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Document de recherche 2012/062

Région des Maritimes

Application of Ecosystem Research Results (ERI) to Fishery Management

Application des résultats de la recherche écosystémique à la gestion des pêches

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ABSTRACT

This Research Document presents results from the Maritimes Region Ecosystem Research Initiatives (ERI) that are applicable to fisheries management decisions. These initiatives were not specifically directed to address fisheries management decisions. Nevertheless, they provide insight and direction on a broad range of ecological interactions relevant to the application in fisheries management of Fisheries and Oceans Canada's (DFO) precautionary approach (PA) framework. Presentations of ERI results are organized into three themes of relevance to fisheries management: Environmental Variability and Climate Change Considerations, Spatial Management Considerations, and Bycatch Considerations.

Environmental Variability and Climate Change Considerations

"**Overview of Circulation in Maritime Canada Region**" describes the major circulation features in the region and how they are interrelated, based on data and circulation model simulations. The importance of the North Atlantic Oscillation (NAO) to circulation properties in the shelf seas of Atlantic Canada is described.

"**Climate Change on the Scotian Shelf: Recent Variability with a Future Outlook**" provides a summary of observed and projected ocean climate changes on the Scotian Shelf. It indicates that changes are occurring in air and ocean temperature, stratification, sea level and ocean acidity that are consistent with expectations for anthropogenic climate change. However, natural variability associated with the NAO and other large-scale forcings remains an important contributor to changes in some variables.

"**Climate Change Summary: State of the Scotian Shelf"** explores potential changes to productivity, species distribution, timing of seasonal events, and ocean chemistry on the Scotian Shelf as a result of climate change.

"**Zooplankton Variability in the Gulf of Maine and Scotian Shelf**" identifies spatial, seasonal, and interannual variability patterns of zooplankton diversity and community composition, and their relationships with environmental variability, to develop a better understanding of how changes in circulation and the physical environment influence the feeding environment for fish.

"**Ecosystem Responses to Climate Variability of the Atlantic Sea Scallop, *Placopecten magellanicus***" challenges previous assumptions on mortality and connectivity of scallop larvae on Georges Bank. By assessing the extent to which biological and physical factors affect retention and exchange among Georges Bank subpopulations, this work improves our understanding of the processes influencing connectivity and larval recruitment and explains the adaptive significance of spring spawned larvae in the life history of Georges Bank scallops.

"**Common Large-scale Responses to Climate and Fishing across Northwest Atlantic Ecosystems**" reports on a common pattern in the biological indicators responsible for the primary multivariate temporal trend in five northerly regions: an increase in abundance of phytoplankton, an increase in biomass at mid-trophic levels, and a decline in predatory groundfish size. While results are consistent with those observed under heavy fishing pressure, a more mechanistic understanding of how the climate affects lower trophic levels is needed to contextualize climate effects in heavily fished ecosystems.

Spatial Management Considerations

"**Spatial Reference Points for Data-Poor Fisheries: A Case Study of Sea Cucumber**" provides an example of how spatial reference points might be developed for fisheries management. Within a cluster in a lightly fished region, high density areas represent superior habitat simply because they support more individuals per unit area than low density habitat. These high density areas are also important to the reproductive cycle of broadcast spawners, and can be used to define fishing zones.

"**Reference Points to Maintain Spatial Distribution: Sea Scallops**" is another example of how spatial structure and habitat preferences can be used to derive reference points for fisheries management. The result of fishing down higher suitability areas to a more or less uniform density (and catch rate) over the entire fishing area creates an opportunity to use density changes rather than biomass as reference points. A lower reference point for the higher productivity areas could be based on mean density levels in the lower productivity areas.

Bycatch Considerations

DFO is developing a "**Bycatch Policy**" to ensure that Canadian fisheries are managed in a manner that supports the sustainable harvesting of aquatic species, minimizes the risk of fisheries causing serious or irreversible harm to bycatch and discard species, and accounts for total catch, including bycatch and discards. Scientific input will be required to support decisions on managing bycatch, and the type of information likely to be required is identified here.

"**Preferred Habitat for Certain Species**" links traditional assessment of bycatch issues through empirical, field-based studies in discrete areas, with habitat suitability measurements based on environmental data layers derived from multi-beam sonar data. These products, in combination with spatially explicit data on fishing pressure, could be used to assess potential conflicts in a multi-species context.

RÉSUMÉ

Le présent document de recherche donne les résultats des initiatives de recherche écosystémique de la région des Maritimes qui s'appliquent aux décisions en matière de gestion des pêches. Ces initiatives ne visaient pas particulièrement à aborder les décisions en matière de gestion des pêches. Néanmoins, elles fournissent des indications et une orientation sur une vaste gamme d'interactions écologiques en lien avec l'application du cadre d'approche préventive de Pêches et Océans Canada (MPO) à la gestion des pêches. Les présentations des résultats des initiatives de recherche écosystémique sont divisées en trois thèmes relatifs à la gestion des pêches : la variabilité de l'environnement et les considérations liées aux changements climatiques, les considérations liées à la gestion spatiale et les aspects relatifs aux prises accessoires.

Variabilité de l'environnement et considérations liées aux changements climatiques

Dans la partie présentant un **aperçu de la circulation dans la région des Maritimes du Canada**, on décrit les caractéristiques les plus importantes de la circulation dans la région et en quoi elles sont interdépendantes, en fonction de données et de simulations des modèles de circulation. De plus, on y décrit l'importance de l'oscillation nord-atlantique pour les caractéristiques de circulation dans les plateaux de la mer du Canada atlantique.

Dans la partie traitant de la **variabilité récente et des perspectives d'avenir quant aux changements climatiques sur le plateau néo-écossais**, on fournit un résumé des changements observés et prévus du climat océanique sur le plateau néo-écossais. Il est indiqué dans cette partie que des changements se produisent en ce qui concerne la température de l'air et des océans, la stratification, le niveau de la mer et l'acidité des océans. Ces changements correspondent d'ailleurs aux prévisions de changements climatiques anthropiques. Toutefois, la variabilité naturelle associée à l'oscillation nord-atlantique et à d'autres forçages à grande échelle continue de contribuer grandement aux changements de certaines variables.

Dans la partie fournissant un **résumé des changements climatiques et un aperçu de l'état du plateau néo-écossais**, on traite des changements de la productivité, de la répartition des espèces, de la synchronisation des événements saisonniers et de la chimie de l'océan qui pourraient se manifester sur le plateau néo-écossais en raison des changements climatiques.

Dans la partie portant sur la **variabilité du zooplancton dans le golfe du Maine et le plateau néo-écossais**, on définit les tendances de variabilité spatiale, saisonnière et interannuelle de la diversité du zooplancton et de la composition de la communauté, ainsi que leurs liens avec la variabilité de l'environnement, afin de mieux comprendre en quoi les changements dans la circulation et l'environnement physique influent sur l'aire d'alimentation des poissons.

Dans la partie traitant des **réactions de l'écosystème à la variabilité climatique du pétoncle géant *(Placopecten magellanicus)***, on remet en question les hypothèses antérieures sur la mortalité et la connectivité des larves de pétoncles sur le banc de Georges. Le présent travail, pour lequel on a évalué la mesure dans laquelle les facteurs biologiques et physiques ont des effets sur la rétention et les échanges parmi les sous-populations du banc de Georges, permet de mieux comprendre les processus qui influent sur la connectivité et le recrutement de larves, et explique l'importance des larves nées au printemps pour l'adaptabilité du pétoncle du banc de Georges au cours de son cycle de vie.

Dans la partie portant sur les **réactions courantes à grande échelle relativement au climat et à la pêche dans l'ensemble des écosystèmes de l'Atlantique Nord-Ouest**, on rend compte d'une tendance courante dans les indicateurs biologiques qui provoque la principale tendance temporelle à plusieurs variables dans les cinq régions plus au nord : l'augmentation

de l'abondance du phytoplancton, l'augmentation de la biomasse à des niveaux trophiques moyens et le déclin de la taille des poissons de fond prédateurs. Tandis que les résultats correspondent à ceux observés dans une forte pression de la pêche, il faut une compréhension plus axée sur les mécanismes de la façon dont le climat a une incidence sur les niveaux trophiques inférieurs afin de mettre en contexte les effets du climat dans les écosystèmes où la pêche est abondante.

Considérations liées à la gestion spatiale

Dans la partie traitant de l'établissement de **points de référence spatiaux pour les pêches peu documentées d'après une étude de cas de l'holothurie**, on fournit des exemples de la façon dont on peut établir des points de référence spatiaux pour la gestion des pêches. Dans une grappe se trouvant au sein d'une région peu exploitée, les zones à haute densité constituent un meilleur habitat tout simplement parce qu'elles soutiennent plus d'individus par unité de zone par rapport à l'habitat à faible densité. Ces zones à haute densité sont également très importantes pour le cycle reproductif des reproducteurs qui libèrent leurs gamètes au hasard et peuvent servir à définir les zones de pêche.

La partie portant sur l'établissement de **points de référence pour maintenir la répartition spatiale d'après la situation du pétoncle géant** est un autre exemple de la façon dont on peut se servir de la structure spatiale et des préférences en matière d'habitat afin d'établir des points de référence pour la gestion des pêches. Les résultats de la pêche dans les zones plus convenables à une densité (et un taux de prise) plus ou moins uniforme dans la zone de pêche entière créent une occasion de se servir des changements de densité comme points de référence au lieu de la biomasse. On pourrait établir un point de référence inférieur pour les zones de productivité plus élevée en se fondant sur les niveaux de densité moyens dans les zones de productivité plus faible.

Aspects relatifs aux prises accessoires

Pêches et Océans Canada est en train d'élaborer une « **politique sur les prises accessoires** » afin de s'assurer que les pêches canadiennes sont gérées de façon à soutenir la pêche durable des espèces aquatiques, à réduire le risque que la pêche entraîne des dommages graves ou irréversibles aux prises accessoires et aux prises rejetées ainsi qu'à rendre compte des prises totales, y compris les prises accessoires et les prises rejetées. Des données scientifiques seront nécessaires afin d'appuyer les décisions relatives à la gestion des prises accessoires. Le type d'information dont on aura probablement besoin est défini dans cette partie.

Dans la partie traitant de l'**habitat de prédilection de certaines espèces**, on lie les problèmes relatifs à l'évaluation traditionnelle des prises accessoires au moyen d'études empiriques sur le terrain dans des zones distinctes et de mesures de la qualité de l'habitat en fonction de couches de données environnementales tirées de données provenant d'un sonar multifaisceaux. Ces produits, en plus de données spatialement explicites sur la pression de la pêche, pourraient servir à évaluer les conflits possibles dans un contexte plurispécifique.

INTRODUCTION

1.0 APPLICATION OF ECOSYSTEM RESEARCH INITIATIVE RESULTS TO FISHERIES MANAGEMENT

S. Leslie and R. Claytor

This Research Document presents results from the Maritimes Region Ecosystem Research Initiatives (ERI) that are applicable to fisheries management decisions. These initiatives were not specifically directed to address fisheries management decisions. Nevertheless, they provide insight and direction on a broad range of ecological interactions relevant to the application in fisheries management of Fisheries and Oceans Canada's (DFO) precautionary approach (PA) framework (DFO 2006, 2009), as well as addressing emerging fisheries management policies such as the draft bycatch policy and the *Policy for Managing the Impact of Fishing on Sensitive Benthic Areas*. For this Research Document, presentations of ERI results are organized into three themes of relevance to fisheries management: Environmental Variability and Climate Change Considerations, Spatial Management Considerations, and Bycatch Considerations.

DFO's "*A fishery decision-making framework incorporating the Precautionary Approach"* (PA Policy) provides guidance on implementing a harvest strategy. In resource management, PA is about being cautious when scientific information is uncertain, unreliable or inadequate and not using the absence of adequate scientific information as a reason to postpone or fail to take action to avoid serious harm to the resource (DFO 2009). Guidance issued by the Privy Council Office (PCO 2003) on implementing a PA instructs that "precautionary measures should generally be implemented on a provisional basis; that is, they should be subject to review in light of new scientific information or other relevant considerations, such as society's level of protection against risk".

An important component of the PA Policy is the development of appropriate reference points (RPs) for fisheries management. An RP is a specific *value* of an appropriate *metric* or *indicator* (e.g., biomass, escapement) around which management *advice* or *action* occurs, and that has the intent of altering that *value* or the relationship to that value. PA and RPs have steadily become part of DFO's proposed means to structure management decisions (PCO 2003; DFO 2006, 2009). Outside of DFO, market demands for eco-certification are also requiring fisheries to demonstrate management under a PA that includes RPs and harvest control rules (HCRs).

The role of RPs within the ecosystem approach to management is still largely peripheral. Currently, RPs and HCRs are developed based on an assumption that the world is fairly unchanging (i.e., that the environment within which the species exists will continue in such a way that it does not materially affect the way the stock grows, reproduces, or responds to human activity pressures). This review of the Application of Maritimes Region Ecosystem Research Initiatives to Fisheries Management issues attempts to demonstrate how to take into consideration a range of ecosystem factors (e.g., changes in ocean conditions) that may affect the productivity of the stock (DFO 2009) when implementing fisheries management policies, and it represents an important first step in incorporating predator-prey interactions, multi-species maximum sustainable yield, climate change, habitat, and other geospatial considerations in fishery management decision making.

1.1 References

DFO. 2006. A harvest strategy compliant with the Precautionary Approach. DFO Canadian Science Advisory Secretariat Science Advisory Report 2006/023.

DFO. 2009. A fishery decision-making framework incorporating the Precautionary Approach. Fisheries and Oceans Canada, Ottawa, Ontario. Available at [Internet] http://www.dfo-mpo.gc.ca/fm-gp/peches-fisheries/fish-ren-peche/sff-cpd/precaution-eng.htm (accessed 1 June 2012).

PCO. 2003. A Framework for the application of precaution in science-based decision making about risk. Privacy Council Office, Ottawa, Ontario. Available at [Internet] http://www.pco-bcp.gc.ca/index.asp?lang=eng&page=information&sub=publications&doc=precaution/precaution_e.htm (accessed 1 June 2012).

ENVIRONMENTAL VARIABILITY AND CLIMATE CHANGE CONSIDERATIONS

2.0 OVERVIEW OF CIRCULATION IN MARITIME CANADA REGION

D. Brickman and J. Loder

The circulation along the eastern seaboard of Canada is characterized by a general southward flow of subpolar (cold, fresh) water from the Labrador Sea, and a northward flow of subtropical (warm, salty) water from the Gulf Stream (Figure 2.1, 2.2 and 2.3. Figure 2.3 contains place names).

The colder, fresher water from the Labrador Sea follows two pathways into the Maritime Canada region. Inshore Labrador shelf water enters the Gulf of St. Lawrence (GSL) through the Strait of Belle Isle (SBI), with a mean transport of about 0.4 Sv and a seasonal cycle of about half this value. Labrador slope water flows along the shelfbreak toward the tail of the Grand Banks, at which point it interacts with the northeastward flowing Gulf Stream.

The seas of Maritime Canada are influenced by numerous river inputs, the most dominant being the outflow of the St. Lawrence Estuary, which provides an annual average of about 15 mSv of freshwater (>10 times the next highest inflow rate). This pulse of low salinity water peaks in April in the northern GSL, and can be traced as it flows southward through Cabot Strait and onto the Scotian Shelf (SS), where it arrives at Halifax in late summer. The volume flux through the SBI is more than 10 times greater than that from the Estuary, and wends its way around the GSL before also passing through Cabot Strait. Thus to first order, the net (southward) transport through Cabot Strait is equal to the inflow at the SBI.

Part of the inflow along the Newfoundland Shelf flows northward through Cabot Strait and does a loop through the GSL before exiting through Cabot Strait. The majority of the shelfbreak flow (about 3-4 Sv at the shelfbreak at the Halifax section) follows bathymetric contours, but exhibits incursions into the Laurentian Channel, the central SS, and the Northeast Channel. The water mass properties of this flow can be predominantly warm slope water (similar to the Gulf Stream) or Labrador Slope water, depending on how much Labrador Current water gets past the tail of the Banks. This, in turn, is thought to depend on the North Atlantic Oscillation (NAO) (see later). The area south of the SS/Gulf of Maine (GoM) is a region of high variability shared by a cold water recirculation gyre and the Gulf Stream. Meanders and warm-core rings shed by the Gulf Stream can influence water properties in the outer SS/GoM shelf area.

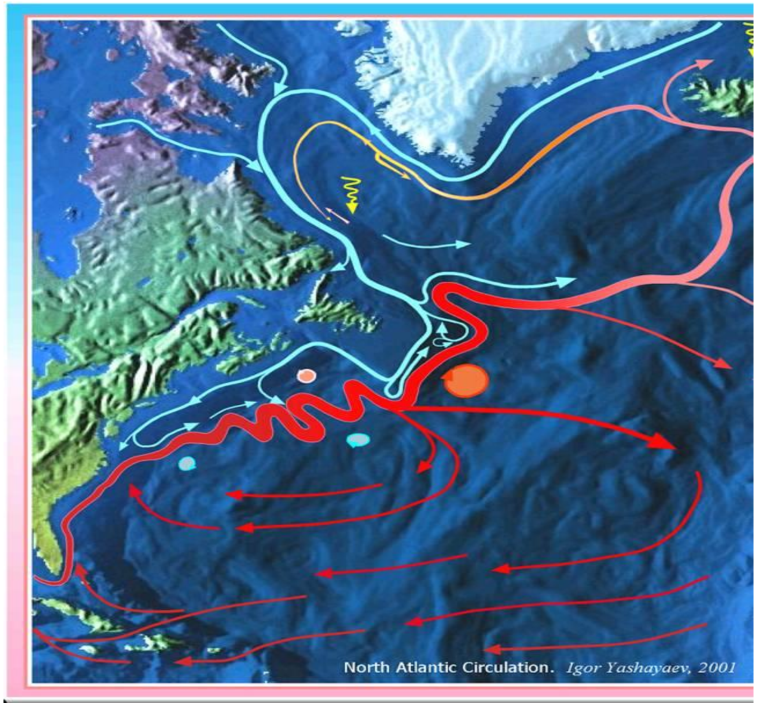


Figure 2.1. Schematic of the large-scale circulation in the North Atlantic. Colours indicate water temperature.

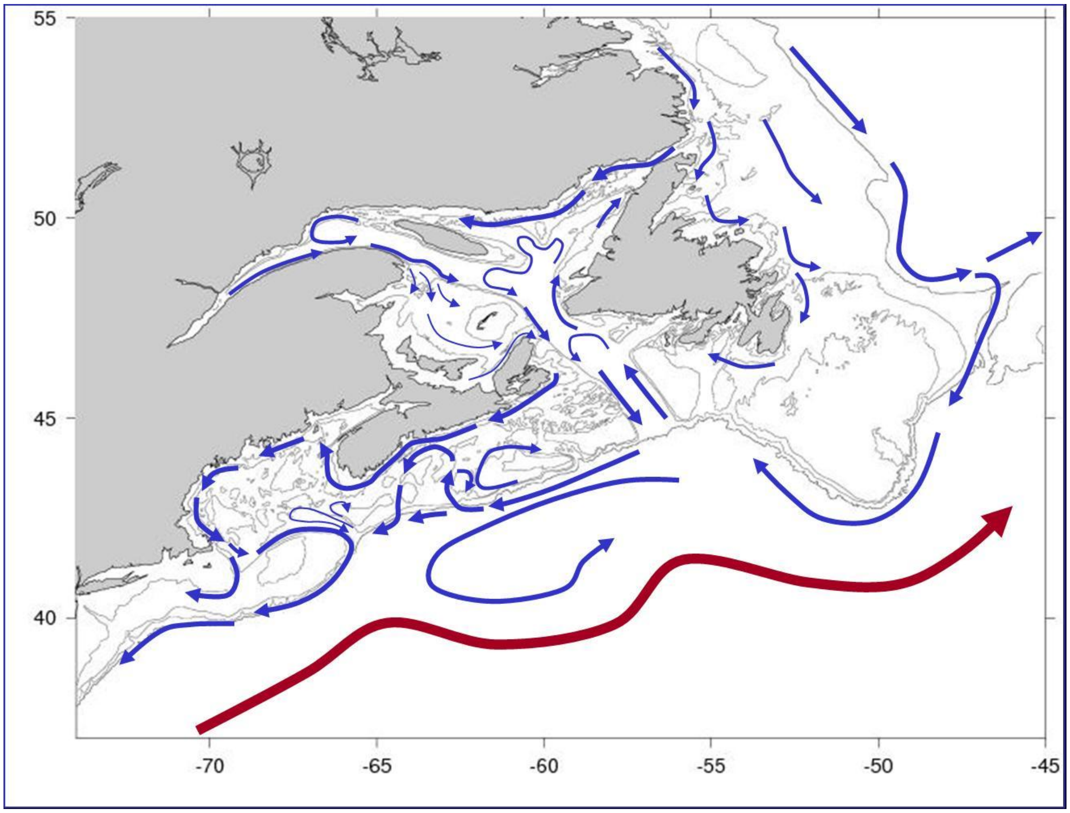


Figure 2.2. Schematic of circulation in Atlantic Canada illustrating finer details of the flow field. Blue arrows denote colder water, red warmer water.

From the above, one can see that external (deep ocean) influences are much greater for the SS/GoM area than the GSL. This supports the view that the GSL acts more like a semi-enclosed sea (i.e., more influenced by surface fluxes) than the SS/GoM, whose properties depend more on the interaction between the southward flow of subpolar water around the tail of the Banks and the northeastward flow of the Gulf Stream. Thus, the SS/GoM can be considered to occupy a “transition” zone between subpolar and subtropical regions. This latter fact also makes modeling the longer (climate) time scale circulation variability on the SS/GoM shelves difficult, as it requires accurate simulation(s) of the larger-scale (deep ocean) circulation. By contrast, more success is expected in simulating the variability in the GSL due to the greater effect of local influences.

The circulation in the shelf seas of Maritime Canada includes numerous gyres and distinct currents (Figure 2.3). Principal among the former is the Anticosti Gyre in the GSL, and topographically steered bank gyres on the SS/GoM (Georges, Browns, Emerald, Western/ Sable-Island, Banquereau). Important current streams are the flows into the GSL from the Newfoundland Shelf, the SBI, and the St. Lawrence Estuary, which combine to form the GSL outflow through Cabot Strait. Part of this outflow becomes the Nova Scotia (NS) coastal current, which continues southwestward and feeds the GoM coastal current, while the rest of it follows the shelfbreak with incursions onto the shelf near Emerald Bank and NEC.

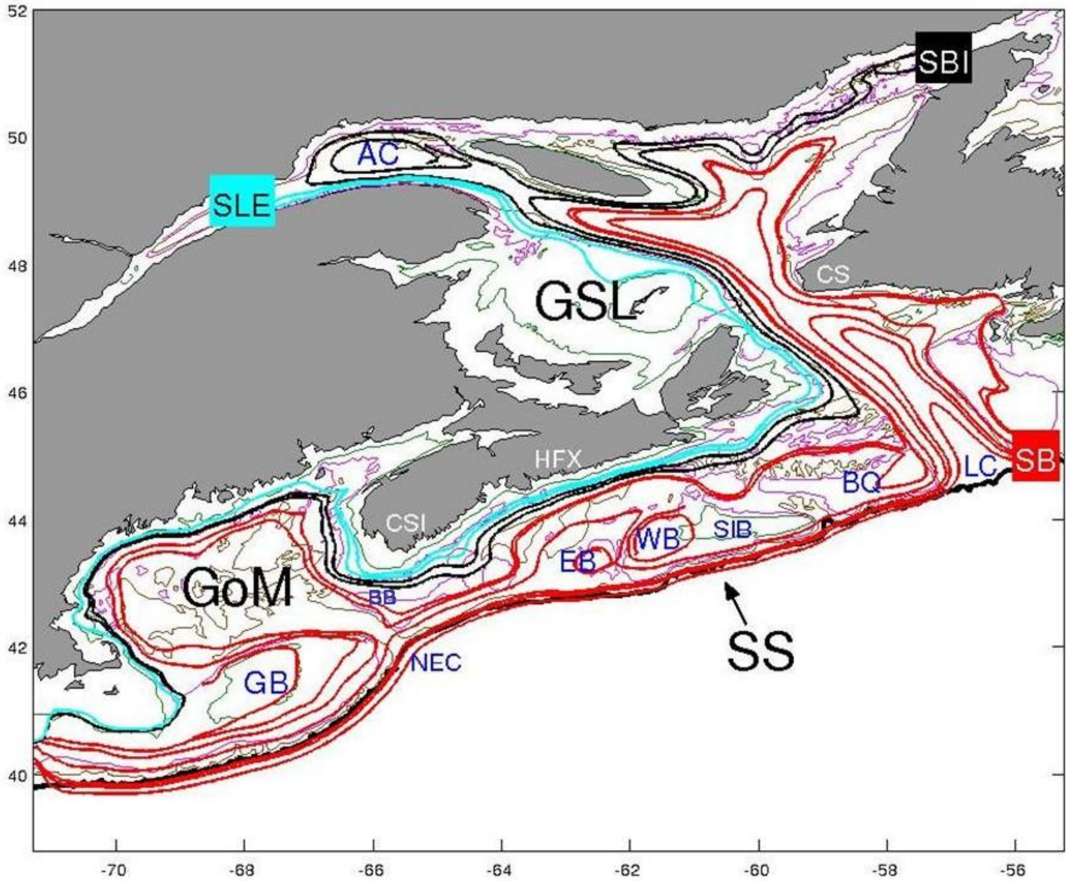


Figure 2.3. Streamlines illustrating key flow pathways and features. Although based on particle tracking experiments, the figure should be considered as a schematic. Abbreviations are: GSL=Gulf of St. Lawrence; SS=Scotian Shelf; GoM=Gulf of Maine; SBI=Strait of Belle Isle; SLE=St. Lawrence Estuary; SB=shelf break; GB=Georges Bank; NEC=Northeast Channel; BB=Browns Bank; EB=Emerald Bank; WB=Western Bank; SIB=Sable Island Bank; BQ=Banquereau Bank; LC=Laurentian Channel; AC = Anticosti; CS=Cabot Strait; HFX=Halifax; CSI=Cape Sable Island.

The shelf waters can be thought of as forming a two layer system in the wintertime, with warm-salty waters derived from slope water intrusions along the shelfbreak and in deep basins (e.g., Emerald Basin), overlain by cold-fresh water to a depth related to wintertime convection (approximately 100 m). During spring-summer a less dense upper layer develops, due to solar and freshwater inputs, creating a three layer system with a cold intermediate layer (the “CIL”) leftover from winter, overlying the densest water at depth.

The development of the GSL ice field follows a characteristic pattern, with ice “growing in” from the coastlines except for the southeastern Gulf, where there is a “hole” due to the inflow of warmer Newfoundland Shelf water (Figure 2.4). Little ice is found on the SS/GoM, aside from nearshore areas.

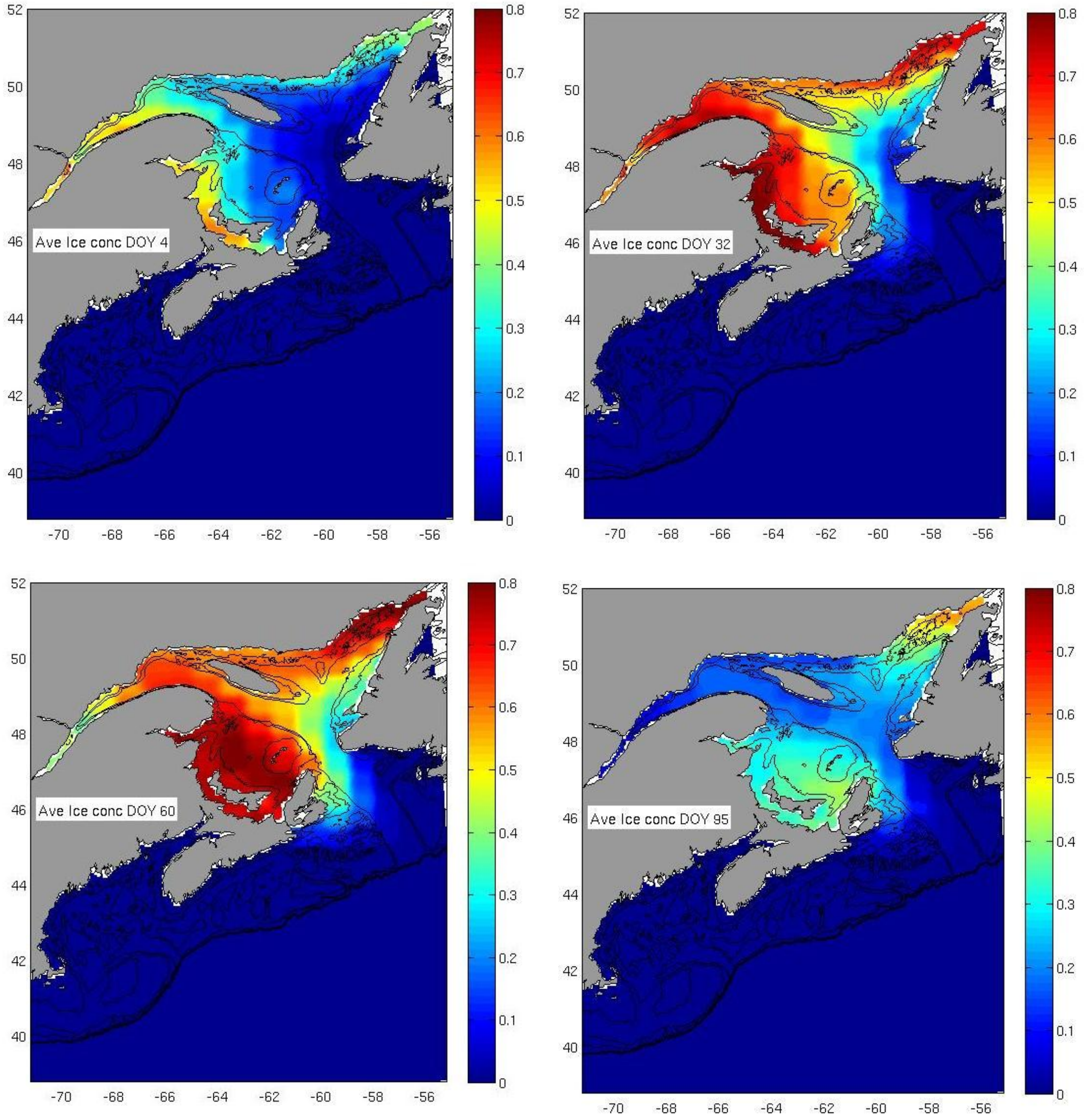


Figure 2.4. Development of the ice field, based on climatological data. Times are early January, February, March, April, (top left-right, bottom left-right).Scale is fractional ice cover.

2.1 Results from Numerical Circulation Model

The variability and relationship between circulation features was explored using a numerical circulation model of the Maritime Canada region (Brickman and Drozdowski 2012). The model was forced by the Common Ocean-ice Reference Experiments Normal Year forcing (CORE NY). This cyclical year atmospheric forcing, which includes the passage of storms, represents the statistical climatology of weather patterns. Output from the model was daily averaged to produce 365 flow fields representing the climatological variability in circulation in the Maritime region. The model, forced in this way, allows analyses not just of mean circulation properties but of expected variability as well.

The principal circulation features analyzed were the AC gyre and the bank gyres (BQ, WB/SIB, EB, BB, GB), the outflow through CS, the NS and GoM coastal currents, and the flow through NEC (Figure 2.2). These features were well represented in the annual mean model circulation (i.e., averaged over the 365 realizations).

2.2 Seasonality of Circulation Features

The only gyres that exhibit a (statistically significant) seasonal cycle are the GB and the AC gyres, with minima during mid-year. The outflow through CS and the NS coastal current also show seasonality with mid-year minima. This seasonality does not extend to the GoM coastal current. The explanation for the seasonal response is that the AC and GB gyres and the NS coastal current are related to the flow through SBI and/or the shelfbreak current, which themselves have a seasonal component.

2.3 Correlation between Circulation Features in the 3-7 Day Time Scale (Storm Band)

A weak correlation was found between bank gyres (vorticity correlations), indicating that these features behave mostly independently of each other. The coastal current (CS to Yarmouth) was found to have a decorrelation length scale of about 150 km (for a correlation of 0.5). The reason for this behaviour is likely due to the complicated horizontal structure of the flow field (i.e., the shelf response) when forced at the time scale(s) associated with moving storms.

2.4 Inflow into the Gulf of Maine

There are two main pathways of inflow into the GoM – the NS coastal current (from approximately 100 m isobath to the coastline – Cape Sable Island section or CSI) and the flow along the eastern flank of the NEC (NEC-e). Water exits the GoM principally via the western flank of the NEC (NEC-w, associated with the GB gyre) and at Great South Channel (approximately 69W,41N). Model transport calculations (from a 50 year simulation) support a picture where increased flow into the GoM at CSI results in increased outflow at GSC and NEC-w with a concomitant decrease of inflow at NEC-e. Model results show that about 10% of the salinity flux into the GoM is provided by the NS coastal current.

2.5 Retention and Connectivity

Particle tracking experiments were performed in order to estimate the retention time scales of the various banks (GB, BB, EB, WB/SIB, BQ). For each day of the year, particles were seeded in the top 20 m and tracked for 100 days. The average time scales for 50% of the particles to remain on-bank were 23, 6, 7, 15, and 10 days for GB, BB, EB, WB/SIB, BQ, respectively – time scales directly proportional to the bank areas. Except for GB, no obvious seasonality in retention was observed in the model results. On GB, retention was strongest during the late summer, when the gyre and wind stress are weakest, suggesting that wind mixing plays a role in bank retention.

With respect to connectivity between banks, it was found that, in general, banks are connected to one neighbour only. On average, BQ retains fewer particles than it exports to WB/SIB; WB/SIB retains about five times more particles than it exports to EB; BB exports about two times more particles to GB than it retains; and GB is not significantly connected to any upstream banks.

2.6 Interannual/Decadal Variability

The circulation in Maritime Canada exhibits variability on seasonal and longer time scales. The best understood interannual variability is related to the NAO – the difference in sea level atmospheric pressure between the Azores and Iceland, with predominant variability in the 5-10 year range (Petrie 2007). When bottom temperature data were grouped, a coherent pattern of spatial anomalies was found, with warmer (colder) temperatures on the Newfoundland Shelf, GSL and eastern SS, and colder (warmer) temperatures on the central SS and westward, related to persistent negative (positive) NAO anomalies (Figure 2.5).

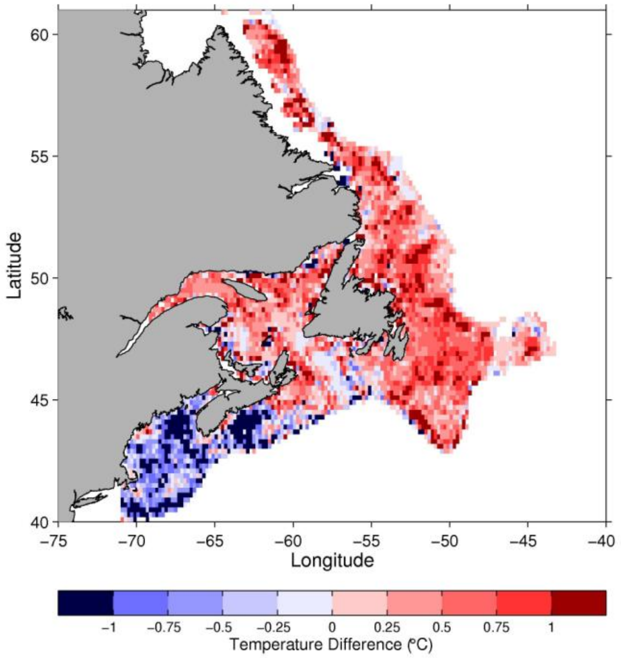
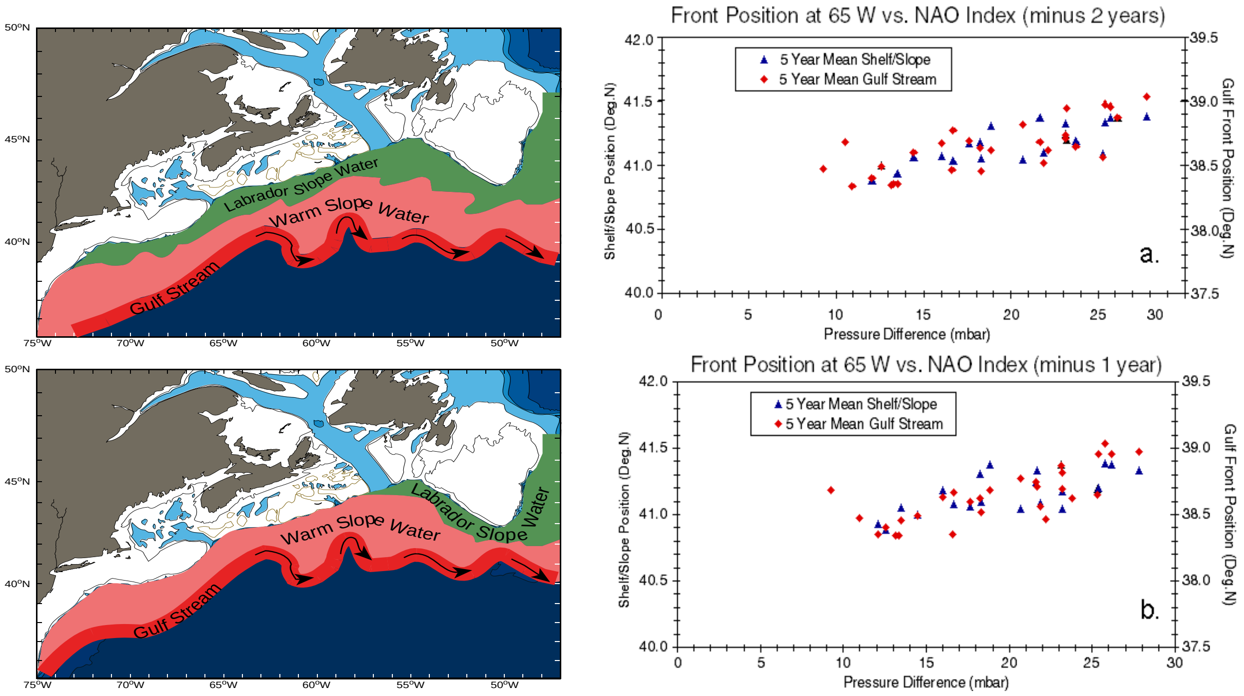


Figure 2.5. Spatial pattern of bottom temperature differences low-NAO minus high-NAO. From Petrie (2007).

The explanation is the following. During periods of high NAO, there are more cold air outbreaks over the Labrador Sea, which enhances deep convection and increases the strength of the Labrador Sea gyre. As a result, the temperature on the Labrador Shelf is lower, which affects the Newfoundland Shelf, GSL and eastern SS due to shelf circulation effects. However, the stronger Labrador Sea gyre results in less transport of cold, fresh Labrador Current water along the shelfbreak past the tail of the Grand Banks so that warm slope water dominates farther downstream with anomalously warm incursions into the deeper shelf regions. The opposite occurs during periods of low NAO, with reduced convection in the Labrador Sea and a more diffuse gyre, which allows **more** Labrador current water to get past the tail of the Grand Banks. The result is warmer bottom temperatures in Newfoundland, GSL and eastern SS waters, but colder fresher waters westward as Labrador Slope water replaces the warm slope water. The observed “cold 60’s” on the SS/GoM is attributed to an extended period of low NAO values. Consistent with this description is the observation that the Gulf Stream moves north (south) during periods of high (low) NAO (Figure 2.6).



Low NAO (top), High NAO (btm)

Gulf Stream position vs NAO

Figure 2.6. Gulf stream and NAO interaction.

The above description highlights the importance of the interaction between the Gulf Stream and the Labrador current in the southern Grand Banks region. As the latter is a narrow stream of water (approximately 20 km in width), it means that, from a modeling point of view, relatively high resolution is necessary in order to simulate this process – requiring computer power that is not yet readily available.

The circulation in Maritime Canada is likely related to other quasi-periodic series (e.g., the Atlantic Multi-decadal Oscillation with 70 year period), but the connection is not yet understood.

2.7 References

Brickman, D., and Drozdowski, A. 2012. Development and Validation of a Regional Shelf Model for Maritime Canada based on the NEMO-OPA Circulation Model. Canadian Technical Report of Hydrography and Ocean Sciences 278.

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3.0 CLIMATE CHANGE ON THE SCOTIAN SHELF: RECENT VARIABILITY WITH A FUTURE OUTLOOK

Summary Overview prepared by:
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With input from:
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3.1 Introduction

This interim summary was prepared to provide input to the Maritimes DFO "Ecosystem Research Initiative Synthesis" regional workshop held October 25-27, 2011. It draws on the scientific literature, various climate change assessments and reports, DFO's ocean and ecosystem monitoring programs, and work carried out in recent targeted DFO programs such as its Climate Change Science Initiative (CCSI), Maritimes Ecosystem Research Initiative (ERI) and International Governance Strategy (IGS) science program.

The summary should be viewed as a work in progress, just a starting point for a description of past and recent ocean climate change on the Scotian Shelf, and projections for the future. More analyses, interpretations and syntheses of existing datasets and studies are required to understand the roles of anthropogenic and natural factors in past climate variability. Much more investigation with improved models of various form is needed to develop projections that can be used with appropriate consideration of uncertainties for future impacts assessments and adaptation plans.

3.2 Natural Physical Oceanographic Variability on the Scotian Shelf

Variability in the physical oceanography of the Scotian Shelf is determined by the competing influences of (i) atmospheric forcing and solar heating; (ii) the western North Atlantic's large-scale current systems (the Gulf Stream and Labrador Current); and (iii) local factors such as tides, river discharge and topography. The Shelf is located in a large-scale oceanographic "transition" zone (Loder at al. 1998; Brock et al. 2012) between the relatively warm and saline (subtropical) offshore waters of the poleward-flowing Gulf Stream, and the cooler and fresher equatorward-flowing shelf waters supplied by the (subpolar) Labrador Current and outflow from the Gulf of St. Lawrence (Figure 3.1). As a result, its waters generally become warmer and saltier proceeding southwestward, offshore and downward, with the exception of the warm near-surface layer that overlies the cold intermediate layer between spring and fall (Figure 3.2).

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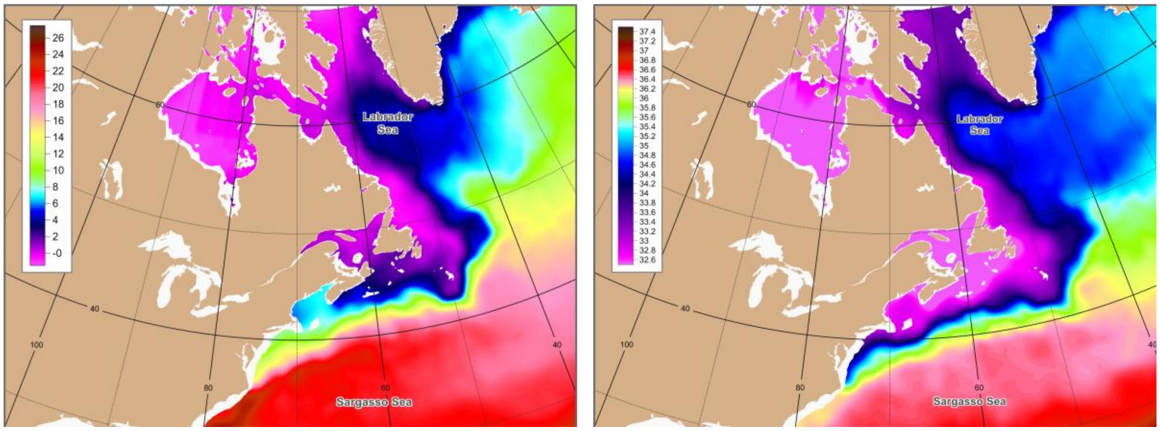

Figure 3.1. Climatological annual-mean distributions of temperature (left) and salinity (right) at 50 m below the sea surface in the Northwest (NW) Atlantic. Courtesy of Igor Yashayaev, DFO at Bedford Institute of Oceanography (BIO), Dartmouth, NS.

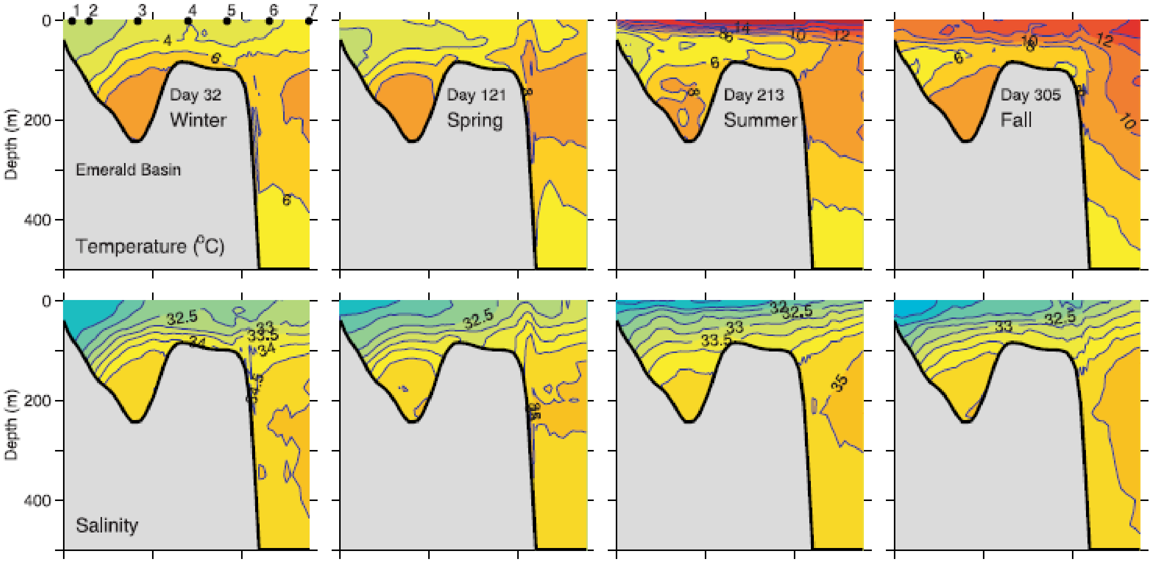

Figure 3.2. Climatological seasonal-mean distributions of temperature (upper) and salinity (lower) on the Halifax Line across the Scotian Shelf and Slope. From Loder et al. (2003).

The time scale of the greatest natural variability in the Scotian Shelf's oceanography is the annual cycle of surface heating and other air-sea fluxes which, together with seasonal changes in the inflow of relatively fresh water from upstream, results in a pronounced seasonal variation in temperature, salinity and stratification in its upper 100 m (Figure 3.2). There is also substantial natural variability on time scales of hours to decades associated with changes in the competing influences noted above. In particular the NAO, a natural mode of variability in the large-scale atmospheric pressure and wind pattern over the North Atlantic with fluctuations on monthly to multi-decadal time scales (e.g., Hurrell and Deser 2010), has been shown to affect various oceanographic properties off Atlantic Canada. These include the north-south position of the Gulf Stream, and the volume of subpolar slope water extending west around the Tail of the Grand Bank, which in turn influences temperature and salinity over the Scotian Shelf (e.g., Petrie 2007). Successive years of positive wintertime NAO anomalies (involving stronger and cooler northwesterly winds over the Labrador Sea) result, on the one hand, in cooler water over the Labrador and Newfoundland Shelves and reaching the eastern Scotian Shelf and, on the other hand, in warmer subtropical slope water intruding onto the central and western Scotian Shelf at depth due to the reduced contribution of subpolar slope water. These opposite effects on water properties on different parts of the Shelf are reversed after successive years of negative NAO anomalies, contributing to a reversing spatial pattern in temperature and salinity anomalies on multi-year time scales (Figure 3.3).

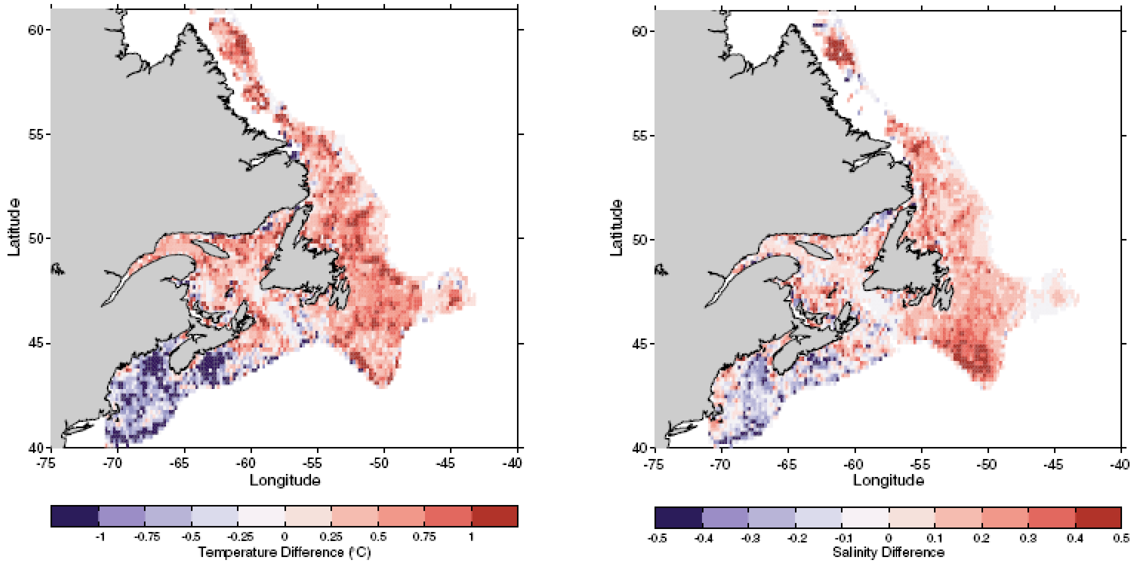

Figure 3.3. Bottom temperature (left) and salinity (right) differences (negative minus positive winter NAO anomalies) for years from 1970-2004 with at least the two previous years having the same sign of the NAO anomaly. From Petrie (2007).

A second natural mode of variability which affects the Scotian Shelf is the Atlantic Multi-decadal Oscillation (AMO) - an out-of-phase fluctuation of sea surface temperature in the northern and southern parts of the North Atlantic with quasi-periodicities of 20-30 and 60-70 years (e.g., Frankcombe and Dijkstra 2011; ICES 2011b). From the 1970s to the past decade, the AMO was in a warming phase for the North Atlantic, which has been suggested to be a contributing factor to observed ocean warming on the Northeast United States (NE US) shelf (e.g., Nye et al. 2009). The mechanisms of the AMO are still being unravelled, with one suggestion that it is associated with a hemispheric-scale atmosphere-ice-ocean interaction involving the North Pacific and Arctic (Dima and Lohmann 2007), and others that it is partly linked to changes in the Atlantic Meridional Overturning Circulation (AMOC) (e.g., Polyakov et al. 2010). The AMOC is the Atlantic component of the so-called global ocean “conveyor belt”, which plays a major role in regulating the Earth’s overall climate system. AMOC variability has also been suggested to affect the north-south position of the Gulf Stream (Joyce and Zhang 2010), and consequently temperature and fish distributions on the NE US shelf between Cape Hatteras and the Gulf of Maine (e.g., Nye et al. 2011), such that the influences of the NAO, AMO and AMOC on the Scotian Shelf may be interrelated.

While the NAO and AMO are notable large-scale features of atmosphere-ocean variability affecting the Scotian Shelf, there is a broad spectrum of other important natural variability (e.g., interannual) in the Shelf’s physical oceanography, which also needs to be considered in assessing the occurrence and importance of anthropogenic climate change.

3.3 Potential Anthropogenic Climate Change on the Scotian Shelf

Natural variability will continue to be a major factor in future ocean climate change. In particular, during the next decade or two while many anthropogenic changes may remain relatively small, climate change on a regional scale like that of the Scotian Shelf may be predominantly influenced by natural variability or anthropogenic perturbations of this variability.

The coupled atmosphere-ice-ocean climate models used in the IPCC's[6] Fourth Assessment Report (AR4) have poor resolution of the western North Atlantic's transition zone, and do not represent the NAO and AMO well. Hence, caution must be used in "down-scaling" the smooth probabilistic broad-scale projections of the AR4 models to the Scotian Shelf, especially for the next decade or two. There are down-scaled projections (Fogarty et al. 2008) of bottom temperature in the Gulf of Maine, which provide an indication of the sign and magnitude (increases by 1-2^{o}C) of probable changes by the mid and late 21st century. However, these were based on AR4 models that, for example, did not resolve the ocean dynamics which resulted in the anomalously cool (by 2-4^{o}C) and fresh (by 0.5-1) conditions on the Scotian Shelf in the 1960s (associated with a period of negative NAO and increased transport of subpolar slope water into the region; see next subsection).

The probable and potential tendencies for mid-century regional ocean climate change can alternatively be estimated from a combination of knowledge of coupled model simulations, atmosphere-ocean dynamics (e.g., ICES 2011; Brock et al. 2012), past regional ocean climate variability, and the IPCC's projected changes in key larger-scale forcings. The tendencies for the physical-chemical variables that are most important ecologically and most likely to change significantly on the Scotian Shelf can be summarized as follows (drawing on Annex 1 in Brock et al. 2012).

Ocean temperature and ocean acidity can be expected to increase associated with a warmer overlying atmosphere with increased carbon dioxide (CO_2) concentrations (IPCC 2007). Increases should be largest in the upper layers (75-100 m in winter and 20-30 m in summer) because of the direct influence of local air-sea fluxes, but are also expected at all depths over the shelf and upper slope as waters ventilated elsewhere and earlier move into the region (Figure 3.2). The increased ocean acidity can be expected to result in a lowering of calcium carbonate saturation in the upper ocean, with effects on calcareous organisms and other aspects of the ecosystem (e.g., ICES 2011).

At a less confident level, there is also considerable reason to expect there to be an additional contribution to ocean warming on the Scotian Shelf from a northward shift of the Gulf Stream and an associated retraction of the subpolar gyre (and hence a reduction in the flow of subpolar slope water west of the Grand Bank). This is based on the expected slowing of the AMOC and the possible tendency for more positive NAO anomalies due to an intensification of the atmospheric polar vortex (IPCC 2007). Such a northward shift in the boundary between subtropical and subpolar water in the western North Atlantic (Figure 3.1) should also provide tendencies for higher salinity in the slope water off the Scotian Shelf, more frequent "warm" slope water intrusions onto the shelf, and perhaps changes in chemical properties at depth, such as nutrients and dissolved oxygen.

Sea level can be expected to continue to rise associated with the global trends of ocean expansion due to heating and melting glaciers, and with regional factors such as continental subsidence and the potential northward expansion of the subtropical gyre. Extreme (e.g., high water) sea levels and coastal erosion can be expected to increase even more, due to the added effects of increasing semi-diurnal tides in the region and possibly larger extreme surges and

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[6] Intergovernmental Panel on Climate Change (IPCC), http://www.ipcc.ch/.

waves due to more intense storms. Note that, although the total number of storms over the North Atlantic is expected to decrease, the number of intense storms is expected to increase and the track of extra-tropical storms is expected to shift northward.

Net regional salinity changes expected on the mid-century time scale are more uncertain because different factors can result in opposing tendencies that may vary seasonally. Increased salinity at depth on the mid/outer shelf and upper slope can be expected due to the increased influence of slope water of subtropical origin. In contrast, melting Arctic sea ice and the intensified hydrological cycle (increased precipitation) at mid to high latitudes are expected to result in reduced salinity of the inflowing upper-ocean water from the Newfoundland Shelf. Changes in the freshwater discharge into the Gulfs of St. Lawrence and Maine (including the Bay of Fundy) are less clear due to complications such as the expected increased evapo-transpiration (due to warmer air) over much of the Great Lakes drainage basin and changes in the seasonality of run-off (e.g., from earlier snow melt) in a warmer climate. There are suggestions that earlier and larger spring peaks in (un-dammed) river discharges into the Gulf of Maine will lead to reduced salinities in local near-surface coastal waters in spring in particular, but the spatial extent and seasonal persistence of this influence are unclear.

A general increase in the vertical density stratification, and shallower near-surface mixed-layer depths, can be expected on the Scotian Shelf from the combined influences of temperature and salinity changes, but the magnitudes will probably vary seasonally and spatially. The tendencies for greater warming of the near-surface layers, reduced near-surface salinity in most areas and seasons, and increased salinity at depth should lead to increased year-round stratification at the shelf-water/slope-water interface at typical depths of 75-150 m (base of the winter surface and summer intermediate layers). The near-surface tendencies should also lead to increased spring-summer stratification near the surface (upper 30 m) and an earlier onset of this stratification. An exception may be the outer shelf and slope where a northward shift of the Gulf Stream could result in higher near-surface salinity, partly offsetting the temperature influence. Changes in vertical mixing due to winds and waves will also contribute to changes in near-surface stratification and mixed-layer depths, but the specifics of these effects are unclear.

The potential northward shift of the Gulf Stream would be part of a change in the large-scale ocean circulation in the western North Atlantic’s transition zone between the subpolar and subtropical gyres’ western boundary currents. In addition, the tendencies for reduced salinity in the coastal and shelf waters, and for increased salinity in the offshore slope water, can be expected to result in an increased cross-shelf density gradient, and hence increased equatorward flow of shelf water over the Scotian Shelf. Thus, while the extension of the subpolar slope water past the Tail of the Grand Bank is expected to be reduced (associated with increased large-scale wind forcing and positive NAO anomalies), the flow of cold fresh shelf water along the Scotian Shelf in the shelf-edge and Nova Scotia currents may increase, due to a stronger shelf-water/slope-water front.

In addition to increased ocean acidity due to increased broad-scale CO_2 input to the surface ocean, reduced atmospheric replenishment of dissolved oxygen in the subsurface waters over the Atlantic Canadian shelf and slope is expected, associated with increased stratification and reduced depths of winter convection. This should contribute to a tendency towards reduced dissolved oxygen concentrations at depths below the winter layer on the Scotian Shelf, such as in the intruded slope water at depth. This tendency should be further exacerbated by the increased subtropical water contribution to this slope water. On the other hand, changes in biological processes and in the biogeochemical properties of run-off will also contribute to dissolved oxygen concentrations, and may be the predominant influences in some areas.

With the expected changes in stratification and in the composition of slope water at depth, there may also be changes in nutrient concentration on the Scotian Shelf. With the increased contribution of subtropical slope water, there should be a tendency towards increased nutrient concentrations, at least at depth. Furthermore, there are already suggestions of an increased flow of Pacific water through the Arctic, and changes in the relative concentrations of nitrate and silicate in the NW Atlantic and as far south as the Gulf of Maine (e.g., Townsend et al. 2010; Yeats et al. 2009). However, as with dissolved oxygen, nutrient concentrations are influenced by multiple factors, including complex biogeochemical processes, such that it is difficult to project the net effects of climate change and other factors.

Other changes in physical and chemical oceanographic conditions can be expected, particularly on local scales where winds, river discharges and tides affect circulations, currents, mixing, water properties and fronts. However, generally it is not possible to project their magnitude or even tendency with any degree of confidence. It must also be emphasized that natural variability associated with the NAO, AMO and other natural variability modes such as ENSO, and interannual atmosphere and ocean “weather” in general, may predominate during the next couple of decades over the tendencies identified above.

3.4 Status and Trends

3.4.1 Temperature

Available data for air and ocean temperature in the NW Atlantic during the past century indicate substantial natural variability on decadal time scales. Together with the few ocean time series that extend back beyond 1950, this variability makes the identification of trends related to anthropogenic climate change very difficult. For example, the 1950s was one of the warmest decades in the 20th century for the air and ocean in the Scotian Shelf region, and the 1960s one of the coldest for the ocean, such that trends estimated from time series starting in the 1950s and 1960s may be very different, with neither being quantitatively representative of the actual longer-term trend or that associated with anthropogenic influences. Extreme caution needs to be used in interpretations of the limited ocean datasets in particular, with regard to their spatial and temporal representativeness and their implications for future change.

Meteorological (and coastal sea level) records, in some cases extending back beyond 1900, provide the best indicators of long-term regional climate change. Coastal air temperature records between the Grand Bank and the Gulf of Maine generally show a net increase over the past century in the 0.6-1.7°C range. Sable Island, which had a change of about 1°C, is probably the most representative of the Scotian Shelf. This magnitude is similar to the observed global and North American average increases of about 1°C reported in IPCC (2007, Ch. 3), to the simulated change of about 0.7°C for eastern North America in IPCC (2007, Ch. 9), and to the down-scaled change of 0.8°C for the NE US (Hayhoe et al. 2006). This suggests that significant anthropogenic warming is occurring in air temperature over the Scotian Shelf (averaged over decadal variability).

The longest records (85-90 years) of ocean temperature and salinity in the region are coastal temperatures measured at St. Andrews and Halifax, and temperature and salinity measured over the 90 m water column at the Prince 5 monitoring station in Passamaquoddy Bay (Figure 3.4). The Bay of Fundy observations indicate an increase of about 1°C per century, which is consistent with the increases observed at US coastal sites in the Gulf of Maine and northern Middle Atlantic Bight (Shearman and Lentz 2010), as well as the air temperature changes noted above. The limited observed change at Halifax (a slight but insignificant decrease) is a conundrum at present (see next paragraph).

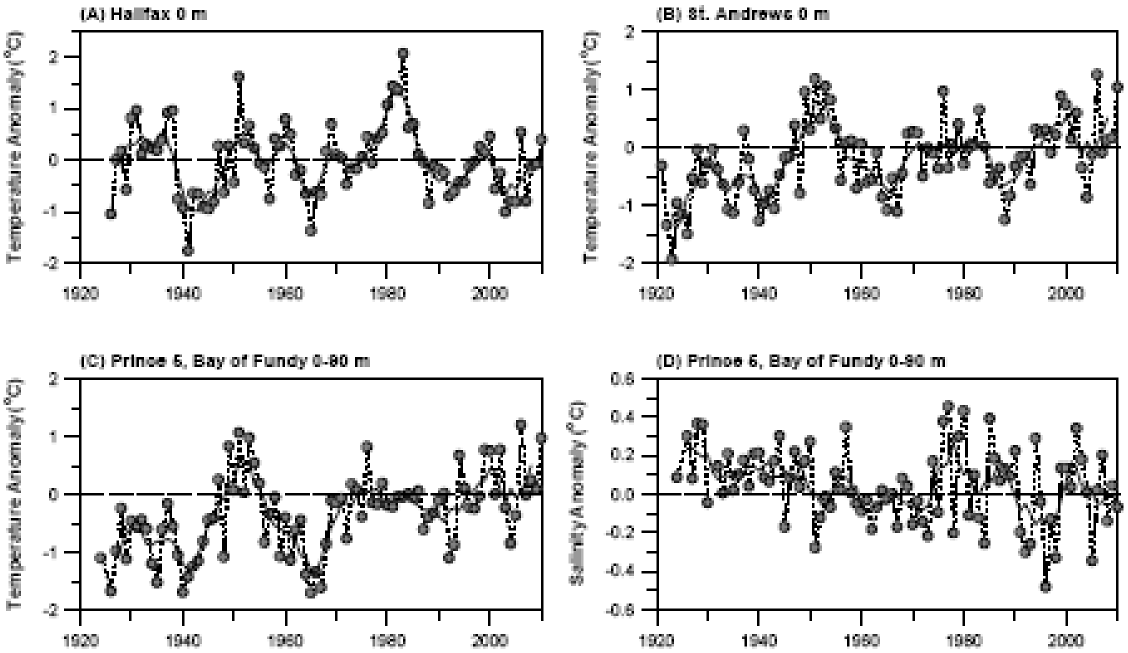

Figure 3.4. Annual anomalies of: coastal temperature (dashed line with circles) and their 5-year running means (heavy black line) for (A) Halifax Harbour and (B) St. Andrews, NB; and depth-averaged (0-90 m) (C) temperature and (D) salinity for the Prince 5 station at the mouth of the Bay of Fundy. The anomalies are relative to the 1971-2000 means. From Hebert et al. (2011).

The longest and most continuous records of offshore temperature and salinity over the water column on the Scotian Shelf are from the Halifax line, for which a station in Emerald Basin is representative of mid-shelf conditions (Figure 3.5). Its surface temperature record shows little net change since the relatively warm 1950s, similar to Halifax in net change but considerably different in decadal-scale variability (Figure 3.4). A record of similar duration from 100 m on Misaine Bank on the eastern Scotian Shelf also shows little net change but some similarity to the Emerald Basin surface variation in multi-year variability. Thus, while there has been a warming trend over the past century in the surface layer in the Gulfs of Maine and St. Lawrence (Shearman and Lentz 2010; Galbraith et al. 2011), a similar trend is not apparent in the available shorter records from the Scotian Shelf. It is unclear whether this is an artefact of the limited duration of the available records (sparse observations from Emerald Basin during the first half of the 20th century suggest this), or an actual regional ocean anomaly during the past half century perhaps associated with an increased inflow of Newfoundland Shelf water or a change in coastal upwelling.

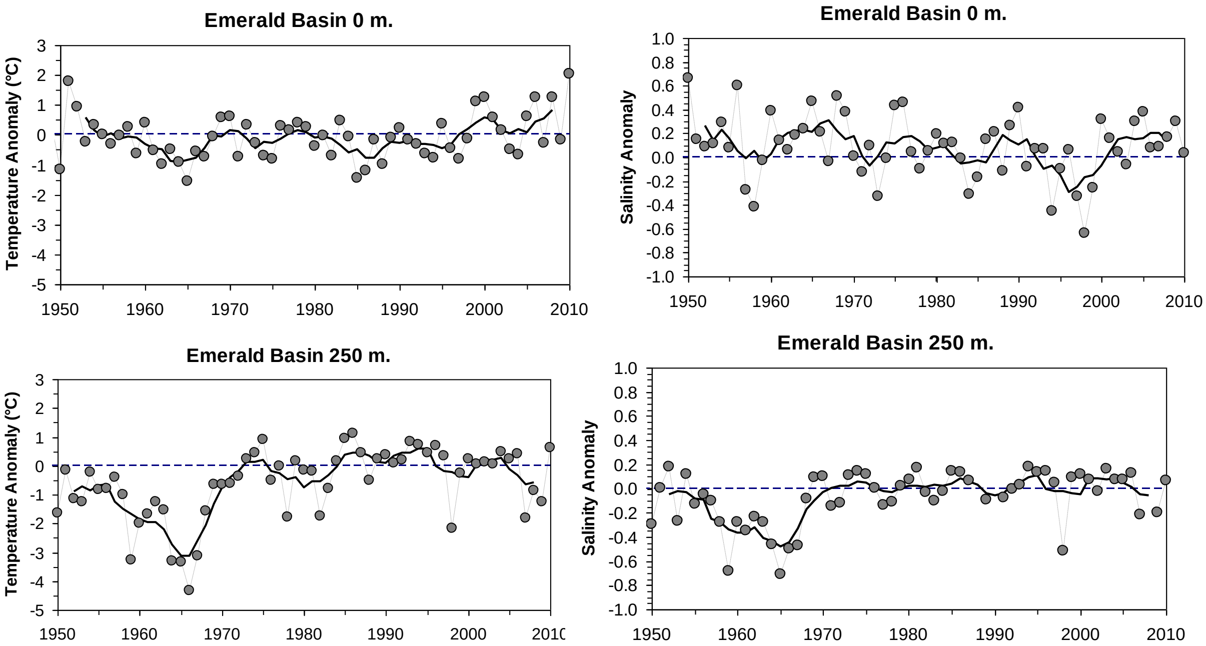

Figure 3.5. Annual-mean temperature and salinity anomalies (dashed line with circles) at the surface and near-bottom at a long-term monitoring site in Emerald Basin on the central Scotian Shelf, with their five-year running means (heavy black line). The anomalies are relative to the 1971-2000 means. Courtesy of Roger Pettipas, DFO at BIO.

The predominant feature of temperature at depth in Emerald Basin (Figure 3.5), like that of other deep basins between the Gulfs of St. Lawrence and Maine, is the cool period of the late 1950s and 1960s when there was an exceptional extension of subpolar slope water west of the Tail of the Grand Bank associated with negative NAO anomalies (e.g., Petrie and Drinkwater 1993; Loder et al. 2001). The records from these basins since 1950 clearly indicate a warming trend, but this is in part due to the NAO-driven cool 1960s period. Available indices for the north-south position of the Gulf Stream show some indication of a positive trend (northward shift) over the past half century (Petrie et al. 2008; Nye 2010), which could be a factor in the warming, but the trend's robustness is unclear considering the strong multi-year and decadal-scale variability. Sparse earlier observations from Emerald Basin and the longer records from Prince 5 and at depth in the Gulf of St. Lawrence (Gilbert et al. 2005) point to a long-term warming trend of 1-2^{o}C at depth during the past century, such that there is a substantial basis for inferring that there has been such a long-term trend on the Scotian Shelf.

It should also be noted that there are suggestions of the occurrence of earlier decadal-scale periods with cooler waters on the US NE shelf associated with increased subpolar slope water and negative NAO anomalies (e.g., Marsh et al. 1999), in particular during the 1880s and possibly 1915-1920 and the 1940s. This decadal-scale variability may also confound the estimates of long-term trends (discussed above) from century-long records, but the influence will not be as large as that on records of half-century length.

There are also suggestions of enhanced ocean warming in the NW Atlantic during the past couple of decades, at least qualitatively similar to that in air temperature (e.g., IPCC 2007), both on larger (e.g., Polyakov et al. 2010) and regional scales (e.g., Nye et al. 2009). Analyses of long-term sea surface temperature (SST) datasets, by Friedland and Hare (2007) using ICOADS data for the Gulf of Maine, and by Belkin (2009) using Hadley climatological SST data for the Scotian Shelf and other large marine ecosystems, indicate a greater warming rate during the past two decades than over the last century. Analyses of SST estimated from remote sensing indicate a widespread increase by over 1^{o}C on the Scotian Shelf since 1985. However, it is important to recognize that the warming phase of the AMO since the 1970s (and perhaps NAO variability too) may be contributing to this recent warming (Belkin 2009; Nye et al. 2009; Polyakov et al. 2010), such that this rate of warming may not continue during the next two to three decades when a cooling phase of the AMO is expected in the North Atlantic.

Finally, it should be noted that there are indications of important changes in the other aspects of ocean temperature, such as extremes and seasonality. For example, an increase in the seasonal range of SST in ICOADS data from the NE US shelf has been reported (Friedland and Hare 2007), associated with warmer summer temperatures.

3.4.2 Salinity

Robust indications of long-term changes in ocean salinity are even more difficult to obtain than those of temperature, because of the greater dearth of high-quality measurements and the potentially differing influences of local and upstream continental run-off and of offshore ocean circulation changes. The change in zonally-averaged salinity in the upper 500 m in the North Atlantic over the period 1955-98 has a reversal in sign at 42^{o}N (the Scotian Shelf's latitude range is 42-44^{o}N), with decreasing (increasing) salinity in the subpolar (subtropical) North Atlantic. This is consistent with the expected long-term anthropogenic change associated with sea-ice melting and an intensified hydrological cycle at high latitudes, and increased evaporation at lower latitudes.

The longest salinity time series from the greater Scotian Shelf region, namely from Prince 5 in the outer Bay of Fundy (Figure 3.4), show strong interannual and decadal variability, and an indication of a net depth-averaged (90 m) decrease by 0.1-0.2 over about 85 years. The Prince 5 changes include a decrease of about 0.3 during 1976-96, which is about the same as that reported for the NE US shelf since 1976 (EAP 2009) and attributed to the melting of Arctic sea ice and increased run-off into the Gulf of Maine (Nye 2010). The longest records from the Scotian Shelf, namely from Emerald Basin (Figure 3.5), also show substantial decadal variability, with an indication of a net decrease by 0.1-0.2 at the surface and a net increase of about 0.2 at depth (over 60 years). However, these net changes are influenced by the relatively-fresh upper-ocean water in the 1990s, related to a large-scale “Great Salinity Anomaly” that moved around the subpolar NW Atlantic, e.g., Belkin (2004), and the relatively-fresh water at depth in the 1960s, related to increased subpolar slope water, e.g., Petrie and Drinkwater (1993). Salinity records at upstream locations on the Atlantic shelf provide some support for the different trends in the upper-ocean “shelf” and deeper “slope-derived” waters: Station 27 off St. John’s shows a small decrease in depth-averaged (175 m) salinity since 1950 (Colbourne et al. 2011), while the deep waters of the Gulf of St. Lawrence show a net increase of 0.1-0.2 since the 1950s, and of over 0.3 since the 1930s if a small dataset from the early 1930s is included (Gilbert et al. 2005). Salinity at depth in the Gulf of Maine since the 1950s shows a similar trend to that at depth in Emerald Basin, confirming that it is a broad-scale feature.

Overall, there are indications of increasing salinity in the Scotian Shelf’s deep waters and, more tentatively, of decreasing salinity in its upper layers over the past 60-85 years. The deep-water changes are consistent with those observed in both upstream and downstream regions, providing strong support for their occurrence. However, there have been decadal-scale variations with comparable (or greater magnitude) such that the contributions of natural and anthropogenic variability remain unclear. There have been suggestions of anthropogenic freshening (via Arctic melting) of the shelf waters during the past two decades (e.g., Greene et al. 2008), but it is unclear whether this is a robust long-term trend or a transient feature associated with natural variability (e.g., the NAO and “Great Salinity Anomalies”).

3.4.3 Stratification

There is convincing evidence for a widespread increase in upper-ocean stratification over the Scotian Shelf and adjoining shelf regions during the past 60 years (Figure 3.6) (Petrie et al. 2011). It has arisen from a combination of the surface warming and freshening described earlier, with warming (freshening) the dominant influence on the western (central and eastern) Shelf (EAP 2009; Petrie et al. 2010). There are indications that there has been an earlier spring onset of stratification in the Gulf of Maine associated with this change, with influences on primary production. However, there has also been substantial multi-year and multi-decadal variability in the stratification, such that the magnitude of the anthropogenic contribution to the change remains unclear.

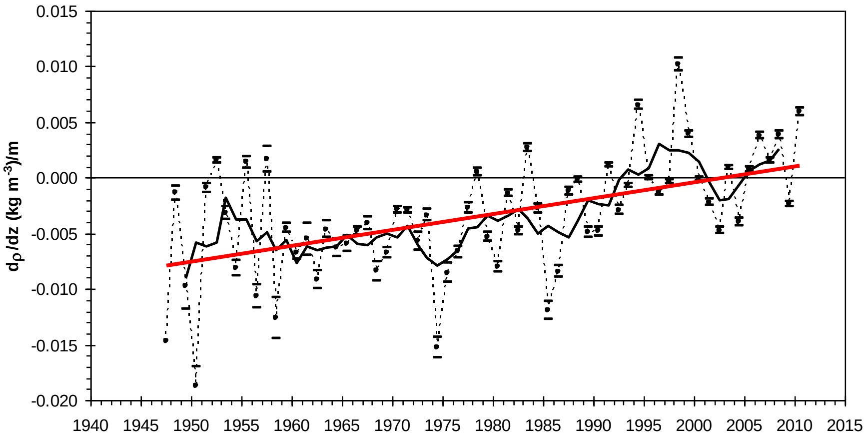

Figure 3.6. Annual-mean anomalies (dashed line with solid circles and standard error estimates) and 5-year running means (heavy black line) of the vertical stratification gradient over the upper 50 m on the Scotian Shelf, based on historical temperature and salinity data. The red line is the long-term trend indicating an increase of 0.4 kg/m^3 over 60 years. From Petrie et al. (2011).

3.4.4 Sea Level

IPCC (2007; Ch.5) reported that global sea level rose by average rates of about 1.7, 1.8 and 3.1 mm/year over the periods 1903-2003, 1961-2003 and 1993-2003, respectively. Their reconstructed rates for the Scotian Shelf region were about 2 and 3 mm/year for the previous half century and decade, respectively, approximating the global changes. Observed sea level at Halifax (relative to land) shows an approximately linear increase over the past 90 years at a rate of 3.3 mm/year, exceeding the global mean (Figure 3.7) (Petrie et al. 2011), but with considerable decadal-scale variability. However, there is little indication of the enhanced global rate of rise during the past few decades, except during the past two years. The higher regional (than global) rate of rise during the first half of the past century can be at least partly explained by the continental subsidence (sinking) of Nova Scotia due to post-glacial rebound, estimated to be about 2 mm/year. The lower regional (than global) rate of rise at Halifax during the past few decades (after removal of the subsidence contribution) indicates that there is an important contribution to regional sea level change from some other factor such as variable ocean circulation (e.g., Yin et al. 2009), changing heat content (thermal expansion) associated with the AMO (e.g., Frankcombe and Dijkstra 2009), or variable alongshore winds (e.g., Sturges and Douglas 2011). One possible contributor is the episodic extension of relatively cool and/or fresh subpolar shelf or slope water into the region as occurred during the 1960s along the slope, and in the 1970s, 1980s and 1990s with the Great Salinity Anomalies, with an associated tendency to lower coastal sea level (there are hints of this in Figures 3.5 and 3.7). Another possibility is lowered sea level on the inner Scotian Shelf associated with increased northeastward winds (EAP 2009) and consistent with limited ocean warming on the inner Scotian Shelf due to increased coastal upwelling. Further investigation of these and other possible explanations for the lack of recent accelerated sea level rise at Halifax is needed.

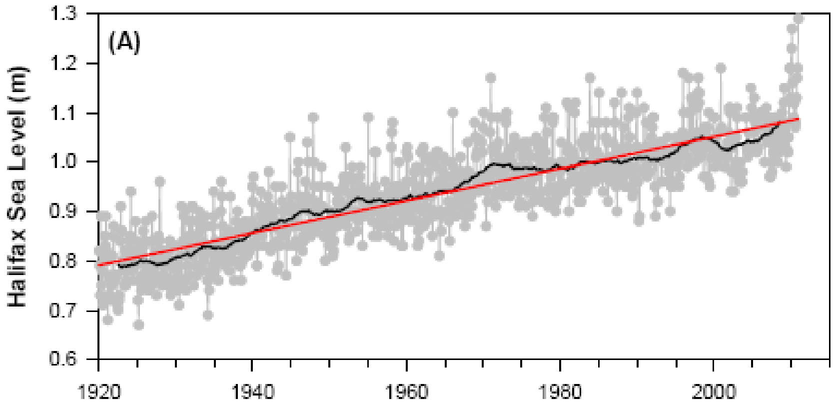

Figure 3.7. Monthly means (grey) and a 5-year running mean (heavy black line) of coastal sea level at Halifax, along with the 1920-2010 linear trend (red). From Petrie et al. (2011).

In addition to (and partly because of) the increase in "mean" sea level that is apparent in Figure 3.7, there have been increases in extreme high water levels associated with the combination of coastal subsidence, mean sea level rise, tides, surges, waves and other processes contributing to instantaneous sea level (e.g., Thompson et al. 2009).

Recent analyses of long coastal sea level records indicate that the amplitude of the predominant semidiurnal M_2 tide in the near-resonant Bay of Fundy and Gulf of Maine system has increased by 2-5% over the past century depending on location (Müller 2011; Greenberg et al. 2012). It appears that this is occurring because of mean sea level rise and is contributing to increasing extreme high water levels. The effects (on Nova Scotia) appear to be limited to southwestern Nova Scotia and the Bay of Fundy, and are not observed at Halifax (which is outside the near-resonant system).

3.4.5 Chemical Oceanographic Properties

There are also indications that important changes in the chemical oceanographic properties on the Scotian Shelf are occurring following large-scale trends, but it is difficult to quantify and interpret the rates because of limited datasets.

There is unequivocal evidence that dissolved inorganic carbon concentrations in the global ocean have been increasing as a result of increased atmospheric CO_2, with associated decreases in the ocean's pH and calcium carbonate saturation state (e.g., Doney et al. 2009). IPCC (2007, Ch.7) reported that pH in the global ocean has decreased by about 0.1 since 1750, and Azetsu-Scott et al. (2010) have estimated a pH decrease of about 0.05 in the Labrador Sea since 1996 from systematic measurements. Sparse data from the Scotian Shelf indicate a decrease in pH exceeding 0.1 since the early 1930s (Worcester and Parker 2010), but there is a lot of scatter. Nevertheless, both the available atmospheric and ocean data, and understanding of the global carbon cycle, point clearly to ongoing ocean acidification on the Scotian Shelf.

There is also evidence for a widespread decrease in dissolved oxygen concentrations and oxygen saturation levels in the slope-derived deep waters in the Gulf of St. Lawrence and on the Scotian Shelf (Figure 3.8) (Petrie and Yeats 2000; Gilbert et al. 2005). Gilbert et al. (2005) reported a 50% reduction in dissolved oxygen concentration at depth in the St. Lawrence Estuary since the 1930s, and estimated that between one-half and two-thirds of this change was associated with the warming and increased fraction of subpolar slope water noted earlier (Section 4.1). Petrie and Yeats (2000) reported higher oxygen at depth on the Scotian Shelf in the 1960s, also consistent with the increased influence of cool and fresh subpolar slope water. Yeats et al. (2010) found a decrease in oxygen on the Scotian Shelf since the 1970s (consistent with Figure 3.8) but concluded that the data were not adequate to identify a statistically-significant trend. Data sparsity and multiple physical and biogeochemical factors affecting oxygen concentrations make it difficult to identify the spatial and seasonal structure of the long-term trend that is apparent in the slope-derived waters.

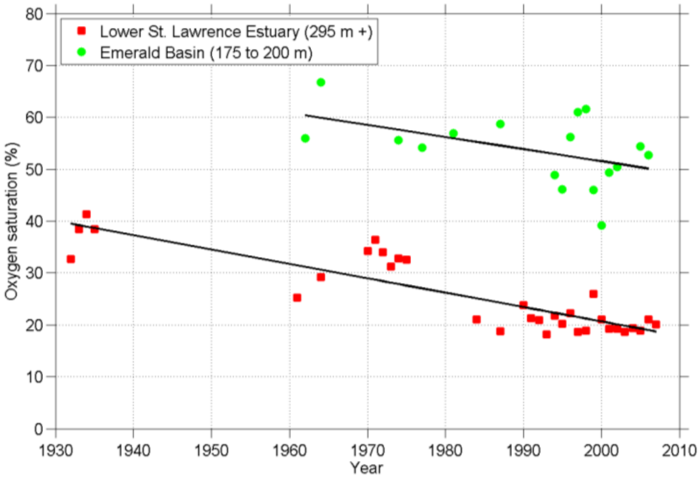

Figure 3.8. Annual means of oxygen saturation at depth in the Gulf of St. Lawrence and in Emerald Basin on the Scotian Shelf. Courtesy of Denis Gilbert, DFO at L'Institut Maurice-Lamontagne, Mont-Joli, PQ.

The longest time series of nutrient data for the Scotian Shelf region are for nitrate and silicate at depths below 100 m in the eastern Gulf of Maine, extending back to the 1960s (Townsend et al. 2010). Their decadal means indicate that the lowest concentrations of nitrate and silicate, and the highest ratio of silicate to nitrate, occurred during the 1960s, which they attributed to the increased contribution of subpolar slope water in the 1960s (e.g., Figure 3.5). The 1970s showed a large increase in nitrate, a slight increase in silicate and a large decrease in the silicate-to-nitrate ratio which were attributed to a large influx of warm (subtropical) slope water. Since then, the data show a smaller decrease in nitrate and smaller increase in silicate, and an increase in the silicate-to-nitrate ratio. Townsend et al. attribute the changes since the 1970s to a combination of an increase in the equatorward transport of subpolar shelf water, and changes in river inputs and biological/sediment processes.

Data from the Scotian Shelf (Yeats et al. 2010) show decreases in nitrate, phosphate and silicate since the 1970s in the 20-40% range depending location and nutrient, and an increase in the silicate-to-nitrate ratio, somewhat similar to that observed in the Gulf of Maine. Yeats et al. suggest that a combination of spatially- and temporally-variable physical and biological factors may be contributing to these changes, including lower nutrient concentrations in the upper waters exiting the Arctic. Johnson et al. (2012) have recently reported that the line-averaged deep-water inventories of nitrate on the Halifax and Browns Bank lines (including the continental slope) have been increasing since 2005-2006 and are currently at their highest levels since 1999, but this change is not apparent in the deep waters on the shelf. Collectively, these datasets and studies indicate that a complex mix of natural and possibly anthropogenic variability in both physical and biogeochemical processes has been affecting nutrient concentrations in the Scotian Shelf region, and that further datasets and understanding will be required to develop projections for future changes.

3.5 Discussion

This interim summary of projected and observed ocean climate change on the Scotian Shelf indicates that, overall, changes are occurring in key properties and indicators such as air and ocean temperature, stratification, sea level and ocean acidity that are consistent with expectations for anthropogenic climate change. However, it appears that natural variability associated with the NAO and other large-scale forcings, as well as with regional physical and biogeochemical processes, remains an important and perhaps predominant contributor to changes in some variables.

Substantial progress in the identification, attribution and projection of climate change in the region can be expected in the next few years, as results from the IPCC's Fifth Assessment Report (presently in preparation), DFO's new Aquatic Climate Change Adaptation Services Program (ACCASP) and various other climate change studies become available. Nevertheless, it should be recognized that the Shelf is located in a complex region with strong natural variability and many competing climate change influences, such that uncertainties can be expected to remain with regards to the rates and spatial structure of the changes, as well as the sign in some cases.

3.6 Acknowledgements

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4.0 CLIMATE CHANGE SUMMARY: STATE OF THE SCOTIAN SHELF

N.L. Shackell

4.1 Impacts on Biota

4.1.1 Productivity

Coupled climate models suggest that primary productivity will increase north/south of 40° latitude by 2040-2060 because of a longer growing season. Primary productivity is predicted to decline in the tropics because increased stratification will impede nutrient mixing in the upper water column (reviewed in Sherman et al. 2011).

Actual global estimates of phytoplankton productivity in response to climate change are varied and it is not clear whether it will increase or decrease (Reid and Valdes 2011). Locally, phytoplankton productivity did increase from the 1960s to the 1990s in the Maritimes Region, but that trend has reversed itself (Head and Pepin 2010). There has been no directional change from 1997-2009 because an increased spring bloom and a decreased fall bloom balanced out (Li et al. 2006, 2009).

Phytoplankton response depends on the local composition of controlling factors. (e.g., light, nutrient availability, stratification, upwelling). The extremely varied responses reflect both the high rates of natural variability and, thus, the uncertainty of whether phytoplankton production will be reduced or increased due to increased stratification. In general, there is agreement that warmer waters favour smaller phytoplankton cells. Importantly, food webs based on small-sized plankton are not as productive, because the energy flow to upper trophic levels is not as efficient (Moran et al. 2010; Reid and Valdes 2011).

In one study, *Calanus finmarchicus* occurrence was found to decrease as stratification increased, especially during the younger copepodite stages (Reygondeau and Beaugrand 2011). *C. finmarchicus* are the main source of oil-rich food for larval fish, such as cod, in our region. If stratification continues to increase, lower availability of *Calanus finmarchicus* might occur at some critical level. Currently, that critical level is locally unknown.

Jellyfish and ctenophores eat zooplankton and fish larvae. Forage fish and groundfish larvae, such as cod, compete with jellyfish/ctenophores for zooplankton (Frank 1986). When forage fish or groundfish larvae decline, jellyfish and ctenophores have more zooplankton to eat and increase (Suthers and Frank 1990). To exacerbate their increase, it turns out that jellyfish benefit in warmer, eutrophied water, and do not mind low levels of dissolved oxygen. Basically, jellyfish and ctenophores thrive in heavily human-impacted waters (Purcell 2011). It might be anticipated that ctenophores may present a problem in Scotian Shelf waters in the future, as has been shown for the Northeast USA (Link and Ford 2006).

Coupled climate models predict that fish productivity in Canada will increase only slightly under a high greenhouse gas scenario, and decrease <10% if emissions stabilized at 2000 levels (Cheung et al. 2010). To date, fisheries productivity has been more influenced by overfishing and size-selective fishing than by climate change. Fishing reduces diversity (e.g., size truncation, loss of sub-populations and genetic variability) and, thus, over-fished populations are less resilient to climate change (Journal of Marine Systems 79: 2010). The ability to adapt to climate change depends on high levels of genetic variation, especially genetic variation that allows traits to adapt to the immediate environment (phenotypic plasticity; Genner et al. 2010).

4.1.2 Species Distribution

Global projections using a bioclimatic model predict that demersal marine organisms in the NW Atlantic will migrate poleward from 2005-2050 at a rate of 2-4 km/year, whereas pelagic marine organisms will migrate poleward 4-6 km/year because the surface layers are expected to warm faster and pelagic species are more mobile (Cheung et al. 2009; Pereira et al. 2010).

A lot of work on cod has predicted that they will suffer on the Scotian Shelf due to their preference of temperatures from 2-12°C. However, using electronic tags, Righton et al. (2010) were able to determine the actual distribution of cod. They found that cod were much more tolerant than previously considered. The thermal niche ranged from -1.5 to 19°C, averaged 12°C, although they were found in 1-8°C during the spawning season. Cod in 8-10°C grew fastest. On a daily basis, cod typically moved through water strata of very different temperatures, which emphasizes their thermal tolerance. In fact , their former dominance and widespread distribution in the temperate and boreal systems can be attributed to their adaptability and concurs with a recent discovery that cod were dominant in Danish waters when sea temperatures were 2° C warmer than now (cf Righton et al. 2010).

On the Scotian Shelf, species composition/distribution is continually modified by temperature, and indirectly by how the North Atlantic Oscillation (NAO) affects temperature and circulation. There have been no examples of a directional trend in distribution, composition or seasonal events that can be related to warming, because they have not been studied directly and any SST trend is weak compared to the pronounced natural variability.

Observed changes in salinity and circulation may have influenced lower trophic species composition in the Gulf of Maine (Townsend et al. 2010) but have not been directly linked to climate change on the Scotian Shelf (Johnson et al. 2011).

To date, fishing has strongly influenced the fish species composition of our region and the Northeast US (Auster and Link 2009; Shackell and Frank 2007).

4.1.3 Timing of Seasonal Events (Phenology)

The ability to adapt seasonal events (such as reproduction, migration) to climate change varies widely among species but can be generally predicted if the seasonal cues (e.g., temperature, light) are well known. Key taxa are plankton because they are the base of the food chain. Phenological changes have been globally observed, but locally no changes since 1998 have been observed. However, salinity, as it affects stratification, is a strong determinant of spring bloom timing (Song et al. 2011), and temperature determines the number of algal cells (Li et al. 2009). We should anticipate both a change in the types and numbers of phytoplankton: warmer water will select for smaller organisms, and increased stratification will cause seasonal events to occur earlier (Moran et al. 2010).

If climate change will shift timing of seasonal events, then it will also affect trophic interactions if predators and their prey respond differently to a shift in seasonal events. Many species have adapted to give birth during a time when peak abundances of their young will coincide with peak abundances of their prey, as survival depends on having enough to eat (reviewed in Stenseth and Mysterud 2002; Durant et al. 2007). That is, the predator’s timing in peak abundances will “match” the peak abundance of their prey. When peak abundances do not coincide, this is referred to as ”mis-match”, and the predator’s likelihood of survival is reduced.

4.1.4 Chemistry

There is concern that the more acidic Arctic outflow will affect Atlantic Canadian waters downstream (Azetsu-Scott et al. 2010). Acidification effects on the food chain are currently understudied.

Hypoxia (low amounts of dissolved oxygen) is not anticipated to be a huge problem in the offshore but remains a potential concern in embayments/harbours etc., and it may be a problem south of 45°N if the NAO remains positive as expected.

4.1.5 What We Should Anticipate Given Natural Variability And Anthropogenic Forcing

As described in the physical climate change summary, natural variability may be greater than anthropogenic change in most areas for the next few decades. The overall average state will change slowly, giving ecosystems some time to adapt. The effect of fishing may have dominated our ecosystems in the past, but since the buffering ability of highly exploited fish can be presumed low, climate effects will start to influence population dynamics, especially through the recruitment stage. The variance of recruitment at low population size is higher-and more susceptible to chance environmental events. However, there are indications that the timing of seasonal events will start to change faster than the mean state. Since most of resource management is based on opening and closing seasons, this is highly significant. For example, in the fall of 2011, the lobster season opened but the water was still warm and too many soft-shelled lobster were landed. For a direct application to management, the relationship between seasonal water temperatures and crustacean moulting should be further investigated.

In general, warmer water will select for smaller organisms. Corrosive (acidic) water will affect physiology and slow calcification rates and favour non-calcifying animals. Increased stratification may cause seasonal events to occur earlier and, as a result, may disrupt or enhance trophic interactions. Invasive and opportunistic species will benefit; jellyfish profit in warmer eutrophied water where predators/competitors have been removed. Jellyfish/ctenophore outbreaks commonly occur in overfished systems.

Organisms have adapted to temperature over millennia, but nowhere in the fossil record is there any evidence that the ocean was ever as acidic as fast as it is predicted to be under climate change (cf Harley et al. 2006). As well, the change in ocean circulation resulting from warming, and subsequent change in water mass composition at any given region, is also a relevant area requiring more research. Changes in seasonal events, particularly at the base of the food chain, should be further investigated due to the anticipated re-organization of the food chain. Finally, details on the buffering ability of commercial species to climate change would be important to know in order to formulate adaptation plans.

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5.0 ZOOPLANKTON VARIABILITY IN THE GULF OF MAINE AND SCOTIAN SHELF

C.L. Johnson

The overall objective of this study was to understand how the zooplankton communities of the Gulf of Maine and Scotian Shelf respond to variability and change in the physical and biological environment. To address this objective, we examined relationships between zooplankton communities and water masses on the Scotian Shelf, the upstream source for the Gulf of Maine, and identified core shelf species and immigrant communities associated with water masses that are advected onto the shelf from the Gulf of St. Lawrence and slope water. We could then identify environmental variables that were most related to the abundance of immigrant groups on the shelf from year to year during the 2000s. We also identified along-shelf differences in seasonal zooplankton community variability at time series stations from the western Gulf of Maine to the Newfoundland Shelf. These patterns suggest that the zooplankton community changes that were observed in the Gulf of Maine in the 1990s may have resulted from changes in the direct input of zooplankton from the Scotian Shelf.

5.1 Background

Climate-driven changes in the biogeographic distribution and phenology (i.e., response to seasonal variability) of plankton can cause changes in fish distributions and recruitment. For example, biogeographic shifts in plankton associated with changes in the spatial extent of the subpolar gyre have led to changes in the distribution of blue whiting in the northeast Atlantic (Hátún et al. 2009), and spatial changes in the distributions of the subarctic copepod *Calanus finmarchicus* and its warmer-water congener *C. helgolandicus* led to long-term changes in cod recruitment in the North Sea, due to differences in the phenology of the two *Calanus* species (Beaugrand et al. 2003).

Interannual variability in advection may induce changes in zooplankton community structure and abundance, for example, by direct advection of communities, by inputs of nutrients that stimulate primary production, by physical changes such as stratification that influence the timing or magnitude of phytoplankton blooms, or by interactions between animal behavior and circulation. Predation mortality also may have a major influence on zooplankton abundance and community structure in some regions (Li et al. 2006; Neuheimer et al. 2009). Understanding the mechanistic linkages between climate forcing and zooplankton community structure and diversity will aid in prediction of the influence of climate change on the Gulf of Maine ecosystem and will provide the understanding of environmental effects on lower trophic levels that is required for development of ecosystem-based management in the Gulf of Maine.

The water properties and circulation in Gulf of Maine and Scotian Shelf are strongly influenced by inflow from upstream regions on the Scotian Shelf and slope, which are in turn influenced by large-scale climate forcing of high-latitude regions of the North Atlantic (Petrie and Drinkwater 1993; Pringle 2006; Smith et al. 2001). The inshore eastern Scotian Shelf is influenced by the Nova Scotia current, the cold, low-salinity outflow from the Gulf of St. Lawrence, while the offshore eastern Scotian Shelf is more influenced by the warmer, saltier continental slope water. The water properties of the western Scotian Shelf, particularly in deep water, are influenced by slope water inflow onto the shelf (Petrie and Drinkwater 1993). Large-scale climate forcing upstream of the region drives the source of the Scotian slope water, which can be either cold Labrador Slope Water (LSW) or Warm Slope Water (WSW) (MERCINA 2001). The pelagic habitat of the Gulf of Maine is strongly influenced by its mean cyclonic circulation, with surface inflow of cold, lower-salinity water from the Scotian Shelf (Smith 1983) and denser slope water through the Northeast Channel (Ramp et al. 1985). Tidal mixing is very strong on the banks and in the eastern Gulf, especially in the Bay of Fundy.

The Gulf of Maine may be vulnerable to climate-driven zooplankton community changes that could influence fish production in the region. For example, zooplankton community composition in the Gulf of Maine and on Georges Bank changed in the 1990s, and the 1990s community may have favored recruitment of some fish stocks (e.g., Georges Bank haddock) but not others (e.g., Georges Bank cod) (Pershing et al. 2005; Kane 2007; Mountain and Kane 2010). The 1990s community shift was related to lower salinity water in the Gulf and is hypothesized to be driven by changes in advection from the Scotian Shelf and/or changes in fall-winter primary production (Pershing et al. 2005). Loss of key zooplankton species in the Gulf of Maine could also influence fish production. The biomass-dominant copepod species in terms of biomass, *C. finmarchicus*, is at the southern edge of its range in the Gulf of Maine. *C. finmarchicus* is a large, lipid-rich (i.e., energy-rich) species that is a key prey item for planktivorous species such as herring, mackerel, sand lance, northern right whales, and phalaropes, and an indirect energy source for large pelagics such as bluefin tuna that feed on planktivorous forage nekton (Beaugrand et al. 2008, 2009). The extent to which other zooplankton species would fulfill the role of *C. finmarchicus* in the event of a range shift is currently unknown, but there is no large, resident, non-*Calanus* species with equivalent lipid content (Johnson et al. 2011).

5.2 Main Outcomes

5.2.1 Influence of Source Waters on Spatial and Interannual Community Variability

Zooplankton diversity in the Gulf of Maine and Scotian Shelf region is characterized by spatial differences in community composition among the neritic (i.e., near-shore) environment, the coastal shelf, and deep offshore waters (Johnson et al. 2011). Spatial variability patterns were examined using zooplankton and environmental data collected by a variety of monitoring programs. Copepod diversity increased with depth on the Scotian Shelf, likely reflecting the spatial transition from the subpolar community on the shelf to the more subtropical community found off the shelf, as well as greater pelagic habitat diversity in the deep shelf water. The cross-shelf zooplankton community gradient is stronger on the eastern Scotian Shelf, where the inshore is influenced by inflow of water from the cold Gulf of St. Lawrence and the offshore is influenced by warmer slope and oceanic waters, than on the Western Scotian Shelf, where water masses are more mixed. In addition to core shelf species, which are ubiquitous on the Scotian Shelf, certain species are associated with Gulf of St. Lawrence water (Arctic *Calanus* species*)* and with warm offshore water and cold offshore water. Close to shore on the coastal shelf, diversity can also be enhanced by the contribution of meroplankton closer to shore.

While warm water zooplankton species' distributions have shifted north in the northeast Atlantic in recent decades, Arctic *Calanus* species in the Northwest Atlantic moved south in the 1990s due to changes in circulation in the region (Beaugrand et al. 2002; Richardson 2008), and they have remained abundant in the 2000s (Head and Pepin 2009), a warm decade across much of the region (Hebert et al. 2011). We compared interannual variability in the abundance of Arctic *Calanus* species, warm offshore species, and warm shelf species with variability in climate and environmental indices reflecting local and remote processes over the period 1999-2009 at the Halifax time series station to identify drivers of change in zooplankton groups living at the edges of their ranges on the Scotian Shelf. Annual abundance anomalies of the two immigrant groups, Arctic *Calanus* species and warm offshore species, were negatively correlated to one another. Arctic *Calanus* (warm offshore species) had a strong positive (negative) correlation to Cold Intermediate Layer Volume and a strong negative (positive) correlation to near-surface and deep temperature, indicating that variability in the outflow from the Gulf of St. Lawrence influences the abundance of both of these groups. In contrast, annual abundance anomalies of warm shelf species were positively correlated with chlorophyll, suggesting that variability in their abundance is more related to local primary production than advection. This work indicates that changes in advection from the Gulf of St. Lawrence appear to influence the abundance of immigrant groups from both the Gulf of St. Lawrence and slope water. The climatic drivers of variability in outflow from the Gulf of St. Lawrence are not currently understood.

5.2.2 Along-shelf variability in zooplankton seasonal cycles

Seasonal variability patterns of zooplankton diversity and community composition were compared at time-series sampling stations in the western Gulf of Maine, Bay of Fundy, central Scotian Shelf, western Gulf of St. Lawrence, and Newfoundland Shelf. Copepod communities throughout the study region were dominated by relatively few species, and species richness was highest on the Scotian Shelf and in the Bay of Fundy. Several dominant shelf species were abundant at all stations, while other shelf species were abundant only at southwestern or northeastern stations. Offshore species were most prevalent at the Scotian Shelf and Bay of Fundy stations, contributing to the high species richness there, due to the influence of on-shelf transport of slope water on the central and western Scotian Shelf.

There was a spatially coherent spatial difference in the seasonal cycle between the Gulf of Maine stations and the upstream, northeastern stations (Scotian Shelf, Gulf of St. Lawrence, Newfoundland Shelf). Zooplankton abundance was higher in the fall-winter at the northeastern stations than in the Gulf of Maine, primarily due to higher abundances of small copepods. The zooplankton community shift in the Gulf of Maine in the 1990s was characterized by higher abundances of small copepod species, particularly in the fall and winter. The spatially coherent pattern of high fall-winter zooplankton abundance east of the Gulf of Maine is consistent with the hypothesis that the Gulf of Maine community shift was driven by direct inputs of zooplankton associated with increased inflow from the Scotian Shelf. However, annual average anomalies of small copepod abundance on the Scotian Shelf were positively related to chlorophyll and stratification in the fall, consistent with the hypothesis that enhanced primary production in fall drives higher small copepod abundance on the Scotian Shelf. Both advection and changes in fall primary production likely contributed to the zooplankton community shift in the Gulf of Maine in the 1990s.

5.3 Conclusions

Changes in ocean circulation and biogeographic boundaries can influence fish recruitment and distribution through lower trophic level production and plankton distribution and phenology. This project identified spatial, seasonal, and interannual variability patterns of zooplankton diversity and community composition and their relationships with environmental variability. This work provides knowledge about zooplankton community variability that is necessary to identify climate-driven biogeographic shifts that may influence higher trophic level production.

Much of the work described above is in preparation for publication, and, therefore, this text should not be cited without prior reference to the author.

5.4 Acknowledgements

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6.0 ECOSYSTEM RESPONSES TO CLIMATE VARIABILITY OF THE ATLANTIC SEA SCALLOP, *Placopecten magellanicus*

C. DiBacco, C.L. Johnson, and W.C. Gentleman

The overall goals of this research project were to better understand (i) how large-scale physical and biological forcing on Georges Bank (GB) and in the Gulf of Maine affects Atlantic sea scallop (*Placopecten magellanicus*) reproductive seasonality; and (ii) how resultant temporal and spatial variability in larval production influences larval dispersal and connectivity among commercially exploited scallop beds on GB, including the Northeast Peak (NEP), Southern Flank (SF), and Great South Channel (GSC) stocks.

The first specific objective was to describe and characterize reproductive seasonality of GB sea scallops. This characterization was based on scallop samples from the NEP stock, where DFO maintained a monthly monitoring program from 1984 to 2004. The initial nine years of this time series (1984 to 1992) have been described via histological and gravimetric gonadal indices that revealed semi-annual spawning events in spring (May to June) and fall (September to October) (DiBacco et al. 1995). This study showed that while fall spawns occurred in every year analyzed, there was no apparent spring spawn in either 1989 or 1992. The onset, duration and magnitude of fall spawning events were more consistent than spring, yet the frequency of spring spawns suggests an adaptive significance of this aspect of *P. magellanicus'* reproductive life history.

The present study builds on the work of DiBacco et al. (1995) in several ways. First, the analysis incorporated an additional 11 years (1993-2004) of the scallop time series data set from the NEP of GB; the 1998 data series was not included since only five months were sampled and since they were not appropriate for determining spawning times. Second, while DiBacco et al.'s (1995) gonosomatic index (GSI) -- defined as the ratio of wet gonad weight to total soft tissue weight -- was employed in this study to monitor the onset and duration of intra- and interannual spawning events, a complementary wet gonad weight (WGW) metric was added as a more accurate estimator of the relative magnitude of spawn events. This choice was made because the GSI metric has been shown to be confounded by relative and often inverse changes in the weight of gonadal versus other soft tissues (e.g., adductor muscle, mantle) (Barber and Blake 2006). For example, while gonad weight increases as a result of development and growth of oocytes, muscle weight typically decreases over the same period due to its role as an energy reserve (i.e., glycogen) used to supplement metabolic processes such as reproduction (e.g., Robinson et al. 1981). Co-variation in tissue weights over the reproductive season can cause the GSI to misrepresent the relative magnitude of spawning events. In contrast, changes in average WGW offered a direct estimate of the mean weight of mature scallop oocytes released during spawning and thereby an estimate of fecundity (e.g., Langton et al. 1987).

New results on the reproductive seasonality of sea scallops sampled from the NEP support the following major findings of DiBacco et al. (1995):

- The occurrence of significant spring spawns in 75-78% of years analyzed (15 out of 20 years versus seven out of nine previously examined).
- The occurrence of significant fall spawn events in every year analyzed.
- The magnitude of the fall spawn, assessed by either GSI or WGW metrics, was always larger than the spring spawn.
- The initiation and duration of the fall spawn, assessed by both GSI and WGW metrics, was less variable than observed in the spring. The fall spawn was typically initiated and completed within a two month period (i.e., August to September) while the spring spawn was usually protracted over a four month period (i.e., April and July).

Novel results from the new study include the following:

- The relative magnitude of spring and fall spawning events (i.e., fecundity), which were used to parameterize hydrodynamic model-based larval dispersal studies (described below), was characterized using the WGW metric, which provides a better estimator (see above discussion) when compared to the previously used GSI index.
- WGW and GSI estimates showed that 25% to 35% of mean annual production of mature oocytes was attributable to the spring spawning event, which argues for the adaptive significance and ecological importance of the spring spawning event.
- While all sea scallop size classes (defined in Table 6.1) participated in both spring and fall spawning events, the largest size class was responsible for about half the total fecundity during both spring and fall spawning events.

Table 6.1. Atlantic sea scallop (Placopecten magellanicus) size classes based on shell height measurements. Age class estimates are based on the von Bertalanffy growth model with equation parameters from Naidu and Roberts (2006).

Size Class	Age Class
50-95 mm	2.6-4.3 yr
95-120 mm	4.3-6.1 yr
120-170 mm	>6.1 yr

The spring versus fall spawning phenology characterized above, including the relative timing, magnitude (i.e., fecundity) and size-class specific fecundity estimates of sampled scallops, was used to parameterize a physical-biological model to evaluate larval drift and connectivity. The model coupled particle-tracking in realistic climatological flow fields (FVCOM) (Chen et al. 2003) with representations of larval growth, behavior and mortality. Two modeling exercises were conducted to examine the relative importance of different factors on the settlement distributions and connectivity among the three major GB scallop stocks (NEP, SF and GSC). The first exercise examined variations in transport-related connectivity due to (i) larval depth-distribution (i.e., behavior); (ii) temperature-dependent planktonic larval duration; and (iii) spawning seasonality (i.e., spring versus fall) (Gilbert et al. 2010). The second exercise examined variations in larval connectivity due to larval production and mortality, using larvae initial distributions based on spatially-explicit adult spawning potential (i.e., the spatial distribution and abundance of adult (spawning) sea scallops, estimated from stock assessment survey data, and scallop size-specific fecundity).

Results from the first exercise demonstrated that, in general, the biological factors considered here could influence larval dispersal at levels comparable to the effects of variation in circulation. Simulations using passive behavior resulted in unrealistic depth-distributions, whereas those imparted with pycnocline-seeking behavior, described by Tremblay and Sinclair (1990), predicted more realistic depth and settlement distributions. In particular, pycnocline-seeking behavior doubled the connection fraction (ca. 25% versus 12%) from GSC and NEP stocks, which support the GSC stock as a major source of larval recruits to the NEP stock. Simulations examining temperature-dependent larval development rates showed that the effect of thermal history on planktonic larval durations could significantly alter connectivity estimates among NEP, SF and GSC commercial stocks, even when mean larval duration changed by only a few days. These results suggest that larval connectivity and recruitment may be influenced by spatial (e.g., through larval depth distribution) and temporal (e.g., intra- and interannual) variations in GB temperatures, which includes both environmental variability and climate change. Finally, larval settlement distributions and connectivity estimates predicted for spring versus fall spawning seasons were similar despite slower development rates and longer planktonic larval durations associated with colder spring temperatures. Simulated spring transport was balanced by slower spring currents compared to faster currents and associated lower planktonic larval durations, due to warmer fall temperatures, in the fall.

The second modeling exercise assessed the influence of temporal and spatial differences in sea scallop larval production on the dispersal and connectivity among GB stocks. Heterogeneous larval production fields were estimated for NEP, SF and GSC stocks based on the (i) spatial distribution and density of adult (spawning) scallops from appropriate Canadian and US stock assessment survey data (1996 to 2004) and (ii) scallop size-class specific mean fecundity estimates for (iii) spring and fall spawning events (see Gilbert 2011). This modeling exercise reflects the relative importance of spring versus fall spawning events on larval dispersal and connectivity among GB stocks. Accounting for temporal and spatial differences in larval production estimates resulted in the following results:

- The NEP accounted for approximately 60% of all larvae spawned from GB in both seasons.
- The spring and fall spawns were responsible for about 1/3 and 2/3 of larval production, respectively.
- Interbed differences in adult density (and resultant larval production) resulted in the NEP being a relatively more important source of recruitment for the GSC and the NEP than implied by particle tracking alone.
- Intra-bed variability in spawning, due to differences in adult distributions, can significantly alter predicted settlement and connectivity due to spatial variability in currents.
- Approximately 42%, 36% and 22% of <u>fall-spawned</u> larvae that settled on GB originated from NEP, SF and GSC stocks, respectively. This suggests that the NEP and SF are the largest contributors of larval recruits to the local GB population in the fall.
- Approximately 42%, 5% and 53% of <u>spring-spawned</u> larvae that settled on GB originated from NEP, SF and GSC stocks, respectively. This suggests that the NEP and GSC are the largest contributors of larval recruits to the local GB population in the spring.
- Of larvae spawned from GB stocks, approximately 5 trillion and 1.4 trillion settle (recruit) on the Bank during fall and spring reproductive events, respectively. So, about 20% of larvae recruiting to the local GB population are spring-spawned.
- In the case of heterogeneous larval production fields, the GSC contributed about 60% more larval recruits to the NEP compared to simulations based on larvae spawned homogenously over the GSC (see first modeling exercise). This difference was attributable to more realistic distributions of larval production, which reflected subregions of the GSC that contributed disproportionately more larvae to the NEP than other GSC subregions.

Finally, this study also challenges the assumption that longer planktonic larval durations must equate to lower survivorship, an expectation based largely on the assumption that planktonic larval mortality rates were comparable between fall and spring spawning seasons coupled with longer springtime planktonic larval durations. In fact, Houde (1989) and others have shown that mortality of planktonic organisms is typically reduced by lower spring temperatures. Here, applying a lower mortality rate in spring led to enhanced survivorship of spring-spawned larvae, which would better explain the adaptive significance of spring spawned larvae in the life history of GB scallops.

By assessing the extent to which these biological and physical factors affect retention and exchange among GB subpopulations, this work improves our understanding of the processes influencing connectivity and larval recruitment. This research also helps direct future research programs by identifying the kinds of data needed to predict the connectivity, sustainability and potential responses of the GB scallop metapopulation to climate change. For example, the first modeling exercise highlights a need for better empirical data describing the vertical distribution of larvae, larval growth rates, and spawning seasonality of scallop stocks to improve population connectivity estimates. The second modeling exercise could be improved with better quantitative data on spatial (i.e., stock) and temporal (i.e., seasonal) fecundity rates, adult distributions and mortality estimates. To this end, ongoing research on this project includes efforts to assess the relationship and effect of environmental factors (e.g., temperature, chlorophyll concentration) on the relative magnitude and seasonality of Atlantic sea scallop reproductive indices (e.g., GSI, WGW).

Finally, a large portion of the above data and results are being reviewed and prepared for publication. As such, results presented here are to be considered preliminary.

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7.0 COMMON LARGE-SCALE RESPONSES TO CLIMATE AND FISHING ACROSS NORTHWEST ATLANTIC ECOSYSTEMS

N. Shackell, A. Bundy, J.A. Nye, and J. Link

In this ERI project, authors investigated whether there were common biological responses to climate and fishing across seven Northwest Atlantic ecosystems. A minimum / maximum autocorrelation factor analysis of biological indicators for each region revealed a common primary multivariate trend: a rapid change during the 1980s to the early 1990s. There was a strong common pattern in the biological indicators responsible for the primary multivariate temporal trend in the five more northerly regions: an increase in abundance of phytoplankton, an increase in biomass at mid-trophic levels, and a decline in predatory groundfish size. The common associations between patterns and drivers were fishing indices, and the Atlantic Multi-decadal Oscillation, although all associations were weakened when co-varying drivers were held constant. Results are consistent with known long-term effects of intense fishing, such as a decline in average size and changes in species composition. Lower fishing pressure has allowed some regions to recover former predatory biomass levels since late 1990s, although the biomass is composed of fewer species. However, fishing was not the only driver; a more mechanistic understanding of how the climate affects lower trophic levels is needed to contextualize climate effects in heavily fished ecosystems (Shackell et al. 2012).

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Shackell, N.L., Bundy, A., Nye, J.A., and Link, J.S. 2012. Common large-scale responses to climate and fishing across Northwest Atlantic ecosystems. ICES Journal of Marine Science 69: 151–162.

SPATIAL MANAGEMENT CONSIDERATIONS

8.0 SPATIAL REFERENCE POINTS FOR DATA-POOR FISHERIES: A CASE STUDY OF SEA CUCUMBER

N. Shackell, D. Brickman, and K. Frank

Minimally, a fishery requires information on abundance, productivity and distribution of the target species. Often, none of these are available, but in some temperate jurisdictions, the spatial distribution of relative abundance is known. Walters (1998) recommended a series of closed areas and the use of minimum biomass estimates to inform an adaptive management plan in developing fisheries when little information is available. Sea cucumber (*Cucumaria frondosa*) is used as an example to demonstrate how distributional data, ecological principles, and knowledge from other jurisdictions can provide a basis for credible science advice for the management of an emerging invertebrate fishery. The idea is that the network would be reviewed and updated in three to five years based on what is learned about replenishment rates/spillover/catch rates, etc. For the purposes of this report, an outline is provided of the methodology designed to conserve the fishery by focusing on protection of high quality habitat. That is, explicit results are not included.

The methodology is applicable to any sessile invertebrate. The lifestyle of benthic invertebrates, often sessile and spatially structured with low recruitment, renders them highly vulnerable to over-fishing. This is further exacerbated by their mode of reproduction. Many benthic invertebrates are broadcast spawners, and their reproductive success is contingent on spawner density. Gametes are released into the water column and depend on contact for fertilization. If the density of adults is too low, the concentration of gametes in the water column can be too diffused and the probability of fertilization is lowered. Below some minimum critical density, reproductive success falls off rapidly and the population is subject to density-dependent reproductive Allee effects (Gascoigne et al. 2009; Lundquist and Botsford 2004; Botsford et al. 2001, 2003, 2004). Of course, densities can also be too high and populations can suffer crowding, but low densities are most relevant to sustainability of exploited species. Density-dependent reproductive success is highly problematic to sustaining a fishery because fishers most often target high-density areas to maximize their catch-per-unit-effort (CPUE) (Caddy 2004).

8.1 Design Methodology (using *Cucumaria frondosa* as a Case Study)

8.1.1 Objectives

a. Protect a large segment of high-density habitat until sufficient data can be obtained to inform management on appropriate harvest strategies/levels (following Duprey et al. 2011).

b. Assign minimally 50% of high density habitat as reserve and remainder as fishable (to keep CPUE high/profitable and lessen gear impacts on low-density habitat).

The design guidelines are as follows: the probability of fertilization is dependent on spawner density, especially male density, and declines rapidly below a given sperm concentration (Hamel and Mercier 1996a). Patches are linked by larval dispersal more than by adult migration. Prime sea cucumber habitat is in estuarine, rock/boulder/gravel mix with high flow (So et al. 2010).

The sequence of design steps was as follows: (i) determine subpopulations or clusters of subpopulations; (ii) determine patch size within clusters (iii) if results from a numerical model are available and there are multiple patches within a cluster, use the probability of retention in, and connectivity of, patches to classify patch type (source, sink, source/sink, isolated); (iv) identify reserve area of each high density patch within cluster and place reserve to maximize protection and enhance recruitment to non-reserve areas; and (v) modify amount of reserve area based on data availability, experience in other jurisdictions, life history and overall habitat quality.

(i) Subpopulations

Clear demarcations in distribution were used to determine distinct clusters. Subpopulations are easily recognized if there is only one isolated high density patch. Where there were multiple and connected high density patches, the cluster was assumed to represent a meta-population. The main assumption is that each cluster is largely self-recruiting. Marine benthic invertebrate populations were once believed to be connected over large spatial scales, but the empirical evidence of fine spatial structure in a variety of taxa has initiated a recent paradigm shift. Marine populations are not necessarily as connected as once believed due to both larval behaviour, that can include vertical migration, and ocean physics (Becker et al. 2007, reviewed in Cowen and Sponaugle 2009). Furthermore, sea cucumber adults do not migrate over large distances. Sea cucumbers in the Northwest Atlantic are genetically similar, suggesting that they form a panmictic population (So et al. 2011). However, subpopulations can be genetically similar yet have different local demographic rates. Based on the mitochondrial DNA patterns, So et al. (2011) concluded that, over longer time periods, larval migrants can reseed distant areas but that local areas are likely supported by local larval production.

(ii) Patch size within clusters

Within each cluster, the spatial structure and patch size was determined using Moran's I spatial autocorrelation analyses. Biological processes (such as dispersal) make nearby populations similar in their properties (e.g., abundance), and most often, similarity between samples decreases as the distance between samples increases. Significantly positive values reflect that samples are similar. A zero value indicates a random spatial pattern (Oksanen 2011). From this, the average patch size can be estimated as the average distance where Moran's I spatial autocorrelation coefficient is significant (Oksanen 2011).

(iii) Retention/Connectivity among multiple patches

The larval phase in sedentary, spatially-structured populations is the dominant form of dispersal (Cowan and Sponaugle 2009). When larval dispersal information is available, the spatial pattern and larval pelagic phase could be used to refine placement of reserves. For example, if distinct sources were found, those would be designated as contributing a significant portion to the entire metapopulation because drift from sources would feed recruits to neighbouring fishable areas. If there were distinct sinks, this would be an ideal place to fish as the fishery would rely solely on recruitment to marginal areas, and would not be jeopardizing source populations. The analysis was refined by estimating larval retention and connectivity in the largest cluster with multiple high density patches.

(iv) Identify reserve area of each high density patch within cluster and place reserve to maximize protection and enhance recruitment to non-reserve areas

Each patch has a probability of particles retained, imported from other patches, and exported to other patches. A combination of these three attributes were used to characterize patches as Sources (high retention, low import, high export), Sinks (low retention, high import, low export), Mixed Source/Sink (medium retention, import, export) and Isolated (high or low retention, low import and export). As the array of patches did not fall strictly into each category, the terms "source" and "sink" were used loosely to compare attributes among patches.

(v) Modify amount of reserve area based on experience in other jurisdictions, life history and overall habitat quality

Where regional assessments even exist, 81% of global sea cucumber fisheries experienced declines while body size was reduced by 35% (Anderson et al. 2011). Apart from unregulated fisheries, their vulnerability to over-exploitation stems from their life history traits (late age at maturity, slow growth, low recruitment rate) and life style (broadcast spawners, spatially-structured, sedentary) (Purcell 2010). Given the global experience, Scotian Shelf sea cucumber provides a good example of a species that could easily be overfished due to data limitations: there is no local information on sea cucumber age at maturity, individual growth rate, population size, growth rate, recruitment or population structure.

Sea cucumbers are often observed at much shallower depths (Singh et al. 1999; So et al. 2010). In one experiment, growth rate was maximal at 20 m. Sea cucumbers are filter feeders, and dependent on floating seston and high flow for maximal feeding (Singh et al. 1998). The amount ingested can increase up to 55 cm/s in the field (Holtz and Macdonald 2009). The rate of feeding is proportional to the quality of seston (Singh et al. 1998). Bottom velocities on Sable/Banquereau, where the major offshore concentrations exist, are very small, around 5 cm/s (D. Brickman, unpublished data). The dependence of growth on both high flow and on chlorophyll a amounts shows that the offshore populations in this study, as distributed in fairly deep, low flowing waters, are living in suboptimal habitat compared to coastal estuarine areas (So et al. 2010).

8.2 Summary

Within a cluster in a lightly fished region, persistent high density areas likely represent superior habitat simply because they support more individuals per unit area than low density habitat. These high density areas are also important to the reproductive cycle of broadcast spawners, and are especially important to sea cucumbers as they release a chemical to initiate synchronous gametogenesis to maximize fertilization rates (Hamel and Mercier 1996b). These observations argue for the protection of high-density habitat. But how much? Biological reference points or limit reference points represent the fraction of the population that can be removed without compromising the population’s sustainability, but classical fisheries models to estimate maximum sustainable yields of stocks are not applicable in these types of fisheries, whereas habitat protection is (Purcell et al. 2011).

The amount placed in reserves in offshore Nova Scotia has to be weighted by their global status of being overfished, and the observations that (1) life-history is vulnerable to over-fishing; (2) they are in suboptimal habitat (growth rate is likely low); (3) they are being fished before or around maturity; (4) there is no information on how fast an area is replenished. Since biological reference points are often based on expert judgement (Caddy 2004), experience in other jurisdictions was used and a precautionary 50-60% of each high density patch spaced appropriately was opted to be designated as a fishery reserve.

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9.0 REFERENCE POINTS TO MAINTAIN SPATIAL DISTRIBUTION: SEA SCALLOPS

Stephen Smith, Peter Lawton, Jessica Sameoto, Craig Brown

The primary components of Fisheries and Oceans Canada's (DFO's) implementation of the Precautionary Approach (PA) are reference points that indicate three major states (Healthy, Cautious and Critical) for stock status (DFO 2009). Management actions are defined according to the current state of stock status. While biomass is the usual indicator for stock status, the policy is flexible with respect to choosing the most appropriate indicator for the stock in question. Use of biomass implicitly assumes that this indicator consistently represents the productivity of the stock over time.

Within the Ecosystem Research Initiative (ERI), one project took advantage of some prior foundational regional marine habitat mapping research to explore new spatially-explicit methods for investigation habitat-productivity relationships.

Management areas for sea scallops (*Placopecten magellanicus*) in the Maritimes Region are generally defined according to the geographical extent of scallop beds and are assessed and managed as quasi-stocks (e.g., DFO 2010a,b). However, productivity can vary considerably within a management area (e.g., Smith et al. 2001; Smith and Rago 2004) leading to the tendency to over-exploit areas of high productivity and under-exploit areas of low productivity. Although depth has been posited to be functionally related to growth and productivity (e.g., Smith et al. 2001), as a single surrogate depth is not adequate enough to explain all of the spatial patterns for all inshore fishing areas.

Foundational marine habitat mapping was undertaken prior to the ERI program, commencing in 2002 as a new scallop fishery was initiated in an area off of southwestern Nova Scotia inshore of German Bank referred to as Scallop Fishing Area (SFA) 29 West. Through a joint funding agreement with the fishing fleets, Natural Resources Canada and Fisheries and Oceans Canada (DFO 2006; Todd et al. 2012), the new fishery area was mapped using multibeam sonar, providing information on the spatial distribution of depth and characteristics of the bottom type through the backscatter.

Bottom areas in SFA 29 West (A–D[1], Figure 9.1) were classified with respect to a measure of habitat suitability for scallops based on environmental data layers derived from multi-beam sonar data (e.g., bathymetry, aspect, slope, backscatter), and presence data on scallops from three image surveys (two years of TowCam surveys and Campod images from a separate survey in the same area, Figure 9.2; Brown et al. 2012). The values of habitat suitability range from 0 to 1.0, where 0 represents the least suitable habitat and 1.0 represents habitat that is the most suitable (Figure 9.2). To understand the relationship between habitat suitability and fishing pressure, this map of habitat suitability was compared with spatial fishing intensity as measured by frequency of returns per square kilometer from Vessel Monitoring Systems (VMS) on scallop vessels. The higher scallop fishing intensities were associated with the higher measures of scallop habitat suitability (Figure 9.3). Density estimates of scallops from annual scallop research surveys also showed that the highest densities were associated with higher measures of scallop habitat suitability (e.g., SFA 29 D; Figure 9.4).

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[1] Area E was mapped using a different sounder from the one used in areas A–D and could not be analysed in the same way. Area E is marginal habitat for scallops and represents a small part of the fishery.

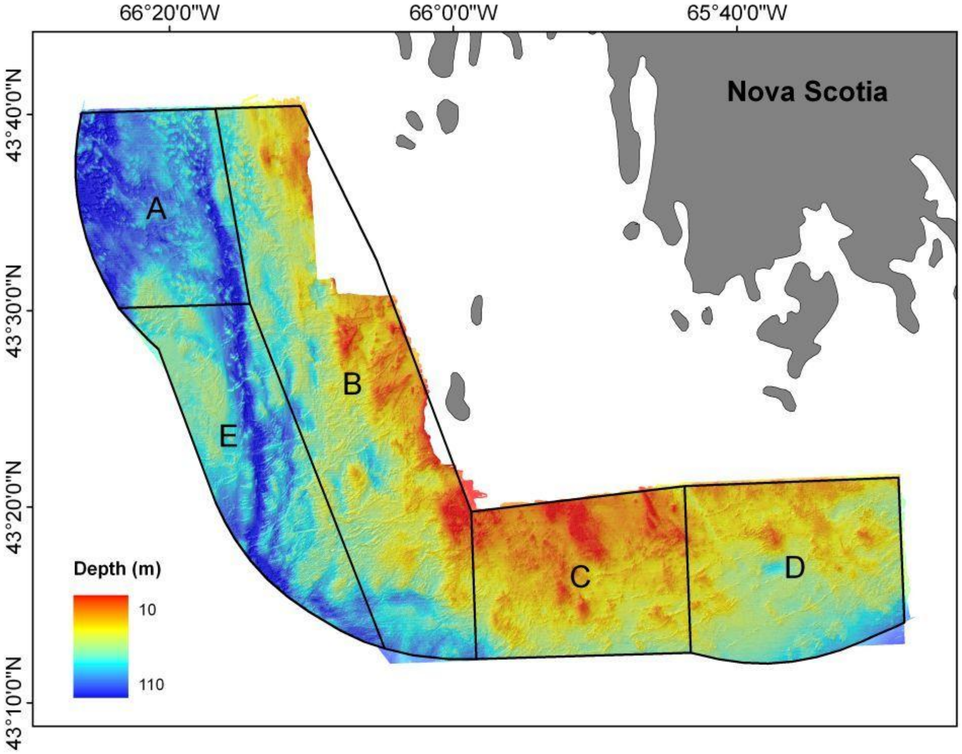

Figure 9.1. SFA 29 with subareas A–E. Multibeam bathymetry indicated.

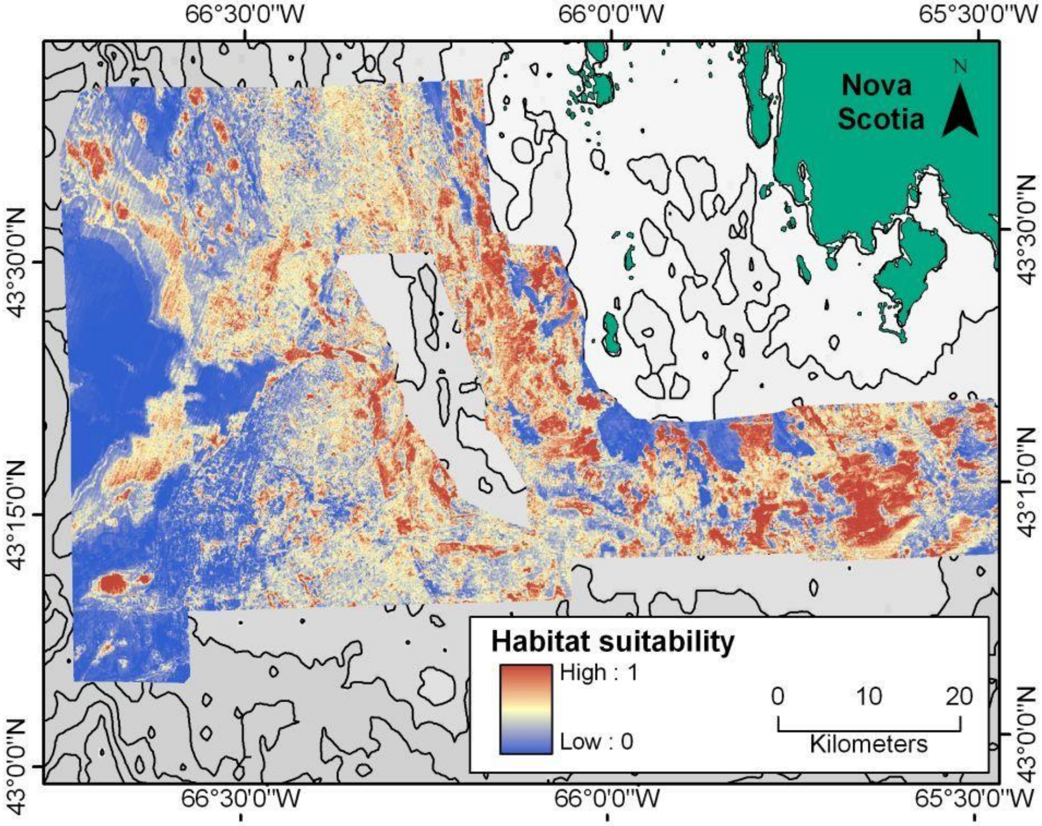

Figure 9.2. Scallop habitat suitability map for German Bank obtained from the Maxent Species Distribution Model. (From Figure 6, top, in Brown et al. 2012.).

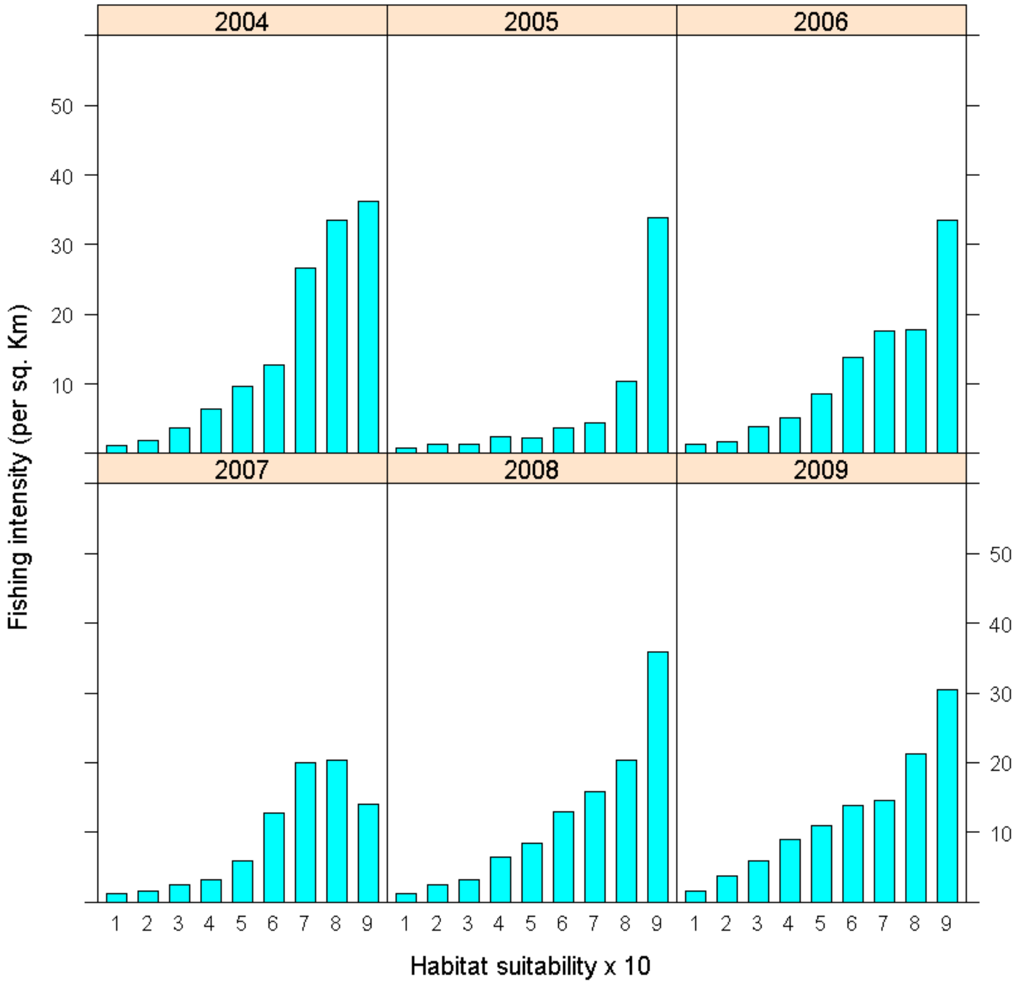

Figure 9.3. Fishing intensity (pings per sq. km) for SFA 29 D from VMS records compared with habitat suitability from Figure 9.2. Note results are preliminary until the full analysis of VMS records has been completed.

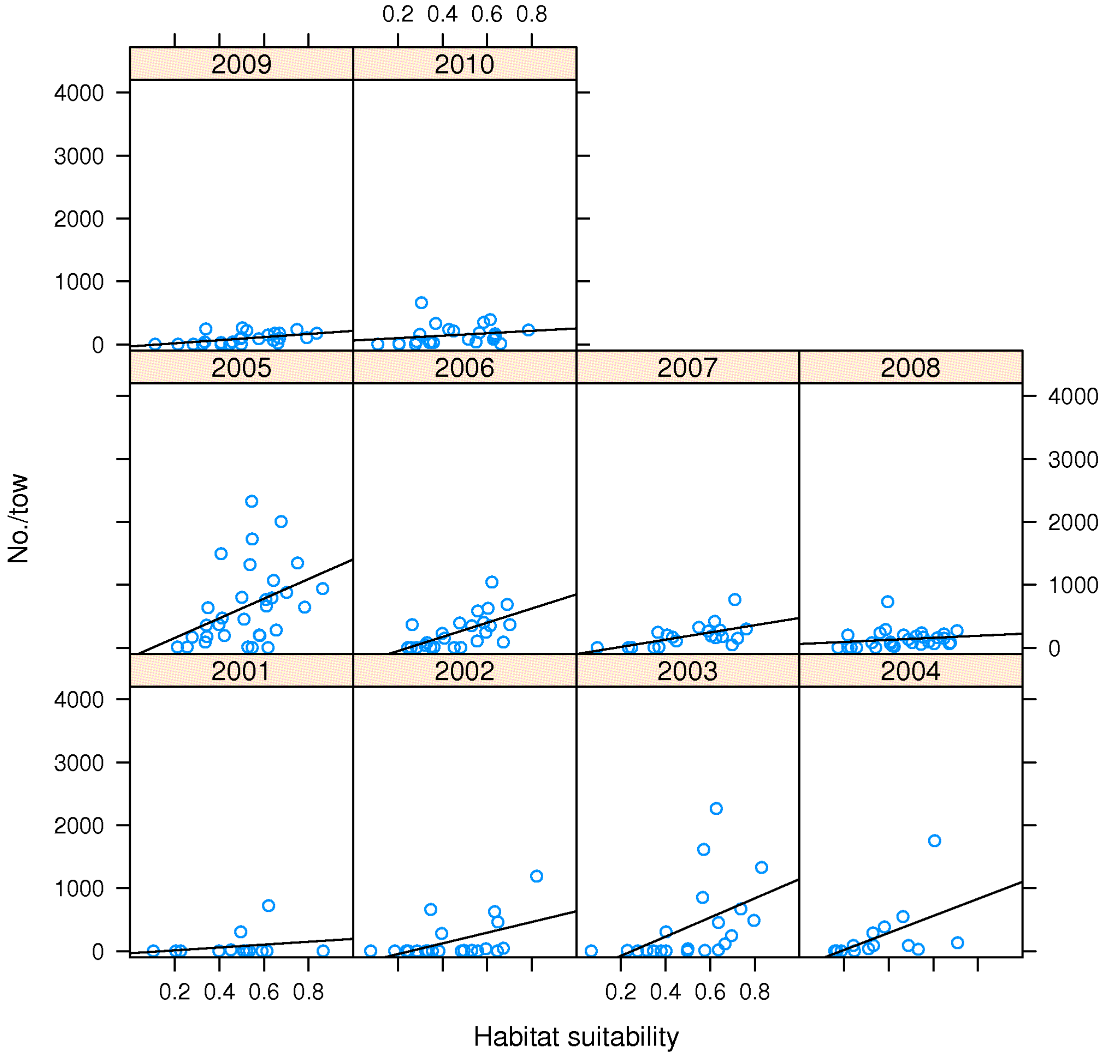

Figure 9.4. Scallop survey abundance (no./tow of scallops with shell heights > 100 mm) compared with habitat suitability (Figure 9.2) by year for SFA 29 D. This area was closed to fishing for 2001 to 2003 to wait for a large year-class to recruit to commercial size. There were limited openings in 2004 and 2005 with the whole area open to fishing starting in 2006. Note that the survey occurs after the fishery each year.

The annual survey time series clearly shows for all four subareas of SFA 29 West that higher densities in the higher suitability areas are fished down until their scallop densities are similar to those levels found in lower suitability areas (e.g., SFA 29 D, Figure 9.4; S.J. Smith, unpublished data, also Smith et al. 2009). This trend of increasing decline in densities from the higher suitability areas follows predications of Caddy's (1998) stages of the spatial impact of a fishery on a population with the condition of similar densities everywhere corresponding to his third stage. Caddy's (1998) fourth and final stage corresponds to fishing out of key areas with continuing declines in commercial catch rate. The observed trend in decreased densities as a function of habitat also follows that predicted by McCall's (1990) basin model for a sedentary species.

McCall (1990) recommended modelling the impact of a fishery on populations exhibiting spatial distributions of productivity using parameters indexed for the different spatially-specific productivity characteristics. In this project, individual surplus production models were fitted to the catch and survey biomass data within SFA 29 A–D with parameters for maximum population biomass and population net growth indexed for habitat suitability in the following ranges: 0.0–0.19, 0.2–0.39, 0.4–0.59, and 0.6–1.0. For this modelling approach, the removals, or catch, must be assigned to its associated habitat suitability range. Catch is typically assigned to an area based on the position information given in fishing logs; however, the spatial resolution from the logs is not precise enough to allocate catch by the geographical location of habitat suitability. As a preliminary approach, the basic relationship between catch and population biomass was used, i.e.,

$$C_i = qE_iB_i$$

where C_i refers to catch in habitat suitability range i, q represents catchability, E_i is effort and B_i is the biomass (or density) with habitat suitability range i. Effort associated with each habitat suitability range was estimated from the VMS data and biomass from the survey data. Total catch was apportioned to each habitat suitability range according to the relative proportion of E_i B_i to the total over all ranges.[2]

The annual commercial catch rate for the whole subarea tends to parallel the annual survey biomass index from the previous year in the 0.6–1.0 habitat suitability range, indicating that most of the fishing impacts are associated with this range of bottom type (e.g., SFA 29 D, Figure 9.5). The predicted density (g/m^2) from the surplus production model for 29 D indicates that current levels are below the maximum sustainable yield (MSY) density (corresponding to 56 t) in the 0.6–1.0 habitat suitability range. Total landings from 2010 and 2011 for 29 D were 72 and 66 t, respectively. The current approach allocates just over half of the landings to the 0.6–1.0 habitat suitability range, but this estimate will be refined once the matching of the VMS records and fishing logs has been completed.

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[2] Currently VMS records and fishing logs are being matched to allocate catch directly.

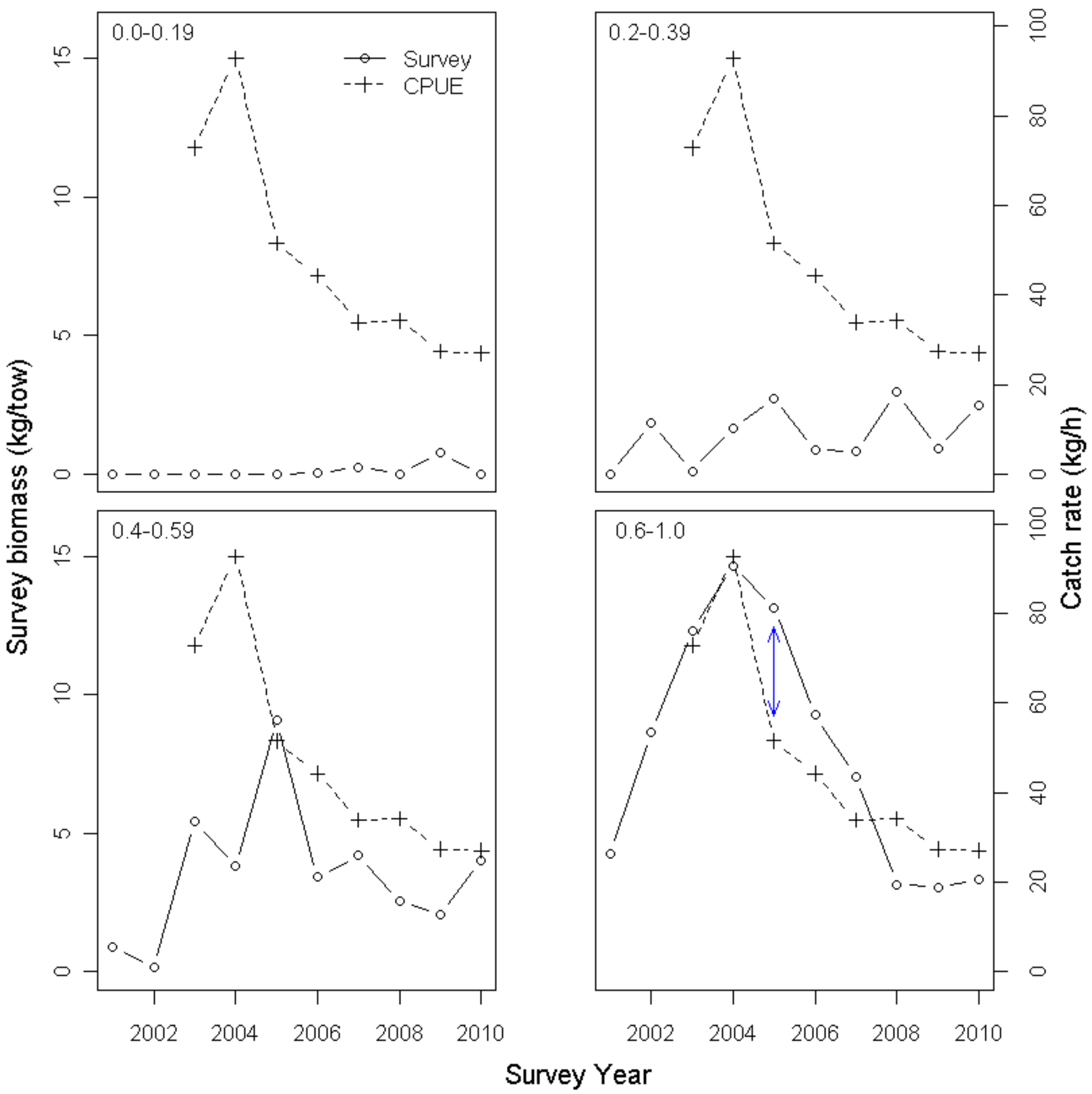

Figure 9.5. Survey biomass (kg/tow) trends for SFA 29 D by habitat suitability range. Commercial catch rate for the whole area indicated on each panel. Note that the survey occurs after the fishery each year and, therefore, catch rate is indexed by survey year (fishing year minus one). Lower right panel: vertical arrow (blue) indicates large discrepancy between the survey in 2005 and the fishery in 2006. Large numbers of clappers (paired empty shells) were reported by the fishery (and subsequent special survey) in the summer of 2006 in 29 D suggesting that natural mortality.

The above results are considered more of a proof of concept than final, and additional work is being done to line up catch and habitat suitability. However, the main points to be made here are that productivity varies spatially with habitat suitability and the fishery concentrates in the higher productivity areas. It is unrealistic to expect that management could be structured for the different habitat suitability ranges given their spatial distribution (Figure 9.2). As an alternative approach with less logistical overhead, consider a reference point system that maintained the productivity of the most productive areas (habitat suitability of 0.6 to 1.0). For example, in SFA 29 D set, the MSY to 56 t for the biomass levels with the corresponding F_{MSY} (0.29). In this way, the total catch should not exceed the productivity of the 0.6–1.0 grounds, and if some catch should come from the other lesser productive areas, then this will be to the benefit to the most productive grounds.

Stock/recruitment relationships are difficult to demonstrate for sea scallops, and large year-classes tend to be more due to favourable environmental conditions than due to larger stock sizes. Caddy (1998) describes the spatial impact of fishing on a population as occurring in four stages progressing from high catch rates with low amounts of effort to actually fishing out areas of former high density. His third stage corresponds to density and catch rate being reduced to similar low levels over all areas of productivity, and this stage has been observed for most of the inshore scallop fishing areas in the Maritimes Region. The only recovery for fishing areas at this stage appears to be the (rare) recruitment of a large year-class. The result of fishing down higher suitability areas is a more or less uniform density (and catch rate) over the entire fishing area. This uniform density (and catch rate) is around the normal level seen in low suitability habitat areas, which could lead to decreased reproductive success due to low density (lower fertilization success), as well as economic issues with respect to the commercial fishery having less than cost-effective catch rates. The lower reference point for the highest productivity area could then be based on this third stage with respect to mean density levels in the lower productive areas.

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BYCATCH CONSIDERATIONS

10.0 BYCATCH POLICY

S. Quigley

Fishing methods and gears are such that they allow for an imperfect selection of fish. In many fisheries, it is virtually impossible to direct for one species without incidentally capturing another. In most fisheries, it is difficult, if not impossible, to avoid entirely the capture of sublegal or undesired specimens of the target species, such as juveniles and females. In some instances, the incidentally caught species may be retained by the fishery. Often they are returned to the water as discards, where rates of survival vary.

Over the years, management measures and fishing practices in Canada have evolved to try to improve the selectivity of fishing. There have been many refinements to fishing gear, and there may be limitations placed on fishing effort, for example, at times or in areas where bycatch of prohibited or sensitive species is likely to be high. Nevertheless, some amount of incidental fishing mortality is unavoidable. DFO is in the process of developing a policy under the Sustainable Fisheries Framework that will address systematically the management of bycatch in fisheries, both retained and discarded.[1] The current draft of the bycatch policy (January 2012) has the following two objectives:

1. "to ensure that Canadian fisheries are managed in a manner that supports the sustainable harvesting of aquatic species and that minimizes the risk of fisheries causing serious or irreversible harm to bycatch and discard species;" and
2. "to account for total catch, including bycatch and discards."

Assuming the final version of the bycatch policy contains these or similar objectives, DFO Resource Management may request advice from Science on the following:

- estimates of incidental mortality from fishing,
- impacts of fisheries on bycatch populations and ecosystems,
- management strategies that minimize risks from fisheries of serious or irreversible harm to bycatch populations and ecosystems,
- measures that reduce incidental mortality in fisheries, and
- conservation priorities for all of the above.

10.1 Estimates of Incidental Mortality

Estimating incidental mortality requires, as a first step, estimating the extent to which a fishery interacts with bycatch species and, as a second step, estimating the extent to which these interactions cause mortality.

Where bycatch is retained for use, estimating the interaction is relatively straightforward: data are recorded by harvesters in commercial logs, which are generally verified at the time of landing by dockside observers. Where bycatch is discarded, estimates are more difficult to obtain. In Maritimes Region, discard estimates are generally derived from at-sea observer data. Resource Management may request scientific advice on the levels of at-sea observer coverage needed to support reliable estimates of discards of bycatch species (including discards of the target species). Given that adequate at-sea observer coverage may not always be achievable,

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[1] In the draft bycatch policy, "discards" are a subset of bycatch.

Resource Management may also request scientific advice on alternative means of estimating the likelihood and extent of interactions of fisheries with discarded species.

The second step, estimating the extent to which interactions cause mortality, may require scientific advice on the likelihood of discard survival, if not rates.

10.2 Impacts on Bycatch Populations and Ecosystems

Resource Management may request scientific advice on the impacts of fisheries on bycatch populations and ecosystems, including ongoing monitoring of impacts. To support such evaluations, scientific research may be requested on abundance of bycatch species, life history characteristics, the magnitude of other sources of mortality, and the role of bycatch species in the ecosystem. Recognizing that such data may not be available for many bycatch species, a national, scientific advisory process was held in February 2012 at the request of Aboriginal and Fisheries Policy Directorate that provided advice on a range of possible techniques and best practices for evaluating impacts, including qualitative techniques.

10.3 Management Strategies

Resource Management may request scientific advice on strategies that minimize the risks of fisheries causing serious or irreversible harm to bycatch populations and ecosystems. These strategies may include, for example, recommendations on safe biological limits to total fishing mortality (i.e., targeted plus incidental) of bycatch species.

Where the bycatch species is the target of another fishery, scientific advice will need to comply with the PA Policy. The PA Policy applies to stocks that are the specific and intended targets of a fishery, and it requires accounting for bycatch of these stocks in other fisheries (DFO 2009).

10.4 Measures that Reduce Incidental Mortality

Incidental mortality can constitute both a risk to conservation and a loss of economic opportunity. For these reasons, Resource Management may request scientific advice on ways of reducing interactions of fisheries with bycatch species. Where interactions are unavoidable, Resource Management may request scientific advice on ways of improving survival of bycatch that is not retained for use (i.e., that is discarded).

10.5 Conservation Priorities

To help prioritize the expenditure of resources, Resource Management may also request advice on conservation priorities, as well as on methodologies for establishing conservation priorities, in all of these areas. In the near term, priorities may be guided by work carried out in recent years to characterize discards in the region's commercial fisheries (Gavaris et al. 2010) and related analyses.

10.6 References

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11.0 PREFERRED HABITAT FOR CERTAIN SPECIES

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Defining the preferred habitat for target species and those commonly caught as bycatch can offer a means of minimizing bycatch. That is, fishing may be regulated in areas of overlap between bycatch species and target species by a number of different measures, such as increased coverage by observers in areas where there is overlap with the option to cease fishing if bycatch levels exceed a set threshold. Traditionally, assessment of bycatch issues has been undertaken through empirical, field-based studies in discrete areas, and largely restricted to documenting the presence of bycatch within the target species fishery. Conversely, studies on defining preferred habitat for some commercial species that may occur as bycatch in other fisheries have largely been focussed on issues related to productivity of the focal species itself (e.g., juvenile lobster settlement monitoring and definition of inshore settlement grounds).

Through the ERI program, there was a unique opportunity to link these two previously separate research streams by investigating lobster bycatch in the SFA 29 scallop fishery. Based on an underwater image survey, Tremblay et al. (2009) found that lobsters were more likely to be seen on habitats with boulders than on habitats with sediments of smaller grain size. The distribution of Cancer *spp.* crabs was similar to that of lobsters, but they were less likely to be found on gravel-sand substrata. Scallops, on the other hand, were most associated with cobble-gravel substrata. In the ERI project, bottom areas on German Bank were classified with respect to a measure of habitat suitability for scallops based on environmental data layers derived from multi-beam sonar data (e.g., bathymetry, aspect, slope, backscatter), and presence-only data on scallops from three image surveys (two years of TowCam surveys and Campod images from a separate survey in the same area (Brown et al. 2012)). This classification has proved quite useful in identifying areas of differing productivity for scallops. Many other species were recorded in the underwater images from the image data and a similar analysis to that for the scallops could be conducted for these other species. Areas of overlap could be identified and compared with available observer data from scallop and other fisheries in the area. These products, in combination with spatially explicit data on fishing pressure, could then be used to assess potential conflicts in a multi-species context. However, there will be some problems with data integration due to differences in the spatial resolution of the habitat suitability data (fine) and the fishery data (coarse).

11.1 References

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