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

9–11 August 2011

Woods Hole, USA and
by Correspondence in 2012

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International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

H. C. Andersens Boulevard 44–46
DK-1553 Copenhagen V
Denmark
Telephone (+45) 33 38 67 00
Telefax (+45) 33 93 42 15
www.ices.dk
info@ices.dk

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Executive summary

A document, *Scientific Guidelines for Designing Resilient Marine Protected Area Networks in a Changing Climate* (Brock *et al.*, 2012; http://www.cec.org/Storage/136/16488_MPA-Scientific_guidelines_en_web.pdf), 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 ICES. SGMPAN developed their eponymous report at a workshop held in Woods Hole, Massachusetts, 15–19 November 2010. 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. That document (Brock *et al.*, 2012) was subsequently reviewed and final changes made through January to May 2012.

The comprehensive report (ICES, 2011) that resulted from the SGMPAN Study Group's writing and review process is considered to be the reference document for the guidelines. However, an updated oceanographic report was created based on the comments of the ICES WGECO and WGDEC reviews (John Loder (Canada), editor). That work is presented here and as an ANNEX in the *Scientific Guidelines for Designing Resilient Marine Protected Area Networks in a Changing Climate* (Brock *et al.*, 2012).

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. The work of SGMPAN has now been completed and the study group has been dissolved.

Brock, R. J., Kenchington, E., and A. Martinez-Arroyo (Eds.). 2012. Scientific Guidelines for Designing Resilient Marine Protected Area Networks in a Changing Climate. Commission for Environmental Cooperation. Montreal, Canada. 95 pp.

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

1 Opening of the meeting

Members of the SGMPAN Study Group, chaired by Robert Brock (USA), Ellen Kenchington (Canada) and Amparo Martinez-Arroyo (Mexico), met 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. The list of participants and contact details are given in Annex 1. This was the final meeting of SGMPAN.

2 Adoption of the agenda

The Agenda (Annex 2) was adopted on 9 August and the meeting proceeded according to the Workplan presented in Plenary Sessions by the Subgroup Leaders. Throughout the meeting, subgroup meetings were scheduled to allow for member participation in a number of subgroups to the degree possible. Daily updates were provided by the Subgroup Leaders in plenary session and as text was finalized it was presented in plenary. Therefore, all of the content of this report pertaining to the ToRs was fully reviewed in plenary sessions of the SGMPAN.

3 Introduction

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, 2011). 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, although the basic physical structure is present, if aspects such as foodwebs 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.

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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.

3.1 References

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4 Updated 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 "Marine Ecoregions" between the Caribbean Sea and the Baffin/Labradoran Arctic in the recent atlas prepared for the Commission for Environmental Cooperation (CEC) by Wilkinson *et al.* (2009; Figure 4.1).

This review is largely a repeat of that in Section 5.1 of the SGMPAN Report (ICES, 2011a). It will draw heavily on the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007), and subsequent or contemporary regional and other assessments (e.g. CCSP, 2008a,b; CCSP, 2009; Cochrane *et al.*, 2009; EAP, 2009; FOCC, 2009; Frumhoff *et al.*, 2007; ICES, 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 are described. 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.

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 1–2 years. Consequently, the present report will focus on important features and expected tendencies for climate change, rather than on quantitative estimates, since significant improvements in the latter can be expected within the time frame of the actual design of MPA networks in the WNA.

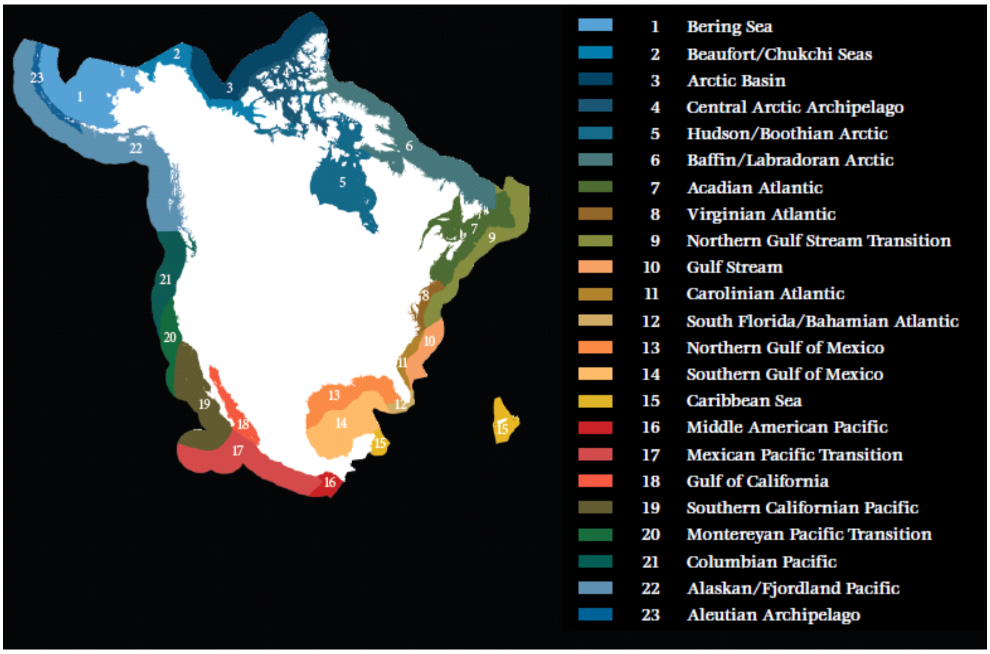

Figure 4.1. Marine ecoregions around North America excluding the Hawaiian Archipelago. From Wilkinson *et al.* (2009).

4.1 Changing climate and relevant factors

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

Terms like "changing climate" and "climate change" are used with a variety of meanings such that, before proceeding, it is important to clarify their meaning in this 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 synonymously here, with climate change following the convention in IPCC (2007) where it is taken to refer to any change or variation of climate over time. The period of immediate interest here is the 20th and 21st centuries. Changing climate will be taken to include both natural and anthropogenic components of recent and future variability of the Earth's coupled atmosphere-ice-ocean-biogeochemical climate system.

There is strong natural variability of the Earth's climate. Pronounced seasonality in the atmosphere and upper ocean, particularly at mid and high latitudes, is a well-known large-scale variation to which various living organisms have adapted. There are other, less-regular, variations on space scales comparable to those of the continents and ocean basins. For the ocean climate along the Atlantic coast of North America, important regional changes occur on decadal and other time-scales associated with modes of natural variability such as the North Atlantic Oscillation (NAO; e.g.

Hurrell and Deser, 2010), the Atlantic Multi-decadal Oscillation (AMO; e.g. Enfield *et al.,* 2001) and the El Niño-Southern Oscillation (ENSO; e.g. Trenberth and Caron, 2000), with indications of associated marine ecosystem changes in many cases. Anthropogenic contributions to climate change, such as those associated with increasing greenhouse gases in the atmosphere; need to be considered in this context for some variables, at least for the next few decades. The recent changing climate needs to be considered as potentially arising from a combination of natural and anthropogenic factors which may be interacting. Similarly, both natural and anthropogenic influences need to be considered in discussions of many potential climate changes in future, particularly during the next two decades.

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

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

Considering the expected increasing magnitude of anthropogenic climate changes and the limited predictability of shorter term natural climate variability, it is useful to consider two time horizons for the projection of changing climate 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, $CO2$ 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 substan-

tially larger in magnitude, and can be expected to dominate decadal-scale natural variability or shift the range of variability of 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 of the WNA is the inadequate resolution in AOGCMs of key dynamics in areas such as the Gulf Stream separation and the linkages with the adjoining Arctic and tropical Atlantic Oceans. The AOGCMs used in IPCC (2007) do not reproduce important ocean features in such regions and thus do not resolve some important influences of the ocean on regional atmospheric climate (e.g. de Jong *et al.*, 2009). Thus, the downscaling of existing climate change scenarios may not be adequate for the spatial scales of many ecosystem issues in the WNA.

4.2 Oceanographic regions of the Western North Atlantic (WNA)

4.2.1 Large-scale setting

The setting of North America's Atlantic coast in relation to the continent and the global ocean is illustrated by the map of bottom topography and major upper-ocean current features of the WNA in Figure 4.2.1.1, and by the climatological distributions of upper-ocean temperature and salinity in the WNA in Figure 4.2.1.2. The Atlantic coastal region is quite complex (Figure 4.2.1.1), with large protrusions and indentations of the coastline, a continental shelf of variable width, and a very complex geometry in the Gulf of Mexico and Caribbean Sea. Pronounced influences of the inflows of relatively cold freshwater from the Arctic Ocean and of relatively warm water from the Western Tropical Atlantic (WTA) are apparent in the temperature and salinity patterns, as well as of the North Atlantic's large-scale horizontal gyres and their western boundary currents – the Labrador Current and Gulf Stream (e.g. Loder *et al.*, 1998a). These predominant circulation features provide a high degree of advective connectivity in the WNA, particularly within the subpolar and subtropical gyres. An additional important factor to the region's coastal ocean climate is its location in the lee of the North American continent with resulting influences through prevailing westerly winds and continental run-off.

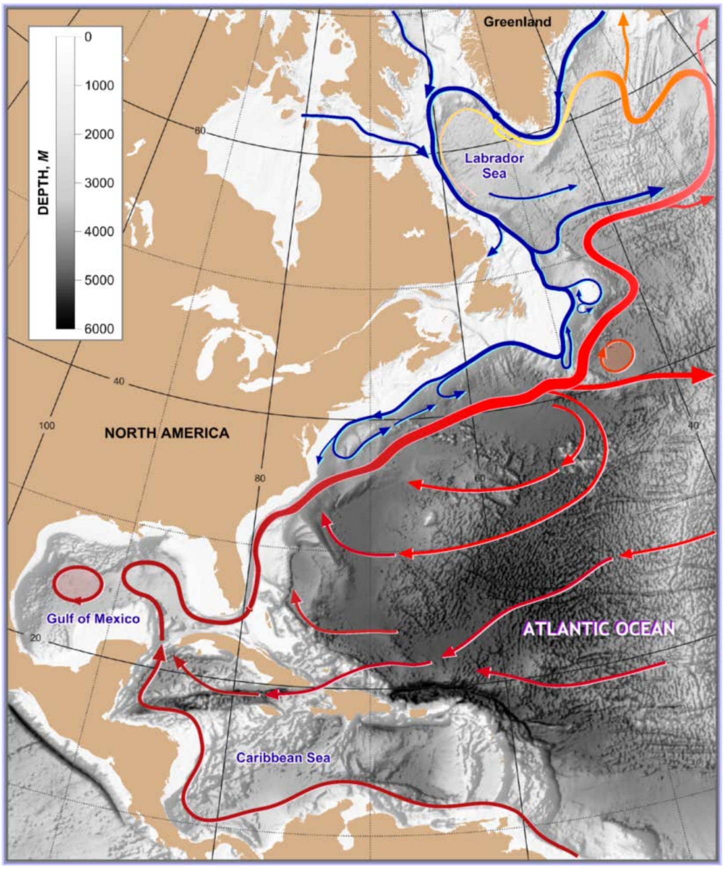

Figure 4.2.1.1. Map showing the complex bottom topography of the WNA, together with a schematic representation of the major upper-ocean circulation features. Warm flows are denoted by red, cold flows by blue and intermediate temperatures by orange-yellow. Courtesy of Igor Yashayaev (Bedford Institute of Oceanography, Fisheries & Oceans Canada).

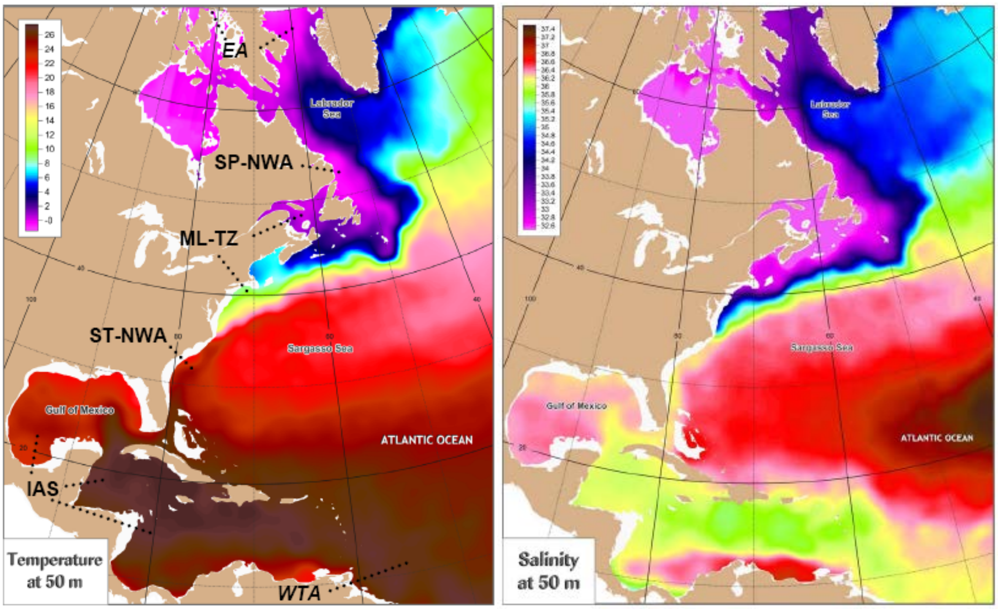

Figure 4.2.1.2. Long-term annual-mean temperature and salinity at 50m in the WNA, from the Yashayaev (1999) climatology. Major oceanographic regions WITHIN and AFFECTING the WNA are labelled on the temperature panel (see Table 1 and text for explanations). Major Oceanographic Regions are labelled: EA = 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).

4.2.2 Major oceanographic regions within and affecting the WNA

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 4.2.1.1 and 4.2.1.2).

- The SubPolar NorthWest Atlantic (SP-NWA), roughly extending from Davis Strait at about 65°N, 60°W to the Tail of the Grand Bank at about 42°N, 50°W. This region is strongly influenced by the North Atlantic's 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 20°N to Cape Hatteras at about 35°N. This region is strongly influenced by the North Atlantic's subtropical gyre (e.g. Boicourt *et al.*, 1998), and in particular by the Gulf Stream which carries subtropical water northward in the upper ocean before turning northeastward away from the shelf edge at Cape Hatteras. (In some ways the Gulf of Mexico and Caribbean Sea could be included in the ST-WNA, but they will be identified as a separate major region here because of their pronounced coastline and bathymetric variability, and their closer proximity to the eastern Pacific Ocean).
- A 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 Bank at 42°N, 50°W. In this region, there are competing influences of the oppositely flow-

ing subpolar and subtropical waters, and a broad "Slope Water" region (with a mixture of waters of subpolar and subtropical origin) north of the Gulf Stream (e.g. Loder *et al.*, 1998b). Waters of subpolar origin have generally dominated this zone's shelf in recent history (Wanamaker *et al.*, 2007), but there are increasing influences of subtropical waters as one proceeds towards Cape Hatteras. (Also, as described below, there are reasons to expect the subtropical influence to increase with anthropogenic climate change).

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

In addition to these major oceanographic regions within the WNA, two other major latitudinal oceanographic regions 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 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 genesis region of tropical cyclones and hurricanes in the North Atlantic, some of which move westward into the IAS and others of which turn northward into the ST-WNA and sometimes reach the ML-TZ and SP-NWA.

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

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 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 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 IAS, such as the contrasting bathymetric structures of the Gulf of Mexico and Caribbean Sea, and the specific settings of the West Florida Shelf, Texas-Louisiana Shelf and Campeche Bank.

The oceanographic regions and subregions identified here have substantial similarity to the "Marine Ecoregions" (Figure 4.1) identified by Wilkinson *et al.* (2009), although the names are different in many cases (Table 4.2.2.1). The latter ecoregions were identified from both ecological and oceanographic considerations, and may be more appropriate for ecosystem planning in some cases. On the other hand, the oceanographic regions and subregions should be particularly helpful in downscaling climate change projections.

Within the subregions in Table 4.2.2.1, there is also a multitude of smaller-scale areas with distinctive oceanographic features that affect particular aspects of coastal and marine ecosystems (e.g. assemblages, populations, phases of life-history cycles). These "local" features include particular estuaries, wetlands, coastal freshwater plumes, fronts, up/downwelling zones, and gyres and water masses related to banks, basins and channels. This hierarchy of oceanographic space scales provides a multiscale "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).

Table 4.2.2.1. 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).

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

4.2.3 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-sized estuaries and wetlands where there are strong influences of shallow water, coastline interactions, changing sea level (e.g. tides) and local run-off;
- "Shelf seas", including large estuaries such as the Gulf of St Lawrence and the upper continental slope in places where it is not dominated by the western boundary current (Cape Hatteras to the Tail of the Grand Bank); and
- The offshore "deep ocean", including the deep basins of the IAS and also the continental slope in places where it is dominated by the western boundary current (e.g. Florida Straits to Cape Hatteras, and Labrador Sea).

4.2.4 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 of 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 WNA'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).

4.2.5 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 of the WNA. In some cases these extend across the space 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.

4.2.5.1 North Atlantic Oscillation (NAO)

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

Multiple mechanisms for the NAO's ocean climate influences have been identified, including direct influences in the SP-NWA region via wind-forced ocean circulation and wintertime water mass modification in the Labrador Sea (with multiple years of positive NAO resulting in increased deep convection; e.g. Yashayaev and Loder, 2009), and via increased wind-forced circulation (positive NAO) resulting in cooler water and more sea ice in the Newfoundland-Labrador Shelf/Slope region (e.g. Han *et al.*, 2010). Of particular note, shelf-slope temperature and salinity in the ML-TZ are also influenced by the NAO but with temperature (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 Bank and hence a greater influence of subtropical waters in the transition zone (Han, 2007; Petrie, 2007). Recent work (Figure 4.2.5.1.1) indicates a significant correlation between the NAO and the north–south position of the Gulf Stream between Cape Hatteras and the Grand Bank (offshore in the ML-TZ), with a more positive NAO resulting in a northward displacement of the Stream and subtropical water, and of some fish distributions (e.g. Nye *et al.*, 2011).

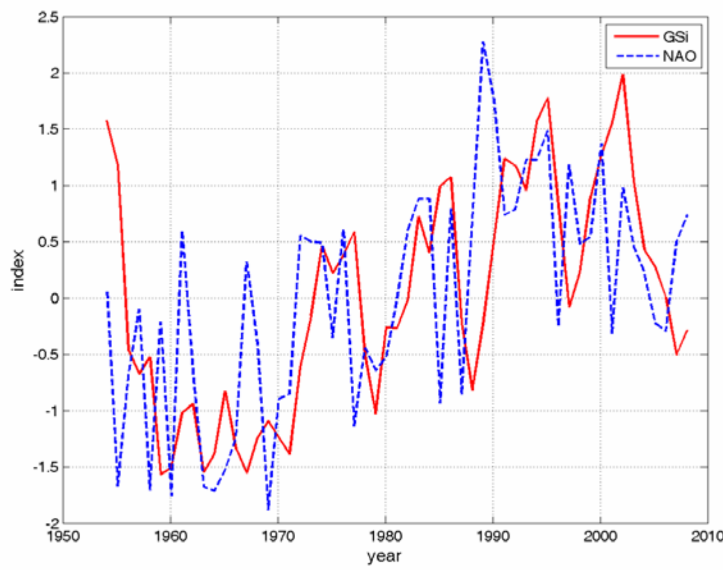

Figure 4.2.5.1.1. Wintertime NAO index taken from the monthly teleconnection analysis of the NOAA Climate Prediction Center, and the Gulf Stream (GS) index from Joyce and Zhang (2010). Over the modern period the two are significantly correlated, although the correlation is diminished (but still significant) if the data are first linearly de-trended. The GS lags the NAO by about 1 year. This result is an update from that first noted in Joyce *et al.* (2000).

While the NAO is a dipole pattern of the north–south sea level pressure difference between Iceland and the Azores, it is also correlated with a tripole pattern of sea surface temperature (SST) anomalies over the North Atlantic in boreal winter/spring. The tripole pattern arises primarily from the oceanic response to wintertime atmospheric variability associated with the NAO.

4.2.5.2 El Niño – Southern Oscillation (ENSO)

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

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

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

4.2.5.3 Tropical Atlantic Variability (TAV)

The two fundamental modes of the TAV (Chang *et al.*, 2006) are illustrated in Figure 4.2.5.3.1:

- A "meridional" mode, active in boreal spring when the ITCZ in the Atlantic is in its southernmost position. In this mode, a stronger-than-normal northward SST gradient drives northward cross-equatorial winds. Trade winds are weaker-than-normal in the north and stronger-than-normal in the south. Rainfall deviation from the seasonal cycle is characterized by a dipolar pattern across the thermal equator. This mode is more strongly connected to the ITCZ behaviour than the zonal mode. The ITCZ tends to spend more time in the hemisphere with the positive SST anomaly. Anomalous SSTs, trade winds, and heat flux patterns suggest a (not fully understood) connection with other Atlantic modes such as the NAO.
- A "zonal" mode active in summer when the ITCZ is at its northernmost position. A cold tongue of SST develops in the equatorial eastern Atlantic. Maxima of SST anomalies in the eastern basin are related to a convergent pattern of equatorial trade winds. This mode is sometimes referred to as the Atlantic "ENSO" although it is quite different from the Pacific ENSO (see Xie and Carton (2004) and Chang *et al.* (2006) for details).

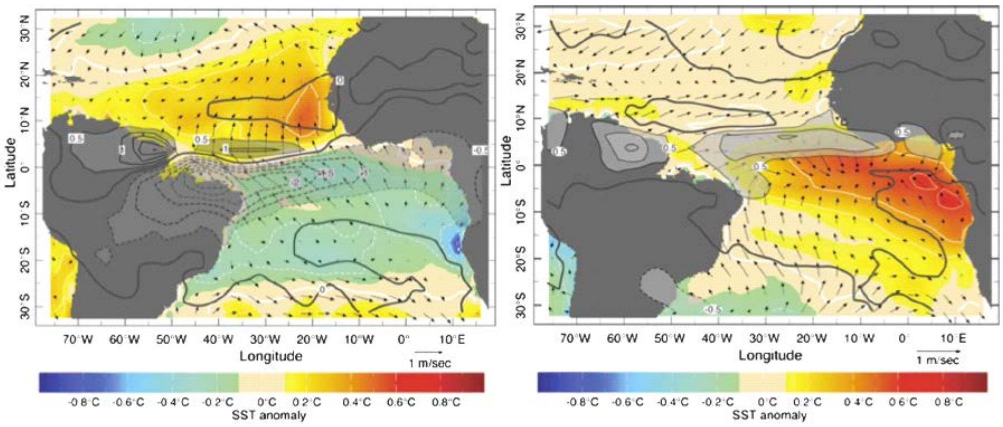

Figure 4.2.5.3.1. The dominant pattern of surface ocean-atmosphere variability of the tropical Atlantic region during (left) boreal spring and (right) boreal summer. The black contours depict the first empirical orthogonal function (EOF) of the regional March-April and June-August rainfall anomaly (from Global Precipitation Climatology Project data 1979–2001; mm day-1). The coloured field is the March-April and June-August SST anomaly regressed on the principal component time-series of the rainfall EOF. Arrows depict the seasonal mean surface wind regressed on the same time-series. From Chang *et al.* (2006).

4.2.5.4 Atlantic Warm Pool (AWP)

The AWP is a region in the WTA and IAS 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 4.2.5.4.1). It is closely related to hurricane activity, with a large (small) warm pool associated with strong (weak) hurricane activity in the Atlantic. Being a heat source for the atmosphere in summer, important teleconnections develop providing a climatic link between the Americas, and between the Atlantic and Pacific. The size and intensity of the AWP in summer are the result of atmospheric forcing during the previous winter and spring, providing potential predictability for summer conditions. Interannual and interdecadal variability of its extension can be as large as the seasonal change.

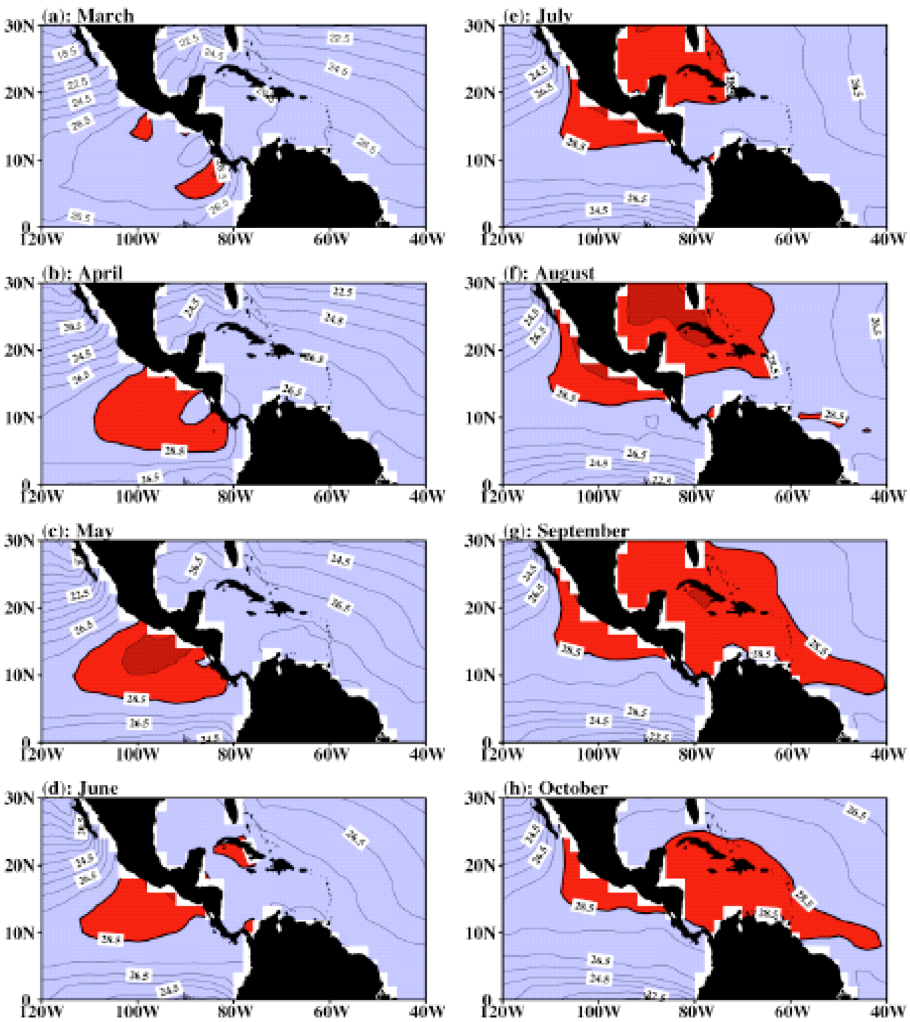

Figure 4.2.5.4.1. Seasonal variation of SST for the tropical WHWP. The shading and dark contour represent water warmer than 28.5°C. From Wang and Enfield (2001) and IASCLIP (2008).

4.2.5.5 Atlantic Multi-decadal Oscillation (AMO)

A large-scale mode of ocean climate variability of importance to the WNA is the AMO through which sea surface temperature in the North and South Atlantic vary out-of-phase over a 65–75 year period (e.g. Enfield *et al.*, 2001). The AMO had a warm phase in the North Atlantic from about 1930 to the early 1960s, then had a cool phase until the mid 1990s (Figure 4.2.5.5.1), and now is in a warm phase which might be projected to last until the 2020s. The statistics, origin and dynamics of the AMO are less well-known (than those of the NAO and ENSO), partly because it typically has only 1–2 periods in many instrumental records. Variability in the Atlantic Meridional Overturning Circulation (AMOC) is generally implicated as a factor in the origin of the AMO, but the dynamics and extent of their interrelation 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 ML-TZ between the 1960s and 1990s have been attributed to the AMO (EAP, 2009), and there is an indication of a possible influence on shelf temperatures in the southern part of the SP-NWA. However, separation of anthropogenic warming and AMO variability in ocean temperature records over the past few decades is problematic (e.g. Polyakov *et al.*, 2010), reflecting the importance of considering both natural and anthropogenic variability in climate change projections.

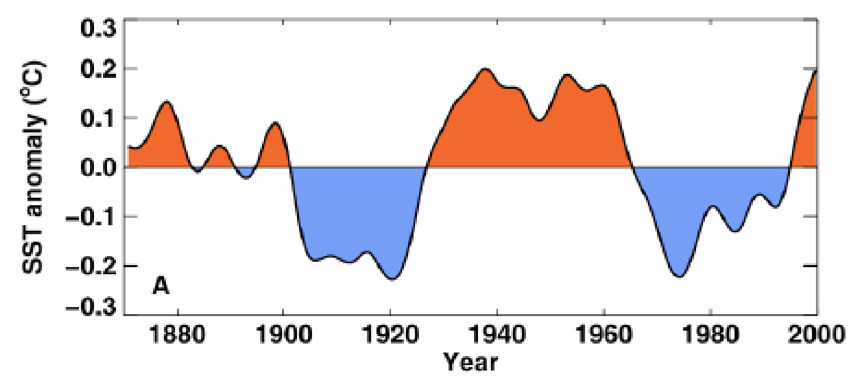

Figure 4.2.5.5.1. De-trended SST anomaly in the North Atlantic which is often used as an AMO index. From Knight *et al.* (2005).

4.2.5.6 Atlantic Meridional Overturning Circulation (AMOC)

The AMOC is a major component of the global climate system, and a large contributor to circulation in the WNA, including flow into the Caribbean. It involves 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 4.2.5.6.1). The associated equatorward 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. AOGCM simulations for the 21st century project a slowing down of the AMOC (Meehl *et al.*, 2007) and show an area of reduced warming south of Greenland which is consistent with a reduction in the poleward upper-ocean transport of warm water in the North Atlantic (offsetting the global tendency for surface ocean warming). There have been observational estimates that the AMOC has been slowing down over the past half century, but there have also been model simulations suggesting that there has been significant decadal-scale variability (e.g. Balmaseda *et al.*, 2007). Various connections among the AMOC, NAO and AMO have been suggested, as well as suggestions of connections between the AMOC and the north–south position of the Gulf Stream in the ML-TZ. A relevant pattern that is emerging from some observational and modelling studies (Joyce and Zhang, 2010) is that a weakened AMOC associated with reduced deep convection in the Labrador and Nordic Seas results in a northward shift in the Gulf Stream in the ML-TZ, and higher ocean temperatures in the Slope Water extending from the Grand Bank to the Mid Atlantic Bight.

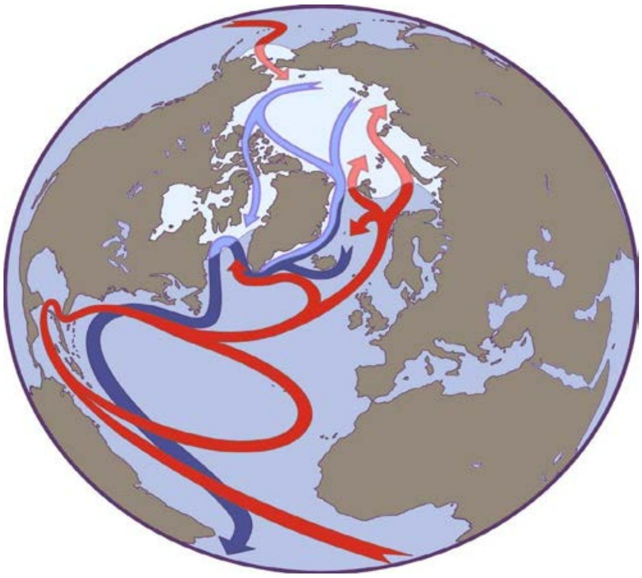

Figure 4.2.5.6.1. Schematic depiction of the linkages between AMOC and the flows in and out of the Arctic, with red indicating warm flows and blue indicating cold flows. From Greg Holloway (Institute of Ocean Sciences, Fisheries and Oceans Canada).

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

4.2.6 Linkages among modes of variability

It is clear from the above discussion that particular oceanographic regions in the WNA are influenced by multiple modes of natural climate variability which are generally interrelated. As one example, Hurrell *et al.* (2006) have provided the following perspective on the interrelation of the NAO, TAV and AMOC, referring to Figure 4.2.6.1:

"The NAO is associated with a meridional displacement of middle-latitude westerly winds (green contours of zonal wind velocity centered at 40°). The [northern hemisphere] tropical lobe of the SST anomaly tripole (the sign of which is associated with the negative index phase of NAO) also is related to the [TAV], in which changes in the cross-equatorial SST gradient interact with the overlying atmosphere to produce changes in ITCZ rainfall. A warm anomaly north of the equator (which also can be induced during a warm ENSO phase) results in anomalous cross-equatorial winds (denoted by three light-grey arrows). During this phase, the ITCZ is displaced northward, producing dry conditions over the Nordeste and wet conditions over sub-Saharan Africa. Changes in the strength and position of tropical convection also may affect the position and strength of the mid-latitude storm track (blue arrows) and thus the phase of the NAO. The schematic representation of the North Atlantic MOC depicts the northward transport of warm water and southward transport of newly ventilated cold water. Changes in the surface density within the Subpolar Gyre and Subarctic basins can influence the strength of the overturning and heat transport. The high-latitude density can change as a result of anomalous advection of Arctic freshwater or changes in air-sea fluxes. The NAO systematically influences the strength of the MOC from both effects. The tropical ocean has two additional shallow overturning cells (thin arrows) driven by Ekman transports in the trade winds zone. They can communicate surface temperature anomalies from subtropical regions to tropical upwelling zones and thus cause a delayed feedback on tropical surface temperatures. The three major climate phenomena in the Atlantic interact, …"

As another example of the interconnectivity among the modes and the influences of multiple modes on a particular region, Table 4.2.6.1 provides a summary of the six modes described above and their impacts from the perspective of the subtropical and tropical Atlantic (the ST-WNA, IAS and WTA regions).

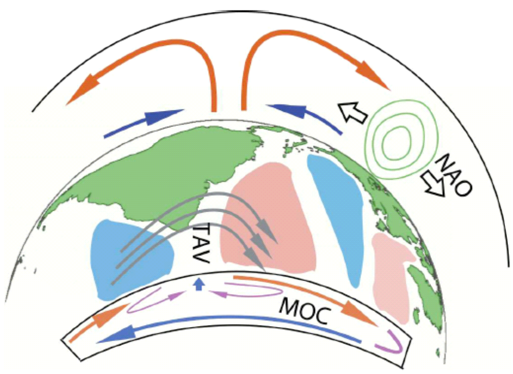

Figure 4.2.6.1. Schematic of the NAO, TAV and Atlantic MOC (AMOC). From Marshall *et al.* (2001); and Hurrell *et al.* (2006).

Table 4.2.6.1. Summary of climate variability modes affecting the WNA and their main features and impacts from the perspective of the subtropical and tropical Atlantic.

Mode	Main Features/ Definition	Impact in the WNA and/or IAS region
NAO	North Atlantic Oscillation. North Atlantic meridional surface pressure gradient index. Boreal winter-spring signal associated with a tri-polar SST pattern in the North Atlantic.	Impacts the northeasterly trades through modification of subtropical high impacting TAV (SST and latent heat flux anomalies). Modifies subtropical gyre.
ENSO	El 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, interannual, multi-decadal).	Large extension related to increased hurricane activity, related to (part of) the AMO. Large extension related to positive rainfall anomalies in the IAS.
AMO	Atlantic Multi-decadal Oscillation. Bi-polar variation in North and South Atlantic SST.	Related to AWP and MOC. Shallow subtropical cells (STCs) in upper ocean.
AMOC	Atlantic Meridional Overturning Circulation. Northward (southward) upper- (lower-) ocean flow of warm (cold) water.	Important contribution to IAS ocean circulation. STC tropical/subtropical connection.

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

4.3 Recent and probable climate changes in important variables

4.3.1 Atmospheric and hydrological

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 which is 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 6.4°C. 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). AOGCMs generally indicate that the change over northeastern North America could be about twice the global mean.
- There is more spatial structure and variability in the projected changes in precipitation than in temperature. Wintertime precipitation is projected to increase over most of North America associated with the intensified global hydrological cycle, but decrease over the southwestern United States and Mexico. Summertime precipitation is projected to increase over the northern half of North America but decrease over the southern half except along the Atlantic coast. A reduction in the fraction of precipitation falling as snow, and earlier snow melting are expected over eastern North America.
- Evaporation rates are generally expected to increase over the eastern half of North America and ST-WNA, but decrease over Mexico and the SP-NWA.
- Widespread changes in the seasonal cycle of freshwater run-off into the ocean are expected, with earlier and generally larger spring peaks. The changes in annual-mean run-off will vary with region depending on seasonal precipitation and evaporation rates, and ice and snow melting. Increased freshwater discharge into the SP-NWA is expected from both North America and Greenland (glacial melting), which may be enhanced by an increased flux of freshwater from the Arctic. The changes in freshwater discharge into the ML-TZ are less certain because of multiple river systems with drainage areas having differing extents into the continental interior. Run-off into the Gulf of St Lawrence is expected to increase in winter and decrease in summer, probably with a net annual-mean increase (but this is more tentative). An increase in annual-mean freshwater discharge into the southern part of the ML-TZ (Gulf of Maine and Mid Atlantic Bight) has been projected. Run-off into the ST-WNA and northern Gulf

of Mexico is generally expected to increase in winter and decrease in summer, while there may be a general decrease in run-off into the remainder of the IAS. However, the operation of dams will be a key factor in several hydrological basins, like the Papaloapan and Grijalva-Usumacinta in the southwestern Gulf of Mexico.

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

4.3.2 Physical oceanographic

The tendencies for probable anthropogenic changes in key upper-ocean physical oceanographic variables in the WNA are summarized in Table 4.3.2.1. For each variable or feature, an indication is provided of the relative magnitude of the expected changes in the four major oceanographic regions, based on the literature and current knowledge. An indication is also provided of the degree of confidence in the projections, based here on uncertainty and gaps in our present knowledge of climate dynamics and change (e.g. physics, models, and interpretations of observations). The indicated changes are all expected to become important in the Longer-Term (by mid century), although some may be less important than natural variability in the Near-Term. The changes indicated as "highly probable" are generally considered to be already occurring, although the observed magnitude in some regions may include a contribution from natural variability.

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 time-scales. 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 ML-TZ. The projection of more positive NAO can also be expected to contribute to a northward expansion of the subtropical gyre (Joyce *et al.*, 2000; Han, 2007) and a retraction (tightening) of the Subpolar Gyre in the WNA (e.g. Lohmann *et al.*, 2009a,b), thereby having significant impacts on both the SP-NWA and ML-TZ. Also as described previously, a weakened AMOC can be expected to result in reduced flow into, and eddy energy in, the IAS with broader implications for both the IAS and ST-WNA.

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 the Near- and Longer-Terms. Changes in the seasonal cycles and extrema, with regional differences, are expected to be important to biological processes.

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

Enhanced warming in the ML-TZ is expected (e.g. Fogarty *et al.,* 2007) associated with poleward expansion of the subtropical gyre (northward shift of the Gulf Stream, 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 ML-TZ and southern part of the SP-NWA, 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 SP-NWA, ML-TZ and ST-WNA 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 AMOC, and in the DWBC in particular, and in their interaction with other circulation features affecting the WNA's deep waters. A counter-intuitive possibility is that changes in the deeper waters affected by the Denmark Strait Overflow Water (depths below 3500m) may occur more quickly than those in the Northeast Atlantic Deep Water (depths of 2500–3500m) due to the present bottom intensification of the DWBC. On the other hand, the lower limb of the AMOC may not have the same depth penetration under a reduced AMOC, such that the ventilation of the WNA's deeper waters may be much slower than at present. Potential changes in the temperature of the deep waters in the IAS 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 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 SP-NWA (e.g. Labrador and Northeast Newfoundland Shelves/Slopes) and ML-TZ (Gulf of St Lawrence) where seasonal ice presently occurs. This can be expected to have major implications for some parts of their regional ecosystems. Sea ice extent and duration have decreased on the NE Newfoundland Shelf/Slope (south of 55oN) during the past decade (e.g. Templeman, 2010), but it is unclear whether this is associated with natural variability (NAO or AMO) or anthropogenic change.

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 AMOC and the horizontal gyres) and currents (e.g. driven by local winds and buoyancy), and (ii) vertical movements of coastal land and seabed due to continental rebound or subsidence, and river delta subsidence. These additional factors can be expected to amplify sea level rise along many parts of the Atlantic coast of North America, and in some cases are already doing so. In particular, relative sea level rise is presently amplified by land subsidence in parts of the ML-TZ (e.g. Nova Scotia) and IAS (e.g. Mississippi delta, and Ciudad Madero), and has been projected to be amplified in the SP-NWA and ML-TZ in future associated with a slowing of the AMOC (e.g. Yin *et al.*, 2009) and northward expansion of the subtropical gyre.

There are now good reasons to believe that sea level will rise faster than projected in IPCC (2007), because of Greenland ice melting and higher-than-projected global warming. Whereas the global–mean projected rise by the 2090s (relative to the 1980s) was in the range 0.18–0.59 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 2m rise.

In addition to the above rise in "mean" (over seasons and longer) sea level, an amplification of extreme high-frequency (periods of hours) variability in sea level is projected for many areas, associated with more intense cyclones and hurricanes in the WNA. Combined with the widespread rise in mean level, this can be expected to contribute to a significant increase in extreme high water levels in most areas. The latter may be further exacerbated in 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 lead to increased coastal flooding and inundation of wetlands, and increased erosion and other alterations of the coastal zone. This may be further exacerbated in some areas by the occurrence of increased wave heights, associated with the more intense storms and hurricanes, and reduced damping of the waves (due to the increasing "mean" sea level). This is a case of multiple re-enforcing factors associated with different aspects of anthropogenic and natural variability contributing to substantial regional and subregional amplifications of the global tendency for rising sea level and coastal damage. Reduced sediment supply due to dam construction, combined with sea level rise, will also increase coastal erosion in some delta areas.

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

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

Salinity changes in the ML-TZ are less clear and will probably have more spatial structure than in the other two regions. With the expected northward expansion of the subtropical gyre and retraction of the Subpolar Gyre, upper-ocean ocean salinity can be expected to generally increase in the offshore deep-ocean and slope portions of the ML-TZ, and also probably at depths below about 100m over the outer and mid shelves. However, salinities in the coastal ocean and near-surface over the inner-mid shelf may be predominantly influenced by changes in local or 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 interrelated and dependent on changes in surface and subsurface temperature and salinity, and wind and wave mixing. Surface ocean warming can be expected to provide a broad-scale tendency towards increasing near-surface stratification and shallower (thinner) mixed layers. Ocean salinity changes can be expected to re-enforce this tendency in the SP-NWA and in coastal areas of the ML-TZ, but at least partly offset this tendency in the ST-WNA. The influence of changes in wind and wave mixing will probably be more spatially and seasonally variable, with perhaps increased mixing in the late summer-fall hurricane and cyclone season, but reduced mixing in spring and summer when seasonal stratification is developing.

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, with magnitude and sign dependent on the wind velocity's orientation to the coastline as well as its magnitude, may be the largest contributor to coastal current changes in many areas.

Table 4.3.2.1. Tendencies for Anthropogenic climate change in key upper-ocean Physical Oceanographic properties affecting ecosystems in the WNA. The time horizon on which these changes might be expected to become more important than natural decadal-scale variability varies with the variable, but all might be expected to do so within a few decades. The large-scale (WNA) tendencies for particular features of these variables are noted, and the relative magnitude of the tendencies among the major oceanographic regions for each feature are indicated using multiple + (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 colour coding for probable occurrence: Highly probable, probable.

Ocean Variable	Feature	Large-Scale Tendencies for WNA	SP-NWA	ML-TZ	ST-WNA	IAS
Large-Scale Ocean Circulation	AMOC	**Slowed AMOC**	–	–	–	–
	SP & ST Gyres	Retracted SP gyre	–			
		Expanded ST gyre & N-shifted Gulf Stream		++	+	
	IAS Inflow Loop Current	Reduced mean & eddy flow in IAS				–
Temperature	Near-Surface	**Widespread surface-intensified warming** with reduced magnitude in north	+	++++	++	++
	Winter modified layer		+	++	+	+
	Shelf/Slope Bottom	Subtropical water expansion in ML-TZ	+	+++	+	+
Sea Ice Extent & Volume	Winter & spring only	**Reduced** where present	––	–––		
Coastal Sea Level (relative to land)	Means	**Widespread increase** with regional variations due to multiple factors	+++	++++	+++	++++
	Extremes	**Widespread additional increase** due to more intense hurricanes & cyclones	++	+++	+++	++++
Coastal Flooding & Erosion	Coastline retreat	**Widespread increase** due to mean & fluctuating sea level, with regional variations due to low-lying coastlines	+	+++	++++	++++
Salinity	Offshore (in upper few 100m)	**Decrease** in SP-NWA **Increase** in ML-TZ, ST-WNA & GM	–––	+++	++	++
	Coastal (in upper 100m)	**Decrease** in SP-NWA Winter-spring (W) decrease & summer (S) increase elsewhere, with subregional variability	W:––– S: –––	W:–– S: +	W:– S: ++	W:–– S: ++

Upper-Ocean Stratification & Vertical Mixing	Surface mixed layers	Widespread **increased stratification**, thinner mixed layers & reduced vertical mixing	+++	++	+	+
Coastal & Shelf Circulation	Buoyancy- & wind-driven currents; Fronts	Enhanced buoyancy flows & fronts; Modified currents depending on local winds	+ ?	+ ?	+ ?	+ ?

4.3.3 Chemical oceanographic

The tendencies for changes in key chemical oceanographic properties, associated with climate changes in non-biological processes, are summarized in Table 4.3.3.1.

Warmer ocean temperatures, increased stratification, and reduced vertical mixing in the upper ocean are expected to provide a tendency for reduced atmospheric replenishment of oxygen to subsurface waters, and hence reduced dissolved oxygen concentrations at depths below 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 CO2 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 which can hold more CO2 than warmer waters (e.g. Doney *et al.*, 2009; Hoegh-Guldberg and Bruno, 2010). As a result, some Arctic waters are already becoming corrosive to calcareous organisms, and the (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 SP-NWA and the ML-TZ associated with Arctic outflows (e.g. Yamagoto-Kawai *et al.*, 2006; Harrison and Li, 2008; Yeats *et al.*, 2010) and a Gulf Stream shift, respectively.

Table 4.3.3.1. Tendencies for Anthropogenic climate change via physical processes in key upper-ocean Chemical Oceanographic properties affecting ecosystems in the WNA. The format and conventions are the same as in Table 3, with the relative magnitude of the changes in different regions indicated by the + and − signs, and probable occurrence by colour coding: Highly probable, probable. Influences of changes in biological processes associated with climate change are not included.

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

4.4 Indices for covariate studies

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

Many indices already exist for atmospheric and ocean climate variability in the WNA, and for their important natural modes described above. 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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5 Scientific Guidelines for Designing Resilient Marine Protected Area Networks in a Changing Climate

The scientific guidelines developed from the work of SGMPAN are available online at: http://www.cec.org/Storage/136/16488_MPA-Scientific_guidelines_en_web.pdf. The table of contents for the report is presented in Figure 5.1. Previous work of SGMAN was distilled into 4 guidelines: 1) Protect Species and Habitats with Crucial Ecosystem Roles, or Those of Special Conservation Concern; 2) Protect Potential Carbon Sinks; 3) Protect Ecological Linkages and Connectivity Pathways for a Wide Range of Species; 4) Protect the Full Range of Biodiversity Present in the Target Biogeographic Area.

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Annex 1: List of participants

Name	Address	Phone/Fax	E-mail
Amparo Martínez-Arroyo **(Co-Chair)**	Departamento Ciencias Ambientales. Centro de Ciencias de la Atmosfera, UNAM Circuito Exterior Ciudad Universitaria 04510 Mexico DF	+52 55 56224076	amparo@atmosfera.unam.mx
Robert Brock **(Co-Chair)**	NOAA National Marine Protected Areas Center, 1305 East-West Highway (N/OCRM), Silver Spring, Maryland, 20910-3282 USA	+1-301-563-1144	Robert.Brock@noaa.gov
Kathryn Scanlon Catanach	US Geological Survey, Center for Marine Science, 384 Woods Hole Road, Quissett Campus, Woods Hole, Massachusetts, 02543-1598 USA	+1-508-457-2323	Kscanlon@usgs.gov
Dvora Hart	NOAA Fisheries Service, Northeast Fisheries Science Center, Population Dynamics Branch,166 Water Street, Woods Hole (F/NEC31), Massachusetts, 02543 USA	+1-508-495-2369 x2369	Deborah.Hart@noaa.gov
Ellen Kenchington **(Co-Chair)**	Department of Fisheries & Oceans, Ecosystem Research Division, Bedford Institute of Oceanography, PO Box 1006, Dartmouth, Nova Scotia, Canada B2Y 4A2	+1-902-426-2030	Ellen.Kenchington@dfo-mpo.gc.ca
John Loder *(by correspondence)*	Department of Fisheries & Oceans, Ocean Sciences Division, Bedford Institute of Oceanography, PO Box 1006, Dartmouth, Nova Scotia, Canada B2Y 4A2	+1-902-426-3146	John.Loder@dfo-mpo.gc.ca

NAME	ADDRESS	PHONE/FAX	E-MAIL
Carlos Garcia-Saez	Direccion General de Operacion Regional Camino al Ajusco 200, 2ª. Piso. Col. Jardines en la Montaña. Deleg. Tlalpan. DF 14210 México		

Annex 2: Agenda

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

9:00 hrs. **11** August 2011 – 16:00 hrs. **13** August 2011

US Geological Survey, Center for Marine Science, 384 Woods Hole Road, Quissett Campus, Woods Hole, Massachusetts, USA

9:00 hrs. 11 August 2011

1) Welcome and Opening Remarks

2) Introductions

Introductions of workshop attendees

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

13:00 hrs. 11 August 2011 – 16:00 hrs. 12 August 2011

4) Break-out group work for each theme

09:00 – 16:00 hrs. 13 August 2011

5) Review of report in plenary

6) Meeting adjourned at 4:00