is, however, no doubt that this greater productivity is due to the admixture of non-arctic water, and that the reason why it is difficult or impossible to demonstrate the limits of such admixture by physical means is simply that the biological indicators are more sensitive than the instruments so far devised. To quote again from Madsen: "The clearest boundary, viz., that north of Angmassalik, is evidently also somehow dependent on the Irminger current here washing the coast, partly intermingling with the polar current". He also correlates this Irminger effect with the increased plankton production south of the boundary in east Greenland. Increased plankton production is commonly met with at the junction of a cold and a warm current.

It will be clear from the present account of the circulation of water in Baffin bay (above) that the conditions at the Upernavik level are not so very different from the Angmassalik conditions, in that in both regions there is a certain amount of Atlantic influence. Madsen's hypothesis of the productivity of the water, therefore, is as likely to be true of northwest Greenland as of east Greenland.

Littorina saxatilis and *Balanus balanoides* are both common in Ungava bay, on all shores (Dunbar, unpublished data from Fisheries Research Board investigations). *Littorina* is also known from Akpatok island (Davis, 1936) and from

Hudson bay (Dall, 1924). Both *Littorina* (under the name *rudis*, var. *groenlandica* Morch), and *Mytilus edulis* were recorded by the Canadian Arctic Expedition of 1913-18, at stations both west and east of the Mackenzie river (Dall, 1919). In other parts of the north the limit of *Littorina saxatilis*, which appears to be the most useful and reliable of the three, coincides with the known or supposed limits of Atlantic or Pacific intrusion. Thus in northern Europe *Littorina* is recorded as far east as the Murman coast, and in Spitsbergen this mollusc is known from the south and west but not from the north and east.

If we are to accept Madsen's criterion for the separation of the arctic from the subarctic, much of the waters immediately north of continental North America must be considered as subarctic, with some admixture of non-arctic water. The central and northwest waters (Beaufort sea, and east) must be considered as influenced to some extent by Pacific water, a fact which is emphasized by the distribution of the Pacific herring into the waters of the northwest. In Hudson bay, it is the Atlantic water which must be held responsible. The possibility of the penetration of a small quantity of Atlantic water into Hudson bay is also suggested by the record of eel-grass (*Zostera marina* L.) in James bay and at stations in Hudson bay by Porsild (1932). The presence of *Zostera* in Hudson bay was formerly thought to be due either to its persistence from a milder, postglacial period, or to the agency of birds; but the possibility of recent transportation by water should not be ignored.

There are other biological indicators which appear to confirm the significance of those already mentioned. One instance is the distribution of the two common sculpins, *Oncocottus quadricornis* Linnaeus, which is an arctic water form, and *Myoxocephalus groenlandicus* Cuv. et Val., which seems to replace *Oncocottus* in subarctic waters (Dunbar, 1947b). Both species are found in Hudson bay and Ungava bay, but the subarctic form is the commoner. Many animals of the true arctic water have receded northward in west Greenland during the warm period of the past 25-30 years, and these also may act as indicators of arctic water in proportion to the stenothermy of their existence. Such an animal is the narwhal, *Monodon monoceros* Linnaeus, whose distribution falls almost entirely outside the subarctic areas discussed here, being rare even in northwest Greenland (south of Thule) except in winter. On the Canadian side, it occurs normally only in the northerly part of Hudson bay and in Foxe basin, and in the waters of the arctic islands, east to approximately Pond inlet and to a lesser extent in along the northeast Baffin coast. It is rare in these years in Cumberland sound, though formerly fairly numerous there (Anderson, 1934, 1946). In Hudson strait it is rare.

Taken all together, these biological indicators agree in making the whole of the west Greenland waters, from cape Farewell to Thule, subarctic, in stamping the eastern part of Hudson strait, together with Ungava bay, also as subarctic, and in at least suggesting the subarctic nature of the Hudson bay water. The Labrador current is certainly subarctic. This means that polygon no. 5, in fig. 3, representing the so-called "arctic" water of the eastern arctic area, in fact has some small admixture of non-arctic water, as has already been indicated above (long term change). There are objections to be made to some of the indicators, not excluding Madsen's three littoral species. Thus *Balanus balanoides* was recorded from Port Foulke in northwest Greenland in 1863, and was described by Jensen as being "common everywhere (in Greenland) between high and low water mark" (Stephensen, 1913). *Mytilus edulis* was known up to Melville bay in 1898, and *Littorina saxatilis* was known up to Upernavik at the same period (Posselt, 1898). Since we have every reason to suppose that the waters of west Greenland were much colder at that time, and since it follows that the subarctic limits should vary over the years with the marine climate, these early records shed a different light on the value of these indicators. However, in the distribution of littoral fauna a certain lag would be expected; the fauna would not follow changes in environment immediately, in all probability. The planktonic indicators, such as *Hybocodon*, and the nectonic forms, such as the Atlantic cod, Atlantic salmon in Ungava bay and west Greenland, and the sculpin *Myoxocephalus*, are no doubt more reliable and more immediate. It will be observed that notwithstanding the criticism of Madsen's indicators, these planktonic and nectonic indicators give the same result approximately as do Madsen's littoral forms.

The real test of the Madsen hypothesis, and of his criteria of arctic and subarctic waters, is the production of life in the water. So far our information on this point in arctic and subarctic regions is fairly crude, and we have no accurate estimate of either the actual production or the potential production (productivity) of arctic or subarctic waters. Such knowledge, which is in process of collection by the Fisheries Research Board, would be of "more" than academic interest, for subarctic waters are normally of considerable economic value. Arctic water has several characteristics which favour the production of life, such as high capacity for dissolved gases, long daylight in the summer, presumably a high concentration of the trihydrol polymer of water, and high viscosity (see Dunbar, in press). This high capacity to produce appears to be inhibited by only one factor, namely the low temperature which slows down growth rates. Where Atlantic or Pacific water meets and mixes with the arctic water, this inhibition is no doubt in part removed.

The west Greenland water in Baffin bay must take some part in the circular "feed-back" rotation in the deeper water of the bay; but it is not known whether it affects the upper layers in the western part of the bay. Certainly it does not appear in the physical observations made in the Canadian current. Madsen (in press) suggests that the Baffin island waters should be reckoned as subarctic, on the basis of scattered records of some of his littoral indicator species. The present writer feels, however, that much more work will have to be done along this eastern coast of Baffin island before this interpretation could be confirmed. The Atlantic influence in the cold Canadian current along Baffin island, if such influence exists at all in the upper 200 to 300 metres, must be exceedingly small.

On the basis of the discussion presented here, the delimitation of the arctic and subarctic zones in the marine environment is tentatively shown in fig. 31, not only for the eastern arctic area, but for the whole circumpolar field. It should be remembered that the line of delimitation fluctuates, probably to some extent seasonally and certainly over the long-range time scale. Of the lines based on all

FIGURE 31. The delimitation of the arctic from the subarctic in the marine environment, according to the criterion suggested in the text. The nature of the Hudson bay water is still doubtful.

possible criteria (including the terrestrial) it is probably the most delicately adjusted and the most immediate to react to environmental change. The time-lag which exists between the marine line suggested here, and the various terrestrial lines based on permafrost, precipitation, tree-line, etc., would be a most interesting subject for future study.

THE GAPS IN OUR KNOWLEDGE

The present account of the oceanography of the eastern arctic will have exposed to the reader the fields and areas which are in most immediate need of study. In the account given below of the field work immediately required, the subjects are treated under approximately the same headings as have been used hitherto.

BATHYMETRY

The western entrance of Hudson strait is probably the most important gap in the bathymetric map. Knowledge of the precise height of any ridge that may exist in that region would greatly assist our estimation of the behaviour of the Hudson bay water. Foxe basin, though known to be shallow, is unknown in bathymetric detail, a fact which is somewhat heavily underlined by the sudden discovery of new islands of considerable area in 1948. We are also very short of bathymetric information from Prince Regent inlet, the gulf of Boothia, Admiralty inlet and Eclipse sound. Soundings are also required in many of the fjords and other inlets in Canadian territory, as mentioned below.

SEDIMENTS

The sediments of the eastern arctic are very little known, as will appear from the chapter on sediments above. There is thus an almost virgin field for study here, although it may turn out to be a somewhat monotonous undertaking. Of particular interest is the origin of the calcium carbonate in the sediments; the accurate estimation of the proportions of marine and terrestrial carbonate in the sediments would be of great help not only in the field of biology but also in the study of the circulation of the ice. It will be remembered that Trask (1932) found that a high proportion of calcium carbonate in the sediments in Davis strait was of terrigenous origin, and hence must have been carried for many hundreds of miles by the ice.

WATER MASSES AND CIRCULATION

There is a serious state of unbalance in our knowledge of the different parts of the eastern arctic waters. The Labrador sea, Davis strait and Baffin bay have been well studied, although most of the work is now twenty years old and there may be important variations in the circulation since that time. Hudson bay and Hudson strait, both important and interesting regions, are known from only meagre and scattered work, none of which has been designed for the dynamic computations of present-day oceanography. This physical circulation of Hudson bay and Hudson strait is without doubt the most urgent of all the work required in the eastern arctic. In the estimation of the circulation, we are at present still guessing from grossly inadequate data and such unsatisfactory information as the reports of ice movement, and local knowledge. Fig. 32 gives a suggested arrangement of sections and stations to be occupied in such a study. In carrying out this work, oxygen determinations should be included in the programme.

Sections of the same sort are also required from the channels between the arctic islands, especially from Prince Regent inlet and the gulf of Boothia, Lancaster sound and Jones sound. The "North water" requires much more exact location than the present accounts allow, and the elaboration of special techniques

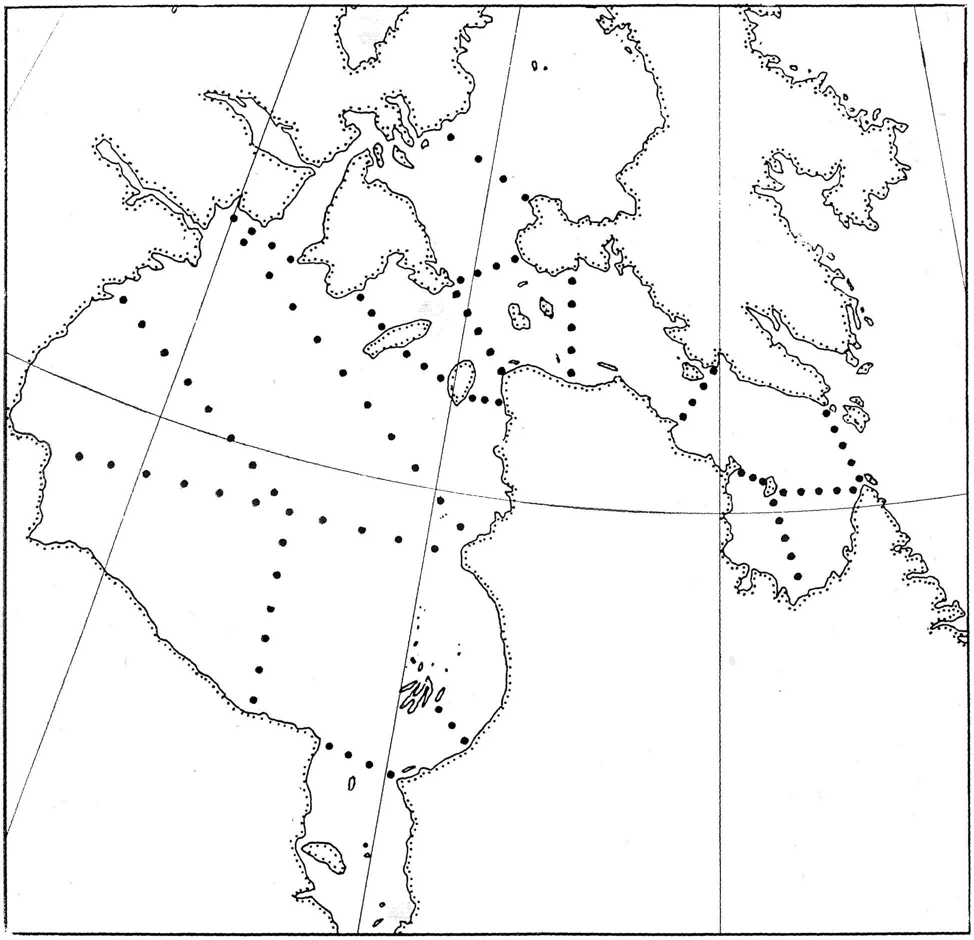


FIGURE 32. Suggested plan of hydrographic stations and sections for a study of Hudson bay and Hudson strait.

for the study of this phenomenon during the winter months would greatly add to our understanding of it.

INTERRELATION OF CYCLES

The examination of the relationships between both seasonal and longer-term cycles in the north offers a fascinating and most rewarding field of study. Although the understanding of these relationships is in reality the culminating phase of one line of research, and as such must lie a long time in the future, there is no reason why a beginning should not be made. The pattern of interrelation between cycles in atmospheric climate, marine climate (cycles within the water masses themselves), permafrost, tree-line, precipitation, and the distribution of biological resources, when finally worked out, will present the whole of the ecology of the north, at least all of it above a certain scale limit. At present we are filling in small details in this pattern without any vision of the total picture, and it is suggested that the opposite approach, that of constructing the large outlines, might be begun now with advantage. Not only would this procedure provide the proper framework into which to fit the more intimate investigations, but it would affect the whole approach to the work. New orientations are valuable. In particular, the study of cyclical inter-relationships would emphasize the dynamic nature of the phenomena observed and studied, and the sense of such a dynamic relationship between the cycles of various phenomena over a considerable period of years, might be a valuable piece of research equipment.

VARIATIONS IN MARINE CONDITIONS

The emphasis on the time-scale is especially significant in the study of variation in the marine conditions, whether seasonally or on the longer term. In the chapter on seasonal cycles, the interest and importance of such studies was underlined, also the fact that they are rare in oceanographic surveys, especially in the less accessible parts of the world. The maintenance of a few stations, which are occupied at intervals throughout the year (or as much of the year as is possible under given conditions) is often of much greater value than the coverage of a larger area in which no one station is occupied more than once in the season. Extending this principle to the longer term changes in hydrography, it is strongly recommended that efforts be made to keep routine observations going over a period of years, or permanently, in the same or comparable positions, so that we may be properly equipped to estimate the progress or regress of these cyclical phases. It has been shown in the discussion of such changes that we are at present greatly handicapped by the sparseness of the data available throughout the period of the present warming of the sea water in west Greenland. Since changes of this order are of the greatest significance, the establishment of routine observations on an adequate scale would not seem to be a fruitless expenditure of effort and money.

FJORDS AND OTHER INLETS

There is an immense amount of work to be done in the hydrography of fjords, suitable, moreover, for small inexpensive expeditions using small vessels. Most of the inlets in the Canadian territory of the eastern arctic have never been studied at all, many of the west Greenland fjords are unknown from the hydrographic point of view, and those which have been studied should be visited again, for much of the work is now out of date; the recent changes in west Greenland, and the possibility of the periodic ventilation of these fjords, show how such field work can become out of date and must be repeated. For any economic development of the fjord waters, such studies are essential, and in addition the purely scientific rewards are considerable. They may be divided into (1) the comparative study of fjords, to show the differences between the conditions within them, dependent upon the presence or absence of a threshold, and the height of the threshold, the type of water outside the fjord, and the effects of land drainage and ice melting; and (2) the circulation of the water within any given fjord or inlet, more especially the presence or absence of marked vertical circulation such as that associated with the "brown zones" (see above), and the extent and transport of the outflowing surface current which is so commonly found in fjords (or any inlets) and which have important effects upon the ecology of the life in the waters and hence upon their productivity. Inlets of especial interest in the Canadian area of the eastern arctic, whose investigation is clearly demanded, are Frobisher bay, Cumberland sound and the Clyde river fjord, all in Baffin island, the first two because they appear to be generally non-threshold inlets in an area where a certain amount of west Greenland influence might be expected, and the latter because it has the appearance, in its visible geomorphology, of being a typical fjord similar to the west Greenland specimens. It is hoped that the "Calanus", the new Fisheries Research Board arctic research vessel, will be working in these areas in the near future.

CHEMISTRY AND BIOLOGICAL PRODUCTION

It has been pointed out that the evaluation of the productivity of the Hudson bay water, and the estimation of the nature of the deep water, would have been easier if oxygen measurements had been made in that region. The question of whether or not the deeper water of Hudson bay is dynamically dead, for instance, could be settled largely on the oxygen figures alone. At present the only areas in the strictly Canadian waters of the eastern arctic, from which we have information of oxygen content, are the mouths of Lancaster and Jones sounds, the waters off southeast Baffin island (all supplied by the "Godthaab" expedition of 1928), and Ungava bay (Fisheries Research Board expeditions of 1947 and 1949). There is thus a wide range of waters whose oxygen content is entirely unknown.

The chemistry of sea water is becoming more and more an instrument of the physical oceanographer as well as of the marine biologist, and water types can be "spotted" all the more easily if their chemistry as well as their physics is known. Therefore in future oceanographic work in the eastern arctic, oxygen determinations are a minimum requirement; it would be better still to include phosphate and hydrogen ion estimations in the field programme as well.

Biological oceanography has been referred to only in passing; were it to be treated in full it would require twice or three times the space of this monograph to do it similar justice. The biological work which stands in most urgent need of being done in the eastern arctic is therefore not included in this chapter. Since, however, the matter of the productivity of the water was brought up in discussing the delimitation of the arctic from the subarctic, it is fitting to include the mention of studies of biological production in this list; the more so since it has been emphasized that biological and physical oceanography are most intimately connected, and that no student of the one can afford to neglect the other. Studies of the production of life in arctic and subarctic water thus stand high on the list of priority for future (and immediate) work, whether the approach to the eastern arctic waters as a whole be physical or biological.

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