CLIMATE CHANGE AND ITS EFFECTS ON ECOSYSTEMS, HABITATS AND BIOTA

State of the Scotian Shelf Report

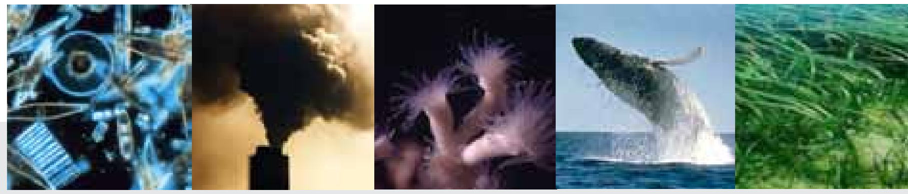
AUTHORS:
Nancy Shackell (Overall Lead) and **John Loder** (Physics)
Fisheries and Oceans Canada
Bedford Institute of Oceanography
PO Box 1006
Dartmouth NS, B2Y 4A2

The material in this document is co-published as:
MacLean M, Breeze H, Walmsley J and Corkum J (eds). 2013.
State of the Scotian Shelf Report. Can. Tech. Rep. Fish. Aquat. Sci. 3074.

First published April 2012

ISBN: 978-0-9869437-7-5

ACZISC
ATLANTIC COASTAL ZONE INFORMATION STEERING COMMITTEE



CONTENTS

1 ISSUE IN BRIEF 4

2 DRIVING FORCES AND PRESSURES 6
2.1 Anthropogenic Climate Change 6
2.2 Natural Conditions 7
2.3 Potential Oceanographic Changes 8

3 STATUS AND TRENDS 10
3.1 Temperature 10
3.2 Salinity 11
3.3 Stratification 12
3.4 Chemical Oceanographic Properties 13

4 IMPACTS 14
4.1 Lower trophic level production 15
4.2 Fisheries production 17
4.3 Chemical Oceanographic Properties 18
4.4 Shifts in Spatial Distribution 18
4.5 Changes in Timing of Ecosystems Events 19

5 ACTIONS AND RESPONSES 21
5.1 Government Policy and Action Plans 21
5.2 Monitoring and Research 23

6 REFERENCES 25

1 ISSUE IN BRIEF

Anthropogenic climate change, including warming, is due to increased greenhouse gas (GHG) emissions largely from the use of fossil fuel. The rate of warming during the past 50 years has been about twice that during the last 100 years (IPCC 2007b). Climate change has had biological effects world-wide (reviewed in Parmesan 2006; Rosenzweig et al. 2008). Consistent with the

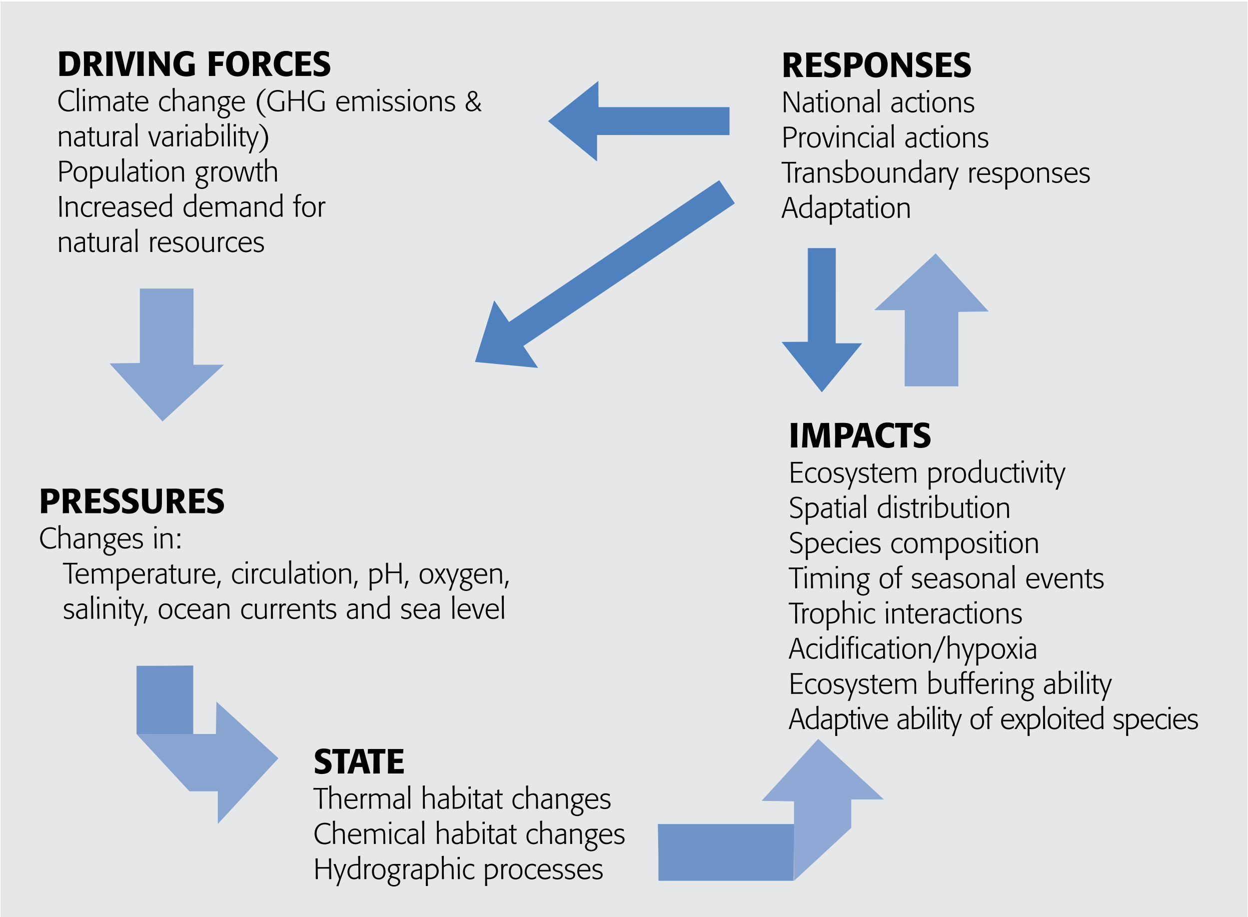
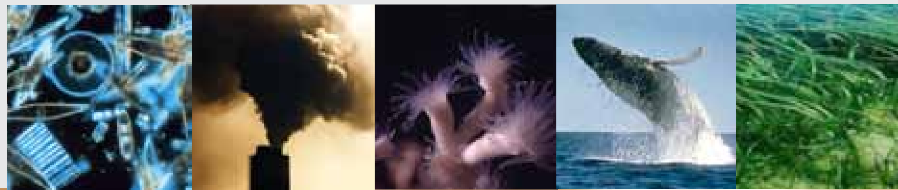


Figure 1. Driving forces, pressures, state, impacts and responses (DPSIR) to climate change on the Scotian Shelf. The DPSIR framework provides an overview of the relation between the environment and humans. According to this reporting framework, social and economic developments and natural conditions (driving forces) exert pressures on the environment and, as a consequence, the state of the environment changes. This leads to impacts on human well-being, ecosystems and materials, which may elicit a societal or government response that feeds back on all the other elements.



expected earlier springs and longer summers, changes in timing of seasonal events and distribution were observed in 59% of 1598 species in the latter half of the 20th century (Parmesan 2006).

This theme paper reviews the potential effects of climate change on ecosystems, habitats and biota on the Scotian Shelf. Driving forces include anthropogenic global climate change and natural climate variability. These drivers in turn affect the environment and biota. Globally, it is expected that climate change will have impacts on productivity, distribution and the timing of seasonal events. However, it is important to recognize there is limited understanding as to how climate change at the global scale will affect regional and local ecosystems. Management and adaptation strategies will have to be based on current understanding of the system (**Figure 1**).

The Scotian Shelf has not yet experienced drastic ecological impacts due to climate change but impacts may accrue slowly over time (e.g., decades). Subpolar water flowing towards the equator and subtropical water flowing poleward both influence the Scotian Shelf oceanography. Changes occurring to the north in the Labrador Current and to the south in the Gulf Stream can be expected to influence the Shelf's climate and ecosystems.

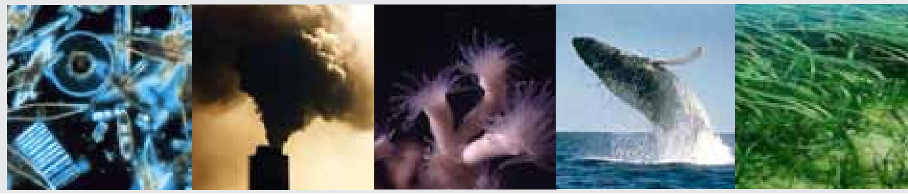
2 DRIVING FORCES AND PRESSURES

2.1 ANTHROPOGENIC CLIMATE CHANGE

While greenhouse gases (GHGs) are naturally released into the environment, those released as a result of human activities are considered to be the main driver of climate change. At a global level, elevated levels of carbon dioxide (CO_2) (a greenhouse gas), are mainly produced by the burning of fossil fuels (59%) but also by land-use change (18%) such as agricultural clearing and timber harvest (Baumert et al. 2004). GHGs absorb radiative energy from the Earth, so the heat gets trapped near the Earth's lower atmosphere instead of escaping into the upper atmosphere—that trapping warms the Earth's temperature. Global average temperature increased by 0.045°C per decade from 1856-2005 and the rate of warming accelerated between 1981 and 2005 (0.18°C per decade) (see Figure 1. of FAQ 3.1, IPCC 2007b). The Northern Hemisphere is warming faster than the tropics, the land is warming faster than the oceans, and the Arctic is warming twice as fast as the global average (IPCC 2007b).

Intergovernmental Panel on Climate Change (IPCC) is a large collection of international scientists, initiated by the United Nations and the World Meteorological Organization, working on climate change and its impacts.

Canada contributes 2% of the total GHG emissions, ranking 9th in absolute amount, 7th on a per capita basis and 1st based on energy consumption per capita (Baumert et al. 2005). From



1990–2008, Canada's GHG emissions increased by 24%. The greatest increases were in energy production (i.e., fossil fuel production and refining subsectors, electricity and heat generation subsector [energy]) and transportation.

The anthropogenically-derived GHG emissions are directly related to economic growth and its continued reliance on fossils fuels (IPCC 2007a). Nova Scotia specifically has a continued reliance on coal as its electricity source. Nova Scotia's population in 2006 was just less than 1 million (934,405) and had grown 5% since 1986, representing 2.9% of Canada's population (Nova Scotia Department of Finance 2006). While the population growth in Nova Scotia is low, economic growth in Nova Scotia is driven largely by international trade. In 2005, the majority (80%) of Nova Scotia's international trade was with the US. The absolute population size of the US, our major international market, as well as demand from other provinces will influence fossil fuel use in the province.

2.2 NATURAL CONDITIONS

The physical oceanography of the Scotian Shelf is described in detail in *The Scotian Shelf in Context*. Its variability 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 Scotian Shelf is located in a large-scale oceanographic "transition" zone (ICES 2011) between the relatively warm and saline (subtropical) offshore waters of the Gulf Stream, and the cooler and fresher shelf waters supplied by the (subpolar) Labrador Current and outflow from the Gulf of St. Lawrence (**Figure 2**).

The greatest natural variability in the Scotian Shelf's oceanography is the seasonal variation. In addition, Atlantic Canada is strongly affected by the North Atlantic Oscillation (NAO), a natural mode of variability in the large-scale atmospheric pressure and wind pattern (see e.g., Hurrell and Deser 2010). The state of the NAO Index (either negative or positive) modifies the volume of subpolar water moving west past the Grand Bank, which influences temperature and salinity over the Scotian Shelf (Petrie 2007). Successive years of positive wintertime NAO anomalies (involving stronger and cooler northwesterly winds over the Labrador Sea) result in cooler water from the Newfoundland Shelf reaching the eastern Scotian Shelf. Negative NAO years result in a reduction in the volume of slope water

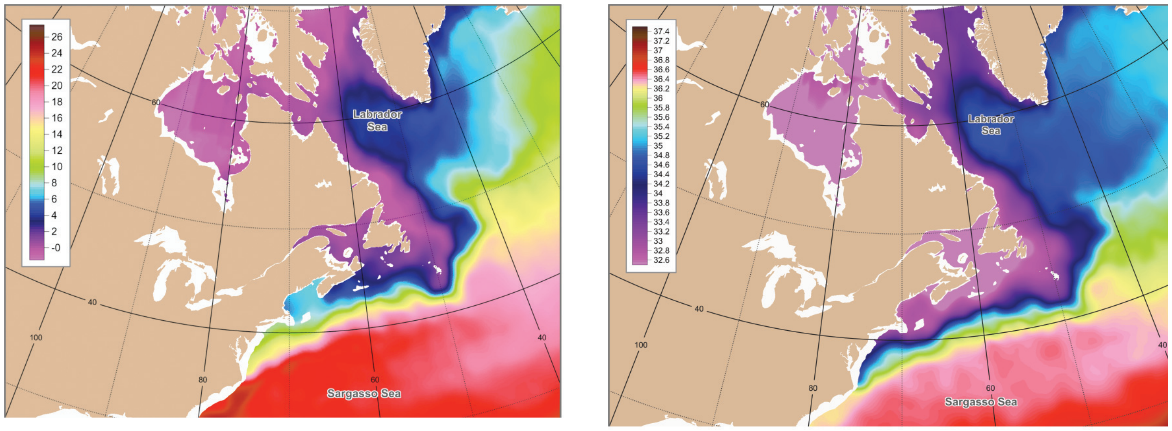


Figure 2. Climatological annual-mean distributions of temperature (left) and salinity (right) at 50 m below the sea surface in the NW Atlantic (I. Yashayaev, Bedford Institute of Oceanography, Fisheries and Oceans Canada).

moving around the Tail of the Grand Bank which then leads to warmer subtropical slope water intruding onto the central and western Scotian Shelf at depth.

Another natural mode of variability which affects the Scotian Shelf is the Atlantic Multidecadal Oscillation (AMO) — a measure of sea surface temperature in the North Atlantic with quasi-periodicities of 20–30 and 60–70 years (Frankcombe and Dijkstra 2011; Reid and Valdés 2011). 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 Northeastern United States shelf (Nye et al. 2009). The mechanisms and periodicities of the AMO are still under debate, and one suggestion is that it is partly linked to changes in the Atlantic Meridional Overturning Circulation (AMOC). The latter is the Atlantic component of the so-called global ocean "conveyor belt." AMOC variability has also been suggested to affect the north-south position of the Gulf Stream (Joyce and Zhang 2010) such that the influences of the NAO, AMO and AMOC on the Scotian Shelf may be inter-related.

2.3 POTENTIAL OCEANOGRAPHIC CHANGES

Natural variability will continue to be a major factor in future ocean climate change. During the next decade or two (while anthropogenic changes are emerging), climate on the Scotian Shelf may still be predominantly influenced by natural variability or anthropogenic perturbations of this variability.

The coupled atmosphere-ocean climate models used in the IPCC's 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 should be used in "downscaling" the global long-term projections of the AR4 models to the Scotian Shelf, especially for the next decade or two. The probable tendencies for mid-century (or late-century) regional climate change in some ocean variables can nevertheless be estimated from a combination of knowledge of atmosphere-ocean dynamics (ICES 2011; Reid and Valdés 2011), past regional ocean climate variability, and AR4'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:

• **Ocean temperature and acidity** can be expected to increase with increased CO_2 concentrations. Increases should be largest in the upper layers (75–100 m in winter and 20–30 m in summer). The increased ocean acidity will result in a lowering of calcium carbonate saturation in the upper ocean, with effects on calcareous organisms and other aspects of the ecosystem.

• **Sea level** can be expected to rise associated with the global trends of increased ocean volume due to heating and melting glaciers, enhanced tides, the potential northward expansion of the subtropical gyre, and natural continental subsidence (sinking) in the region. The number of intense storms is expected to increase and the track of extra-tropical storms is expected to shift northward resulting in higher extreme storm surges, which would further enhance extreme high-water levels and coastal erosion.

• Net **salinity** changes on the mid-century time scale are uncertain because multiple factors can cause opposite tendencies. Increased salinity at depth on the mid to outer shelf can be expected due to the increasing influences of slope water of subtropical origin. In contrast, melting Arctic sea ice and the increased precipitation at mid to high latitudes are expected to result in reduced salinities of the (shelf) water moving onto the Scotian Shelf from the Newfoundland Shelf. The influence of regional freshwater run-off (from land) is less clear due to complications such as the expected changes in precipitation varying with season and increased evapo-transpiration (due to warmer air) affecting run-off . However, it is expected that there will be reduced salinities in near-surface coastal waters in spring.

• Warmer, fresher surface water should result in an increase in the vertical density **stratification** and an increase in mixed-layer depths, but the effect can be expected to vary seasonally and spatially. At the shelf-water/slope-water interface at depths of 75–150 m (base of the winter surface and summer intermediate layers), the warmer fresher surface water combined with increased (slope-water) salinity at depth should lead to increased year-round stratification, as well as an earlier onset of spring-summer stratification near the surface (upper 30 m).

• Large-scale changes in **ocean circulation** may include a northward shift of the Gulf Stream and a reduction in the extent of sub-polar slope water west of the Grand Bank. This is based on the expected tendencies for a slowing of the AMOC and more positive NAO anomalies because of the intensification of the atmospheric polar vortex (IPCC 2007b). This would result in higher salinity in the slope water off the Scotian Shelf, more frequent "warm" slope water intrusions onto the shelf, and changes in chemical properties such as nutrients and dissolved oxygen.

• Increased stratification and reduced depths of winter convection can be expected to result in reduced **dissolved oxygen** concentrations at depths below the winter layer on the Scotian Shelf, such as in the intruded slope water at depth. This would be further exacerbated by the expected increased contribution of dense subtropical water.

• With the expected changes in stratification and in the source of slope water at depth, there will probably also be changes in **nutrient concentration**. 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.

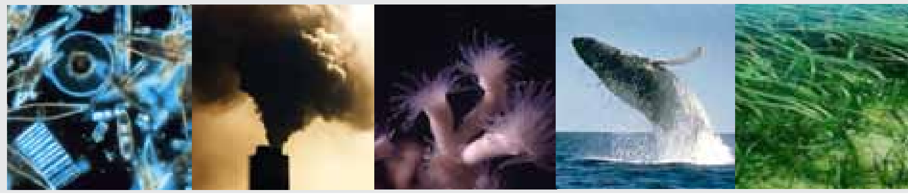
3 STATUS AND TRENDS

3.1 TEMPERATURE

Available data for air and ocean temperature in the NW Atlantic during the past century indicate substantial natural variability on decadal time scales. For example, the 1950s was one of the warmest decades in the 20th century for air and ocean temperature in the Scotian Shelf region while the 1960s was one of the coldest. Trends estimated from time series starting in the 1950s may be very different from those estimated from those starting in the 1960s. Caution needs to be used in interpretations of the limited existing ocean datasets with regard to their implications for future change.

Meteorological records, in some cases extending back before 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 averages of about 1°C reported in IPCC (2007b, Chapter 3), and to the simulated change of about 0.7°C for eastern North America in IPCC (2007b, Chapter 9). 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, Halifax, and the Prince 5 monitoring station in the Bay of Fundy (**Figure 3**). The Bay of Fundy observations indicate an increase of about 1°C per century, 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) may reflect a local influence (e.g., coastal upwelling) such that the pattern observed at Halifax may not represent the entire shelf.



The longest and most continuous record of offshore/mid-shelf temperature and salinity is from Emerald Basin (**Figure 4**). Its surface temperature shows little net change since the relatively warm 1950s but, considering patterns both to the north (e.g., Newfoundland) and south (US), it is plausible that a longer record would show a net increase. Sparse earlier observations from Emerald Basin, and the longer records from Prince 5 and the Gulf of St. Lawrence (Gilbert et al. 2005) point to a long-term warming trend of the deep water shelf waters during the past century, such that there is a substantial basis for inferring that there has been such a trend in the Scotian Shelf's subsurface waters.

Since 1985, SST estimates from remote sensing indicate a widespread increase by over 1°C on the Scotian Shelf. However, the natural warming phase of the AMO since the 1970s may be contributing to the recent warming (Nye et al. 2009; Polyakov et al. 2010).

3.2 SALINITY

Robust indications of long-term changes in ocean salinity are even more difficult to obtain than those for temperature, because of the

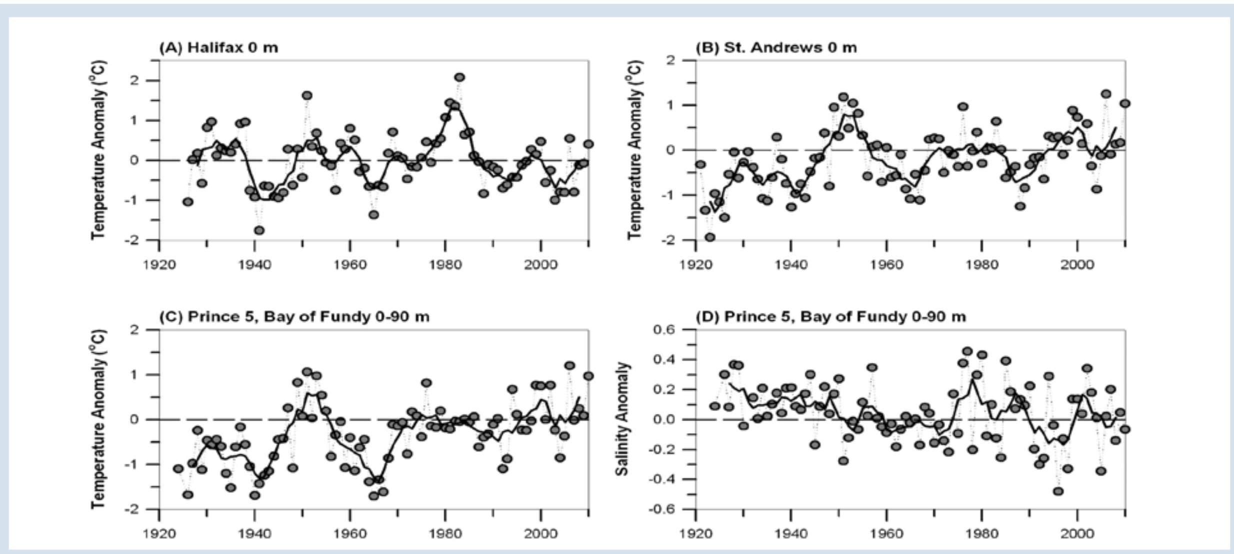


Figure 3. The longest ocean temperature and salinity records available for the Scotian Shelf and Bay of Fundy: annual anomalies of coastal temperature (circles joined by dashed line) and their 5-year running means (heavy black line) for (A) Halifax Harbour and (B) St. Andrews, NB; and annual anomalies of depth-averaged (0–90 m) (C) temperature and (D) salinity for the Prince 5 monitoring station at the mouth of the Bay of Fundy. The anomalies are relative to the 1971–2000 means (Petrie et al. 2011).

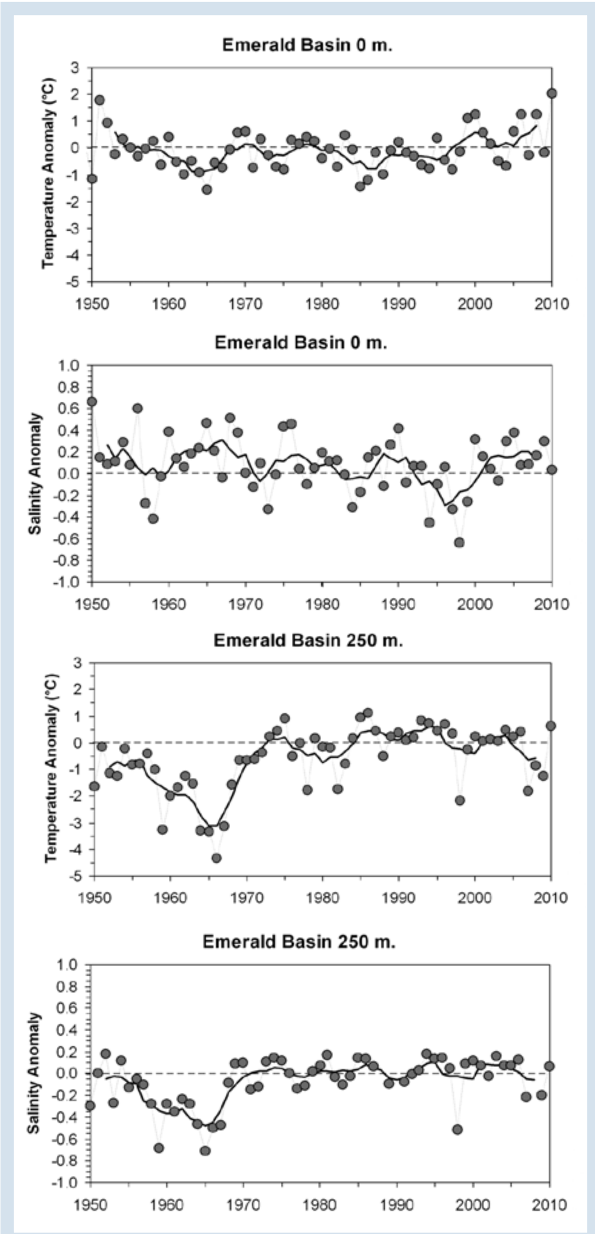


Figure 4. Annual-mean temperature and salinity anomalies (circles joined by dashed line) at the surface and near-bottom at a long-term monitoring site in Emerald Basin on the central Scotian Shelf, with their 5-year running means (heavy black line). The anomalies are relative to the 1971–2000 means (R. Pettipas, Bedford Institute of Oceanography, Fisheries and Oceans Canada).

greater dearth of high-quality measurements. Salinity in the upper 500 m of the North Atlantic north of 42°N (the Scotian Shelf's latitude range is 42–44°N) has decreased over the period 1955–98 (IPCC 2007b), consistent with the expected change associated with sea-ice melting and more rain at high latitudes.

The salinity time series from Prince 5 in the outer Bay of Fundy (**Figure 3**) indicates a net depth-averaged (90 m) decrease of 0.1–0.2 psu over about 85 years. The salinity time series from Emerald Basin (**Figure 4**) indicates a net decrease of 0.1–0.2 psu at the surface and a net increase of about 0.2 psu at depth. These net changes are clearly influenced by natural variability.

Overall, there have been decadal-scale variations with magnitudes comparable to (or greater than) the long-term changes, such that the contributions of natural and anthropogenic variability are unclear. There have been claims of anthropogenic freshening of Arctic origin during the past two decades (e.g., Drinkwater et al. 2004), but it is unclear whether this is a reliable long-term trend or a transient feature associated with natural variability.

3.3 STRATIFICATION

Upper-ocean stratification has increased over the Scotian Shelf and adjoining shelf regions during the past 60 years (**Figure 5**) (Petrie et al. 2011). Analyses suggest that 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 (Brian Petrie, Bedford Institute of Oceanography, Fisheries and Oceans Canada, pers. comm.).

Typically, in the spring/summer, warmer, fresher, less dense water lies over colder, saltier denser water, creating a boundary so the vertical water column is "stratified." The winter winds and cooling break down this stratification and cause vertical mixing that takes oxygen to the deeper water and brings nutrients to the surface, feeding phytoplankton growth in the spring.

3.4 CHEMICAL OCEANOGRAPHIC PROPERTIES

3.4.1 pH

The ocean routinely absorbs carbon dioxide (CO_2), but the additional CO_2, produced through increased human activities, has changed the ocean's chemical balance. Atmospheric concentrations of CO_2 are about 40% higher than before industrialization, and about 33% of that excess has entered the surface of the ocean (Doney et al. 2009). The CO_2 absorbed in the ocean forms carbonic acid which lowers the pH as the net CO_2 input increases.

Global surface ocean pH has decreased by 0.1 units (i.e. the surface ocean has become more acidic) since pre-industrialization beginning in 1750 (IPCC 2007b), and is expected to reduce further by 0.3 to 0.4 units by 2100 (reviewed in Doney et al. 2009). Sparse data from the Scotian Shelf indicate a decrease in pH of 0.1–0.2 since the early 1930s (Worcester and Parker 2010). The available atmospheric and ocean data, and current understanding of the global carbon cycle, point clearly to ongoing ocean acidification on the Scotian Shelf. There is concern that the increasingly acidic Arctic outflow will affect Atlantic Canadian waters downstream (Azetsu-Scott et al. 2010; see also *Ocean Acidification* theme paper).

3.4.2 Dissolved Oxygen

There has been 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 6**; 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 subtropical slope water noted earlier. 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 during that decade. However, data sparseness makes it difficult to identify any long-term trends on the Scotian Shelf.

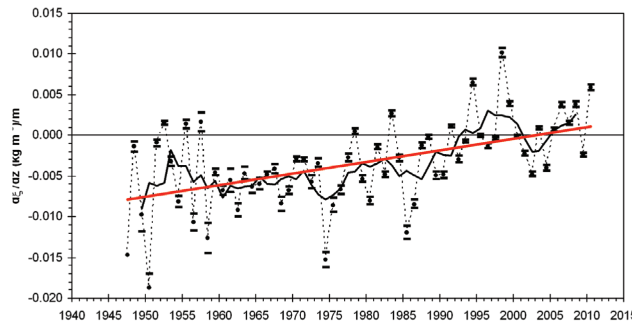


Figure 5. Annual-mean anomalies (solid circles joined by dashed line with standard error estimates) and 5 year running means (heavy black line) of the vertical stratification gradient over the upper 50 m on the Scotian Shelf, based on historical temperature and salinity data. The red line is the long-term trend indicating an increase of 0.4 kg/m³ over 60 years (Petrie et al. 2011).

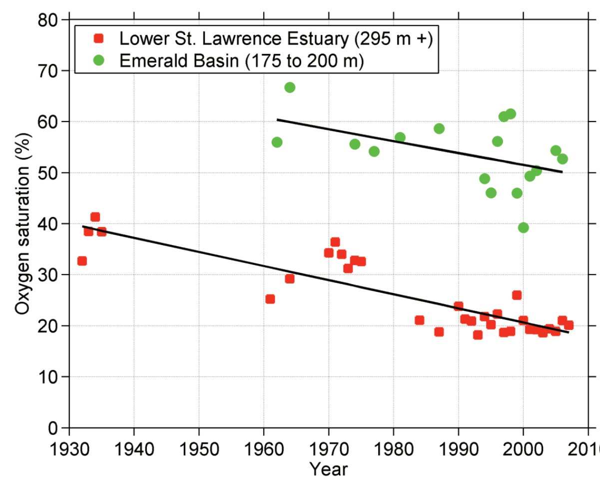
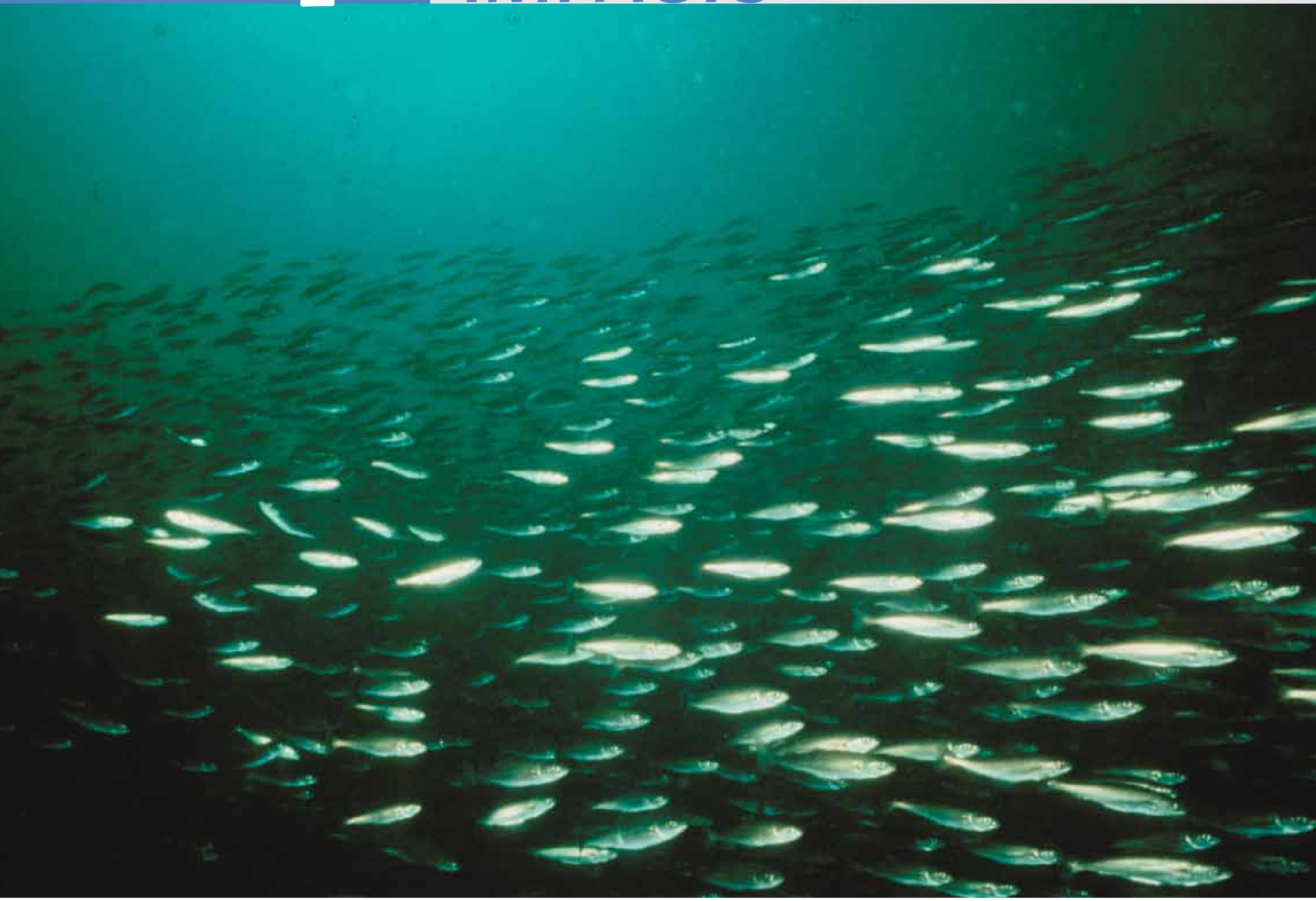
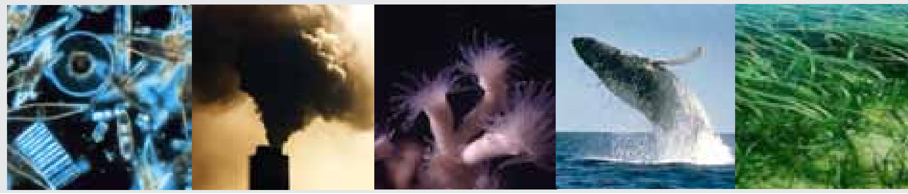


Figure 6. Annual means of oxygen saturation at depth in the Gulf of St. Lawrence and in Emerald Basin on the Scotian Shelf (D. Gilbert, Institut Maurice-Lamontagne, Fisheries and Oceans Canada).

4 IMPACTS



While the short term (seasonal, decadal) natural variability swamps anthropogenic change, we can anticipate more gradual anthropogenic change over the longer term (50 years). To date, the surface water has been warming since the 1980s, similar to the air temperature. There is some evidence of localized lower levels of dissolved oxygen and increased acidity, although no clear evidence of a long term trend in the circulation. Much of the relevant science topics (e.g., effects of acidification) are still highly active areas of research. While a comprehensive



and precise assessment is not yet possible, there is enough knowledge to broadly assess potential climate change impacts. Related documents include Frank et al. (1990) and Fogarty et al. (2007). Climate change affects species' physiology, phenology and distribution. Those changes will in turn affect species interactions, which then affect species composition of an ecosystem.

4.1 LOWER TROPHIC LEVEL PRODUCTION

Plankton are tightly coupled to climate variability. Changing oceanographic conditions affect not only the abundance of plankton, but also the composition. Coupled climate models suggests that phytoplankton production will increase in northern latitudes by 2040–2060 because of a longer growing season, and decline in the tropics because increased stratification will impede nutrient mixing in the upper water column (reviewed in Sherman et al. 2011).

Globally, the range of responses to climate change will vary because phytoplankton abundance is dependent on local combinations of controlling factors including nutrient availability, vertical and horizontal mixing, light regime, amount of UV radiation, and level of thermal stratification. In general, in subpolar waters the warming/freshening of the surface waters may lead to longer or stronger stratification. That stratification would impede vertical mixing and limit nutrient availability. In contrast, coastal upwelling may increase due to an increase in the land/sea temperature gradient, which would increase nutrient availability. To date, there is no clear picture as to whether anthropogenic climate change will increase or decrease primary production (Reid and Valdés 2011). On the Scotian Shelf there is typically a larger spring bloom, followed by a lesser, but longer duration fall bloom. The current trend on the Scotian Shelf indicates that phytoplankton abundance was higher in the early 1990s as compared to the 1960s (Head and Pepin 2010) whereas there was no annual trend in chlorophyll (index of phytoplankton growth) from 1997–2009 because of an increased

The **spring bloom** refers to the seasonal increase of phytoplankton abundance in the spring, dependent on light, nutrient upwelling, temperature and seasonal stratification of the water. In our region, there is also a lesser fall bloom when fall winds cause stratification to break down a bit, surface waters start to cool and the warmer deeper waters rise delivering new nutrients to the surface.

spring bloom and a decreased fall bloom (Li et al. 2006; Li et al. 2009). Also, phytoplankton abundance more than doubled in the Labrador Sea that has warmed in the spring at a rate of (0.19+/-0.07°C/yr) since the mid 1990s (Li et al. 2006). What happens in the Labrador Sea will eventually influence the Scotian Shelf.

In terms of composition, warmer water favours more numerous but smaller organisms (for example picoplankton), while colder water favours fewer bigger organisms (Moran et al 2010; Reid and Valdés 2011; reviewed in Bode et al. 2011). This pattern could be used to predict that a warmer ocean will result in a change in the types and numbers of phytoplankton (Moran et al. 2010). The effects of stratification could exacerbate the preference for smaller sizes. As well, the increased amounts of picoplankton (really small plankton <2 μm) in Arctic Ocean outflow may eventually affect the Scotian Shelf (reviewed in Bode et al. 2011).

Phytoplankton size is relevant to the higher trophic levels. Fewer bigger organisms generally transfer energy more efficiently up the food chain. If higher temperatures lead to smaller organisms, energy flow through the ecosystem will be re-directed and less efficient (Li et al. 2006) and could not support the productivity of historical fisheries (Bode et al. 2011).

ADAPTIVE ABILITY OF SPECIES

High levels of dispersal and genetic variability, and the ability of an organism to adapt to the environment within their lifetime are crucial to evolutionary adaptation. The copepod *Calanus finmarchicus* is highly capable of tracking suitable habitat. Provan et al. (2009) used DNA analysis to show that this important zooplankton was able to keep high levels of genetic variability over millennia, through ice ages (359 000–566 000 BP), and through high dispersal rates. The life history traits of small organisms lead them to grow fast, reproduce early and die young so that they can adapt faster through shorter generation times (Genner et al. 2010). Small-bodied organisms are favored in warmer waters possibly due to metabolic laws. Metabolic rate increases with temperature, which increases growth rate so they can reproduce earlier. Warmer temperatures would favor smaller-bodied organisms.

> *"Reducing fishing mortality in the majority of fisheries, which are currently fully exploited or overexploited, is the principal feasible means of reducing the impacts of climate change."*
>
> – Brander 2007.

Zooplankton eat phytoplankton and are tightly coupled to their dynamics. To date, there have been no directional shifts in zooplankton production nor in species composition, although their dynamics are intimately tied to water mass composition (Johnson et al. 2011). *Calanus finmarchicus* occurrence has been experimentally shown to decrease as stratification increases, especially the younger copepodite stages. *Calanus finmarchicus* are the main source of fatty oil-rich food for larval fish, such as cod, in our region. If stratification continues to increase, we might expect lower availability of *Calanus finmarchicus* at some critical level (Reygondeau and Beaugrand 2011). Currently, that level is locally unknown.

4.2 FISHERIES PRODUCTION

Climate change is expected to redistribute the global fish catch potential. Catch is predicted to decline in the tropics and increase in northern latitudes. Canada's catch potential is expected to increase by about 5% by 2050 in a high GHG emission scenario but decrease <10% if emissions stabilized at 2000 levels (Cheung et al. 2010). When this model was reconfigured to account for expected effects of acidification, lower oxygen and smaller-celled phytoplankton, catch potential estimates were much reduced (Cheung et al. 2011).

The early life stages of fish populations are critical determinants of fish productivity and in a healthy population, are determined by climate and food availability. There is no question that climate plays a critical role in the population dynamics of northern temperate regions (Groger and Fogarty 2011) but so too does fishing (Frank et al. 2005). In the past few decades, researchers have tried to partition the effects of climate and the fishery on ecosystems. Increasingly, the view has evolved to acknowledge that the effects of climate and exploitation cannot be separated (see Journal of Marine Systems 79 [2010] and ICES Journal of Marine Science 68[6] [2011]).

Heavy fishing causes a reduction in diversity from the individual to the ecosystem level and diversity is the main buffer against climate variability (Perry et al. 2010; Planque et al. 2010). At the ecosystem level, an inability to tolerate both intense fishing and environmental variability can lead to community changes. For example, 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, jellyfish benefit in warmer, eutrophied water, and low levels of dissolved oxygen (Purcell 2011). Jellyfish and ctenophores thrive in human-impacted waters (Link and Ford 2006; Purcell, 2011).

At the population/species level, intense fishing can lead to a truncation in the age/size structure, loss of sub-populations and a change in life-history traits, all of which renders them much more susceptible to environmental variability and chance events (Perry et al. 2010; Planque et al. 2010). Population variability increases at high levels of fishing and the population is less able to buffer environmental variability (Botsford et al. 2011). In effect, fishing renders populations more sensitive to climate variability (Hsieh et al. 2008).

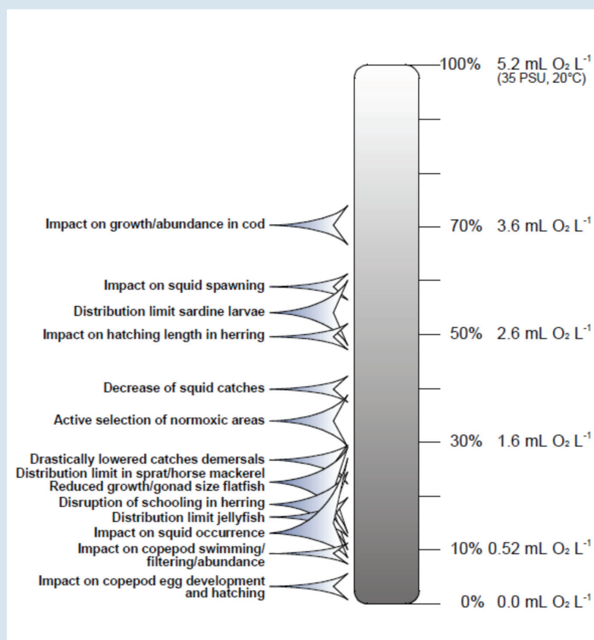


Figure 7 . Behaviour and physiology responses of marine organisms to various oxygen saturation levels (Ekau et al. 2010).

Importantly, in a global analysis of how fish production will respond to climate change, Brander (2007) asserts that fishing will remain the largest threat to fish production, including both captive (aquaculture) and wild fisheries, but that the impacts of climate and fishing interact. It is these interactions, which are not completely understood, that limits our ability to predict how production will change (Murawski 2011). A very generalized prediction for temperate regions is that there will be a community turnover through the arrival of warm-water species and the loss of cold-water species (MacNeil et al. 2010).

4.3 CHEMICAL OCEANOGRAPHIC PROPERTIES

4.3.1 Ocean Acidification

Acidification is expected to impact physiology, including reproduction, and calcification processes (see *Ocean Acidification* theme paper). Such impacts will affect plankton and favour non-calcifying species. The effects of acidification are compounded by the expected increase in temperature and the solubility of CO_2. Such complex effects translate into complex ecological effects on bacteria (that produce CO_2) and zooplankton (that eat phytoplankton). This reorganization of the lower food chain will penetrate the rest of the food chain (Blackford 2010).

4.3.2 Hypoxia

Oxygen is essential for aerobic metabolism and the amount of dissolved oxygen (DO) affects growth, distribution and productivity. Warmer water cannot hold as much oxygen. When levels of dissolved oxygen become too low for biota, the condition is called hypoxia, and that lower threshold depends on the species. For example, there is an impact on growth and abundance of cod below 70% oxygen saturation level (Ekau et al. 2010; see refs in Gilbert et al. 2005; see refs in Chabot and Claireaux 2008).

In general, sediment-dwelling, longer-lived, immobile species would be most vulnerable (**Figure 7**). These species are actively involved in re-working the sediments through bio-irrigation (tube and burrow animals transport oxygen to the deeper sediments by breathing and flushing water from their tubes/burrows, thereby enhancing aerobic respiration and exchange of nutrients) and bioturbation (moving the sediment around and distributing oxygen below the surface and exchanging nutrients—much like earthworms). As such, their absence would clearly affect other organisms. Larger benthic organisms including echinoderms such as sea cucumber, and crustaceans such as lobster, need more oxygen and so are also vulnerable in low oxygen settings, whereas annelids, molluscs and cnidarians are less sensitive (reviewed in Middleburg and Levin 2009). Oxygen is declining at a faster rate in the coastal ocean than in open ocean (>100 km offshore) (Gilbert et al. 2010), which implies that coastal populations will be more affected than offshore populations.

4.4 SHIFTS IN SPATIAL DISTRIBUTION

Temperature is arguably the major determinant of growth, reproduction, feeding and distribution for all marine biota. As the temperature of the ocean changes, so does the distribution of organisms that live in the ocean, as described above for plankton. Global projections using a bioclimatic model predict that demersal marine organisms in the Northwest Atlantic will migrate poleward from 2005–2050, whereas pelagic marine organisms will migrate faster because the surface layers are expected to warm faster and pelagic species are more mobile (Cheung et al. 2009). The most extreme responses to climate change have been documented in the Northeast Atlantic and the Northwest Pacific, where SST has been consistently increasing (Parmesan 2006; reviewed in Drinkwater et al. 2010).

Seasonal patterns of animals are evolved behaviours adapted to environmental conditions. In temperate marine climates, there is often a limited window when conditions for growth, feeding or reproduction are optimal. The timing of these events is called **phenology**.

Locally, temperature regime continually modifies fish distribution and composition. When the eastern Scotian Shelf was inundated by cold water, cold-adapted capelin flourished (Frank et al. 1996). Variations in the NAO induce temperature anomalies and can cause changes in the latitudinal diversity gradient of fish (Fisher et al. 2008). Species in the temperate to subarctic North Atlantic feed and spawn from -2 to 20°C, but the majority feed at 0–4°C and spawn from 2–7°C (Rose 2005). Warming will influence changes in distribution. However, it is possible that the temperature tolerances of opportunistic species have been underestimated by using simple survey data. Using electronic tags, Righton et al. (2010) were able to determine that cod were much more tolerant than previously considered.

There have been shifts in distribution at lower latitudes (Nye et al. 2009) as well as in the eastern North Atlantic (Hofstede et al. 2010), where change is occurring rapidly. However, large changes in community assemblages on the Scotian Shelf up to the mid 2000s have been due to intense fishing, not warming (Frank et al. 2005; Shackell and Frank 2007). The same is true for the Northeast US (Fogarty and Murawski 1998; Auster and Link 2009; Shackell et al. 2012) and elsewhere in temperate waters (Blanchard 2001). The mechanism of change is that the removal of dominant commercial fish allows either their prey or less commercial species to thrive as was observed on the Scotian Shelf (Koeller et al. 2009).

4.5 CHANGES IN TIMING OF ECOSYSTEMS EVENTS

4.5.1 Seasonal Events

Climate change has caused a shift in the timing of seasonal events (phenology) of plants, animals and marine organisms around the world (reviewed in Visser and Both 2005). The ability to adapt phenology (the timing of 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) to seasonal behaviour are well known. Seasonal cues are known for many (Greve et al. 2005) but not all key species.

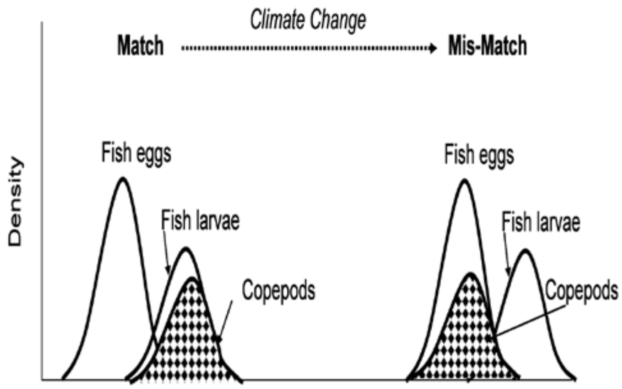


Figure 8. Match-Mismatch in the marine environment. Many fish are adapted to spawn so that peak larvae abundance will coincide with their copepod prey. If copepod peak abundance occurs earlier due to climate-induced shift in seasonal cues, and fish do not adapt in the same direction, peak abundances between predator and prey will be mismatched.

A key taxon is the plankton, the base of the food chain. There was no directional trend towards earlier spring blooms on the Scotian shelf since 1998 (see Figure 4a in Song et al. 2010) although fresher surface waters can cause earlier spring blooms and later fall blooms (Song et al. 2011). However, the observed trend in salinity changes is expected to eventually affect phytoplankton phenology given that salinity is one of the strong determinants of spring bloom timing from 1998–2008 (Song et al. 2010). The authors hypothesize that the additional influx of surface freshwater from the fresher (low-salinity) Scotian Shelf water helps set up stratification, in addition to warming in the spring.

Although several global examples of changes in marine plankton phenology exist (see also Li et al. 2006), plankton are naturally extremely variable. Researchers are working on how to assess changes in phenology in response to climate change so that a more uniform and global picture can be achieved (reviewed in Ji et al. 2010). The current time series of remote sensing (since 1998) of chlorophyll may be too short to detect long-term change because the natural intrinsic variability is so high, but researchers are developing models to improve interpretation of observational, noisy data (Platt et al. 2009).

4.5.2 Trophic Interactions and Match-Mismatch Theory

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 are 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 "mismatch," and the predator's likelihood of survival is reduced. Suppose that two trophic levels, fish larvae and their copepod prey are triggered by different seasonal cues. It follows that a mismatch may be more likely if those different cues do not co-vary in a changing climate (**Figure 8**). However, if phytoplankton abundance increases as a result of climate change, this might offset the effects of a mismatch between predator and prey (Durant et al. 2007).
In a review of 11 species showing changes in phenology, 8 were mismatched because of the trend in climate change (Visser and Both 2005 and see review in Durant et al. 2007). Such mismatches are expected to affect energy flow to higher trophic levels, and will have implications on the ecosystem.

5 ACTIONS AND RESPONSES

5.1 GOVERNMENT POLICY AND ACTION PLANS

The United Nations Framework Convention on Climate Change (UNFCCC) has set targets to reduce GHG emissions and has asked nations for effective accountability measures to meet those targets. Reductions in GHG emissions requires international action and responses. Canada ratified the United Nations Framework Convention on Climate Change in 1992. There have been several international UN fora designed to negotiate among countries to combat climate change. The most notable to date was the Kyoto Protocol designed in the late 1990s. The Kyoto protocol is an international agreement to fight global warming and calls for emissions reductions. Targets varied for developed and developing countries. For Canada, the target was a reduction of 6% of greenhouse gas emissions from 1990 levels by the 2008–2012 period. That is, the average level of GHG emissions should be 6% lower than the 1990 levels during the period 2008–2012. Canada ratified the Kyoto protocol in 2002 and so committed the country to reduce GHG emissions. However, Canada's 1990 emissions were 592 megatonnes (Mt) CO2 equivalent, and in 2007 they were 747, representing a 26.2% increase in Canadian GHG emissions (**Figure 9**), meaning Canada was 33.8% above the Kyoto target in 2007 (Government of Canada 2010). Canada announced that it would withdraw from the Kyoto protocol in December 2011; however, current Canadian legislation remains in force.

UN fora subsequent to Kyoto (e.g. Bali, Copenhagen) set other targets under other accords (Government of Canada 2010). Canada's current commitment is as follows: "The Government of Canada is committed to reducing Canada's total greenhouse gas emissions by 17 per cent from 2005 levels by 2020 – a target that is inscribed in the Copenhagen Accord and aligned

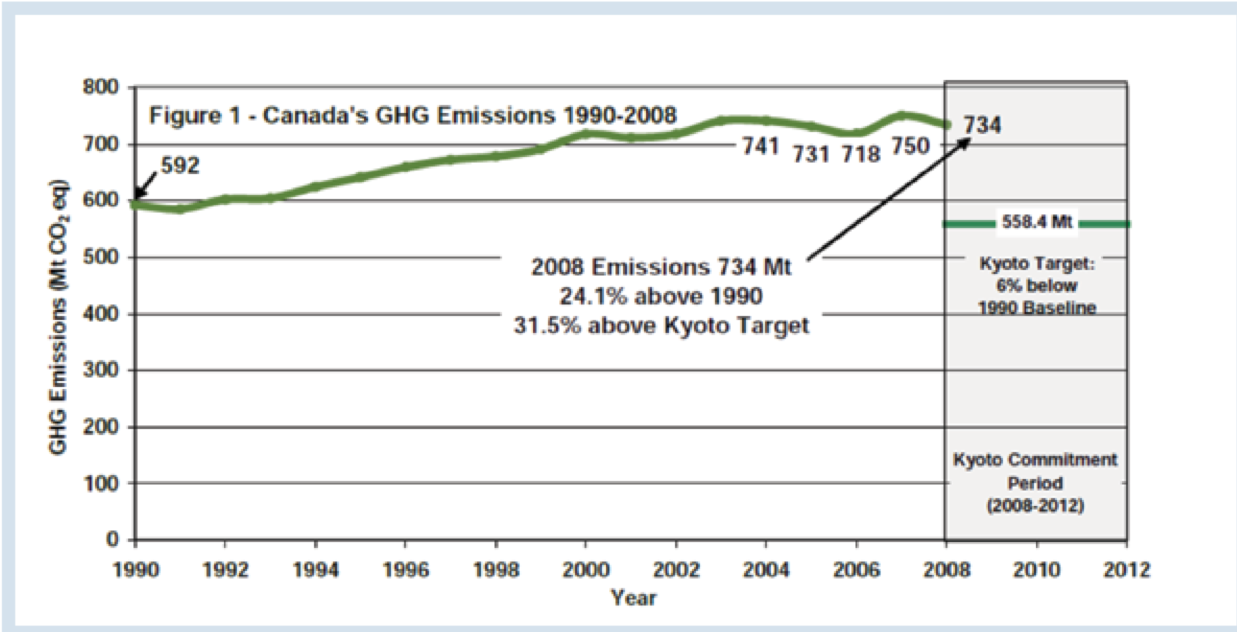


Figure 9. Canadian GHG Emission Trend and Kyoto Target from National Inventory Report 1990–2008: Greenhouse Gas Sources and Sinks (Government of Canada 2010)

with the United States" (Government of Canada 2011). That reduction would be 17% of 731, which would mean a target of 606.73 Mt CO2 equivalent GHG emissions by 2020.

The *Kyoto Protocol Implementation Act* (2007) is Canada's legislation to address climate change. The act requires the government to formulate a climate change plan every year until 2013. Nova Scotia has a climate change action plan (Province of Nova Scotia 2011a). The Nova Scotian government has set targets under the *Environmental Goals and Sustainable Prosperity Act* (EGSPA) proclaimed in 2007. In 2010, the province had fully articulated goals and objectives to reduce its environmental footprint, including GHG emission reduction. This legislated target is 10% below 1990 GHG levels by 2020. Legislation of targets is still rare and should be noted (Province of Nova Scotia 2011b).

In addition to reducing greenhouse gas emissions, there is also a need to respond to changes in the ecosystems that are already occurring or predicted to occur. The Nova Scotia Climate Change Directorate (within the Department of Environment) is responsible for ensuring all departments understand the impacts of climate change on their operations and develop adaptation plans to ensure they are prepared for climate changes and their subsequent impacts. The Government of Canada has a national Climate Change Adaptation Program, which funds activities in several departments. From a global perspective, Canada is considered a country with a high capacity to adapt to climate change based on a suite of indicators, including health, education, size of the economy and governance system (Allison et al. 2009).

5.2 MONITORING AND RESEARCH

Atlantic Canada marine ecosystems are monitored by Canadian provincial and federal agencies, principally, Fisheries and Oceans Canada (DFO) and Environment Canada. In 1999, DFO established the *Atlantic Zonal Monitoring Program* (AZMP) (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/index-eng.html). The main objectives of AZMP are to collect and analyze biological, chemical, and physical data to characterize and understand the causes of oceanic variability at different time scales; and to provide the multidisciplinary data sets that can be used to establish relationships among the physical, chemical and lower trophic level components of the ecosystem and their links to higher trophic levels.

Global generalities may be projected, but each region needs to be examined for local effects. Globally, researchers have created models that use IPCC-class climate results to examine ecosystem scenarios. For example, Cheung et al. (2009) used a "bioclimate envelope" global model and predicted that by 2050, there will be local extinctions and invasions, resulting in a 60% species turnover relative to current biodiversity patterns. The general consensus is the field has progressed greatly, but would be improved by a better mechanistic understanding of how climate shapes biology, as well as an improvement in IPCC-class climate model predictions, in particular at regional and local scales (Stock et al. 2010).

Numerous changes in phenology, species distribution, community composition have been ascribed to climate change in the last 30 years (reviewed by many but see Walther et al. 2002). Our ability to know what communities and ecosystems will look like is hampered because global climate change affects regions so differently. More importantly, it is difficult to predict complex ecological interactions in the absence of climate change, and even harder in its presence. It will always be difficult to predict beyond broad generalities. It is the broad generalities outlined in this paper that may be used to inform policy, and for identifying future research avenues.

"The principal brake to climate change remains reduced CO_2 emissions that marine scientists and custodians of the marine environment can lobby for and contribute to."

– Brierley and Kingsford, 2009

In the fall of 2011, the DFO announced a new program called the Aquatic Climate Change Adaptation Services Program (ACCASP). The goal is integrate the evident climate change into existing DFO planning processes. This "adaptation" will be accomplished through directed research on climate change projections and impacts on freshwater and marine ecosystems as well as other vulnerable areas of DFO responsibility. The program also aims to develop adaptation tools for use in DFO management and decision-making.

INDICATOR SUMMARY*

INDICATOR	POLICY ISSUE	DPSIR	ASSESSMENT[1]	TREND[2]
GHG emissions	Global warming and other long-term climate changes.	Driving Force	Poor	-
Natural climate variability	Regional near-term climate change.	Driving Force	Good	/
Gulf Stream position	Potential northward shift resulting in increased subtropical influences.	Pressure	Good	/
Increasing ocean temperature	Implications for sustainable and prosperous ecosystems.	Pressure	Fair	/
Increasing vertical (density) stratification	- Effects on primary production. - Effects on oxygenation of subsurface waters.	Pressure	Fair Fair	/ -
Ocean acidification (pH)	Low growth and high mortality in some species.	Pressure	Fair	-
Ecosystem productivity	Climate-induced reduction of ecosystem services with respect to phytoplankton and fishery yield.	Impact	Good	/
Shifts in species distribution	Change in availability of fishery resources.	Impact	Fair	/
Ecological timing	Change in timing of seasonal events may affect trophic interactions.	Impact	Unknown	?
Nova Scotia's Action on Climate Change	Province of Nova Scotia's response to climate change.	Response	Unknown	?
Aquatic Climate Adaptation Services Program (DFO)	Integration of climate change into existing DFO planning processes.	Response	Unknown	?

[1]Assessment: assessment of the current situation in terms of implications for the state of the environment. Categories are poor, fair, good, unknown.
[2]Trend: is it positive or negative in terms of implications for the state of the environment? It is not the direction of the indicator, although it could coincide with the direction of the indicator.

Data Confidence:
- Available datasets for atmospheric variables and ocean temperature and salinity are adequate for describing regional climate variability during the past 60–90 years, but the ocean datasets are not widespread or long enough for separating anthropogenic and natural climate variations with confidence.
- The sparser and shorter available data sets for chemical and plankton variables are adequate for describing variability during the past decade or two, but also not long enough for identifying whether there are changes occurring due to anthropogenic climate change.
- Longer datasets for upper trophic levels of fish are adequate for identifying changes but the latter tend to be dominated by fishing influences such that it is difficult to identify climate change influences.
- While existing climate models represent large-scale variations in the Earth's climate system well, they do not have an adequate representation of the Gulf Stream, Labrador Current and Atlantic Canadian shelves to provide projections of regional ocean climate change with confidence.

Key:
Negative trend: -
Unclear or neutral trend: /
Positive trend: +
No assessment due to lack of data: ?

Data Gaps:
- The limited duration of all available ocean and marine ecosystem datasets limits the identification of anthropogenic climate change and its impacts. Ongoing monitoring programs and resulting indices are needed, including sensitive biogeochemical variables such as ocean acidity and dissolved oxygen.
- Improved indices of large-scale ocean circulation changes (e.g. Gulf Stream, Labrador Current) are needed since such changes could lead to regime shifts at some trophic levels.
- Since there can be important influences on both lower and higher trophic levels from changes in the ocean climate's seasonality (e.g. onset of spring stratification affecting plankton blooms and fish recruitment), it is important that climate and ecosystem indices resolve the seasonal cycle in key variables.
- Development of metrics for fish populations which include fishing impacts is needed in order to identify climate change influences on fish.

*Indicator Summary: Several Indicators derived from J. Loder (Draft Report on Physics and Climate Change)

6 REFERENCES

Allison EH, Perry AL, Badjeck M-C, Adjer WN, Brown K, Conway D, Halls AS, Pilling GM, Reynolds JD, Andrew N and NK Dulvy. 2009. Vulnerability of national economies to the impacts of climate change on fisheries. Fish and Fisheries 10: 173–196.

Azetsu-Scott K, Clarke A, Falkner K, Hamilton J, Jones EP, Lee C, Petrie B, Prinsenberg S, Starr M and Yeats P. 2010. Calcium carbonate saturation states in the waters of the Canadian Arctic Archipelago and the Labrador Sea. Journal of Geophysical Research. 115: C11021, doi:10.1029/2009JC005917.

Auster PJ and JS Link. 2009. Compensation and recovery of feeding guilds in a northwest Atlantic shelf fish community. Marine Ecological Progress Series 382: 163–172

Baumert KA, Herzog T and Pershing J. 2005. Navigating the Numbers: Greenhouse Gas Data and International Climate Policy. World Resources Institute.

Baumert K, Pershing J and Herzog T. 2004. Climate Data: Insights and Observations. Arlington, VA: Pew Center on Global Climate Change. 50 pp. http://www.pewclimate.org

Blackford JC. 2010. Predicting the impacts of ocean acidification: challenges from an ecosystem perspective. Journal of Marine Systems 81: 12–18.

Blanchard F. 2001. The effect of fishing on demersal fish community dynamics: an hypothesis. ICES Journal of Marine Science 58: 711–718.

Bode A, Hare J, Li WKW, Morán XAG and Valdés L. 2011. Chlorophyll and primary production in the North Atlantic. In: PC Reid and L Valdés (eds), ICES status report on climate change in the North Atlantic. ICES Cooperative Research Report 310. pp. 77–102.

Botsford LW, Holland MD, Samhouri JF, White JW and Hastings A. 2011. Importance of age structure in models of the response of upper trophic levels to fishing and climate change. ICES Journal of Marine Science 68: 1270–1283.

Brander KM. 2007. Global fish production and climate change. Proceedings of the National Academy of Sciences USA 104:19709–19714.

Brierley AS and Kingsford MJ. 2009. Impacts of Climate Change Review on Marine Organisms and Ecosystems. Current Biology 19: R602–R614. DOI 10.1016/j.cub.2009.05.046

Chabot D and Claireaux G. 2008 Environmental hypoxia as a metabolic constraint on fish: The case of Atlantic cod, *Gadus morhua*. Marine Pollution Bulletin 57: 287–294.

Cheung WWL, Dunne J, Sarmiento JL and Pauly D. 2011. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. ICES Journal of Marine Science 68: 1008–1018.

Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson R and Pauly D. 2009. Projecting global marine biodiversity impacts under climate change scenarios. Fish and Fisheries 10: 235–251.

Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson R, Zeller D and Pauly D. 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Global Change Biology 16: 24–35, doi: 10.1111/j.1365-2486.2009.01995.x

Drinkwater KF, Beaugrand G, Kaeriyama M, Kim S, Ottersen G, Perry RI, Pörtner H, Polovina JJ and Takasuka A. 2010. On the processes linking climate to ecosystem changes. Journal of Marine Systems 79: 374–388.

Drinkwater KF and Gilbert D. 2004. Hydrographic variability in the waters of the Gulf of St. Lawrence, the Scotian Shelf and the eastern Gulf of Maine (NAFO Subarea 4) during 1991–2000. Journal of Northwest Atlantic Fisheries Science 34: 83–99.

Doney SC, Fabry VJ, Feely RA and Kleypas JA. 2009. Ocean acidification: The other CO2 problem. Annual Review of Marine Science 1: 169–192.

Durant JM, Hjermann DO, Ottersen G and Stenseth NC. 2007. Climate and the match or mismatch between predator requirements and resource availability. Climate Research 33: 271–283

Ekau W, Auel H, Portner H-O and Gilbert D. 2010. Impacts of hypoxia on the structure and processes in pelagic communities (zooplankton, macro-invertebrates and fish). Biogeosciences 7: 1669–1699, www.biogeosciences.net/7/1669/2010/ doi:10.5194/bg-7-1669-2010

Fisher JAD, Frank KT, Petrie B, Leggett WC and Shackell NL. 2008. Temporal dynamics within a contemporary latitudinal diversity gradient. Ecology Letters 11:883-97.

Fogarty M, Incze L, Wahle R, Mountain D, Robinson A, Pershing A, Hayhoe K, Richards A and Manning J. 2007. Potential climate change impacts on marine resources of the Northeastern United States. Northeast Climate Impacts Assessment Technical Series. 33 pp. http://www.northeastclimateimpacts.org/#Papers

Fogarty MJ and Murawski SA. 1998. Large-scale disturbance and the structure of marine systems: fishery impacts on Georges Bank. Ecological Applications 8: S6–S22.

Frank KT. 1986.Ecological significance of the ctenophore *Pleurobrachia pileus* off southwestern Nova Scotia. Canadian Journal of Fisheries and Aquatic Science 43: 211–222.

Frank KT, Carscadden JE and Simon JE. 1996. Recent excursions of capelin (*Mallotus villosus*) to the Scotian Shelf and Flemish Cap during anomalous hydrographic conditions. Canadian Journal of Fisheries and Aquatic Sciences 53: 1473–1486.

Frank KT, Perry RI and Drinkwater KF. 1990. Predicted response of Northwest Atlantic invertebrate and fish stocks to CO2-induced climate change. Transactions of the American Fisheries Society 119:353–365.

Frank KT, Petrie B, Choi JS and Leggett WC. 2005. Trophic cascades in a formerly cod-dominated ecosystem. Science 308: 1621–1623.

Frankcombe LM and Dijkstra HJ. 2011. The role of Atlantic-Arctic exchange in North Atlantic multi-decadal climate variability. Geophysical Research Letters 38: L16603, doi: 10.1029/2011GL048158.

Genner MJ, Sims DW, Southward AJ, Budd GC, Masterson P, McHugh M, Rendle P, Southall EJ, Wearmouth VJ and Hawkins SJ. 2010. Body size-dependent responses of a marine fish assemblage to climate change and fishing over a century-long scale. Global Change Biology 16: 517–527, doi: 10.1111/j.1365-2486.2009.02027.x

Gilbert D, Rabalais NN, Díaz RJ and Zhang J. 2010. Evidence for greater oxygen decline rates in the coastal ocean than in the open ocean. Biogeosciences 7: 2283–2296.

Gilbert D, Sundby B, Gobeil C, Mucci A and Tremblay G-H. 2005. A seventy-two-year record of diminishing deep-water oxygen in the St. Lawrence estuary: the northwest Atlantic connection. Limnology and Oceanography 50: 1654–1666.

Greve W, Prinage S, Zidowitz H, Nast J, and Reiners F. 2005. On the phenology of North Sea ichthyoplankton. ICES Journal of Marine Science 62: 1216–1223.

Gröger JP and Fogarty MJ. 2011. Broad-scale climate influences on cod (Gadus morhua) recruitment on Georges Bank. ICES Journal of Marine Science 68: 592–602.

Government of Canada. 2010. National Inventory Report 1990–2008: Greenhouse Gas Sources and Sinks in Canada. The Canadian Government's Submission to the UN Framework Convention on Climate Change. Environment Canada. 221 pp.

Government of Canada. 2011. Canada's Action on Climate Change. http://www.climatechange.gc.ca/default.asp?lang=En&n=72F16A84-0

Head EJ and Pepin P. 2010. Spatial and inter-decadal variability in plankton abundance and composition in the Northwest Atlantic (1958–2006). Journal of Plankton Research 32: fbq090 321633–1648. doi:10.1093/plankt/fbq090

Hsieh CH, Reiss CS, Hewitt RP and Sugihara G. 2008. Spatial analysis shows that fishing enhances the climatic sensitivity of marine fishes. Canadian Journal of Fisheries and Aquatic Sciences 65: 947–961.

Hofstede R ter, Hiddink JG and Rijnsdorp AD. 2010. Regional warming changes fish species richness in the eastern North Atlantic Ocean. Marine Ecological Progress Series 414: 1–9.

Hurrell JW and Deser C. 2010. North Atlantic climate variability: the role of the North Atlantic Oscillation. Journal of Marine Systems 79: 231–244.

IPCC (Intergovernmental Panel on Climate Change). 2007a. Climate Change 2007—Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Geneva: IPCC.

IPCC. 2007b. Climate Change 2007—The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC. Geneva: IPCC.

ICES (International Council for the Exploration of the Sea). 2011. Report of the study group on designing Marine Protected Area Networks in a Changing Climate (SGMPAN), 15–19 November 2010, Woods Hole, Massachusetts, USA. ICES CM 2011/SSGSUE:01. 155 pp. http://www.ices.dk/workinggroups/ViewWorkingGroup.aspx?ID=500

Ji R, Edwards M, Mackas DL, Runge JA and Thomas AC. 2010. Marine plankton phenology and life history in a changing climate: current research and future directions. Journal of Plankton Research 32: 1355–1368

Joyce TM and Zhang R. 2010. On the path of the Gulf Stream and the Atlantic Meridional Overturning Circulation. Journal of Climate 23: 3146–3154.

Johnson CL, Runge JA, Curtis KA, Durbin EG, Hare JA, Incze LS, Link JS, Melvin GD, O'Brien TD and Van Guelpen L. 2011 Biodiversity and ecosystem function in the Gulf of Maine: pattern and role of zooplankton and pelagic nekton. PLoS ONE 6(1): e16491. doi:10.1371/journal.pone.0016491

Koeller P, Fuentes-Yaco C, Platt T, Sathyendranath S, Richards A, Ouellet P, Orr D, Skúladóttir U, Wieland K, Savard L and Aschan M. 2009. Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean. Science 324: 791–793.

Li WKW, Harrison WG and Head EJH. 2006. Coherent assembly of phytoplankton communities in diverse temperate ocean ecosystems. Proceedings of the Royal Society B – Biological Sciences 273: 1953–1960.

Li, WKW, McLaughlin FA, Lovejoy C and EC Carmack. 2009. Smallest algae thrive as the Arctic Ocean freshens. Science 326: 539.

Link JS and Ford MD. 2006. Widespread and persistent increase of Ctenophora in the continental shelf ecosystem off NE USA. Marine Ecological Progress Series 320:153–159

MacNeil MA, Graham NAJ, Cinner JE, Dulvy NK and Loring PA. 2010. Transitional states in marine fisheries: adapting to predicted global change. Philosophical Transactions of the Royal Society B 365: 3753–3763.

Middelburg JJ and Levin LA. 2009. Coastal hypoxia and sediment biogeochemistry. Biogeosciences 6: 1273–1293.

Moran XAG, Lopez-Urrutia A, Calvo-Diax A and Li WKW. 2010. Increasing importance of small phytoplankton in a warmer ocean. Global Change Biology 16: 1137–1144, doi: 10.1111/j.1365-2486.2009.01960.x

Murawski SA. 2011. Summing up Sendai: progress integrating climate change science and fisheries. ICES Journal of Marine Science 68: 1368–1372.

Nova Scotia Department of Finance. 2006. Nova Scotia at a glance 2006. http://www.gov.ns.ca/finance/publish/FACTS/2006/NS-At-A-Glance.PDF

Nye JA, Link JS, Hare JA and Overholtz WJ. 2009. Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Marine Ecology Progress Series 393: 111–129. doi: 10.3354/meps08220

Parmesan C. 2006. Ecological and evolutionary responses to recent climate change. Annual Review of Ecology, Evolution, and Systematics 37:637–69.

Perry RI, Cury P, Brander K, Jennings S, Moellmann C and Planque B. 2010. Sensitivity of marine systems to climate and fishing: concepts, issues and management responses. Journal of Marine Systems 79: 427–435.

Petrie B. 2007. Does the North Atlantic Oscillation affect hydrographic properties on the Canadian Atlantic continental shelf? Atmosphere-Ocean 45: 141–151.

Petrie B, Pettipas RG, and Hebert D. 2011. Physical oceanographic conditions on the Scotian Shelf and in the eastern Gulf of Maine (NAFO areas 4V,W,X) during 2010. NAFO Scientific Council Research Document 11/014, Serial No. N5896. Dartmouth, NS: Northwest Atlantic Fisheries Organization. 22 pp.

Petrie B and Yeats P. 2000. Annual and interannual variability of nutrients and their estimated fluxes in the Scotian Shelf–Gulf of Maine region. Canadian Journal of Fisheries and Aquatic Sciences 57: 2536–2546.

Planque B, Fromentin J-M, Cury P, Drinkwater KF, Jennings S, Perry RI and Kifani S. 2010. How does fishing alter marine populations and ecosystems sensitivity to climate? Journal of Marine Systems 79: 403–417.

Platt T, White III GN, Zhai L, Sathyendranath S and Royd S. 2009. The phenology of phytoplankton blooms: ecosystem indicators from remote sensing. Ecological Modelling 220: 3057–3069.

Polyakov IV, Alexeev VA, Bhatt US, Polyakov EI and Zhang X. 2010. North Atlantic warming: patterns of long-term trend and multidecadal variability. Climate Dynamics 34: 439–457.

Provan J, Beatty GE, Keating SL, Maggs CA and Savidge G. 2009. High dispersal potential has maintained long-term population stability in the North Atlantic copepod *Calanus finmarchicus.* Proceedings of the Royal Society B: Biological Sciences 276: 301–307

Province of Nova Scotia. 2011a. Nova Scotia's Climate Change Action Plan. http://climatechange.gov.ns.ca/content/actionplan

Province of Nova Scotia. 2011b. Environmental Goals and Sustainable Prosperity Act: Progress Report 2010. http://www.gov.ns.ca/nse/egspa/docs/EGSPA.2010.Annual.Report.pdf

Purcell J.E. 2011. Jellyfish and ctenophore blooms coincide with human proliferations and environmental perturbations. Annual Review of Marine Science. Review in Advance first posted online on July 8, 2011. DOI: 10.1146/annurev-marine-120709-142751

Reid PC and Valdés L. 2011. ICES status report on climate change in the North Atlantic. ICES Cooperative Research Report 310. 262 pp.

Reygondeau G and Beaugrand G. 2011. Water column stability and *Calanus finmarchicus*. Journal of Plankton Research 33: 119–136.

Righton DA, Andersen KH, Neat F, Thorsteinsson V, Steingrund P, Svedäng H, Michalsen K, Hinrichsen HH, Bendall V, Neuenfeldt S, Wright P, Jonsson P, Huse G, van der Kooij J, Mosegaard H, Hüssy K and Metcalfe J. 2010. Thermal niche of Atlantic cod *Gadus morhua*: limits, tolerance and optima. Marine Ecological Progress Series 420: 1–13.

Rose GA 2005. On distributional responses of North Atlantic fish to climate change. ICES Journal of Marine Science 62: 1360–1374.

Rosenzweig C, Karoly D, Vicarelli M, Neofotis P, Wu Q, Casassa G, Menzel A, Root TL, Estrella N, Seguin B, Tryjanowski P, Liu C, Rawlins S and Imeson A. 2008. Attributing physical and biological impacts to anthropogenic climate change. Nature 453: 353–357.

Shackell NL, Bundy A, Nye JA and Link JS. 2012. Common patterns across large-scale ecosystems in the Northwest Atlantic. ICES Journal of Marine Science. doi:10.1093/icesjms/fsr195.

Shackell NL and Frank KT. 2007. Compensation in exploited marine fish communities on the Scotian Shelf, Canada. Marine Ecological Progress Series 336: 235–247.

Shearman RK and Lentz SJ. 2010. Long-term sea surface temperature variability along the U.S. east coast. Journal of Physical Oceanography 40: 1004–1017.

Sherman K, O'Reilly J, Belkin IM, Melrose C and Friedland KD. 2011. The application of satellite remote sensing for assessing productivity in relation to fisheries yields of the world's large marine ecosystems. ICES Journal of Marine Science 68: 667-676, doi:10.1093/icesjms/fsq177.

Song H, Ji R, Stock C, Kearney K and Wang Z. 2011. Interannual variability in phytoplankton blooms and plankton productivity over the Nova Scotian Shelf and in the Gulf of Maine. Marine Ecology Progress Series 426: 105–118.

Song H, Ji R, Stock C and Wang Z. 2010. Phenology of phytoplankton blooms in the Nova Scotian Shelf–Gulf of Maine region: remote sensing and modeling analysisJournal of Plankton Research 32: 1485-1499, doi:10.1093/plankt/fbq086

Stenseth, NC and Mysterud A. 2002. Climate, changing phenology, and other life history traits: nonlinearity and match–mismatch to the environment. Proceedings of the National Academy of Sciences 99: 13379–13381.

Stock CA, Alexander MA, Bond NA, Brander K, Cheung WWL, Curchitser EN, Delworth TL, Dunne JP, Griffies SM, Haltuch MA, Hare JA, Hollowed AB, Lehodey P, Levin SA, Link JS, Rose KA, Rykaczewski RR, Sarmiento JL, Stouffer RJ, Schwing FB, Vecchi GA and Werner FE. 2010. On the use of IPCC-class models to assess the impact of climate on living marine resources. Progress in Oceanography 88:1–27, doi:10.1016/j.pocean.2010.09.001

Suthers IM and Frank KT. 1990. Zooplankton biomass gradient off south-western Nova Scotia: nearshore ctenophore predation or hydrographic separation? Journal of Plankton Research 12: 831–850.

Visser ME and Both C. 2005. Shifts in phenology due to global climate change: the need for a yardstick. Proceedings of the Royal Society B: Biological Sciences 272: 2561–2569.

Walther G-R, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J-M, Hoegh-Guldberg O and Bairlein F. 2002. Ecological responses to recent climate change. Nature 416: 389–395.

Worcester T and Parker M. 2010. Ecosystem Status and Trends Report for the Gulf of Maine and Scotian Shelf. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document 2010/070. vi + 60 pp.