Report of the Study Group on Designing Marine Protected Area Networks in a Changing Climate (SGMPAN)

15–19 November 2010

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Executive summary

The Study Group on Designing Marine Protected Area Networks in a Changing Climate (SGMPAN), chaired by Robert J. Brock, USA, Ellen Kenchington, Canada, and Amparo Martínez-Arroyo, Mexico, met at Woods Hole, Massachusetts, USA from 15–19 November 2010.

The overall aim of this Study Group Report was to develop general guidelines for MPA network design processes that adapt to and mitigate anticipated effects of climate change on marine ecosystems. The Study Group was established jointly between ICES and the North American Marine Protected Areas Network (NAMPAN – a sub-committee of the Commission for Environmental Cooperation (CEC)). Participants were from Mexico, the United States and Canada. The area of interest extended from the Western Tropical Atlantic, including the Caribbean Sea and the Gulf of Mexico, northward to (and including) the Labrador Sea.

The introductory part of the report is followed by more substantive sections numbered 3 to 7, which were the focus of five terms of reference. Section 3 provides an overview, extracted from the scientific literature, of the traits which increase the ability of populations, habitats and ecosystems to adapt to a changing environment. This is discussed in terms of the concept of ecosystem resilience, defined in our report as 'the magnitude of the disturbance that a system can absorb without fundamentally changing.'

Section 4 examines how MPA network design components and properties might influence those traits to help ecosystems to adapt to climate change effects. These sections provide generic information that can be applied to any marine system and will be useful beyond the immediate goal of considering MPA network design.

Section 5 begins with a high level overview of the nature and tendencies of probable ocean climate changes in the study area. This is information which biologists can consider when trying to foresee in detail the potential impact of such changes on specific populations, habitats and ecosystems. Section 5 also provides a similar literature-based overview of expected biological responses to the physical forecasts. This is based on existing data for reflecting trends in environmental parameters that may be related to species' distributions and abundances—which could serve as covariates in future analyses.

Section 6 provides a list of species and habitats that deliver important ecosystem services, and a summary of available data, to ensure that they are not overlooked in any MPA network or other marine spatial planning exercise. The final section reviews the analytical framework for assessing biological responses to physical climate change and for evaluating management options. MPA networks could represent just a part or all of the management response to the climate impacts. A brief summary of our conclusions follows:

The ocean climate off eastern North America naturally varies strongly with latitude and season, with the strength of the seasonality also varying with latitude. It is heavily influenced by atmospheric forcing, continental run-off, Arctic outflows and tropical inflows, the North Atlantic's major gyral circulations, and the complex geometry of the coastline and continental margin. The region's climate is also strongly influenced by several large-scale natural modes of atmosphere and/or ocean variability on time scales of months to multiple decades. These include the North Atlantic Oscillation (NAO), the Tropical Atlantic Variability (TAV), and the Atlantic Multidecadal

Oscillation (AMO). Some of these, or modified versions of them, are expected to re-main very important to regional ocean climate for at least the next few decades (Section 5.1).

Anthropogenically-influenced changes in many ocean variables off eastern North America are already occurring and are expected to become of increasing importance relative to natural variability (and predominant in many cases) as the century proceeds (see Table 5.1.4.2.1 and related text). The direction of the recent changes in some variables, such as increasing ocean temperature, acidity, coastal sea level and coastal erosion, is expected to continue to be widespread following the global trend, although there will probably be important regional variations in magnitude. On the other hand, the direction of the changes in some coastal variables (e.g., currents and stratification) that are heavily influenced by local run-off and winds may vary regionally and seasonally, such that it is more difficult to project their relevant changes to particular ecosystem issues.

The North Atlantic's major western boundary currents, the Labrador Current and Gulf Stream, provide a high level of spatial (latitudinal) connectivity within the subpolar and subtropical waters, respectively, off eastern North America. In addition, the transports of cold fresh water southward by the Labrador Current, and of warm saline water northward by the Gulf Stream, , result in a pronounced mid-latitude ocean climate "transition zone" between the Grand Bank and Cape Hatteras. Enhanced climate changes in some variables (e.g., salinity) are expected in this zone, associated with a probable northward shift of the Gulf Stream's position.

While available climate change projections provide a good indication of the probable changes for many variables on large scales, the models used do not adequately resolve many important regional oceanographic features in the western North Atlantic. Thus, there remains substantial uncertainty in the magnitude of future ocean climate change on the space and time scales of importance to many coastal and marine ecosystem issues. Furthermore, present and projected greenhouse gas emission rates, and recent climate change assessments, indicate that the rates of future anthropogenic climate change may be near the high end of those outlined in the Fourth Assessment of the Intergovernmental Panel on Climate Change. This means that some major climate changes (such as rising sea level and coastal erosion) may occur earlier than previously projected.

There is also uncertainty in how ecosystems will respond to climate change, although some generalized effects are anticipated (Section 5.2 and 5.4). Changes in species' distribution across all trophic levels are expected. These are unlikely to be synchronous, which will cause changes in trophic interactions and ecosystem function. Energy cycling is predicted to change as a result of decreases in primary productivity in low latitude ecosystems and increases in primary productivity in high latitude systems. The generalized effects of climate-driven oceanographic change in relation to key components of the ecosystem are summarized (Section 5.4).

MPA networks can be designed to be integrated, mutually supportive and focussed on sustaining key ecological functions, services and resources (Sections 4, 7). As such, they can provide a mechanism to adapt to and mitigate climate change effects on ecosystems. MPA networks are especially suited to address spatial issues of connectivity (e.g., connecting critical places for life stages of key species), habitat heterogeneity, and the spatial arrangement and composition of constituent habitats, all of which can contribute to ecosystem resilience (Sections 3, 4). A suite of properties of ecosystems, habitats and populations are described that confer increased resilience to ma-

rine systems (Section 3). Some of these properties can be supported through the size and placement of protected areas (e.g., abundance and size structure of upper trophic levels, species richness). Others are not amenable to management; they are properties of marine systems which can be used to predict their vulnerability to climate change (e.g., phenological matches, flexibility of migration routes, and dependence on critical habitats, functional redundancy, response diversity, community evenness, and distance to ecotones). We identify species and habitats which are crucial to ecological functioning and may merit special conservation consideration (Section 6).

The sections of this report collectively inform how MPA networks designed for conservation of biodiversity could help enhance ecosystem robustness to climate change. We envision that other ICES expert groups, as well as other similar bodies, will assess the various ecosystem components following the framework that is developed herein (Section 7). A next step for the Study Group will be to take the information in this report and develop it into more accessible guidelines for MPA network and other marine spatial planning.

1 Opening of the meeting and acknowledgements

The NAMPAN-ICES Study Group on Designing Marine Protected Area Networks in a Changing Climate (SGMPAN) met at the U.S. Geological Survey, Center for Marine Science, 384 Woods Hole Road, Quissett Campus, Woods Hole, Massachusetts, USA, from Monday 15 November to Friday 19 November 2010. The list of participants from Canada, Mexico and the United States (Figure 1.1) and contact details are given in Annex 1.

SGMPAN would particularly like to thank Karen Schmidt of the NAMPAN Secretariat and Claire Welling of the ICES Secretariat for their support in enabling the meeting to run smoothly. We would like to further thank Hans Hermann for his assistance to the Chairs in organizing the meeting and for his help throughout. We thank Walter Barnhardt and the U.S. Geological Survey for use of their wonderful facility and for logistical support for the meeting.

We also thank the following scientists: Jake Rice of Fisheries and Oceans Canada (DFO) for his assistance in developing the terms of reference for the meeting, Igor Yashayaev of DFO at the Bedford Institute of Oceanography for providing the circulation schematic (Figure 5.1.2.1.1) and temperature and salinity climatologies (Figure 5.1.2.1.2) for the oceanographic review in Section 5; Augustine van der Baaren of Wolfville, Nova Scotia for making available her literature review of climate change in the Northwest Atlantic; and Rhian Waller, University of Maine.

Figure 1.1. Workshop participants. Back Row: Karel Allard, Juan Pablo Carricart-Ganivet, Michael Moore, Brad Barr, Jack Lawson, Brad De Young, Mary Rothfels, Ellen Kenchington, Camille Mageau, Dvora Hart, John Loder, Porfirio Alvarez Torres, Kathryn Scanlon, Mike Fogarty, Robert Brock. Middle Row: Jorge Zavala Hidalgo, Terry Joyce, Angelia Vanderlaan, Dave Kulka, Linda Deegan, Janet Nye, Carin Ashjian, Laura Sartí Martínez, Amparo Martínez-Arroyo, David Gutierrez Carbonell, Jonathan Fisher (kneeling). Front Row: Julio Sheinbaum Pardo, Hans Herrmann, Kimberly Murray, Erica Head, Vladimir Pliego, Álvaro Hernández Flores.

2 Adoption of the agenda and working format

The Agenda (Annex 2) was adopted on 15 November and the meeting proceeded according to the Workplan presented in Plenary Sessions by the Subgroup Leaders. Throughout the meeting, subgroup meetings were scheduled to allow for member participation in a number of subgroups to the degree possible. Daily updates were provided by the Subgroup Leaders in plenary session and as text was finalized it was presented in plenary. Therefore, all of the central content of this report pertaining to the ToRs was reviewed in plenary sessions of the SGMPAN. Meeting participants were given one week to comment on the final report before submission and another two days to comment on the revised version.

3   Properties of populations, habitats and ecosystems which increase resilience of marine systems to climate change

ToR a) Determine what properties of populations, habitats and ecosystems increase the resilience of marine systems to impacts of climate change in the region of the NW-Atlantic to the Caribbean.

Climate change, including both natural and anthropogenic factors, is expected to affect virtually every aspect of marine ecosystem structure and function from community composition and biogeochemical cycling, to the prevalence of diseases. Since climate change will affect populations, habitats, and ecosystems differently depending on their underlying characteristics, we summarized the relevant properties of the biodiversity components expected to increase resilience of marine ecosystems to climate change. We have excluded a review of some of the physiological mechanisms that underlie the higher level dynamics (for reviews see Rijnsdorp *et al.*, 2009; Pörtner and Peck, 2010).

Table 3.1. Summary of properties of ecosystems, habitats, and populations related to increased resilience of marine systems.

Ecosystems	Habitats	Populations
Connectivity (spatial fluxes, trophic connections, mobile link species)	Heterogeneity	Connectivity
Abundance and size structure of upper trophic levels	Spatial arrangement and composition	Dependence on critical habitats
Community size structure of plankton	Foundation species	Sensitivity to environmental conditions
Phenological matches	Ecosystem engineers	Flexibility in migration routes
Species richness	Disturbance	Population size and age structure
Functional redundancy (taxonomic diversity)	Bathymetery, topography and rugosity	Geographic distribution
Response diversity	Transparency, suspended solids and turbidity	Number of population subunits or metapopulations
Community evenness	Habitats supporting critical life stages	Phenology
Beta-diversity	Biogeographic transition zones	
	Distance to ecotones	
	Buffer zones	
	Temperature	
	Salinity	
	Circulation and winds	

Considering the influences of climate change on MPA network design is relatively novel. Despite projected spatial variation in climate impacts (see Section 5.1), MPA networks are being designed on the basis of contemporary environmental and habitat conditions (Gaines *et al.*, 2010). To address this information gap, we asked—**which properties of populations, habitats, and ecosystems increase the magnitude of disturbance that an ecosystem can absorb?**

We begin with a definition of ecosystem 'resilience,' of which there are many. Resilience has been widely used as a metaphor and theoretical construct (e.g., Côté and Darling, 2010) that has infrequently been defined operationally (Carpenter, 2001). Resilience is generally characterized as an attribute of a system based on its potential recovery from disturbances (Grimm and Wissel, 1997) and/or its resistance to disturbances. We have adopted Holling's (1973) original definition: 'the magnitude of the disturbance that a system can absorb without fundamentally changing.'

The properties considered are summarized in Table 3.1.

3.1 Ecosystem properties that increase resilience to climate change

Ecosystems are complex, dynamic networks of interacting abiotic and biotic components with intrinsic capacity to adapt to perturbations such as climate change. Within ecosystems, it is individual organisms that perceive and respond to perturbations either directly through physical responses to abiotic factors or indirectly through interaction mechanisms such as predation and competition. When large numbers of individuals are affected the response reverberates through higher levels of organization.

Connectivity is a property that influences the structure, diversity, productivity, dynamics, and resilience of marine ecosystems by providing feedbacks and subsidies of organisms, nutrients, and energy across ecosystem boundaries. Connectivity is perhaps most evident in spatial fluxes, as most marine ecosystems maintain strong connections with adjacent and distant ecosystems through the flux of juvenile and adult organisms across ecosystem boundaries (Shanks *et al.*, 2003). Given the importance of connectivity to MPA network design and analyses (see also Section 7.2), understanding the influences of climate change on different components of connectivity remains a key research need.

In addition to passive dispersal, organisms that actively move across the landscape and connect habitats in space and time ('**mobile link organisms**': Lundberg and Moberg, 2003) may contribute strongly to marine ecosystem resilience (see also Section 6.1). Mobile link organisms may be essential components in the dynamics of ecosystem development and resilience because they provide a buffering capacity between sites and can be sources for recolonization after disturbance. However, the importance of mobile species in ecosystem dynamics is not well understood. An open question is whether top-down effects are more likely when large mobile predators aggregate in specific areas or ecosystems. The paucity of empirical data on the migratory patterns of mobile link organisms and their use of geographically separate areas represents a fundamental obstacle to any comprehensive understanding of connectivity and its contribution to ecosystem resilience.

Trophic interactions also maintain **food web** connections within and among ecosystems. Changes in resource availability at the bottom of food webs induced by climate change will propagate upward altering abundances at higher trophic levels. Additionally, alterations in the abundance and/or body size structure of **species at upper trophic levels** may directly and indirectly precipitate changes in abundances of lower trophic levels via predation (e.g., Deegan *et al.*, 2007) and alterations of the behaviours of other species (Heithaus *et al.*, 2008). There is a long history of work, from rocky shores to sea otters and sharks that has established that top predators have a profound influence on the structure and function of marine ecosystems (Baum and Worm, 2009). One specific type of top-down impact termed a "trophic cascade" is an alternating pattern of increased and decreased abundance in successively lower tro-

phic levels (Terborgh and Estes, 2010). In some ecosystems the loss of herbivores in coral reefs or sea otters in kelp forests leads to top down changes that produce a major shift in ecosystem structure and energy flow. As a consequence, food web condition is a determinant of the resilience of many ecosystems, such as the reduced resilience of heavily fished Mexican coral reefs to the effects of hurricanes (Figure 3.1.1). Understanding the effects of climate change on the relative importance of top-down and bottom-up forcing is a critical research need to understand trophic connectivity and the resilience of ecosystems (Hoekman, 2010) (see also Section 6.1).

Community size structure at the base of marine food webs is an important component of ecosystem response to climate change with implications for trophic interactions and biogeochemical cycling. For example, within the Canada Basin, Arctic Ocean, increases in the relative abundance of small phytoplankton were associated with an increase in temperature, a decrease in salinity, and a decrease in nutrients, but no change in total plankton biomass (Li et al., 2009). Small phytoplankton have lower sinking rates and higher surface area to volume ratios that maximize uptake and competition for limited nutrients during the warmer ocean conditions. Similar changes in plankton community size structure are expected to increase with the increasing temperatures resulting from climate change (Finkel et al., 2010). These declines in phytoplankton size also have implications for carbon sequestration and biogeochemical cycles. The loss of large cells may reduce sequestration rates due to the larger cells playing a larger role in export, because large cells sink more rapidly when they become senescent and because they are grazed more efficiently by larger zooplankton forms, which make larger more rapidly sinking faecal pellets.

Phenology (the annual timing of ecological events) in the marine environment is altered dramatically by climate change (Kirby et al., 2007; Sydeman and Bograd, 2009). Changes in phenology are important to ecosystem resilience because the rates of phenological response to climate change are expected and observed to vary across functional groups and trophic levels (Thackeray et al., 2010). The decoupling of phenological relationships has important ramifications for trophic interactions by altering food-web structure that can lead to ecosystem-level changes in biomass and productivity.

The relationship between species richness and ecosystem resilience to perturbations is generally assumed to be positive. However this relationship has been studied in a number of ecological contexts and over a range of spatial scales, and the resulting large variability in response has limited such generalizations or predictions to specific variables and trophic contexts (Schläpfer and Schmid, 1999). Native species diversity along with connectivity and habitat heterogeneity are the three ecological attributes most commonly identified as critical for maintaining marine ecosystem functioning (Foley et al., 2010).

One source of this variability lies in the fact that evolutionary history constrains responses through physical and chemical similarities among closely related taxa. Ecosystems with high species richness may not have greater inherent resilience to climate unless there is an effective degree of taxonomic relatedness. Taxonomic relatedness must be low enough to confer a certain amount of functional redundancy to the system, yet high enough to ensure a diversity of responses to environmental change among species contributing to the same ecosystem function (response diversity) (Elmqvist et al., 2003). The combination of response diversity and functional redundancy of the ecosystem determines its intrinsic ability to compensate for perturbations without seriously altering ecosystem function. However, these properties are

not easily accessed and can operate in multiple dimensions responding in non-linear ways (Loureau, 2004).
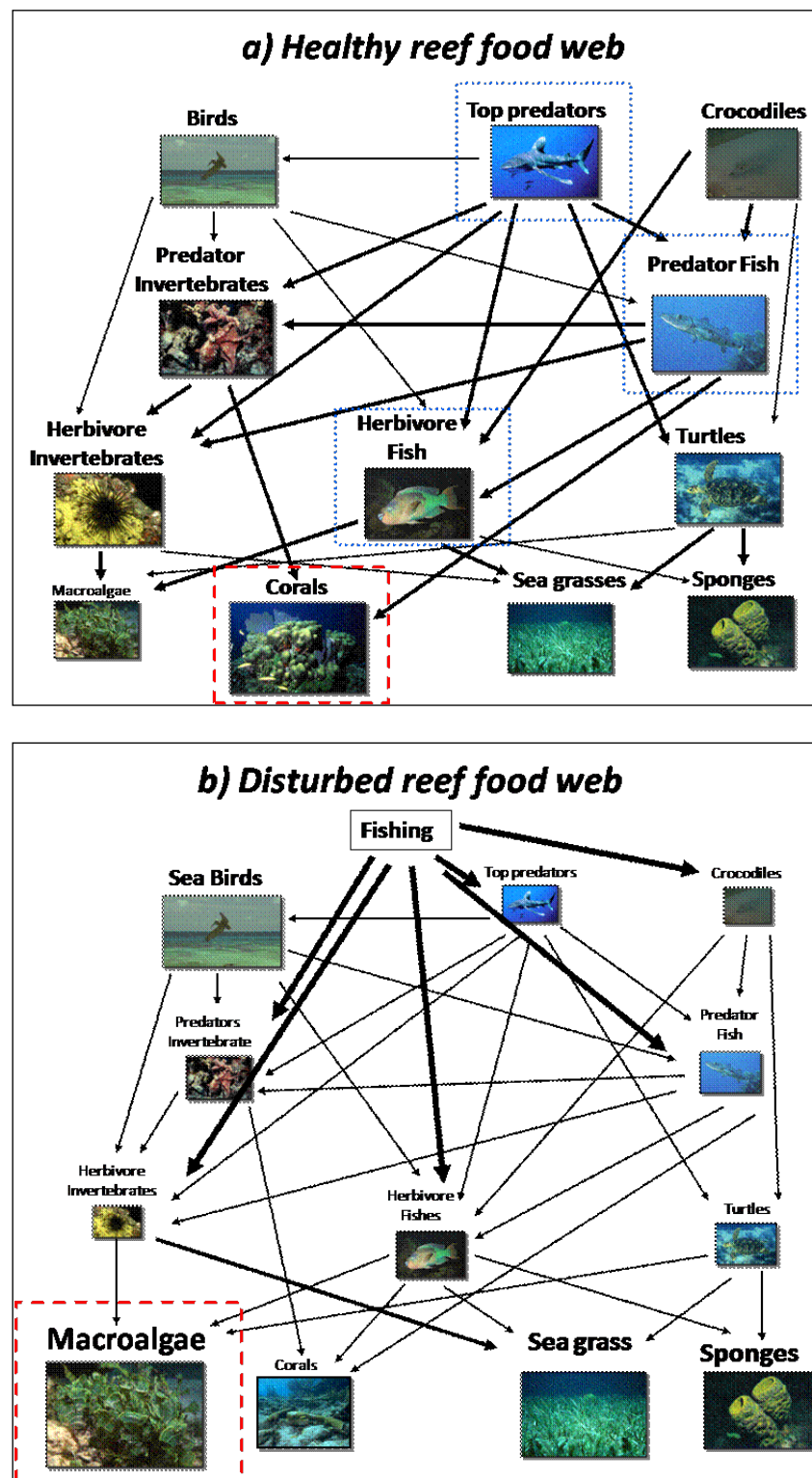

Figure 3.1.1. An illustration of changes in coral reef food webs in locations differentially affected by fishing. Box sizes illustrate relative abundance and 'disturbed' reef food webs are less resilient to the effects of hurricanes (from Rodriguez-Zaragoza, 2007).

The relative abundance of individuals among species, or '**evenness**' within ecosystems represents the distribution of functional traits (Hillebrand *et al.*, 2008) and contributes to resilience and ecosystem functioning. At biogeographic spatial scales, and among a range of assemblages, those with high species richness also tend to exhibit relatively high evenness (Hubbell, 2001). Additionally, experimental evidence has revealed that when communities are highly uneven or the abundance/biomass is concentrated in only a few species, their functioning is less resistant to environmental stress (Wittebolle *et al.*, 2009).

At large spatial scales, **beta-diversity** (i.e., spatial turnover in species composition of communities) may play a role in enhancing ecosystem resilience in the face of large-scaled environmental changes. Local species pools may provide a level of redundancy at large scales that may confer resilience. This concept has not been as well-developed in the marine literature, although the potential for increased resilience via community 'rescue' from local and regional sites has been degraded in recent decades within some exploited marine ecosystems (Shackell *et al.*, in review).

3.2 Habitat properties expected to increase resilience to climate change

Those parts of the environment that together make a place for organisms to survive and prosper are defined as 'habitat' and include physical, chemical, and biological components. **Physical structure** is often the most visible aspect of a habitat and is therefore the basis for most habitat classifications. However, physical structure alone is not sufficient to provide a functional habitat for an organism. Habitats can be dysfunctional, even though the basic physical structure is present, if aspects such as food webs or primary production have been altered. In addition, environmental properties such as temperature, salinity, and nutrient (food) availability greatly influence the use of these areas.

Habitat heterogeneity is one of the most commonly identified habitat characteristics considered critical for maintaining marine ecosystem functioning (Foley *et al.*, 2010). Habitat heterogeneity is created and maintained by interrelated geologic, biogenic and disturbance factors at multiple scales, from millimeters to kilometers.

Spatial arrangement and **composition**. There is increasing evidence that the spatial structure of habitats profoundly influences the dynamics, composition, and biodiversity of communities (Tilman, 1994). At the regional scale, however, stable coexistence requires spatial niche differentiation among habitats (Mouquet and Loreau, 2002). Such a spatial niche differentiation is likely to also make more diverse regional systems more productive and connected via mobile species. If some habitats suffer changes or disappear, the neighbourhood will be modified, which in turn will reduce the resilience of other habitats and ecosystems.

Organisms that are important in creating and modifying habitats, such as **foundation species** (dominant primary producers such as salt marshes, mangroves, kelp) and **ecosystem engineers** (any organism that creates, builds or modifies habitats, e.g., corals, bioturbators), may cause some of the most profound and non-reversible effects in ecosystems in response to climate change (Jordán and Scheuring, 2002). Given the importance of biogenic habitat in marine ecosystems, the maintenance of foundational species is key to maintaining ecosystem resilience (see also Section 6.2).

Another habitat property expected to maintain ecosystem resilience is spatial extent and magnitude of **disturbance**. In keeping with the intermediate disturbance hypothesis (Connell, 1978), habitats that are disturbed periodically and on small scales may contain non-equilibrium communities composed of a mix of organisms with

diverse life history types. Therefore disturbance can increase the range of trait variation within a habitat.

Bathymetry, topography and rugosity (measures of variations in the heights of surfaces) are important features that represent an axis of habitat diversity that may provide refuges at multiple spatial scales. Bathymetry (water depth) determines the presence of many marine species, and the literature contains many examples showing that species spatial distribution is highly associated to this variable (e.g., cold-water corals). This characteristic also affects species phenology, because different stages of species tend to occupy different habitat associated to a depth gradient. Topography and rugosity offer regions of unique characteristics that provide food and shelter for species.

Transparency, suspended solids and **turbidity** of the water column are inter-related properties and key to the initiation and duration of organism development, particularly for primary producers and corals (Carriquiry and Horta-Puga, 2010). Frequently transparency is affected by sewage or other human impacts, which may interact with climate change.

As an example of the importance of habitats **supporting critical life stages**, marine birds are anchored to the locations of breeding habitats including colonies and breeding islands. Breeding sites therefore represent terrestrial extensions of marine habitats. Given that some marine birds rely heavily on shallow coastal habitats as foraging and/or nesting sites, predicted sea level rise will directly affect those species.

Biogeographic transition zone habitats (e.g., between ecotypes) are important habitats that have been described as a core conservation objective based on the overlap of species geographic range limits. Within an MPA network, these transition zones are ideally placed to monitor shifts in species distributions arising from climate change (Roberts *et al.*, 2003).

Distance to ecotones (i.e., transitions between habitat types) is closely related to the spatial composition and neighbourhood of habitats. This metric is often related to the potential negative impacts that changes in the ecotones will produce on species with specific habitat needs.

In order to increase ecosystem resilience, MPA networks should include additional **buffering habitats** intended to shield a portion of a different habitat from potential catastrophic disturbances that may increase in frequency or intensity as a function of climate change (e.g., fringing mangroves protect mudflats from hurricanes). In the context of habitat contributions to ecosystem resilience, it is worthwhile to note that 'resilience' has also been defined as insurance against large-scale shifts (Thrush *et al.*, 2009).

Temperature is a critical factor in defining habitats and their suitability for different organisms. For example, the extent and duration of sea ice habitats and their associated species depend directly on the maintenance of an appropriate range of temperatures. This factor also determines many biological rates, from photosynthesis (although photosynthesis by phytoplankton is not very strongly influenced by temperature) and metabolism to reproduction (Woodward *et al.*, 2010). Temperature variations affect many ecological processes, and in some cases minor deviations from the "normal" conditions may trigger large-scale events. For example, changes in temperature may cause red tides (harmful algal blooms) which may occur very quickly with negative consequences for the ecosystem. Similarly, increases in summer maxima may cause mass mortality in intertidal and shallow subtidal shellfish.

Salinity affects both the metabolism of individual organisms and the circulation patterns of the ocean that affect species distributions. This characteristic is associated with different oceanographic phenomena, which in turn contribute to abiotic stress for organisms. Salinity plays a particularly important role in coastal ecosystems where conditions can change dramatically over a few days due to river discharges, which affect stratification and contribute high levels of nutrients. In some cases these conditions favour the development of intense phytoplankton blooms, which sink out and are utilised by oxygen consuming bacteria, sometimes causing hypoxia over relatively large areas.

Currents and circulation (global, regional and local scales). Some currents and circulation patterns have an important interannual variability in strength and location linked to large scale atmospheric forcing, which suggests that in a changing climate these habitat features may be affected, being stronger or weaker depending on the evolution of the large scale atmospheric patterns (Zavala-Hidalgo *et al.*, 2003). Connections between anticyclonic eddies, loop currents, and cyclones will affect local conditions, such as dispersal between habitats and upwelling seasonality and strength that are both key factors for biological production.

Additional **chemical properties** of marine habitats, including dissolved oxygen, ocean acidity, and nutrients contribute to the resilience of marine ecosystems by providing essential inputs and a suitable range of conditions for habitat development (e.g., foundation species) and species occurrence. Given the tendency for anthropogenic climate change to affect chemical oceanographic properties at large scales (see Table 5.1.4.3.1), the magnitude of climate impacts on these foundational habitat components may be critical to the future resilience of marine ecosystems.

3.3 Population properties expected to affect resilience to climate change

Climate can affect all life-history stages through direct and indirect mechanisms. Certain characteristics may increase the resilience of marine species to climate change while other characteristics decrease the resilience of a species' ability to adapt to climate change. Both should be considered in the design of MPA networks.

Within marine species, **population connectivity** is a key characteristic with direct relevance to the scale and spacing of MPA networks (see also Section 7.2). The planktonic larval durations (PLD) of marine fishes and invertebrates among species represents an index of potential connectivity that varies on small scales and across biogeographic regions (Figure 3.3.1). Corresponding declines in reproductive isolation with increasing PLD, the negative relationships between PLD and temperature both within and among species (O'Connor *et al.*, 2007) suggest that changes in ocean currents, stratification, and temperature will affect the dispersal and survival of populations during this life history stage.

Population **dependence on critical habitats** and **sensitivity to environmental conditions** are also key properties. For example, bleaching events involve the disruption of the symbiotic relationship between corals and their zooxanthellae (intracellular dinoflagellate endosymbionts of various marine animals and protozoa). Bleaching occurs when a combination of elevated temperature and irradiance is present (Brown, 1997); prolonged bleaching can result in the death of corals. Populations with life stages dependent on living coral illustrate the links between these two key properties.
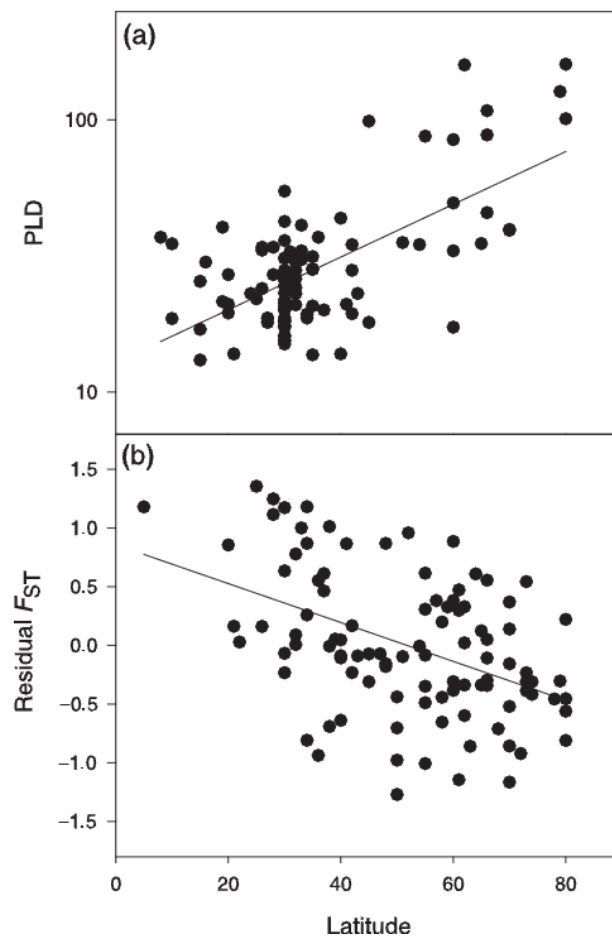
Figure 3.3.1. General characteristics of gene flow (F_{ST}) and dispersal relationships of marine fish populations. (a) Planktonic larval durations (PLD) of 96 marine fish species versus maximum latitude (north or south) occupied by marine fish species. (b) Residuals of FST-scale (km) relationship versus maximum latitude (north or south) occupied by each of 100 marine fish species (from Laurel and Bradbury, 2006).

Flexibility in migration routes for migratory species represents a critical population characteristic. High flexibility within populations of large whales, sea turtles, tunas, swordfish, sharks, and seabirds may confer some resilience to climate change. Large pelagic fishes, including Atlantic bluefin tuna (*Thunnus thynnus*) may be able to adapt to varying temperatures during migration and while in their feeding areas, due to their ability to tolerate a large temperature range (Walli *et al.*, 2009). However, they are highly sensitive to sea-surface temperatures in their spawning areas in the Gulf of Mexico (Teo *et al.*, 2007) a property that will decrease their resilience to climate change in those areas. Migrating baleen whales may be resilient to climate change but currently face longer journeys and reduced feeding opportunities (Learmonth *et al.*, 2006). Potential loss of stopover sites and longer migratory pathways may have deleterious effects on fitness.

In contrast to these examples, some marine birds are severely constrained in their migratory routes due to the location of physical features (specific headlands, straits, etc.). These act as migratory 'bottlenecks', which must be passed during each migration event (Figure 3.3.2) and illustrate examples of extreme inflexibility in migratory routes.
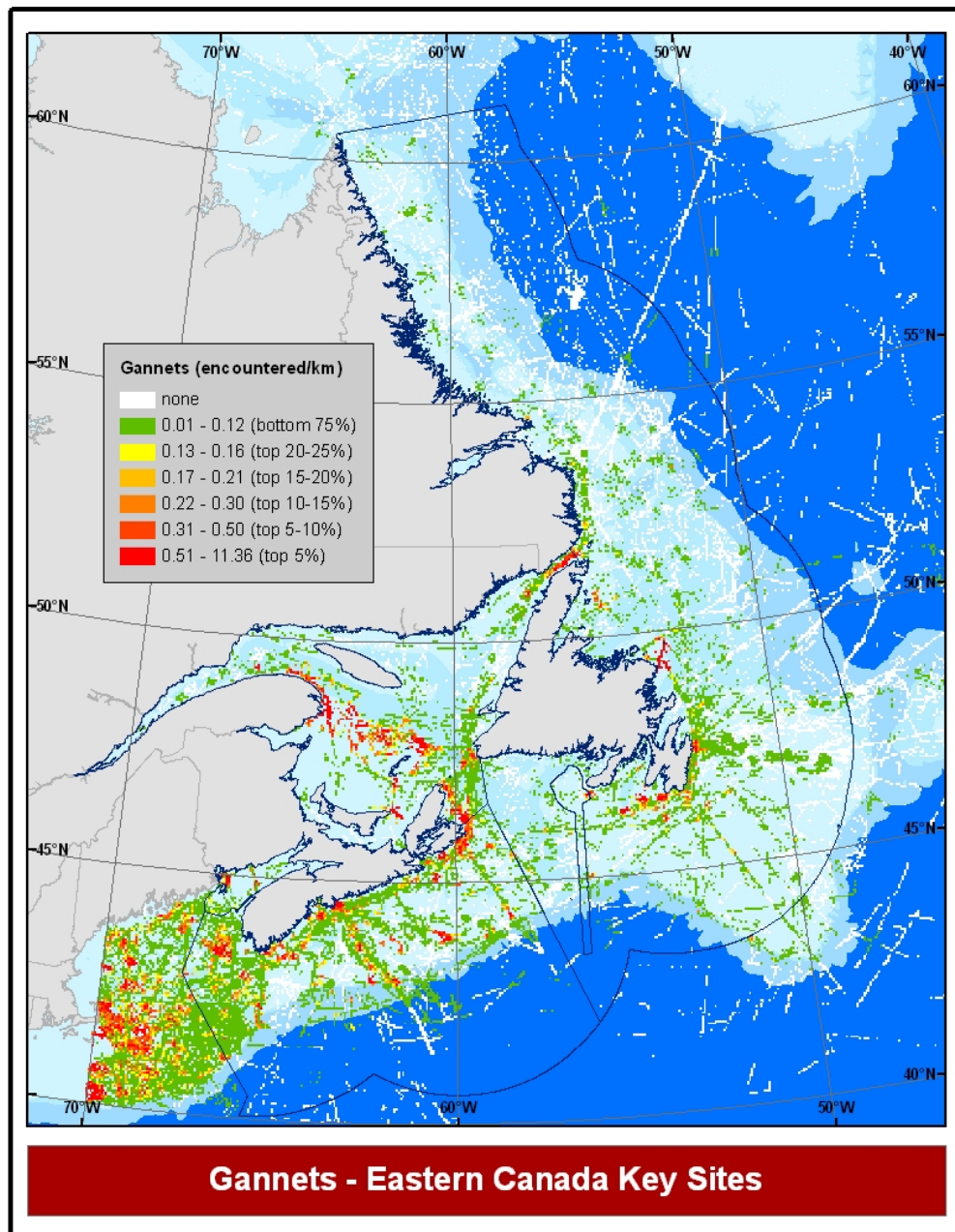
Figure 3.3.2. This map illustrates the migratory bottleneck effect for a marine bird species, the northern gannet (*Morus bassanus*) especially in the area immediately north of Cape Breton Island, Nova Scotia, Canada, where no nesting sites are found. The concentrations detected in that area are of individuals during their entry and exit of the Gulf of St. Lawrence, in which three (of six in total for North America) large colonies are located (Bonaventure Island, QC; Bird Rocks, Magdalen Islands, QC; Falaise aux Goélands, Anticosti Island, QC). (Data are from Environment Canada's Canadian Wildlife Service and are the result of the Seabirds at Sea monitoring program (Carina Gjerdrum, Biologist)).

Maintenance of population **size and age structure** and **geographic distribution** are key components that may buffer ecosystems and are expected to interact with climate variability but which may currently be modified due to exploitation and other human influences (Figure 3.3.3). Within many marine populations, local abundance and geographic distribution are positively correlated with implications for population connectivity within MPA networks (Jennings, 2000).
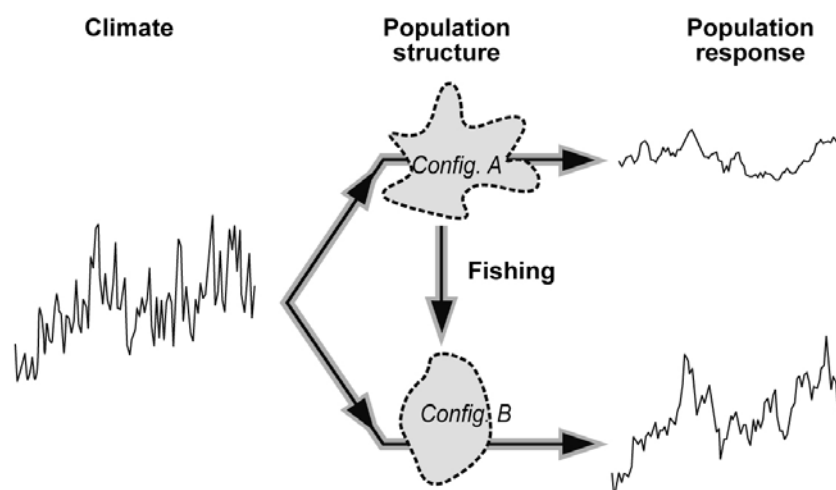
Figure 3.3.3. A schematic representation of increased correlation of a marine population (e.g., abundance) to climate forcing when under exploitation (from Perry *et al.*, 2010).

The **number of population subunits** or **metapopulation structure** contributing to produce an aggregate trend provides some insurance against variability that would be reduced in a single population (Schindler *et al.*, 2010).

Phenology (the annual timing of ecological events) in the marine environment is altered dramatically by climate change and is a key contributor to population dynamics in addition to the trophic interactions listed above. For populations that rely on temperature as an environmental cue, climate change will have serious effects on phenology. Temperature and photoperiod are two fundamental physical factors that also influence the timing of biological cycles including phytoplankton production and the reproductive cycle of some marine invertebrates (Lawrence and Soame, 2004). Species that rely more heavily on a photoperiod cue may be more resilient to climate change as photoperiod is a less variable and more reliable cue compared to temperature.

3.4   Identification of unanswered questions

The importance of 'novel ecosystems' where some species shift faster than others is only beginning to emerge as a potential important impact of climate change (Thackeray *et al.*, 2010).

Tackling the complexity of multiple drivers on ecosystems remains a critical challenge to understanding the influence of climate (Woodward *et al.*, 2010). In an early analysis of potential climate change influence on Northwest Atlantic marine fishes, Frank *et al.* (1990) reported that a number of uncertainties related to the output of climate models including terrestrial inputs, direct and indirect effects on ocean climate, and vertical structure of the water column, and limited forecasts of the impacts of climate change on marine populations and species. Since then improvements in models and monitoring have reduced some of these gaps but also revealed greater complexity of the climate system associated with natural variability (see also Section 5.1, Table 5.1.4.2.1). Therefore, moving from predictions about the influence of single drivers on populations and species to multiple drivers on ecological network structure adds additional complexities, indirect effects, and associated uncertainties.

3.5   References

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4   Properties of MPA networks

ToR b) Review what properties of MPA networks are most relevant to providing the elements described in ToR a.

IUCN (2008) defines an MPA network as "a collection of individual MPAs or reserves operating co-operatively and synergistically, at various spatial scales and with a range of protection levels that are designed to meet objectives that a single reserve cannot achieve." MPA networks range in complexity from simple, involving only a few sites linked within a common management framework, to constructs of nested and interacting networks established collaboratively by multiple jurisdictional authorities operating at scales ranging from local to international. In geographic scale they can encompass any or all of inshore waters, estuaries and rivers important for anadromous species, coral reefs and reef tracks, and offshore waters such as habitat areas that are critical for highly migratory pelagic species and abyssal features like seamounts and hydrothermal vents.

Ideally, MPA networks can be designed to be integrated, mutually supportive and focused on sustaining key ecological functions, services and resources for maintaining a robust ecosystem. As such, they can provide a mechanism to mitigate or adapt to climate change effects. From a species perspective, MPAs, MPA networks and other management measures can work together to address some spatial and temporal shifts (e.g., anticipated shifts in species distribution, assemblage composition and trophic relationships) resulting from climate change

New conditions require managers to be adaptive in their use of available tools, and new approaches must be developed if the existing tools are not sufficient. Marine and coastal ecosystems are highly dynamic, and climate change increases the rate, scope and intensity of this changing environment. For example, convergence zones, very critical habitat areas for pelagic resources, move in both space and time. Effective management requires that such variability be taken into account when management actions are contemplated.

Perhaps our concept of MPA networks needs to change and evolve to more effectively integrate the dynamic nature of the environment being managed. Examples of novel approaches to MPA network design mentioned in Agardy *et al.* (2010) include: "…the introduction of dynamic MPA boundaries (*sensu* Hyrenbach *et al*., 2000) for the protection of fluctuating habitats... as was recently proposed by Shillinger *et al*. (2008) to protect leatherback turtles in the Central Eastern Pacific, and implemented as Dynamic Area Management fishery closures by the U.S. National Marine Fisheries Service to protect right whales from entanglements in fishing gear of Massachusetts (Johnson, 2005)." Given the uncertainty associated with climate change projections and interactions within and external to the network, it is important to monitor and adapt network management and design to address unanticipated impacts.

The need to adapt our approach to MPA network design is particularly important in the face of the potential re-distribution of species unable to adapt to new local environmental conditions. For example, North Atlantic Right whales (*Eubalaena glacialis*) now feed commonly in the Bay of Fundy where they are protected, with a few individuals migrating up to Roseway Basin and the Gulf of St Lawrence (E. Head, pers. comm.). Climate change predictions suggest these whales might desert the Bay of Fundy entirely and relocate to an unprotected area.

As greater certainty is acquired with respect to ecological responses to climate change, MPA network design may need to be adjusted (e.g., one or more MPAs may need to be relocated or reconfigured).

Using a "place-based" mechanism like the establishment of marine protected areas – and by extension MPA networks – to effectively manage these ecosystems needs to be undertaken with some care, and as part of a larger management and governance framework. This is not to say that MPA networks cannot be valuable tools in increasing resilience of ecosystems, but they are only a part of the approach, and interact with other international, regional and targeted resource management efforts.

Thus ocean governance will need to adjust to reflect a new imperative: maintaining structure, function, processes and biodiversity of ecosystems to enhance resilience to change. A highly coordinated and integrated approach to oceans governance will clearly be central to implementing this new imperative, necessitating some mechanism to enhance consistency and coherency across sectors and regions (Gjerde *et al.*, 2008). This may be particularly important with regard to the establishment and operation of transboundary MPA networks.

4.1 What are the benefits of MPA networks with respect to enhancing or increasing resilience in the context of climate change?

According to the IUCN (2008), MPA networks offer three inter-related functions and benefits:

- Maintain functional marine ecosystems by encompassing the temporal and spatial scales of ecological systems;
- Help resolve and manage conflicts in the use of natural resources; and
- Facilitate the efficient use of resources.

The potential benefits of MPA networks have been further summarized by UNEP-WCMC (2008) as follows:

- Ensuring that all types of biodiversity (both species and ecosystems) are protected;
- Helping to maintain the natural range of species;
- Ensuring that protection of unique, endemic, rare, and threatened species is spread over a fragmented habitat;
- Enabling adequate mixing of the gene pool to maintain natural genetic characteristics of the population;
- Ensuring protection of ecological processes essential for ecosystem functioning, such as spawning and nursery habitats, and large-scale processes, such as gene flow, genetic variation and connectivity, that promote an ecosystem-based approach to management;
- Ensuring that social and economic connections between protected areas are addressed;
- Bringing sectoral agencies together, and helping conservationists, fishery managers and other stakeholders with diverse interests to find a common goal;
- Facilitating the sharing of information and lessons learned; and
- Allowing for a more efficient use of resources, through cost sharing.

There are additional benefits where national networks are linked into larger international networks:

- Ensuring the protection of an ecosystem or species that cannot be adequately protected in one country, such as migratory species;

- Ensuring that transboundary protected areas are given adequate attention;

- Sharing effective conservation approaches across similar sites in different regions;

- Developing collaboration between neighboring countries to address common challenges and issues; and

- Strengthening capacity by sharing experiences and lessons learned, new technologies and management strategies, and by increasing access to relevant information.

The social benefits of networks are a critical element with regard to ecosystem resilience. The building of capacity, opportunities for enhancing a learning environment, the building of trust among managers and constituencies, and establishing and gaining experience in problem solving all contribute to building the resilience of socio-ecological systems of MPA networks. Given the dynamic nature of marine ecosystems, having high resilience would help to maintain stability and sustain biotic communities and ecosystem services upon which humans depend. In this regard, Hughes *et al.* (2005) suggest that managers:

i) Embrace uncertainty and change;

ii) Build knowledge and understanding of resource and ecosystem dynamics;

iii) Measure, interpret and respond to ecological feedback; and

iv) Support flexible institutions and social networks in multi-level governance systems.

Effective resource management to increase resilience of marine systems in the face of climate change, therefore, should focus on maximizing diversity in all its forms, recognizing and embracing change and uncertainty while avoiding directional change if possible. Fostering innovation and learning through inclusive, transparent public engagement is also an important part of flexible and innovative governance mechanisms.

4.2 What properties of MPA networks increase ecological resilience in the face of climate change effects?

There are basic design properties of an MPA network that have been advanced through international fora. The following blend of IUCN (2008) and UNEP-WCMC (2008) properties are the focus of this discussion, and have been explored in the context of climate change in Table 4.2.1:

- <u>Representativity (or Representation)</u>: covers the full range of biodiversity, rare and threatened species;

- <u>Connectivity</u>: ensuring linkages between sites through currents, migratory species, larval dispersal;

- <u>Replication/Redundancy</u>: protecting more than one example of a given feature;

- <u>Adequacy/Viability</u>: appropriate size, spacing, shape of MPAs.

Table 4.2.1 includes both these network properties and site-specific MPA criteria such as EBSAs (Ecologically and Biologically Significant Areas) for network component areas, as derived from sources such as CBD (2009). Site-specific criteria were included to identify attributes of MPAs that facilitate the building of MPA networks that increase ecosystem resilience under climate change. Each component and property is defined, tangible examples are provided, the scale(s) at which the component or property operates is discussed, and the respective role with regard to climate change is articulated. Cross-references to Section 3 are also identified.

Table 4.2.1. Network components and properties that facilitate the building of networks designed to sustain or enhance ecosystem resilience to climate change.

NETWORK COMPONENTS AND PROPERTIES (CBD; PSSA)	DESCRIPTION	EXAMPLES	SCALE CONSIDERATIONS	ROLE IN SCENARIO OF CLIMATE CHANGE	CROSS-REFERENCE WITH ToR a) RE. CLIMATE CHANGE PROPERTIES
NETWORK COMPONENTS					
EBSAs (ECOLOGICALLY & BIOLOGICALLY SIGNIFICANT AREAS)					
Uniqueness or rarity - of an area or ecosystem; of species (importance for species at risk, declining spp. and/or habitats); includes genetic diversity; could also include unique processes (e.g., hyper-saline seagrass beds).	These are "the only one of their kind", such as nurseries or certain feeding, breeding, or spawning areas that are rare or unique. In particular, areas containing habitat for the survival and recovery of endangered, threatened, or declining species or areas with significant assemblages of such species (which usually occur only in one area, or only in a few locations, or have been seriously depleted across their range.)	Open ocean waters • Sargasso Sea, eddies and gyres, persistent polynyas Deep sea habitats • endemic communities around submerged atolls; hydrothermal vents; seamounts; pseudo-abyssal depression Species, e.g., Hawksbill sea turtle (*Eretmochelys imbricata*)	Generally local / small in scale, but of regional or international significance. A unique ecosystem may extend beyond national borders.	Probably more likely to be affected by climate change; implications of the loss of these areas to climate change effects has more significance for resilience.	Translocated species (accidental or intended) may pose threat; Home ranges and boundaries; Reproduction, Dispersal and Migration; Endemism; Marine population genetics (Section 3)
Special importance for life-history stages	An area that is required for a population to survive and thrive.	Area containing: (i) breeding grounds, spawning areas, nursery areas, juvenile habitat or other areas important for life history stages of species; or (ii) habitats of migratory species (feeding, wintering or resting areas, breeding, molting, migratory routes)	Variable; could be inshore spawning ground (few km), could be distant area used by highly migratory species	These are areas that are likely to shift; can we anticipate new locations? If where it is shifting to has new habitat features, is its survivability jeopardized?	Life history as a focus; Home ranges and boundaries; Reproduction, Dispersal and Migration; Endemism; Phenology (timing of events) (Section 3.3)

Network Components and Properties (CBD; PSSA)	Description	Examples	Scale considerations	Role in scenario of climate change	Cross-reference with ToR a) re. climate change properties
Vulnerability, fragility, sensitivity, or slow recovery	An area that contains a relatively high proportion of sensitive habitats; biotopes or species that are functionally fragile (i.e., highly susceptible to degradation or depletion by human activity or by natural events) or with slow recovery	Biotic communities associated with coastal habitats (tropical coral reef, mangroves) or offshore (deep cold water corals, sponge grounds)	Site-specific or local, but not large scale	May have a low tolerance to changes in environmental conditions, if they exist close to the limits of their tolerance (e.g., water temperature, salinity, turbidity or depth)	
Biological productivity	An area that has a particularly high rate of natural biological production (and endemism) due to biological and physical processes which result in an increase in biomass.	Frontal areas; hydrothermal vents; upwellings; seamounts; polynyas; some gyres; coral reefs.	Site-specific or local, but not large scale	Areas one would most want to ensure withstand climate change effects. Likely fairly robust unless climate change alters the driver of productivity.	
Biological diversity / dependency	An area that has an exceptional variety of species or genetic diversity or includes highly varied ecosystems, habitats, and communities. An area where ecological processes are highly dependent on biotically structured systems. Such ecosystems often have high diversity, which is dependent on the structuring organisms.	Coral reefs, kelp forests, sponge reefs, mangrove forests, seagrass beds. Dependency embraces the migratory routes of fish, reptiles, birds, mammals, and invertebrates.	Tend to be site-specific, like most EBSAs	High biodiversity areas tend to be more resilient to the abiotic effects of climate change, so these areas would be desirable in a network of MPAs. If climate change affects the structuring organisms / habitat, then the contribution of these areas towards the network may be diminished.	The role of species diversity (species richness, beta-diversity [aka community turnover]) (Section 3.1); Dependence of some ecosystem functions on foundation species; Dependence of some ecosystem functions on foundation species (both Section 3.2); Marine population genetics; Phenology (timing of events) (both Section 3.3)

NETWORK COMPONENTS AND PROPERTIES (CBD; PSSA)	DESCRIPTION	EXAMPLES	SCALE CONSIDERATIONS	ROLE IN SCENARIO OF CLIMATE CHANGE	CROSS−REFERENCE WITH TOR A) RE. CLIMATE CHANGE PROPERTIES
Ecological integrity	An area that is a biologically functional unit; an effective, self-sustaining ecological entity.	Georges Bank; Meso-American barrier reef system; Florida keys; Veracruz reef system	Generally large sometimes ecoregional	Relatively resistant to climate change effects	Maintenance of trophic balance and food web structure (Section 3.1); Home ranges and boundaries; Reproduction, Dispersal and Migration; Endemism (Section 3.1)
Naturalness	An area that has experienced a relative lack of human-induced disturbance or degradation.	Most ecosystems and habitats have examples with varying levels of naturalness.	Variable; could be remnant pockets of naturalness, or large expanses like the Arctic	Will likely diminish / be altered by climate change effects (a form of human impact).	
AREAS OF SOCIAL, CULTURAL AND/OR ECONOMIC VALUE					
Social, economic or cultural dependency	An area meriting protection because the environmental quality or the use of living marine resources are of particular social or economic importance, or where there is particular importance for the support of traditional subsistence or food production activities or for the protection of the cultural resources of local populations.	Fishing, recreation, tourism, and the livelihoods of people who depend on access to the area; bio-prospecting; indigenous hunting of marine mammals and gathering of marine organisms (e.g., inter-tidal collecting of mollusks for food or crafts).	Local / regional	If the ecosystem changes as a result of climate change, the value of the area (environmental services; cultural value) to the community will be diminished.	

NETWORK COMPONENTS AND PROPERTIES (CBD; PSSA)	DESCRIPTION	EXAMPLES	SCALE CONSIDERATIONS	ROLE IN SCENARIO OF CLIMATE CHANGE	CROSS−REFERENCE WITH ToR A) RE. CLIMATE CHANGE PROPERTIES
Cultural heritage	An area that is of particular cultural importance to a given community	Significant historical and archaeological sites; indigenous cultural heritage (e.g., ceremonial value)	Local / regional	Maritime cultural heritage can be degraded by climate change; e.g., changes in water temperature can increase degradation of historical artefacts such as ship wrecks; change in species composition can increase populations of organisms that degrade wood and metal. Because of increases in storms and erosion / melting of permafrost, etc., culturally or historically significant coastal areas could be eroded.	
AREAS OF SPECIAL SCIENTIFIC OR EDUCATIONAL VALUE					
Research	An area that has high scientific interest	Use of MPA as a control for a scientific study	Variable	Control could reveal climate change effects	
Baseline for monitoring studies	An area that provides suitable baseline conditions with regard to biota or environmental characteristics, because it has not had substantial perturbations or has been in such a state for a long period of time, such that it is considered to be in a natural or near-natural condition	Use of MPA as a sentinel site	Variable, but generally site-specific	Provides for long-term tracking of climate change effects on ecosystems	

Network Components and Properties (CBD; PSSA)	Description	Examples	Scale considerations	Role in scenario of climate change	Cross-reference with ToR a) re. climate change properties
Education	An area that offers an exceptional opportunity to demonstrate particular natural phenomena	Outreach programs that inform the public about the role of MPAs; visitor centres to enhance awareness	Variable – site-specific / local / national / international	Important role in educating the public about climate change. Education is tied to resilience – having a public that is well-informed and engaged facilitates adaptation	
Network Properties					
Representativity / Representation	Protection of areas that are outstanding and illustrative examples of specific biodiversity, ecosystems, ecological or physiographic processes / ecological functions, or community or habitat types or other natural characteristics.	Areas that either contain rare biogeographic qualities or are representative of a biogeographic "type" or types, or that contain unique or unusual biological, chemical, physical, or geological features	Ecoregional levels I & II (CEC terminology); can apply to varying scales but not too large a scale. A full range of examples across a biogeographic habitat, or community classification; relative health of species and communities; relative intactness of habitat(s); naturalness	Larger areas that can maintain ecosystem function in the face of physical and biological change	The role of species diversity (species richness, beta-diversity [aka community turnover]) (Section 3.1); Biogeographic representation (Section 3.2); Home ranges and boundaries; Reproduction, Dispersal and Migration; Endemism (Section 3.3)

Network Components and Properties (CBD; PSSA)	Description	Examples	Scale considerations	Role in scenario of climate change	Cross-reference with ToR a) re. climate change properties
Connectivity* [*Understanding connectivity within and between ecosystems will provide information critical to finding appropriate spatial scale for the network/management activities (CAMEO Science Steering Committee, 2010)]	Linkages whereby protected sites benefit from larval and/or species exchanges, and functional linkages from other network sites. In a connected network individual sites benefit one another.	Sources and sinks (areas where larvae are produced linked to areas where they settle to as adults); life history sites; currents; gyres; physical bottlenecks such as land barriers; migration routes; species dispersal; detritus; functional linkages. Isolated sites, such as isolated seamount communities, may also be included.	Variable; could connect inshore spawning grounds (few kms), could connect distant areas used by highly migratory species.	*Promotes genetic flow among populations of marine organisms with life history phases/ habitats; **influx and export of organisms, energy and nutrients among ecosystems [*Agardy *et al.*, 2010; **CAMEO Science Steering Committee, 2010]	Ecosystem size and connectivity and physical limits (Section 3.1); Home ranges and boundaries; Reproduction, Dispersal and Migration; Endemism; Marine population genetics (Section 3.3)
Replication / Redundancy Accounting for uncertainty, natural variation and the possibility of catastrophic events.	Replication of ecological features means that more than one site shall contain examples of a given feature in the given biogeographic area. The term "features" means "species, habitats and ecological processes" that naturally occur in the given biogeographic area	Features that exhibit less natural variation or are precisely defined may require less replication than features that are inherently highly variable or are only very generally defined	Replicates cannot be so close together that they might be wiped out by same catastrophic event, yet cannot be so distant that they are not similar enough to qualify as replicates	Insurance policy in the face of smaller- scale catastrophic events that might adversely affect one type of MPA; refugia for species whose habitats are being degraded. Provides a "control" for within-habitat comparisons in network monitoring protocols	"Insurance factors" required to buffer systems from catastrophic loss (Section 3.2); Home ranges and boundaries; Reproduction, Dispersal and Migration; Endemism (Section 3.3)
Adequacy/Viability	Adequate and viable sites indicate that all sites within a network should have size and protection sufficient to ensure the ecological viability and integrity of the feature(s) for which they were selected	Adequacy and viability will depend on size; shape; buffers; persistence of features; threats; surrounding environment (context); physical constraints; scale of features/processes; spillover/ compactness	Could apply at all network scales (e.g., coral reef, mangroves vs. larger networks)	Final check on network design with anticipated climate change effects in mind – are there enough sites of the right size, the right level of protection, the right locations, etc.?	Home ranges and boundaries; Reproduction, Dispersal and Migration; Endemism (Section 3.3)

4.3 References

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5 Review of atmospheric, oceanographic and biological information

ToR c) Review the atmospheric, oceanographic and biological information for the east coast of North America that could be used to address the knowledge needs identified in ToR a).

For oceanographic data the review would include but not be limited to:

i) *A high level overview of physical properties which are projected to change over the next decades to centuries including the direction, magnitude and the spatial location and extent of that change as well as a description of the level uncertainty associated with each property;*

ii) *Information / data to serve as suitable covariates for quantifying how species' distributions and abundances respond to changes in oceanography / climate and are available on the spatial scales needed for linking to biological distributions and abundances;*

For species and ecosystem properties above the species level the review would include but not be limited to:

iii) A summary of information/data that allows identification of historical patterns of change in abundance and distribution (including seasonal distribution, which is crucial);

iv) A summary of information/data that allows partitioning alternative causes of any changes in distribution and abundance;

5.1 Introduction to atmospheric and oceanographic overview

The overall goal of the study group is to develop guidelines for the design of networks of Marine Protected Areas (MPAs) in a changing climate along the Atlantic coast of North America, including estuaries, shelves and deeper waters. This area, extending from the Caribbean Sea to the northern Labrador Shelf, includes "Marine Ecoregions" between the Caribbean Sea and the Baffin/Labradoran Arctic in the recent atlas prepared for the Commission for Environmental Cooperation (CEC) by Wilkinson *et al.* (2009; Figure 5.1.1).

The following summary of ocean climate change will draw heavily on the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007), and subsequent or contemporary regional and other assessments (e.g., CCSP, 2008a,b; CCSP, 2009; Cochrane *et al.*, 2009; EAP, 2009; FOCC, 2009; Frumhoff *et al.*, 2007; ICES, 2008; New *et al.*, 2011; Nicholls *et al.*, 2011; Ning *et al.*, 2003; PCGCC, 2009; Richardson *et al.*, 2009; Vasseur and Cato, 2007).

Section 5.1.1 will discuss aspects of ocean climate change that need to be considered in making and using projections, and in particular the difficulties and uncertainties associated with the limited predictability of the Earth's climate system. Section 5.1.2 will describe the major oceanographic features of the Western North Atlantic (WNA), and the dominant modes of natural temporal and spatial variability affecting its ocean climate. Building on this description of the present state of the ocean, probable changes in key oceanographic properties will be described, with indications of regional differences and uncertainties.
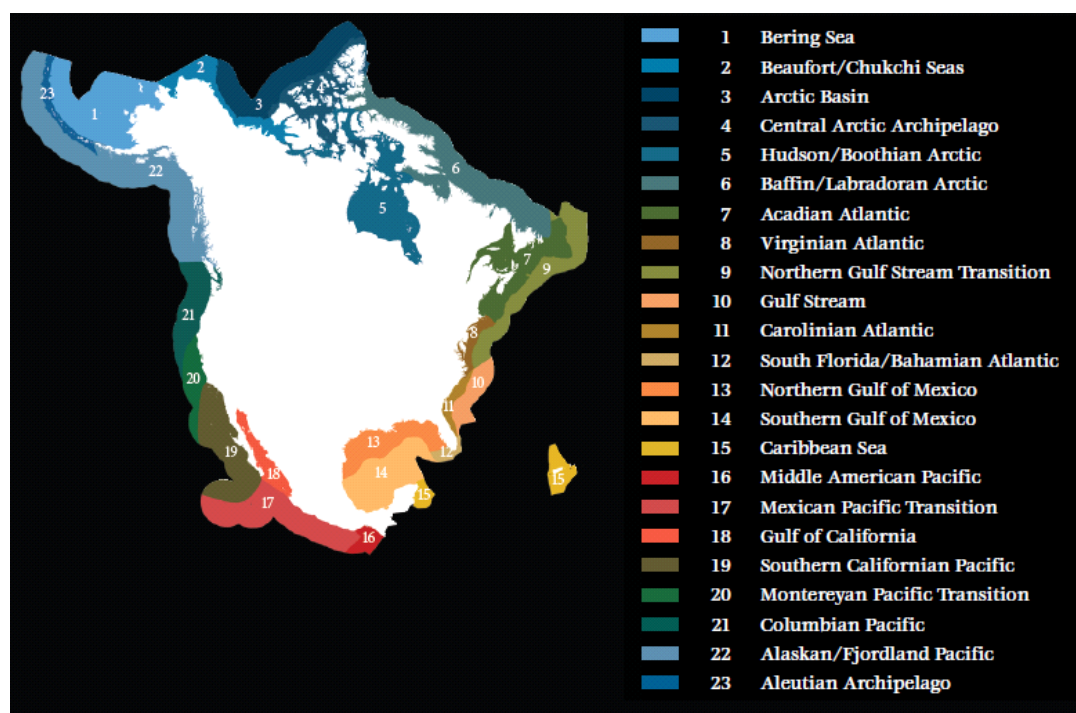
	1	Bering Sea
	2	Beaufort/Chukchi Seas
	3	Arctic Basin
	4	Central Arctic Archipelago
	5	Hudson/Boothian Arctic
	6	Baffin/Labradoran Arctic
	7	Acadian Atlantic
	8	Virginian Atlantic
	9	Northern Gulf Stream Transition
	10	Gulf Stream
	11	Carolinian Atlantic
	12	South Florida/Bahamian Atlantic
	13	Northern Gulf of Mexico
	14	Southern Gulf of Mexico
	15	Caribbean Sea
	16	Middle American Pacific
	17	Mexican Pacific Transition
	18	Gulf of California
	19	Southern Californian Pacific
	20	Montereyan Pacific Transition
	21	Columbian Pacific
	22	Alaskan/Fjordland Pacific
	23	Aleutian Archipelago

Figure 5.1.1. Marine ecoregions around North America excluding the Hawaiin Archipelago (from Wilkinson *et al.*, 2009).

There are considerable limitations in our ability to project the magnitude of future climate changes with confidence, especially at the regional scales of most relevance to coastal and marine ecosystems. Most of the presently available climate change projections are derived either directly or indirectly from model simulations carried out more than five years ago for IPCC (2007). There is emerging concern (e.g., Betts *et al.*, 2011) that anthropogenic change in global mean temperature may reach 4°C in this century. A new set of AOGCM simulations with improved physics and resolution is presently being carried out in preparation for the IPCC's Fifth Assessment Report planned for release in 2013, with publications expected to appear in peer-reviewed journals over the next 1–2 years. Consequently, the present report will focus on important features and expected tendencies for climate change, rather than on quantitative estimates, since significant improvements in the latter can be expected within the timeframe of the actual design of MPA networks in the WNA.

5.1.1 Changing climate and relevant factors

There is overwhelming evidence that the climate of the atmosphere and ocean is changing because of the increasing concentrations of greenhouse gases in the atmosphere. There are clear global trends in some properties such as ocean temperature, acidity and sea level that reflect changes in most regions, while the changes in other properties such as continental run-off and ocean salinity have different signs in different regions (Bindoff *et al.*, 2007). These changes need to be considered in various marine and coastal management decisions and planning, depending of course on their magnitude relative to those of other pressures on the ecosystems of interest.

Terms like "changing climate" and "climate change" are used with a variety of meanings such that, before proceeding, it is important to clarify their meaning in this report. "Climate" is usually considered to be the state or statistics of shorter-term (e.g., weather) variability over an extended period. It includes means, seasonal cycles and

other descriptors (e.g., extremes) of variability on various time scales within the period of interest.

"Changing climate" and "climate change" will be used synonymously here, with climate change following the convention in IPCC (2007) where it is taken to refer to any change or variation of climate over time. The period of immediate interest here is the 20th and 21st centuries. Changing climate will be taken to include both natural and anthropogenic components of recent and future variability in the Earth's coupled atmosphere-ice-ocean-biogeochemical climate system.

There is strong natural variability in the Earth's climate. Pronounced seasonality in the atmosphere and upper ocean, particularly at mid and high latitudes, is a well-known large-scale variation to which various living organisms have adapted. There are other, less-regular, variations on space scales comparable to those of the continents and ocean basins. For the ocean climate along the Atlantic coast of North America, important regional changes occur on decadal and other time scales associated with modes of natural variability such as the North Atlantic Oscillation (NAO; e.g., Hurrell and Deser, 2010), the Atlantic Multi-decadal Oscillation (AMO; e.g., Enfield *et al.*, 2001) and the El Niño-Southern Oscillation (ENSO; e.g., Trenberth and Caron, 2000), with indications of associated marine ecosystem changes in many cases. Anthropogenic contributions to climate change, such as those associated with increasing greenhouse gases in the atmosphere, need to be considered in this context for some variables, at least for the next few decades. The recent changing climate needs to be considered as potentially arising from a combination of natural and anthropogenic factors which may be interacting. Similarly, both natural and anthropogenic influences need to be considered in discussions of many potential climate changes in the future, particularly during the next two decades.

The projection of future climate change on the hierarchy of space scales of relevance to coastal and marine ecosystem issues is difficult because of the coupled climate system's complexity and wide range of interacting space and time scales. Climate change with resolution of decadal-scale and regional natural variability is not presently predictable in any deterministic sense. The projections available from IPCC (2007) are probabilistic and highly smoothed through the compositing of ensembles of simulations from multiple Atmosphere Ocean General Circulation Models (AOGCMs). While clear and apparently-robust spatial and temporal patterns are apparent for many variables, they are generally on large space scales with relatively-monotonic temporal changes because of the compositing and spatial smoothing, as well as the poor resolution of natural variability.

Dynamical (with higher resolution models) and statistical (using empirical relationships) spatial "downscaling" techniques are commonly used to provide regional climate change projections (e.g., Hayhoe *et al.*, 2008). However, these approaches are generally most useful to the longer-term (mid to late century) anthropogenic changes which will generally be of greater magnitude than those expected during the next two decades, and thereby of greater importance relative to the natural variability.

Considering the expected increasing magnitude of anthropogenic climate changes and the limited predictability of shorter-term natural climate variability, it is useful to consider two time horizons for the projection of changing climate for consideration in MPA network design:

- The "**Near-Term**" (say, the next two decades), for which observed recent variability may be the most useful guide to future change, whether this observed variability is a long-term trend or a variation on time scales of years

to decades that may be primarily associated with a natural mode of variability. For some ocean properties such as large-scale heat content, acidity and sea level whose recent trends are "cumulative" (largely reflecting anthropogenic warming, CO_2 emissions and melting ice over the past half century), a regionally-adjusted continued trend may be a reasonable indicator of probable change on this time horizon. However, for others such as regional stratification whose recent changes may have been predominantly influenced by natural variability, the recent variability may be a much less reliable basis for near-term projection and may even be misleading. Since the smoothed projected anthropogenic changes on this time horizon are small in magnitude for some variables, some aspects of the changing climate may be dominated by (a possibly-modified form of) the natural variability.

- The "**Longer-Term**" (mid- to late-century, or longer), for which the smoothed anthropogenic changes from available projections are substantially larger in magnitude, and can be expected to dominate decadal-scale natural variability or shift the range of variability in some ocean properties to significantly different extremes. The available projections are generally most useful to this time horizon (although they do not include regional modes of natural variability which are expected to continue to be important). It should be noted, however, that there is now concern that the IPCC (2007) projections for some variables such as coastal sea level (see later) may be significant underestimates.

A particular challenge to the prediction of anthropogenic climate variability in the WNA is the inadequate resolution in AOGCMs of key dynamics in areas such as the Gulf Stream separation and the linkages with the adjoining Arctic and tropical Atlantic Oceans. The AOGCMs used in IPCC (2007) do not reproduce important ocean features in such regions and thus do not resolve some important influences of the ocean on regional atmospheric climate (e.g., de Jong *et al.*, 2009). Thus, the downscaling of existing climate change scenarios may not be adequate for the spatial scales of many ecosystem issues in the WNA.

5.1.2   Oceanographic regions of the Western North Atlantic (WNA)

5.1.2.1 Large-scale setting

The setting of North America's Atlantic coast in relation to the continent and the global ocean is illustrated by the map of bottom topography and major current features of the WNA in Figure 5.1.2.1.1, and by the climatological distributions of upper-ocean temperature and salinity in the WNA in Figure 5.1.2.1.2. The Atlantic coastal region is quite complex (Figure 5.1.2.1.1), with large protrusions and indentations of the coastline, a continental shelf of variable width, and a very complex geometry in the Gulf of Mexico and Caribbean Sea. Pronounced influences of the inflows of relatively cold fresh water from the Arctic Ocean and of relatively warm water from the Western Tropical Atlantic (WTA) are apparent in the temperature and salinity patterns, as well as of the North Atlantic's large-scale horizontal gyres and their western boundary currents – the Labrador Current and Gulf Stream (e.g., Loder *et al.*, 1998a). These predominant circulation features provide a high degree of advective connectivity in the WNA, particularly within the subpolar and subtropical gyres. An additional important factor to the region's coastal ocean climate is its location in the lee of

the North American continent with resulting influences through prevailing westerly winds and continental run-off.
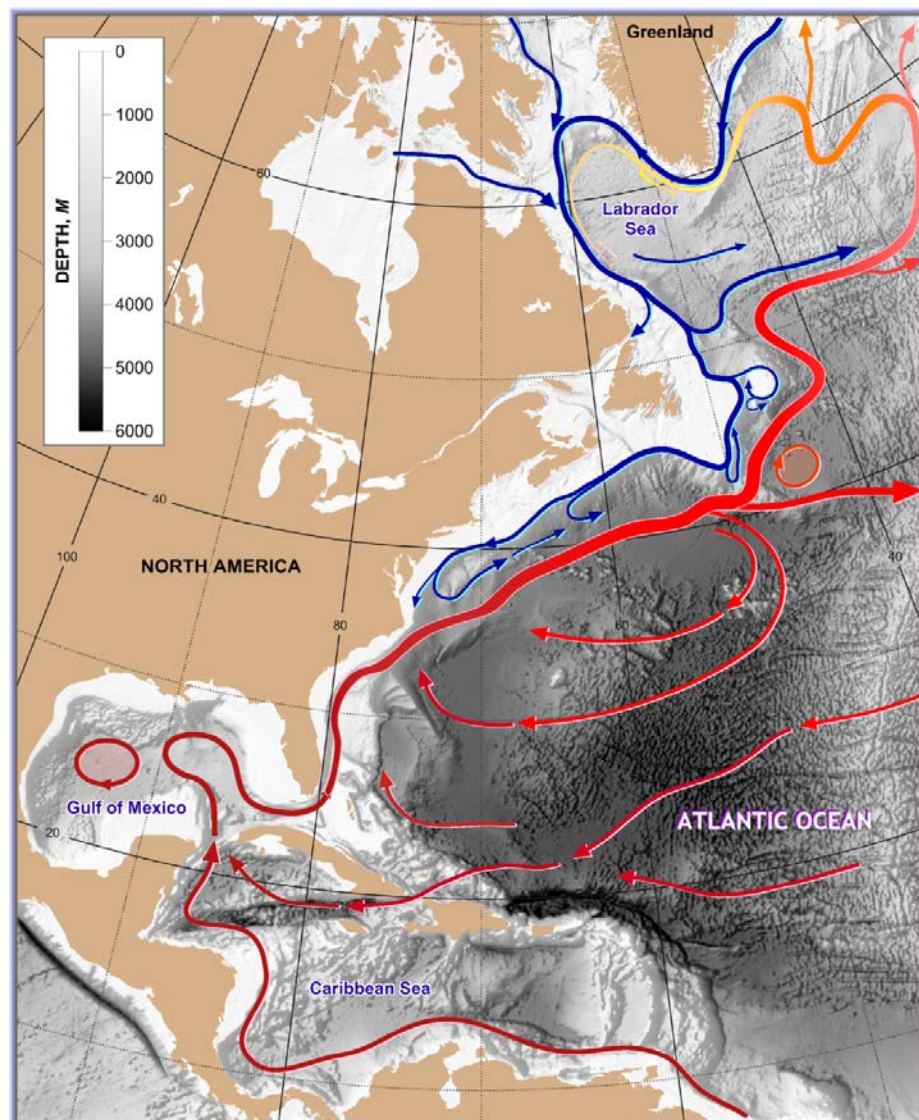

Figure 5.1.2.1.1. Map showing the complex bottom topography of the WNA, together with a schematic representation of the major circulation features. Warm flows are denoted by red, cold flows by blue, and intermediate temperatures by orange-yellow. Courtesy of Igor Yashayaev (Bedford Institute of Oceanography, Fisheries & Oceans Canada).
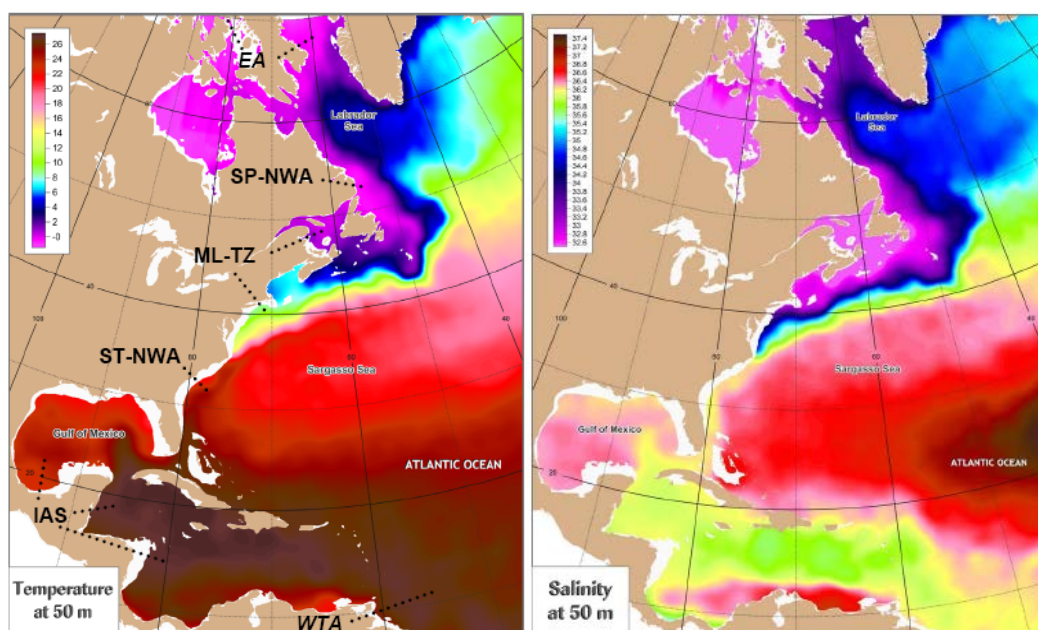
Figure 5.1.2.1.2. Long-term annual-mean temperature and salinity at 50m in the WNA, from the Yashayaev (1999) climatology (http://www2.mar.dfo-mpo.gc.ca/science/ocean/canwa/canwa.htm). Major oceanographic regions WITHIN and *AFFECTING* the WNA are labeled on the temperature panel (see Table 5.1.2.2.1 and text for explanations). Major Oceanographic Regions are labelled: EA=Eastern Arctic; SP-NWA=SubPolar NW Atlantic; ML-TZ=MidLatitude Transition Zone; ST-WNA=SubTropical Western North Atlantic. IAS=Intra-Americas Sea; WTA=Western Tropical Atlantic. Courtesy of Igor Yashayaev (Bedford Institute of Oceanography, Fisheries & Oceans Canada).

5.1.2.2 Major oceanographic regions within and affecting the WNA

Four major latitudinal oceanographic regions <u>within</u> the WNA can be identified from the large-scale structure of the coastline, and the water property distributions and associated circulation (Figures 5.1.2.1.1 and 5.1.2.1.2).

- The **SubPolar NorthWest Atlantic (SP-NWA),** roughly extending from Davis Strait at about 65°N, 60°W to the Tail of the Grand Bank at about 42°N, 50°W. This region is strongly influenced by the North Atlantic's sub-polar gyre (e.g., Loder *et al*., 1998b), and in particular by the Labrador Current (e.g., Colbourne *et al*., 2010) which carries subArctic and subpolar water southward to mid latitudes in the upper ocean (2000m).

- The **SubTropical Western North Atlantic (ST-WNA)**, roughly extending along the continental margin from the Greater Antilles at about 20°N to Cape Hatteras at about 35°N. This region is strongly influenced by the North Atlantic's subtropical gyre (e.g., Boicourt *et al*., 1998), and in particular by the Gulf Stream which carries subtropical water northward in the upper ocean before turning northeastward away from the shelf edge at Cape Hatteras. (In some ways the Gulf of Mexico and Caribbean Sea could be included in the ST-WNA, but they will be identified as a separate major region here because of their pronounced coastline and bathymetric variability, and their closer proximity to the eastern Pacific Ocean).

- A **MidLatitude "Transition Zone" (ML-TZ)**, extending northward along the eastern North American coastline from Cape Hatteras at about 35°N, 76°W to include the largely-enclosed Gulf of St Lawrence (extending to

52°N, 60°W), and then eastward to the Tail of the Grand Bank at 42°N, 50°W. In this region, there are competing influences of the oppositely-flowing subpolar and subtropical waters, and a broad "Slope Water" region (with a mixture of waters of subpolar and subtropical origin) north of the Gulf Stream (e.g., Loder *et al.*, 1998b). Waters of subpolar origin have generally dominated this zone's shelf in recent history (Wanamaker *et al.*, 2007), but there are increasing influences of subtropical waters as one proceeds towards Cape Hatteras. (Also, as described below, there are reasons to expect the subtropical influence to increase with anthropogenic climate change).

- The **Gulf of Mexico and Caribbean Sea (GM-CS)**, also referred to as the **Intra-Americas Sea (IAS)** in an oceanographic systems approach to climate change (e.g., Mooers and Maul, 1998). The Gulf is a large nearly-enclosed sea with depths that reach 3700m, both wide and narrow shelves, and more than 30 rivers discharging into its basin. Its circulation is characterized by the intrusion of the Loop Current (LC) in the east, and the formation, separation and subsequent propagation of LC eddies into the western Gulf. The Caribbean Sea is partially-enclosed with a deep basin in the west and a broad complex of topography and islands in the east. The Gulf communicates with the Caribbean Sea through the Yucatan Channel (sill depth of ~2000m) and with the ST-WNA region via the Straits of Florida (sill depth of ~800m).

In addition to these major oceanographic regions within the WNA, two other major latitudinal oceanographic regions <u>affecting</u> the WNA can be identified. These regions link the WNA with the global ocean, and their oceanographic variability has strong advective influences on the adjoining WNA regions in particular.

- The **Eastern Arctic (EA)**, comprising the Canadian Archipelago (a large set of islands and narrow channels) and Baffin Bay, through which Arctic waters flow directly into the SP-NWA (e.g., Dickson *et al.*, 2007). Additional Arctic waters flow into the North Atlantic east of Greenland and affect the SP-NWA via circulation around southern Greenland in the subpolar gyre.

- The **Western Tropical Atlantic (WTA)** through the currents associated with the subtropical gyre, the North Brazil Current and associated eddies (e.g., Johns *et al.*, 2003). There is also an important influence of the Eastern Tropical Atlantic which is the genesis region of tropical cyclones and hurricanes in the North Atlantic, some of which move westward into the IAS and others of which turn northward into the ST-WNA and sometimes reach the ML-TZ and SP-NWA.

The six oceanographic regions identified above provide a natural stepping stone for a discussion of climate change tendencies on scales that are at the margins of the spatial resolution of major oceanographic features by most existing AOGCMs. Their linkage to both larger- and smaller-scale oceanographic features provides potential for improved projections from the combination of AOGCM results, dynamical understanding, recent higher-resolution model studies, and analysis of observational data.

Table 5.1.2.2.1. Major large-scale oceanographic regions in or affecting the WNA, their predominant features, their primary modes of climate/weather variability (see Section 5.1.3) and their coastal/shelf oceanographic subregions and additional key distinguishing features. The "Marine Ecoregions" identified for the CEC (Wilkinson *et al.*, 2009) are also indicated (for cross-referencing).

MAJOR OCEANOGRAPHIC REGIONS	PREDOMINANT OCEANOGRAPHIC FEATURES	MODES OF CLIMATE VARIABILITY	MARINE ECOREGIONS	COASTAL/SHELF OCEANOGRAPHIC SUBREGIONS	ADDITIONAL KEY SUBREGIONAL FEATURES
Eastern Arctic (EA)	Sea ice; Arctic outflows to SP-NWA	NAO AO	Central Arctic Archipelago	Canadian Archipelago	Straits; Throughflows
			Baffin / Labradoran Arctic	Baffin Bay	Cyclonic gyre; Melting glaciers
Sub-Polar NW Atlantic (SP-NWA)	Labrador Current (southward flow); Seasonal sea ice; Wintertime deep convection ; Seasonally-varying stratification	NAO direct AO remote AMOC AMO		Labrador Shelf, Slope & Sea	Run-off; Hudson Strait outflow
				NE Newfoundland Shelf & Slope	2-3 layer stratification
			Acadian Atlantic (shelf); Northern Gulf Stream (NGS) Transition (slope)	Grand Bank & Flemish Cap	Clockwise gyres; 2-3 layer stratification
Western North Atlantic (WNA) Mid-Latitude Transition Zone (MTZ)	Labrador Current Extension (equatorward shelf flow); Slope Water; Gulf Stream (offshore); Strong seasonality (continental lee); Estuaries	NAO via advection AMO AMOC		Gulf St Lawrence (GSL)	Run-off; Seasonal sea ice
				Scotian Shelf	GSL outflow; Banks & basins
				Gulf of Maine & Bay of Fundy	Tidal influences; Run-off; Banks & basins
			Virginian Atlantic (shelf); NGS Transition	Mid Atlantic Bight	Run-off; Barrier beaches; Coastal fronts & flows
Sub-Tropical Western North Atlantic (ST-WNA)	Gulf Stream (GS; northward flow); Barrier beaches & coastal wetlands; Hurricanes & cyclones	NAO AMO AMOC TAV AWP	Carolinian Atlantic (shelf); Gulf Stream (slope)	South Atlantic Bight	Shelf-edge GS; Reversing shelf flow; Run-off
			South Florida/ Bahamian Atlantic	South Florida Shelf & Slope	Predominant GS; Gyres in Keys

Table 5.1.2.2.1. continued.

MAJOR OCEANOGRAPHIC REGIONS	PREDOMINANT OCEANOGRAPHIC FEATURES	MODES OF CLIMATE VARIABILITY	MARINE ECOREGIONS	COASTAL/SHELF OCEANOGRAPHIC SUBREGIONS	ADDITIONAL KEY SUBREGIONAL FEATURES
Gulf of Mexico & Caribbean Sea (GM-CS), Or Intra-Americas Seas (IAS)	Loop Current; Eddies; Seasonal wind-driven currents & up/downwellings; Barrier beaches & coastal wetlands; Hurricane & cyclones	TAV AWP ENSO AMO AMOC	Northern Gulf of Mexico	West Florida Shelf	Season-varying stratification; Wind-driven shelf currents; Offshore gyre & eddies; Run-off
				Texas-Louisiana Shelf	
			Southern Gulf of Mexico	Tamaulipas-Veracruz Shelf	
				Campeche Bank	
			Caribbean Sea	Western Caribbean Sea	Yucatan Current
				Eastern Caribbean Sea	Islands & Channels
Western Tropical Atlantic (WTA)	Northward flow of tropical water	TAV AWP ENSO AMO AMOC			North Brazil Current

Within the six oceanographic regions, there are a number of coastal and/or shelf sub-regions with differing oceanographic conditions that are known to influence ecosystem structure and species distributions and for which different conditions may be projectable. These sub-regions are listed in Table 5.1.2.2.1, together with some of their distinguishing features. Consideration of climate change on this sub-regional scale (where possible) may be necessary for identifying ecosystem impacts and developing management strategies (such as the MPA network design of interest here). As examples, the Gulf of St. Lawrence and the Gulf of Maine-Bay of Fundy are distinctive subregions within the ML-TZ associated with their seasonal sea ice cover and strong tides, respectively, as well as being partially-enclosed (in contrast to the other open-shelf sub-regions of the ML-TZ). Similarly, there are many distinctive features of the indicated subregions within the complex IAS, such as the contrasting bathymetric structures of the Gulf of Mexico and Caribbean Sea, and the specific settings of the West Florida Shelf, Texas-Louisiana Shelf and Campeche Bank.

The oceanographic regions and subregions identified here have substantial similarity to the "Marine Ecoregions" Figure 5.1.1) identified by Wilkinson *et al*. (2009), although the names are different in many cases (Table 5.1.2.2.1). These ecoregions were identified from both ecological and oceanographic considerations, and may be more appropriate for ecosystem planning in some cases. On the other hand, the oceanographic regions and subregions should be particularly helpful in downscaling climate change projections.

Within the subregions in Table 5.1.2.2.1, there is also a multitude of smaller-scale areas with distinctive oceanographic features that affect particular aspects of coastal and marine ecosystems (e.g., assemblages, populations, phases of life history cycles). These "local" features include particular estuaries, wetlands, coastal freshwater plumes, fronts, up/downwelling zones, and gyres and water masses related to banks, basins and channels. This hierarchy of oceanographic space scales provides a multi-scale "downscaling" challenge in projecting some aspects of climate change. However, the important role of large-scale atmospheric and oceanographic features de-

scribed in this report can provide guidance in addressing this issue, in addition to the predominant large-scale climate change tendencies for many variables (e.g., temperature, sea level and acidity).

5.1.2.3 Cross-margin structure

Another very important spatial structure is the large gradient in many oceanographic properties proceeding away from the coast towards the deep ocean, due to both the increasing water depth and the increasing distance from continental influences (e.g., run-off). As a first approximation, the oceanographic regions (and many of the sub-regions) described above can be subdivided into three cross-(continental)-margin domains:

- The "**coastal zone**", including the inner shelf, small-to-mid-sized estuaries and wetlands where there are strong influences of shallow water, coastline interactions, changing sea level (e.g., tides) and local run-off;

- **"Shelf seas"**, including large estuaries such as the Gulf of St Lawrence and the upper continental slope in places where it is not dominated by the western boundary current (Cape Hatteras to the Tail of the Grand Bank); and

- The offshore **"deep ocean"**, including the deep basins of the IAS and also the continental slope in places where it is dominated by the western boundary current (e.g., Florida Straits to Cape Hatteras, and Labrador Sea).

5.1.3 Natural/observed modes of variability

A number of regionally-amplified natural modes of coupled atmosphere-ice-ocean variability on scales ranging from months to multiple decades have now been shown to influence ocean climate variability in the WNA. In most cases these extend across the space scales of ocean basins and continents. These modes are briefly described here as important considerations in the projection of near-term climate change in particular.

5.1.3.1 North Atlantic Oscillation (NAO)

The NAO is the predominant natural mode of atmospheric weather/climate variability over northeastern North America and the northern North Atlantic on time scales ranging from months to multiple decades (e.g., Hurrell and Deser, 2010). It is primarily manifested in changes in sea level pressure and large-scale wind fields but also includes changes in air temperature, and precipitation, and results in changes in ocean and ice conditions. The NAO is generally considered to be part of larger-scale patterns of climate variability at mid to high latitudes in the Northern Hemisphere such as the Arctic Oscillation (AO) and the Northern Annular Mode (NAM). Its influences are largest in winter when a positive NAO (usually taken as an increased atmospheric pressure gradient between the Azores and Iceland) results in a more intense Icelandic low, stronger and northward-shifted mid-latitude westerly winds over the North Atlantic, and stronger and colder northwesterly winds from the Canadian subArctic extending over the Labrador Sea.

Multiple mechanisms for the NAO's ocean climate influences have been identified, including direct influences in the SP-NWA region via wind-forced ocean circulation and wintertime water mass modification in the Labrador Sea (with multiple years of positive NAO resulting in increased deep convection) (e.g., Yashayaev and Loder, 2009), and via increased wind-forced circulation (positive NAO) resulting in cooler

water and more sea ice in the Newfoundland-Labrador Shelf/Slope region (e.g., Han *et al.*, 2010). Of particular note, shelf-slope temperature and salinity in the ML-TZ are also influenced by the NAO but with temperature changes in an opposite sense to those in the SP-NWA (i.e., positive NAO resulting in warmer water in the transition zone). This occurs through a more indirect influence of NAO variability with positive NAO contributing to a tighter subpolar gyre with reduced transport of the cold Labrador Current around the Tail of the Grand Bank and hence a greater influence of subtropical waters in the transition zone (Han, 2007; Petrie, 2007). Recent work (Figure 5.1.3.1.1) points to a significant correlation between the NAO and the north-south position of the Gulf Stream between Cape Hatteras and the Grand Bank (offshore in the ML-TZ), with a more positive NAO resulting in a northward displacement of the Stream and subtropical water.

While the NAO is a dipole pattern of the north-south sea level pressure difference between Iceland and the Azores, it is also correlated with a tripole pattern of sea surface temperature (SST) anomalies over the North Atlantic in boreal winter/spring. The tripole pattern arises primarily from the oceanic response to wintertime atmospheric variability associated with the NAO.
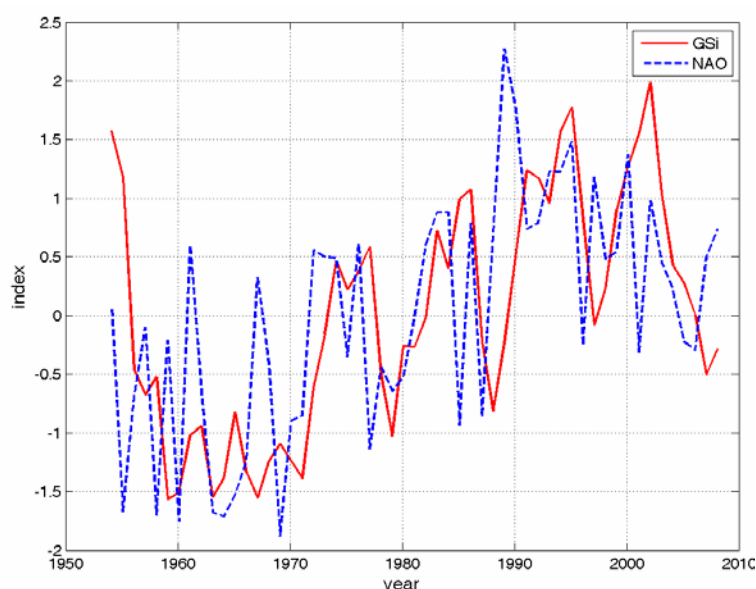
Figure 5.1.3.1.1. Wintertime NAO index taken from the monthly teleconnection analysis of the NOAA Climate Prediction Center, and the Gulf Stream (GS) index from Joyce and Zhang (2010). Over the modern period the two are significantly correlated, although the correlation is diminished (but still significant) if the data are first linearly de-trended. The GS lags the NAO by about 1 year. This result is an update from that first noted in Joyce *et al.* (2000).

5.1.3.2 El Nino – Southern Oscillation (ENSO)

Another well-known natural mode of coupled atmosphere-ocean variability that affects ocean climate in the WNA, especially in the IAS and ST-WNA, is ENSO (e.g., Chen and Taylor, 2002; Trenberth and Caron, 2000). It originates in the equatorial Pacific Ocean but affects atmospheric circulation over much of North America, and over the Southern and Western United States, Mexico, the Gulf of Mexico and Caribbean Sea in particular. El Niño conditions result in a more persistent Pacific jet stream extending across the Gulf of Mexico, while La Niña results in the jet stream shifting northward off western North America and drier and warmer air moving over the ST-WNA. Coupling between the eastern Pacific and WNA via the atmosphere has a par-

ticular influence on hurricane and tropical storm tracks in the WNA which can have influences extending poleward to the SP-WNA.

During El Niño, the Inter-Tropical Convergence Zone (ITCZ) in the Pacific migrates south leading to negative rainfall anomalies over substantial parts of the Caribbean, Central America, and Southern and Central Mexico during summer. Hurricane activity is reduced over the Atlantic during El Niño. Although not completely symmetric, the reverse happens during La Niña events.

The most significant influences of El Niño in the tropical Atlantic sector as summarized by Chang *et al.* (2006) are: 1) a zonal see-saw in sea level pressure between the eastern equatorial Pacific and Atlantic Oceans during the onset and peak phase of ENSO, with a high sea level pressure anomaly in the northern tropical Atlantic; 2) a weakening in the meridional sea level pressure gradient between the North Atlantic subtropical high and the ITCZ accompanied by weaker-than-average northeasterly trades; 3) a warming of SST during boreal spring following the mature phase of ENSO; and 4) a northward shift of the ITCZ and decrease of rainy season precipitation in northeastern Brazil. ENSO impacts over the IAS are stronger in winter since, in summer, the anomalies related to the Atlantic Warm Pool (see later) tend to have the opposite sign to those of ENSO.

5.1.3.3 Tropical Atlantic Variability (TAV)

The two fundamental modes of the TAV (Chang *et al.*, 2006) are illustrated in Figure 5.1.3.3.1:

- A "meridional" mode, active in boreal spring when the ITCZ in the Atlantic is in its southernmost position. In this mode, a stronger-than-normal northward SST gradient drives northward cross-equatorial winds. Trade winds are weaker-than-normal in the north and stronger-than-normal in the south. Rainfall deviation from the seasonal cycle is characterized by a dipolar pattern across the thermal equator. This mode is more strongly connected to the ITCZ behaviour than the zonal mode. The ITCZ tends to spend more time in the hemisphere with the positive SST anomaly. Anomalous SSTs, trade winds, and heat flux patterns suggest a (not fully understood) connection with other Atlantic modes such as the NAO.

- A "zonal" mode active in summer when the ITCZ is at its northernmost position. A cold tongue of SST develops in the equatorial eastern Atlantic. Maxima of SST anomalies in the eastern basin are related to a convergent pattern of equatorial trade winds. This mode is sometimes referred to as the Atlantic "ENSO" although it is quite different from the Pacific ENSO (see Xie and Carton (2004) and Chang *et al.* (2006) for details).
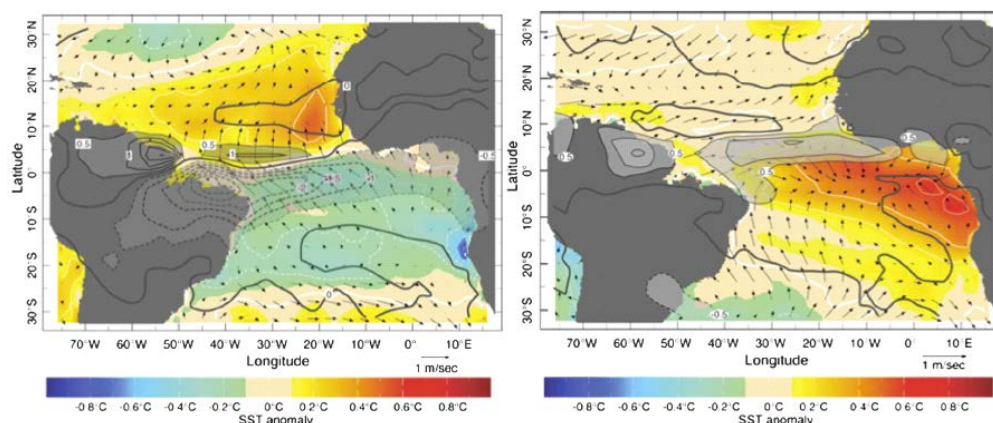
Figure 5.1.3.3.1. The dominant pattern of surface ocean-atmosphere variability in the tropical Atlantic region during (left) boreal spring and (right) boreal summer. The black contours depict the first empirical orthogonal function (EOF) of the regional March-April and June-August rainfall anomaly (from Global Precipitation Climatology Project data 1979-2001) (mm day^{-1}). The coloured field is the March-April and June-August SST anomaly regressed on the principal component time series of the rainfall EOF. Arrows depict the seasonal mean surface wind regressed on the same time series. From Chang *et al.* (2006).

5.1.3.4 Atlantic Warm Pool (AWP)

The AWP is a region in the WTA and IAS (5.1.2.1.2) with SSTs higher than 28.5°C (Wang and Enfield, 2001). It is part of the Western Hemisphere Warm Pool (WHWP) which also includes a component in the equatorial Eastern Pacific. The AWP has its largest extent in summer and disappears in winter (Figure 5.1.3.4.1). It is closely related to hurricane activity, with a large (small) warm pool associated with strong (weak) hurricane activity in the Atlantic. Being a heat source for the atmosphere in summer, important teleconnections develop providing a climatic link between the Americas, and between the Atlantic and Pacific. The size and intensity of the AWP in summer are the result of atmospheric forcing during the previous winter and spring, providing potential predictability for summer conditions. Inter-annual and inter-decadal variability of its extension can be as large as the seasonal change.
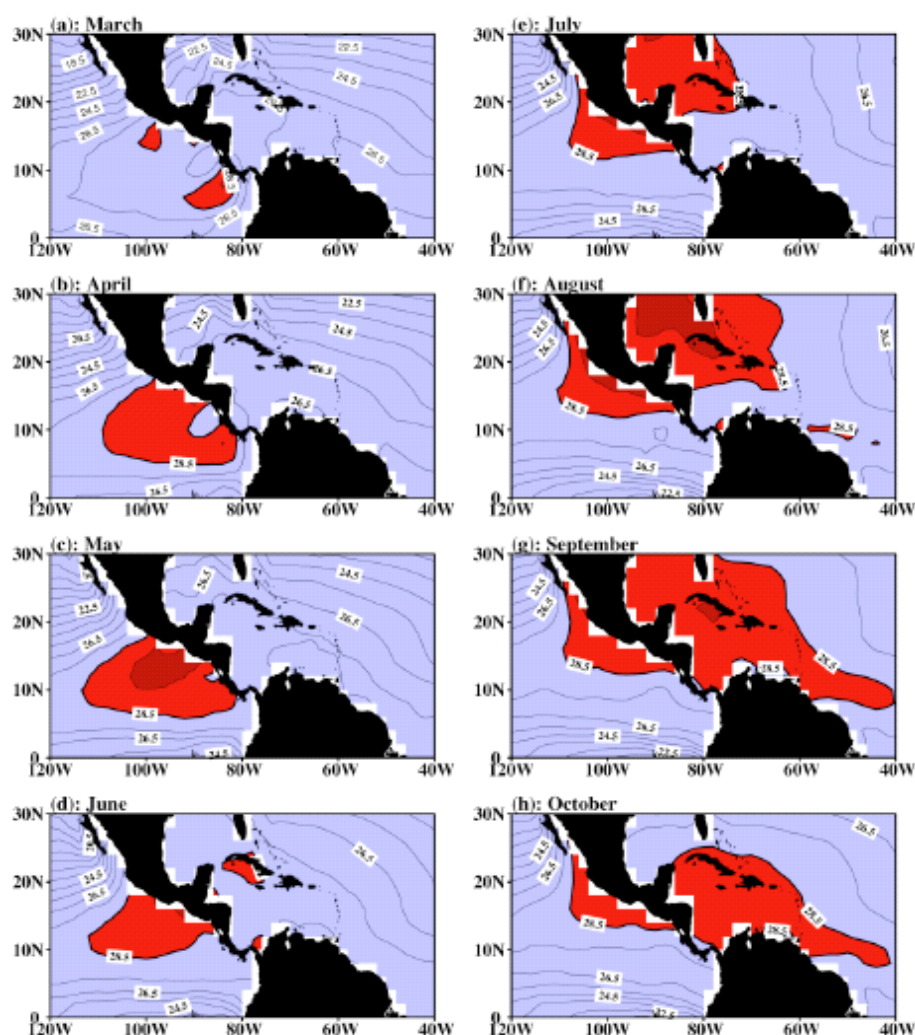
Figure 5.1.3.4.1. Seasonal variation of SST for the tropical WHWP. The shading and dark contour represent water warmer than 28.5°C (from Wang and Enfield, 2001; IASCLIP, 2008).

5.1.3.5 Atlantic Multi–decadal Oscillation (AMO)

A large-scale mode of ocean climate variability of importance to the WNA is the AMO through which sea surface temperature in the North and South Atlantic vary out-of-phase over a 65–75 year period (e.g., Enfield *et al.*, 2001). The AMO had a warm phase in the North Atlantic from about 1930 to the early 1960s, then had a cool phase until the mid 1990s (Figure 5.1.3.5.1), and now is in a warm phase which might be projected to last until the 2020s. The statistics, origin and dynamics of the AMO are less well-known (than those of the NAO and ENSO), partly because it typically has only 1–2 periods in many instrumental records. Variability in the Atlantic Meridional Overturning Circulation (AMOC) is generally implicated as a factor in the origin of the AMO, but the dynamics and extent of their inter-relation are presently not well understood. The AMO has also been suggested to influence atmospheric variability over both southern and northern North America, western Africa and across the North Atlantic, such that some atmospheric coupling is present. Ocean warming and some biological changes in the southern part of ML-TZ between the 1960s and 1990s have been attributed to the AMO (EAP, 2009), and there is an indication of a possible influence on shelf temperatures in the southern part of the SP-NWA. However, separation of anthropogenic warming and AMO variability in ocean temperature records

over the past few decades is problematic (e.g., Polyakov *et al.*, 2010), reflecting the importance of considering both natural and anthropogenic variability in climate change projections.

Figure 5.1.3.5.1. De-trended SST anomaly in the North Atlantic which is often used as an AMO index (from Knight *et al.*, 2005).
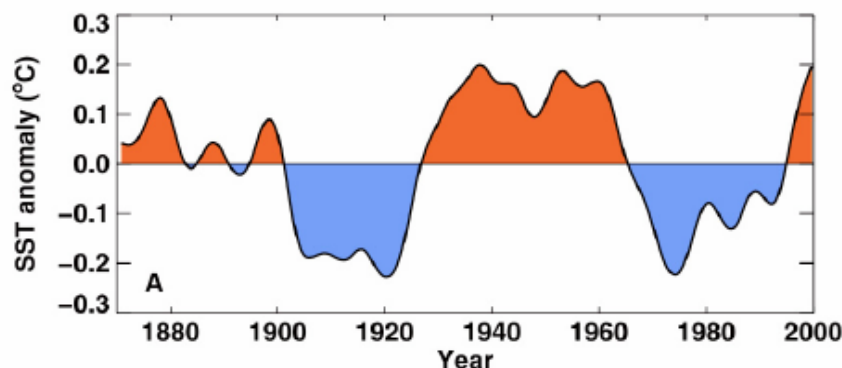
5.1.3.6 Atlantic Meridional Overturning Circulation (AMOC)

The AMOC is a major component of the global climate system, and a large contributor to circulation in the WNA, including flow into the Caribbean. It involves the wintertime cooling and sinking of surface waters in the Labrador and Nordic Seas, their southward flow at depth in the North and South Atlantic, and a compensating northward flow of warm and saline water in the upper ocean (shown schematically in Figure 5.1.3.6.1). Variability in the AMOC has been implicated as a major factor in the origin of past glacial periods, and it is expected to be an important factor in the climate system's response to modern-day anthropogenic increases in atmospheric greenhouse gases. AOGCM simulations for the 21st century project a slowing down of the AMOC (Meehl *et al.*, 2007) and show an area of reduced warming south of Greenland which is consistent with a reduction in the poleward upper-ocean transport of warm water in the North Atlantic (offsetting the global tendency for surface ocean warming). There have been observational estimates that the AMOC has been slowing down over the past half century, but there have also been model simulations suggesting that there has been significant decadal-scale variability (e.g., Balmaseda *et al.*, 2007). Various connections among the AMOC, NAO and AMO have been suggested, as well as suggestions of connections between the AMOC and the north-south position of the Gulf Stream in the ML-TZ. A relevant pattern that is emerging from some observational and modelling studies (Joyce and Zhang, 2010) is that a weakened AMOC associated with reduced deep convection in the Labrador and Nordic Seas results in a northward shift in the Gulf Stream in the ML-TZ, and higher ocean temperatures in the Slope Water extending from the Grand Bank to the Mid Atlantic Bight.

Since the surface return flow of AMOC is a large contributor to the Caribbean circulation and Gulf Stream current sources (Yucatan and Loop Currents), changes in its strength and pathways may substantially impact the ocean circulation in the IAS region. Observational and modeling studies (e.g., Johns *et al.*, 2002; Andrade *et al.*, 2003; Jouanno *et al.*, 2008) indicate that both mean and eddy kinetic energy in the IAS region would be substantially weaker if the AMOC contribution was absent. The mean transport through the southern passages in the Lesser Antilles is into the Caribbean due to the AMOC contribution. A subsurface return flow is both observed and

modeled along these passages, and has been linked to the Sverdrup return flow associated with the tropical gyre. Models suggest that the strong shear between this subsurface current and the surface flow from the North Brazil-Guyana Current is an important source of eddy development for the Caribbean (e.g., Cherubin and Richardson, 2007). Changes in the strength of the main currents and the general characteristics of the open ocean eddy field (e.g., caused by a change in the AMOC in the region) can impact the circulation in Coral Reef Lagoons of the Mesoamerican Barrier Reef System, as shown by Coronado *et al.* (2007).
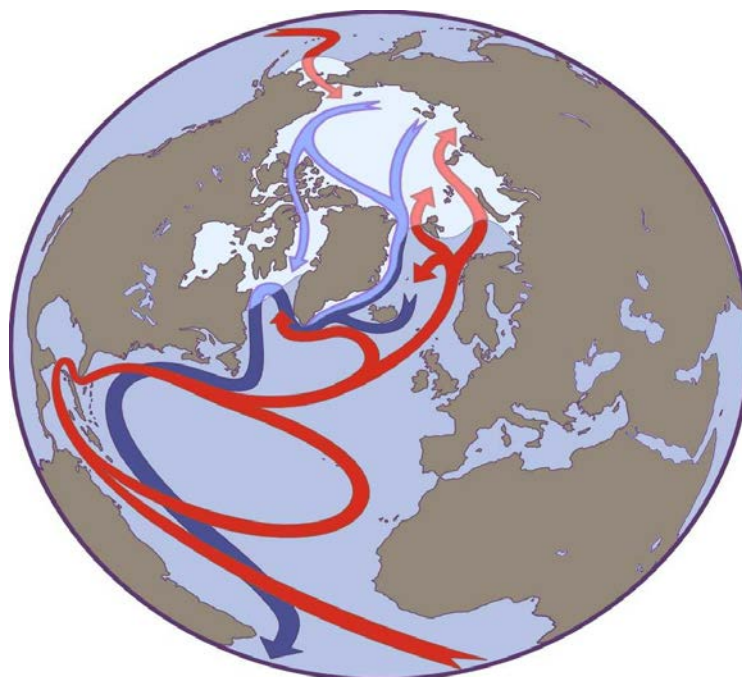
Figure 5.1.3.6.1. Schematic depiction of the linkages between AMOC and the flows in and out of the Arctic, with red indicating warm flows and blue indicating cold flows (from Greg Holloway of the Institute of Ocean Sciences, Fisheries and Oceans Canada).

5.1.3.7 Linkages among modes of variability

It is clear from the above discussion that particular oceanographic regions in the WNA are influenced by multiple modes of natural climate variability which are generally inter-related. As one example, Hurrell *et al.* (2006) have provided the following perspective on the inter-relation of the NAO, TAV and AMOC, referring to Figure 5.1.3.7.1:

"The NAO is associated with a meridional displacement of middle-latitude westerly winds (green contours of zonal wind velocity centered at 40°). The [Northern Hemisphere] tropical lobe of the SST anomaly tripole (the sign of which is associated with the negative index phase of NAO) also is related to the [TAV], in which changes in the cross-equatorial SST gradient interact with the overlying atmosphere to produce changes in ITCZ rainfall. A warm anomaly north of the equator (which also can be induced during a warm ENSO phase) results in anomalous cross-equatorial winds (denoted by three light-gray arrows). During this phase, the ITCZ is displaced northward, producing dry conditions over the Nordeste and wet conditions over sub-

Saharan Africa. Changes in the strength and position of tropical convection also may affect the position and strength of the mid-latitude storm track (blue arrows) and thus the phase of the NAO. The schematic representation of the North Atlantic MOC depicts the northward transport of warm water and southward transport of newly ventilated cold water. Changes in the surface density within the subpolar gyre and subarctic basins can influence the strength of the overturning and heat transport. The high-latitude density can change as a result of anomalous advection of Arctic freshwater or changes in air-sea fluxes. The NAO systematically influences the strength of the MOC from both effects. The tropical ocean has two additional shallow overturning cells (thin arrows) driven by Ekman transports in the trade winds zone. They can communicate surface temperature anomalies from subtropical regions to tropical upwelling zones and thus cause a delayed feedback on tropical surface temperatures. The three major climate phenomena in the Atlantic interact, …"
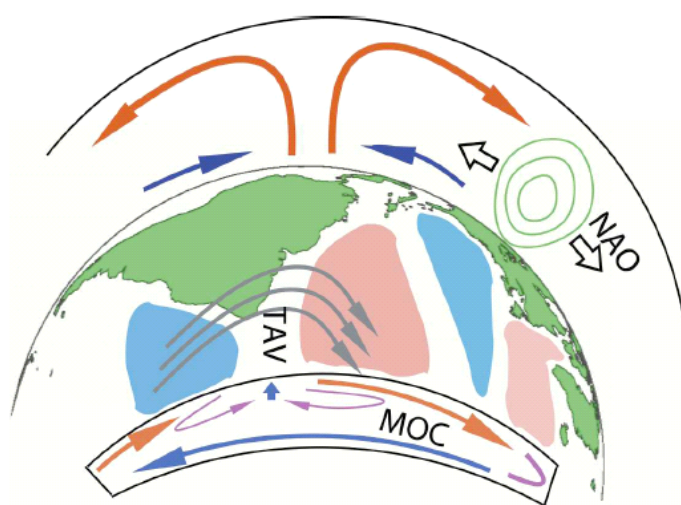
Figure 5.1.3.7.1. Schematic of the NAO, TAV and Atlantic MOC (AMOC) (from Marshall *et al.*, 2001; Hurrell *et al.*, 2006).

As another example of the interconnectivity among the modes and the influences of multiple modes on a particular region, Table 5.1.3.7.1 provides a summary of the six modes described above and their impacts from the perspective of the subtropical and tropical Atlantic (the ST-WNA, IAS and WTA regions).

The various interconnections that have been identified (or suggested) among the six modes identified here indicate strong spatial connectivity in the regional climate system. The modes should be a valuable basis for downscaling larger-scale and longer-term climate change projections to the scales of relevance to coastal and marine ecosystems. As a further example, the suggested (although still not established in detail) relations of the NAO to the strength of the atmospheric polar vortex, of the AMO to AMOC, and of the Gulf Stream position to both NAO and AMOC (on different times scales) provide the potential for advances in downscaling such projections to the regional scale of the ML-TZ.

Table 5.1.3.7.1. Summary of climate variability modes affecting the WNA and their main features and impacts from the perspective of the subtropical and tropical Atlantic.

MODE	MAIN FEATURES/ DEFINITION	IMPACT IN THE WNA AND/OR IAS REGION
NAO	North Atlantic Oscillation North Atlantic meridional surface pressure gradient index. Boreal winter-spring signal associated with a tri-polar SST pattern in the North Atlantic.	Impacts the northeasterly trades through modification of subtropical high impacting TAV (SST and latent heat flux anomalies). Modifies subtropical gyre.
ENSO	El Nino – Southern Oscillation Tropical Pacific-global atmosphere mode possibly modulated by some Indian/Atlantic Ocean phenomena and mid-latitude long-term oscillations (e.g., Pacific Decadal Oscillation).	(+) Southward displacement of the ITCZ (Pacific) but northward in the tropical eastern Atlantic. Negative rainfall anomalies over Caribbean/Central America, South & Central Mexico. Reduced number of hurricanes in the Atlantic. Major impact in boreal winter in the IAS.
TAV	Tropical Atlantic Variability Meridional mode (boreal spring) related to inter-hemispheric tropical near-equatorial SST gradients. Zonal mode (boreal summer) related to cold tongue in equatorial SST.	ITCZ modification in the IAS by the TAV meridional mode
AWP	Atlantic Warm Pool Area of the Atlantic where SST > 28.5°C. Multi-scale variability (seasonal, inter-annual, multi-decadal).	Large extension related to increased hurricane activity, related to (part of) the AMO. Large extension related to positive rainfall anomalies in the IAS
AMO	Atlantic Multi-decadal Oscillation Bi-polar variation in North and South Atlantic SST	Related to AWP and MOC. Shallow subtropical cells (STCs) in upper ocean.
AMOC	Atlantic Meridional Overturning Circulation Northward (southward) upper-(lower-) ocean flow of warm (cold) water.	Important contribution to IAS ocean circulation. STC tropical/subtropical connection

5.1.4   Recent and probable climate changes in important variables

5.1.4.1 Atmospheric and hydrological

The following is a brief summary of changes in atmospheric variables that are important to WNA ocean climate, drawing on IPCC AR4 (especially Trenberth *et al.*, 2007, and Meehl *et al.*, 2007), previously-referenced recent reviews, a recent literature review by van der Baaren (2010), and just-published papers (e.g., Betts *et al.*, 2011) .

- Increasing surface air temperatures have been observed over North America and the WNA during the past century and are expected to continue through the next century. The magnitude of the change generally increases northward over eastern North America and by a reduced amount over the North Atlantic, and varies seasonally with larger changes in winter, especially at high latitudes. The reduced latitudinal gradient over the NA is associated with an area of reduced warming south of Greenland which is consistent with a weakened AMOC. IPCC (2007) projected an increase in

global mean temperature (relative to pre-industrial values) in the range of 1.6 to 6.9°C depending on the emissions scenario, but there are now increasing concerns about so-called "dangerous" climate change (e.g., Richardson *et al.*, 2009) and suggestions that a 4°C global change could occur by the 2070s (Betts *et al.*, 2011). AOGCMs generally indicate that the change over northeastern North America could be about twice the global mean.

- There is more spatial structure and variability in the projected changes in precipitation than in temperature. Wintertime precipitation is projected to increase over most of North America associated with the intensified global hydrological cycle, but decrease over the southwestern United States and Mexico. Summertime precipitation is projected to increase over the northern half of North America but decrease over the southern half except along the Atlantic coast. A reduction in the fraction of precipitation falling as snow, and earlier snow melting are expected over eastern North America.

- Evaporation rates are generally expected to increase over the eastern half of North America and ST-WNA, but decrease over Mexico and the SP-NWA.

- Widespread changes in the seasonal cycle of freshwater run-off into the ocean are expected, with earlier and generally larger spring peaks. The changes in annual-mean run-off will vary with region depending on seasonal precipitation and evaporation rates, and ice and snow melting. Increased freshwater discharge into the SP-NWA is expected from both North America and Greenland (glacial melting), which may be enhanced by an increased flux of freshwater from the Arctic. The changes in freshwater discharge into the ML-TZ are less certain because of multiple river systems with drainage areas having differing extents into the continental interior. Run-off into the Gulf of St. Lawrence is expected to increase in winter and decrease in summer, probably with a net annual-mean increase (but this is more tentative). An increase in annual-mean freshwater discharge into the southern part of the ML-TZ (Gulf of Maine and Mid Atlantic Bight) has been projected. Run-off into the ST-WNA and northern Gulf of Mexico is generally expected to increase in winter and decrease in summer, while there may be a general decrease in run-off into the remainder of the IAS. However, the operation of dams will be a key factor in several hydrological basins, like the Papaloapan and Grijalva-Usumacinta in the southwestern Gulf of Mexico.

- The polar vortex is expected to deepen and the mid-latitude jet stream is expected to intensify and shift north. A tendency for the NAO to be more positive has been projected (Meehl *et al.*, 2007), but changes in the monthly to decadal temporal variability are unclear.

- The occurrence of strong hurricanes and intense extratropical cyclones over the WNA is expected to increase (e.g., Mann and Emanuel, 2006) with their tracks shifted northward.

5.1.4.2 Physical oceanographic

The tendencies for probable anthropogenic changes in key physical oceanographic variables in the WNA are summarized in Table 5.1.4.2.1. For each variable or feature, an indication is provided of the relative magnitude of the expected changes in the four major oceanographic regions, based on the literature and current knowledge. An

indication is also provided of the degree of confidence in the projections, based here on uncertainty and gaps in our present knowledge of climate dynamics and change (e.g., physics, models, and interpretations of observations). The indicated changes are all expected to become important in the Longer-Term (by mid century), although some may be less important than natural variability in the Near-Term. The changes indicated as "highly probable" are generally considered to be already occurring, although the observed magnitude in some regions may include a contribution from natural variability.

Large–Scale Ocean Circulation

As described in the previous section, the AMOC is expected to weaken in the Longer-Term (Meehl *et al.*, 2007), resulting in a reduced ocean transport of heat into the northern North Atlantic and a northward shift of the Gulf Stream in the ML-TZ. The projection of more positive NAO can also be expected to contribute to a northward expansion of the subtropical gyre (Joyce *et al.*, 2000; Han, 2007) and a retraction (tightening) of the subpolar gyre in the WNA (e.g., Lohmann *et al.*, 2009a,b), thereby having significant impacts on both the SP-NWA and ML-TZ. Also as described previously, a weakened AMOC can be expected to result in reduced flow into, and eddy energy in, the IAS with broader implications for both the IAS and ST-WNA.

Ocean Temperature

Widespread surface-intensified warming of the upper ocean is already occurring (Trenberth *et al.*, 2007), and is expected to continue in large- and decadal-scale averages over both the Near- and Longer-Terms. Changes in the seasonal cycles and extrema, with regional differences, are expected to be important to biological processes.

Long-term warming related to the global trend is expected to continue in the ST-WNA and IAS. A reduced rate of warming in the northern North Atlantic south of Greenland is expected associated with the weakening AMOC. Changes in the SP-NWA are expected to vary spatially due to the competing influences of amplified high-latitude atmospheric warming and increasing stratification (favouring warming), and reduced AMOC, more positive NAO and possibly increased Arctic outflows (favouring cooling).

Enhanced warming in the ML-TZ is expected (e.g., Fogarty *et al.*, 2007) associated with poleward expansion of the subtropical gyre (northward shift of the Gulf Stream) and retraction of the subpolar gyre (in addition to surface warming). There are suggestions (e.g., Friedland and Hare, 2007; Lucey and Nye, 2010) that a northward regime shift is already occurring due to a combination of climate and fishing pressure in the southern part of the ML-TZ (Mid Atlantic Bight to Gulf of Maine). This shift can be expected to continue and expand northward in the Longer-Term. Collectively these changes may result in an enhanced latitudinal temperature gradient in the ML-TZ and southern part of the SP-NWA, in contrast to the reduced latitudinal gradient expected more widely.

Sea Ice Extent and Volume

The extent and volume of summertime sea ice in the Arctic has decreased substantially during the past two decades (e.g., Kwok and Rothrock, 2009), including within the Canadian Archipelago (Howell *et al.*, 2009). An overall decline in Arctic sea ice extent and volume associated with anthropogenic climate change is expected to continue, possibly at an increased rate (e.g., Wang and Overland, 2009) (although there

may be local deviations within the Archipelago). In the Longer-Term, large reductions in sea ice extent and volume are expected in the parts of the SP-NWA (e.g., Labrador and Northeast Newfoundland Shelves/Slopes) and ML-TZ (Gulf of St. Lawrence) where seasonal ice presently occurs. This can be expected to have major implications for some parts of their regional ecosystems. Sea ice extent and duration have decreased on the NE Newfoundland Shelf/Slope (south of 55oN) during the past decade (e.g., Templeman, 2010), but it is unclear whether this is associated with natural variability (NAO or AMO) or anthropogenic change.

Coastal Sea Level

A global rise in sea level over the last half century is well-documented (e.g., Bindoff *et al.*, 2007), with contributions from ocean thermal expansion and melting sea ice and glaciers that are generally consistent with anthropogenic climate change. Additional contributing factors to coastal sea level variability (relative to local land) on the time scale of seasons and longer are regional and subregional changes associated with (i) ocean circulation (e.g., the AMOC and the horizontal gyres) and currents (e.g., driven by local winds and buoyancy), and (ii) vertical movements of coastal land and seafloor due to continental rebound or subsidence, and river delta subsidence. These additional factors can be expected to amplify sea level rise along many parts of the Atlantic coast of North America, and in some cases are already doing so. In particular, relative sea level rise is presently amplified by land subsidence in parts of the ML-TZ (e.g., Nova Scotia) and IAS (e.g., Mississippi delta, and Ciudad Madero), and has been projected to be amplified in the SP-NWA and ML-TZ in the future associated with a slowing of the AMOC (e.g., Yin *et al.*, 2009) and northward expansion of the subtropical gyre.

There are now good reasons to believe that sea level will rise faster than projected in IPCC (2007), because of Greenland ice melting and higher-than-projected global warming. Whereas the global–mean projected rise by the 2090s (relative to the 1980s) was in the range 0.18-0.59m for the various emissions scenarios in IPCC (2007), recent papers suggest a probable sea level rise of 0.5 to 1 m by 2100 (e.g., Richardson *et al.*, 2009; Nicholls *et al.*, 2010), with some suggesting a possibility of a 2m rise.

In addition to the above rise in "mean" (over seasons and longer) sea level, an amplification of extreme high-frequency (periods of hours) variability in sea level is projected for many areas, associated with more intense cyclones and hurricanes in the WNA. Combined with the widespread rise in mean level, this can be expected to contribute to a significant increase in extreme high water levels in most areas. The latter may be further exacerbated in the Bay of Fundy-Gulf of Maine tidal system since there are indications that its natural resonance period is moving closer to the period of the M_2 tide resulting in increasing tidal amplitudes (D. Greenberg, personal communication, 2010).

Coastal Flooding and Erosion

The projected increased occurrence of extreme high waters along the Atlantic coast can be expected to lead to increased coastal flooding and inundation of wetlands, and increased erosion and other alterations of the coastal zone. This may be further exacerbated in some areas by the occurrence of increased wave heights, associated with the more intense storms and hurricanes, and the increasing "mean" sea level (reduced damping of the waves). This is a case of multiple re-inforcing factors associated with different aspects of anthropogenic and natural variability contributing to

substantial regional and subregional amplifications of the global tendency for rising sea level and coastal damage. Reduced sediment supply due to dam construction, combined with sea level rise, will also increase coastal erosion in some delta areas.

The issue is further compounded by the extensive areas of barrier beaches, wetlands and low-lying coastal land in the IAS, ST-WNA and ML-TZ in particular (e.g., FOCC 2009; Wu *et al.*, 2009). As a result of these multiple factors and the new information on faster sea level rise than previously projected, climate change needs to be given special consideration in management and adaptation strategies for coastal ecosystems in these regions, as well as for coastal infrastructure and human populations.

Ocean Salinity

Changes in upper-ocean salinity are expected to have different signs in different regions and perhaps subregions (e.g., Meehl *et al.*, 2007). In the SP-WNA, there is expected to be a widespread decrease in salinity associated with a combination of increased river discharge (associated with the amplified hydrological cycle), increased glacial and sea-ice melting, and possibly increased freshwater fluxes from the Arctic. In contrast, salinity is expected to generally increase across the ST-WNA and IAS associated with increased evaporation with warmer temperature. A probable exception to the latter is coastal areas where there is substantial river discharge which may result in local amplifications of, or reductions in, the salinity increases, or perhaps even reductions in salinity. The coastal waters affected by the Mississippi outflow would appear to have the greatest potential for a subregional anomaly, with probable increases in winter-spring discharge resulting in a reduction in the salinity increase (or a salinity decrease locally), and probable decreases in summer run-off resulting in amplified seasonal salinity increases.

Salinity changes in the ML-TZ are less clear and will probably have more spatial structure than in the other two regions. With the expected northward expansion of the subtropical gyre and retraction of the subpolar gyre, upper-ocean ocean salinity can be expected to generally increase in the offshore deep-ocean and slope portions of the ML-TZ, and also probably at depths below about 100m over the outer and mid shelves. However, salinities in the coastal ocean and near-surface over the inner-mid shelf may be predominantly influenced by changes in local or sub-regional run-off, at least in winter and spring. Thus, it appears likely that there will be reduced salinities in the upper layers of the Gulf of St. Lawrence in winter and spring, and also in coastal areas of the southern half of the ML-TZ, associated with increased seasonal run-off. On the other hand, increased near-bottom salinities can be expected to occur in the Gulf of St. Lawrence, as elsewhere in shelf basins and channels in the ML-TZ, as a result of the intrusion of more-saline Slope Water.

Upper–Ocean Stratification and Vertical Mixing

Changes in upper-ocean density stratification and vertical mixing are expected to be inter-related and dependent on changes in surface and subsurface temperature and salinity, and wind and wave mixing. Surface ocean warming can be expected to provide a broad-scale tendency towards increasing near-surface stratification and shallower (thinner) mixed layers. Ocean salinity changes can be expected to re-inforce this tendency in the SP-NWA and in coastal areas of the ML-TZ, but at least partly offset this tendency in the ST-WNA. The influence of changes in wind and wave mixing will probably be more spatially- and seasonally-variable, with perhaps increased mixing in the late summer-fall hurricane and cyclone season, but reduced mixing in spring and summer when seasonal stratification is developing.

Table 5.1.4.2.1. Tendencies for Anthropogenic climate change in key Physical Oceanographic properties affecting ecosystems in the WNA. The time horizon on which these changes might be expected to become more important than natural decadal-scale variability varies with the variable, but all might be expected to do so within a few decades. The large-scale (WNA) tendencies for particular features of these variables are noted, and the relative magnitude of the tendencies among the major oceanographic regions for each feature are indicated using multiple + and – signs (with a "?" indicating uncertainty in the sign of the tendency). Different uncertainties in the tendencies associated present knowledge gaps are indicated by the following colour coding for probable occurrence: Highly probable, probable.

OCEAN VARIABLE	FEATURE	LARGE–SCALE TENDENCIES FOR WNA	SP– NWA	ML– TZ	ST– WNA	IAS
Large-Scale Ocean Circulation	AMOC	Slowed AMOC	–	–	–	–
	SP & ST Gyres	Retracted SP gyre; Expanded ST gyre & N-shifted Gulf Stream	+			
	IAS Inflow			++	+	
	Loop Current	Reduced mean & eddy flow in IAS				–
Temperature	Near-Surface	Widespread surface-intensified warming with reduced magnitude in north	+	++++	++	++
	Winter modified layer		+	++	+	+
	Shelf/Slope Bottom	Subtropical water expansion in ML-TZ	+	+++	+	+
Sea Ice Extent & Volume	Winter & spring only	Reduced where present	––	–––		
Coastal Sea Level (relative to land)	Means	Widespread increase with regional variations due to multiple factors	+++	++++	+++	++++
	Extremes	Widespread additional increase due to more intense hurricanes & cyclones	++	+++	+++	++++
Coastal Flooding & Erosion	Coastline retreat	Widespread increase due to mean & fluctuating sea level, with regional variations due to low-lying coastlines	+	+++	++++	++++
Salinity	Offshore (in upper few 100m)	Decrease in SP-NWA Increase in ML-TZ, ST-WNA & GM	–––	+++	++	++
	Coastal (in upper 100m)	Decrease in SP-NWA Winter-spring (W) decrease & summer (S) increase elsewhere, with subregional variability	W:––– S: –––	W:–– S: +	W:– S: ++	W:–– S: ++
Upper-Ocean Stratification & Vertical Mixing	Surface mixed layers	Widespread increased stratification, thinner mixed layers & reduced vertical mixing	+++	++	+	+
Coastal & Shelf Circulation	Buoyancy- & wind-driven currents; Fronts	Enhanced buoyancy flows & fronts; Modified currents depending on local winds	+ ?	+ ?	+ ?	+ ?

Earlier and increasing seasonal stratification has been observed in recent decades in parts of the shelf in the ML-TZ with apparent influences on phytoplankton production (e.g., EAP, 2009; Worcester and Parker, 2010; B. Petrie, personal communication, 2010), indicating that significant anthropogenic change is already occurring in this

region with biological impacts. Another expected result of increased stratification is a reduction in the spatial extent of year-round vertically well-mixed areas in tidally-energetic areas like the Gulf of Maine (e.g., Georges Bank).

Coastal and Shelf Circulation

Changes in circulation patterns, currents, fronts, freshwater plumes and up/downwellings on the sub-regional and local scales in the coastal zone and on the continental shelf can be expected. While many of these will be influenced by the regional and larger-scale tendencies described above, they can generally be expected to be heavily influenced by local factors such as run-off and winds. The large-scale tendency for increased run-off in winter and spring can be expected to contribute to earlier seasonal stratification and stronger fronts and associated flows in most coastal regions in spring. However, coastal fronts may be weaker in some areas with reduced run-off in summer. On the other hand, seasonally- and spatially-variable wind influences, with magnitude and sign dependent on the wind velocity's orientation to the coastline as well as its magnitude, may be the largest contributor to coastal current changes in many areas.

5.1.4.3 Chemical oceanographic

The tendencies for changes in key chemical oceanographic properties, associated with climate changes in non-biological processes, are summarized in Table 5.1.4.3.1.

Warmer ocean temperatures, increased stratification, and reduced vertical mixing in the upper ocean are expected to provide a tendency for reduced atmospheric replenishment of oxygen to subsurface waters, and hence reduced dissolved oxygen concentrations at depths below the wintertime ventilation zone (e.g., Keeling *et al.*, 2010). This should provide a tendency for "older" subsurface subtropical waters to become closer to hypoxic conditions, and could compound problems with hypoxia and anoxia in coastal areas with significant nutrient loadings from coastal discharges. Changes in biological processes are also expected to make an important contribution to dissolved oxygen changes, which may dominate in some areas. The expected enhanced primary production in subpolar regions (see below) may further reduce the oxygen concentrations there, while the reduced production in offshore subtropical waters can be expected to partly offset the oxygen reduction due to reduced ventilation (Keeling *et al.*, 2010). In coastal waters with increased run-off, any additional nutrient loading could lead to enhanced biological production and an additional decrease in oxygen concentrations.

A clear and direct consequence of increasing atmospheric CO_2 concentrations is a widespread increase in ocean acidity (reduced pH) and lowering of calcium carbonate saturation in the upper ocean, particularly in cold waters which can hold more CO_2 than warmer waters (e.g., Doney *et al.*, 2009; Hoegh-Guldberg and Bruno, 2010). As a result, some Arctic waters are already becoming corrosive to calcareous organisms, and the depth horizons below which calcareous and aragonitic shell growth is impaired can be expected to gradually rise through the coming century. This is expected to have adverse impacts on coral reef ecosystems in particular.

Increased upper-ocean stratification can be expected to contribute to a widespread reduction in the supply of nutrients to the euphotic zone, which should result in reduced phytoplankton growth in temperate and subtropical areas where the growth is nutrient-limited. In contrast, the increased stratification is expected to lead to increased phytoplankton growth (because of increased time in the euphotic zone) in

subpolar waters where growth is light-limited. In coastal regions, the seasonal and spatial variability of various subregional physical oceanographic processes (e.g., upwelling) may be the predominant influence on nutrient availability to the euphotic zone. Large-scale changes in circulation may also lead to changes in nutrient concentrations in areas such as the SP-NWA and the ML-TZ associated with Arctic outflows (e.g., Yamagoto-Kawai *et al.*, 2006; Harrison and Li, 2008; Yeats *et al.*, 2010) and a Gulf Stream shift, respectively.

Table 5.1.4.3.1. Tendencies for Anthropogenic climate change via physical processes in key Chemical Oceanographic properties affecting ecosystems in the WNA. The format and conventions are the same as in Table 5.1.4.2.1, with the relative magnitude of the changes in different regions indicated by the + and – signs, and probable occurrence by colour coding: Highly probable, probable. Influences of changes in biological processes associated with climate change are not included.

Ocean Variable	Feature	Large-Scale WNA	SP–NWA	ML–TZ	ST–WNA	IAS
Dissolved Oxygen	Subsurface minima	Widespread reduced concentration in layer below new shallower depth of wintertime ventilation	––	–	–	–
Ocean Acidity	Upper-ocean	Widespread increase in winter ventilated areas More severe in colder waters	+++	+	+	+
Nutrients	Vertical supply to euphotic zone	Widespread reduction	–	–	–	–
		Subregional differences in coastal and shelf areas	?	?	?	?
	Altered levels due to circulation changes	Increases and decreases in different nutrients associated with changing Arctic outflows	+/–	+/–		
		Decrease in ML-TZ due to increased subtropical influence		–		

5.1.5 Indices for co–variate studies

Considering the complexity, multiple factors and uncertainties associated with climate change, it will be important to have indices of both climate forcings and key oceanographic variables, for use in making links to ecosystem variability. The indices for past variability will generally need to be observationally-based, but could include some from assimilative models for key oceanographic and atmospheric phenomena that are expected to change and affect aspects of the ecosystem. Indices of the ocean variables and features that directly affect marine organisms can be expected to be the most useful for developing understanding and confident projections of climate change impacts. Indices of the atmospheric and hydrological variables that can be considered as key forcings of ocean climate change will also be important, especially in identifying large-scale connections and linkages.

Many indices already exist for atmospheric and ocean climate variability in the WNA, and for their important natural modes described above. The next section on ecosystem variability includes a large number of existing variables and indices that have been used to identify climate-ecosystem linkages and potential coupling mechanisms. These indices are natural candidates for further use, especially those for the strongest and most understandable linkages and that will continue to be available. However, as

our understanding of the linked climate and marine ecosystems increases over the coming years, through both model simulations and interpretation of observational data, it will be important to assess the representativeness of these indices and identify the more relevant ones. Nevertheless, it may be equally important to maintain existing long time series (e.g., ICES, 2010), even if they are not the best indicators of some features.

5.2   Introduction to biological/ecological overview

Climate change will fundamentally alter oceanographic structures and features with direct implications for marine ecosystems and human societies (Everett *et al.*, 1995; McLean *et al.*, 2001). Oceanographic features including currents, fronts, upwelling and downwelling zones and ice cover will be strongly influenced by these variations in temperature, salinity, and winds. Changes in temperature, salinity, and winds are expected to increase stratification in temperate regions which will have profound effects on the ecosystem (e.g., Mann and Lazier, 1996). Some of the potential pathways for atmospheric effects on oceanic dynamics and biological response are depicted in Figure 5.2.1. These changes will be manifest on scales ranging from the relatively small spatial and temporal scales characteristic of turbulent mixing processes to those of the deep ocean circulation with global-scale changes occurring over millennia. Tracking processes occurring on this spectrum of spatial and temporal scales is critical to understanding the potential effects of global climate change on marine populations and ocean ecosystems. In this section, we focus on how climate change will affect ecosystem components and identify data sources to detect these changes primarily because information on abundance and distribution is collected separately for each ecosystem component. The classification of marine ecosystem components is loosely based on the different sampling techniques necessary to survey changes in abundance and distribution.
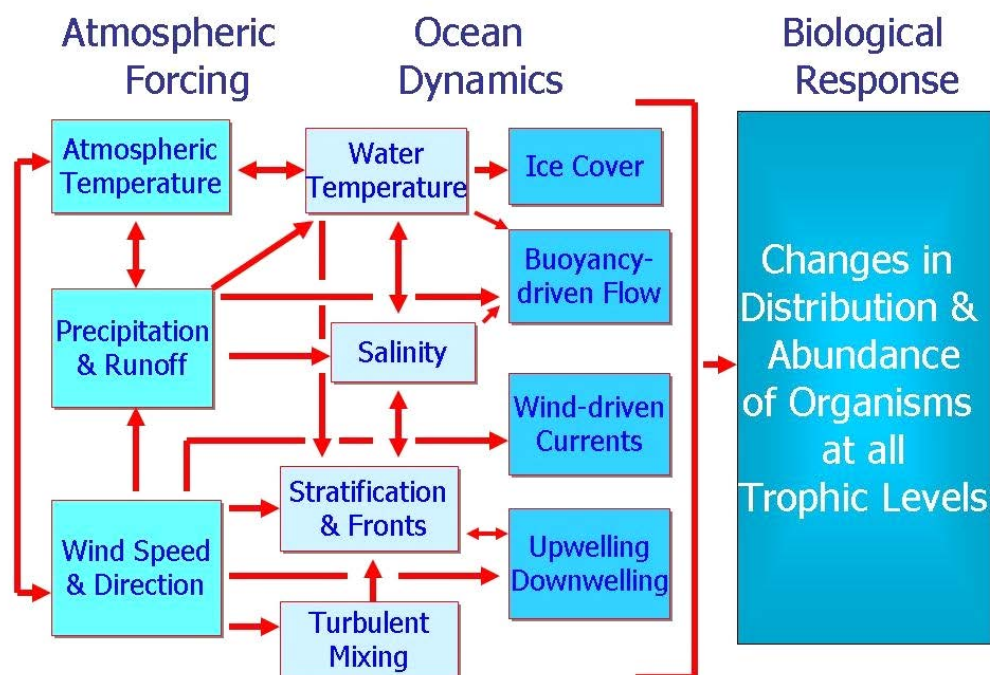
Figure 5.2.1. Interactive pathways between changes in atmospheric forcing, ocean dynamics, and biological response in production processes. Changes in atmospheric temperature, precipitation, and winds will affect stratification, buoyancy-driven flows, upwelling/downwelling, sea ice and other factors. These will potentially affect production at all trophic levels.

5.2.1 Phytoplankton and zooplankton

Phytoplankton and zooplankton (microzooplankton, mesozooplankton, and mega-zooplankton such as jellyfish) are inextricably linked trophically, so that climate-related changes in the phytoplankton community composition will cascade upwards to impact the zooplankton (bottom-up control) and changes in the zooplankton community cascade downward to influence the phytoplankton via their grazing activity (top-down control). Phenological changes (change in seasonality) will also occur in both phytoplankton and zooplankton populations.

Plankton are quite sensitive to changes in water temperature, with warmer temperatures associated with shifts in phytoplankton size to smaller forms (Finkel *et al*., 2010), and with increased growth, development and metabolic rates in zooplankton (e.g., Campbell *et al*., 2001), which will also likely to result in smaller "size-at-stage" and increased abundances of smaller species (e.g., Beaugrand *et a*l., 2002; 2009). Specific species may be intolerant of warmer temperatures and not thrive, while jellyfish, which exert considerable predatory pressure on mesozooplankton and ichthyoplankton are more likely to bloom at warmer water temperatures (Purcell *et al*., 2005). Increasing temperatures can impact plankton phenology, so that, for example, spring blooms may occur earlier and the ecologically important copepod species *Calanus finmarchicus* may reproduce and develop faster, produce more generations per year, but spend more of the year at depth.

Increasing surface temperatures will lead to higher levels of stratification in the ocean, year-round and at all latitudes. At southern latitudes (sub-tropical gyres), where phytoplankton growth is nutrient-limited for much of the year, increased stratification will likely lead to a decrease in the level of "new" primary production

(Doney, 2006). New primary production is the portion that is fuelled by nutrients mixed up from depth, which is available either for transfer to higher trophic levels or for export to depth via the biological pump. Decreases in primary production in southern regions will thus likely lead to reduced carbon sequestration and to reduced levels of production in the zooplankton. In northern regions (sub-polar gyres), nutrient concentrations do not generally limit phytoplankton growth in summer, because frequent wind-driven vertical mixing events of the water column means that phytoplankton growth is limited by light (Harrison and Li, 2007). In these regions increased stratification may lead to increased primary production, which could increase zooplankton abundance (Head and Pepin, 2010). In some regions mixed layers may become thinner and warmer which will exacerbate the overall effects of increasing stratification. In northern regions of the North American continental shelf (eco-regions 6 and 7) stratification is driven to a greater or lesser degree by the melting of ice and southerly advection of freshwater. In the 1990s, increased freshwater flux to the Scotian Shelf and Gulf of Maine led increased stratification, which apparently led to phytoplankton blooms occurring in winter, following vertical mixing caused by high winds and storms in fall (Ji *et al.*, 2007; Head and Pepin, 2010). In winter phytoplankton are subject to relatively low grazing pressure, since the most important grazers in these regions have seasonal life cycles that are tuned to grazing on blooms occurring in spring. Hence winter blooms may result in increased carbon flux to the benthos. Phytoplankton growth in these shelf regions is nutrient limited in summer, so that the net effect of increased stratification on phytoplankton growth will probably be negative. Increased stratification also favours the growth of dinoflagellates over diatoms, because the former can swim down to depths to take up nutrients at night, and swim up to the surface to photosynthesise during the day. Since the 1990s the Newfoundland Shelf has had a large increase in the abundance of dinoflagellates (Johns et al. 2003), which may have been a poor food source for *Calanus finmarchicus*, a dominant member of the zooplankton community (Head and Pepin, 2010).
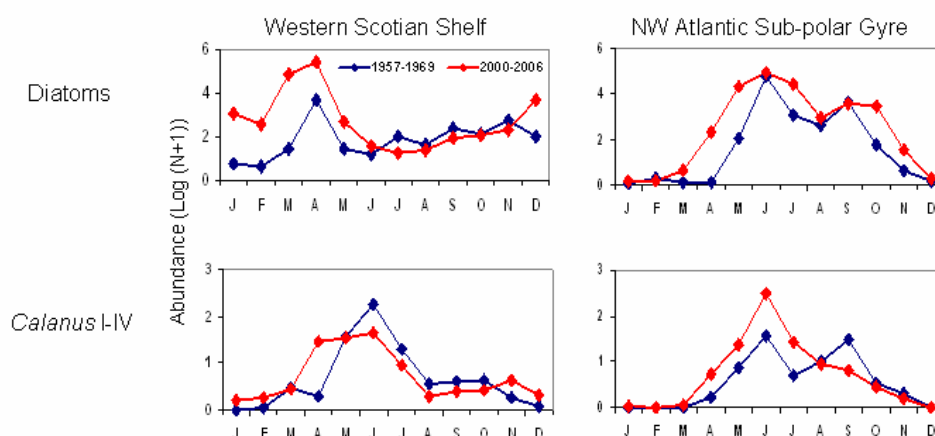
Figure 5.2.1.1. Inter-decadal changes in seasonal cycles of diatom and young stage *Calanus* abundance on the Western Scotian Shelf and in the NW Atlantic Sub-polar Gyre as determined by Continuous Plankton Recorder sampling. Warming between the late 1950s and the early 2000s led to earlier and more intense diatom blooms and earlier emergence of young stage *Calanus*. (Redrawn after Head and Pepin, 2010).

Changes in wind patterns and increases in the frequency and duration of storm events, including hurricanes, may reduce stratification and increase vertical mixing and the supply of nutrients to the photic zone in some areas, which may lead to local increases in primary production and in the subsequent growth and development of

zooplankton. Both storms and intensification of the hydrologic cycle (e.g., more precipitation at northern latitudes) will lead to increased runoff and river input to the ocean that will increase nutrient supply and turbidity in coastal areas, the latter which could shade phytoplankton and decrease primary production locally, and the former which could promote the development of harmful algal blooms (*Alexandrium tamarensis* in the Gulf of Maine and *Karenia brevis* on the Western Florida Shelf, e.g., Anderson *et al.*, 2005; Smayda, 2006; Vargo *et al.*, 2008). The increased input of freshwater through hydrologic changes including river runoff and advection of freshwater will also promote stratification (see above).

Changes in broad scale ocean circulation patterns, including a northward shift of the Gulf Stream with the weakening of the AMOC, will produce changes in species distributions and ranges and an increased predominance of smaller, warm-water forms in northern regions. It will also modify nutrient availability (and primary and secondary production in response), and could lead to the introduction and success of expatriate species such as Pacific Species into the NW Atlantic or Atlantic species into the Arctic (Reid *et al.*, 2007; Greene *et al.*, 2008). Changes in mesoscale circulation patterns (e.g., eddy formation) will change exchange processes between ocean regimes (e.g., shelf and basin) and could reduce or enhance physically mediated plankton patchiness that is exploited by upper trophic levels (e.g., the copepod *Calanus finmarchicus* and the North Atlantic Right Whale; Wishner *et al.*, 1988).

Reduction in seasonal ice cover (extent and duration) in northern regions will change the relative proportions of ice algal vs. pelagic phytoplankton primary production and shift the timing of water column primary production earlier (Wu *et al.*, 2007). There will be attendant impacts on zooplankton phenology and production (Head *et al.*, in press) and change in distributions of ice-associated flora and fauna. There could also be an increase in the supply of nutrients to the surface layers due to increased vertical mixing in fall/winter resulting from the prolonged open water season.

Rising temperatures and decreased water column oxygen levels will likely lead to increases in the occurrence of "jellyfish blooms" (e.g., Shoji *et al.*, 2005; Richardson *et al.*, 2009), which are deleterious to the fishing industry, since jellyfish prey on larval and juvenile fish and their zooplankton prey, and interfere with fishing (e.g., by clogging and bursting nets). These events may be exacerbated by introductions of exotic species (e.g., the Australian spotted jellyfish, *Phyllorhiza punctata*, first spotted in the Gulf of Mexico in 2000 (Graham *et al.*, 2003) and since found as far north as North Carolina, thought to have been introduced via ships' ballast waters). In addition, ocean acidification, which is especially imminent in polar regions (Yamamoto-Kuwai *et al.*, 2009) and their outflows, will affect calcifying organisms such as Coccolithophores (phytoplankton), pteropods and foraminifera (zooplankton); these organisms are important in the sequestration of carbon in the sediments and as food for higher trophic levels.

5.2.1.1 Data sources

Over the last decade there has been a proliferation of reports of changes in the abundance and distribution of phytoplankton and zooplankton in the North Atlantic that have occurred over the last few decades and that have been linked to climate change. Many of these have been derived from the Continuous Plankton Recorder (CPR) survey in the North Atlantic, operated by the Sir Alister Hardy Foundation for Ocean Science (http://www.sahfos.ac.uk). CPR sampling coverage is greatest in the NE Atlantic and North Sea, but a route between Reykjavik and the New England coast has been run since 1957, with extra CPR sampling lines operated by NMFS (National

Marine Fisheries Service) near the US coast since the 1970s. In the NW Atlantic, plankton samples have also been collected by DFO (Department of Fisheries and Oceans, Canada) at stations on the Canadian Continental Shelf and in the Gulf of St Lawrence since 1999. Sampling occurs along a series of cross-shelf sections 2-3 times per year and at several coastal time series stations at roughly monthly intervals. Data are reported annually in DFO Research Documents (http://www.meds-sdmm.dfo-mpo.gc.ca/csas-sccs/applications/publications/index-eng.asp). Zooplankton surveys have also been carried out by the US National Marine Fisheries Service (NMFS) in the Gulf of Maine/Georges Bank/Mid-Atlantic Bight region, firstly in the in MARMAP program and currently in the ECOMON. As well there has been phytoplankton and zooplankton monitoring in Narragansett Bay since 1999 carried out by scientists from the University of Rhode Island (http://www.gso.uri.edu/phytoplankton) and in Bedford Basin, by scientists from DFO since 1992 (http://www2.mar.dfo-mpo.gc.ca/science/ocean/BedfordBasin/index.htm). In addition, the ICES Working Group on Zooplankton Ecology (WGZE) compiles a status report for time series stations throughout the ICES area at 2 year intervals. These are published by ICES (http://www.wgze.net/plankton-status-report). A review on plankton trends in the ICES area was recently prepared by members of the ICES WGZE, which will be published soon. Zooplankton data are also available for the BATS (Bermuda Atlantic Times Series) site (http://web.vims.edu/bio/zooplankton/BATS/Data.html?svr=www). Zooplankton were collected as part of the SEAMAP program in the Gulf of Mexico (www.SEAMAP.org), with data available through the COPEPOD data portal (http://www.st.nmfs.noaa.gov/plankton/). Other data sets also are available through this web site. Shorter term (e.g., five year) records are available at specific sites associated with larger programs, such as zooplankton data from the Georges Bank GLOBEC program that are available form 1995-1999 at www.bco-dmo.org.

Ocean color from satellites can be used to examine primary productivity globally, but this information has only become available since the late 1990s. There are also limitations in the algorithms converting ocean colour to primary productivity particularly in coastal regions at high latitudes, where observations are also missing for the winter (dark season) months. Nevertheless, information regarding phytoplankton abundance and composition (e.g., diatom abundance) also can be extracted from ocean color data.

5.2.2 Benthic invertebrates

Changes in temperature and circulation will have profound effects on distribution and abundance of benthic organisms. Few time series exist for small benthic infaunal species. However, time series of commercially important macrobenthic species, particularly those that support commercial fisheries are available. Shifts in distribution have been observed in some of these species, particularly surfclams *Spisula solidissima solidissima* (Figure 5.2.2.1), which has essentially made fishing for this species uneconomical in the southern part of their range (Weinberg, 2005). Ocean acidification will have a major effect on benthic organisms that use calcium carbonate in the formation of their shells. Several recent studies have started to elucidate the ways in which ocean acidification may affect organisms. An analysis of eighteen marine calcifiers found very different responses for each species (Ries *et al.*, 2009). Some species like the blue crab and American lobster grow shell faster in low pH treatments. However, most organisms responded unfavorably to increasing acidity, particularly bivalve species that constitute important commercial fisheries such as American oyster, soft shell clams, and ocean quahog. Studies have documented decreases in calcification

(or a softening) of shells, decreases in growth, and increases in mortality in marine species (Green *et al.,* 2009; Findlay *et al.,* 2010). Secondly, a change in pH may have metabolic costs such that growth decreases. A decrease in growth of marine calcifiers like American lobster, ocean quahog, and scallops would mean less shellfish meat to sell and eat. There is considerable uncertainty about the degree to which ocean acidification will affect marine organisms, particularly at the time scale of anthropogenic climate change. The NOAA Fisheries Service Science Centers have developed Ocean Acidification Research Plans and are a good source of what is known and what information gaps exist (http://www.st.nmfs.noaa.gov/st7/AcidResearch.html). Although uncertainty exists, the effects of ocean acidification on marine ecosystems could be severe.
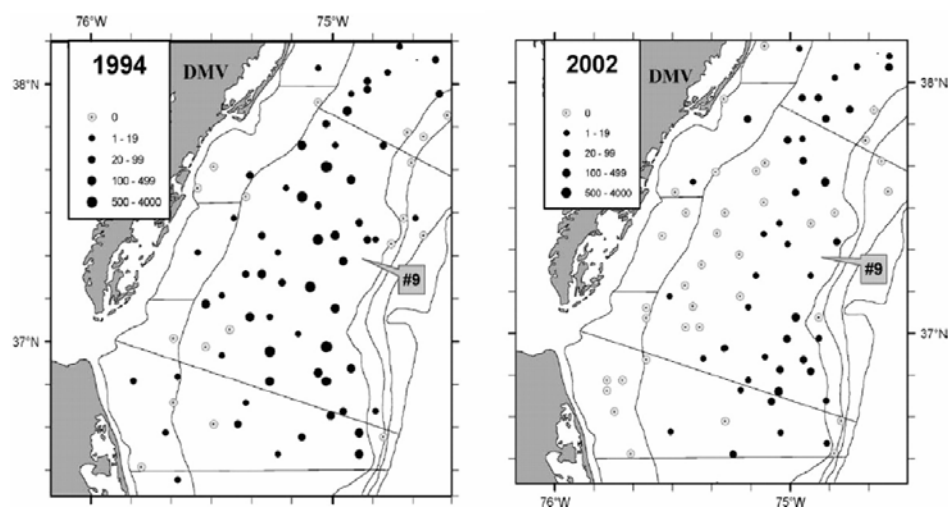
Figure 5.2.2.1. Shift in depth of surfclams *Spisula solidissima solidissima* in response to increasing temperatures in the MidAtlantic (modified from Weinberg, 2005).

Shifts in community structure have been observed in North Atlantic nearshore benthic communities by the synergistic effects of climate change and overfishing. Species invasions by opportunistic species are more common when overfishing occurs in a warming environment (Harris and Tyrell, 2001). Shellfish living in the intertidal zones and in shallow waters are likely to experience mass mortality events brought on by increasing temperatures as such events are already documented when summer temperatures have been anomalously high (Tsuchiya, 1983). Associated with increased water temperatures may be an increase in the prevalence of diseases.

5.2.2.1 Data sources

Local surveys of benthic organisms exist, particularly in Atlantic estuarine waters (http://www.csc.noaa.gov/benthic/mapping/applying/epamaia.htm). However, no analogous surveys exist for offshore regions. Surveys exist to sample benthic macro-invertebrates of commercial importance that are carried out by the Northeast Fisheries Science Center, including a sea scallop *Placopecten magellanicus* dredge survey that occurs in the summer roughly from Cape Hatteras to Georges Bank (http://www.nefsc.noaa.gov/femad/ecosurvey/mainpage/index.html). Recently efforts have been made to quantify the abundance and distribution of macroinvertebrates, particularly sea scallops, which also collect more refined information on benthic organisms and habitats using mobile (http://habcam.whoi.edu/) and fixed (e.g., Adams *et al.*, 2010) camera devices.

5.2.3 Fish

Temperature is a controlling factor in fish physiology (Fry, 1971) and numerous examples exist to illustrate the effect of temperature on fish consumption, metabolism, and growth, many of which are species specific. With an increase in temperature a northward shift in species distribution is expected and has been observed in the Northwest Atlantic (Nye *et al.*, 2009, Overholtz *et al.*, in press). Species are also expected to move to deeper depths to remain within their preferred temperature range (Nye *et al.*, 2009, Dulvy *et al.*, 2008). A shift to deeper depths may be the dominant response in the Gulf of Maine and Gulf of Mexico because northward movements of

fish are limited by these coastlines. Declines in growth rates and reproductive success are expected for cold water species especially at the southern limit of their range (Fogarty *et al*., 2007), but the opposite might be expected for warm water species at the northern extent of their range (Hare *et al*., 2010). These changes in productivity for species at the edges of their ranges will also manifest itself in shifts in distribution and species composition.
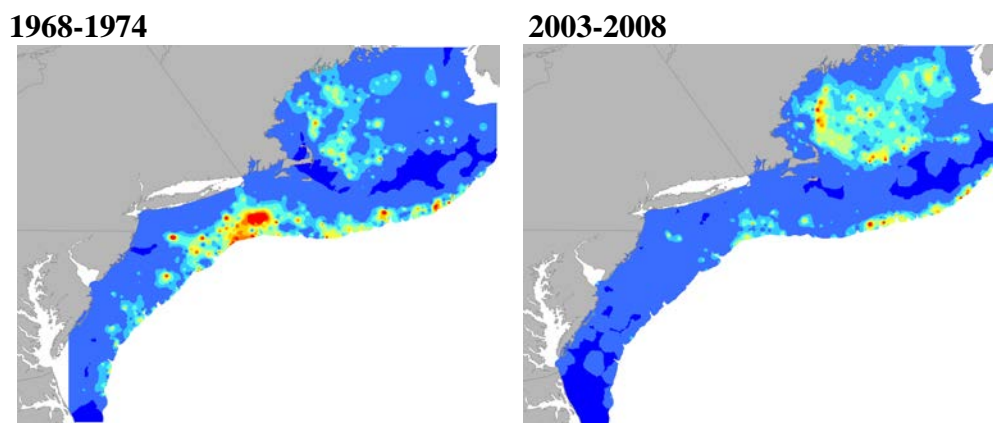
1968-1974   **2003-2008**

Figure 5.2.3.1. Shift in red hake biomass from (left) 1968-1974 to (right) 2003-2008. Red indicates highest biomass, dark blue lowest biomass.

Salinity and dissolved oxygen are also known to affect growth rates of fish, but to a lesser degree than temperature (Niklitschek and Secor, 2005). For coastal and estuarine species salinity will change more dramatically with changes in precipitation and land runoff, having a profound effect on growth and production. However, for marine species salinity will not change enough to elicit such a direct response. For marine fish, changes in salinity and consequent changes in stratification will affect primary production and the prey resources upon which fish depend. Changes in wind patterns will most directly affect dispersal and recruitment of marine fish and invertebrates (Checkley *et al*., 1988; Montane and Austin, 2005). There are numerous examples of reduced growth rates in temperate marine and estuarine fish mainly as a consequence of chronic hypoxia caused by eutrophication (Eby and Crowder, 2005). Eutrophication will likely intensify at high latitudes where precipitation and extreme rainfall events is expected to increase and will exacerbate the effects of eutrophication. At low latitudes, frequency of drought is expected to increase, which might to some extent mitigate the impact of eutrophication and low dissolved oxygen levels on fish. In the open ocean, oxygen minimum zones have been expanding. Whether due to expanding oxygen minimum zones in offshore waters or hypoxia in coastal waters, even a modest decline in ocean oxygen levels may reduce thermal tolerance (Portner and Knust, 2007) and growth rates of fish (Munday *et al*., 2009b).

Ocean acidification has been shown to reduce growth and cause mortality in fish only at levels well outside the level expected as a result of anthropogenic climate change (see Fabry *et al*., 2008 for comprehensive review across all trophic levels). Nonetheless, declines in pH have been shown to inhibit tropical fish from settling on coral reefs and these fish engage in risky behaviors, making them more vulnerable to predators (Munday *et al*., 2009). Thus, the greatest effect of ocean acidification on fish will likely result from expected changes in primary productivity (bottom-up processes) or from higher predation rates (top-down processes).

Reduced sea ice will indirectly affect fish via changes in circulation and stratification especially as a result of changes at lower trophic levels. An increase in sea ice melt

has been shown to elicit a southward shift in distribution of high latitude fish (Mueter *et al.*, 2008). Reductions of sea ice may also create more coastal habitats for some marine species, for example, salmon in the Arctic.

5.2.3.1 Data sources

Bottom trawl surveys that collect information on fish and macroinvertebrates have been conducted by the Federal agencies in the US (Autumn: 1963-present, Spring: 1968-present) and by Canada (July: 1970-present, February since 1980s on Eastern Georges Bank, since 1970s on Grand Banks and Labrador Shelf (see Figure 6.2.5.1)). Nearly all states in the US from Maine to North Carolina conduct trawl surveys to sample fish and macroinvertebrates in more nearshore habitats including bays and estuaries. Many of these surveys are conducted such that seasonal information is available, but the time series are usually of shorter duration (since the 1980s). South of Cape Hatteras, the SEAMAP program samples fish using various sampling techniques and includes three operational components, SEAMAP-Gulf of Mexico, which began in 1981, SEAMAP-South Atlantic, implemented in 1983 and SEAMAP-Caribbean, formed in 1988 (http://www.gsmfc.org/default.php?p=sm_ov.htm).

5.2.4 Marine birds

The term 'marine birds' broadly includes all bird species that rely on or are typically associated with marine habitats. To avoid systemic bias against some species, the term 'seabird' is avoided. 'Marine birds' as used herein includes the following bird orders: Anseriformes (e.g., waterfowl), Charadriiformes (e.g., alcids, gulls, terns, shorebirds), Gaviiformes (e.g., loons), Podicipediformes (e.g., grebes), Procellariiformes (e.g., fulmars, shearwaters, storm-petrels), Pelecaniformes (e.g., pelicans, frigatebirds), Phaethontiformes (e.g., tropicbirds), and Ciconiiformes (e.g., herons, storks). The most productive marine habitats are typically associated with localised ocean upwelling or where nutrient-rich freshwater from terrestrial systems enters the marine environment. Such sites are often known to support both large numbers and high diversities of marine bird species, including shorebirds, waders, waterfowl and seabirds. Birds occupying marine habitats face threats related to commercial fishing, pollution, habitat loss and alien species invasions. More recent data derived from studies where marine birds breed, tracking studies, as well as land-based, aerial, and ship-based coastal and pelagic surveys, have revealed direct and indirect effects (Mitchell and Frederiksen, 2008) of climate change on marine bird distribution (Mitchell *et al.*, 2004), abundance (Irons *et al.*, 2008), reproductive success (Thompson and Ollason, 2001; Sandvik and Erikstad, 2008) and survival (Harris *et al.*, 2005; Sandvik *et al.*, 2005). Repercussions of climate change effects are expected first at species range limits (Montevecchi and Myers, 1997) and have been quantified at breeding locations (Gjerdrum *et al.* 2003; above refs), within waters adjacent to breeding colonies (Mitchell *et al.*, 2004), at migration and wintering sites (Quillfeldt *et al.*, 2010), and broad pelagic habitats (Péron *et al.*, 2010). However, because most marine birds are long-lived, responses to important climate change effects could take many years before being expressed, and detected (Thompson and Ollason, 2001).

5.2.4.1 Data sources
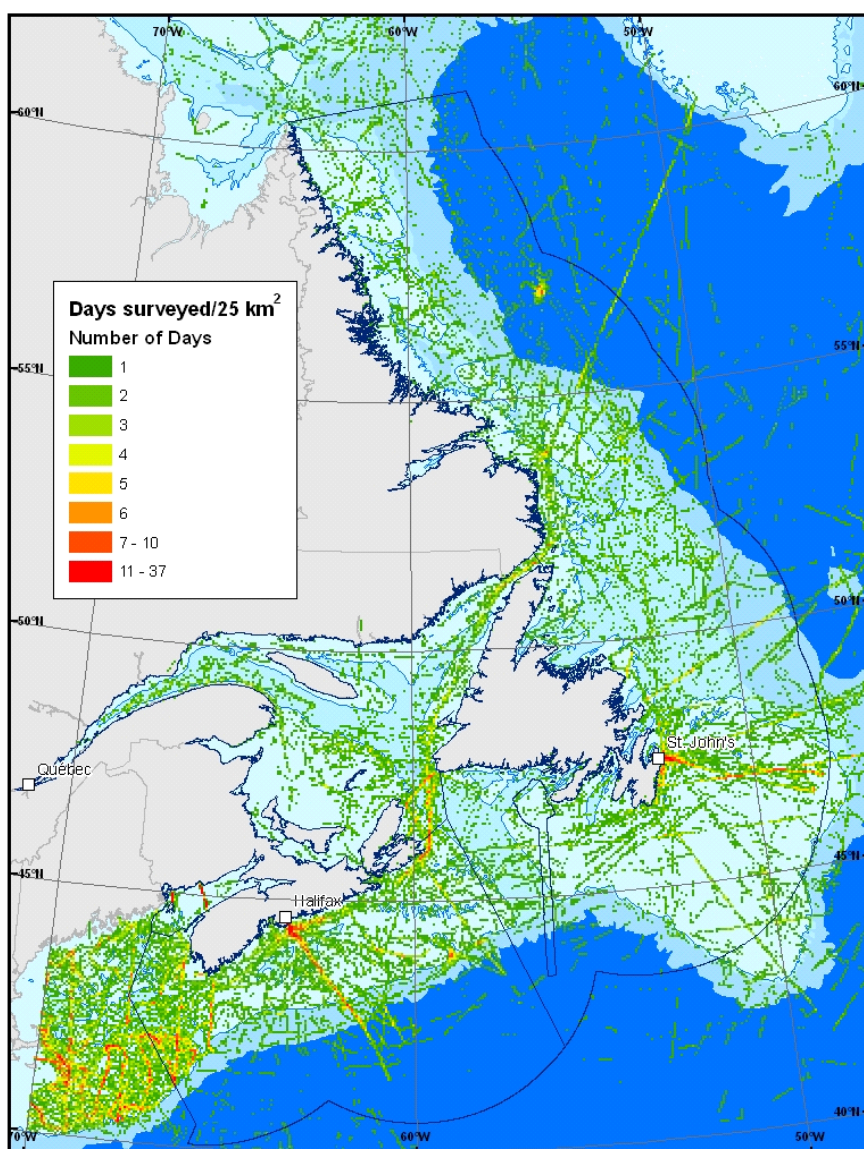
Figure 5.2.4.1. Survey effort for the Environment Canada Seabird at Sea (EC SAS) database, including data from the earlier Programme Intégré de Recherches sur les Oiseaux Pélagiques (PI-ROP). Some data coverage exists that extends beyond the map area (GoM and Arctic, for example).

Time-series data are required to assess responses to stressor effects across species. Large spatial scale time series data include the US Fish and Wildlife Service North American Waterfowl Survey that spans parts of Mexico, the US and Canada. The US FWS Migratory Bird Program conducts aerial and ground surveys of shorebirds, migratory birds, and waterfowl (samigbird.ncusfws.org). The Canadian Wildlife Service of Environment Canada manages active monitoring programs that populate databases including: Colonial Waterbird databases for the Gulf of Saint Lawrence and Atlantic Canada (colonies of seabirds, eider ducks and waders), aerial Coastal Survey databases (geese, dabbling ducks, bay ducks and sea ducks), Seabirds at Sea database with coverage extending from the Arctic to Cape Cod and out beyond Canada's Ex-

clusive Economic Zone, Beached Bird Survey database (Newfoundland) and the Atlantic Canada Shorebird Survey database. In many instances, data gathering efforts are shared and assessed across state, provincial and national jurisdictions through collaborative joint ventures (Atlantic Coast Joint Venture, Sea Duck Joint Venture, Eastern Habitat Joint Venture, Black Duck Joint Venture). Other valuable large spatial and temporal scale datasets originating from international non-governmental initiatives include large repositories of bird sightings (ebird.org) and breeding bird atlases (http://www.bsc-eoc.org/norac/atlaspubld.htm). Bird Studies Canada also has undertaken beached bird surveys, and hosts the Canadian Migration Monitoring Network (bsc-eoc.org).

5.2.5   Turtles

Sea turtles are long-lived species, with a complex life cycle that includes long migrations, different types of habitats and physiological characteristics that make them vulnerable to drastic changes in the environment. Therefore, climate change can affect different stages of their life cycle in two important phases: land and ocean.

Sea turtles have survived a long history of climate changes in the past. However, current added pressures, mainly from human origin, such as pollution, hunting, or coastal development have depleted many populations in a way that might hinder their resilience and enhance the detrimental effects of climate change.

On land, nesting habitat will be under pressure from elevated sea surface temperatures (SSTs), the subsequent rise of sea level, and changes in the hydrogeological cycle or storm events, such as hurricanes, which have the potential to impact the abundance of sea turtles if their breeding beaches are disturbed or lost. Some sea turtle populations with weaker nesting site fidelity might find other areas, but these new areas probably will not have the same physicochemical conditions and may be unsuitable for incubation. In any case, conditions such as incubation temperature might not allow for a stable population (e.g., due to skewed sex ratios or poor hatching success).

For the oceanic environment, an increase in the temperature of the water can affect distributions of turtles. Changes in sea surface temperature and oceanic circulation patterns can alter the timing of migratory movements and foraging behaviors, with subsequent effects on reproductive rates and timing of reproduction.

Climate change can also have an indirect effect on sea turtle populations by affecting the abundance and distribution of food sources. Factors like ocean acidification, changes in stratification, thinner mixed layers, hypoxia areas and eutrophication could lead to increased or decreased primary and secondary productivity which will impact the food availability for sea turtles.

Data sources for sea turtle abundance, distribution, and life history events such as feeding and mortality are limited relative to some other marine species. Due to the pelagic nature and transboundary distribution of many sea turtles (particularly males) annual stock assessments for specific feeding areas, or range-wide, are rarely available. Also, since for most turtle species there is a lack of multi-decadal population census data, detection of population trends related to climate change or other factors will be difficult, except for those species where reliable beach counts are conducted for breeding females, which would provide at least an abundance index of adult females.

Most conservation efforts occur at nesting beaches, but recently there have been initiatives to monitor and protect foraging and development in marine areas. Five sea turtle species have important nesting beaches or foraging areas in the Gulf of Mexico U.S. Atlantic and Mexican Caribbean. Some of these areas are protected or have been internationally recognized for their ecological importance (as Ramsar Sites).

5.2.5.1 Data sources

For information on the abundance and distribution of turtles in U.S. waters, including ESA status reports, stock assessments, recovery plans, and other literature, see http://www.nmfs.noaa.gov/pr/species/turtles/ or http://www.sefsc.noaa.gov/seaturtlepublications.jsp. Individual researchers' data are also available, with permission, at OBIS - http://www.iobis.org/, a permanent repository for spatially referenced data on turtle sightings and satellite tagging information. Tagging data and other sea turtle information is also available at http://www.seaturtle.org, and http://gturtle.net.

The Canadian Department of Fisheries and Oceans is a partner of the Canadian Sea Turtle Research Project (http://webdev.ucis.dal.ca/ramweb/cstrp, which monitors the distribution, movement, and population dynamics of leatherbacks and other sea turtles in Canadian waters. As part of this collaboration, the Department is working to demonstrate the importance of protecting juvenile and adult turtles to ensure their survival.

In Mexico, the National Commission for Natural Protected Areas (CONANP, Comisión Nacional de Areas Naturales Protegidas) has established conservation priorities http://procer.conanp.gob.mx/tortugas/sitio/Prioridades.php and compiled information about abundance and distribution of the sea turtles in Mexico http://procer.conanp.gob.mx/tortugas/sitio/index.php. Nevertheless, there are gaps in knowledge regarding Mexican offshore foraging areas, migration routes, genetic composition, sand temperature and sandy beach profiles.

5.2.6 Marine mammals

Some cetacean species will experience more important changes in climatic conditions than others because of their life history characteristics. For example, since harbour porpoises, *Lagenorhynchus* species, and the genus *Cephalorhynchus* prefer cooler and shelf waters, they may exhibit changes in distribution or abundance as a result of warming temperatures (MacLeod, 2009). Habitat selection by a number of rorqual species (blue, fin, humpback and minke whales) has been shown to be a function of the location of thermal fronts in the Gulf of St. Lawrence (Doniol-Valcroze *et al.*, 2007). This is likely a general phenomenon for cetaceans so that changes in the sea surface temperature due to climate change could result in widespread changes in distributions. Analysis of a sighting series of deep water cetaceans in the context of sea surface temperature indicated that diversity increased with temperature, although the predicted response for a warming ocean was a decline of cetacean diversity and resilience across the tropics and increases at higher latitudes (Whitehead *et al.*, 2008). A recent analysis of the Scottish cetacean stranding record since 1948 (MacLeod *et al.*, 2005) showed the local cetacean community structure to be driven by increases in local water temperature. The authors concluded that if such temperature trends continue, some formerly abundant cold-water species, such as white-beaked dolphins, may be lost from this cetacean community and more warm water species had been recorded in recent years. In a wider context, such changes may lead to populations of cetaceans moving out of areas specifically designated for their protec-

tion as they respond to changes in local oceanic conditions. It has also been suggested that increasing sea water temperatures may increase the risk of infectious disease transmission and host–pathogen associations in Arctic marine mammals due to altered pathogen transmission or host resistance (Burek *et al.*, 2008).

Reductions in sea ice cover could be a significant driver for changes in polar bear and seal habitat, seal breeding and whale distributions, and could protect some whale, pinniped and fish species from predation by air-breathing predators such as killer whales (e.g., Stirling *et al.*, 1999; Ferguson *et al.*, 2000; Stirling, 2000; Smith and Harwood, 2001; Wiig *et al.*, 2003; Higdon and Ferguson, 2009). The distribution of air-breathing marine mammals can be strongly influenced by the extent and thickness of sea ice. The distributions of bowhead whales in northern regions (e.g., Heide-Jørgensen *et al.*, 2007), and whales (e.g., blue, beluga, minke) and pinnipeds (e.g., harp, hooded, ringed, and grey seals) on the Labrador Shelf and in the Gulf of St. Lawrence, are driven to some extent by ice cover (e.g., Mosnier *et al.*, 2010)

Changes in wind patterns could change the distribution (i.e., the ice cover could be reduced or eliminated locally (e.g., Thorndike and Colony, 1982; Stenson *et al.*, 2009) and form (i.e., strong winds could cause pan ice to break into pieces too small to support breeding seals) of sea ice in both coastal and offshore areas in ways that could be detrimental to the breeding success of pinniped species that give birth to and nurse their pups on ice substrates (e.g., harp, hooded, ringed, grey and bearded seals).

Hester *et al.* (2008) proposed that ocean acidification will result in significant decreases in marine sound absorption for frequencies lower than ~10 kHz. If this occurs, ambient noise levels in the marine environment would be expected to increase, with potentially negative impacts on marine mammals which use sound for communication, navigation, and hunting.

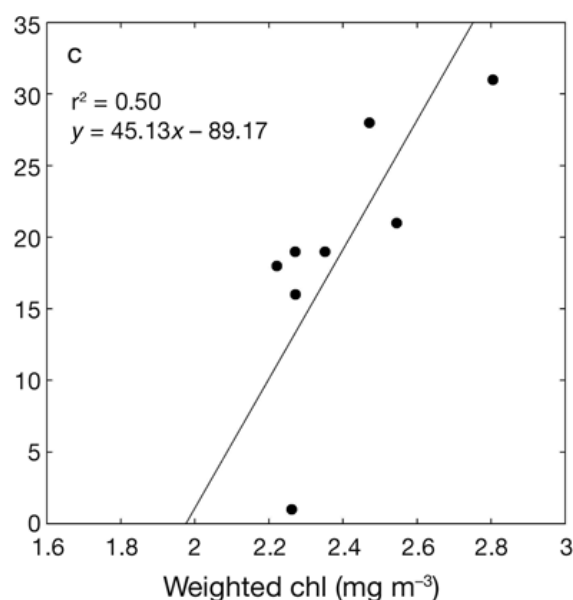
Figure 5.2.6.1. Relationship between the number of calves observed and the 2 year average of chlorophyll (modified by Hilsta *et al.*, 2009).

North Atlantic Right whale distribution and calf productivity is strongly correlated with changes in chlorophyll a (proxy for phytoplankton) concentration in time and space, presumably via effects on the intermediary between these tophic levels, the

copepod (*Calanus finmarchicus* Hlista *et al.*, 2009). Thus, changes in Chl*a* resulting from climate change will likely be reflected in the right whale population (Figure 5.2.6.1).

5.2.6.1 Data sources

Data sources for North Atlantic right whale abundance, distribution and life history events such as calving and mortality are available at http://rwcatalog.neaq.org. A recent North Atlantic right whale stock assessment can be found at http://www.nefsc.noaa.gov/nefsc/publications/tm/tm213/pdfs/F2009NARW.pdf. Canadian right whale, beluga whale and other marine mammal sightings are available for the Maritimes Region at http://www2.mar.dfo-mpo.gc.ca/sabs/speciesatrisk-especesenperil/sardata-eng.html. Data for other Atlantic areas are not yet available on the web, but can be accessed through contact with Department of Fisheries and Oceans (DFO) researchers in the Gulf of St. Lawrence, Newfoundland and Labrador, and the eastern Arctic (see researcher listings at http://www.dfo-mpo.gc.ca/science/coe-cde/cemam/index-eng.html).

Despite annual stock assessments for US marine mammals (http://www.nefsc.noaa.gov/nefsc/publications/tm/tm213/) there is a serious lack of multi-decadal marine mammal population census data, reflecting a lack of year-by-year consistent survey effort in time and space. A recent study (Pyenson, 2010) of the linkage between survey data and stranding data on the US west coast showed that 'the stranding record samples the living cetacean community with high fidelity, across fine and coarse taxonomic ranks, and at large geographic scales (1000 km of coastline). The stranding record is also richer than the live surveys, with live-dead ratios between 1.1 and 1.3. The stranding record recovers similar rank-order relative abundances as live surveys, with statistical significance.' Therefore, where there is a significant marine mammal stranding record, such as in the US east coast since the 1970's, the data provide a useful source, in addition to survey data, for assessing change in population size and distribution in the context of a changing climate. Analysis of the NOAA Marine Mammal Stranding Database https://mmhsrp.nmfs.noaa.gov/msdbs/ for spatial and temporal trends in the context of indicators relevant to climate change would enable a detailed analysis of historical patterns of abundance changes.

In Atlantic Canada, there are relatively few multi-decadal marine mammal surveys, except for several pinniped species (e.g., harp seals, hooded seals, grey seals) and beluga whales in the Gulf of St. Lawrence. DFO has a mandate to monitor these populations and results of the assessments are available on the web (Canadian Science Advisory Secretariat at http://www.dfo-mpo.gc.ca/csas/), and in the primary literature (e.g., Lesage and Kinglsey, 1998; Lawson and Gosselin, 2009; Hammill and Stenson, 2010).

5.2.7 Plants–mangroves and seagrasses

The term "mangrove" can refer to either the ecosystem or individual plants. Individual mangrove species have varying tolerances to physical variables related to climate. There are five main species in the southern ecoregions. Mangrove species zones are related to shore profile, soils, and salinity, and changes in these can lead to changes in mangrove species composition. One indirect impact on mangroves of increased temperature and CO_2 is the degradation of coral reefs caused by mass bleaching and impaired growth (Hoegh-Guldberg, 1999). Damage to coral reefs may adversely impact mangrove systems that depend on the reefs to provide shelter from wave action.

A national inventory of mangroves has monitored the health and status of mangroves in Mexico over the past three decades that will be used to monitor the health of the ecosystem in the future (CONABIO, 2009). More information can be found at: http://www.biodiversidad.gob.mx/ecosistemas/manglares/manglares.html

Recent declines in sea grass habitats that have been observed can at least be partially attributed to climate variability such as increased temperatures, losses from changes in bird migration patterns, and changes in storm patterns. However, there may be some positive effects of climate change on aquatic plants. Sea level rise will increase leaf size with greater water depth and there may be increases in production with an increase in atomospheric carbon dioxide. By far the greatest impacts on seagrass habitat result from anthropogenic effects other than climate change, such as deforestation, sedimentation, nutrient pollution, shoreline hardening, dredging, boating, and fishing (Short and Neckles, 1999). Figure 5.2.7.1 explains the potential effects of sea level rise and a change in sedimentation that would change the elevation of coastal seagrass and marsh habitat. Sediment supply could be low either due to drier conditions under climate change and/or if the human demand for freshwater increases. At high latitudes an increase in precipitation is expected, leading to high sedimentation rates and tightly packed substrate. As sea level rises and storm events are more frequent and extreme, submerged plants and marshes are more likely to remain attached. However, if sediment supply is low, plants will not be firmly rooted in the bottom substrate making it easier for them to be displaced in a storm event. The sediment supply is especially important because shifts in distribution to adapt to climate change may be inhibited by bluffs, coastal development, or other hard substrate that are unsuitable for aquatic plants.

In the Caribbean ecoregions (ecoregion 13, 14, 15) there are 10 species of seagrasses, but the most common are turtle grass (*Thalassia testudinum*), manatee grass (*Syringodium filiforme*), and shoal grass (*Halodule wrightii).* A recent global assessment indicates that about one-third of the seagrass area has been already lost, and that these losses are accelerating, from less than 0.9% per year in the 1970's to more than 7% per year since 2000 (Waycott *et al.*, 2009).

Seagrass monitoring at Cape Cod National Seashore (NS), Fire Island NS, and Assategue NS (ecoregion 7) provides these parks with information on changing distribution of seagrass resources and site-specific trends in habitat characteristics. This information is valuable for assessing system-wide responses to estuarine nutrient enrichment and on the overall condition of seagrass resources throughout park estuaries. The Northeast Coastal and Barrier Network (NCBN) developed an estuarine water quality monitoring program capable of diagnosing local causes of nutrient enrichment, detecting changes in nutrient loads, and determining if nutrient inputs are near to exceeding thresholds that would result in shifts in ecosystem structure and function. Monitoring of seagrass, mangroves, and benthic habitats has been ongoing in Florida since the early 1990s (http://www2.fiu.edu/~seagrass/).

Low Sediment Supply

High Sediment Supply
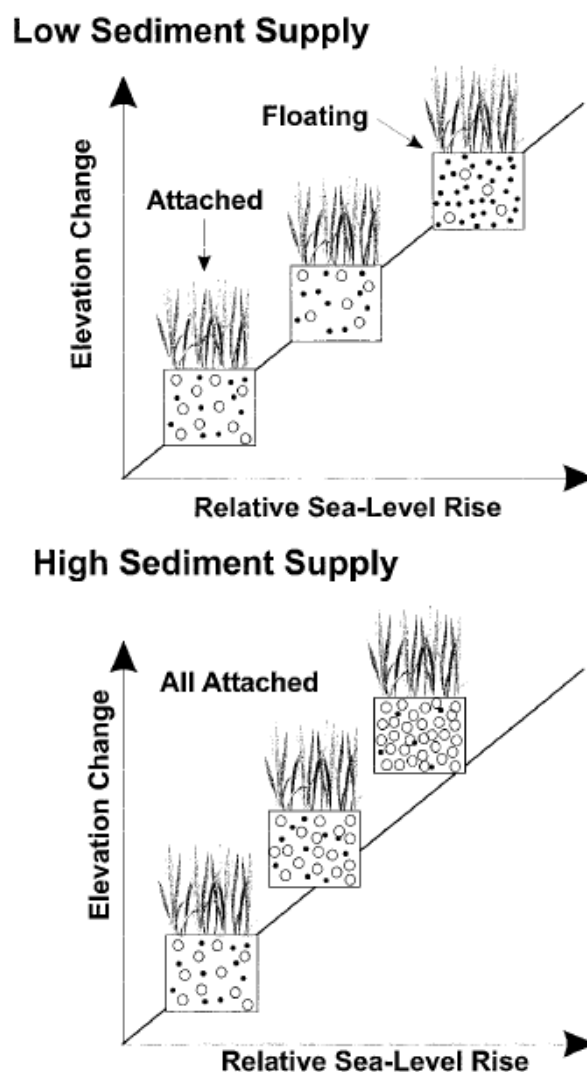
Figure 5.2.7.1. Response of coastal wetlands to concurrent changes in relative sea level (elevation change) and sediment supply. Density of open circles indicates the amount of sediment and black dots indicate the amount of organic matter (modified from Reed (1999) and Scavia *et al*. (2002).

5.2.8   Corals

In the Mexican Atlantic coast (Gulf of Mexico and Caribbean) there are crrently four types of coral reef: atolls, barriers, platforms and fringing reefs. They are located near the coast, with exception of those of the Campeche Bank and Chinchorro Bank in the Caribbean. There are 57 reef building coral species in the Mexican Atlantic, all of them inhabitants of Mexican Caribbean, 42 in the Campeche Bank and 37 in Veracruz.

Elevated temperature have been cited as the cause for the increase in bleaching events (Figure 5.2.8.1), but tropical corals are subject to many stressors in the North Atlantic including increased nutrient input from coastal development and indirect effects of overfishing. The growing incidence of coral diseases, as well as disease prevalence and rate of spread on coral colonies, is attributed to increases in pathogen

prevalence and virulence associated with global warming and low water quality. Reef-building corals are an important ecosystem component because they provide habitat for many species and as such they are discussed in more detail in Section 6.

Some cold-water (azooxanthellate) scleractinian corals form extensive reefs, such as the *Oculina varicosa* reefs on Oculina Bank off eastern Florida or the *Lophelia pertusa* mounds on the slope and rise off the southeastern United States. These reefs thrive at 100s to 1000s of meters water depth, below the photic zone, by capturing food particles from the water column instead of relying on symbiotic zooxanthellae like tropical corals. Because of these differences, it is expected that cold-water corals will respond to climate changes differently from tropical corals.
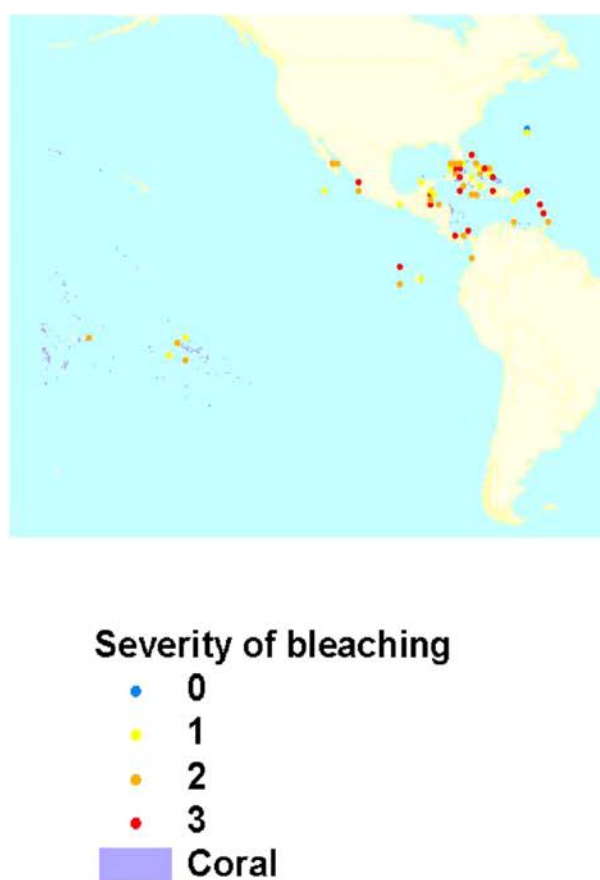
Figure 5.2.8.1. Distribution of coral bleaching events in 1998 which also indicates regions where corals are monitored.

Cold-water corals are thought by some scientists to be more vulnerable to climate changes than their shallow water counterparts (Kleypas *et al.*, 2006; Turley *et al.*, 2007), but physiological data for these species are scarce. Limited laboratory studies on adult reef-building cold-water species showed an increase in oxygen consumption with warming (Dodds *et al.*, 2007), and a reduction in calcification rates with reduced pH (Maier *et al.*, 2009). Several recent studies have documented the effects of ocean acidification on the ability of cold-water corals to create skeletal material (Kleypas and Yates, 2009). Also, temperature changes are thought to produce reproductive changes in cold-water corals (Waller, 2008).

Rising sea level and increasing severe storms, which are serious threats to shallow-water tropical corals, should not have a significant direct effect on cold-water corals.

Because they rely on food carried by currents or falling from above, however, cold-water coral reefs are likely to be affected as much as or more by changes in ocean current regimes than tropical corals.

Little is known about the controls on distribution of cold-water corals, but temperature, salinity, and currents are all thought to have an effect (Cairns, 2007; Guinotte *et al.*, 2006). In high latitude regions where azooxanthellate corals can thrive in shallower waters, loss of sea ice would increase light levels and may allow the overgrowth of algae on substrate originally available to settling by corals. These factors, however, are less important than the depths of the aragonite and calcite saturation horizons (Cairns, 2007). Ocean acidification, in addition to having a deleterious effect on existing reefs, is likely to change the geographic distribution of cold-water corals.

5.2.8.1 Data sources

A consensus among U.S. coral reef scientists and managers is that their current ability to monitor both coral reef condition and threats are inadequate for protection (Guerry *et al.*, 2005). Considerable expense is associated with data collection on coral reefs requiring non-destructive sampling techniques (unlike dredging and trawling that can be used for sampling other benthic organisms and fish for example). Sonar mapping technology has now been used to create benthic habitat maps that accurately depict hard bottom substrate that could be colonized by corals (Rohmann *et al.*, 2005; NOAA, 2009a). These maps are useful because they identify limits and extent of potential coral reef areas and provide an essential tool to identify coral reef monitoring locations. In some cases, sonar mapping can detect hard bottom areas covered with sediment; corals may have previously inhabited these areas (Bradley *et al.*, 2010).

The USGS Cold-Water Coral Geographic Database (CoWCoG) provides a tool for researchers and managers interested in studying, protecting, and/or utilizing cold-water coral habitats in the Gulf of Mexico and western North Atlantic Ocean (Scanlon *et al.*, 2010). The database makes information about the locations and taxonomy of cold-water corals available to the public in an easy-to-access form while preserving the scientific integrity of the data. The database includes over 1700 entries, mostly from published scientific literature, museum collections, and other databases (http://pubs.usgs.gov/of/2008/1351/title_page.html).

5.3 Partitioning alternative causes of changes in distribution and abundance

The effects of climate on ecosystem components discussed below are based on the modes of variability and potential effects of anthropogenic climate change discussed in Section 5.1. Much of what is expected to happen in terms of long-term climate change is based on historical analysis of the effects of climate variability on various ecosystem components. The effects of many factors, in particular temperature and stratification, are well-studied such that the responses of marine organisms to these effects can be commented upon with confidence. In contrast, data on the effects of ocean acidification has only recently started to accumulate. The cumulative effects of multiple interacting physical changes associated with climate on ecosystem components, is more difficult to predict. Furthermore, the interaction among various ecosystem components may yield unexpected results. Coordinated research and sampling programs amongst the various ecosystem components is needed to understand the ecosystem effects of climate change, as was discussed in Section 3.

Alternative stressors on various ecosystem components include:

- previous harvest from which recovery is ongoing;

- changes in ongoing harvest driven by regulatory or economic parameters;

- fishery by-catch;

- changes in non-intentional mortality and morbidity factors such as, vessel collisions and acoustic stressors (vessel noise, seismic survey, and military sonar) for marine mammals;

- lack of prey or predatory release associated with fishing practices;

- toxicant impacts on reproductive success; and changes in terrestrial use patterns that change coastal water and benthic quality through riverine, outfall, or atmospheric input, such as altered loads of fresh water, nitrogen, silt, oxygen consuming biota, and toxicants.

One aspect of the above that is partially linked to climate change is the propensity of coastal development to change location as seasons and weather patterns change, opening up new areas for commercial and recreational uses. Such changes will be enabled by climate change, but controlled by economics and evolving cultures. Partitioning such changes versus climate change in terms of causation versus correlation is extremely difficult. Necessary data include: the degree to which each stressor has changed through time; a mechanistic understanding of how such change alters distribution and abundance; and the integration of all such stressors into a predictive model that recognizes the primary forcing factors. In this way the role of climate change versus other stressors might be evaluated using methods discussed in Section 7. We stress that the effects of climate and the many stressors identified above interact to have additive, synergistic, or even antagonistic responses at both the species and ecosystem level.

Longer time series on abundance and distribution are available at higher trophic levels such as fish and macroinvertebrates of commercial value and marine mammals, the latter because stranding records are useful indices of abundance (Pyenson, 2010), and these records are available throughout the area of interest. The organisms at these trophic levels also reflect the integrated effects of climate, as illustrated in the way in which right whale breeding success is correlated with chlorophyll concentration in the preceding two years. The terms of reference specified a need for information on seasonality. Seasonal information has been presented, or noted where it exists, for various ecosystem components, but time series for seasonal data are severely lacking. In general there are instead isolated seasonal studies at various trophic levels over relatively short periods of time. Identification of this data gap is important because one of the most likely and important ecosystem effects may be a change in the timing of ecological events, including the timing of phytoplankton blooms and zooplankton abundance peaks and the timings of seasonal migrations and reproduction at higher trophic levels (see Section 3).

5.4 Summary of key atmospheric, oceanographic and biological properties related to climate

A table summarizing the generalized effects of climate-driven oceanographic change on key ecosystem components (Table 5.4.1) illustrates a number of key points:

- Changes in distribution are expected across all trophic levels.

- Decreases in primary productivity are expected in low latitude ecosystems, but increases in primary productivity are expected in high latitude systems.

- The greatest impacts of climate change are likely to be changes in trophic interactions.
- Top predators can be seen as integrators of lower trophic level processes for which less data exist.
- Data gaps are greater at low latitudes, at high latitudes (Arctic), and for offshore ecosystems.
- To understand the effect of multiple stressors on an ecosystem, coordinated research and data collection are needed at and across all trophic levels.

Table 5.4.1. Generalized effects of climate driven oceanographic changes on components of the ecosystem. Colors indicate the likelihood of the response where blue indicates "extremely likely", green indicates "more than likely", red indicates likely, and unknown effects are indicated with ?. The expected effects are described at the scale of ecoregion or broader, recognizing that effects will vary at smaller spatial scales and that some effects will not directly affect some ecoregions (i.e. ice melt will not directly affect tropical species, but may indirectly affect them via changes in global circulation). "Changes in vital rates" refers to changes in growth, reproductive success, and/or mortality that ultimately change population abundance and the relative increase/decrease in vital rates is not specified because the direction and magnitude of the change in vital rates is species specific.

	ECOSYSTEM COMPONENTS								
PRESSURE	PHYTOPLANKTON	ZOOPLANKTON	BENTHOS	FISH	MARINE MAMMALS	TURTLES	MARINE BIRDS	MANGROVES AND SEAGRASSES	CORALS
Increase in Temperature (water and/or air)	Smaller average size; Dominance of smaller species; Changes in vital rates	Increases in jellyfish abundance; Increases in metabolism, growth and development; Trophic effects lead to reduced condition	Northward shift in distribution; Shifts to deeper depths; Change in vital rates; Mass mortality events in sessile species; Increased disease	Northward shift in distribution or shift to deeper depths; Change in vital rates	Change in vital rates dependent on prey response; Thermoregulation issues	Changes in distribution, timing of migration and reproduction; Change in hatching sex ratios and change in vital rates dependent on prey response	Change in migratory timing and routes; Changes in distribution; Indirect effects of invasive species; Thermoregulatory stress	Change in species composition and distribution	Bleaching and decrease in calcification leading to mortality in many cases; Changes in vital rates; Shifts in distribution
Intensification of hydrological cycle	Changes in primary production in coastal waters. Increase in nutrient runoff lead to increases in HABs	Increased sediment loading impairs feeding in coastal species; HABs may/may not impact zooplankton vital rates.	Changes in salinity will affect growth especially in coastal areas	Resulting salinity affects growth especially in coastal areas; Changes in reproductive success leading to changes in species composition	Change in vital rates dependent on phytoplankton response particularly HAB	Destruction of nesting habitat	Reduction in breeding habitat and nest sites; Increased incubation time, wetting, thermoregulation of young, development, increased pollutants and sediment in coastal breeding habitats	Changes in sedimentation rate will decrease light availability and negatively affect productivity of seagrasses	Increased incidence of bleaching leading to mortality in many cases; Salinity will affect health, algal smothering

	ECOSYSTEM COMPONENTS								
PRESSURE	**PHYTOPLANKTON**	**ZOOPLANKTON**	**BENTHOS**	**FISH**	**MARINE MAMMALS**	**TURTLES**	**MARINE BIRDS**	**MANGROVES AND SEAGRASSES**	**CORALS**
Changes in stratification	Primary production increases in northern and decreases in southern and shelf regions. Earlier and more intense spring blooms at temperate latitudes, change in species composition	Follows changes in primary production	Change in flux of organic material to benthos, leading to changes in productivity	Change in vertical position of pelagic eggs and larvae; Change in trophic interactions	Change in sound propagation affecting communication and predator avoidance Reduced feeding opportunities	Changes in vital rates dependent on prey availability	Changes in vital rates dependent on prey availability ?	Negligible for mangroves, but perhaps reduced light availability for seagrasses ?	Changes in light availability, shifts in distribution Shifts in distribution
Increase in sea level	?	?	Increase in habitat for coastal species	Increased habitat for coastal species	Enhanced coastal margin habitat for manatees	Change in availability of nesting sites	Flooding of low-lying breeding habitat; Change in breeding cycle; Change in quality of intertidal habitat	Decline in species diversity; Change in species composition and distribution; Increase blade size of seagrass	Change in light availability and vertical migration; Drowning in tropicals; Shifts in distribution

	ECOSYSTEM COMPONENTS								
PRESSURE	PHYTOPLANKTON	ZOOPLANKTON	BENTHOS	FISH	MARINE MAMMALS	TURTLES	MARINE BIRDS	MANGROVES AND SEAGRASSES	CORALS
Change in wind patterns, storm tracks and hurricanes	Increase in vertical mixing leads to increase in spring primary production	Increased growth and development if primary production increases	Effects on pelagic egg and larval dispersal which affects recruitment	Effects on pelagic egg and larval dispersal which affects recruitment	Shift in pinniped ice breeding substrate; Increase in stranding rates; prey availability	Disturbance of nesting and foraging; Effects on hatchling success	Change in prey availability, change in distribution and migration timing, destruction of breeding habitat, reduced breeding success	Destruction of these habitats in severe storms and hurricanes	Destruction of reefs in severe storms and hurricanes
Changes in ocean circulation patterns	Northward shift of warm-water speces, introduction of Pacific species from Arctic	Northward shift of warm-water speces, introduction of Pacific species from Arctic, increase in diversity in northern latitudes	Northward shift in warm-water species, change in larval dispersal and population connectivity	Northward shift in warm-water species, change in larval dispersal and population connectivity	Altered migratory and residency patterns, altered prey availability will affect vital rates	Changes in vital rates dependent on prey availability, Changes in migratory routes	Changes in vital rates dependent on prey availability	Change in seed dispersal	Change in larval dispersal and in reef connectivity leading to shifts in distribution, Change in food availability
Ocean acidification	Reduced production of calcifying phytoplankton and possible extinction	Reduced production of calcifying organisms if unable to form skeletal structures and possible extincttion	Lower growth and decrease in shell strength of benthic calcifiers	Little change in growth or mortality, but reduced ability to settle on coral reefs and avoid predators	Better sound propagation, changes in prey availability and abundance	Change in vital rates dependent on prey availability	Change in vital rates dependent on prey response	?	Decreases in calcification rates, change in reproduction, decrease in food availability

	ECOSYSTEM COMPONENTS								
PRESSURE	PHYTOPLANKTON	ZOOPLANKTON	BENTHOS	FISH	MARINE MAMMALS	TURTLES	MARINE BIRDS	MANGROVES AND SEAGRASSES	CORALS
Increase in oxygen minimum zones/Hypoxia	No effect	Species distributions may change, Jellyfish become more prevalent	Increase in mortality due to coastal hypoxia, change in species composition and distribution	Decrease in habitat, reduced growth and thermal tolerance, change in vital rates dependent on prey availability	Change in vital rates dependent on prey availability	Change in vital rates dependent on prey availability	Change in vital rates dependent on prey availability	Negligible for mangroves, but increased shading of seagrasses as a result of hypoxia	Negligilbe for tropical corals, but habitat reduction and mortality in cold water corals
Reductions in sea ice cover	Change in species assemblage, earlier pelagic blooms, Higher primary production	Change in species assemblage, increased production	Change in species composition, Predatory release	Southward shift of Arctic species, increase in available coastal habitat in North	Reduced polar bear and seal habitat including seal breeding habitat	No effect	Earlier arrival of birds, loss of breeding habitat, changes in distribution	No effect	No effect in tropical corals, food delivery changes for shallow cold water corals, algal overgrowth
Reduced AMOC (Northward shift of Gulf Stream)	Introduction of warm water species to northern ecosystems	Introduction of warm water species to northern ecosystems	Introduction of warm water species to northern ecosystems	Change in migration, introduction of warm water species to northern ecosystems	Change in vital rates dependent on prey availability	Affects distribution and migration as well as prey availability	Shift in distribution and change in vital rates dependent on prey availability	?	?

5.5 Geology of habitat

Geology is the foundation of habitat; it defines the shape, composition, and physical properties of a habitat. These things, however, are not static; geological processes, such as sedimentation, erosion, or uplift, act to alter the habitat on a wide range of timescales. It is important to have a basic knowledge of geology and geologic processes to understand habitats and how they will be affected by climate change. Three major aspects of geology that are important to habitats and can be altered by climate change are physiography, composition of substrate, and sedimentary processes.

Physiography is the shape of the land or seafloor surface and can be illustrated by topographic and bathymetric maps. Physiographic features are created by tectonic (e.g., plate movements) and geologic (e.g., erosion) processes and evolve through time. Climate change may alter the rate of change of these features or bring different processes to bear. For example, if ocean currents change the rate of erosion of a sediment habitat may change. If sea level rises, formerly subaerial coastal habitats will be subjected to sediment transport processes. When considering the effects of climate change in marine habitats, some types of physiographic feature are particularly important, including (but not limited to: 1) steep slopes, such as those on seamounts (e.g., New England Seamounts) or escarpments (e.g., Blake Escarpment) where upwelling frequently occurs and outcrops of hard substrate provides attachment surfaces for sessile organisms; 2) narrows (e.g., Laurentian Channel) or places where high-relief features (e.g., the Virgin Islands or the Puerto Rico Trench) block or restrict the movement of water or biota; and 3) morphologically complex areas (e.g., Lydonia Canyon and karst areas on the Yucatan Shelf).

The composition of the substrate includes not only the materials comprising the substrate (e.g., rock, mud) but also other physical characteristics such as the state of consolidation of sediment or the degree of weathering of a rocky substrate. Although climate change may not directly affect the composition of a substrate, rising sea level will introduce new substrates to the marine environment. Some examples of important substrates for marine habitats include (but are not limited to: 1) rock substrate, which sessile organisms require and which provides refuge for small and juvenile fish; 2) carbonate rock substrate, which is an example of composition being important since corals prefer carbonate rock for settlement; 3) clay substrate, which is an example of the state of consolidation being important (e.g., tilefish make burrows in clay substrate off the southeast USA, see Section 6.2.9.1.2) and 4) sand substrate, in which species such as red grouper can dig pits on the West Florida Shelf.

Geologic processes continuously modify the seafloor. In some places the processes work very slowly (e.g., dissolution of rock); in other places, the processes may be rapid (e.g., deposition from a submarine landslide after an earthquake). Probably the most ubiquitous geologic processes in the ocean are deposition and erosion due to currents. Changes in the location, direction, or speed of oceanographic currents could have a profound effect on the seafloor geology and hence the seafloor habitats. For example, a rocky substrate swept clean of any sediment by a strong current could be rapidly buried by sedimentary deposits if the current relocates. Similarly, unconsolidated sediment, deposited in a protected basin will be eroded if a rise in sea level were to breach the protective barrier and allow a current to flow through.

The region covered by this report – the ocean areas bordered by eastern North America and parts of the Caribbean Sea – includes a wide range of physiographic features, substrate types, and geologic processes. To support rational management decisions, it

is important that they be mapped and understood, both on the scale of individual habitats and in the larger context of entire ocean basins.

The region is comprised of ten marine ecoregions (Wilkinson *et al.*, 2009) ranging from the Baffin/Labradoran Arctic to Caribbean areas surrounding Puerto Rico and adjacent to the Yucatan Peninsula of Mexico. The general physical and geomorphological features of each ecoregion are summarized in the Marine Ecoregions of North America book.

5.6 References

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6 Species and habitats with crucial ecosystem roles, or those of special conservation concern

ToR d) Provide a list of species and habitats with crucial ecosystem roles, or those of special conservation concern that should be considered in the context of climate change and MPA network design.

i) For species with crucial ecosystem roles, or those of special conservation concern provide a summary of information / data that allows identification of places associated with their major life-history functions including spawning, feeding, nursery areas, over-wintering areas, migration corridors, etc.

6.1 Introduction

The question as posed by Mills *et al.* (1993) – "Can we identify a set of species that are so important in determining the ecological functioning of a community that they warrant special conservation efforts" – concisely reflects our term of reference.

Paine (1969) first coined the term "keystone" but what constitutes keystone or crucial species in an ecosystem is often vague, and determining what species fit the criteria differs among taxa and areas. Nonetheless, it is commonly advocated that keystone species must be an important consideration in the efforts to maximize biodiversity protection (Mills *et al.*, 1993). Clearly, every species within any ecosystem plays a role and thus influences the ecological processes. The challenge is to identify species and habitats that are more influential or not substitutable to those processes. Mills *et al.* (1993) indicated that the presence of keystone species would be crucial in maintaining the organization and diversity within the ecological community. It is implicit that such species are exceptional, relative to the rest of the community, in their importance.

The functional types of keystone species (modified from Mills *et. al.* 1993) that are most relevant to the development of marine protected areas are:

- Predator – Increase in one or several predators/consumers/competitors which subsequently profoundly affect abundance of prey/competitor species. This is usually considered in the context of 'Top Down' control processes.

- Prey – If removed, other species more sensitive to predation may be highly affected. These species maybe of critical importance in maintaining biodiversity as these species essentially 'protect' other species in the ecosystem from depletion, and can be a major path for the movement of energy through the ecosystem food web.

- Link – A link species is one that provides an important ecological function on which the life history processes, i.e., reproduction, recruitment, growth, of other species depends. Migratory animals are also a type of mobile link organism that connect habitats in space and time (see also Section 3.1). They transport nutrients across ecosystem boundaries that may be critical to the productivity of the ecosystem and may be particularly important in determining marine ecosystem resilience.

- Engineer/modifier - Loss or alteration of structures/materials that constitute important habitat and affect energy flow. The classic marine example is coral, which builds the physical structure of the ecosystem through the

calcification processes (see also Section 3.2). Alteration in structure in the marine environment may also include variable physical processes in the water column such as warming of the water, ocean currents and acidification (the actual oceanographic process are discussed in more detail under Section 5, atmospheric, oceanographic and biological information).

Both animals and plants play important roles in structuring ecosystems. In the marine environment, plants are a dominant primary producer but also commonly constitute 'foundation species', i.e., species that provide physical structure to the ecosystem that determines energy flow and defines the habitat (for example kelp, seagrasses and mangroves).

Some species may have multiple, key roles in ecosystems. Coral for example is both a 'foundation species' (i.e., provides important primary productivity) and an ecosystem engineer (an animal that builds the structure of the ecosystem). Multiple roles may also be life-stage dependent. For example, Atlantic cod (*Gadus morhua*), because of its abundance in the larval stage, has a functional role as prey, while as an adult, serves an important function as predator. This is also an example of a species that because of its widespread distribution and very high abundance constitutes a keystone species.

The terms of reference also indicate that crucial ecosystem roles should be considered in the context of climate change. However, this tends to be problematic within the area of interest, the Northwest Atlantic to the Caribbean Sea, where fluctuations in climate rather than trends have been observed in recent years particularly in the northern extent of the study area (Colbourne *et al.*, 2010). In this area, other anthropogenic influences, primarily fishing, may mask oceanographic changes (see Section 5, under oceanographic processes) and key physical attributes other than temperature and salinity are usually temporally and spatially not widely measured. One clear effect of climate warming is the increase in sea level, affecting coastal ecosystems.

6.2 Examples of species and habitats of special conservation concern or with crucial roles in the ecosystem

In this section, we examine species (or grouped taxa) and as well, habitats that are of special conservation concern or have crucial roles in the ecosystem. Section 6 follows on the ecological and oceanographic descriptions put forth under Section 5 in two ways: describing some species and their roles within the general taxonomic groups listed in Section 5, Table 5.4.1 and habitats (benthic and pelagic, physical and biological) providing explicit examples that fit the description of what is crucial. As well, species of conservation concern such as charismatic species or those at risk of extinction are included.

6.2.1   Zooplankton north of the Gulf Stream

Two zooplankton species emerge as having *crucial ecosystem roles* in the Northwest Atlantic north of the Gulf Stream; the copepod *Calanus finmarchicus* and the euphausiid *Meganyctiphines norvegica.* Both of these species are widely distributed and are critical linkages in the trophic structure of the ecosystem, providing food for a range of upper trophic level consumers several of which are commercially important or are endangered. Both species are vulnerable to potential impacts of climate change that would change their distribution.

6.2.1.1 *Calanus finmarchicus*

The copepod *Calanus finmarchicus,* a keystone species in the North Atlantic dominates the zooplankton biomass in oceanic and shelf waters in spring/summer and is found throughout the North Atlantic north of the Gulf Stream, from the Gulf of Maine and Georges Bank in the southwest to the Norwegian and Barents Seas in the northeast (Conover, 1988). Throughout much of its range *C. finmarchicus* has an annual life cycle with reproduction and recruitment occurring in spring and summer. Individuals spend part of the year (generally summer-winter) as pre-adult stage 5 (CV) copepodites at depth in a resting state called diapause. In spring over-wintered individuals migrate up to the surface to moult to adulthood, to mate and to reproduce. Females (Figure 6.2.1.1.1) lay eggs before and/or during the spring phytoplankton bloom (Diel and Tande, 1992; Melle and Skjoldal, 1998; Niehoff *et al.*, 1999; Gislason, 2003; Debes and Eliason, 2006), releasing them into the near surface layers, where they hatch and develop through to the CV stage in summer, when they return to depth, having accumulated a large store of lipid to fuel their metabolism over the winter. Because *C. finmarchicus* diapause in deep water, they are largely absent from shelf waters in winter, and are instead concentrated in adjacent deep waters such as the Gulf of Maine, the basins of the Scotian Shelf, the Laurentian Channel and slope waters along the shelf-break. Ocean currents transport over-wintered *C. finmarchicus* back to the shelves each spring, to start the cycle over again.

Figure 6.2.1.1.1. A *Calanus finmarchicus* female (~ 2.8 mm in body length).

The timing of *C. finmarchicus* reproduction can vary from year-to-year within a given area. In general it occurs earlier in warm years and/or in years with early spring blooms (Head and Pepin, 2008; Head and Pepin, 2010; Head *et al.*; in press). Such inter-annual changes have important consequences for recruitment success of several commercially important fish species, whose larval and juvenile stages feed on *C. finmarchicus* eggs and young life-history stages (e.g., Ellertsen *et al.*, 1989; Brander *et al.*, 2001; Beaugrand *et al.*, 2003; Heath and Lough, 2007). This is because while the timing of phytoplankton blooms and *C. finmarchicus* reproduction can vary by up to 6 weeks or more, spawning times for fish are less variable. If these events are not well matched in time (i.e. are "mis-matched" *sensu* Cushing, 1990) recruitment is poor. In

the future, if temperatures rise, it seems likely that there will be an increasing degree of mis-match for dependent fish and invertebrate species, although *C. finmarchicus* itself may be less affected.

C. finmarchicus late life-history stages are important as food for pelagic fish, such as Atlantic mackerel (*Scomber scombrus*) and Atlantic herring (*Clupea harengus*), and also for endangered North Atlantic right whales (*Eubalaena glacialis*) (Kenney *et al.*, 1995; Woodley and Gaskin, 1996) and some marine birds. When broadly dispersed, *C. finmarchicus* is not particularly useful as prey for the planktivorous right whales, since ambient concentrations are insufficiently dense for the whales to feed efficiently (Mayo and Marx, 1990). However, physical and biological mechanisms together produce aggregations of the copepod that can be used by the whales. For example, dense patches of *C. finmarchicus* are formed in spring in the upper water column in the Great South Channel that lies between Cape Cod, MA and Georges Bank (Kann and Wishner, 1995; Wishner *et al.*, 1995; Kenney *et al.*, 1995; Kenney, 2001) and associated with frontal features in Cape Cod Bay (Mayo and Marx, 1990), and over Stellwagen Bank in Massachusetts Bay; these locations are recognized right whale feeding sites. In addition as large numbers enter diapause in summer, dense aggregations near the bottom are fed on by deep diving North Atlantic right whales in the Gulf of Maine and Bay of Fundy and Roseway Basin on the Scotian Shelf (e.g., Baumgartner and Mate, 2003; Baumgartner *et al.*, 2003; Elvin and Taggart, 2008). Thus, "critical locations" for *C. finmarchicus* should include places where they provide appropriate feeding opportunities for the upper trophic level predators. These would include shallow banks, where groundfish spawn (or downstream of them), coastal upwelling areas, where shore birds (phalaropes) feed, and the channels and deep basins where baleen whales (right and sei whales (*Balaenoptera borealis*)) feed.

A "plastic" phenotypic response of *C. finmarchicus* to environmental conditions is a pre-requisite for such a broadly distributed species, but there are limits. Thus, *C. finmarchicus* abundances have recently been greatly reduced in the North Sea and southern Norwegian Sea, with the population centre moving north; apparently as the result of rising temperatures and changes in circulation thought to be linked to climate change (Beaugrand *et al.*, 2002). Its dramatic decline in the North Sea has occurred at the same time as there has been poor recruitment for cod (Beaugrand *et al.*, 2003). An analysis over the entire North Atlantic has suggested that there is a critical thermal boundary, north of which ecosystem conditions are favourable for *C. finmarchicus* and cod and south of which they are not (Beaugrand *et al.*, 2008). This critical thermal boundary corresponds to an annual average sea surface temperature of ~9–10°C and it is suggested that in the Northwest Atlantic this boundary will move north such that by the end of the century cod and *C. finmarchicus* could be confined to areas north of the northern Newfoundland Shelf. The exclusion of *C. finmarchicus* from much of the North American continental shelf would no doubt be accompanied by a major re-structuring of the ecosystem.

6.2.1.2 *Meganyctiphanes norvegica*

Considerably less is known about the distribution and occurrence of the euphausiid *M. norvegica* (Figure 6.2.1.2.1) in the Northwest Atlantic than is known regarding *C. finmarchicus*. It occurs widely in the Gulf of Maine, Bay of Fundy, Labrador and Scotian Shelves, and in the Gulf of St. Lawrence (Mauchline and Fisher, 1969; Kulka *et al.*, 1982; Simard and Lavoie, 1999; Descroix *et al.*, 2005; Everson, 2000). *M. norvegica* follows a 2.5 year life cycle, with the exact timing of reproduction varying between loca-

tions (Mauchline and Fisher, 1969; Nicol and Endo, 1997). Adulthood is reached during the first year, with reproduction occurring during the second and third years.

During winter, *M. norvegica* appears to reduce metabolic rate and shrink (e.g., Boysen and Buchholz, 1984) and may migrate to depth, forming dense layers (Greene *et al.*, 1988). Adults and juveniles follow diel vertical migration, spending the daylight hours at depth (generally 100-300 m) and migrating to the surface to coincide with darkness (Mauchline and Fisher, 1969; Widder *et al.*, 1992). These migrations produce variation in the distributions of euphausiid layers that frequently are detected acoustically as "scattering layers" (Sameoto, 1983; Greene *et al.*, 1992; Simard and Lavoie, 1999).

Figure 6.2.1.2.1. *Meganyctiphanes norvegica.*

Both physical (internal waves, fronts, topography; Simard *et al.*, 1986; Simard and Lavoie, 1999; Stetson *et al.*, 2010) and biological mechanisms can produce aggregations of euphausiids. In particular, swarming of krill near surface results in extensive (10s of km) layers and patches (Sameoto, 1983; Nicol, 1984, 1986; Sameoto *et al.*, 1993; Nicol and Endo, 1997) and downward diel vertical migration during the day produces dense near-bottom aggregations (Greene *et al.*, 1988)).

M. norvegica in the Northwest Atlantic is utilized as prey by a range of upper trophic level predators including fin (*Balaenoptera physalus*) and blue (*Balaenoptera musculus*) whales (Woodley and Gaskin, 1996; Metcalfe *et al.*, 2004), juvenile Atlantic cod (Heath and Lough, 2007), Atlantic salmon (*Salmo salar*) smolt (Lacroix and Knox, 2005), silver hake (*Merluccius bilinearis*)(Cochrane *et al.*, 2000), harbor porpoise (*Phocoena phocoena*) calves (Smith and Read, 1992), and occasionally North Atlantic right whales (Murison and Gaskin, 1989). Aggregations of euphausiids have been found persistently at locations where such predators are known to feed (e.g., Simard and Lavoie, 1999). Abundances of euphausiids and silver hake covaried, suggesting either a dependence on the availability of euphausiid prey by the hake or a common dependence on external forcing for the two species.

The abundance of *M. norvegica* has decreased in recent years (2005-2008) in the Gulf of St. Lawrence (Dufour *et al*., 2010), potentially in response to changes in circulation. Such changes in range are predicted in association with future environmental change, as has been observed for warm-water vs. cold-water copepod assemblages in the North Sea (Beaugrand *et al*., 2002).

6.2.1.3 Gelatinous zooplankton

This category contains 1,000 to 1,500 marine and aquatic species, which are broadly distributed, occurring in all the seas and oceans of the world, from the surface to the sea floor, sometimes having large population biomass (e.g., Lynam *et al*., 2006). Gelatinous zooplankton, including jellyfish, salps (Figure 6.2.1.3.1) and appendicularians, have distinct distributions with an apparent segregation of some species (e.g., Doyle *et al*., 2006).
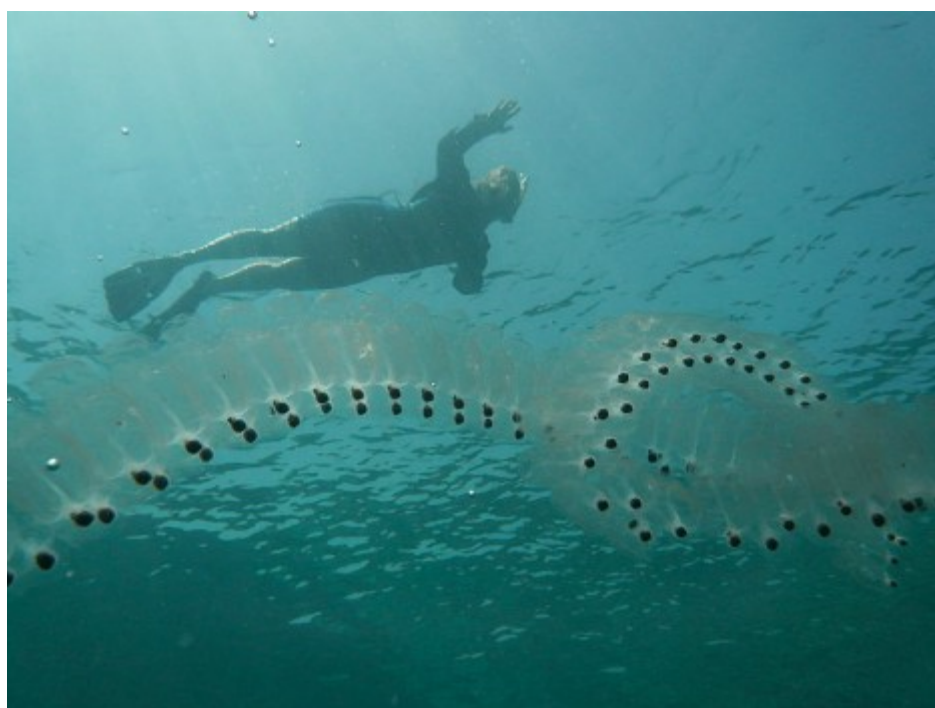

Figure 6.2.1.3.1. Salps occur in colonies of individuals, which take the form of long chains. (Photo from Wikipedia, Lars Ploughman).

These organisms are extremely important ecosystem components as they function both as consumers and as sources of food. As consumers, some gelatinous zooplankton can have significant impacts (top down control) on invertebrate and vertebrate populations as they are very effective in clearing the nearby water of eggs, larvae and small adult animals (e.g., Martinussen and Båmstedt, 1995; Spadinger and Maier, 1999; Purcell and Arai, 2001, Hansson *et al*., 2005; Lynam *et al*., 2005a; Richardson *et al*., 2009). Other groups, such as salps and appendicularians, consume small particles, including the smallest phytoplankton that are not grazed by large copepods, to produce dense rapidly sinking faecal pellets, contributing significantly to carbon sequestration (e.g., Pfannkuche and Lochte, 1993; Urban *et al*., 1993). Sea turtles and sunfish (*Mola mola*), amongst other marine and aquatic predators, consume gelatinous and other plankton, often at ocean fronts and eddies (e.g, Bolton *et al*., 1998), and as such the gelatinous zooplankton are probably essential prey for some species.

Climate change has the potential to alter the distribution and abundance of gelatinous zooplankton populations (e.g., Parson, 2002; Lynam *et al.*, 2004; Lynam *et al.*, 2005b), although most gelatinous zooplankton species are thought to be resilient to or positively influenced by climate change. For instance, rising sea temperatures are thought to be linked to the apparent global increase in the biomass of many jellyfish species (e.g., Richardson *et al.*, 2009) and jellyfish are also tolerant of waters with low oxygen levels (Shoji *et al.*, 2005).

Jellyfish and other gelatinous forms are often regarded as nuisance species, because of their deleterious effects on fish, and because they clog or burst fishing nets, in one case causing a fishing vessel to sink. Nevertheless, a strategically-designed network of MPAs may be needed to protect and link important habitats used by various life stages of the gelatinous zooplankton species that are necessary to sustain their predators (e.g., sea turtles). Further studies of the abundance, distribution, and trophic linkages of gelatinous zooplankton populations are needed, however, in order to understand potential climate-related changes in marine and aquatic ecosystems within this study area.

6.2.1.4 Other planktonic species

There are several other plankton species or species groups that are of concern because of their critical ecosystem function. Harmful Algal Bloom phytoplankton species, such as *Alexandrium tamarensis* in the Gulf of Maine and *Karenia brevia* on the western Florida Shelf, are key members of those ecosystems (e.g., Smayda, 2006), with high abundances and toxic impacts to upper trophic level organisms. Conservation of these species is of course not desirable but it is possible that climate change effects may lead to their more frequent occurrence so that attention should be given to understanding their role in the ecosystem. The small copepod *Pseudocalanus* spp. can be of pivotal importance to upper trophic levels such as larval cod on Georges Bank (Heath and Lough, 2007). With a potential decline in abundance or northward shift in range of the larger *Calanus finmarchicus* in response to climate change, the importance of the *Pseudocalanus* spp. to Northwest Atlantic ecosystems, such as the Gulf of Maine or the Scotian Shelf, may increase. As well, in the northern portion of our focus region, the very large copepods *C. hyperboreus* and *C. glacialis* provide a key prey resource for marine birds such as Little Auks (*Alle alle*) (Karnovsky *et al.*, 2010) that could be imperilled if the ranges of these copepods shift further to the north.

6.2.2 Reef-forming cold-water scleractinian corals

Some cold-water (azooxanthellate) scleractinian corals form extensive reefs, such as the *Oculina varicosa* reefs on Oculina Bank off eastern Florida or the *Lophelia pertusa* mounds on the slope and rise off the southeastern United States. These reefs thrive at 100's to 1000's of meters water depth, below the photic zone, by capturing food particles from the water column instead of relying on symbiotic zooxanthellae like tropical corals. Because of these differences, it is expected that cold-water corals will respond to climate changes differently from tropical corals.

Cold-water corals are thought by some scientists to be more vulnerable to climate changes than their shallow water counterparts (Kleypas *et al.*, 2006; Turley *et al.*, 2007), but physiological data for these species are scarce. Limited laboratory studies on adult reef-building cold-water species showed an increase in oxygen consumption with warming (Dodds *et al.*, 2007), and a reduction in calcification rates with reduced pH (Maier *et al.*, 2009). Several recent studies have documented the effects of ocean acidification on the ability of cold-water corals to create skeletal material (Kleypas

and Yates, 2009; Maier *et al*., 2009; Ries *et al*., 2006; Ries *et al*., 2010; Turley *et al*., 2007). Also, temperature changes are thought to produce reproductive changes in cold-water corals (Waller *et al*., 2008).

Rising sea level and increasing severe storms, which are serious threats to shallow-water tropical corals, would not have a significant effect on cold-water corals. Because they rely on food carried by currents or falling from above, however, cold-water coral reefs are likely to be affected by changes in ocean current regimes as much as or more than tropical corals.

Little is known about the controls on distribution of cold-water corals, but temperature, salinity, and currents are all thought to have an effect (Cairns, 2007; Guinotte *et al*., 2006, Waller *et al*., in press). In high latitude regions where azooxanthellate corals can thrive in shallower waters, loss of sea ice would increase light levels and may allow the overgrowth of algae on substrate originally available to settling of corals. Those factors, however, are less important than the depths of the aragonite and calcite saturation horizons (Cairns, 2007). Ocean acidification, in addition to having a deleterious effect on existing reefs, may change the geographic distribution of cold-water coral habitats.

6.2.3   Non-reef building cold-water corals and sponges

Reef-forming coral and sponge species are well known for their roles in temperate and tropical ecosystems; however non-reef forming coldwater corals (Figure 6.2.3.1) and sponges (Figure 6.2.3.2) also have important functions as benthic suspension feeders along the continental slopes of eastern North America and in the Caribbean Sea. Many also provide services as ecosystem engineers (Coleman and Williams, 2002; Levin and Dayton, 2009) (see Sections 3.2, 6.1); that is, organisms that alter the structure of the seafloor in ways that are used by other organisms. Marine megafauna over 5 cm in height have been considered as structure-forming and can have a strong influence on biodiversity (Tissot *et al*., 2006), and species greater than 1 m in height can profoundly affect benthic community structure. Coldwater coral colonies can reach heights of greater than 1 m and many taxa are over 15 cm in height. Sponges, while generally shorter in stature can form dense aggregations or sponge grounds creating structural habitat over large spatial scales (Boutillier *et al*., 2010). The importance of the structural habitat they form in relation to ecosystem function has been documented in many studies and reviewed in Freiwald and Roberts (2005), Valentine and Hecht (2005), Roberts *et al*. (2006, 2009) and Hogg *et al*. (2010). Key functions of bioengineers include shelter from predation for small fish and invertebrates (e.g., Grabowsky, 2004; DeMartini and Anderson, 2007; Pratchett *et al*., 2008; Wang *et al*., 2009), foraging centers particularly for grazers and predators with sit-and-wait predation strategies (Husebø *et al*., 2002; Costello *et al*., 2005; Auster, 2007; Mumby *et al*., 2007; Rilov *et al*., 2007), resting sites from strong currents (Johansen *et al*., 2008) and more generally serving as aggregation features for marine life (Hughes *et al*., 2002; Claudet and Pelletier, 2004).
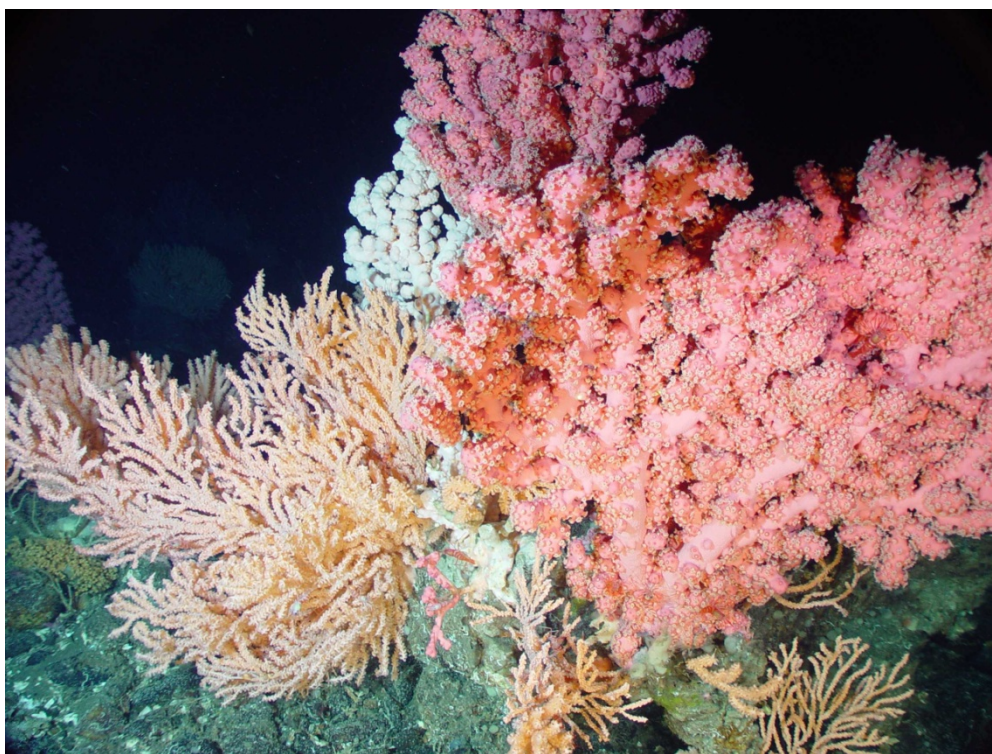
Figure 6.2.3.1. Aggregations of gorgonian corals from the Northeast Channel off Nova Scotia Canada. (Photo courtesy of Discovery Corridor 2006, image by the Canadian Scientific Submersible Facility; Centre for Marine Biodiversity, Fisheries and Oceans Canada, Dalhousie University, Fisheries, Memorial University).

Figure 6.2.3.2. Dense aggregations of sponges (*Geodia* spp.) along the continental slope of Flemish Cap, Northwest Atlantic. (Photo Courtesy of Fisheries and Oceans Canada).

In areas of the continental margins where there is very little abiotic structure in the habitats, biogenic structures are fragile and patchy but provide these specialized habitats for often unique assemblages of animals (Levin and Dayton, 2009; Kenchington *et al.*, 2010). Aggregations of sea pens (a group of cold-water corals; Figure 6.2.3.3) may provide important structure in low-relief sand and mud habitats where there is little physical habitat complexity. Also, these organisms may provide refuge for small

planktonic and benthic invertebrates, which in turn may be preyed upon by fishes. They are known to alter water current flow, thereby retaining nutrients and entraining plankton near the sediment (Tissot *et al.*, 2006).

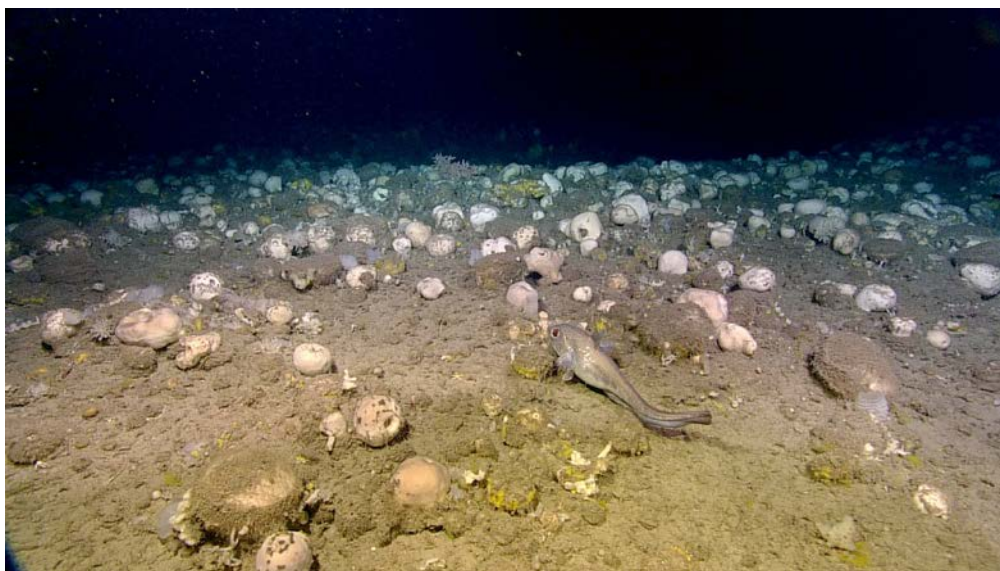**Figure 6.2.3.3. Dense aggregations of sea pens along the continental slope of the Grand Banks, Northwest Atlantic. (Photo Courtesy of Fisheries and Oceans Canada).**

The conservation importance of these habitats has been widely recognized. They are highlighted as "vulnerable marine ecosystem" components in the FAO Deep Sea Fisheries Guidelines (2009a), as examples of ecosystems that are highly sensitive and vulnerable to impacts of fisheries using bottom-contacting gear. In Canada, the locations of significant concentrations of corals (Figures 6.2.3.4, 6.2.3.5) and sponges (Figure 6.2.3.6) to depths of 1500 m have been mapped from Davis Strait in the north, to the Scotian Shelf (Cogswell *et al.*, 2009; Kenchington *et al.*, 2010). In the USA as part of their procedures to identify and manage Essential Fish Habitat, these organisms fall under their definition of Habitat Area of Particular Concern (HAPC).
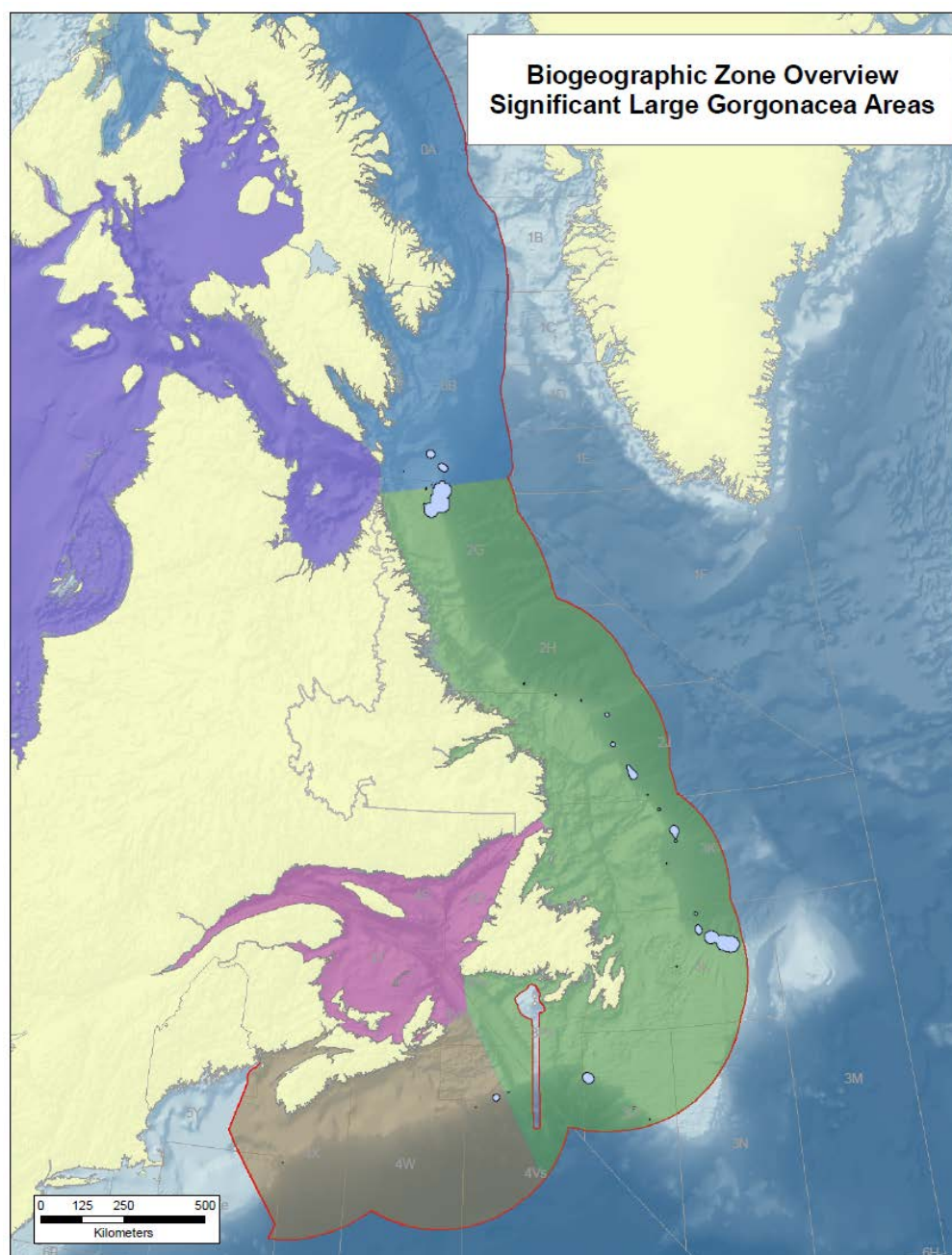
Figure 6.2.3.4. Distribution of significant concentrations of large gorgonian corals (Genera: *Primnoa, Paragorgia, Keratoisis*) within each of four biogeographic zones (DFO, 2009) in Eastern Canada (from Kenchington *et al.*, 2010).

While these taxa typically inhabit deeper waters below 200 m they may nevertheless be susceptible to the impacts of climate change. Cold-water corals, including sea pens and some sponges gain structural support from calcium carbonate (calcite) spicules in their mesoglea. Calcareous sponges comprise more than 90% of extant species and are found in relatively shallow marine waters where production of calcium carbonate is most efficient. Both groups may be susceptible to ocean acidification. The saturation horizon of calcite occurs at a greater ocean depth than that for aragonite which is of concern to the scleractinian corals, but both horizons have moved closer to the surface by between 50 and 200m compared to the 1800s. Unfortunately there is almost no scientific understanding of the impacts of climate change and ocean acidification on deep-water sponge grounds (Hogg *et al.*, 2010) or on cold-water coral

species. However, the NOAA Fisheries Service Science Centers have developed Ocean Acidification Research Plans (http://www.st.nmfs.noaa.gov/st7/AcidResearch.html).

Shifts in primary productivity in surface waters as a result of climate change could alter the distribution of deep-water corals and sponge grounds as well as other benthic filter feeders.

Some of the coral genera which are included in this habitat are: *Paragorgia*, *Primnoa*, *Paramuricea*, *Keratoisis*, *Radicipes*, *Acanella*, *Pennatula*, *Halipterus*, *Anthoptilum*, *Funiculina.* Sponge genera which form dense aggregations include but are not limited to: *Geodia*, *Stelletta*, *Iophon*, *Thenea*, *Stryphnus* and *Vazella.*
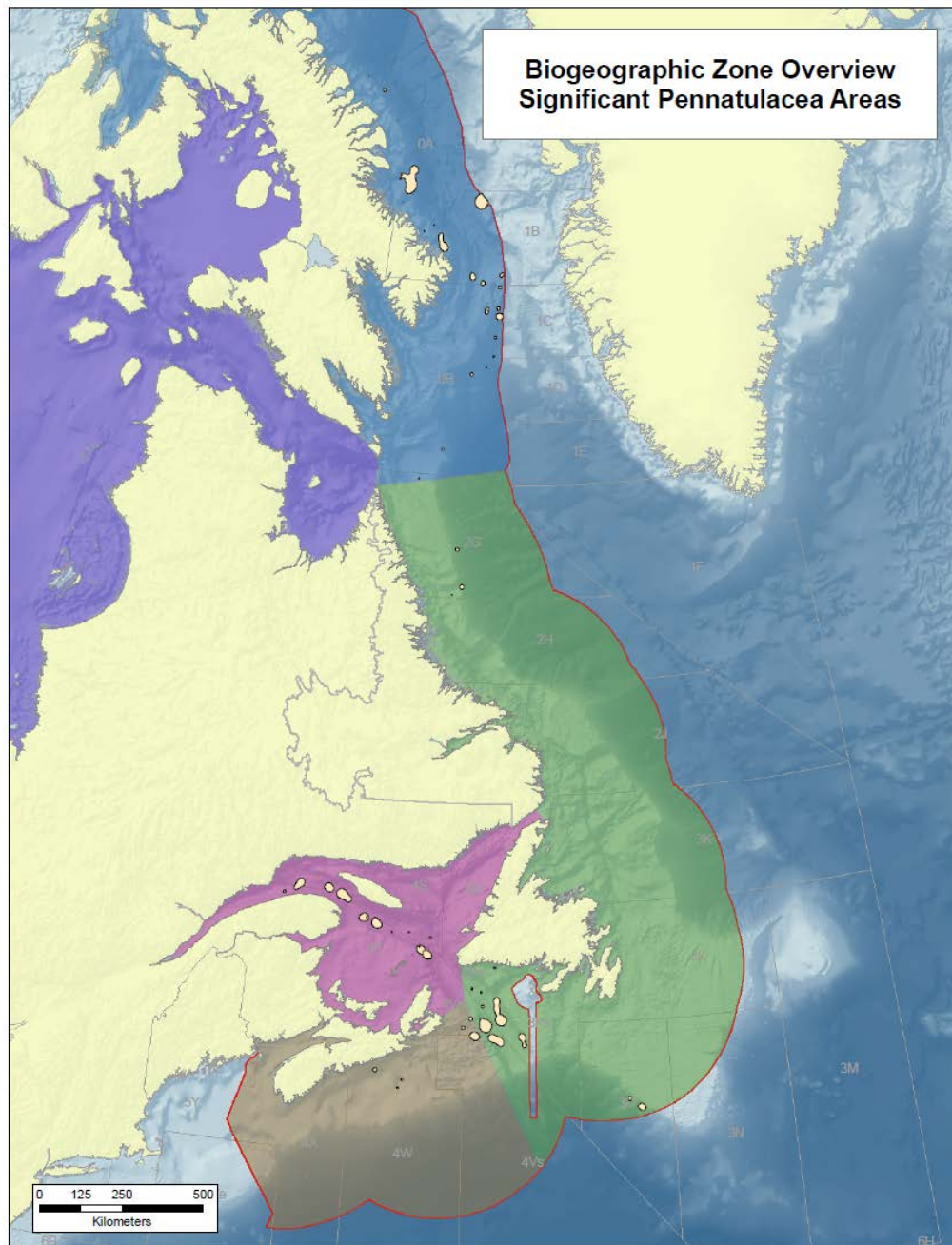
Figure 6.2.3.5. Distribution of significant concentrations of sea pens *within* each of four biogeographic zones (DFO, 2009) in Eastern Canada (from Kenchington *et al.*, 2010).
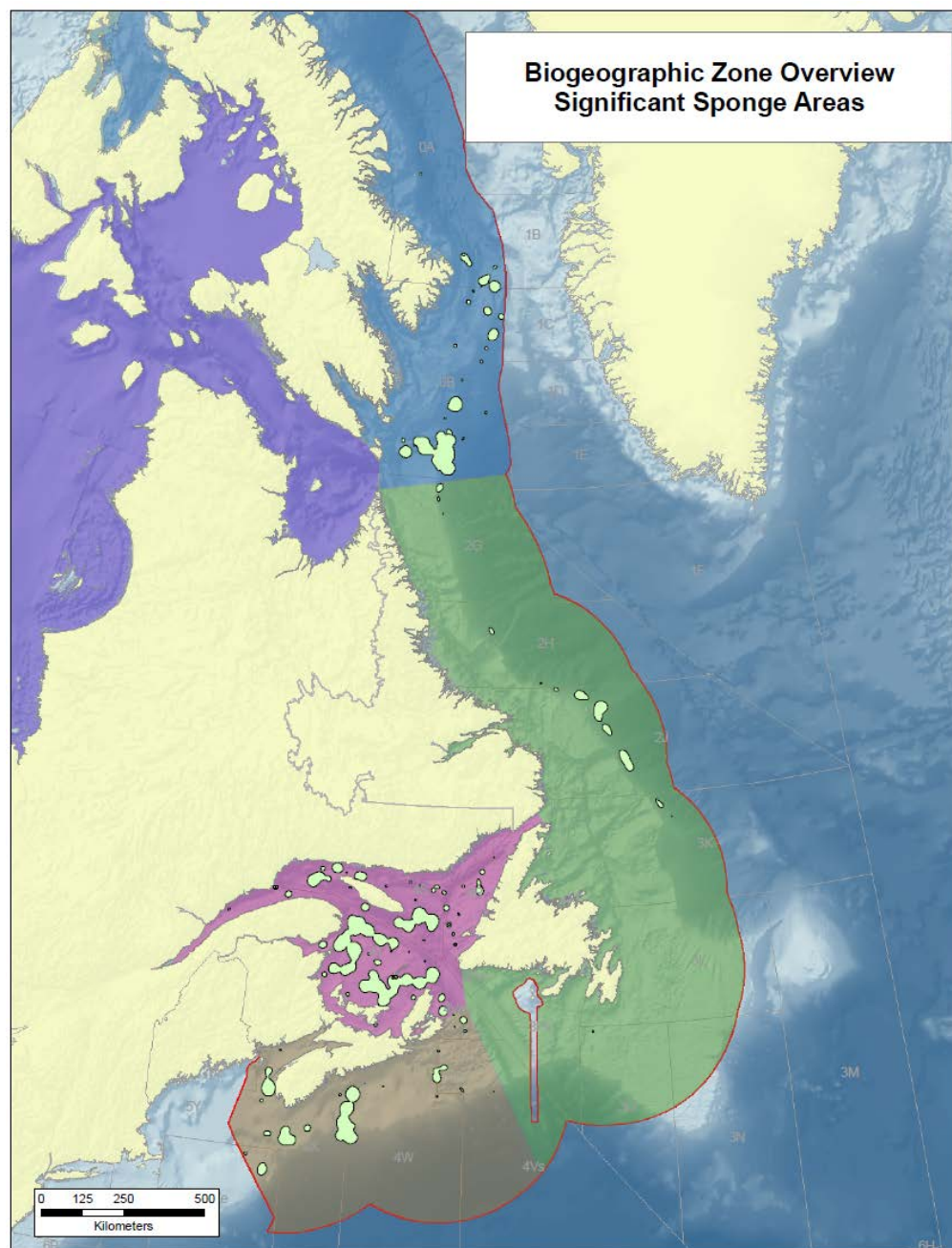
Figure 6.2.3.6. Distribution of significant concentrations of sponges (sponge grounds) *within* each of four biogeographic zones (DFO, 2009) in Eastern Canada (from Kenchington *et al.*, 2010).

6.2.4 Benthic Molluscs

The Mollusca are a diverse group with about 110,000 species known to science, most of which live in marine environments. They occur over a large range of habitats including rocky shores, coral reefs, mud flats, and sandy beaches. Benthic molluscs include gastropods, bivalves and some cephalopods (octopus), many of which are key species in structuring benthic assemblages. Gastropods and cephalopods are active predators and can influence community structure, while some of the bivalves can form reef-habitats or through burrowing, alter sediment chemistry and hence community structure. Mussels and oysters often dominate rocky intertidal and shal-

low subtidal zones around the globe. On rocky shores they are major competitors for space where they can out-compete macrophytes. Large concentrations of gastropods and bivalves are found at hydrothermal vents in the deep sea. Many molluscs have shells made from calcium carbonate and so there are concerns that ocean acidification could weaken the shells making the animals more vulnerable to predation. In the context of this report only a few examples of benthic molluscs that are important determinants of benthic ecosystems are highlighted. Many more examples can be found in the literature.

6.2.4.1 Mussel and oyster beds and reefs

Marine mussels of the genus *Mytilus* are known to monopolize space on rocky intertidal habitats (Seed and Suchanek, 1992). Subtidally, they form beds or reefs composed of living animals with accumulated sediment and organic matter forming a "mussel matrix", on substrata ranging from muddy soft bottoms to exposed hard bottoms. *Mytilus* beds can influence biodiversity by facilitation and inhibition of other species (Norling and Kautsky, 2008). Mussels have been shown to supply the associated community with 24 to 31% of its energy demand (Norling and Kautsky, 2007) and thus are considered key species. Living in the intertidal zone and shallow subtidal, mussels may be susceptible to mass mortality associated with increased temperatures (Tsuchiya, 1983).

Oysters play a similar ecological role to mussels creating habitat for a large number of species. Over 303 different species of animals have been reported from the oyster beds of the estuary of the Newport River, in the Beaufort area of North Carolina, USA (Wells, 1961). Oysters are susceptible to viruses and disease and warming waters may bring on mass mortality events.

6.2.4.2 Queen conch: a species of cultural and ecological importance

The queen conch (*Strombus gigas*) has been a highly prized species since pre-Columbian times, dating the period of the Arawak and Carib Indians. Early human civilizations utilized the shell as a horn for religious ceremonies, for trade and jewellery, as well as for excavating tools. The species has been reported in Florida, Bermuda, the Bahamas, the Caribbean Islands and Gulf of Mexico, as well as the Caribbean shelves of the Central and South America. They are herbivorous gastropods, and both the juvenile and adult conch feed on a variety of algae, detritus and seagrass blades. They have a major influence on the abundance of seagrass detritus which determines the macrofaunal communities.

6.2.5 Fish

Fishery resources have sustained human populations for millennia. However, the continual escalation of fishing pressure and demand, related to the burgeoning human population, has resulted in declines in many previously abundant fishery resources. Total reported yield from marine capture fisheries has levelled off at approximated 85 million tons after a period of rapid development over the last half century (FAO, 2009b). Estimates of the production potential of the seas in coastal and continental shelf systems are on the order of 100 million tons. Fifty-two percent of the world's fisheries for which assessments are possible are considered to be fully exploited with no capacity for further development, 19% are considered to be overexploited, 8% depleted and not currently capable of supporting fisheries, 18% are moderately exploited, 1% are recovering and 2% are considered underexploited

(FAO, 2009b). Cleary, species classified as depleted or in recovery are *species of special conservation concern*.

A number of iconic species such as Atlantic cod (*Gadus morhua*) are currently depleted and classified as overfished in both Canada and the United States. For waters off North America conservation of commercial species of concern are addressed in varying fashion by Mexico, USA and Canada. For Canada, commercial species that are depleted are regulated, generally by closure or limited quota under a single legislation, the Fisheries Act. In the United States, marked differences exist in the number of species or stocks under the control of regional fishery management councils are classified as overfished. A total of 16 stocks regulated by the New England Fishery Management Council are overfished, one by the Mid-Atlantic Council, 5 by the South Atlantic Council and 4 each in the Gulf of Mexico and Caribbean Councils. Species classified as overfished under this system are of special conservation concern and are managed under strict rebuilding plans (Milazzo, in review) as noted below.
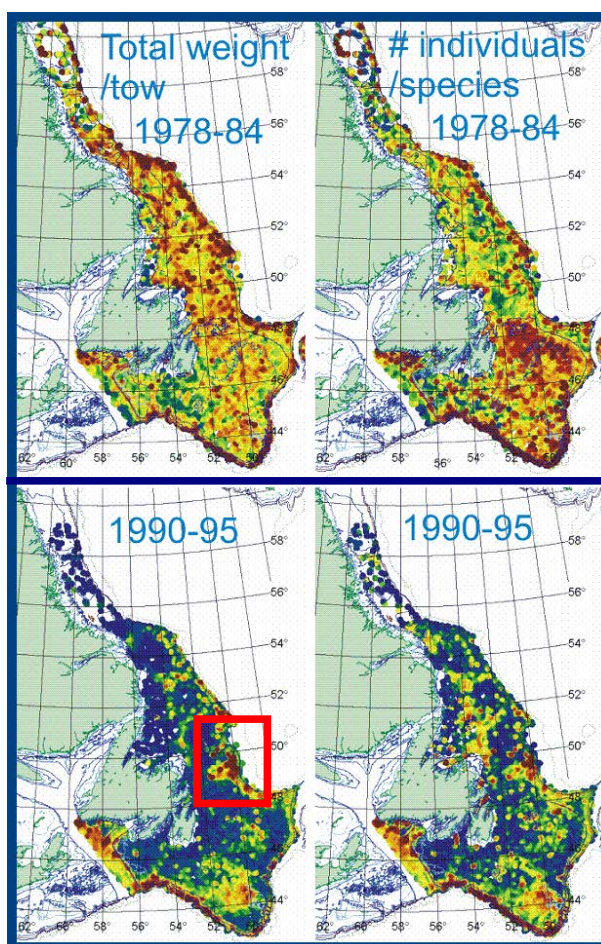
Figure 6.2.5.1. Reduction and shift in distribution of demersal fish species from the Grand Banks to Labrador Shelf. Data are derived from Fisheries and Oceans demersal trawl surveys. Red indicates large values of total weight per tow and number of individuals per species, blue low values (Kulka, unpublished data).

A key example the depletion of marine fish occurred of Newfoundland, Canada. During the late 1980s to early 1990s, a shift was observed from a system dominated by large demersal fish to one dominated by shrimp and crab species (Lilly *et al*., 2000;

ICES, 2009). Many demersal fish species, including the northern cod stock that inhabited the warmer, outer extent of the northern Grand Banks to the Labrador Shelf underwent a dramatic decline in abundance. Rose and Kulka (1999) noted that the distribution of formerly widespread and abundant species contracted and hyperaggregated to a specific location at the shelf edge such that by the early 1990s the last area of high density concentrations of fish was located at the north eastern edge of the Grand Bank (red area within the red box, Figure 6.2.5.1).

As well, at the same time, populations of wolffish species (*Anarhichas* spp.) declined and their distribution contracted, concentrating at the same location as the remnant cod population. Figure 6.2.5.2, (from Kulka *et al.*, 2004) illustrates a shift in centre of mass for two wolffish species to that location. Thus, this specific location appears to be an important habitat for a number of demersal fish including not only Atlantic cod, but also redfish (*Sebastes spp.*) and wolffish.

It is at this location that cod and wolffish are now both showing the first signs of recovery. Why this area is important cod and wolffish and to a number of other demersal fish is uncertain; however it appears to be *an area of crucial ecosystem importance*.
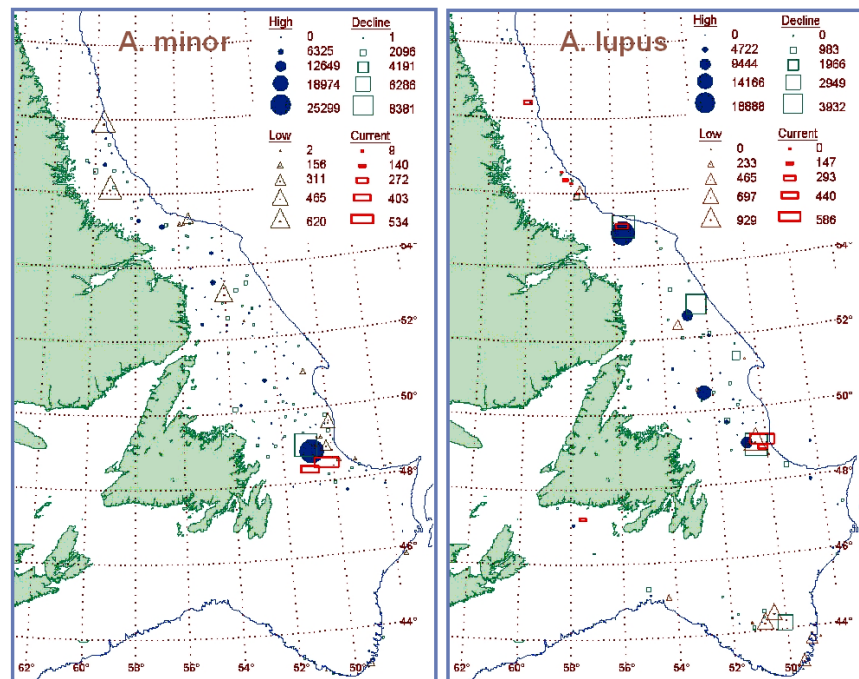
Figure 6.2.5.2. Density centroids of spotted wolffish (*A. minor*) and striped wolffish (*A. lupus*) on the Grand Banks to Labrador Shelf.

Exploitation status clearly can be exacerbated by climate-related impacts. Species at the southern extent of their range can be expected to exhibit reduced productivity and greater vulnerability to exploitation under increasing temperatures. Understanding the potential for synergistic interactions between climate and exploitation is critical in devising appropriate management approaches. Populations of exploited marine species are strongly shaped by climate variability on a broad range of space and time scales. High frequency variation in environmental forcing plays an important role in variability in the growth and survival of young fish while lower frequency forcing on broad spatial scales affects overall levels of productivity on multidecadal time scales. Fishery management strategies must contend with the uncertainties introduced by large-scale variation in the number of young surviving the

critical early months of life and must consider the implications of low frequency climate-induced changes on broader time horizons.

6.2.5.1 Fish Species of Special Conservation Concern

Among the species groups of special conservation concern are top predator species such as sharks and certain billfish and tunas. These species are also play an important role as Link species as defined in this section (see Section 6.1 and also 3.1 and 3.3) because of their characteristically large-scale migration patterns. Sharks are particularly vulnerable to exploitation because of low fecundity and delayed maturation. For species such as Atlantic bluefin tuna (*Thunnus thynnus*), the very high price they command on the market results in high levels of fishing pressure. Currently a substantial number of apex predator species are currently being managed under rebuilding plans subject to sharp restrictions on exploitation in the eastern United States. Among large shark species, these include dusky (*Carcharhinus obscurus*), sandbar (*C. plumbeus*), and porbeagle sharks (*Lamna nasus*). Billfish species currently managed through rebuilding plans include Atlantic blue marlin (*Makaira nigricans*) and white marlin (Tetrapturus albidus) as well as Atlantic sailfish (*Istiophorus albicans*) (Milazzo, in review). Tuna species within this overall category include albacore (*Thunnus alalunga*), yellowfin (*T. albacares*), and bluefin tunas. Because of their large-scale movement patterns, the design of effective MPA networks as a principal management tool for these species is likely to be challenging. Species characterized by low productivity or reproductive capacity (k-selected) such as elasmobranches or extremely high value species such as tunas and swordfish are particularly vulnerable to overexploitation.

The conservation status of marine fish (and other taxa) is assessed globally by the IUCN but designations of risk by this organization are not supported legislatively. For waters off North America, Mexico, USA and Canada, conservation of species of concern are addressed in varying fashions. For Canada, commercial species that are depleted are regulated, generally by closure or limited quota under the Fisheries Act. Species of conservation concern are evaluated for risk of extinction by COSEWIC (Committee on the Status of Endangered Wildlife in Canada). A list of the 18 marine fish species, including the iconic Atlantic cod and 8 species of elasmobranches that have been assessed by COSEWIC to date, can be found at www.sararegistry.gc.ca. However, only three of those species have been afforded legal protection by being placed on Schedule 1 of Canada's Species at Risk Act.

In subtropical and tropical systems off the eastern U.S., although not protected under the Endangered Species Act, several grouper species are currently managed under rebuilding plans. Snowy grouper in the South Atlantic Bight and three grouper species complexes under the control of the Caribbean Fishery Management Council are currently under rebuilding plans (Milazzo, in review).

Although relatively few fish species can be categorized as Engineer/Modifiers as defined in this section, one group, the tilefish, is known to excavate extensive burrow systems in deeper water systems (particularly canyon areas) the region of interest. Tilefish are currently under a rebuilding plan administered by the Mid-Atlantic Fishery Management Council (Milazzo, in review). Relatively sedentary species such as the grouper complex and tilefish are potentially strong candidates for effective implantation of MPAs as management tools.

6.2.5.2 Fish Species with crucial ecosystem roles: Forage species

Forage fish such a capelin (*Mallotus villosus*), herring (*Clupea spp.*) and Spanish sardine (*Sardinella aurita*) are consumed by a broad spectrum of predators including marine birds, marine mammals and other fish species. These species play critical roles in ecosystem dynamics. The maintenance of forage species populations to preserve food web structures is a principal concern in ecosystem-based management. In the United States, forage species such as Atlantic herring and mackerel are now managed with explicit consideration of food requirements of other species. For herring, the estimated amount consumed by predators is now substantially higher than the harvest itself. The amount of herring consumed by natural predators has increased as the abundance of this species has increased. Many predators are opportunistic and will feed on the most abundant prey items they encounter. In recent years, marine mammals and fish consumed roughly equal amounts of herring, with far lower consumption by marine birds and apex predators such as tunas and billfish. There has, however, been a change in the relative importance of different predator groups with time. For example, in the early 1990s, the dominant natural predators of herring were other fish, accounting for 70% of the natural predation and consuming nearly three times the herring eaten by marine mammals (W.J. Overholtz, pers. comm.).

6.2.6 Marine Mammals

Marine mammals comprise a diverse assemblage of life history strategies. All species migrate to varying degrees, and many cross national boundaries. In the Gulf of Mexico there are 30 species of marine mammals, one species of the Order Carnivora, one species of the Order Sirenia, and 28 species of the Order Cetacea. Habitat requirements include: suitable haul-outs for seals - land for some, ice for others, and suitable prey patches for all. For many, suitable habitat also includes access to migration paths or seasonal refugia (e.g., ice-free waters in winter for northern latitude species). Suitable prey includes tropical vegetation for manatees, benthic invertebrates for walrus (*Odobenus rosmarus*) and bearded seals, copepods for right whales, small fish for various balenopterid whales and seals, squid for sperm (*Physeter macrocephalus*) and beaked whales, and other marine mammals for killer whales. Most of these marine mammal species are protected from harvesting in Mexico, the USA and Canada, although there are specific exceptions, such as the Canadian hunts for harp (*Pagophilus groenlandicus*), hooded(*Cystophora cristata*), and grey seals (*Halichoerus grypus*), and beluga (*Delphinapterus leucas*), narwhal (*Monodon monoceros*), and bowhead (*Balaena mysticetus*) whales.

For many marine mammal species, particularly cetaceans, it would be difficult to propose a particular area or season for which an MPA designation or an MPA network could be shown to contribute to the enhanced resiliency of a population. The exceptions include the following four cetacean species and the manatee for which we have relatively good life history data and which conduct important parts of their life history processes in known, limited areas, some of which have already been designated as protected areas to varying degrees, for specific issues.

6.2.6.1 Humpback whale (*Megaptera novaeangliae* – found in NAMPAN marine ecoregions 6–15)

Northwest Atlantic humpback whales migrate from calving areas in the Caribbean to feeding areas in the Gulf of Maine, Canadian Maritimes, Newfoundland and Labrador, Greenland, and Iceland (Wilkinson *et al.*, 2009). Hence, the population spans most of the area considered by NAMPAN, and depends on prey stocks in each of

these areas for the resilience of each feeding sub-stock. Thus the status of each of these humpback sub-stocks integrates changing prey conditions in different regions; prey which includes sand lance, herring, and capelin. In contrast to commercially harvested fish predators, this species is protected from harvesting, except in Greenland, and thus can give an independent assessment of ecosystem status.

6.2.6.2 Right whale (*Eubalaena glacialis* – found in NAMPAN marine ecoregions 7–13)

Northwest Atlantic right whales calve off the Florida/ Georgia coast at the beginning of the year, and migrate to feed in New England waters in spring and summer and in the Canadian Maritimes in the fall (Kraus *et al.*, 1986). Non-reproducing animals may spend the entire year in temperate waters. Right whale numbers were decimated by whaling in previous centuries, and the remnant population occupies some parts of the US, Canadian and Mexican areas considered by NAMPAN, depending on prey stocks in each of these areas for its resilience. Stock recovery after the cessation of whaling has been limited by poor reproductive success, likely associated with copepod abundance fluctuations (see also Figure 5.2.6.1), vessel collisions, and fishing gear entanglements. In contrast to southern right whales (*Eubalaena australis*), whose population has been growing at around 7% per year, population growth estimates for Northwest Atlantic right whales range from a decline (Fujiwara and Caswell, 2001), to 2% per year (NOAA, 2009). Leaper *et al.* (2006) showed 'a strong relationship between calving output and SST anomalies at South Georgia in the autumn of the previous year and also with mean El Niño 4 SST anomalies delayed by 6 years' for the closely related southern right whale.

6.2.6.3 Blue whale (*Balaenoptera musculus* – found in NAMPAN marine ecoregions 6–15)

North Atlantic blue whales calve in the tropics in winter, and migrate to feed in temperate and subpolar waters in the spring and summer (Sears, 2002). Non-reproducing animals may spend the entire year in temperate waters. The small Atlantic population occupies parts of the US, Canadian and Mexican areas being considered by NAMPAN, and depends on prey stocks in the US and Canada (Edds and MacFarlane, 1987; Yochem and Leatherwood, 1985). Stock recovery after the cessation of whaling has been limited for reasons that are not known, but that may include poor reproductive success, vessel collisions, and fishing gear entanglements. In Canadian waters the primary feeding area, the Gulf of St. Lawrence, is subject to anthropogenic disturbance and changing thermal and prey regimes.

6.2.6.4 Beluga whale (*Delphinapterus leucas* – found in NAMPAN marine ecoregions 6–13)

Beluga whale stocks in the temperate and sub-polar areas of interest calve and feed mainly in near-coastal waters. The small Gulf of St. Lawrence population depends on prey stocks from a relatively small area (Lesage and Kingsley, 1998). The stock abundance and distribution after the cessation of whaling has been limited for reasons that may include by poor reproductive success due to high contaminant loads (McKinney *et al.*, 2006), and vessel collisions. In Canadian waters the primary feeding area, the Gulf of St. Lawrence, is subject to anthropogenic disturbance and changing thermal and prey regimes. A negative synergy between stress responses to disturbance and contaminants has been postulated for this population, and some others (Martineau, 2007).

6.2.6.5 Sperm whale (*Physetor macrocephalus* – found in NAMPAN marine ecoregions 6–15)

These large whales exhibit a broad distribution in all ice-free waters, although there is sex segregation such that large males travel to northern latitudes to feed. The sperm whale integrates the productivity of the deep waters off the continental shelf, although they also cross continental shelves to migrate and feed in shallower waters as well (Waring *et al.*, 2008; Whitehead, 1986). This species is not harvested in the Northwest Atlantic on a commercial scale now and thus provides an independent assessment of ecosystem status. The population recovery from past whaling will confound assessment of population change due to factors related climate change. Sperm whales are generalist predators, which focus on large cephalopods and some fish. Regionally they can develop aggressive depredation habits, on long-line fisheries especially. Seamounts occur within sperm whale habitat, so that MPA's designed to protect seamount habitat should also consider sperm whale protection.

6.2.6.6 Manatee (*Trichechus manatus* – found in NAMPAN marine ecoregions 11–14)

Manatees are herbivores that graze mainly on plants in relatively shallow, marshy coastal areas and rivers of the Gulf of Mexico and Caribbean Sea, although they are able to migrate in marine coastal areas (Landry and Costa, 1999; Mullin and Hansen, 1999; Rathbun and Wallace, 2000). Two subspecies are present in the Gulf, one lives in the north of the Gulf of Mexico, in Florida and up to Louisiana where but their low metabolic rate makes this the northern edge of their primary range (Irvine, 1983). The second subspecies lives in the Caribbean; however, it used to live in Mexican waters from Tamaulipas to the Yucatan Peninsula but due to habitat degradation and the killing of individuals, it can only be found today in the coastal lagoon of Alvarado, several small rivers and estuaries of Veracruz, the lagoon of Terminos, the Grijalva Usumacinta River system, Celestun, and in Quintana Roo (Ortega-Ortiz *et al.*, 2004).

Stock changes occur as a function of vessel strikes, fishing gear entanglements and cold temperature events. The aquatic feeding areas for this species are subject to increasing anthropogenic disturbance. The changes to the thermal regimes, aquatic plant communities, and habitat and water flow patterns that might result from climate change could have significant impacts on the abundance and distribution of this species. MPA networks designed to protect aquatic plant communities and coastal habitats should also consider manatee protection (for aquatic feeding areas and marine migratory routes).

6.2.7 Marine birds

Habitats used by marine birds include island and coastal cliff colony sites, marshes, mudflats, beaches, rocky shores, shallower coastal zones, and pelagic areas. In addition to these, estuarine habitats characterized by the presence of seagrass and mangrove vegetation constitute distinctively important ecosystems for birds. Together these habitats host an important diversity of bird species and in turn each of these habitats can be considered crucial to those species that occupy them. Monitoring and assessment of marine bird habitats is an essential step in the identification of places that are or have the potential to become key sites for major life-history functions, especially given under-use of habitats related to widespread population declines in some species (Gaillard *et al*, 2010; Delany and Scott, 2006).

Marine birds are top predators and many perform crucial ecosystem roles as such (Karnovsky and Hunt, 2002; Barrett *et al.*, 2006). Marine bird species tend to be abun-

dant, wide-ranging, conspicuous and charismatic. Many also are relatively large in size, exhibit delayed maturity and are long-lived. These and other characteristics have led to identification of certain marine bird species as ecosystem sentinels (Nettleship and Duffy, 1993; Burger and Gochfeld, 2004). Sentinel species ideally are monitored easily, and are associated with time series data at multiple sites within their range. Thus data can be used to assess ecosystem health through long-term studies and monitoring of physiological and reproductive parameters, foraging habits, migration patterns and use of non-breeding habitat. Examples of such data sources are presented in Section 5.2.4 of this document relating to marine birds.

Presented here are examples of marine birds identified as sentinel species and known to occur over large portions of the Northwest Atlantic to Caribbean zone. These examples provide evidence of marine bird responses to climate fluctuations. They also exemplify how data gathered through monitoring efforts during different life history stages are necessary to understand relative importance of geographically distinct sites that may be used by a given species. Such knowledge can inform decision-making as part of broader conservation strategies, specifically marine protected area planning.

Colony surveys and field studies have been vital in documenting and understanding dramatic population increases and breeding range expansion in the Northern Fulmar (*Fulmarus glacialis*) in both the North and Northwest Atlantic (Thompson and Ollason, 2001; Garthe *et al*., 2004; Lewis *et al*., 2009). At-sea surveys reveal highest concentrations of this species occurring on the northern Newfoundland and Labrador Shelves (EC CWS, Seabird at Sea database), a pattern supported by satellite tracking data (Mallory *et al*., 2008). Similar work at a colony in the Canadian Arctic led to detection of Razorbills (*Alca torda*) that occurred in unison with incursions of their preferred capelin (*Mallotus villosus*) prey well beyond the species' previously known northern range limit (Gaston and Woo, 2008; EC CWS, Colonial Waterbirds databases).

Higher sea surface temperatures and increased mackerel (*Scomber scombrus*) availability in the vicinity of Newfoundland colonies have favoured Northern Gannet (*Morus bassanus*) breeding performance resulting in consequent population increases (Montevecchi and Myers, 1997). Northern Gannets breed at only six colonies in North America, three of which are located within the Gulf of St. Lawrence (EC CWS, Colonial Waterbirds databases). These birds winter in the Gulf of Mexico, and twice per year skirt headlands along the Atlantic coast, with many having to fly through migratory bottlenecks (e.g., northern Cape Breton Island; see Figure 3.3.2 in Section 3; EC CWS, Seabird at Sea database).

Examples from the Northwest Atlantic also provide evidence of changing diets of colonial species during breeding. Atlantic Puffin (*Fratercula arctica*) breeding performance largely was unaffected by a fundamental change in prey consumed and delivered to chicks, from preferred capelin to post-larval sandlance (*Ammodytes* sp.) and other prey (Baillie and Jones, 2004). Conversely, Common Murres (*Uria aalge*) have exhibited flexible foraging tactics, instead of switching, in response to changing availability of preferred prey (Hedd *et al*., 2009). Other considerations, such as temporal mismatch between prey availability and important life cycle stages demonstrate potential for increased vulnerability during critical periods (Wilhelm, 2008). During the winter non-breeding period, murres (*Uria* spp.) have shown decreases in Arctic cod (*Boreogadus saida*) and capelin components to their winter diet (Rowe *et al*., 2000), a reflection of broader year-round changes in prey availability in this system.

The International Union for Conservation of Nature (IUCN) lists eight species as either critically endangered (2), endangered (2), or near threatened (4) that are also known to occur within the Northwest Atlantic to Caribbean zone. None are listed as vulnerable. Of these, two are shorebirds. Present use of marine habitats by Eskimo Curlew (*Numenius borealis*; critically endangered) is unknown but the species is known to have used certain marine habitats historically during its southward migration (Gill *et al.*, 1998). Conversely, the Piping Plover (*Charadrius melodus*; near threatened) is reliant on wintering habitats consisting of sandy bays, lagoons and mudflats in parts of the US southeast coast, the Gulf of Mexico and Caribbean. Fifty-two percent of the population is believed to nest on beaches along the Atlantic Coast of North America (Haig and Elliott-Smith, 2004). Monitoring of this species is extensive, especially within its breeding range. The Piping Plover is vulnerable to habitat loss through degradation and destruction. Sea level rise, increases in hydrological cycles and occurrence of earlier and more frequent severe tropical storm and hurricane events can be expected to have increasing repercussions for this species (Seavey, 2009). The Reddish Egret (*Egretta rufescens*; near threatened) is an essentially coastal species that breeds on islands and in mangroves. It is found on mudflats, shallow estuarine waters, as well as more exposed shallow coastal waters (Lowther, 2002). Disturbance, habitat loss, and pesticide runoff have been identified as threats for this species (Texas Parks and Wildlife, 2010). The Ivory Gull (*Pagophila eburnea*; near threatened) known only as a winter visitor within the northernmost part of the Northwest Atlantic to Caribbean zone. This pagophilic species is typically associated with ocean areas where ice cover is of 70–90% (IUCN, 2010) and could be expected to exhibit changes in distribution with decreasing ice extent. The remaining four species are Procellariiformes, none of which breed within the Northwest Atlantic to Caribbean zone. Confirmed observations of Jamaica Petrel (*Pterodroma caribbaea*; critically endangered) have not occurred anywhere since 1879 (IUCN). Recent evidence from a study of Bermuda Petrel (*Pterodroma cahow*; endangered) nesting in Bermuda, using geolocation tags, suggests that three separate females reached Canadian waters as part of foraging trips during the chick rearing period (Jeremy Madeiros, unpublished data). At-sea distribution of Black-capped Petrel (*Pterodroma hasitata*; endangered) is largely unknown, although increased survey effort in waters beyond the continental shelf could lead to increased detection of the species (EC CWS, Seabirds at Sea database). Dramatic declines in occurrence of Sooty Shearwater (*Puffinus griseus*) in the California current suggest important population declines or changes in distribution (Oedekoven, 2001). Declines have also been detected at southern hemispheric breeding colonies (Hamilton *et al.*, 1997). Attempts to assess trends in at-sea distribution of this species within the Northwest Atlantic to Caribbean zone have not yet been undertaken, but are warranted (EC CWS, Seabirds at Sea database).

Climate change impacts on marine birds are most likely to be felt indirectly through impacts on availability of prey, and/or directly through modification of marine habitats. For this reason, identification and monitoring of sentinel species and sentinel habitats is required (Sanger *et al.*, 2008). The same can be said for species of concern where identification of critical habitat is of prime importance. Examples of rapid and large-scale range expansion, prey switching, plasticity in foraging tactics, as responses to changing prey distribution, suggest that certain species with crucial ecosystem roles and of special conservation concern may exhibit some resiliency to climate fluctuations. However, the potential complex cascading effects of perturbations to species assemblages and trophic structure as components respond to changing conditions cannot be underestimated as sources of concern.

6.2.8 Sea Turtles

There are five species of marine sea turtles present from the Northwest Atlantic to the Caribbean waters, all of which are listed as either endangered or critically endangered under the IUCN, or are protected under the U.S. Endangered Species Act. These are the loggerhead (*Caretta caretta*), Kemp's ridley (*Lepidochelys kempii*), green (*Chelonia mydas*), leatherback (*Dermochelys coriacea*), and hawksbill (*Eretmochelys imbricata*) turtles. These species are of special conservation concern because populations are at risk throughout all or a significant portion of their range. These species span nine of the NAMPAN ecoregions (numbers 7-15; Wilkinson *et al.*, 2009; Figure 5.1.1) from Canada to Mexico, from the shoreline to the pelagic ocean. The widespread distribution of turtles over their natural life cycle makes the taxon a good candidate for MPA networks. Here we present some general examples of how the effects of climate change might influence life history characteristics of sea turtles, and the general habitats that would be involved in the design of MPAs. It is by no means exhaustive; readers should refer to the literature or to databanks for more in-depth sources of information, particularly with regards to high-use areas or critical habitats.

All turtle species utilize different habitats throughout various life stages. During nesting, females come ashore to lay eggs, returning several times to lay multiple clutches within one breeding season (Carr *et al.*, 1978). Nest temperatures determine hatchling sex, with higher temperatures producing female turtles, while the combination of temperature and water content of the sand will determine the hatching success (Ackerman 1997, Foley *et al.*, 2006). Hatchlings disperse to open-ocean foraging areas, where as juveniles they may spend many years feeding on gelatinous and other plankton, often at ocean fronts and eddies (Bolton *et al.*, 1998). Loggerhead, green, hawksbill, and Kemp's ridley turtles make a developmental shift from pelagic to neritic habitat as juveniles, while leatherbacks remain largely pelagic throughout their lives. Of the former species, most large juveniles and adults spend the majority of their lives in the neritic zone, migrating long distances to foraging and breeding grounds to which they show site fidelity (Avens *et al.*, 2003). All sea turtles are slow-growing species, with some reaching sexual maturity over several decades.

Climate change has the potential to alter the distribution and abundance of marine turtle populations (Hawkes *et al.*, 2009; Poloczanska *et al.*, 2009), either where they nest or where they develop and feed. Some populations may be more resilient to climate effects than others depending on their breadth of suitable nesting sites or foraging habitats (Figure 6.2.8.1). Turtle species that migrate and forage over large spatial scales, such as loggerheads and leatherbacks, may have greater resilience and adaptive capacity to the effects of climate change (Figure 6.2.8.2; Hawkes *et al.*, 2007, 2009). Some aspects of climate change may prove beneficial for leatherback turtles by providing more prey over a larger geographic area. For instance, rising sea temperatures are one factor used to explain the apparent global increase in the biomass of many jellyfish species (e.g., Richardson *et al.*, 2009), a main prey item for leatherbacks. For those turtle species that have more geographically-restricted prey sources, or prey sources that are negatively impacted by sea temperature increases, climate change could have deleterious impacts. For example, the effect of increased temperatures, salinities, and storm surges on seagrass beds could have adverse effects on herbivorous green turtles (Hawkes *et al.*, 2009), although it is unknown how quickly green turtles may be able to adapt their foraging behaviour to changes in seagrass distribution and availability. Similarly, hawksbill turtles in some regions feed primarily on a few species of sponges (Meylan, 1988), and it is unknown how sponges may react to climate change effects (see Section 6.2.3 above).
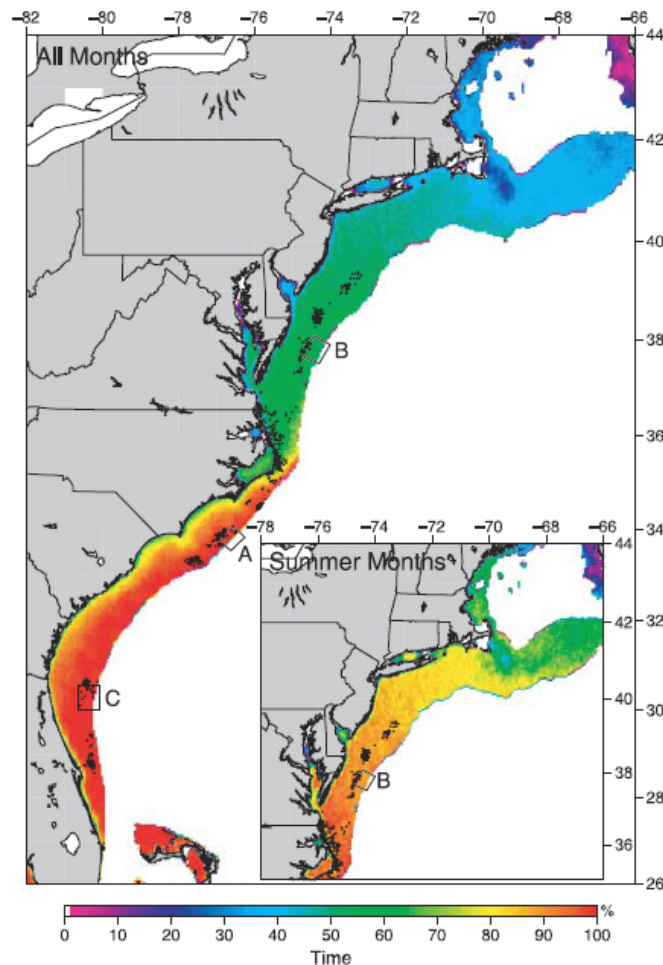
Figure 6.2.8.1. Habitat suitability model for loggerheads in the Northwest Atlantic, (from Hawkes *et al.*, 2007). The image depicts the broad habitat suitability for loggerheads based on SST (>13.3˚C) and depth (<104m). The authors note that individual turtles appear to use more discrete areas and are probably driven by local-scale factors in the areas where they are foraging or wintering, perhaps associated with underwater features or structures.

Environmental mechanisms such as air and sea surface temperatures, current systems, and oceanic productivity can influence sea turtle demographic rates (National Research Council, 2010), such as breeding rates and adult-recruitment probabilities, fecundity (egg and hatchling production), survival probabilities, dispersal probabilities, growth and age to sexual maturity, and sex ratios. Therefore, turtles may be vulnerable to the aspects of climate change that drive these environmental mechanisms. For instance, hatching success and sex ratio are dependent on the incubation temperature of the nest. Warming over the next century may result in shifts to 100% female-producing beaches for some populations (Poloczanska *et al.*, 2009). On the other hand, some species, such as the loggerhead, have shown adaptive strategies to warming temperatures by shifting the timing or location of nesting sites to cooler seasons or areas (Pike *et al.*, 2006; Weishampel *et al.*, 2004).
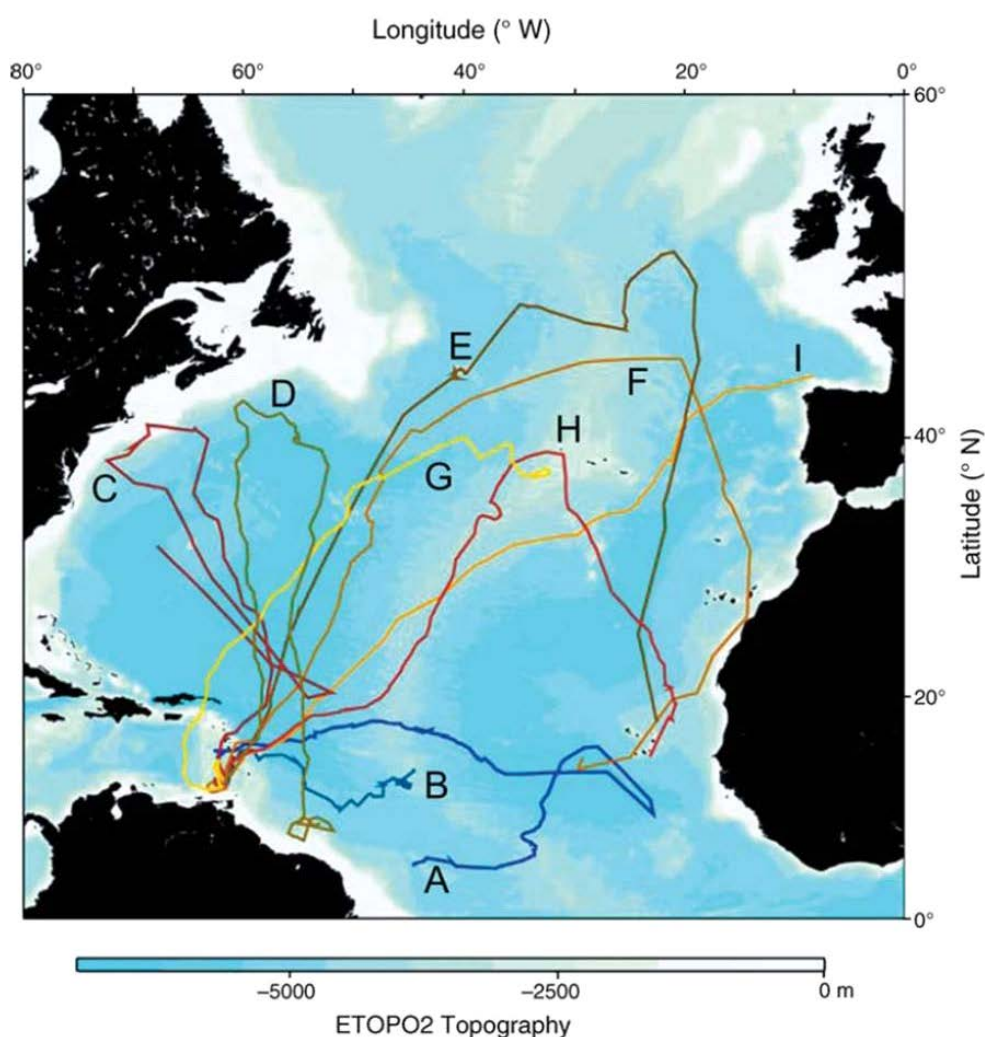
Figure 6.2.8.2. Post nesting movements of nine leatherback turtles (from Hays *et al.*, 2006).

Suitable nesting habitat may be altered, modified, or even lost with rising sea levels, especially when combined with coastal development and fortification. For example, available nesting habitat for the hawksbill on the beaches of Campeche, Mexico is being lost to sea level rise and loss of substrate due to coastal development. There are also clear examples of coastal erosion at priority nesting beaches for sea turtles in Mexico; according to Márquez (2008), there was a net loss of around 160 m in width of beach, or 5.3 m per year, from 1970 to 2005. Main causes of this coastal retreat (receding) could be dam construction and hydrological modifications in continental areas, road development, and canal construction. Moreover, this effect could be enhanced with sea level rise due to climate change.

The cumulative effect of these stressors may compromise the ability of small populations to recover from population declines. A strategically designed network of MPAs may be able to link important habitats used in various life stages of sea turtle populations. Unfortunately, supporting data are few with which to predict the likely results of changing climate on turtle populations with confidence (Hawkes *et al.*, 2009). Hawkes *et al.* (2009) recommend that future research on climate change should focus on: 1) climate change effects on key habitats on which turtles depend; 2) factors that influence nest site selection; 3) the consequences of skewed primary sex ratios; and 4)

the effect on climate change on turtles at sea, for example range shifts and dietary breadth.

6.2.9 Tropical ecosystems: examples of crucial habitats

Tropical ecosystems consisting of stony and soft corals and associated habitats such as sponges, seagrass beds, and mangrove shorelines are facing increasing threats due to climate change, with corresponding damage from increasingly severe tropical hurricanes, more frequent temperature-induced coral bleaching events, and diminished skeletal integrity due to ocean acidification. Potential threats from climate change to these habitats include but are not limited to rising sea levels, changing tidal regimes, UV radiation damage, sediment hypoxia and anoxia, increases in sea surface temperatures and increased storm and flooding events.

Seagrass beds, the ecosystem role they fill (e.g., primary production, food source for herbivores), and the ecosystem services that they provide (e.g., protection from predators for juvenile fish) are threatened by a multitude of environmental factors that are currently changing or are expected to change in the future. Temperature stress on seagrasses will result in distribution shifts, changes in patterns of sexual reproduction, altered seagrass growth rates, metabolism, and changes in their carbon balance (Short *et al.*, 2001; Short and Neckles, 1999). Coles *et al.* (2004) found that when temperatures reach the upper thermal limit for individual species, seagrass in tropical systems generally die. Another negative consequence associated with warmer sea surface temperatures is the increase in the growth of competitive algae and epiphytes, which can then overgrow seagrasses and reduce the available sunlight seagrass needs to survive.

Changes in weather patterns and severity of storms may also negatively impact seagrasses by reducing available light levels due to increased cloudiness, increased turbidity (e.g., from increased wind speeds), or by increased water depth caused by sea level rise. For example, increase in runoff (and nutrients) may increase epiphyte loads, thus causing competition for sunlight and nutrients.

McLeod and Salm (2006) have prepared an excellent summary of the possible effects of expected changes in temperature, CO2, precipitation, hurricanes and storms, and sea level rise on the physiological ecology of tropical mangroves as well the crucial ecosystem roles they provide to the life history characteristics of organisms such feeding areas and refugia for juveniles (e.g., mangrove prop roots).

Rising water temperatures and lowering of pH (increasing ocean acidification) can have negative consequences on stony and soft corals in a number of ways. Emerging threats to coral reefs are bleaching and mortality associated with global warming. Elevated sea surface temperatures (SST) are widely recognized as the primary cause of coral bleaching where coral tissues lose their symbiotic algae (zooxanthellae) during times of stress. These elevated SSTs are lethal when they exceed the corals' physiological thresholds for an extended period of time (weeks to months). The cascading ecological impacts occur when coral habitat is lost, a negative consequence for associated species of fish and invertebrates (Sale, 2006). An even more critical factor, however, is that a drop in pH leads to a loss of carbonate ions, which are required for all marine calcifiers, including corals, to build their skeletons. The impacts of acidification are already visible as waters are becoming increasingly corrosive to calcifying organisms, such as corals.

Table 6.2.9.1. Spatial ontogeny of select reef fish species found in tropical environments. Source: Jerry S. Ault, University of Miami/RSMAS

SPECIES	SPAWNING AREAS	PRINCIPLE LARVAL SETTLEMENT AREAS	JUVENILE AREAS	ADULT FEEDING AREAS	REFERENCES
Atlantic tarpon (*Megalops atlanticus*)	100 km's offshore	Anoxic swamps	Coastal bays and barrier islands	River mouths (Mississippi River)	Ault, 2008
Bonefish (*Albula vulpes*)	Shelf-edges	Surf zone beaches	Grassbeds behind barrier islands	High velocity flats in bays & around barrier islands	Ault, 2008
Permit (*Trachinotus falcatus*)	Deep coral reefs	Surf zone beaches	Sandy bottoms around grassbeds	Oceanside flats around barrier islands	Adams *et al.*, 2006; Crabtree *et al.*, 2002
Common snook (*Centropomus undecimalis*)	Passes at barriers islands	Mangroves	Mangroves and grassbeds	Beaches, sand bars, high-velocity channels	Taylor *et al.*, 1998
Red grouper (*Epinephelus morio*)	Shelf-edges	Inshore oceanside grassbeds	Passes at barrier islands	Low relief hardbottom reef areas	Jory and Iversen, 1989; SEDAR, 2009
Black grouper (*Mycteroperca bonaci*)	Coral reef ledges	Oceanside barrier islands	Patch reef environment	Rugose coral reefs	Jory and Iversen, 1989
Schoolmaster snapper (*Lutjanus apodus*)	Shelf-edges	Mangrove and grassbeds in coastal bays	Mangroves and grassbeds	Rugose coral reefs	Luckhurst, 2003; Rooker *et al.*, 2004
Gray snapper (*Lutjanus griseus*)	Shelf-edges	Freshwater fringe/seagrass/mangroves	Mangroves and grassbeds	Coral reefs & other structured environments	Domeir *et al.*, 1997
Striped mullet (*Mugil cephalus*)	100 km's offshore	Freshwater fringe/seagrass/mangroves	Bays, bayous, and flat channels	River mouths & other high flow areas	Gerking, 1994
Goliath grouper (*Epinephelus itajara*)	Shelf-edges	Freshwater fringe/seagrass/mangroves	Mangrove-lined channels	Rugose coral reefs	www.bio.fsu.edu/coleman

As seen in Table 6.2.9.1, habitats such as stony and soft corals, sponges, seagrass beds, and mangroves (especially their prop roots) play a crucial ecosystem role in tropical coral reef ecosystems at various life stages of many species. As climate change may have differing impacts on these habitats (e.g., from coral bleaching to seagrasses being impacted by increasing epiphytes), it may also impact the location, timing, and success of important activities associated with the indicated life stages.

The southeast Gulf of Mexico has experienced a significant loss of wetlands over decades. Marsh, seagrass, and mangrove habitats have been lost due to man-induced

activities such as residential construction and industrialization as well as to more naturally occurring phenomena, such as rises in sea level and the subsidence of land. Wetland degradation has also occurred due to diversions of freshwater for agricultural, domestic, and industrial uses, and through channelling, dredging, damming, ditching and the draining of rivers and their floodplains. Reductions in wetlands from 1780 to 1980 have been estimated at 60% in the U.S. Gulf region. Louisiana marshes in particular have experienced habitat loss rates that once approached 129 sq. km (50 sq. miles) per year. Between the mid-1950s and the mid-1970s, over one-third of Texas' 4,000 sq. km (1,544 sq. miles) of coastal marsh may have been lost. In Tampa Bay, Florida, more than 80 percent of the seagrass beds have been lost. It is clear that efforts to preserve what remains, and restore what has been lost, are urgently needed.

6.2.9.1 Coral reef ecosystems

Coral reefs are among the most biologically diverse, productive and economically important ecosystems on the planet, providing ecosystem services that are vital to human societies and industries through fisheries, coastal protection, building materials, new biochemical compounds, and tourism (Moberg and Folke, 1999). Estimates of coral reef cover range from approximately 0.1–0.5% of the ocean floor (Spalding and Grenfell, 1997; Smith, 1978; Copper, 1994). Nevertheless, 25% of marine species inhabit these ecosystems, almost a third of the world's marine fish species are found on coral reefs, and the catch from reef areas constitutes around 10% of the fish consumed by humans (Smith, 1978; McAllister, 1991). More than 100 countries have coastlines with coral reefs. In those countries tens of millions of people depend on coral reefs for part of their livelihood or for part of their protein intake (Salvat, 1992).

Rising water temperatures can have negative consequences to coral reefs. Bleaching events, the disruption of the symbiotic relationship between corals and their zooxanthellae, occur when a combination of elevated temperature and irradiance is present (Brown, 1997); sometimes, prolonged bleaching can result in the death of corals (Hoegh-Guldberg, 1999). When coral habitat deteriorates through events such as bleaching, the loss of associated species of fish and invertebrates can cause cascading ecological impacts (Sale, 2006). There is also a growing incidence of coral diseases, as well as disease prevalence and rate of spread on coral colonies, which has been attributed to increases in pathogen prevalence and virulence associated with global warming and low water quality (Bruckner and Bruckner, 1997; Kim and Harvell, 2002; Bruno *et al.*, 2003; Cervino *et al.*, 2004; Weil *et al.*, 2006; Harvell *et al.*, 2007).

Calcification is one of the most important processes occurring in coral reef systems. A decline in pH leads to a reduction of carbonate ions which are required for all marine calcifiers, including corals, to build their skeletons, (Kleypas *et al.*, 1999; Hoegh-Guldberg *et al.*, 2007). Reef–building corals produce large amounts of calcium carbonate rock, which counter physical erosion of the reef structure. The impacts of ocean acidification are already visible as waters are becoming increasingly corrosive to corals. In general reef-building corals that experience thermal stress exhibit reduced calcification rates (Wórum *et al.*, 2007), and reduced rates of coral calcification have been reported during bleaching events (e.g., Goreau and MacFarlane, 1990). Porter *et al.* (1989) reported coral calcification ceased during 1987–1988 in the U.S. Virgin Islands and Leder *et al.* (1991) demonstrated that a prolonged bleaching can result in the loss of an entire year's coral growth.

6.2.9.1.1   Shallow–Water Reef Fish

Numerous species of shallow-water reef fish are distributed widely in the Gulf of Mexico. Adults typically use high and low relief hard bottom habitats, patch reefs, or sandy areas near reefs. After spawning, planktonic egg and larval stages can be found in the water column near reef locations. Larvae and early juveniles move into shallower areas and may enter the bays and sounds. Early juveniles may occupy habitats such as seagrass beds, marsh areas, shallow hard bottoms, or they may occupy waters around piers, jetties, or artificial structures. Late juveniles move into deeper waters and occupy habitats similar to adults. Some juveniles are closely associated with coral heads or crevices. Late juveniles and adults are typically demersal and are usually associated with nearshore habitats such as coral reefs, hard-bottom substrates, wrecks, or artificial structures on the shallower areas of the continental shelf.

6.2.9.1.2   Deep–Water Reef Fish

Deep-water reef fish include snappers, groupers, and tilefish. Snappers and groupers inhabit coral reefs, live and hard bottom habitats, submerged aquatic vegetation, artificial reefs, and medium to high profile outcroppings around the shelf break from shore to at least 183 m where the annual water temperature is sufficiently warm to maintain adult populations. Most eggs and larval stages are planktonic. Triggerfish, on the other hand, spawn benthic eggs in sandy depressions adjacent to hard bottom ledges. Tilefish are bottom dwellers that prefer clay and mud substrates and living in burrows at depths from 80 to 450 m. Most individuals, however, occur between 250 and 350 m.

6.2.9.1.3   Semi–Pelagic reef fish

Semi-pelagic reef fish include several species of jacks. The greater amberjack (*Seriola dumerili*) is pelagic and epibenthic as an adult. It occurs around reefs, oil and gas rigs, buoys, and irregular bottoms with high relief. As a juvenile, it is pelagic but attracted to floating debris and *Sargassum*. The adults occur to depths of 400 m.

6.2.9.2 Mangroves

The principal threats to mangrove habitat include land-use change, infrastructure, and pollution - especially hydrocarbon extraction and transformation. The coastal margins of the Gulf of Mexico and the Gulf States are under continuing stress from a variety of factors, including wind-borne (eolian) erosion, hurricane damage, floods, sea level rise, and human development such as construction or altered water quality and oil spills. Degradation and loss of natural coastal habitats such as wetlands or marshes, mangrove ecosystems, seagrass beds and sand dunes have impacts not only on future use by local human populations for commerce, navigation, housing, coastline protection, water quality, and recreation but also on trans-boundary migratory organisms such as fishes and waterfowl that use these habitats at various times during their life cycles.

In the Gulf of Mexico there are extensive coastal wetlands which are critical ecosystems for the exceptional productivity of fish and shellfish. Wetlands (particularly salt marshes and mangroves) provide essential habitat for shorebirds, colonial nesting birds, and migratory waterfowl. They constitute home to an incredible array of indigenous flora and fauna, endangered species such as sea turtles, manatee, crocodiles, orchids, etc.

In addition, the estuaries and coastal wetlands are recognized as vital in providing food and shelter for wildlife, improving water quality, in sediment filtration, and in flood and erosion control. Mexico is one of the countries with the most extensive area of these types of ecosystem, but the annual rate of loss of mangrove vegetation in the Gulf of Mexico is calculated to be 2.8%, nearly a full percentage point above the rate of loss in the Pacific coast, indicating a high threat level and suggesting an immediate need for intervention.

Low energy coastlines are often dominated by coastal mangrove ecosystems. In areas of low population density, these mangroves are still healthy so that there is still the possibility of protecting them through zoning or purchase and by declaring them marine reserves or protected areas. These areas should also be recognized for the role they could play in mitigating the effects of sea level rise. Land-use planning should include prevention or restriction of upland development.

Some of these pristine mangrove ecosystems have recently been damaged or destroyed by hurricanes, and therefore they represent opportunities for active restoration whether it be by planting new seedlings or by clearing fallen trees, re-grading the land, and restoring the hydrological cycle.

In the more populous areas around water bodies in Mexican coastal areas (e.g., Terminos Lagoon MPA with adjacent cities such as El Carmen), mangrove ecosystems have been subject to degradation from a variety of sources, including conversion to aquaculture ponds, housing or other building construction, alteration of water inflow rates or amounts, and nutrient additions. Each of these problems presents opportunities to restore mangrove structure and function to some extent while remaining in harmony with human occupation and activity. The Terminos Lagoon Marine Protected Area, is also protected as a Ramsar site, and forms part of the Man and the Biosphere (MAB) global network of protected areas; is located in the wider area providing the opportunity to generate global benefits in addition to safeguarding the environmental goods and services provided to the Gulf of Mexico marine ecosystem by these areas, consistent with criteria 2, 3 and 4 of the Ramsar Convention. It is expected that additional elements will be generated to also further comply with criterion 8 of the Convention, on sustaining (shared) fish stocks.

Mangroves are often found adjacent to other wetland vegetation (salt and fresh water marshes) and next to submerged seagrass beds, at least in water bodies with relatively lower river input (and high water clarity) such as the Laguna Madre de Tamaulipas. Conservation of mangroves should be combined with that of wetlands and seagrass beds for a more holistic ecosystem restoration and/or protection end point.

6.2.9.3 Seagrass beds

Seagrass is of particular importance in the near-shore communities of the Gulf of Mexico. Some researchers have described seagrass communities as the marine equivalent of tropical rainforests. Estimates of seagrass production can reach 10 tons of leaves per acre per year. It provides food, habitat, and nursery areas for important vertebrate and invertebrate organisms. An acre of seagrass, for example, can provide habitat for as many as 40 thousand fish and 50 million small invertebrates. It is sensitive to changes in water quality, and therefore it reflects the general health of the particular coastal ecosystem. Unfortunately, major storms, excessive herbivore grazing, diseases, pollution, water clarity, excessive nutrient levels in runoff, sedimentation and propeller scarring are serious threats to seagrass communities. Constant

mapping and monitoring of the health of seagrass communities in the Gulf of Mexico could provide important bench marks as well as means for determining overall shifts in ecosystem health.

Seagrass beds serve to stabilize sediments and to protect the coastline zone from erosion, providing a platform for the growth of flora and fauna, like fish and invertebrates such as shrimps that graze and reproduce on it, while also providing an important input of organic matter food supply and being the origin of a large food web. Seagrass beds are directly affected by waterfront development and natural hydrometeorological events and are an important habitat for fisheries resources like shrimps in the Gulf of Mexico.

The need for conservation of seagrass beds, along with wetlands, mangroves and sand dunes, and their connectivity, in an integrated manner is considered a priority activity within the Gulf of Mexico region.

6.2.10 Tropical Sharks

Some sharks are apex predators and can have a large influence on ecosystem structure (Section 3.1), however not all sharks fulfil this ecosystem role. There are four main diet types: fish, cephalopods and turtles (e.g., many pelagic shark species such as oceanic whitetip (*Carcharhinus longimanus*)), mammals (e.g., great white shark (*Carcharodon carcharias*)), crustaceans (e.g., deep-sea cat sharks, bonnethead (*Sphyrna tiburo*)) and plankton (e.g., basking sharks). Sharks are found throughout the world's oceans but diversity is particularly high in the Gulf of Mexico where 49 species are known to occur with 48 species documented for the Caribbean Sea and 42 for the entire east coast of North America (Shark Foundation Database: http://www.shark.ch/index.html).

Small coastal sharks in tropical waters include the Atlantic sharpnose shark (*Rhizoprionodon terraenovae*), blacknose shark (*Carcharhinus acronotus*), bonnethead (*Sphyrna tiburo*), and finetooth shark (*Carcharhinus isodon*). Small coastal species are generally distributed in coastal bays and estuaries. There is some evidence of spatial segregation. Adult female Atlantic sharpnose shark, for example, are usually found offshore while adult males and juveniles typically occupy coastal areas. Most species prefer warmer water temperatures of 20–34°C, but some species, such as bonnethead, are captured in water temperatures down to 15°C.

Large coastal sharks include the sandbar shark (*Carcharhinus plumbeus*), silky shark (*C. falciformis*), tiger shark (*Galeocerdo cuvieri*), blacktip shark (*C. limbatus*), spinner shark (*C. brevipinna*), bull shark (*C. leucas*), lemon shark (*Negaprion brevirostris*), nurse shark (*Ginglymostoma cirratum*), scalloped hammerhead shark (*S. lewini*), great hammerhead shark (*S. mokarran*), and smooth hammerhead shark (*S. zygaena*). Large coastal sharks are found in a wide variety of habitats. Bull sharks, for example, have been known to occur in freshwater while silky and smooth hammerhead sharks are more of an offshore, epipelagic species. Adults of many species are found offshore while juveniles occupy the inshore nurseries.

Pelagic sharks include the shortfin mako (*Isurus oxyrinchus*), blue shark (*Prionace glauca*), oceanic whitetip (*Carcharhinus longimanus*), and thresher shark (*Alopias vulpinus*). These tend to occupy habitats greater than 180 m. Pelagic sharks are generally found in water temperatures from 10–25°C, although mako sharks have been reported in temperatures as high as 27°C. Studies using acoustic telemetry have indicated that there is some vertical migration by pelagic sharks in offshore areas: blue

and mako sharks may occupy the upper water column at night and remain at depths of 100-500 m during the day.

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7 Analytical approaches

ToR e) Describe the types of analyses that are appropriate to both the scientific questions that need to be answered and simultaneously to inform network design for the very complex task of enhancing and protecting ecosystem resilience.

The objectives of an MPA network should be clear and transparent before analyses are done. Here, we take the primary objective of such networks to be the maintenance and enhancement of ecosystem resilience and resistance in the face of climate change (see Section 3). Resilience here is considered more broadly than the strict definition from theoretical ecology, where it is a measure of the return time to a stable equilibrium. For this discussion we define resilience as the ability of the ecosystem to withstand stressors (both pulse and press perturbations) such as climate change without major structural changes. Besides the primary objective, there are a number of secondary objectives that also need to be considered. These include protection of species at risk, augmenting fisheries, and maintenance or enhancement of ecosystem services.

7.1 Design considerations

The size of individual MPAs and the spacing of them within an MPA network are of critical importance (Sale *et al.*, 2005). MPAs tend to offer more protection to sedentary species and perhaps to more sedentary individuals within a species (Kramer and Chapman, 1999). To mitigate this effect, MPAs need to be large enough so that the majority of adults of most species will be retained within the MPA. For highly migratory species, the best approach may be to establish MPAs that protect critical life history stages such as spawning/breeding grounds. Larval transport is also an important consideration. Placement of MPAs in "source" locations, which may seed the areas to the outside with larvae from the MPAs, may be desirable if recruitment is larval-limited and enhancement of recruitment outside the areas outside the MPAs via larval spillover is important. Analysis of adult and larval movement and their implications for MPA design are discussed in more detail below.

Implementation of MPAs may induce displacement of fishing effort from the MPAs to the remaining areas. The extent that displacement may occur in the absence of explicit management depends on the relative mobility of the displaced fishing fleet, the economic costs of traveling to potentially more distant locations, and the possible alternative employment for the crews and alternative uses for the vessel. Quotas and effort regulations can be altered to prevent increases in effort outside the MPAs.

A large proportion of existing MPA models focus on a single species only. The design of MPA networks in an ecosystem context requires consideration of multiple species, each with its own scales of adult and larval movement. Network designs that are optimized for the larval transport of a given species may do poorly for other species. For these reasons, it is desirable to design networks that are effective across a range of movement scales, and are thus robust to variations and uncertainties in movement patterns.

A high proportion of MPAs and studies of MPAs have been conducted in coral reef systems (Mora *et al.*, 2006). While these studies are important, and coral reefs systems may be ideal candidates for MPA networks, it is not clear that observations from coral reef MPAs will always transfer to non-reef systems that are typical at higher latitudes (Laurel and Bradbury, 2006). In particular, organisms on coral reefs tend to

have smaller home and larval dispersal ranges, and there is less variability in movement scales than for non-reef systems. Spatial scales for fish movement are typically 100s of meters to kilometers in coral reef systems but are quite commonly 100s to 1000s of kilometers for higher latitude bank systems.

Monitoring of an MPA network after its establishment is important, even if it was designed using best practices. Determination of the benefits or effectiveness of a network of MPAs also requires a network of control sites and sampling in both the reserve and control sites before and after the creation of the MPA. Public support for MPAs often hinges on the quality of the evidence that can be provided demonstrating their effectiveness. Such clear evidence requires good and persistent monitoring but observations alone will not ensure that we have adequate information to determine the success of the MPA network in meeting its objectives. It is also necessary that the network be designed in a manner such that its benefits can be clearly demonstrated. The simplest approach is to compare conditions inside the MPA before its creation with conditions observed afterwards. While necessary, this approach does not take into account changes in natural conditions that may have occurred after the creation of the MPA. One common approach to the design of sampling and comparison strategies is referred to as BACI – Before After Control Impact (Stewart-Oaten and Bence, 2001). It is important that there be monitoring begun before the network development which is followed by monitoring both inside and outside the protected areas.

When selecting sampling sites for monitoring, it is highly desirable to select sites in and out of the MPA network with similar characteristics. Adding sites that are not paired in this way does not necessarily improve statistical confidence because of the spatial cross-correlation. Likewise temporal autocorrelation limits the benefit from increasing the temporal resolution of the sampling. There is often limited data for MPAs before their creation, thereby limiting possible analysis or comparisons after.

As has been discussed above, there is often great uncertainty regarding many critical parameters such as movement rates so that the network may not perform as anticipated. Additionally, changes in environmental factors such as climate may alter species' ranges and life history parameters (Mumby *et al.*, 2010) so that the effectiveness of a spatially rigid MPA network may be reduced over time. Periodic assessments of the network should be made and changes in management of the network should be considered if there have been shifts in species distributions or if the monitoring indicates that the network objectives are not being achieved.

7.2   Movement of organisms and MPA network design

As noted earlier, a central question to the consideration of MPA network design is the dispersal range of the species, as larvae, juveniles and adults. The goal is to understand where organisms move, how quickly they move and how their movement and position influences their growth and survival. The dispersal can be determined empirically through field measurements, and the analysis of field data, or through modelling of dispersal itself (Gerber *et al.*, 2003). In addition, estimates of adult and larval movement are subject to considerable uncertainty; changes due to climate change may make them even more uncertain in the future.

Genetic differences among populations can provide a strong indication that movement among the populations is negligible. However, finding of genetic similarity between populations does not imply that there must be substantial exchange among the populations. Even very limited exchange of individuals, which can occur as rare events or a few stray individuals, can mask genetic difference and homogenize the

genetic pool. In some cases, stable isotope or geochemical analysis can be used to infer the level of movements among populations (Botsford *et al.*, 2009).

7.2.1   Quantification of Adult Movement

Adult movement rates can be inferred from tagging data; see for instance Quinn and Deriso (1999, Ch 10), and Miller and Anderson (2008). There are three distinct types of adult movement: random walk (diffusive), periodic migratory and non-periodic directed movement. Random walk type movement can occur because of small-scale foraging behaviour or escapes from predators. Periodic migratory movement occurs when a species moves according to the seasons or other periodic time scales. This includes not only large-scale migrations, but also regular onshore-offshore seasonal movement, and seasonal movement related to prey densities. Ontogenetic movement (e.g., from shallow to deeper depths) is an example of directed non-periodic movement.

Random/diffusive movement can be modeled using either random walk (stochastic) models or diffusion (partial differential equation) models. Directed motion can be added to both modeling approaches, which then become random walk with drift and advection-diffusion models. Individual-based models allow modeling of variable movement, both among species or among individuals within a species. A simpler approach is to use metapopulation/box models (Tuck and Possingham, 2000). The version for a single MPA would model the populations inside and outside the MPA as well-mixed sub-populations MPA. The sub-populations are linked by movement parameters between the two areas. This model can be easily extended to include multiple MPAs as well as multiple fished areas. While this model is much simpler than the stochastic or partial differential equation approaches, it requires estimates of movement parameters that are estimated external to the model. As discussed above, much of the MPA literature is focused on coral reef systems, where most fish remain resident to a particular reef, so that adult movement away from the reef can be neglected. In systems that lack a defining structure such as a coral reef, there can be expected greater levels of movement as well as greater variability in movement among species or even within species. In such cases, a proposed MPA network design needs to be tested using a multispecies model that includes the movement of adults.

7.2.2   Quantification of larval dispersal

Movement of larvae, and especially the extent of larval spillover from MPAs, can also be an important consideration of MPA network design. Post-settlement density-dependent processes can in some cases limit the effects of larval supply to recruitment. In particular, larval transport and supply can be irrelevant to population dynamics if there already were sufficient larvae prior to MPA establishment to have induced saturation of recruitment. Such was apparently the case for Georges Bank sea scallops, for which there has been no significant increase in recruitment despite over an order of magnitude increase in scallop biomass within three large MPAs after their closure (Hart and Rago, 2006).

Larval transport is inherently a coupled bio-physical problem (Largier, 2003) that strongly influences biological connectivity (Cowen *et al.*, 2006). The factors that influence fish larval growth, survival and distribution (e.g., temperature and zooplankton abundance) are all influenced by the movement of the water and contribute to connectivity of marine ecosystems (Werner *et al.*, 2007). For this reason, spatially explicit models of the circulation, coupled with biological models of the organism are re-

quired to understand the dispersal and movement of fish larvae (deYoung *et al.*, 2010). There are many different features of the coastal circulation that influence the movement and dynamics of larvae including wind- and buoyancy-driven currents, fronts and associated jets, tides (including residual currents, internal tides and bores), and surface and bottom boundary layers. These models have mostly been applied to planktonic larvae, since that is the stage where movement is primarily driven by currents.
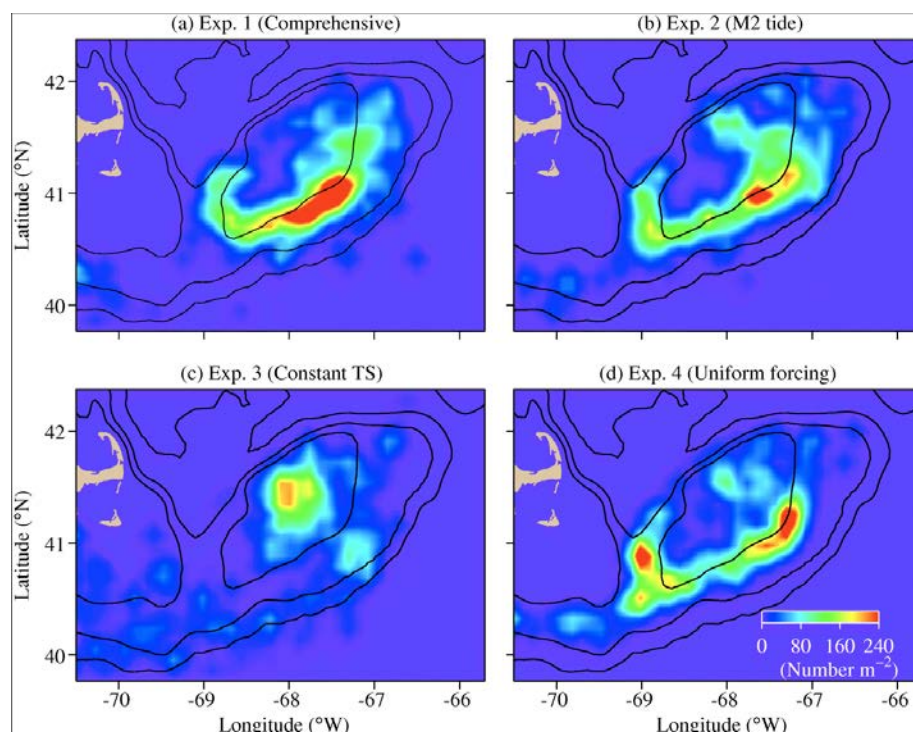

Figure 7.2.2.1. Abundance distribution of settled scallop larvae spawned in Closed Area I (CAI) predicted by the four simulation experiments in which model larvae are released from a closed area and driven by (a) all the physical forcing tides, (b) the M2 tide alone (c) constant temperature and salinity and (d) spatially uniform forcing of winds and fluxes. Black continuous lines are the contours of the 60, 100 and 200 m isobaths. The different model simulations enable the separation of the different forcing terms that influence the scallop larval dispersal (from Tian *et al.*, 2009).

It is the advance of coastal ocean circulation models, often now embedded in larger regional, basin or global model that has enabled the quantitative study of the physical processes that determine larval transport. Most commonly the organisms are represented as individuals within the model. These individuals can have varying degrees of biological realism, from none (meaning that they are just particles) to quite realistic models of growth and behaviour, including such things as predator-prey interactions. Individual representation enables such behaviour as the daily vertical migration to be included, an important behaviour of many marine organisms that is often found to limit the range of dispersal.

These models have been used to determine the pathways of larval fish from nursery to settlement grounds, retention on submarine banks (see Figure 7.2.2.1), the long-term dispersal by tidal currents and the influence of interannual variability on dispersal. While some of these models do include explicit representation of predation and feeding, most use a proxy such as temperature to model growth.

These models have already been used to explore interannual variability directly, typically through hindcast simulations, but can also be used in a simulative forecast mode by coupling with or connecting to climate forecast simulations. There are, for example, versions of global climate simulations that can include high-resolution shelf models to which biological models can be coupled. Such models could then be used to explore how dispersal dynamics might change in the future. Even without such explicit coupling to climate models, such studies could be done simply by taking the output forecasts from such models, such as the ocean temperature fields, and determining how the changing temperature field in a warmer planet might influence larval dispersal.

7.3   Empirical Statistical Models

In this Section, we describe statistical methods needed to analyze monitoring data for MPA networks and to attempt to distinguish effects of climate change from other anthropogenic and natural drivers of change. In general, the available approaches include statistical methods to determine the relationship between the response variables to one or more independent variables representing climate and other forcing factors.

In the most basic case, this can involve a simple linear regression relating a dependent variable such as abundance (or a metric related to distribution such as mean latitude) to an independent variable such as temperature. A similar approach explicitly accounting for the time-series nature of the indicator or metric data would involve the development of transfer function models (Box and Jenkins, 1976) for the system. These approaches are readily extended to more than one independent variable.

For the case of multiple response variables (e.g., simultaneous consideration of abundance and mean latitude) one can apply a multivariate generalization of multiple regression analysis, Canonical Redundancy Analysis (RDA) (Legendre and Legendre, 1998). This approach examines the relationship between a matrix of output variables and a set of input or explanatory variables. RDA differs from related multivariate methods such as Canonical Correlation Analysis in making an explicit distinction between the dependent or output variables and the set of explanatory variables. The ordination of the output variables is constrained to represent a linear combination of the explanatory variables.

The methods above examine linear relationships between dependent and independent variables. It is also possible to construct flexible nonlinear models for these systems. Generalized Additive Models (Hastie and Tibshirani, 1990) employ a spline approximation structure to accommodate potentially complex nonlinear relationships. This approach further relaxes the typical assumption in linear models of a Gaussian error structure. Generalized Linear Models involve a single dependent variable but can readily incorporate multiple explanatory variables.

To examine relationships among multiple dependent and independent variables, drivers and pressures and among pressures and ecosystem state variables, we can apply a nonlinear regression approach, Multivariate Adaptive Regression Splines (Friedman, 1991; Hastie and Tibshirani, 1997). In this non-parametric approach, the relationship among response variables and one or more predictor variables is represented by a piece-wise basis function composed of linear segments, each defined by a slope and inflection points or 'breaking knots'. Knots are initially chosen using a forward step-wise procedure (knots can be placed at any point along the range of the predictor variable(s) with the objective of minimizing the residual sums of squares of

the model). Once a fully determined model is selected (maximum number of basis functions identified), model simplification is attempted in which the basis functions that contribute least to the model fit are progressively removed. The performance of the simplified model is evaluated by cross-validation and the model with the highest predictive capability is chosen.

For the case where we wish to determine the effectiveness of a marine protected area, it is possible to utilize time series of abundance estimates or other metrics before and after the implementation of a closure and inside and outside the MPA to assess its impact. For example, areas with ongoing research vessel surveys that were initiated before the MPA was implemented may be suitable for this purpose. If an adequate site outside the MPA can be identified as a reference location, an intervention model (Box and Taio, 1975) can be applied. An intervention analysis incorporates an additional variable to serve as an 'on-off' switch to mark the implementation of the MPA. The dependent variable is the difference (on a logarithmic scale) of the survey mean between the within-closed area estimates and the corresponding reference site estimate. We can directly test for the effect of the 'switch' while also accounting for autocorrelation in the time series estimates used in the analysis.

7.4 References

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8   Workplan for next meeting

ToR f) Develop a workplan with tasks, deliverables, and timetable to inform a second workshop of species, habitat and ecosystem specialists who would assess those components following the framework established above, including an evaluation of their current and potential vulnerability to ocean–atmospheric processes (which include not only climate and meteorology but also interaction processes related with climate like gases exchange and acidification). [Guided by the workplan and peer–reviewed report developed at the first workshop, the second workshop will allow subject specialists to take all available scientific information into account in assessing what species and habitats appear to be most vulnerable to climate change as well as where future highly productive areas are predicted to occur and what the current level of protection is in these areas. The first workshop will produce high–level subject overviews and summarize what is currently known. The second workshop will take what is known and use that to identify what species and habitats appear most vulnerable to climate change and what areas appear to be most in need of protection.]

ToR g) Determine the most appropriate method for the outreach of the study group's findings, such as considering publication of finding in an ICES Cooperative Research Report.

The report of the SGMPAN will be reviewed by the Working Group on the Ecosystem Effects of Fishing Activities (WGECO) and the Working Group on Deep-water Ecology (WGDEC) in 2011. Those reviews should be available by late May 2011. Review comments and additions will be considered by SGMPAN by correspondence during June 2011 and a revised document produced if necessary. This document could be published as a joint ICES-NAMPAN report in the ICES Co-operative Research Report Series or as a special publication of NAMPAN.

In June/July 2011 SGMPAN Chairs will initiate correspondence with ICES expert group chairs to formulate ToR for consideration at the ICES annual meeting in September 2011. Species, habitat and ecosystem specialists in ICES expert groups (and elsewhere as appropriate) would be asked to assess ecosystem components following the SGMPAN guidelines produced in this report in order to identify what species and habitats appear most vulnerable to climate change and what areas appear to be most in need of protection. Expert groups under consideration include:

Acronym	Name	Chair*	Committee
AFWG	Arctic Fisheries Working Group	Bjarte Bogstad	ACOM
BEWG	Benthos Ecology Working Group	Steven Degraer	SSGEF
WGBIODIV	Working Group on Biodiversity	Jim Ellis	SSGEF
WGEF	Working Group on Elasmobranch Fishes	Graham Johnston	ACOM
WGFE	Working Group on Fish Ecology	Dave Kulka	SSGEF
WGMME	Working Group on Marine Mammal Ecology	Sinead Murphy	ACOM
WGOOFE	Working Group on Operational oceanographic products for fisheries and environment	Morten D. Skogen Mark Dickey-Collas	SSGSUE

ACRONYM	NAME	CHAIR*	COMMITTEE
WGPBI	Working Group on Modelling of Physical/Biological Interactions	Uffe Thygesen Elizabeth North	SSGEF
WGPME	Working Group on Phytoplankton and Microbial Ecology	Xose Anxelu G. Moran William Li	SSGEF
WGSE	Working Group on Seabird Ecology	Jim Reid	SSGEF
WGSPEC	Working Group on Small Pelagic Fishes their Ecosystems and Climate Impact	Jürgen Alheit	SSGEF
WGZE	Working Group on Zooplankton Ecology	Mark Benfield	SSGEF

*Chair in December 2010.

Expert groups would complete their work through the winter of 2011/12 and SGMPAN would hold its second and final meeting in the summer of 2012 to collate the reports of the expert groups and to produce a report on the species and habitats most vulnerable to climate change from the Gulf of Mexico to the Canadian Arctic. This report could also be published as a joint ICES-NAMPAN document.

Annex 1: List of participants

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Annex 2: Agenda

**NAMPAN – ICES Study Group
on Designing Marine Protected Area Networks
in a Changing Climate (SGMPAN)**

13:00 Monday November 15, 2010 – 12:00 November 19, 2010

U.S. Geological Survey, Center for Marine Science, 384 Woods Hole Road, Quissett Campus, Woods Hole, Massachusetts, USA

13:00 Monday 15 November

<u>Plenary Session</u>

Welcome and Opening Remarks:

Dr. Larry Madin, Vice-President for Research of the Woods Hole Oceanographic Institution

Dr. Walter Barnhardt, Chief Scientist, U.S. Geological Survey Center for Marine Science

Evan Lloyd, Executive Director, Commission for Environmental Cooperation (CEC)

<u>Introductions</u>

Introductions of workshop attendees

Presentation on using Sharepoint/Printer and other logistical services (Karen Schmidt, Commission for Environmental Cooperation)

Overview of workshop agenda and work plan (Robert Brock, Ellen Kenchington, and Amparo Martinez, SGMPAN Chairs)

Presentation on SGMPAN approach to **ToR a)**: Determine what properties of populations, habitats and ecosystems increase the resilience of marine systems to impacts of climate change in the region of the NW-Atlantic to the Caribbean. [For example, the degree to which life history traits are tied to places, flexibility of migration routes, etc.] Lead: Jonathan Fisher

Presentation on SGMPAN approach to **ToR b)**: Review what properties of MPA networks are most relevant to providing the elements described in ToR a). Lead: Brad Barr

Presentation on SGMPAN approach to **ToR c)**: Review the atmospheric, oceanographic and biological information for the east coast of North America that could be used to address the knowledge needs identified in ToR a). Leads: John Loder, Janet Nye and Mike Fogarty

Review format and logistics for subject discussion groups for ToRs a), b), c); Uploading of material to Sharepoint site.

15:00 Tuesday 16 November

<u>Plenary Session</u>

Progress report from ToRs a), b), and c) Leaders

Presentation on SGMPAN approach to **ToR d)**: Provide a list of species and habitats with crucial ecosystem roles, or those of special conservation concern that should be considered in the context of climate change and MPA network design. Lead: Dave Kulka

Presentation on SGMPAN approach to **ToR e)**: Describe the types of analyses that are appropriate to both the scientific questions that need to be answered and simultaneously to inform network design for the very complex task of enhancing and protecting ecosystem resilience. Leads: Dvora Hart and Brad DeYoung

Presentation on SGMPAN approach to **ToR f)**: Develop a workplan with tasks, deliverables, and timetable to inform a second workshop of species, habitat and ecosystem specialists who would assess those components following the framework established above, including an evaluation of their current and potential vulnerability to ocean-atmospheric processes (which include not only climate and meteorology but also interaction processes related with climate like gases exchange and acidification). Lead: Ellen Kenchington

***** Meeting to follow a format of break-out group and plenary discussion as required with times to be posted daily based on progress *****

9:00   Friday 19 November

Discussion groups for all ToRs

The last plenary session will be scheduled for first thing in the morning. The remaining time will be spent tidying up the report, finalizing references, and the like.

12:00   Friday 19 November

Meeting to adjourn.

Annex 3: SGMPAN Terms of Reference for the next meeting

The **Study Group on Designing Marine Protected Area Networks in a Changing Climate** (SGMPAN), chaired by Robert J. Brock, USA, Ellen Kenchington, Canada, and Amparo Martinez Arroyo, Mexico, will meet in June 2012 by correspondence to:

a) Synthesize responses from other ICES expert groups who have applied the guidelines detailed in the 2010/11 SGMPAN report towards identifying candidate areas for a network of MPAs which take into consideration climate change effects.

SGMPAN will report by September 2012 (via SSGSUE) to the attention of SCICOM.

Supporting Information

Priority:	The proposed activities of this Group will lead ICES into issues related to the Strategic Initiative on Biodiversity with direct links to two other Strategic Initiatives (Area-Based Science and Management (SIASM) and Climate Change). Consequently, these activities are considered to have a very high priority.
Scientific justification and relation to action plan:	Action Plan No: 1. Term of Reference a) The goal of the first meeting of SGMPAN was to provide scientific guidance for designing MPA networks in the northwestern Atlantic and adjacent seas. We anticipate that other ICES expert groups would review that plan (WGDEC and WGECO in 2011) and also assess the various ecosystem components following the framework that is developed (winter 2010). The proposed second (and likely final) meeting of SGMPAN would then bring together the results of work undertaken in applying the guidance to the information on the northwest Atlantic and adjacent and produce a more detailed report of the populations, habitats and ecosystems on the east coast of North America that should be considered in MPA network design. Such a report could be similar to the ICES CRR 293.
Resource requirements	The research programmes which provide the main input to this group are already underway, and resources are already committed. The additional resource required to undertake additional activities in the framework of this group is negligible.
Participants	A group such as this is normally attended by some 20–25 members and guests.
Secretariat facilities	None beyond standard administrative support.
Financial:	No financial implications.
Linkages to other committees or groups	SGMPAN is very relevant to the Working Group on Ecosystem Effects of Fisheries and to many other expert groups within ICES. It is anticipated that the following WGs would participate in applying the guidance detailed in the 2010/11 SGMPAN report: AFWG, Arctic Fisheries Working Group; BEWG, Benthos Ecology Working Group; WGBIODIV, Working Group on Biodiversity; WGEF, Working Group on Elasmobranch Fishes; WGFE, Working Group on Fish Ecology; WGMME, Working Group on Marine Mammal Ecology; WGOOFE, Working Group on Operational oceanographic products for fisheries and environment; WGPBI, Working Group on Modelling of Physical/Biological Interactions; WGPME, Working Group on Phytoplankton and Microbial Ecology; WGSE, Working Group on Seabird Ecology; WGSPEC, Working Group on Small Pelagic Fishes their Ecosystems and Climate Impact; and WGZE,Working Group on Zooplankton Ecology.

Linkages to other organizations	There is a very close working relationship with the Commission for Environmental Cooperation (CEC) and it's subcomittee on North American Marine Protected Areas Network (NAMPAN). NAMPAN has been active in the Pacific where there is an opportunity to link with PICES.

Annex 4: Recommendations

RECOMMENDATION	FOR FOLLOW UP BY:
1. Review of the 2010/11 SGMPAN report (already accepted ToR for WGECO and WGDEC)	WGECO, WGDEC
2. Terms of reference for 2011/2012 will be prepared after consultation with WG Chairs for a number of ICES expert groups which have been selected to provide more detailed information on ecosystem components or physical properties. These ToR, all pertaining to the application of the guidelines will be prepared prior to the business meetings of ICES in September 2011.	AFWG, Arctic Fisheries Working Group; BEWG, Benthos Ecology Working Group; WGBIODIV, Working Group on Biodiversity; WGEF, Working Group on ElasmobranchFishes; WGFE, Working Group on Fish Ecology; WGMME, Working Group on Marine Mammal Ecology; WGOOFE, Working Group on Operational oceanographic products for fisheries and environment; WGPBI, Working Group on Modelling of Physical/Biological Interactions; WGPME, Working Group on Phytoplankton and Microbial Ecology; WGSE, Working Group on Seabird Ecology; WGSPEC, Working Group on Small Pelagic Fishes their Ecosystems and Climate Impact; and WGZE,Working Group on Zooplankton Ecology.