Scientific Guidelines for Designing Resilient

Marine Protected Area Networks

in a Changing Climate

Commission for Environmental Cooperation

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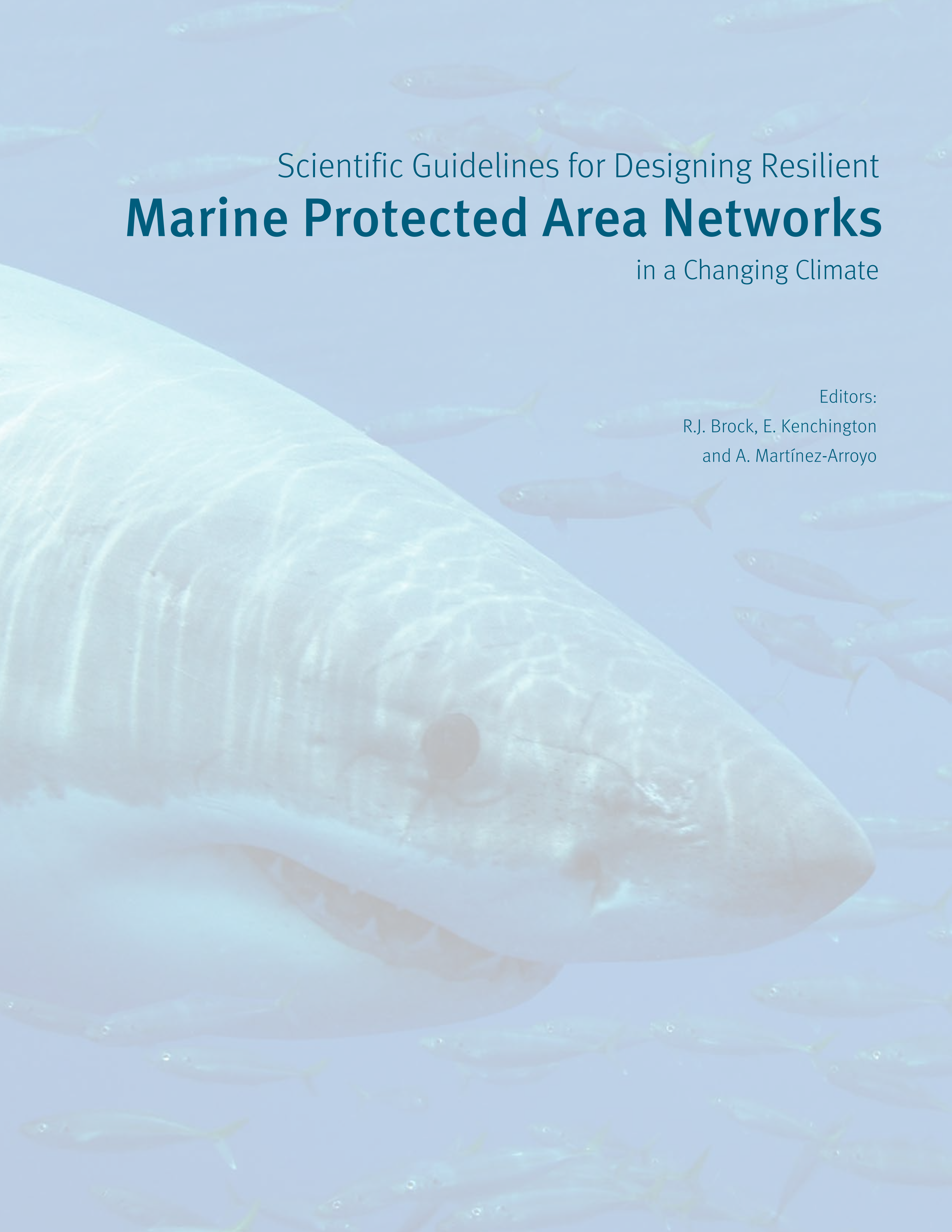

Scientific Guidelines for Designing Resilient

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Selected Definitions

In these Guidelines we follow the International Union for the Conservation of Nature/World Commission on Protected Areas (IUCN/WCPA) definitions for protected area and protected area network.[1] Note that the definitions apply to any or all of land, inland water, marine and coastal protected areas. The definitions for mitigation and adaptation have been drawn from the Intergovernmental Panel on Climate Change (IPCC)'s Fourth Assessment Report.[2]

Protected area

A clearly defined geographical space recognized, dedicated, and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values. [Note: "Marine reserve" is a more specific term, which denotes a no-take area.]

Protected area network

A collection of individual protected areas that operates cooperatively and synergistically, at various spatial scales, and with a range of protection levels, in order to fulfill ecological aims more effectively and comprehensively than individual sites could alone.

The *role* of a network of marine protected areas is to connect and protect those areas needed to bolster ecosystem functioning so that the overall health of the ocean is not jeopardized by human uses. This report presents Guidelines that consider the ability of marine protected areas and networks to adapt in the face of current and future climate change and mitigate its effects.

Mitigation

Technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks.

Adaptation

Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected *climate change* effects. Various types of adaptation exist, e.g., *anticipatory* and *reactive, private* and *public,* and *autonomous* and *planned*.

1. IUCN. 2008. Guidelines for Applying Protected Area Management Categories. N. Dudley, ed. Gland, Switzerland: International Union for the Conservation of Nature, http://data.iucn.org/dbtw-wpd/edocs/PAPS-016.pdf.
2. IPCC. 2007. Fourth Assessment Report. Geneva, Switzerland: Intergovernmental Panel on Climate Change, http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html.

Abbreviations and Acronyms

AOGCM	Atmosphere Ocean General Circulation Models
AMO	Atlantic Multi-decadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
AWP	Atlantic Warm Pool
CBD	Convention on Biological Diversity
CEC	Commission for Environmental Cooperation
CO_2	Carbon dioxide
COP	Conference of the Parties
DWBC	Deep Western Boundary Current
EA	Eastern Arctic
EBSA	Ecologically and Biologically Significant Area
ENSO	El Niño–Southern Oscillation
IAS	Intra-Americas Sea
ICES	International Council for the Exploration of the Sea
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
IUCN	International Union for the Conservation of Nature
MAR	Meso-American Reef
ML-TZ	Mid-Latitude Transition Zone
MPA	Marine protected areas
NAMPAN	North American Marine Protected Areas Network
NAO	North Atlantic Oscillation
NOAA/OER	National Oceanic and Atmospheric Administration Ocean Exploration and Research
SGMPAN	Study Group on Designing Marine Protected Area Networks in a Changing Climate
SP-NWA	Subpolar Northwest Atlantic
SST	Sea Surface Temperature
ST-WNA	Subtropical Western North Atlantic
TAV	Tropical Atlantic Variability
UNEP-WCMC	United Nations Environment Program-World Conservation Monitoring Centre
WCPA	World Commission on Protected Areas
WHWP	Western Hemisphere Warm Pool
WNA	Western North Atlantic
WTA	Western Tropical Atlantic

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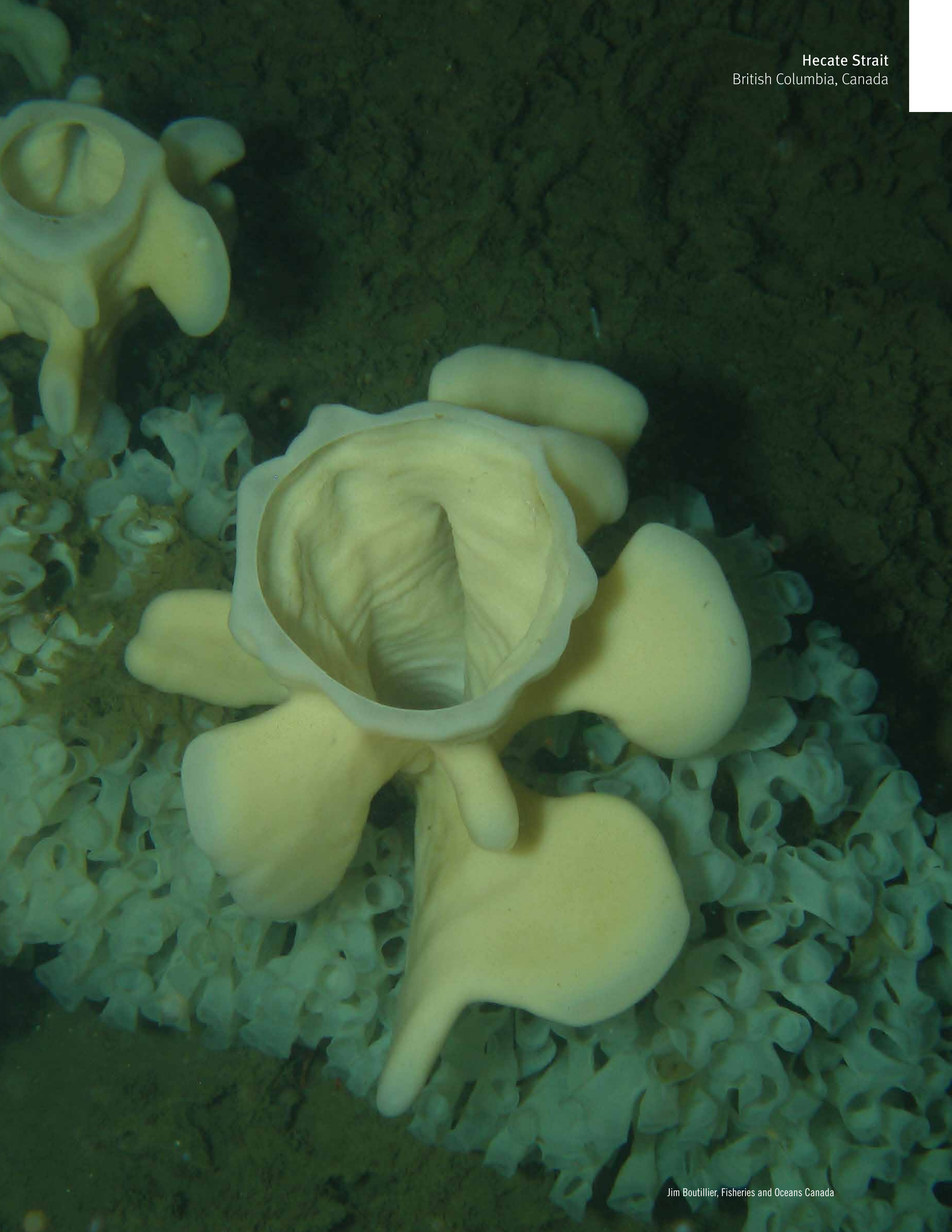
Foreword

This document, *Scientific Guidelines for Designing Resilient Marine Protected Area Networks in a Changing Climate*, was developed from a larger report by the Study Group on Designing Marine Protected Area Networks in a Changing Climate (SGMPAN), a joint study group of the Commission for Environmental Cooperation (CEC) through its North American Marine Protected Area Network (NAMPAN) Technical Group and the International Council for the Exploration of the Sea (ICES). SGMPAN developed their eponymous report at a workshop held in Woods Hole, Massachusetts, 15–19 November 2010 [3]. The area of interest for the study group and report extended from the Western Tropical Atlantic, including the Caribbean Sea and the Gulf of Mexico, northward to (and including) the Labrador Sea.

Members of the SGMPAN Study Group, chaired by Robert Brock (USA), Ellen Kenchington (Canada) and Amparo Martinez-Arroyo (Mexico), met again in Woods Hole from 9–11 August 2011, to incorporate changes to the SGMPAN report, resulting from a six-month peer review of the document. They also developed scientifically based guidelines for the design of a marine protected areas (MPAs) network that would take into consideration expected climate change impacts on marine ecosystems.

The comprehensive report (ICES 2011a)[4] that resulted from the SGMPAN Study Group's writing and review process is considered to be the reference document for the guidelines presented here. The chairs thank all the members of the Study Group and all who contributed to the drafting, reviewing, editing, and printing of these draft guidelines for their dedication and time; together they have produced a comprehensive set of guidelines for designing marine protected areas and networks in a changing climate.

3. The list of workshop participants from Canada, Mexico and the United States is found in **Annex 3**.
4. ICES. 2011a. Report of the Study Group on Designing Marine Protected Area Networks in a Changing Climate (SGMPAN), 15–19 November 2010, Woods Hole, Massachusetts, USA. ICES CM 2011/SSGSUE:01. 155 pp.



Hecate Strait
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Introduction

Scientific Guidelines for Designing Resilient Marine Protected Area Networks in a Changing Climate

> **KEY CONCEPT**
>
> RESILIENCE has been widely used in theoretical context but seldom has been defined operationally. Resilience is generally characterized as an attribute of a system and relates to its potential recovery from disturbances and/or its resistance to disturbances. Holling's (1973) original definition has been adopted for these Guidelines as: "the magnitude of the disturbance that a system can absorb without fundamentally changing."

Climate change, resulting from 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. Climate can affect all life-history stages through direct and indirect processes and the possible effects of climate change for marine populations include changes in population dynamics (body size, reproduction), community composition and geographical distributions. Climate change can be expected to affect populations, habitats, and ecosystems differently depending on their underlying characteristics (ICES 2011a, b). Although there are many uncertainties about the rates and spatial structure of future climate change, the probable and potential changes need to be considered in ecosystem management planning.

Ecosystems are complex, dynamic networks of interacting abiotic and biotic components, with a certain 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.

Those parts of the environment that together comprise 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 also 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.

What properties increase the magnitude of disturbance that an ecosystem can absorb?

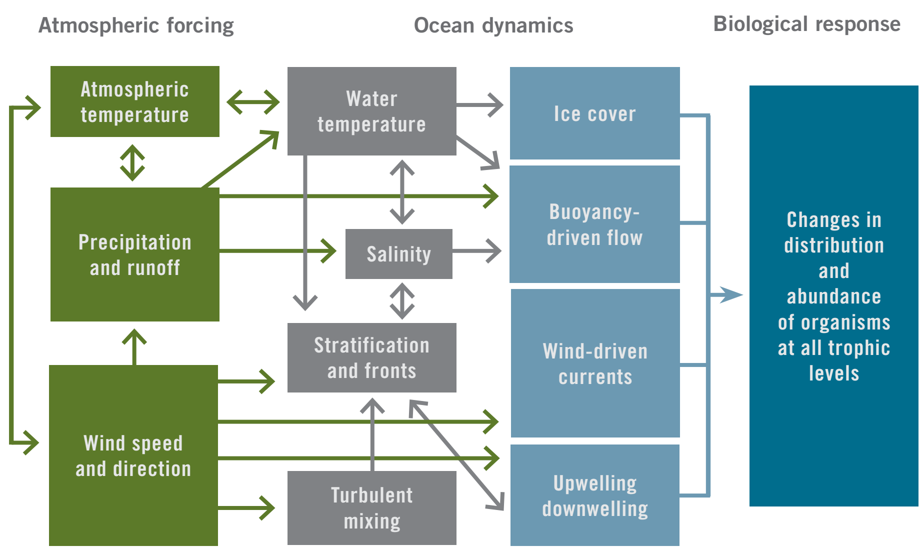
A sample of some of the potential pathways for atmospheric effects on oceanic dynamics and biological response are depicted in the box below (**Figure 1**). These changes will be manifest on scales ranging from the relatively small spatial and temporal scales characteristic of turbulent mixing processes, to global-scale changes in deep ocean circulation occurring over millennia. Tracking processes that occur 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. Some of the properties of populations, habitats and marine ecosystems that may be sensitive to and affected by climate change are indicated in **Table 1**. Given the importance of connectivity to marine protected area (MPA) network design, understanding the influences of climate change on different components of connectivity remains a key research need (**Figure 2**) with the idea of using MPAs and MPA networks to make various ecosystem components more resilient to these anticipated climate change impacts (**Figure 3**).

What are the generalized effects of climate-driven oceanographic change on key ecosystem components?

The SGMPAN report (ICES 2011a) identified a number of generalized effects of climate change on selected ecosystem components:

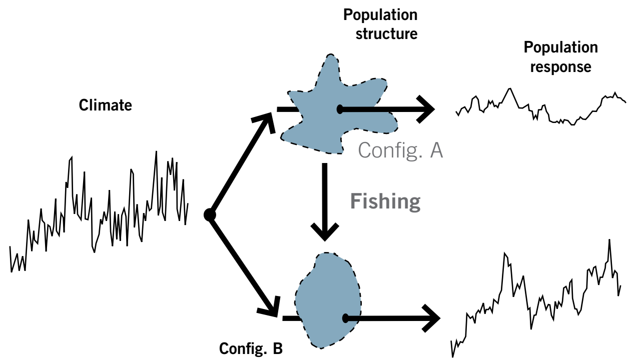
- Changes in distribution are expected across all trophic levels.
- Decreases in primary productivity are expected in low latitude ecosystems, but increases in primary productivity are expected in high latitude systems.
- Changes in trophic-level interactions.
- Integration of lower trophic level processes by top predators

Figure 1 Interactions between the atmosphere, the ocean and living organisms



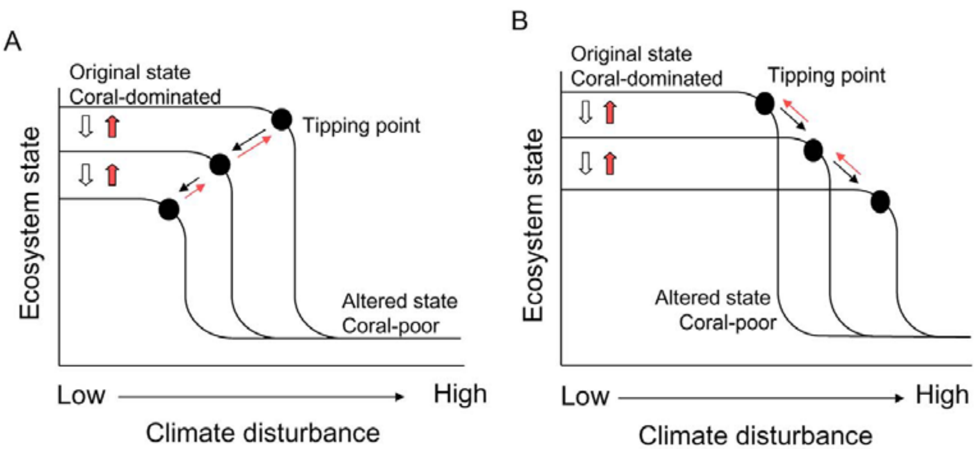
Some of the potential interactive pathways for atmospheric effects on oceanic dynamics and biological response in production processes include but are not limited to those illustrated above. Changes in atmospheric temperature, precipitation, and winds will affect stratification, buoyancy-driven flows, upwelling/downwelling, sea ice and other factors. These will potentially affect production at all trophic levels. 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.

Figure 2 Climate change rarely is the only stressor on marine systems



Predicting multiple climate influences coupled with additional stressors such as fishing adds additional complexities, indirect effects, and associated uncertainties. This figure is a schematic representation of the increased vulnerability of a marine population variable (e.g., abundance) to climate change effects when also affected by exploitation (from Perry *et al.* 2010).

Figure 3 Shifting baselines



Managing coral reefs for resilience to climate change. **A.** The conventional view of resilience. Natural communities are highly resilient to climate change, i.e., the tipping point (black circle) leading to an alternative ecosystem state is far to the right and attained only at high levels of climatic disturbance. As chronic anthropogenic disturbances gradually degrade the original ecosystem (open block arrows), the tipping point in response to climate change gradually shifts to the left (black arrows), making the ecosystem less resilient to climatic disturbance. Management that seeks to control local anthropogenic disturbances should reverse degradation (red block arrows), shifting the tipping point back to the right, towards higher resilience (red arrows). **B.** A possible counter-intuitive effect of managing coral reefs for resilience to climate change. If the effect of chronic anthropogenic disturbances, which gradually degrade the original ecosystem (open block arrows), is to remove disturbance-sensitive individuals and/or species, the tipping point in response to climate change will gradually shift to the right (black arrows), making the ecosystem more resilient to climatic disturbance. Management that seeks to control local anthropogenic disturbances and reverse degradation (red block arrows) will inadvertently shift the tipping point back to the left, towards lower resilience (red arrows) to climatic disturbance. From: Côté and Darling (2010). MPA network designers should consider the impacts of previous anthropogenic stressors when setting objectives related to current states of ecosystems. While not all climate change impacts affecting species and habitat traits to can be mitigated by or adapted through MPAs or MPA networks, overall, MPAs are a useful tool in the climate change adaptation toolbox.

Table 1 Properties with marked influence on the resilience of marine systems that may be impacted by climate change

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

What role can Marine Protected Area networks play in adapting and mitigating the effects of climate change?

Marine Protected Area (MPA) networks must be designed to be integrated, mutually supportive and focused on sustaining key ecological functions, services and resources. 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. Some of those properties can be supported through the size and placement of protected areas (e.g., abundance and size structure of upper trophic levels, species richness), and the reduction of other pressures such as fishing. Some ecosystem properties may not be amenable to spatial management tools but can be used to predict their vulnerability to climate change (e.g., phenological matches, flexibility of migration routes, dependence on critical habitats, functional redundancy, response diversity, community evenness: ICES 2011a).

KEY CONCEPT

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, integrated, and adaptive 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 will be particularly important with regard to the establishment and operation of transboundary MPA networks.

Ecological traits for which climate change impacts *cannot* be mitigated by MPAs may still benefit from other protection or conservation approaches. MPA managers (with the support of scientific experts and scientific guidance) will need to determine whether those traits should still be protected in the network (e.g., no protection for those traits, short term protection until climate change exerts its effects, or protection in perpetuity with the hope that those traits can be partially salvaged from climate change) or whether alternative management measures can be applied to protect those traits.

Considering how MPA networks can be designed to adapt to and mitigate the influences of climate change on ecosystems is relatively novel. Despite projected spatial and temporal variation in climate impacts, MPA networks are still being designed on the basis of contemporary environmental and habitat conditions (Gaines *et al.* 2010). Managers and planners will need to assess whether the objective(s) considered when establishing MPA sites and networks today will be met in the future under climate change scenarios and their uncertainties. Managers and planners may also want to establish MPA sites and networks *with the objective* of increasing or maintaining resilience to climate change impacts on populations, habitats and ecosystems. Both of these require managers and planners to be adaptive in their use of available tools, and new approaches must be developed if the existing tools are not sufficient to incorporate the dynamic nature of this challenge.

The CEC/NAMPAN-ICES Initiative

The Commission for Environmental Cooperation (CEC), through its North American Marine Protected Areas Network (NAMPAN) Technical Group, joined with the International Council for the Exploration of the Sea (ICES) and established a Study Group on Designing Marine Protected Area Networks in a Changing Climate (SGMPAN) to develop scientifically based guidelines for marine protected areas (MPA) network design which take into consideration expected climate change impacts on marine ecosystems (ICES 2011a). Participants were from Canada, Mexico, and the United States. The SGMPAN comprehensive report is considered to be the reference document for the guidelines tabled here.

The intent is that these guidelines will improve the ability of the three countries to design, manage, assess and adapt MPA networks in light of probable or potential climate change at national and continental scales. However, we emphasize that 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 marine planning process both nationally and internationally. An integrated policy is needed that includes other management measures addressing anthropogenic stressors such as fishing, pollution control, and that links with other protected areas and networks—including terrestrial areas which impact estuarine and marine systems. This allows the development of scientific advice that assesses and monitors the effectiveness of various management actions as part of a total package. We fully realize that the three countries may have very different legal mechanisms for implementing place-based management or any more suitable response to expected climate change. We also are sensitive to the possibility that the three countries may possess different technical and financial capabilities of enforcing and assessing any place-based management or other climate change response decision. Therefore, scientific research directed towards improving projections of climate change and its effects on marine communities must also be part of the global strategy.

KEY CONCEPT

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

- Facilitating the protection of an ecosystem or species that cannot be adequately protected in one country, such as migratory species;
- Enhancing the level of attention given to transboundary protected areas so they receive 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.

Using these Guidelines

These guidelines were produced to promote best practices, consistency of approach and collaboration, when designing marine protected area (MPA) sites and MPA networks, between managers, planners and scientists studying climate change effects on populations, habitats and ecosystems. A number of documents cover aspects of these Guidelines. In particular, the IUCN/World Commission on Protected Areas report, "Establishing Marine Protected Area Networks—Making It Happen," and the National Oceanic and Atmospheric Administration's "Adapting to Climate Change: A Planning Guide for State Coastal Managers" provide excellent and relevant overviews.

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 discussion in the context of climate change in the background document to these guidelines (i.e., ICES 2011a):

- Representativity (or Representation): covers the full range of biodiversity, rare and threatened species;
- Connectivity: ensuring linkages between sites through currents, migratory species, larval dispersal;
- Replication/Redundancy: protecting more than one example of a given feature; and
- Adequacy/Viability: appropriate size, spacing, shape of MPAs.

Table 4.2.1 of the SGMPAN report (ICES 2011a) is an informative resource and highlights these network properties as well as site-specific MPA criteria such as Ecologically and Biologically Significant Areas (EBSAs) for network component areas, as derived from sources such as the Convention on Biological Diversity (CBD) (2009). Table 1 in the 2011 "IUCN Ecologically or Biologically Significant Areas in the Pelagic Realm: Examples and Guidelines Workshop Report"[5] lists the various criteria used by various UN Agencies and Programs for identifying EBSAs. 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 and listed, along with concrete examples, the scale(s) at which it operates, and its relation to climate change.

Four high-level objectives which the SGMPAN considered to be critical to conferring resilience in the face of climate change are presented as guidelines:

- **Guideline 1: Protect species and habitats with crucial ecosystem roles, or those of special conservation concern**
- **Guideline 2: Protect potential carbon sinks**
- **Guideline 3: Protect ecological linkages and connectivity pathways for a wide range of species**
- **Guideline 4: Protect the full range of biodiversity present in the target biogeographic area**

For each guideline we present steps for scientists, managers and planners to follow when evaluating the impact of climate change on the objective. One of these steps is to ask whether spatial management tools (in particular, MPA sites and/or MPA networks, fisheries closures, etc.) can be used to mitigate or adapt against projected impacts. It is envisioned that specialist groups will follow the steps proposed in these guidelines and provide scientifically based reports that can be used to design any appropriate response, such as a dynamic MPA framework stretching from the Caribbean to the Labrador Sea and extending, as required, into the high seas. It is worth noting that there are other approaches that may be more politically feasible than dynamic MPAs. Managers will need to consider a suite of approaches, including dynamic MPAs, larger MPAs, MPAs where the zoning is dynamic but the outer boundaries of the sites are not, restriction of fishing gear types, spatial restrictions, etc.

5. See http://data.iucn.org/dbtw-wpd/edocs/2011-055.pdf.

In addition, a management guide for the guidelines, developed by MPA practitioners, will be especially helpful to assist MPA managers and planners in how best to understand and use these guidelines (expected publication date: Autumn 2012).

These guidelines may also be complimentary to one another. A management action pertaining to one guideline may fulfill another guideline objective as well. For instance, protecting a mangrove coastline may clearly fulfill Guideline 1 (e.g., habitat with crucial ecosystem role), Guideline 2 (e.g., clearly a potential carbon sink), Guideline 3 (e.g., fish spawned on a coral reef may migrate to the mangrove prop roots and adjacent seagrass bed as juveniles), and Guideline 4 (e.g., protecting mangrove habitat also protects the biodiversity associated with this habitat). In this instance, one may get the most "bang for the buck" by implementing this action.

Permanent and coordinated monitoring of key terrestrial, atmospheric and oceanographic environmental variables along the MPA network will allow for adaptive management and must be strategic in assessing MPA networks and their development. It would be advantageous to assess the level of information available beforehand and develop a clear strategy for filling any information gaps. It is also advisable that a clear indication of the level of difficulty and cost associated with each Guideline be articulated and clearly understood. Each guideline may be very different in terms of information needed, the level of technical expertise necessary to obtain the required information, and the costs associated with each step. Each guideline should be monitored, evaluated, and reviewed using appropriate analytical methods.

Data gaps on past changes and effects 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. It is even more difficult to project future climate change and its impacts, especially on some of the spatial and time scales that are important to ecosystems. Thus, the confidence and uncertainties associated with future projections need to be considered in decisions that are based on them.

Annex 1 to this report provides a high-level overview of the physical (atmospheric and oceanographic) properties that are projected to change over the coming decades, including the direction, magnitude and spatial extent of the projected changes, and an indication of the level of uncertainty. This Annex can be used to by topic specialists to estimate the time-scale over which their subject is expected to respond to climate change and hence trigger a re-evaluation of the MPA boundaries. With the rapidly evolving knowledge of and improving predictive capabilities for climate change, it is expected that more reliable and specific projections of climate change and impacts will become available during the MPA planning process, such that updated information should be regularly considered.

Annex 2 provides generalized effects of climate change driven oceanographic changes on components of the ecosystem. Practitioners are urged to consult the full report (ICES 2011a) for further information, including analytical techniques and availability of suitable databases and a much more detailed discussion of the material that is summarized in **Annex 2**.

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Guideline 1

Protect Species and Habitats with Crucial Ecosystem Roles, or those of Special Conservation Concern

Step 1 Identify species and habitats with crucial ecosystem roles or those of special conservation concern.

Step 2 Identify the traits of those species/habitats identified in Step 1 that are vulnerable to projected climate change impacts.

Step 3 Determine whether the impacts of climate change on the traits identified in Step 2 can be mitigated by or adapted through MPAs or MPA networks.

Step 4 If impacts on the traits identified in Step 2 can be mitigated by MPAs or MPA networks, specialists should estimate the timescale over which their subject is expected to respond to climate change and trigger a re-evaluation of the boundaries of the MPA, or design the MPA or MPA network to be robust to these changes.

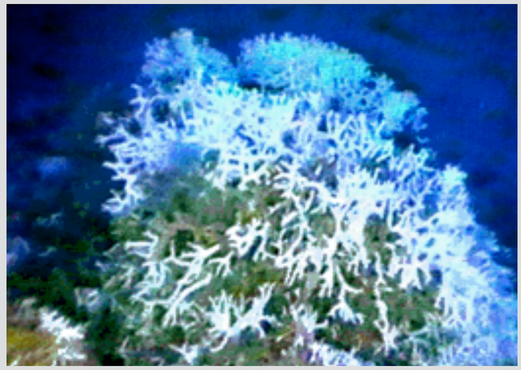
Step 1

Identify species and habitats with crucial ecosystem roles or those of special conservation concern.

It is important to protect species and habitats that seem to "drive" or "structure" ecosystems and ecosystem processes. That is, they are considered vital for a particular species, group of species, or for the functioning of an ecosystem. The presence of a particular predator, prey, grazer, bioengineer, or habitat may impact many other members of the ecosystem, and if its population or coverage dwindles or disappears, there can be far-reaching consequences for the ecosystem. If, for example, the predator is removed, dramatic changes result in the varieties and population densities of all the other species in the community. If an important prey species is removed, species that rely on this food source may dwindle or disappear as well. Loss of habitat and the ecological functions it may provide (such as aggregating species for spawning and feeding and providing refuge for juveniles) may be followed by changes in the distribution and abundance of particular species as well as overall community structure. Areas containing either species or habitats with crucial ecosystem roles or of special conservation interest are considered Ecologically and Biologically Significant Areas (EBSAs) according to the CBD's international EBSA guidance, though not all EBSAs indicate the presence of species and habitats with crucial ecosystem roles. For example, EBSAs identified for naturalness would not qualify, while other categories such as EBSAs identified for uniqueness and rarity may sometimes qualify.

Planktonic species such as the copepod *Calanus finmarchicus* and euphausiid *Meganyctiphanes norvegica* serve as food for a wide range of upper trophic level commercially and ecologically important species in the North Atlantic. The timing and availability of these species to larval and juvenile stages of many fish species plays a key role in recruitment success. **Forage fish species** such as capelin (*Mallotus villosus*), herring (*Clupea* spp.), and Spanish sardine (*Sardinella aurita*) play a very similar role as they are consumed by a variety of predators including marine birds, marine mammals, other fish species, and apex predators such as billfish and tunas. These forage fishes play a crucial role in ecosystem dynamics, transferring energy from plankton and small fish to the larger species. Many **marine mammals**, primarily the cetaceans, depend on large amounts of copepods, squid, and forage fish such as sand lance (*Ammodytes* spp.), herring, and capelin being

An example of a situation that could be monitored and mitigated by moving the marine protected area boundaries over time to encompass the target habitat.



An *Oculina varicosa* mound near the shelf-edge off eastern Florida, showing the coral's delicate branching habit.

Image courtesy of Islands in the Stream, 2001, NOAA/OER

Oculina Bank near the shelf edge (70 to 120 meters water depth) off east central Florida is an example of a unique and vulnerable habitat. It is the only known site of reefs of *Oculina varicosa*, a delicate branching deep-sea (azooxanthellate) coral that can form mounds and pinnacles tens of meters high. This habitat is a productive spawning and foraging place for several economically important fish species, including groupers (gag, scamp, Warsaw, and snowy) amber jack, and speckled hind. The thicket-like growth pattern of the coral provides complex interstices that support a highly diverse community of molluscs and crustaceans (Reed *et al.* 1982; Reed and Mikkelsen 1987; Gilmore and Jones 1992).

Oculina Bank and adjacent shelf areas have been trawled for shrimp for several decades, destroying many of the coral pinnacles (Koenig *et al.* 2000). *Oculina varicosa* breaks easily and grows slowly, making it particularly vulnerable to physical impacts and slow to recover. About 300 square miles of *Oculina* Bank have been designated as a Habitat Area of Particular Concern by the South Atlantic Fishery Management Council. This designation protects the remaining reef habitat from mobile fishing gear and from other potentially damaging mechanical impacts. The protection has allowed new coral growth to occur on experimental coral transplant blocks, deployed in an effort to assist the recovery of the *Oculina* reefs, and large groupers have been sighted in the closed area.

Establishing an MPA around *Oculina* Bank appears to be a good strategy to mitigate the effects of trawl and anchor impacts on the unique and vulnerable habitat. However, it is not as obvious whether impacts from climate change, such as increased water temperature, ocean acidification, or changing current regimes could be addressed effectively by a marine protected area. For example, if the current which carries food to the corals on *Oculina* Bank were to shift further off-shore, the habitat would no longer be conducive to the growth of *Oculina varicosa* and the remaining reefs would die, regardless of the existence of a protected area. On the other hand, new recruits may settle and new reef mounds may grow in the path of the relocated current and its entrained food supply. In this scenario, the vulnerable habitat may no longer be within the MPA.

present as their stock status is strongly dependent on favorable prey species conditions. Similarly, many **marine birds** prey upon similar forage species and are dependent upon healthy numbers of Atlantic mackerel (*Scomber scombrus*), for example, being available to feed their chicks. **Top predator species** such as sharks and certain billfishes and tunas can have a "top down" impact on ecosystem structure, consuming large amounts of the prey base. Stomach content analyses of Atlantic bluefin tuna (*Thunnus thynnus*) revealed that they consume similar forage species (e.g., capelin, herring, sand lance) and that spatial variation in prey availability is the primary driver in influencing the distribution of the top predators.

Filter-feeding species such as mussels, oysters, clams, and scallops occur over a wide range of habitats (e.g., rocky shores, coral reefs, mud flats, sandy bottoms). They can alter sediment chemistry through burrowing and nutrient availability through filter-feeding, and are major competitors for space. **Structure-providing species** such as zooxanthellate coral reefs alter water flow, provide substrate for sessile organisms and refugia for juvenile or prey species, and are foraging centers for a variety of species. Cold-water (azooxanthellate) corals and sponges serve similar important ecosystem functions. Coral reefs provide ecological services that are vital to tens of millions of people worldwide.

A Species of Special Conservation Concern is any species or subspecies that is undergoing a long-term decline in abundance or that is vulnerable to a significant decline due to low numbers, restricted distribution, dependence on limited habitat resources, or sensitivity to environmental disturbance. These species may or may not have crucial ecosystem roles and may or may not be protected by legislation.

A habitat is the physical place where an assemblage of organisms lives and is comprised of attributes such as substrate type, rugosity, depth, temperature, etc. A habitat is unique if no others or few others like it are known to exist. A habitat is vulnerable if it is easily damaged (by human or natural impacts) and/or will take a long time to recover from damage. Vulnerable habitats can be unique, but may also be common. Their vulnerability can be the result of physical fragility (e.g., a coral) and/or being slow to recover from impacts (e.g., having a slow growth rate). Vulnerable habitats are likely to be disproportionately affected by climate change. A habitat may be used in a transitory way by other species for foraging, settling, or breeding. In such cases, habitats may be crucial to survival of a species. For example, there are only six Northern Gannet breeding colonies in North America, three of which are located within the Gulf of St. Lawrence (Environment Canada/Canadian Wildlife Service, Waterbird Colony Database). These birds winter in the Gulf of Mexico.

The spatial extent of unique, rare, or vulnerable habitats is usually relatively small, but the significance of these habitats may be much larger in scale, affecting surrounding ecosystems. It is also important to consider how climate change might affect these habitats, as well as the timescale of effects. Vulnerable habitats may be more severely impacted on first encounters with stressors and may take longer to recover. For example, a single trawl pass can destroy long-lived deep-water corals and their recovery, if recovery is possible at all, could take hundreds of years. In contrast, a similar pass over communities composed of high-turnover species in high-energy habitats may have much shorter-lived effects.

Step 2

Identify the traits of those species/habitats identified in Step 1 that are vulnerable to projected climate change impacts.

Plankton species are very sensitive to water temperature, which also has a strong influence on body size, growth, development, and metabolic rates of species. Some species of microzooplankton and mesozooplankton are intolerant of warmer water temperatures, whereas expected increases in megazooplankton such as jellyfish with warmer water conditions may change the availability of food for ichthyoplankton and juvenile fish due to increased predation on smaller zooplankton species. Increasing surface water temperature also leads to higher levels of stratification in the water column and impacts primary production.

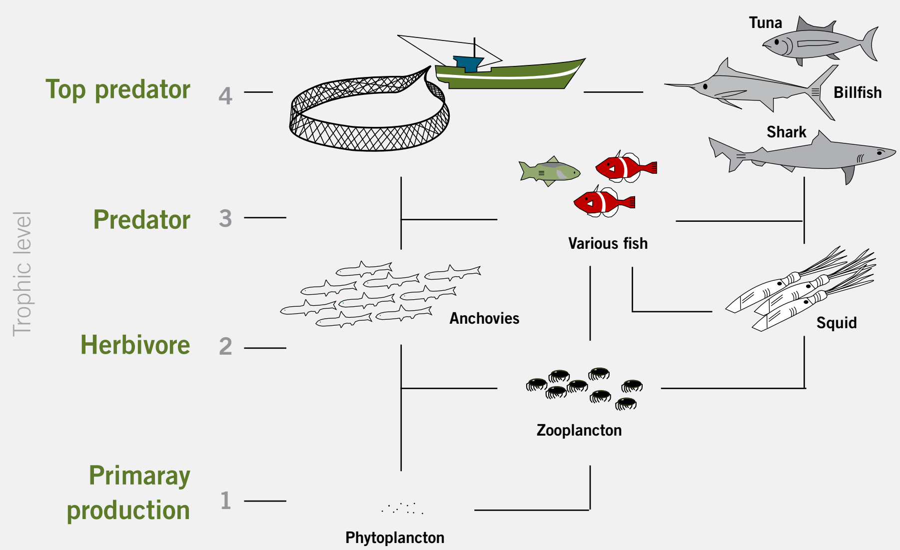
Temperature, along with salinity and dissolved oxygen, has similar effects on the physiology and distribution of **forage fish species**. The United States recognizes the important role of forage species such as herring and mackerel as food for other species and that the distribution of prey species influences the distribution of their predators; forage species are therefore the focus of several ecosystem-based management plans due to their co-varying traits of small body sizes and high abundances. Herring, mackerel and other such small-bodied forage species are particularly sensitive to temperature changes and change their geographic distributions to match preferred temperatures (Murawski 1993; Perry *et al.* 2005).

Marine mammals, particularly whales, are sensitive to the availability of suitable seasonal *refugia* (e.g., ice-free waters) necessary for breeding and calving and the presence of suitable prey. Relatively free from whaling, marine mammals are now most impacted by the stock levels of prey species, vessel traffic and vessel collisions, and fishing gear entanglements.

Marine bird species appear to be opportunistic feeders that are also sensitive to stock levels of suitable prey as well as to availability of suitable habitat (e.g., cliffs, marshes, mud flats, rocky shores).

KEY CONCEPT

TOP PREDATORS are reliant on lower trophic levels and if increasing water temperatures change the size, abundance, and distribution of these lower trophic species, top predators will also be impacted. Increasing water temperatures are associated with shifts to smaller size phytoplankton and zooplankton. Small herbivorous forage fish such as anchovies and herring consume principally phytoplankton as well as zooplankton and their growth may be negatively impacted by smaller-sized plankton. These forage species represent an important food link to juvenile species (referred to as "various fish" below), which in turn may be preyed upon by squid. Squid are an abundant prey item for adult cod, marine mammals, and apex predators such as tuna, billfish, and shark.



The Northern Gannet (*Morus bassanus*) appears to be sensitive to the availability of mackerel while the Atlantic Puffin (*Fratercula arctica*) appears to have a flexible diet of prey species, changing from preferred capelin to post-larval sandlance as a response to availability.

Many **top predator species** (e.g., sharks, billfish, tuna) are both ecologically important as well as species of special concern. They are highly sought after for recreational and commercial fisheries. Their abundance and distribution appear to coincide with the most favorable physical oceanographic conditions and availability of suitable prey. Climate change influences on the location and strength of preferred oceanographic features may directly influence their abundance and distribution. Other species, such as sea turtles, are very sensitive to anthropogenic disturbances to habitats where they nest, develop, and feed (e.g., sandy beaches, nearshore seagrass beds). Suitable habitat could easily be modified or lost due to rising sea levels caused by climate change, for example.

It is hypothesized that changes in water temperature and water movements will have significant impacts on the distribution and abundance of marine benthic invertebrates. Ocean acidification will impact benthic organisms that use calcium carbonate in the formation of their shells. Recent studies on commercially important species such as the American oyster, soft shell clam, and ocean quahog have documented softening of the shells and decreases in growth in waters exhibiting increasing acidity.

Annex 2 provides a description of climate change effects on selected ecosystem components. Section 5.2 of the SGMPAN report (ICES 2011a) also focuses on how climate change will affect ecosystem components and identifies data sources to detect those changes. The selection of marine ecosystem components is loosely based on the different sampling techniques necessary to survey changes in abundance and distribution and on the availability of databases. The ecosystem components discussed include phytoplankton and zooplankton, benthic invertebrates, fish, marine birds, turtles, marine mammals, plants (mangroves and seagrasses), and corals. The SGMPAN report (ICES 2011a; Section 7.3) describes 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.

Step 3

Determine whether the impacts of climate change on the traits identified in Step 2 can be mitigated by or adapted through MPAs or MPA networks.

Not all traits which are expected to respond to climate change impacts can be influenced by spatial area closures. For example, marine calcifiers develop exoskeletons that may be vulnerable to ocean acidification caused by atmospheric changes (see **Annex 2**). This includes ecologically important habitat (e.g., corals) and species (e.g., crustacean copepod zooplankton).

Step 4

If the impacts on the traits identified in Step 2 can be mitigated by MPAs or MPA networks, specialists should estimate the timescale over which their subject is expected to respond to climate change and trigger a re-evaluation of the boundaries of the MPA, or design the MPA or MPA network to be robust to these changes.

Refer to **Annex 1** of this report for a high-level overview of the physical (atmospheric and oceanographic) properties that are projected to change over the coming decades, including the direction, magnitude and spatial extent of the projected changes, and an indication of the level of uncertainty. This Annex can be used by specialists to estimate the timescale over which their subject is expected to respond to climate change and hence trigger a re-evaluation of the MPA boundaries.

The “Plaice Box” Example

A partially closed area, the “Plaice Box” was implemented in the North Sea in 1989, and was intended to reduce the discarding of undersized plaice. The Plaice Box has had limited effectiveness because juvenile plaice have moved further offshore, outside of the protected area, due to increased water temperatures (van Keeken *et al.* 2007). This example emphasizes the need to reassess MPA boundaries at appropriate intervals in light of changing environmental conditions.

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Guideline 2

Protect Potential Carbon Sinks

Step 1 Identify habitats and species that function as potential carbon sinks

Step 2 Describe the carbon flux system, including carbon sources and the sinks identified in Step 1

Step 3 Determine whether the carbon flux system is vulnerable to impacts from climate change that can be mitigated by MPAs or MPA networks

Step 4 If impacts on the system from climate change that are identified in Step 3 can be mitigated by MPAs or MPA networks, topical specialists should estimate the trends and timescale over which the impacts are expected and trigger a re-evaluation of the boundaries of the MPA, or design the MPA or MPA network to be robust to these changes

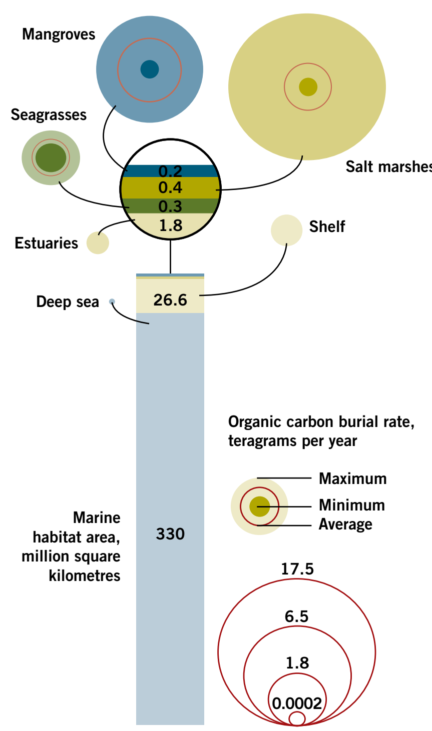
Increasing atmospheric carbon dioxide (CO_2) and other greenhouse gas emissions are contributing to climate change. MPAs and MPA networks are important tools that may help mitigate the effects of climate change by preserving and protecting coastal and marine species, ecosystems and habitats that are most critical for carbon sequestration. Such networks may also produce co-benefits for food security and shoreline protection. However, as many of these ecosystems are near-coastal and estuarine, they are influenced by a suite of stressors, including land-derived impacts, and will require integrated management approaches.

A **carbon sink** may be defined as any process, activity or mechanism that removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere (IPCC 2007). Carbon sinks are reservoirs of carbon and "blue carbon sinks" are those in which living organisms capture carbon in sediments from mangroves, salt marshes and seagrasses (**Figure 4**). The process of creating a carbon sink is called **carbon sequestration** (Chopra *et al.* 2005).

Habitats that act as critical natural carbon sinks need to be properly managed to ensure they retain as much of the carbon trapped in the system as possible, and do not tend to become 'sources' to the atmosphere through poor management. Often the release of trapped carbon as carbon dioxide is accompanied by the release of other powerful greenhouse gases such as methane, which exacerbates global climate concerns (Laffoley and Grimsditch 2009).

Current and future potential MPAs should be evaluated both individually and regionally with respect to their carbon sequestration capabilities, taking into account not only the ecosystems and the species composition but also their biological integrity (functioning). The contributions

Figure 4 Blue carbon sinks



Source: Nellemann, C *et al.* 2009

a network can make, as opposed to individual MPAs, are to make sure: 1) that the best carbon sink sites are protected; and 2) that enough of them are protected (number / size).

Step 1

Identify habitats and species that function as potential carbon sinks.

The world's ocean is the major sink for carbon dioxide. Tidal salt marshes, mangroves, seagrass, and kelp are the marine habitats with major carbon sink capabilities (Laffoley and Grimsditch 2009; Nelleman *et al.* 2009). Unfortunately, human activities such as coastal development have caused these habitats to decrease in size around the world. With the loss of these habitats comes a corresponding loss of carbon sequestration capability. **Figure 5** depicts the alarming decline of seagrass habitat around the world over the last 50 or so years. The biomass and productivity of other species and populations have been reported to have implications for carbon sequestration. The smallest organisms also represent a significant carbon sink. Recent research has discovered that phytoplankton account for close to 50 percent of the ocean's carbon fixation processes (Jardillier *et al.* 2010).

Figure 5 Global loss of a carbon sink: seagrasses

Source: UNEP-WCMC, 2009; Waycott *et al.*, 2009

Phytoplankton and Blue Carbon Sinks

Salps occur in colonies of individuals, which take the form of long chains.

Photo from Wikipedia, Lars Ploughman

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 their important role in export, because large cells sink more rapidly when they become senescent. Also they are grazed more efficiently by larger zooplankton forms, which make larger more rapidly sinking faecal pellets.

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).

KEY CONCEPT

Oceans play a significant role in the global carbon cycle. Not only do they represent the largest long-term sink for carbon but they also store and redistribute CO_2. Some 93 percent of the earth's CO_2 (40 teratons) is stored and cycled through the oceans. Out of all the biological carbon captured in the world, over half (55 percent) is captured by living marine organisms (Nelleman *et al*. 2009). If you lose these marine habitats and organisms, you lose this capability.

Step 2

Describe the carbon flux system, including carbon sources and the sinks identified in Step 1.

Organic and inorganic carbon, carbon dioxide, and methane produced in coastal and marine ecosystems, are delivered to the environment or captured in water, sediments or biological structures, depending on several biotic and abiotic conditions (hydrodynamics, methane producing microorganisms, water temperature, etc.). A management plan can be developed through the identification of both environmental conditions and the spatial and time scales surrounding the carbon flux processes from where carbon emissions or captures occur (that is, identifying both sources and sinks to preserve systems).

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 (Jordan and Scheuring 2002). The maintenance of these foundation species is key to ensuring ecosystem resilience to climate change, and this goal coincides with the carbon biogeochemical cycling efficiency.

Step 3

Determine whether the carbon flux system is vulnerable to impacts from climate change that can be mitigated by MPAs or MPA networks.

The carbon cycle could be affected by several conditions related to climate change (ocean acidification, warmer temperatures, winds strength) that must be identified locally and regionally both at ecosystem level as well as at population or species level.

The proposed steps must include production of an integrated map of the target biogeographic area or marine ecoregion that documents all types of marine and coastal carbon sinks in order to identify, through risk assessment, the ones that are in most immediate need of preservation and amenable to mitigation efforts. This process can be started at different scales (local and regional) but full identification of far-field influences will require large spatial scale overviews to identify the most critical areas for carbon sequestration at the oceanic scales over which some of these carbon flux systems operate.

Step 4

If impacts on the system from climate change that are identified in Step 3 can be mitigated by MPAs or MPA networks, topical specialists should estimate the trends and timescale over which the impacts are expected and trigger a re-evaluation of the boundaries of the MPA, or design the MPA or MPA network to be robust to these changes.

Direct and indirect interactions involving a suite of climate driven changes (i.e., frequency and intensity of storms) are likely to have large impacts on the production and storage of carbon. Increasing our understanding about the processes by means of prediction models as well as *in situ* monitoring will allow better management programs to maximize carbon uptake within the MPA network.

Refer to **Annex 1** for a high-level overview of the physical (atmospheric and oceanographic) properties that are projected to change over the coming decades, including the direction, magnitude and spatial extent of the projected changes, as well as an indication of the level of uncertainty. This Annex can be used by specialists to estimate the timescale over which their subject is expected to respond to climate change and hence trigger a re-evaluation of the MPA boundaries.

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Guideline 3

Protect Ecological Linkages and Connectivity Pathways for a Wide Range of Species

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Step 1 Identify potential ecological linkages and physical drivers such as prevailing currents

Step 2 Build and apply dynamic models of adult movement and migration to test hypothesized connectivity among areas, including potential source-sink regions and migratory patterns

Step 3 Build and apply dynamic models of larval transport to estimate connectivity between regions and identify sources and sinks

Step 4 Determine whether the critical linkages and pathways identified above are vulnerable to impacts from climate change that can be mitigated by MPAs or MPA networks

Step 5 If the impacts on the linkages and pathways identified above can be mitigated by MPAs or MPA networks, specialists should estimate the timescale and distances over which the impacts may be expected and trigger a re-evaluation of the boundaries of the MPA, or design the MPA or MPA network to be robust to these changes

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In ecological terms, **connectivity** is the exchange of individuals among geographically separated populations. Setting up MPA networks to optimize connectivity is something with which MPA planners must constantly grapple. In fisheries management, if an MPA is created that is too small, too few larvae will settle inside the MPA boundary to sustain the population. This will lessen overall connectivity because few organisms will stay inside the MPA and "connect" with those outside, but simply migrate through it. On the other hand, in an MPA that is too big, the larvae settle and the juveniles remain inside it, reducing the larval and adult spillover benefits to adjacent areas. This will lessen overall connectivity with adjacent areas because few organisms from inside the MPA move outside it and "connect" with organisms in adjacent areas. Connectivity is perhaps most evident in the movement of species, as most marine ecosystems maintain strong connections with adjacent and distant ecosystems through the movement of juvenile and adult organisms across ecosystem boundaries (Shanks *et al.* 2003, Planes *et al.* 2009).

Interspecies variation in adult and/or larval connectivity can create difficulties in designing an MPA network intended to increase the biomass of a suite of species. Spacing between individual MPAs that may be optimal for one species may not be appropriate for others that have different larval durations. For sedentary species, a large number of small MPAs may be optimal in order to maximize export of larvae. But for more mobile species, a few large MPAs, that increase the probability that adults remain in the MPAs, is likely more appropriate. MPA networks should include a variety of MPA sizes and spacing if larval and adult movement varies greatly among species. A "stepping-stone" approach can be used to protect known key habitats of migratory species that are spaced far apart (such as a whale's key feeding and breeding ground). In addition, having a well-designed MPA network that incorporates representative habitats, EBSAs, and replication will ensure some degree of connectivity. Conventional effort or quota-based management outside the MPAs can also help reduce the disparate effects of MPAs on species with different movement patterns. Communities associated with reefs or other structures may have more coherence in adult movement and thus may be especially attractive for MPA or other space-based management. Climate change can potentially alter connectivity patterns by changing larval duration times, adult movement patterns as well as species distributions. Given the importance of connectivity to MPA network design, understanding the influences of climate change on different components of connectivity remains a key research need.

Step 1

Identify potential ecological linkages and physical drivers such as prevailing currents.

Within marine species, **population connectivity** is a key characteristic with direct relevance to the scale and spacing of MPA networks. 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 6**). Corresponding declines in reproductive isolation with increasing planktonic larval durations, and the negative relationships between those durations 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.

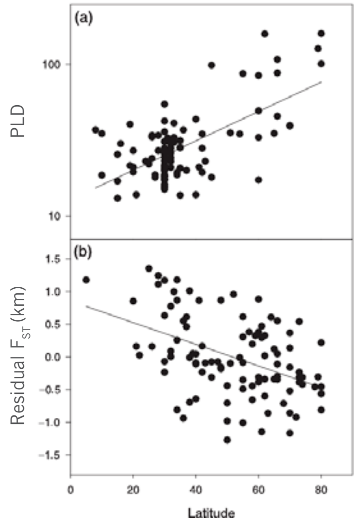
In addition to passive dispersal, organisms that actively move across the landscape and connect habitats in space and time ('**mobile link organisms**': Lundberg and Moberg 2003) may contribute strongly to marine ecosystem resilience. Mobile link organisms may be essential components in the dynamics 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. However, the advent of electronic tagging devices over the last decade is beginning to generate remarkable data on the movement patterns of mobile link and other species.

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), which will decrease their resilience to climate change in those areas. Migrating baleen whales may be fairly resilient to climate change, but currently face longer journeys and reduced feeding opportunities (Learmonth *et al.* 2006). Potential loss of stopover sites and even longer migratory pathways resulting from climate change will likely have deleterious effects on fitness.

Food Web Connections

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 in the behaviors of other species (Heithaus *et al.* 2008). A long history of work, from rocky shore communities to sea otters and sharks, has established that top predators have a profound influence on the structure and function of marine ecosystems. One specific type of top-down

Figure 6 Gene Flow and Dispersal Relationship of Marine Fish Populations



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) Residual F_{ST} versus maximum latitude (north or south) occupied by each of 100 marine fish species. (From Laurel and Bradbury 2006).

CASE STUDY

Three large areas on Georges Bank and Nantucket Shoals have been closed to most trawling and scallop dredging since December 1994 to help rebuild groundfish and scallop stocks. Prior to this time these areas were closed during the spring only and were designed to protect groundfish spring spawning aggregations. A few stocks, namely Georges Bank sea scallops (*Placopecten magellanicus*), haddock (*Melanogrammus aeglefinus*), and yellowtail flounder (*Limanda ferruginea*), have exhibited substantial increases inside the closed areas. However, many other species, such as Atlantic cod (*Gadus morhua*) have shown little or no response (Murawski *et al*. 2000, 2005; Stone *et al*. 2002; Hart and Rago 2006; O'Brien *et al*. 2008), because they tend to move out of these areas during warmer months. This example demonstrates that migratory patterns need to be considered to provide year-round protection for species such as cod. It also emphasizes the need to consider the original conservation objectives of an MPA or MPA network when adding new objectives to existing site boundaries.

impact, termed a 'trophic cascade', is an alternating pattern of increased and decreased abundance in successively lower trophic 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. Researching the effects of climate change on the relative importance of top-down and bottom-up forcing factors is critical to understanding trophic connectivity and the resilience of ecosystems (Hoekman 2010).

Step 2

Build and apply dynamic models of adult movement and migration to test hypothesized connectivity among areas, including potential source-sink regions and migratory patterns.

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 behavior 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. Tagging, genetic and biogeochemical evidence can all help inform on adult movement.

Step 3

Build and apply dynamic models of larval transport to estimate connectivity between regions and identify sources and sinks.

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 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 required 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. Therefore, models should consider variability in larval behavior and duration both between and within species as well as inter-annual variability in physical transport (e.g., strengths of gyres and locations of frontal zones). Genetic and/or biogeochemical evidence can help confirm hypothesized connections.

It is the advance of coastal ocean circulation models, often now embedded in larger regional, basin or global models that have 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 behavior, including such things as predator-prey interactions. Individual representation enables such behavior as the daily vertical migration to be included, an important behavior 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, 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.

Step 4

Determine whether the critical linkages and pathways identified above are vulnerable to impacts from climate change that can be mitigated by MPAs or MPA networks.

Steps 2 and 3 above give some guidance to identifying and modeling expected biophysical changes. Once one has identified potential ecological linkages and developed sufficient models, knowledge gained from model output will give a better idea on how one can configure an MPA network that enhances connectivity and whether these connections are sufficient enough to withstand expected changes brought about by changing climate. If possible, known food webs can be modeled to ascertain if critical linkages and pathways are expected to be interrupted or altered in the context of climate change.

Step 5

If the impacts on the linkages and pathways identified above can be mitigated by MPAs or MPA networks, specialists should estimate the timescale and distances over which the impacts may be expected and trigger a re-evaluation of the boundaries of the MPA, or design the MPA or MPA network to be robust to these changes.

Refer to **Annex 1** of this report for a high-level overview of the physical (atmospheric and oceanographic) properties that are projected to change over the coming decades - including the direction, magnitude and spatial extent of the changes, as well as an indication of the level of uncertainty. This Annex can be used by topic specialists to estimate the timescale over which their subject is expected to respond to climate change and hence trigger a re-evaluation of the MPA boundaries.

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Gulf of the Farallones National Marine Sanctuary
United States

Kevin L. Stierhoff / SWFSC / NOAA

Guideline 4

Protect the Full Range of Biodiversity Present in the Target Biogeographic Area

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Step 1 Identify biodiversity in the target biogeographic area or marine ecoregion

Step 2 Assess the projected impacts from climate change as stressors and threats to the biodiversity of those areas identified in Step 1

Step 3 Determine whether the impacts on biodiversity from climate change (Step 2) can be mitigated by MPAs or MPA networks

Step 4 Assuming MPAs or MPA networks can mitigate the impacts from climate change identified in Step 3, topical specialists should predict the spatial/timescale over which their subject is expected to respond and trigger a re-evaluation of the MPA boundaries, or design the MPA or MPA network to be robust to these changes.

Step 1

Identify biodiversity in the target biogeographic area or marine ecoregion

Biodiversity is one of the current concepts in conservation. Distinctions can be made between functional and compositional perspectives in approaching biodiversity. Functional refers primarily to a concern with ecosystem and evolutionary processes, while compositional has organisms aggregated into populations, species, higher taxa, communities, and other categories (Callicott *et al.* 1999).

Biodiversity includes not only the species of the world, with their unique evolutionary histories, but also the genetic variability within and among populations of species and the distribution of species across local habitats, ecosystems, landscapes, and whole continents or oceans. Understanding what constitutes and defines biodiversity is essential for managers, planners and policy makers who must attempt to incorporate its values into their land and water management plans. Biodiversity management options are inevitably constrained by a combination of biological and sociopolitical realities.

In biodiversity-related sciences, such as population biology, ecology, systematics, evolution, and genetics, biodiversity has a specific meaning: "the variety and variability of biological organisms" (Keystone Center 1991; Noss and Cooperrider 1994; Wilson and Peter 1988). The Convention on Biological Diversity (CBD) similarly defines biodiversity as the "variability among living organisms from all sources."

The individual components of biodiversity—genes, species, and ecosystems—provide society with a wide array of goods and services. Genes, species, and ecosystems of direct, indirect, or potential use to humanity are often referred to as "biological resources" (McNeely *et al.* 1990; Reid and Miller 1989). Examples include the genes that plant breeders use to develop new crop varieties; the species that we use for various foods, medicines, and industrial products; and the ecosystems that provide services, such as water purification, prevention and/or mitigation of climate change and flood control. The components of biodiversity are interconnected. For example, genetic diversity provides the basis for continual adaptation to changing conditions. Similarly, a change in the composition and abundance of the species that make up an ecosystem can alter the services that can be obtained from the system.

The oceans cover 70 percent of the planet's surface area, with marine and coastal environments that contain diverse habitats supporting an abundance of biodiversity. Life in our seas produces a third of the oxygen that we breathe, offers a valuable source of protein and moderates global climatic change. Examples of marine and coastal habitats include mangrove forests; coral reefs; sea grass beds; estuaries in coastal areas; hydrothermal vents; seamounts; and soft sediments on the ocean floor a few kilometers below the surface (Norse 1993).

The Convention on Biological Diversity 2004 Program of Work on Protected Areas committed the Parties to the establishment of a comprehensive MPA network within an overall ecosystem approach by 2012. This target coincides with the 2002 World Summit on Sustainable Development commitment to establish marine protected areas, including representative networks, by 2012. At the recent Nagoya Biodiversity Summit (CBD-COP 10), member nations agreed to protect 10 percent of the world's marine and coastal area by 2020, especially areas of particular importance for biodiversity and ecosystem services, through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures.

Biogeographic areas

The patterns of species distribution across geographical areas at various scales can usually be explained through a combination of historical factors such as: speciation; extinction; continental drift; glaciation, in combination with the geographic constraints of landmass areas and isolation; and the available ecosystem energy supplies.

Biogeographical areas are large areas defined by the presence of distinct biotas that have at least some cohesion over evolutionary time frames. These areas may hold some level of endemism, principally at the level of species. Although historical isolation will play a role, many of these distinct biotas have arisen as a result of distinctive abiotic features that circumscribe their boundaries. These may include geomorphological features (isolated island and shelf systems, semi-enclosed seas); hydrographic features (currents, upwelling areas, ice dynamics); or geochemical influences (broadest-scale elements of nutrient supply and salinity). In ecological terms, cohesive units are likely, for example, to encompass the broader life history variability among many constituent taxa, including mobile and dispersive species. In order to capture the full range of biodiversity in an MPA network, it is important to protect representative samples of each habitat type in a biogeographical area as well as all species and habitats that appear to play crucial ecosystem roles.

Marine ecoregions are areas of relatively homogeneous species composition, clearly distinct from adjacent systems. The species' composition is likely to be determined by the predominance of a small number of ecosystems and/or a distinct suite of oceanographic or topographic features. The dominant biogeographic forcing agents defining the ecoregions vary from location to location but may include isolation, upwelling, nutrient inputs, freshwater influx, temperature regimes, ice regimes, exposure, sediments, currents, and bathymetric or coastal complexity. In ecological terms, these are strongly cohesive units, sufficiently large to encompass ecological or life history processes for most sedentary species. Although some marine ecoregions may have important levels of endemism, this is not a key determinant in ecoregion identification, as it has been in terrestrial ecoregions (Spalding *et al.* 2007).

Step 2

Assess the projected impacts from climate change as stressors and threats to the biodiversity of those areas identified in Step 1

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).

CASE STUDY

Stretching for 625 miles along the coastline of Honduras, Guatemala, Belize and Mexico, the Mesoamerican Reef (MAR) is the second largest barrier reef in the world. It encompasses a rich mosaic of coastal wetlands, lagoons, mangrove, seagrasses, sandy cays and a common structure, the coral reefs. These ecosystems host more that 500 fish species, 60 coral species, 350 mollusk and other marine mammals, algae and seagrasses. They are home to critically endangered species, like the largest population of manatees in the Western Caribbean, saltwater crocodile, sea turtles (green, hawksbill and loggerhead), Nassau and Goliath grouper, and the largest aggregation of whale sharks in the world. The MAR is an important stopover area on the major North American-South American flyway for migratory birds and the first stopover after passing over the Gulf of Mexico. Many bird species are year-round residents.

An estimated two million people are highly dependent on the MAR's healthy ecosystems for food, water, livelihoods and income. Thousands of artisanal (small-scale) fishermen and the fishing industry in Honduras depend on its fisheries, including lobster, conch, snapper and grouper. Its marine and coastal ecosystems provide the foundation for the region's rich tourism industry, which brings in nearly US$5 billion per year, spent by more than 11 million tourists.

Under future climate change scenarios, beach stabilization will be important due to the vulnerability of the MAR to sea level rise and stronger tropical storms. http://www.reefresilience.org/Toolkit_Coral/C8_MAR.html

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-scale 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.

Functioning ecosystems are one of the important factors that control the global climate. The biogeochemical cycling of gases is greatly controlled by the living biota, particularly in the marine realm. For example, phytoplankton remove carbon dioxide from the surface waters while releasing oxygen. When the phytoplankton die, they sink and add to the super saturation of carbon dioxide in the deep sea. This results in a vertical gradient of CO_2 in the ocean, which has been termed the 'Biological Pump.' Any impact on marine phytoplankton or other biota could disrupt the biological pump and create a loss of the efficiency of CO_2 sequestering by the deep sea. In turn, this loss could add to the level of CO_2 in the atmosphere. Given that the CO_2 level has been increasing ever since the industrial revolution and is already high, a further increase due to a loss of efficiency of the biological pump is not desirable. Thus, preserving the diversity of these organisms could be essential in controlling the level of CO_2 in the atmosphere (Raven and Falkowski 1999).

Annex 2 summarizes some possible physical climate change projections on various ecosystem components. By assessing the various biodiversity ecosystem components identified in Step 1 with changes expected due to physical conditions, it might be possible to construct a threat assessment model. What is the predicted level of threat to the diverse biological and habitat components in the MPA network? As the important hypothesis is biodiverse areas are likely to be resilient and therefore less vulnerable to climate change, MPA networks should strive to contain as diverse an assemblage of organisms and habitats as possible.

Step 3

Determine whether the impacts on biodiversity from climate change (Step 2) can be mitigated by MPAs or MPA networks

By constructing a threat assessment model (e.g., the vulnerability of organisms and habitats to anticipated climate change), it may become clear whether resilience can be improved by spatial area closures. For example, habitats may be less vulnerable to climate change if they are less vulnerable to pressures such as bottom trawling, bottom tending gear, cable laying, anchoring, and other human disturbances. Organisms may be less vulnerable to climate change impacts if they are not subjected to fishing pressure. Unfortunately, not all vulnerable characteristics that may respond to climate change impacts can be influenced by spatial area closures. This will have to be determined by determining what the traits that make them most vulnerable to climate change are and whether these traits can be strengthened through spatial area closures.

Step 4

Assuming MPAs or MPA networks can mitigate the impacts from climate change identified in Step 3, topical specialists should predict the spatial/timescale over which their subject is expected to respond and trigger a re-evaluation of the MPA boundaries, or design the MPA or MPA network to be robust to these changes.

Refer to **Annex 1** of this report for a high-level overview of the physical (atmospheric and oceanographic) properties that are projected to change over the coming decades, including the direction, magnitude and spatial extent of the changes, as well as an indication of the level of uncertainty. This Annex can be used by topic specialists to estimate the timescale over which their subject is expected to respond to climate change and trigger a re-evaluation of the MPA boundaries, or design the MPA or MPA network to be robust to these changes.

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Nadia Olivares, Comisión Nacional de Áreas Naturales Protegidas

Annex 1

Review of Atmospheric and Oceanographic Information

The overall goal of the SGMPAN is to develop and apply 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 the Marine Ecoregions catalogued 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 A1.1**).

The atmospheric and oceanographic review of this Annex is largely a repeat of that in Section 5.1 of the SGMPAN report (ICES 2011a). It draws 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 2008a,b; ICES 2011b; New *et al.* 2011; Nicholls *et al.* 2011; Ning *et al.* 2003; PCGCC 2009; Richardson *et al.* 2009; Vasseur and Cato 2007).

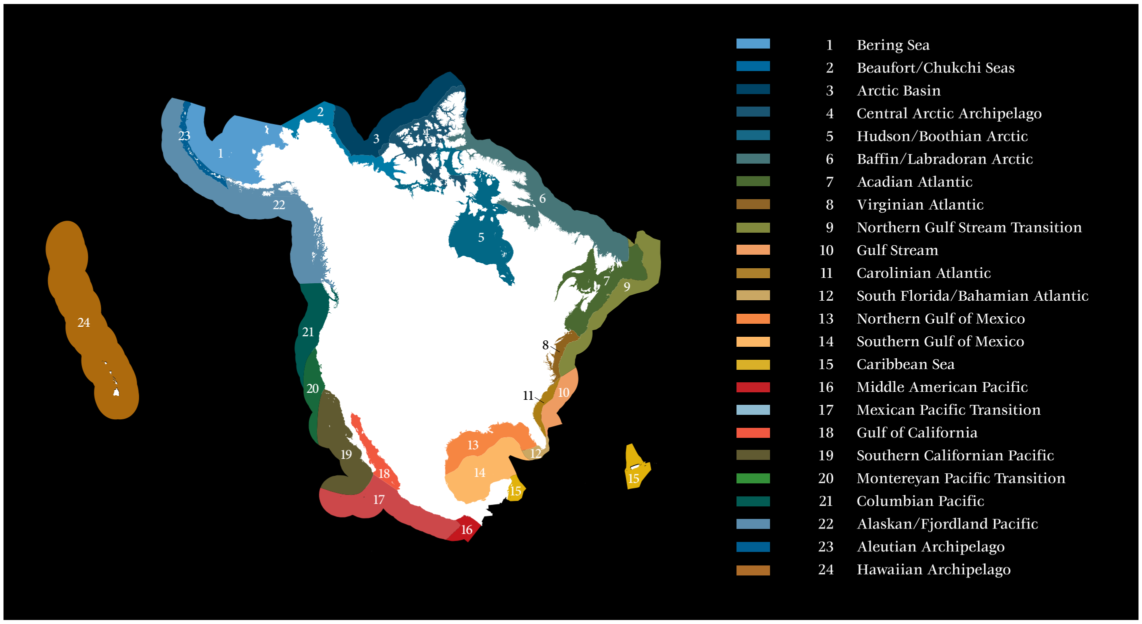
Aspects of ocean climate change that need to be considered in making and using projections, and in particular the difficulties and uncertainties associated with the limited predictability of the Earth's climate system are discussed. The major oceanographic features of the Western North Atlantic (WNA), and the dominant modes of natural temporal and spatial variability affecting its ocean climate described should be kept in mind when implementing management actions necessary to fulfill various guidelines. 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. It is anticipated that these atmospheric and oceanographic changes will be the principle drivers of biological changes as well.

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 coupled climate model simulations with improved resolution and representations of physical and biogeochemical processes 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 one to two 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.

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

Figure A1.1 Marine ecoregions surrounding North America



clear global trends in 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 often used with a variety of meanings such that, before proceeding, it is important to clarify their meaning in this review. "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 interchangeably 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 layers of the 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 spatial scales comparable to those of the continents and ocean basins. For the oceanic 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 that 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 spatial scales of relevance to coastal and marine ecosystem issues is difficult because of the coupled climate system's complexity and wide range of interacting spatial 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 (AOGCM). While there are clear and apparently robust spatial and temporal patterns for many variables, they are generally on large spatial 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 with respect to 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 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 Atmosphere Ocean General Circulation Models (AOGCM) of key dynamics in areas such as the Gulf Stream separation and the linkages with the adjoining Arctic and tropical Atlantic Oceans. The AOGCM 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.

Oceanographic regions of the Western North Atlantic (WNA)

Large-scale setting

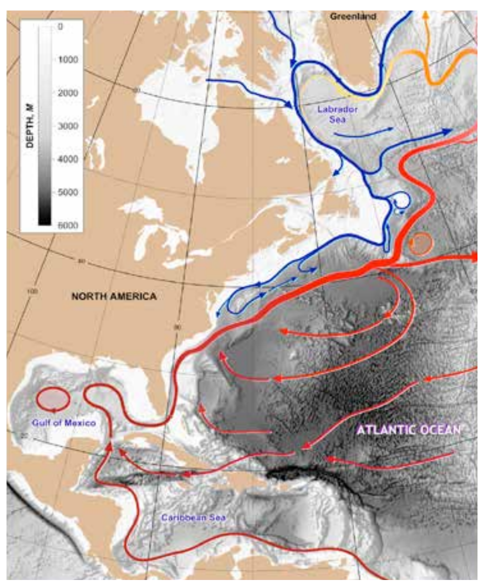
The setting of North America's Atlantic coast in relation to the continent and the global ocean is illustrated by the map of bottom topography and major upper-ocean current features of the WNA in **Figure A1.2**, and by the climatological distributions of upper-ocean temperature and salinity in the WNA in **Figure A1.3**. The Atlantic coastal region is quite complex (**Figure A1.2**), 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.

Major oceanographic regions within and affecting the Western North Atlantic

Four major latitudinal oceanographic regions within the WNA can be identified from the large-scale structure of the coastline, and the water property distributions and associated circulation (**Figures A1.2** and **A1.3**).

- The **SubPolar Northwest Atlantic (SP-NWA),** extending roughly from Davis Strait, at about 65ºN, 60ºW, to the Tail of the Grand Banks, 42ºN, 50ºW. This region is strongly influenced by the North Atlantic's subpolar 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 20ºN to Cape Hatteras at about 35ºN. 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

Figure A1.2 Map showing the complex bottom topography of the Western North Atlantic

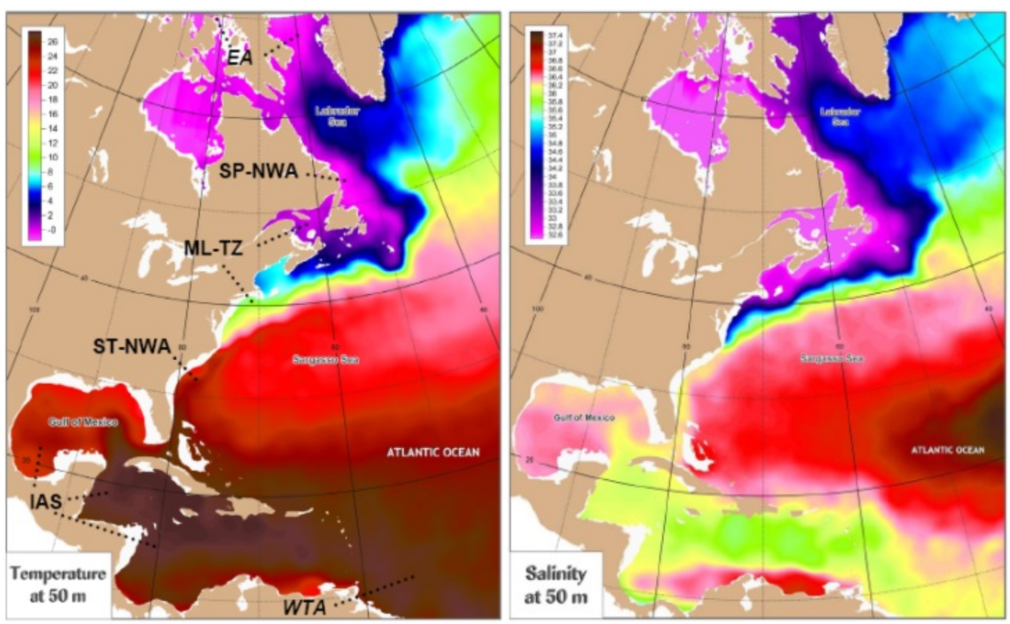


Map showing the complex bottom topography of the Western North Atlantic, together with a schematic representation of the major upper-ocean circulation features. Warm flows are denoted by red, cold flows by blue, and intermediate temperatures by orange-yellow. (Courtesy of Igor Yashayaev, Bedford Institute of Oceanography, Fisheries & Oceans Canada.)

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 **Mid-Latitude 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 Banks at 42°N, 50°W. In this region, there are competing influences of the subpolar and subtropical waters, which flow in opposite directions, 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 that features depths reaching 3700m, both wide and narrow shelves, and more than 30 rivers discharging into its basin. Its circulation

Figure A1.3 Long-term annual-mean temperature and salinity



Long-term annual-mean temperature and salinity at 50m in the WNA, from the Yashayaev (1999) climatology. Major oceanographic regions *within* and *affecting* the WNA are labeled on the temperature panel (see **Table A1.1** and text for explanations). Major Oceanographic Regions are labeled: EA = Eastern Arctic; SP-NWA = SubPolar NW Atlantic; ML-TZ = Mid-Latitude 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).

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 Subtropical Western North Atlantic region via the Straits of Florida (sill depth of ~800m).

In addition to these major oceanographic regions within the Western North Atlantic (WNA), two other major latitudinal oceanographic regions affecting 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 Subpolar Northwest Atlantic (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 (see ICES 2011b) for more detail on influences of the Arctic and Northeast Atlantic).
- 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 region that gives rise to tropical cyclones and hurricanes in the North Atlantic, some of which move westward into the Intra-Americas Sea and others of which turn northward into the Subtropical Western North Atlantic and sometimes reach the Mid-Latitude Transition Zone and Subpolar Northwest Atlantic.

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 Atmosphere Ocean General Circulation Models (AOGCCM). 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.

Within the six oceanographic regions, there are a number of coastal and/or shelf subregions with differing oceanographic conditions that are known to influence ecosystem structure and species distributions and for which different conditions may be projectable. These subregions are listed in **Table A1.1**, together with some of their distinguishing features. Consideration of climate change on this subregional 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 Mid-Latitude Transition Zone (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 subregions of the ML-TZ). Similarly, there are many distinctive features of the indicated subregions within the complex Intra-Americas Sea, 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 A1.1**) identified by Wilkinson *et al.* (2009), although the names are different in many cases (**Table A1.1**). The latter ecoregions were identified from both ecological and oceanographic considerations, and may be more appropriate for ecosystem management in some cases. On the other hand, the oceanographic regions and subregions should be particularly helpful in downscaling climate change projections.

Table A1.1 **Major large-scale oceanographic regions in or affecting the Western North Atlantic**

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
SubPolar NW Atlantic (SP-NWA)	Labrador Current (southward flow); Seasonal sea ice; Wintertime deep convection; Seasonally varying stratification	NAO direct, AO remote, AMOC, AMO	Baffin / Labradoran Arctic	Baffin Bay	Cyclonic gyre; Melting glaciers
				Labrador Shelf, Slope & Sea	Run-off; Hudson Strait outflow
				NE Newfoundland Shelf & Slope	2-3 layer stratification
Western North Atlantic (WNA) Mid-Latitude Transition Zone (ML-TZ)	Labrador Current Extension (equatorward shelf flow); Slope Water; Gulf Stream (offshore); Strong seasonality (continental lee); Estuaries	NAO via advection, AMO, AMOC	Acadian Atlantic (shelf); Northern Gulf Stream (NGS) Transition (slope)	Grand Banks & Flemish Cap	Clockwise gyres; 2-3 layer stratification
				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
Subtropical 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
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

Major large-scale oceanographic regions in or affecting the WNA, their predominant features, their primary modes of climate/weather variability (see next section) 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).

Within the subregions in **Table A1.1**, 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 spatial 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 described in this review 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).

Cross-margin structure

Another important horizontal spatial feature 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 subregions) described above can be subdivided into three cross-(continental-) margin domains:

- The "**coastal zone**," including the inner shelf, small to mid-size 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 Banks); and
- The offshore **"deep ocean,"** including the deep basins of the Intra-Americas Sea 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).

Vertical structure

A very important spatial feature in most ocean regions, particularly from the perspectives of atmospherically driven climate change and bottom-up ecosystem change, is the pronounced variation of many oceanographic properties and ecosystem components with depth below the sea surface. This review will primarily focus on the upper ocean, which is ventilated annually (winter mixing to depths of 100–1000m typically), or on time scales reckoned in years, through the combination of surface layer mixing, subduction and/or upwellings/downwellings. However, climate changes can be expected to penetrate to intermediate (1000–2500m) and greater depths on the time scales of years to decades over much of the Western North Atlantic's continental margin, associated with the Atlantic Meridional Overturning Circulation (see below) and the equatorward flow of relatively "new" deep waters in the Deep Western Boundary Current (DWBC).

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 Western North Atlantic. In some cases these extend across the spatial scales of multiple ocean basins and continents, and hence are referred to as "teleconnection" mechanisms (e.g., ICES 2011b). These modes are briefly described here as important considerations in the projection of near-term climate change in particular.

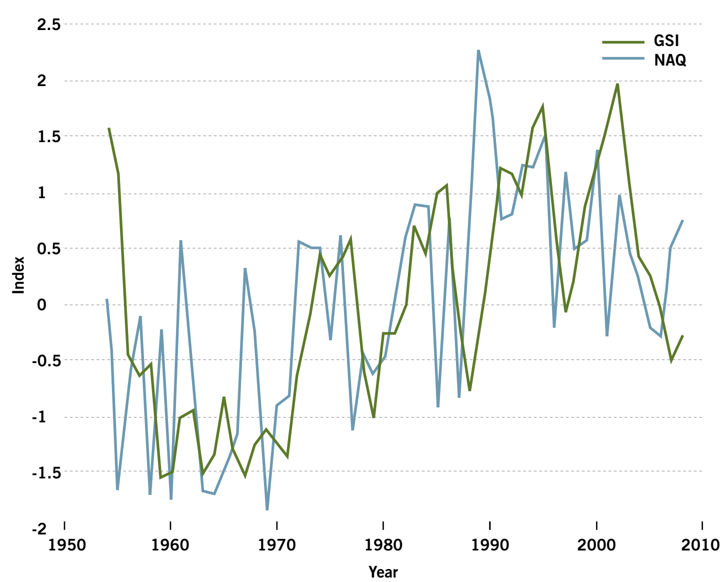
North Atlantic Oscillation

The North Atlantic Oscillation (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 understood 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 sub-Arctic, extending offshore over the Subpolar Northwest Atlantic.

Multiple mechanisms for the North Atlantic Oscillation's ocean climate influences have been identified, including direct influences in the Subpolar Northwest Atlantic 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 Mid-Latitude Transition Zone are also influenced by the NAO but with temperature (and salinity) changes in an opposite sense to those in the SP-NWA (i.e., positive NAO resulting in warmer and more saline 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 (and fresh) Labrador Current around the Tail of the Grand Banks and hence a greater influence of subtropical waters in the transition zone (Han 2007; Petrie 2007). Recent work (**Figure A1.4**) indicates a significant correlation between the NAO and the north-south position of the Gulf Stream between Cape Hatteras and the Grand Banks (offshore in the Mid-Latitude Transition Zone), with a more positive NAO resulting in a northward displacement of the Stream and subtropical water, and of some fish distributions (e.g., Nye *et al.* 2011).

While the North Atlantic Oscillation is a dipole pattern of the north-south sea level pressure difference between Iceland and the Azores,

Figure A1.4 Wintertime North Atlantic Oscillation index, 1950s–2009



Wintertime North Atlantic Oscillation 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).

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 North Atlantic Oscillation.

El Niño–Southern Oscillation

Another well-known natural mode of coupled atmosphere-ocean variability that affects ocean climate in the WNA, especially in the Intra-Americas Sea and Subtropical Western North Atlantic, is the El Niño-Southern Oscillation (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 Subtropical Western North Atlantic. Coupling between the eastern Pacific and WNA via the atmosphere has a particular influence on hurricane and tropical storm tracks in the WNA, which can have influences extending poleward to the Subpolar Northwest Atlantic.

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.

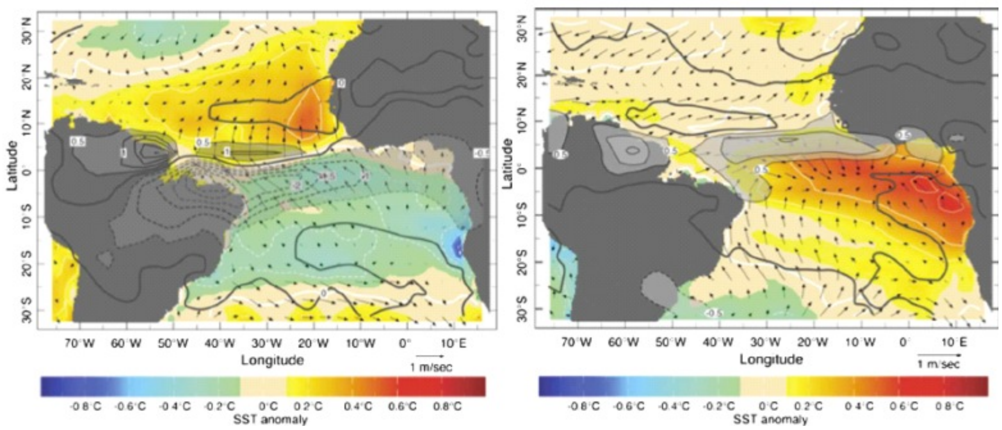
The most significant influences of El Niño in the tropical Atlantic sector as summarized by Chang *et al.* (2006) are: 1) a zonal see-saw in sea level pressure between the eastern equatorial Pacific and Atlantic Oceans during the onset and peak phase of ENSO, with a high sea level pressure anomaly in 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 sea surface temperature 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 Intra-Americas Sea are stronger in winter since, in summer, the anomalies related to the Atlantic Warm Pool (see below) tend to have the opposite sign to those of ENSO.

Tropical Atlantic Variability

The two fundamental modes of the Tropical Atlantic Variability (TAV) (Chang *et al.* 2006) are illustrated in **Figure A1.5**:

- A "meridional" mode, active in boreal spring when the Inter-Tropical Convergence Zone (ITCZ) in the Atlantic is in its southernmost position. In this mode, a stronger-than-normal northward sea surface temperature 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 behavior than the zonal mode. The ITCZ tends to spend more time in the hemisphere with the positive sea surface temperature anomaly. Anomalous sea surface temperatures, trade winds, and heat flux patterns suggest a (not fully understood) connection with other Atlantic modes such as the North Atlantic Oscillation.
- A "zonal" mode active in summer when the ITCZ is at its northernmost position. A cold tongue of sea surface temperature develops in the equatorial eastern Atlantic. Sea surface temperature maxima anomalies in the eastern basin are related to a convergent pattern of equatorial trade winds. This mode is sometimes referred to as the Atlantic "El Niño–Southern Oscillation" although it is quite different from the Pacific ENSO [see Xie and Carton (2004) and Chang *et al.* (2006) for details].

Figure A1.5 Surface ocean-atmosphere variability in the tropical Atlantic region



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 of the regional March-April and June-August rainfall anomaly (from Global Precipitation Climatology Project data 1979-2001) (mm day-1). The colored field is the March-April and June-August SST anomaly regressed on the principal component time series of the rainfall empirical orthogonal function. Arrows depict the seasonal mean surface wind regressed on the same time series. From Chang *et al.* (2006).

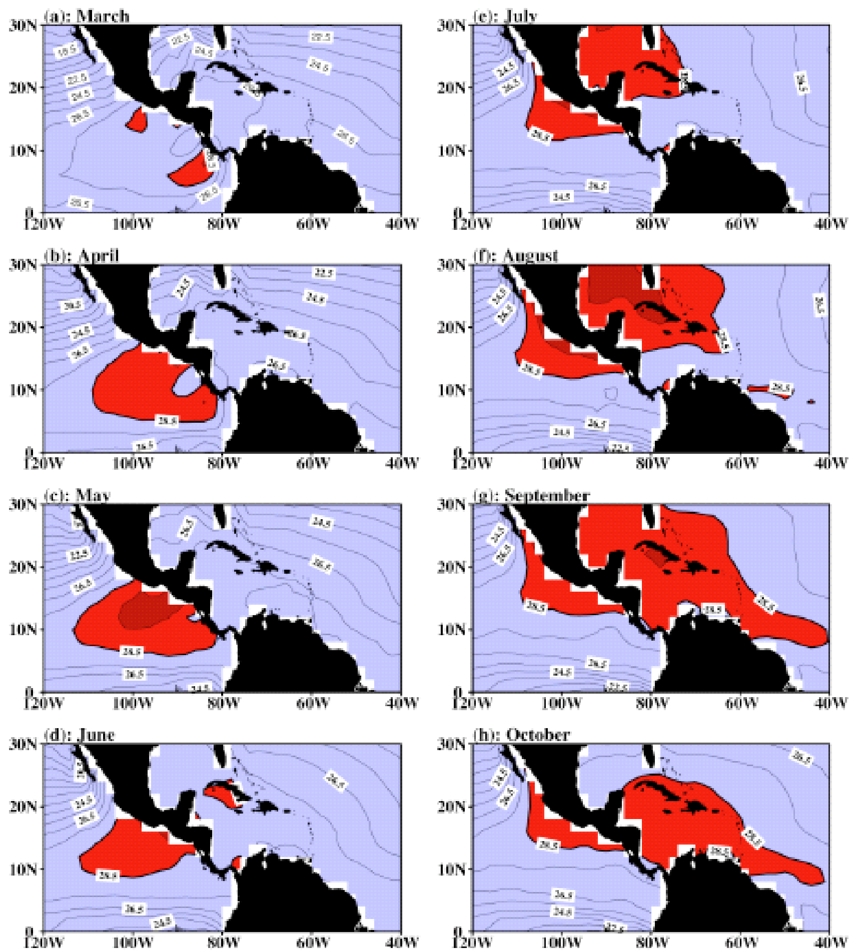
Atlantic Warm Pool

The Atlantic Warm Pool (AWP) is a region in the WTA and Intra-Americas Sea 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 A1.6**). 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.

Atlantic Multi-decadal Oscillation

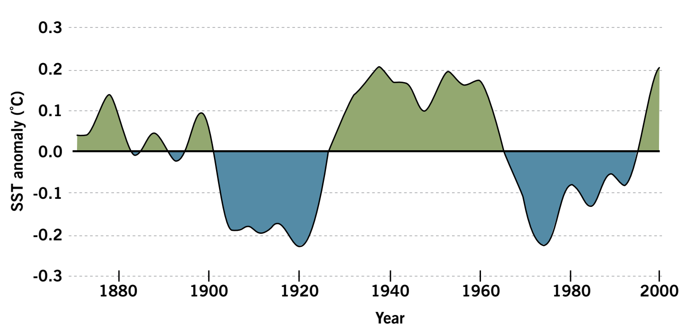
A large-scale mode of ocean climate variability of importance to the WNA is the Atlantic Multi-decadal Oscillation (AMO), through which sea surface temperature in the North and South Atlantic vary out-of-phase over a 65–75-year period (e.g., Enfield *et al.* 2001). The AMO had a warm phase in the North Atlantic from about 1930 to the early 1960s, then a cool phase until the mid-1990s (**Figure A1.7**), 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 North Atlantic Oscillation and El Niño–Southern Oscillation), partly because it typically has only one or two periods in many instrumental records. Variability in the Atlantic Meridional Overturning Circulation (AMOC) is generally implicated as a factor in the origin of the Atlantic Multi-decadal Oscillation (AMO), but the dynamics and extent of their inter-relation are presently not well understood (e.g., ICES 2011b). 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 Mid-Latitude Transition Zone 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 Subpolar Northwest Atlantic. However, separation of

Figure A1.6 **Seasonal variation of sea surface temperature for the tropical Western Hemisphere Warm Pool**



Seasonal variation of sea surface temperature for the tropical Western Hemisphere Warm Pool. The shading and dark contour represent water warmer than 28.5°C. From Wang and Enfield (2001) and IASCLIP (2008).

Figure A1.7 **De-trended sea surface temperature anomaly in the North Atlantic**



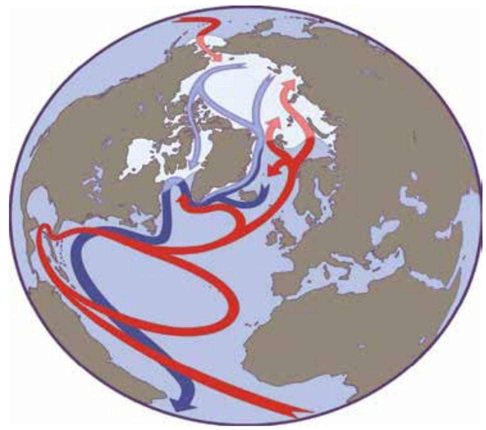
De-trended sea surface temperature anomaly in the North Atlantic, which is often used as an AMO index. From Knight *et al.* (2005).

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.

Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (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 intermediate and greater depths in the North and South Atlantic, and a compensating northward flow of warm and saline water in the upper ocean (shown schematically in **Figure A1.8**). The associated equatorial flow of recently ventilated water in the DWBC results in faster penetration of atmospherically induced water property changes to the lower water column over the WNA's continental slope and rise than in most other deep regions of the global ocean. 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. Atmosphere Ocean General Circulation Model 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—consistent with a reduction in the poleward upper-ocean transport of warm water in the North Atlantic (offsetting the global tendency for ocean surface 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 Atlantic Meridional Overturning Circulation, North Atlantic Oscillation and Atlantic Multi-decadal Oscillation have been suggested, as well as suggestions of connections between the AMOC and the north-south position of the Gulf Stream in the Mid-Latitude Transition Zone. A relevant pattern that is emerging from some observational and modeling 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 Mid-Latitude Transition Zone, and higher ocean temperatures in the Slope Water extending from the Grand Banks to the Mid-Atlantic Bight.

Figure A1.8 Linkages between the Atlantic Meridional Overturning Circulation and the flows in and out of the Arctic



Schematic depiction of the linkages between the Atlantic Meridional Overturning Circulation and the flows in and out of the Arctic, with red indicating warm flows and blue indicating cold flows. From Greg Holloway (Institute of Ocean Sciences, Fisheries and Oceans Canada).

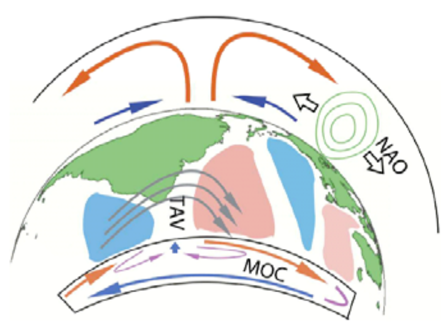
Since the surface return flow of Atlantic Meridional Overturning Circulation is a large contributor to the Caribbean circulation and Gulf Stream current sources (Yucatan and Loop Currents), changes in its strength and pathways may substantially impact the ocean circulation in the Intra-Americas Sea region. 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 Intra-Americas Sea region would be substantially weaker if the AMOC contribution were 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).

Linkages among modes of variability

It is clear from the above discussion that particular oceanographic regions in the Western North Atlantic are influenced by multiple modes of natural climate variability that are generally inter-related. As one example, Hurrell *et al*. (2006) have provided the following perspective on the inter-relation of the North Atlantic Oscillation, Tropical Atlantic Variability and Atlantic Meridional Overturning Circulation, referring to **Figure A1.9**:

> 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 sea surface temperature anomaly tripole (the sign of which is associated with the negative index phase of the North Atlantic Oscillation) also is related to the TAV [Tropical Atlantic Variability], in which changes in the cross-equatorial sea surface temperature gradient interact with the overlying atmosphere to produce changes in ITCZ [Inter-Tropical Convergence Zone] rainfall. A warm anomaly north of the equator (which also can be induced during a warm El Niño–Southern Oscillation 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 Northeast 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 [Atlantic] 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 A1.9 **Schematic of the North Atlantic Oscillation, Tropical Atlantic Variability and Atlantic Meridional Overturning Circulation**



Schematic of the NAO, TAV and Atlantic MOC (AMOC). From Marshall *et al.* (2001); and Hurrell *et al.* (2006).

Table A1.2 Summary of climate variability modes affecting the Western North Atlantic 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 Niño – 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. Connection between shallow tropical/subtropical cells

As another example of the interconnectivity among the modes and the influences of multiple modes on a particular region, **Table A1.2** provides a summary of the six modes described above and their impacts from the perspective of the subtropical and tropical Atlantic (the Subtropical Western North Atlantic, 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 North Atlantic Oscillation to the strength of the atmospheric polar vortex, of the Atlantic Multi-decadal Oscillation to Atlantic Meridional Overturning Circulation, and of the Gulf Stream position to both North

Atlantic Oscillation and AMOC (on different times scales) provide the potential for advances in downscaling such projections to the regional scale of the Mid-Latitude Transition Zone.

Recent and probable climate changes in important variables

Atmospheric and hydrological variables

The following is a brief summary of projected 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 (2011) 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—consistent with a weakened AMOC. IPCC (2007) indicated that the likely range of the increase in global mean temperature from the late 20th century to the late 21st century for a wide range of emissions scenarios is 1.1 to 6.4ºC. However, considering present-day and expected near-term emissions, it would now seem unlikely that the increase will be near the lower end of this range. 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). Atmosphere Ocean General Circulation Models 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 Subtropical Western North Atlantic but decrease over Mexico and the Subpolar Northwest Atlantic.
- 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 Subpolar Northwest Atlantic 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 Mid-Latitude Transition Zone 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 Mid-Latitude Transition Zone (Gulf of Maine and Mid Atlantic Bight) has been projected. Run-off into the Subtropical Western North Atlantic 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 Intra-Americas Sea. 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 northward. A tendency for the North Atlantic Oscillation 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 with their tracks shifted northward, although the number of all cyclones in winter is projected to decrease (e.g., Mann and Emanuel 2006; Ulbrich *et al.* 2009).

Physical oceanographic variables

The tendencies for probable anthropogenic changes in key upper-ocean physical oceanographic variables in the Western North Atlantic are summarized in **Table A1.3**. 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.

In considering the implications of these projected changes, it is critical to consider the documented natural variability in the North Atlantic's ocean climate, particularly on decadal and multi-decadal timescales. An overview of most aspects of this variability, especially for the Northeast Atlantic, is provided by the recent ICES Status Report on Climate Change in the North Atlantic (ICES 2011b). An illustration of the importance of decadal-scale variability in the northern North Atlantic is provided by the recent assimilative hindcast study of Häkkinen *et al.* (2011).

a) 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 Mid-Latitude Transition Zone (ML-TZ). The projection of more positive North Atlantic Oscillation 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 Subpolar Northwest Atlantic and ML-TZ. Also as described previously, a weakened AMOC can be expected to result in reduced flow into, and eddy energy in, the Intra-Americas Sea (IAS) with broader implications for both the IAS and Subtropical Western North Atlantic.

b) 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 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 Subtropical Western North Atlantic and IAS. A reduced rate of warming in the northern North Atlantic south of Greenland is expected associated with the weakening Atlantic Meridional Overturning Circulation. Changes in the Subpolar Northwest Atlantic are expected to vary spatially due to the competing influences of amplified high-latitude atmospheric warming and increasing stratification (favoring warming), and reduced AMOC, more positive North Atlantic Oscillation and possibly increased Arctic outflows (favoring cooling).

Table A1.3 **Tendencies for anthropogenic climate change in key upper-ocean physical oceanographic properties affecting ecosystems in the Western North Atlantic**

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	–			
	IAS Inflow	Expanded ST gyre & N-shifted Gulf Stream		++	+	
	Loop Current	Reduced mean & eddy flow in IAS				–
Temperature	Near-Surface	Widespread surface-intensified warming with reduced magnitude in north Subtropical water expansion in ML-TZ	+	++++	++	++
	Winter modified layer		+	++	+	+
	Shelf/Slope Bottom		+	+++	+	+
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	W:–––	W:––	W:–	W:––
		Winter-spring (W) decrease & summer (S) increase elsewhere, with subregional variability	S:–––	S:+	S:++	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	?	?	?	?

Note: 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 + (increase) and – (decrease) 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 color code rating for probable occurrence: Highly probable, probable.

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, e.g., Nye *et al.* 2011) 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 Mid-Latitude Transition Zone and southern part of the Subpolar Northwest Atlantic, in contrast to the reduced latitudinal gradient expected more widely.

The temperature of the intermediate and deeper waters over the continental slope and rise in the Subpolar Northwest Atlantic, Mid-Latitude Transition Zone and Subtropical Western North Atlantic can also be expected to increase, but more slowly and with much smaller magnitude than the upper-ocean waters. The details of these changes will depend on variability in the structure and intensity of the Atlantic Meridional Overturning Circulation, and in the Deep Western Boundary Current (DWBC) in particular, and in their interaction with other circulation features affecting deep waters of the Western North Atlantic. A counter-intuitive possibility is that changes in the deeper waters affected by the Denmark Strait Overflow Water (depths below 3500 m) may occur more quickly than those in the Northeast Atlantic Deep Water (depths of 2500–3500 m) due to the present bottom intensification of the DWBC. On the other hand, the lower limb of the Atlantic Meridional Overturning Circulation may not have the same depth penetration under a reduced AMOC, such that the ventilation of the Western North Atlantic's deeper waters may be much slower than at present. Potential changes in the temperature of the deep waters in the Intra-Americas Sea are even less clear due to the possibility of local circulation changes associated with its complex geometry.

c) 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 that 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; ICES 2011b) (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 Subpolar Northwest Atlantic (e.g., Labrador and Northeast Newfoundland Shelves/Slopes) and Mid-Latitude Transition Zone (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 (North Atlantic Oscillation or Atlantic Multi-decadal Oscillation) or anthropogenic change.

d) 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 Atlantic Meridional Overturning Circulation 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 Mid-Latitude Transition Zone (e.g., Nova Scotia) and Intra-Americas Sea (e.g., Mississippi Delta, and Ciudad Madero), and has been projected to be amplified in the Subpolar Northwest Atlantic and Mid-Latitude Transition Zone 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 the 2007 IPCC report because Greenland ice is melting faster than predicted and the rate of global warming seems to be higher than projected. Whereas the global–mean projected rise by the 2090s (relative to the 1980s) was in the range 0.18–0.59 m 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 2 m 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 Western North Atlantic. 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 areas with strong semi-diurnal tides, such as the Bay of Fundy-Gulf of Maine tidal system, since there are indications that these tides are increasing in amplitude, possibly also related to climate change (Müller 2011).

e) Coastal Flooding and Erosion

The projected increased occurrence of extreme high waters along the Atlantic coast can be expected to exacerbate coastal flooding and inundation of wetlands, and increased erosion and other alterations of the coastal zone. This may be worsened in some areas by increased wave heights, associated with more intense storms and hurricanes, and reduced damping of the waves (due to the increasing "mean" sea level). This is a case of multiple reinforcing 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 Intra-Americas Sea, Subtropical Western North Atlantic and Mid-Latitude Transition Zone, in particular (e.g., FOCC 2009; Wu *et al.* 2009). As a result of these multiple factors and the new information on faster than previously projected sea-level rise, 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.

f) 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 Subpolar Northwest Atlantic, a widespread decrease in salinity is expected, 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 Subtropical Western North Atlantic and Intra-Americas Sea because of increased evaporation as temperatures warm. A probable exception is coastal areas where substantial river discharge may result in local amplifications of or 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 Mid-Latitude Transition Zone (ML-TZ) are less predictable 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 salinity can be expected to generally increase in the offshore deep water and slope portions of the ML-TZ, and also probably at depths below about 100 m 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 subregional 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.

g) 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. Ocean surface 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 reinforce this tendency in the Subpolar Northwest Atlantic and in coastal areas of the Mid-Latitude Transition Zone, but at least partly offset this tendency in the Subtropical Western North Atlantic. 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.

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; Petrie *et al.* 2011), 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).

h) Coastal and Shelf Circulation

Changes in circulation patterns, currents, fronts, freshwater plumes and up/downwellings on the subregional 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 (magnitude and direction) may be the largest contributor to coastal current changes in many areas.

Chemical oceanographic properties

The tendencies for changes in key chemical oceanographic properties, associated with climate changes in non-biological processes, are summarized in **Table A1.4**.

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, and 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 dissolved inorganic carbon and acidity (reduced pH) and lowering of calcium carbonate saturation in the upper ocean, particularly in cold waters that 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

Table A1.4 Tendencies for anthropogenic climate change via physical processes in key upper-ocean chemical oceanographic properties affecting ecosystems in the Western North Atlantic

Oceanvariable	Feature	Large-scaletendencies for 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		–		

Note: The format and conventions are the same as in Table A1.3, with the relative magnitude of the changes in different regions indicated by the + and – signs, and probable occurrence by color coding: Highly probable, probable. Influences of changes in biological processes associated with climate change are not included.

corrosive to calcareous organisms, and the (different) 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, but there is also a wide array of other potential adverse effects of increasing ocean acidity on biogeochemical processes affecting marine organisms and ecosystems (e.g., ICES 2011b). 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 Subpolar Northwest Atlantic and the Mid-Latitude Transition Zone 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.

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 Western North Atlantic and for their important natural modes described above. ICES (2011a) provides an overview of ecosystem variability and 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.

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Annex 2

Generalized Effects of Climate-driven Oceanographic Changes on Components of the Ecosystem

The Executive Summary of ICES (2011a) describes the work of the Study Group on Designing Marine Protected Area Networks in a Changing Climate (SGMPAN) to present the general effects of oceanographic changes on the ecosystem components of the Atlantic based on current atmospheric and oceanographic physical conditions. Of particular relevance are sections 5 and 6:

"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. 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 remain 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 sub-polar 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 eco-system 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)…

…Section 6 of the report identifies species and habitats which are crucial to ecological functioning and may merit special conservation consideration."

The interpretations and justifications in Table A2.1 *Generalized effects of climate-driven oceanographic changes on components of the ecosystem* below are based on the analyses and deductions presented in ICES (2011a) and summarized above.[6]

6 ICES. 2011a. Report of the Study Group on Designing Marine Protected Area Networks in a Changing Climate (SGMPAN), 15–19 November 2010, Woods Hole, Massachusetts, USA. ICES CM 2011/SSGSUE:01. 155 pp.

Table A2.1 **Generalized effects of climate-driven oceanographic changes on components of the ecosystem***

Ecosystem components

Pressure	Phytoplankton	Zooplankton	Benthos	Fish
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
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
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
Increase in sea level	?	?	Increase in habitat for coastal species	Increased habitat for coastal species

*Note: 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 as the direction and magnitude of the change in vital rates is species-specific.

	Marine Mammals	Turtles	Marine birds	Mangroves and seagrasses	Corals
	Change in vital rates dependent on prey response; Thermoregulation issues	Changes in distribution, timing of migration and reproduction; Change in hatching sex ratios; 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
	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
	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 and vertical migration; Shifts in distribution
	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

Table A2.1 Generalized effects of climate-driven oceanographic changes on components of the ecosystem (cont')

Ecosystem components

Pressure	Phytoplankton	Zooplankton	Benthos	Fish
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
Changes in ocean circulation patterns	Northward shift of warm-water species; Introduction of Pacific species from Arctic	Northward shift of warm-water species; 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
Ocean acidification	Reduced production of calcifying phytoplankton and possible extinction	Reduced production of calcifying organisms if unable to form skeleton and possible extinction	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
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
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 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

Note: 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 as the direction and magnitude of the change in vital rates is species-specific.

	Marine Mammals	Turtles	Marine birds	Mangroves and seagrasses	Corals
	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
	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
	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
	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
	Reduced polar bear and seal habitat including seal breeding habitat	No effect	Earlier arrival of birds at breeding grounds; Changes in distribution	No effect	No effect in tropical corals, food delivery changes for shallow cold water corals, algal overgrowth
	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	?	?


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Annex 3

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