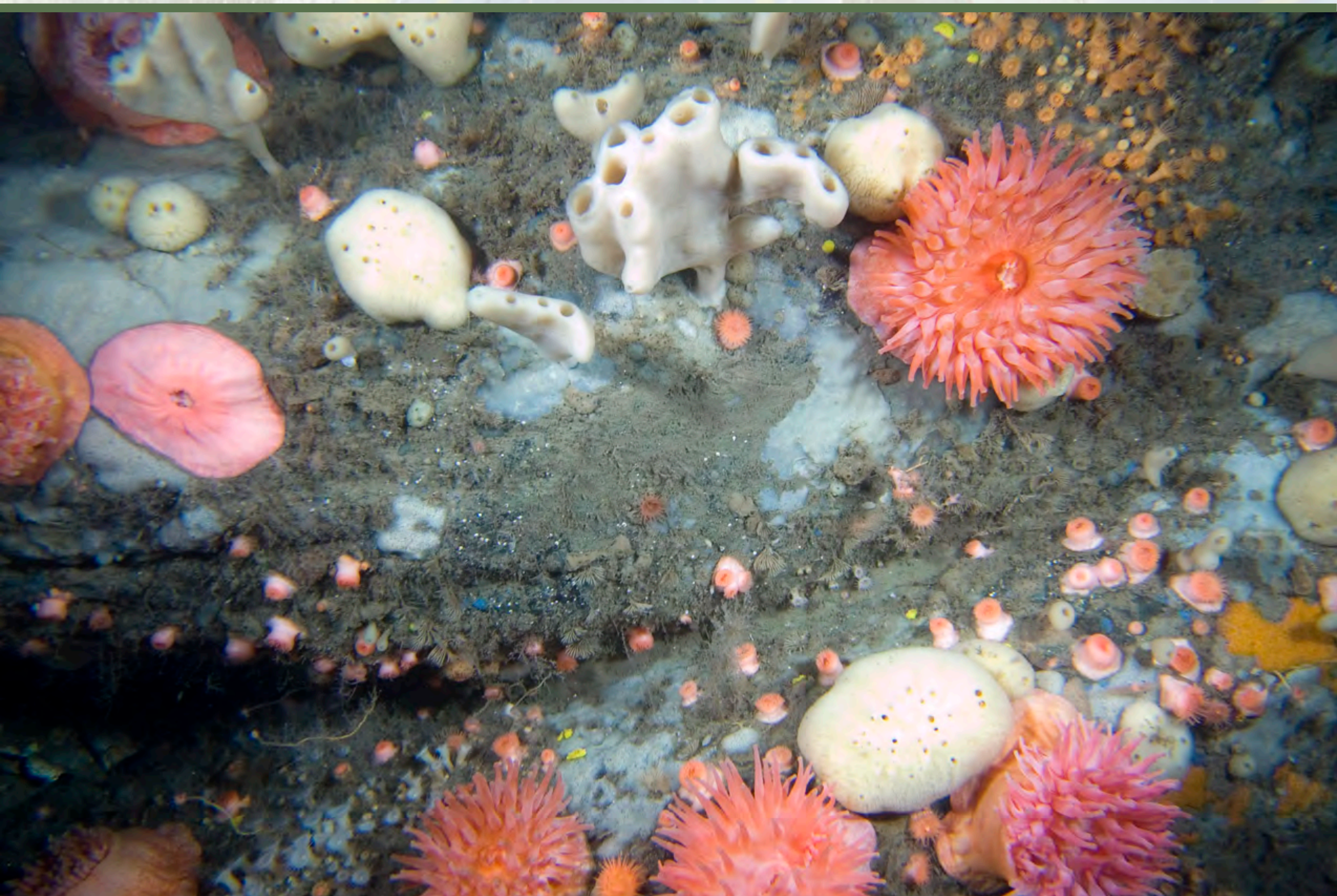
OFFSHORE ECOSYSTEMS AND HABITATS

STATE OF THE GULF OF MAINE REPORT



Gulf of Maine
Council on the
Marine Environment

October 2012

OFFSHORE ECOSYSTEMS AND HABITATS

STATE OF THE GULF OF MAINE REPORT

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Gulf of Maine Council on the Marine Environment

Fisheries and Oceans Canada   Pêches et Océans Canada

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The Gulf of Maine Council on the Marine Environment was established in 1989 by the Governments of Nova Scotia, New Brunswick, Maine, New Hampshire and Massachusetts to foster cooperative actions within the Gulf watershed. Its mission is to maintain and enhance environmental quality in the Gulf of Maine to allow for sustainable resource use by existing and future generations.

The *State of the Gulf of Maine Report*, of which this document is a part, is available at www.gulfofmaine.org/stateofthegulf.

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Cover photo: Diverse community of sponges, anemones and other attached marine animals discovered on rocky outcrops in Jordan Basin, 2005. Canadian scientists have since revisited this area and other offshore regions in the northern Gulf of Maine, investigating seabed diversity patterns as part of the Canadian Healthy Oceans network, www.chone.ca (Photo credit: Fisheries and Oceans Canada, Bedford Institute of Oceanography).

Cover map (background): Courtesy of Census of Marine Life/Gulf of Maine Area Program

1. Issue in Brief

The 115 950 square kilometre (44 770 square mile) Gulf of Maine (CSL-WWF 2006) is one of the most diverse and productive temperate marine areas in the world, and has a very complex food chain (Link et al. 2007; Sherman and Skjoldal 2002; Overholtz and Link 2006). As such, it has long attracted human attention for resource extraction, research, and pure interest and appreciation. This document summarizes existing information about the offshore waters of the Gulf of Maine, including Georges Bank and the outer Bay of Fundy. It does not deal in detail with the inner coastal shelf and its complexities, which have been presented in the *State of the Gulf of Maine* theme paper titled *Coastal Ecosystems and Habitats*. Yet the offshore Gulf of Maine oceanography and species productivity is inherently linked to the coastal ecosystems and their driving forces and pressures, adding further complexity to the dynamic state of the offshore.

To provide an overview of the offshore ecosystems of the Gulf of Maine, this document highlights some of the fundamental natural and human-induced (anthropogenic) driving forces, pressures, state, impacts, and responses (DPSIR) for the offshore habitats of the Gulf of Maine. The DPSIR framework, shown in Figure 1, allows us to better understand the biological interactions and the physical-biological interactions between the habitats and the organisms that together form the ecosystems of the Gulf.

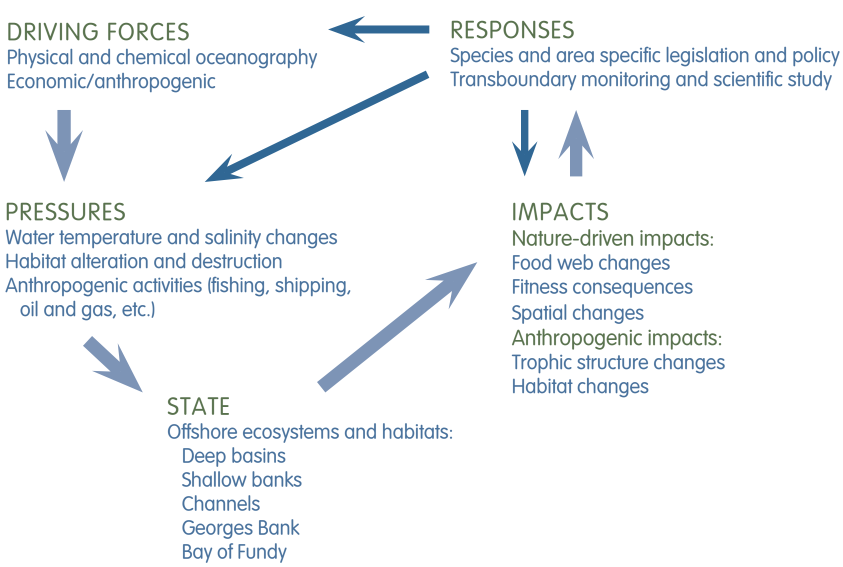


Figure 1: Driving forces, pressures, state, impacts and responses (DPSIR) for the offshore habitats and ecosystems in the Gulf of Maine. This framework provides an overview of the relationship between the environment and humans. Social and economic developments and natural conditions (driving forces) exert pressures on the environment and, as a consequence, the state of the environment changes. This leads to impacts on human health, ecosystems and materials, which may elicit a societal or government response that feeds back on all the other elements.

LINKAGES

This theme paper also links to the following theme papers:

- Coastal Ecosystems and Habitats
- Watershed Status
- Marine Invasive Species
- Climate Change and its Effects on Ecosystems, Habitats, and Biota

Although many people think of "habitat" as being a physical structure, in the open ocean it is just as much about the different water masses created by variable depths, salinities, temperatures, and currents as it is about features such as sand, canyons, and vegetation. Water masses are sometimes referred to as the pelagic (within the water column) habitats, whereas substrates and ocean floor features are key components of benthic (nearest the sea floor) habitat in the marine environment. In contrast to habitats, ecosystems are not just habitats, but also the vegetation and animals found within those habitats and all of the complex relationships that exist both among living organisms and between living organisms and their habitats. In providing this offshore ecosystem overview, focus has been given to the driving forces/pressures, current status and trends, and impacts on the benthic and pelagic components of a group of three broad key physical habitats. These habitats are:

- Shallow banks (Jeffreys, Stellwagen),
- Deep basins (Georges, Wilkinson, Jordan), and
- Channels (Northeast, Great South).

Two additional habitats have been dealt with separately because of both their uniqueness within the Gulf of Maine and the relatively greater scientific study and knowledge of these habitats. They are:

- Georges Bank, and
- Bay of Fundy.

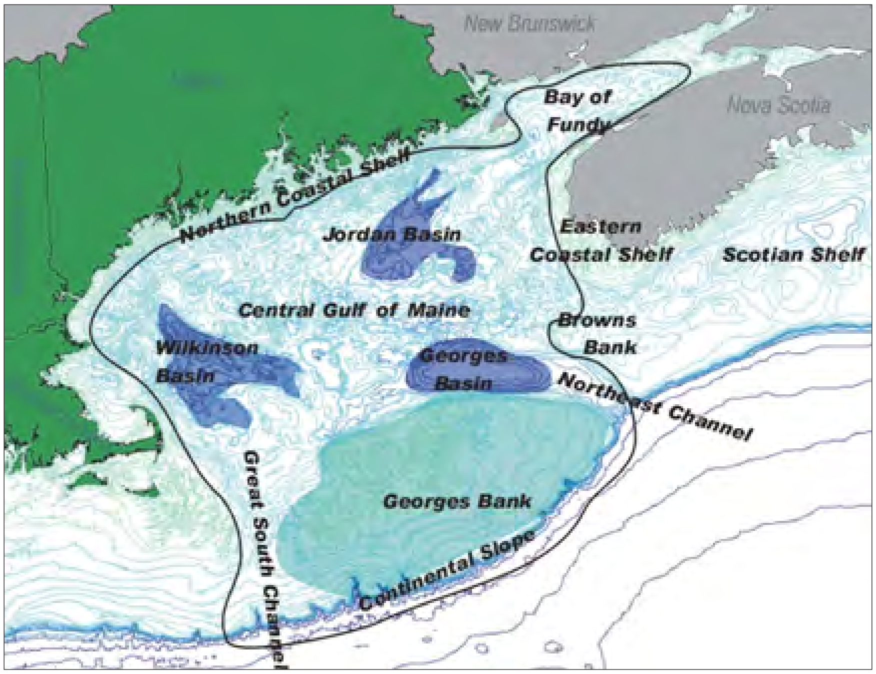


Figure 2: This bathymetric map shows the relative location of dominant bathymetric features of the Gulf of Maine, including major banks, basins, and channels. At a finer resolution, further complexity would be revealed, such as smaller banks and basins, canyons, shoals, sand wave fields, and pinnacles (adapted from USGS 2008).

2. Driving Forces and Pressures

Within the Gulf of Maine's offshore ecosystem – areas deeper than about 50 m (164 ft) in depth – the drivers and resulting pressures are complex. Drivers are of both anthropogenic and natural origin. These "driving forces" are human influences and activities as well as the natural conditions that underpin environmental change. "Pressures" are direct or indirect pressures on the functioning and quality of the environment resulting from driving forces.

2.1 NATURAL DRIVERS: PHYSICAL AND CHEMICAL OCEANOGRAPHY

The physical and chemical oceanography of the Gulf of Maine strongly influence where particular species can survive and thrive, what time of year they will reproduce and grow, and spatially where their eggs and food gets transported. The surface waters of the Gulf of Maine are strongly influenced by waters from the Scotian Shelf, while deep water from the continental slope enters the Gulf through the Northeast Channel, modulating temperatures and providing a source of nutrients to portions of the Gulf of Maine. The Eastern Maine Coastal Current carries low-salinity, nutrient-rich water along the coast of Maine, influencing the ecosystems found in that region. The Gulf Stream and associated gyres bring warmer, more saline water into the region and tend to have most influence in the fall. Frontal zones – areas where there are sudden changes in temperature and salinity of the water – occur regularly in the Gulf of Maine and tend to be areas of high biological activity. More details on the region's oceanography can be found in the *Gulf of Maine Ecosystem Overview Report* (East Coast Aquatics 2011) and *The Gulf of Maine in Context* (Thompson 2010).

The influence of various natural drivers on the Gulf of Maine, such as air temperature, freshwater inputs, and the North Atlantic Oscillation (NAO), is extremely variable both in terms of time (seasonally, or over a period of years) and space (deep water relative to surface water, Georges Bank relative to Wilkinson Basin). For example, the year to year water temperatures in the Gulf of Maine are among the most variable in the entire North Atlantic Ocean (DFO 2008), and during the year range from more than 20°C (68°F) in August to 2-3°C (35-37°F) in February–March (Friedland and Hare 2007). The seasonal patterns of light and temperature affect the stratification (layering) of the Gulf of Maine waters, nutrient availability, and thus productivity and patterns of species distribution. Whether at the scale of months or decades, the drivers that alter the physical (i.e., currents, temperature, salinity) and chemical (i.e., nutrients, dissolved oxygen) oceanography of the Gulf tend to have the greatest influence on the living organisms.

North Atlantic Oscillation (NAO)

The NAO is a fluctuation in atmospheric pressure at the surface of the North Atlantic Ocean that is influenced by movements in a southern high pressure zone near the islands of the Azores Archipelago and a northern low pressure area between Iceland and Greenland. Through the NAO and ocean currents, the Gulf of Maine is linked to environmental conditions that occur in the Atlantic Ocean as far north as Newfoundland and Labrador and as far south as the Gulf of Mexico. Over the past 30 years, the NAO index has primarily been "high," a state that promotes more warm, saline marine water from the continental slope entering the Gulf of Maine while largely excluding cold Labrador Slope water. This warming effect on the Gulf of Maine is independent of the record warm air temperatures (COOC 2007). When the NAO is "low," the reverse tends to be true and colder and fresher (less saline) water has an increased influence in the Gulf. There have only been two major cooling periods over the past decade, both relatively short (Fogarty and Trollan 2006). NAO-related trends in salinity, temperature, and water density within the Gulf of Maine have typically changed on a time scale of less than ten years from a warmer, more saline to a colder, more fresh water influence, or vice versa (Ottersen et al. 2001). Subsurface ocean temperature and salinity data show evidence of extended periods with abnormal cool and fresh ocean conditions from the late 1930s to the early 1940s and from the late 1950s to the mid-1960s. During a decadal-scale cooling and freshening of upper ocean waters in the Gulf of Maine region around the 1960s, temperatures dropped an estimated 4.63°C and salinities dropped 0.7 PSUs (practical salinity units – a measure of salt content) (Loder et al. 2001). The above example highlights the temporal variability of natural drivers of the Gulf of Maine ecosystem, which might cause changes to occur for a decade or more at a time.

Salinity and Temperature

Other oceanographic changes occur independently of the NAO. During the 1990s, surface salinity freshened (decreased) by about 0.5 PSUs across the Gulf of Maine relative to the previous decade, and deep waters of the western Gulf of Maine (Wilkinson Basin) exhibited warming during the same timeframe. The warming in Wilkinson Basin is thought to have been driven by a reduced winter cooling exchange with the atmosphere, a response tied to the freshening of the surface layer that increased the stratification of the water column that inhibited convection of atmospheric cooling into the deep layers of the basin (Mountain 2004). Seasonally during winter, the ocean releases heat to the atmosphere and the water becomes cooler. Although the air temperature is typically colder near the coastline, the outer Gulf of Maine air-to-sea temperature difference is larger because the continental slope water east of Georges Bank is much warmer than that closer to the coast. By March and April, the inner Gulf begins to receive net downward heat flux from the atmosphere to the ocean, warming as seasonal air temperature rises (Xue et al. 2000). During the summer months, solar radiation becomes the major contributor to the variability in heat exchange between the ocean and the atmosphere and corresponds to a time when layering of warm water over cooler water (thermal stratification) is strongest (Mountain et al. 1996). Because there is increased potential to trap atmospheric heat in layered water near the surface that does not mix with cooler deep water, stratification typically becomes stronger during the warm days of the summer months when the water column is already highly stratified (Friedland and Hare 2007). Based on data for the period of 1979 to 1987, it has been found that the interannual variability of surface water temperature in the western Gulf of Maine is significantly correlated with the changes in the rate of heat exchange between the Gulf waters and the atmosphere. However, in the eastern Gulf, no relationship is found in the exchange of heat between the water and the air, and instead water temperature is more greatly influenced by the different water sources entering the eastern Gulf (Mountain et al. 1996). These differences highlight the spatial variability of driving forces (in this case atmospheric temperature) influence on the Gulf of Maine. In short, the same driver may not have the same effect across all areas of the Gulf at the same time.

Freshwater Inputs

Along with the NAO and atmosphere-ocean heat exchange, freshwater inputs are a significant natural driver of environmental change in the offshore Gulf of Maine ecosystem. The combined discharge of the four largest rivers (Saint John, Penobscot, Kennebec, and Merrimack) entering the Gulf of Maine has been estimated at about 60 billion cubic metres (78.5 billion cubic yards) of freshwater per year. This freshwater "plume," by which it is often referred, has a profound influence on water properties and dynamics not just in the estuaries close to land, but also all along the Gulf of Maine coast (Xue et al. 2000). The Saint John River in New Brunswick, Canada, remains the largest river entering the Gulf of Maine, and discharges a comparable amount to the sum of the three American rivers (Geyer et al. 2004). Although the salinity variability of the western Gulf and Georges Bank appears to be more greatly influenced by local precipitation and this coastal river runoff (Mountain and Taylor 1998), the overall freshwater budget for the Gulf of Maine is dominated not by river inflow, but by the inflow to the Gulf of relatively cold, low-salinity ocean water from the north, off the Scotian Shelf (Smith 1983; Brown and Irish 1993 cited by Pettigrew et al. 1998). This inflowing current brings fresh water from the St. Lawrence River and from melting sea ice to the north (Houghton and Fairbanks 2001).

In summary, many natural drivers modify the environmental conditions associated with the physical and chemical oceanography of the Gulf of Maine. The North Atlantic Oscillation, atmospheric heat exchange, and freshwater inputs are but a few, and the spatial and temporal range of their influence can be extremely varied across the Gulf. Along with these natural drivers, economic and anthropogenic drivers also influence changes in the habitat and biota of the Gulf of Maine.

2.2 ECONOMIC/ANTHROPOGENIC DRIVERS

The ocean economy includes sectors such as fishing, aquaculture, offshore oil and gas, shipping, and coastal tourism. It also captures government services, including national defence (ocean based), fisheries management, coast guard, and marine environmental protection. Although there is currently no oil and gas industry operating within the Gulf of Maine, the petroleum resources that exist there drive much interest regarding their future potential extraction. Along with fisheries, shipping is currently a significant economic driver within the Gulf of Maine. Ports from Boston to Saint John move billions of dollars in imported and exported goods across the Gulf of Maine.

Fisheries

From the Canadian portion of Georges Bank the total annual landed value of all fish species caught in 2008 was approximately $105 million, down from the 2005 ten-year high of $150 million. However, with additional fish processing value added, the Georges Bank fishery value in 2008 topped C$168 million (DFO 2011). In 2010, New England fishery landings were approximately US$950 million dockside (NMFS 2011); generally a large proportion of New England landings are from Georges Bank (USGS 2003). The three largest value Canadian fisheries on Georges Bank are the shellfish fisheries (e.g., scallop, lobster, and crab), groundfish fisheries (e.g., cod, haddock, and yellowtail flounder), and pelagics fisheries (e.g., swordfish, various tuna species, herring, mahi mahi and various shark species). On average, the shellfish fisheries contributed approximately 77% of the annual total landed value (DFO 2011). During the period from the late 1980s to the early 2000s, many commercial fish populations on the American portion of Georges Bank declined, including cod, haddock, herring, and sea scallops, while populations of non-commercial species expanded rapidly (USGS 2003).

Shipping

The waters of the Gulf of Maine are on the Great Circle Route, an international shipping route between the eastern seaboard of North America and Europe. Boston, Portsmouth, Portland, Eastport, and Saint John are the largest shipping centers within the Gulf of Maine. Together more than 1000 large ships a year will pass through the Gulf of Maine to these ports (World Port Source 2012). More than 115 cruise ships visited the Port of Boston in 2008 (World Port Source 2012). Bilge water, grey water, sewage waste, and ballast water are all waste streams of large ocean going ships that may get disposed of within the Gulf of Maine. Considering the number of large vessels sailing across the Gulf of Maine, the cumulative impact potential is not insignificant. For example, during a typical one-week voyage, a large cruise ship is estimated to generate 790 000 litres (210 000 U.S. gallons) of sewage; 3800 m^3 (1 million U.S. gallons) of grey water (wastewater from sinks, showers, and laundries); and 95 m^3 (25 000 U.S. gallons) of bilge water (RITA 2012). Shipping poses several potential ecosystem impacts, including oil discharges, exotic organisms and pathogens introduced by ballast water, shipboard wastes (including black and grey waters), noise pollution (Coffen-Smout et al. 2001), and ship strikes of marine mammals (IMO 2002).

Other

The Gulf of Maine, with its significant resources of marine life and offshore oil and gas, is linked through exploitation to a number of social, economic, and cultural values. These values can drive how much, how quickly, and in what manner humans exploit resources. The result of this exploitation is the socioeconomic impact, both positive and negative, on the Gulf of Maine ecosystem. Although Georges Bank is known world-wide as a productive and diverse fishing ground, it also has significant petroleum resource potential beneath its seafloor. On the Canadian portion of Georges Bank, there are an estimated 60 million barrels of oil and 1.3 trillion cubic feet of natural gas, although exact amounts remain uncertain (Procter et al. 1984 cited in DFO 2011). The U.S. Bureau of Environmental Management estimates that the entire Atlantic Outer Continental Shelf, which includes the American portion of Georges Bank, has 3.82 billion barrels of oil (CLF 2012). The size and value of this potential resources has made Georges Bank an area of interest for offshore petroleum exploration and development for more than four decades (NRCan and NSPD 1999). Both the governments of Canada and the United States issued their first permits for offshore petroleum exploration on the Bank in the 1960s, and eight wells were drilled on the Bank, but were not developed because they did not yield significant product (DFO 2011). The potential interactions between the ecosystem and offshore petroleum activities have been assessed as part of a recent moratorium review on the Canadian portion of Georges Bank. Potential impacts have generally been categorized as seismic noise, drill muds, spills, blowouts and malfunctions, and produced water (DFO 2011).

Some anthropogenic impacts, such as climate change, originate far away from the Gulf waters. Yet, climate change has the potential to affect marine habitats. Atmospheric warming and melting of sea ice are altering the physical oceanography of the Gulf of Maine, while higher levels of atmospheric carbon dioxide (CO_2) may alter ocean chemistry, both of which will have effects on the ecosystem (Nye 2010, see *Climate Change and its Effects on Ecosystems, Habitats, and Biota*). For example, by changing water temperature and salinity, two key habitat components that help determine the spatial distribution of individual species, climate change will impact species distribution.

Other human activities with the potential of having ecosystem impacts are naval operations, government research, ocean disposal, submarine cables, and pipelines. Within the Gulf, the demand for aquaculture sites has led to examination of open ocean aquaculture, at least within the Bay of Fundy, as the number of viable coastal sites becomes limited. Physical constraints of water temperature and waves, the need for technology advancement, and conflicts with other uses and values, such as traditional fishing, shipping, and species at risk, are challenges to expanding the aquaculture industry to open ocean areas (Chang et al. 2005).

3. Status and Trends

As noted earlier, habitats are formed both within "water masses" and around physical structures and support a variety of communities of living organisms. Many organisms travel vast distances to the Gulf of Maine to benefit from the high productivity and diversity of habitats that exist there. Still other birds, plants, and animals spend their entire life cycle within the Gulf, finding all they need to support every stage of development. The Gulf forms a unique boundary between cold water northern species and warm water southern species. Natural fluctuations occur in the vast volumes of warm salty and cold fresh water flowing into the Gulf, influencing the diversity of species that may be found within the ecosystem. This section examines the status and trends of some of the primary habitats and their associated marine communities within the offshore Gulf of Maine. It also examines in further detail two of the prominent habitats within the Gulf, Georges Bank and the Bay of Fundy.

3.1 MARINE HABITATS

Generalized offshore marine habitats of the Gulf of Maine are pelagic (water masses) or benthic. Benthic habitats are those that are near the ocean floor, and are in part characterized by the state of the ocean floor. Benthic habitats have been categorized as banks, basins and channels.

Water Masses

The NAO, atmospheric heat exchange, and flow of freshwater into the Gulf of Maine initiate water movement both vertically (i.e., upwelling and downwelling) and horizontally (i.e., currents and gyres). Water movements, coupled with the underlying shape of the ocean floor and the variable density of the water (created by salinity and temperature differences influenced by the driving forces (as discussed in Section 2.1) form areas of mixing or layers of stratification that are relatively homogenous masses of water. Each of these water masses can be considered a habitat that may be favoured by a particular group of species that prefers the temperature, salinity, or some other characteristic of the water mass. The location and characteristics of these masses is variable over the year as the driving forces change, and this variability is part of the reason that some aquatic organisms of the Gulf of Maine migrate to different areas of the ocean throughout the year.

Spatially there are areas of the Gulf of Maine that are more likely to be vertically mixed than others. Areas of mixing create uniquely different marine habitats than areas where the water column is stratified. Generally, within the Gulf of Maine stratified waters occur where there is minimal bathymetric relief and circulation, and well-mixed waters occur where there is varied bathymetry and relatively strong ocean circulation. The eastern and southern portions of the Gulf, including the Bay of Fundy, Jordan and Georges basins, the Northeast Channel, and Georges Bank, are vertically well mixed by vigorous tidal activity. The western portion of the Gulf of Maine, including Wilkinson Basin, is less well mixed as cold fresh riverine water enters the Gulf along the Maine Coastal Current and rests on top of the more dense marine water in the western Gulf. The result is a tidally mixed eastern region separated from the stratified western region by a tidal front (Xue et al. 2000).

There are three primary sources of water to the Gulf of Maine, each with its own temperature, salinity, and nutrient regime. Concentrations of each of these flows create identifiable water masses. The marine inflow to the Gulf of Maine is the sum of two of the primary water sources receiving both relatively shallow northern inflow from the Scotian Shelf around Cape Sable and deep oceanic inflow through the Northeast Channel (Mountain 1991). These waters move predominantly in a counter-clockwise direction around the perimeter of the Gulf of Maine (see Figure 3). It has been estimated that it takes about three months for water to circulate around the periphery of the Gulf (Van Dusen and Hayden 1989). These source waters are a significant influence on marine water temperature in the Gulf of Maine (DFO 2008). Atlantic temperate slope water from the open Atlantic is warmer and saltier, while Labrador Current water is cooler, less saline, less dense, and has lower nutrients (Fogarty and Trollan 2006). Temperature, salinity, and nutrients are key water characteristics that influence what marine species will live where, and changes in the biological communities within the Gulf of Maine are expected when there are changes in the NAO.

As these offshore water sources enter the Gulf of Maine along the Northeast Channel, they appear to drive the eastern portion of the counter-clockwise Gulf of Maine gyre, one of two main gyres (prevailing circular currents) in the Gulf, and initiate the overall counter-clockwise direction of flow around the Gulf of Maine. The majority of the inflow turns southwestward near Grand Manan Island and the mouth of the Bay of Fundy, but part flows cyclonically into the Bay of Fundy before eventually leaving the Bay to move along the New England coastline (Xue et al. 2000). The Gulf of Maine gyre is influenced not only by the inflow around southwest Nova Scotia and by the inflow of dense, deep water through the Northeast Channel, but also by the spring runoff from the region's rivers and daily tides (Van Dusen and Hayden 1989). Water circulates in the Gulf gyre counter-clockwise around Jordan Basin, located at the mouth of the Bay of Fundy, and around Georges Basin, located at the head of the Northeast Channel. Vigorous tidal stirring keeps the water vertically well mixed in this eastern portion of the Gulf of Maine and the Gulf gyre (Pettigrew et al. 1998).

The third primary source of water to the Gulf of Maine is the relatively fresh water of the Maine Coastal Current. This current is driven by inputs originating from the four largest rivers entering the Gulf of Maine coastline. The Saint John River, Kennebec River, Penobscot River, and Merrimack River, along with freshwater

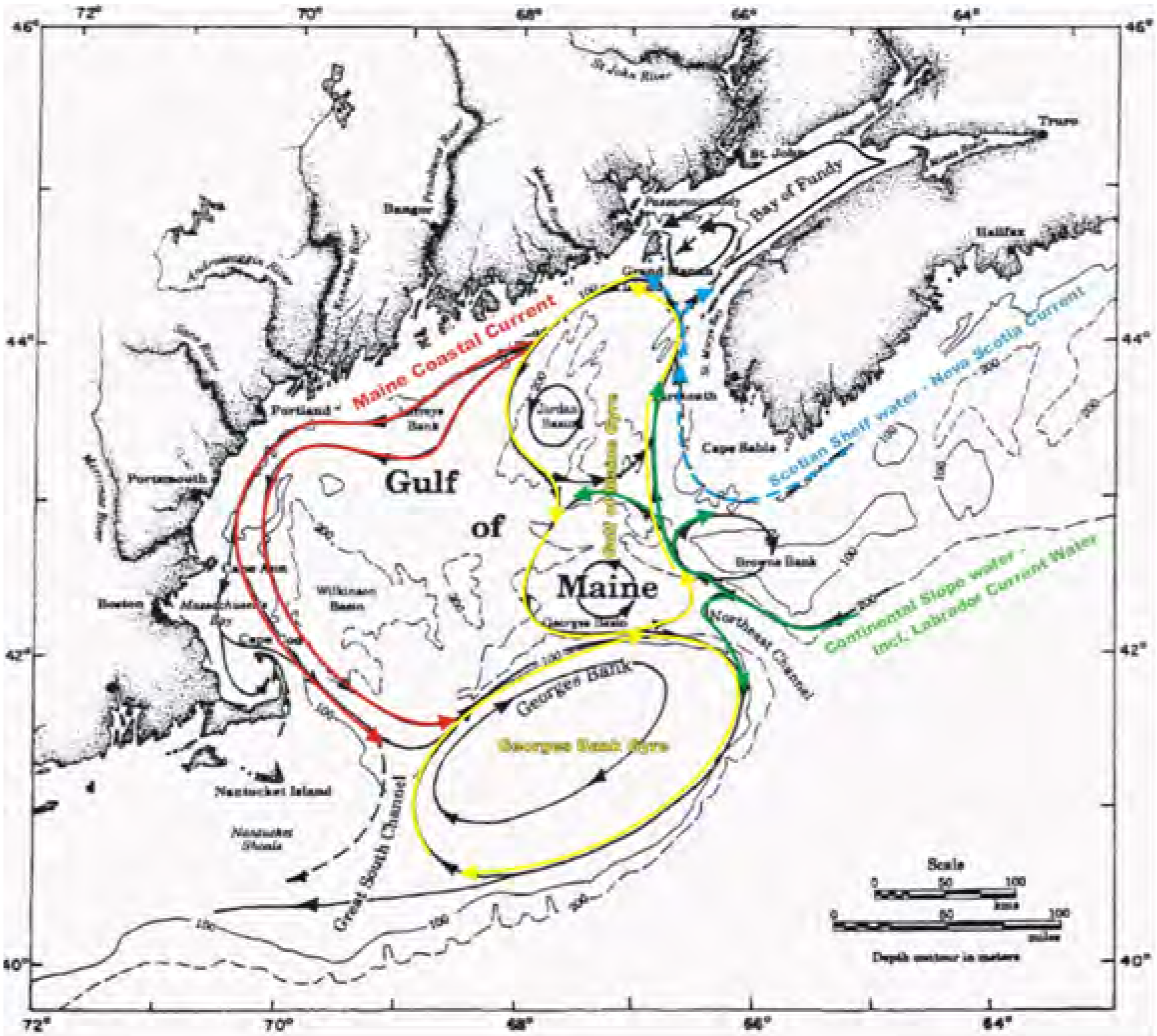


Figure 3: Schematic of springtime circulation in the Gulf of Maine based on 1994 observations. Circulation varies seasonally, annually, and with depth, but the features highlighted here are typically present and dominant (adapted from Pettigrew et al. 1998, as cited in Xue et al. 2000).

inputs of precipitation falling on the Gulf of Maine, is about 80 times less than the combined mean Northeast Channel and Scotian Shelf inflows of 400 000 cubic metres per second (Mountain 1991), yet is enough to promote movement along the Gulf of Maine coast (Xue et al. 2000).

The second main gyre in the Gulf of Maine exists over Georges Bank (Van Dusen and Hayden 1989). Along with the counter-clockwise gyre in the Gulf, the gyre over Georges Bank dominates water circulation in the Gulf of Maine (Link et al. 2007). Like the Gulf gyre, the Georges Bank gyre is also vertically well mixed due to tidal stirring (Loder and Greenberg 1986 cited in Xue et al. 2000). The Georges Bank gyre's strongest currents exist on the northward side of the Bank during summer months (Xue et al. 2000). Eggs and juvenile fish species such as cod and haddock have been noted to drift within the gyre around Georges Bank. This current both helps keep them on the Bank where conditions for young fish are favourable, and distributed around the Bank until they grow large enough to swim to other habitats within the Gulf of Maine (Lough et al. 1989).

As demonstrated in the preceding paragraphs, there are a number of water masses within the Gulf of Maine that have particular characteristics of movement, salinity, and temperature, and that may represent preferred habitats for a community of species. There have also been some widespread observable trends in some of these characteristics. For example, there has been a long-term trend in sea surface temperature range (the difference between the coldest and warmest temperature of the year). A decreasing range was observed at the beginning of the twentieth century, followed by an increase in range from 1920 to the late 1980s. The range has remained high through to the present. Although the mean annual sea surface temperature in the Gulf of Maine is currently trending below historical levels (1854–2005), the intensity of summer warming is at or near its highest levels, and winter sea surface temperatures are remaining relatively constant and cool (Friedland and Hare 2007). Spring warming rate has increased during the last half of the twentieth century on the order of 0.5°C per month. A regime shift in spring warming rate was identified around 1940 in the eastern Gulf of Maine, although not in the western Gulf or on Georges Bank. Conversely, autumn cooling rates have decreased over the time series (1854–2005) on the order of 0.5°C per month. Notably, a shift to more rapid fall cooling occurred around 1987 in five regions of the northeastern continental shelf, including the western Gulf, suggesting a relatively widespread phenomenon (Friedland and Hare 2007).

GYRES – A PHYSICAL BIOLOGICAL LINKAGE

An oceanic gyre is a prevailing circular current. Although spatially one of the smaller gyres in the Gulf of Maine, the Bay of Fundy gyre has large vertical tidal velocities which are thought to be a major factor in the nutrient pump that brings deep water nutrients to the surface water. When nutrients reach sunlight in the photic zone close to the surface, they contribute to phytoplankton growth. The physical shape of the Bay of Fundy promotes the formation of a gyre that is linked to exceptionally high biological productivity at the mouth of the Bay of Fundy.

Along with observed temperature trends, there have been salinity trends documented in the Gulf of Maine. Salinity measurements have been taken since 1924 at a fixed station near St. Andrews, New Brunswick, adjacent to the entrance of the Bay of Fundy. For surface salinity, there appears to have been a decrease in salinity from the mid-1970s to the mid-1990s (low in 1996), followed by an increase to 2002. This was followed again by a decline (DFO 2008). This pattern is consistent with the pattern of salinities measured by the Northeast Fisheries Science Center on the continental shelf (Gulf of Maine) since the 1970s (Ecosystem Assessment Program 2009).

WHAT LIVES IN THE GULF?

Some 3317 species of flora and fauna have been inventoried from the Gulf of Maine (Valigra 2006). Approximately 2350 of those are also found in the Bay of Fundy (Census of Marine Life 2007). More than 652 species of fish have been documented living in, or migrating through, the Gulf of Maine. It is estimated that 87 (13%) of these fish species are resident (live their whole lives) within the Gulf of Maine (Valigra 2006). At least 14 species of coral live in the Gulf of Maine (Mortensen et al. 2006).

Table 1. Surface area, total volume of water overlying the feature, and mean depth of the Gulf of Maine ecosystem bathymetric features (from Wolff and Incze 1998). Total volume is all water below the surface for the area defined by each region.

REGION	NAME	SURFACE AREA (km^2)	TOTAL VOLUME (km^3)	MEAN DEPTH (m)
2	Browns Bank	2951	268	-85
3	Eastern Coastal Shelf	7760	481	-57
4	Bay of Fundy	12 544	920	-68
5	Northern Coastal Shelf	14 116	832	-54
6	Southern Coastal Shelf	8203	457	-51
8	Georges Bank	41 934	3353	-75
9	Georges Basin	4110	1246	-298
10	Jordan Basin	6694	1524	-222
11	Wilkinson Basin	7078	1655	-228
12	Central Gulf of Maine	59041	10357	-170
	GULF OF MAINE	164 431	21093	-131

Although water masses are a critical habitat component for many marine species, substrates and the shape of the ocean floor also play a significant role in where particular communities of organisms will be found. Even though the morphology of the Gulf of Maine is spatially dominated by the Central Gulf, a 90 000 km^2 (35 000 $miles^2$) inner lowland area with an average depth of 150 m (490 ft), a number of large features exist as shown in Table 1. From the shallow banks to the deep basins, a diversity of physical habitats influences the composition of biological communities.

Both demersal (near bottom) and pelagic (mid-to-upper water column) fish communities can be found in identifiable water masses within the ocean that have their own range of temperature and salinity, augmented by other characteristics such as degree of mixing, level of nutrients, and pattern of circulation. A recent study based on 35 years of groundfish data (1968-2002) for the Gulf of Maine found that fish are distributed according to habitat parameters of depth and temperature, rather than according to substrate type in both autumn and spring (Methratta and Link 2006). The results further indicate that four separate demersal "communities" exist within the Gulf of Maine, as shown in Table 2. The results also show that the fish communities are not always seeking consistency in either depth or temperature, but rather follow a consistent pattern of depth and temperature that may mean moving from cold to warm water or shallow to deep water.

Table 2: Four "community" groups have been identified from a 35-year time series study of 24 demersal fish species within the Gulf of Maine. These groupings indicate a seasonal preference for temperature and depth over substrate type. Adapted from Methratta and Link (2006).

	SEASONAL HABITAT KEYS	DEMERSAL SPECIES
Community 1	• Remained in relatively deep waters in both autumn and spring. • Experienced the relatively cooler portion of the region in the autumn and the relatively warmer portion of the region in the spring.	White hake, silver hake, Acadian redfish, goosefish, witch flounder, thorny skate, and pollock.
Community 2	• Remained in relatively shallow habitats in both seasons. • Experienced wide temperature fluctuations.	Winter flounder, yellowtail flounder, winter skate, little skate, windowpane, longhorn sculpin, and sea raven.
Community 3	• Moved from shallow areas in the autumn to deep areas in the spring. • Maintained relatively warm waters.	Spiny dogfish, summer flounder, fourspot flounder, barndoor skate, and red hake.
Community 4	• Travelled from the deep portion of the region in the autumn to the shallow portion of the region in the spring. • Maintained relatively cool waters.	Atlantic cod, haddock, American plaice and ocean pout.

Shallow Banks and Associated Communities

The Gulf of Maine banks are shallow, offshore areas. There are a number of these offshore bank areas around the Gulf of Maine, including Stellwagen Bank and Jeffreys Bank. Unlike Georges Bank of the outer continental shelf, most of these shallow bathymetric features are found on the central continental shelf, and are located a short distance offshore in the western Gulf of Maine. Stellwagen Bank, for example, is located some 40 km (25 miles) from the coast, and is a glacial deposit of sand, gravel, and rock that today lies a mere 20 m (65 ft) below the surface (NOAA 2012b). Light typically penetrates to the sea floor through the water column, above these shallow geological features. Waves and currents tend to keep the water over the banks well mixed, at least for certain periods of the year.

Even now, surface sediments and features of the banks are being reworked and reshaped by tidal and storm-generated currents. Over time, the shallow areas affected by these processes have become coarser as sand and mud are removed and gravel remains (Butman et al. 2004). Ocean substrate grain size influences the size of benthic organisms and infauna, as well as which species might attach to, forage over, and spawn on the surface of the substrate (Etter and Grassle 1992). Surficial geology of the banks, which form a variety of habitats, is a result of the basic geological structure of the banks and their interaction with ocean processes. Like basins and channels, the Gulf of Maine banks attract their own community of living organisms. One group within that community is the demersal fish living at or near the bottom of the ocean. Based on depth alone, Mahon et al. (1998)

identified three North Atlantic assemblages of demersal fish that exist in the Gulf of Maine in waters less than 200 m (655 ft) deep, or primarily the Central Gulf of Maine including the banks but excluding the deep basins. Mahon et al. (1998) suggested that the demersal fish assemblages in the Gulf of Maine should be interpreted as quite loose in nature and potentially adaptable entities rather than as rigid ecological constructs because the assemblages that were identified were persistent in composition through time, but appeared to shift in location.

Although many species of fish will move from the banks to deeper water, or vice versa, during different times of the year when water masses over the banks change, Methratta and Link (2006) identified a demersal community of winter flounder, yellowtail flounder, winter skate, little skate, windowpane, longhorn sculpin, and sea raven that remain in relatively shallow waters year round. These species also experience wide temperature fluctuations on a seasonal basis, with warmer temperatures in the autumn and cooler temperatures in the spring (Methratta and Link 2006).

Deep Basins and Associated Communities

Basins are some of the deepest areas of the Gulf, and typically are more than 200 m (655 ft) deep. Because of their bowl-like structure, basins tend to hold a deep, stratified layer of cold saline water, have little to no current movement, have virtually no light penetration to the sea floor, and have very fine-grained silt and mud surficial sediment. These characteristics influence what organisms will be found in basins. The deepest point in the Gulf of Maine is at the bottom of Georges Basin, some 377 m (1235 ft) deep (Backus and Bourne 1987). Although a number of deep basins exist within the Gulf of Maine, only 1.5% of the Gulf is deeper than 300 m (985 ft) (Wolff and Incze 1998). Georges Basin, Wilkinson Basin, and Jordan Basin are the three largest basin features in the Gulf, and comprise approximately 11% of the area of the Gulf of Maine. Numerous other (20+) smaller basins can be found within the Gulf, including the Murray Basin, Grand Manan Basin, Rogers Basin, Howell Basin, and Crowell Basin. In total, basins make up about 30% of the floor area of the Gulf of Maine (Backus and Bourne 1987).

Chemical analyses have found continental slope water from east of Georges Bank at the bottom of the Wilkinson Basin (Fairbanks 1982). This deep-water layer is only located in a few deep basins and is rarely, if ever, vertically mixed with the layers above. Jordan Basin and Georges Basin, located in the eastern Gulf of Maine, are linked to each other through the circulation of the Gulf gyre. The bottom temperatures in these two eastern basins are warmer than the bottom temperature in the western Gulf's Wilkinson Basin, which is influenced in part by the Maine Coastal Current. The eastern basins exhibit a single-season, minimum bottom temperature in late spring, whereas Wilkinson Basin in the western Gulf of Maine demonstrates both a spring minimum and a second, cool autumn period. Observations of marine data indicate that when the winter transfer of temperatures through the water in Wilkinson Basin is stronger, the resulting deep-layer temperatures are colder (and vice versa), and the likelihood of deep winter mixing in the western Gulf of Maine is greater when cold saline coastal waters drop deep into the basin (Taylor and Mountain 2009).

Mud accumulates where still-water conditions favour the slow settling of small particles or their entrapment by sessile (slow-moving) organisms, such as polychaete worms. For this reason, a thick layer of mud sediments has been deposited in Georges Basin (Backus and Bourne 1987). In fact, present day tidal and storm-generated currents continue to erode and transport sediments from the shallow areas of the Gulf of Maine into the deeper basins. This process means the deeper basins have been built up as they receive the eroded sand and mud (Maine Geological Survey 2005; Butman et al. 2004), although thick deposition of postglacial mud (King and Fader 1986) in the relatively deep basins has created proportionally small changes in bathymetry. These muddy regions are the most common areas on the continental shelf in waters deeper than 100 m (330 ft) (Barnhardt et al. 1996), and poorly sorted silt (mud) can be found in most Gulf of Maine basins (Backus and Bourne 1987).

Scientists have identified a demersal fish community within the Gulf of Maine that tends to remain in relatively deep waters (>200m or 655 ft) in both autumn and spring. In such areas, demersal fish experience a relatively cooler portion of the region in the autumn and a relatively warmer portion of the region in the spring. This deep-water community includes white hake, silver hake, Acadian redfish, goosefish, witch flounder, thorny skate, and pollock (Methratta and Link 2006). As shown in Table 3, two assemblages of demersal fish have been identified by Mahon et al. (1998) based on depth and temperature that spend a portion of the year in deepwater. Although fish and shellfish tend to be the marine organisms for which the most spatial data are available within the Gulf of Maine, a host of other algae, plants and animals also occupy deep water habitats. For example, at least 14 species of coral live in the Gulf of Maine, and several have been found in the deep basins such as Jordan Basin (DFO 2006; Mortensen et al. 2006).

Table 3: Two deep water assemblages of demersal fish identified by Mahon et al. (1998) based on data from between 1975 and 1994. The assemblages were derived from the 108 most abundant demersal species in the North Atlantic and were based, in part, on the depth of water in which they were found.

DEPTH CLASS	DEMERSAL FISH ASSEMBLAGE	BOUNDARY RELEVANCE TO THE GULF OF MAINE	PRIMARY ASSEMBLAGE SPECIES	
>200m	Temperate deepwater	From the Gulf of Maine northwards; the Gulf of Maine is the approximate southern extent.	Marlin - spike Black dogfish Atlantic argentine	Longfin hake Barracudinas Roughnose grenadier
>200m	Southern deepwater	From the Gulf of Maine southwards; the Gulf of Maine is the approximate northern extent.	Blackbelly rosefish Offshore hake Shortnose greeneye Shortfin squid	Buckler dory Beardfish Slackjaw cutthroat eel Armoured searobin

Channels and Associated Communities

Two large channels, the Northeast and Great South channels, lie east and west of Georges Bank, providing passageways from the Gulf of Maine to the open Atlantic Ocean (Backus and Bourne 1987). The channel areas, shown in Figures 2 and 3, are predominantly more than 100 m (330 ft) deep and, in some locations, may be even deeper than the basins. However, these deep offshore channels have the added feature of significant water velocities and areas of exposed bedrock or coarse geological substrates not typical of basins. A "channel" function is performed by the Northeast and Great South channels, circulating ocean water into and out of the Gulf of Maine respectively. The sill depth (shallowest cross section) of the Northeast Channel is 230 m (755 ft) below the ocean surface while the considerably shallower sill of the Great South Channel is only about 75 m (245 ft) below the ocean surface (Backus and Bourne 1987). Warm slope waters enter the Gulf of Maine from the edge of the continental shelf through the bottom of the Northeast Channel at depths >100m (330 ft). This is a stark contrast to the cold Labrador Shelf water that enters the Gulf of Maine through the upper water column of the Channel (Houghton and Fairbanks 2001).

Sand, transported by modern tidal and storm generated currents flowing north to south out through the Great South Channel, form large east-west trending dunes and ridges typically 5 to 10 m (15-33 ft) in height (Valentine et al 2002; Todd et al. 2001). During glacial times, the sea floor of the Northeast Channel was extensively scoured by the keels of icebergs. Under the influence of strong tidal and storm generated currents, fine grained sediment has been winnowed from the coarse sediment of these relict iceberg furrows, leaving a gravel pavement with cobbles and boulders over much of the seafloor (Todd et al. 2001).

The Northeast Channel is home to a community of organisms that are not typically found in great numbers within the Gulf of Maine. This area has the highest known density of large seacorn octocorals (*Primnoa resedaeformis*) and bubblegum coral (*Paragorgia arborea*) in Atlantic Canada (DFO 2006). These corals are more abundant on the western side of the Northeast Channel, presumably due to a combination of favourable environmental factors that include a high concentration of food particles in circulating water. In a study of corals around Nova Scotia, the highest abundance of corals were characterized by a depth greater than 400 m (1310 ft), a maximum water temperature less than 9.2°C, and a relatively high percentage coverage of cobble and boulders (Mortensen et al. 2006). The presence of these corals also appears to attract its own unique community of other organisms. One hundred and fourteen invertebrate species were recently found associated with the corals in the Northeast Channel. The most frequently occurring associated community of species included an unidentified encrusting white sponge and three species of sea anemones. It has also been noted that redfish were almost four times more common in video sequences of corals of the Northeast Channel than in sequences with boulders but no corals (Metaxas and Davis 2005; Mortensen et al. 2006).

3.2 GEORGES BANK

Georges Bank is a prominent marine habitat within the Gulf of Maine, and as such is discussed separately from, and less generically than the previous shallow banks habitat section. The features and organisms of Georges Bank are some of the most studied in the offshore Gulf of Maine. Georges Bank is a bedrock cuesta: an area of gently tilted sedimentary rocks that have a steep slope on one side exposed as a cliff or escarpment. It is similar in this regard to other outer continental shelf banks off Nova Scotia (Davis and Browne 1996a). The 28 800 km^2 (11 120 square mile) offshore bank is often considered its own biogeographic area within the Gulf of Maine because of its relatively unique characteristics (Wolff and Incze 1998). With its ovoid shape, the most southwesterly point of Georges Bank is bounded by the Great South Channel and its northeasterly tip is bounded by the Northeast Channel.

Georges Bank is the shallowest part of the offshore Gulf of Maine, with approximately 50% of its area being shallower than 60 m (200 ft) (Backus and Bourne 1987). It rises to within 30 m (100 ft) of the ocean's surface on the northern edge at a location called Georges Shoal (Backus and Bourne 1987). The shoal is a series of sand ridges that run in a northwest-southeast trending direction. In addition to the shoals, there are overlying sand waves patterns (Twichell et al. 1987 cited in Lynch and Naimie 1993). Gravel dominates the remainder of the Bank (Todd et al. 2001), and a series of eleven incisions exist between the outer edge of the Bank and the open Atlantic. Oceanographer Canyon and Lydonia Canyon are but two of the incisions, known as submarine canyons, that can be up to 1 km (0.62 miles) deep (Backus and Bourne 1987).

On Georges Bank, sediment type has been found to have significant effect on the diversity, total abundance, and total biomass of species living both within and on top of the seafloor. The greatest number of different species has been found in biogenic sands, while minimum richness was observed in underwater mineral sand dunes (Thouzeau et al. 1991). Biogenic sands contain skeletal material of marine plants and animals such as clams and sea snails. According to Thouzeau et al. (1991), six communities of organisms are associated with two major substrates (biogenic sand-gravel and sand-shell fauna) on Georges Bank. The biogenic sand-gravel assemblage of the northeastern bank area includes an abundance of suspension-feeding organisms that stay in one place (i.e., barnacles, tunicates, sponges, non-burrowing bivalves, and tube-dwelling polychaete worms). A number of species are exclusive to the biogenic substrate, such as the brittle star *Ophiura sarsi*, Icelandic scallop, Arctic salt water clam *Hiatella arctica*, Arctic moonsnail, the arctic mollusc *Margarites costalis*, boreal topsnail, the tunicate sea peach, pink shrimp, and spiny lebbeid shrimp. The typical fauna of the sand-shell substrate is found on most of the southern half of Georges Bank. Ocean quahog and common sand dollar are the common species of this community, while the sea anemone *Actinothoe gracillima*, sand coral, the hermit crab *Pagurus arcuatus*, Atlantic surf clam, bamboo worm, and sea mouse worms are also typical

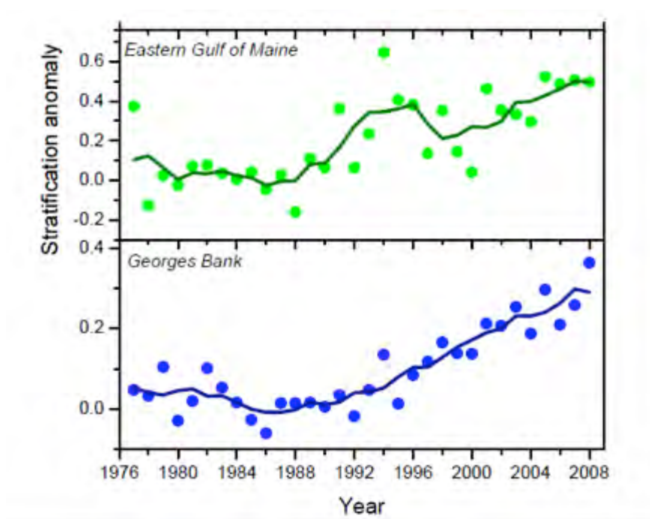
(Thouzeau et al. 1991).

Thouzeau et al. (1991) noted that a total of 140 species of large invertebrates have been identified on eastern Georges Bank. Some 76% are part of the epibenthic taxa, or organisms living on the surface of the sea floor. Bivalves are both the most abundant and have the greatest biomass. The large number of suspension feeders on Georges Bank is in part a reflection of the Bank having virtually the highest annual total primary production (phytoplankton) on the U.S. northwest Atlantic shelf (Thouzeau et al. 1991), a significant food source for suspension feeders. The strong tidal forces on the Bank, coupled with topographic features, result in the establishment of a circular current (gyre) that supports a partial retention of planktonic organisms. In addition, the currents also facilitate the upwelling of nutrients onto the Bank and into the photic zone, leading to enhanced plankton production that supports a diverse food web (DFO 2011; Backus and Bourne 1987).

Important spawning areas for giant sea scallop are found on gravel lag areas of Georges Bank (Todd et al. 2001), and the Bank has supported the world's largest natural sea scallop resource (Marino and Stokesbury 2005). Although there is an abundance of organisms that live on the substrates of Georges Bank, most show sharp decreases in density and biomass in deeper water (Thouzeau et al. 1991), limiting their presence in the offshore Gulf of Maine primarily to the top of Georges Bank. Although the populations of these bottom-dwelling organisms are a distinctive characteristic of Georges Bank, the area also provides permanent or temporary habitat for many of the life stages of various fish, including bluefin tuna and swordfish, seabirds, marine mammals, turtles, and corals (DFO 2011).

A study of water column stratification on Georges Bank has shown that each year, the mean date of first transient stratification coincides with the historical maximum abundance of early-stage (<6 mm) cod larvae and copepods. Historical maximum abundance of haddock larvae occurs on Georges Bank at the same time that permanent or "seasonal" stratification is established (Bisagni 2000). These results suggest that a physical-biological interaction is at play where water column stratification may influence the recruitment of zooplankton, fish eggs and larvae to southern Georges Bank. Furthermore, increased concentrations of chlorophyll (produced by phytoplankton) and zooplankton are often associated with the development of seasonal stratification on southern Georges Bank during the spring (O'Reilly et al.

Figure 4. Trends in stratification for the eastern Gulf of Maine and Georges Bank (M. Taylor, unpublished data, Northeast Fisheries Science Center, Oceanography Branch, 2009).



1987; Meise and O'Reilly 1996 cited in Bisagni 2000). If the physical stratification of the Georges Bank water column promotes a concentration of phytoplankton and small zooplankton (plankton blooms), such a linkage is likely an important factor controlling growth and survival of larger zooplankton and larval fish at lower trophic levels of the food chain. While many of the biological processes occurring on Georges Bank appear to be linked in some way to physical processes and hydrography, much more work needs to be completed before exact mechanisms can be proven (Mavor and Bisagni 2001). However, changes in stratification trends, with increased stratification in the eastern Gulf of Maine and Georges Bank since the mid-1980s (Figure 4), are likely to drive biological changes.

3.3 BAY OF FUNDY

Like Georges Bank, the Bay of Fundy is a prominent marine habitat within the Gulf of Maine, and as such is discussed separately from, and less generically than other marine habitats. The Bay of Fundy is a narrow, funnel-shaped body of water that lies between Nova Scotia and New Brunswick. This large, macro-tidal (having tides greater than 4 m or 13 ft) embayment and its oceanography are closely linked to the greater Gulf of Maine (Aretxabaleta et al. 2008; Chang et al. 2005; Desplanque and Mossman 2001; Xue et al. 2000). It is 270 km (168 miles) long and 60 km (37 miles) wide at its widest point, and encompasses offshore oceanic features such as shallow banks and deep channels (Willcocks-Musselman 2003). The Bay can be divided into two large regions, the inner Bay and the outer Bay, based on oceanographic parameters and biotic assemblages (Hunter and Associates 1982). The outer-Bay component is considered part of the offshore Gulf of Maine. Also called the "mouth" of the Bay of Fundy, this area is more oceanic than the inner Bay of Fundy, with cold summer and warm winter temperatures, high current velocities, and high salinity. The sea floor of the outer Bay consists of exposed bedrock and a coarse sand-and-gravel substrate sorted by tidal currents (Davis and Browne 1996b).

The defining characteristic of the Bay of Fundy is its gigantic tides, ranging from a mean height of 5 m (16 ft) in the outer Bay to a maximum 16 m (52 ft) in the

THE LIVING REEF

A biogenic (composed of living and dead marine organisms) type of reef that is found in the Gulf of Maine is the horse mussel reef. Bivalve reefs are an important linkage between pelagic (mid to upper water column) and benthic (near bottom) environments. Preliminary studies show that horse mussels are mostly limited to harder, more stable gravel/cobble, gravel/scallop bed, and mottled gravel substrates, but also to sand with bioherms. Bioherms are raised features formed by the horse mussels growing on megarippled sand. The mussels grow faster or slower depending on which type of substrate they grow on (Wildish et al. 1998). Although horse mussel reefs have been identified throughout the Bay of Fundy, little is known about their status at this time (Wildish and Fader 1998).

furthest reaches of the inner Bay, the highest in the world (Desplanque and Mossman 2001). The combination of strong tidal currents and complex bottom topography results in tidal rips, whirlpools, upwelling, and intense mixing throughout the region (Breeze et al. 2002), particularly in the outer bay "Bay of Fundy" gyre (Aretxabaleta et al. 2008). The mixing "pumps" nutrient-rich water from deep in the water column towards the surface of the Bay and the daily sunlight (Pettigrew et al. 1998 cited in Xue et al. 2000). As the nutrients reach the sunlight, they are taken up by phytoplankton, thus promoting growth at the base of the food chain. In this manner, the physical attributes of the outer Bay of Fundy are linked to its biological productivity, supporting a diverse intermediate (TRAC 2006) and top trophic level community (NOAA 2006).

Erosion has significantly deepened the sea floor in some places within the Gulf of Maine (Shaw et al. 2002), and even far offshore it is possible for water movement to resuspend ocean floor sediments. Suspended sediment concentrations reach a high of 500–1000 ug/l on the top of Georges Bank during the winter (Backus and Bourne 1987), likely the highest concentration in central and outer shelf regions of the Gulf of Maine. However, in comparison, suspended sediments within large portions of the inner Bay of Fundy may be 100 to 200 times higher during every tidal cycle (Greenberg and Amos 1983; Swift et al. 1971). At the mouth of the Bay of Fundy, it is thought that the strong tidal currents associated with the large tidal range within the Bay may have eroded older muddy sediment and prevented new material from accumulating (Maine Geological Survey 2005). The significant water movements have aided in the formation of fields of sand waves that are 4-12 m (13-40 ft) high and 0.75 km (0.45 mile) long in the south central portion of the Bay, an area known as the Margaretsville Dunefield (Percy et al. 1997). The sorted substrates of the outer Bay of Fundy provide a diversity of habitats for communities of marine organisms, such as a sand bottom community that primarily includes free moving species such as sea urchin, starfish and fish (Hunter and Associates 1982), and a sixteen-species sublittoral hard substrate sponge community near Grand Manan Island dominated by *Isodictya deichmannae* and *Eumastia sitiens* (Ginn et al. 2000).

4. Ecosystem Impacts

Ecosystem impacts are generally very challenging to fully quantify and understand because of the complex linkages and biological interactions that exist within an ecosystem. Impacts to an ecosystem can be natural or anthropogenic, and result from alteration of one or more ecosystem drivers. By altering one of the driving forces, pressure is placed on the functionality or quality of the environment that may result in measurable or observable changes. This section presents a sampling of known ecosystem impacts in the Gulf of Maine. Impacts have been categorized as natural or anthropogenic, although it is not always possible to clearly attribute them to a single category.

4.1 NATURAL IMPACTS

Given the magnitude of human influence on the natural ecosystem of the Gulf of Maine, from centuries of fishing to global climate change, it becomes difficult to determine what impacts are natural in the strictest meaning of the word. However, the following are observed impacts and changes that seem to be predominantly influenced by natural drivers, or at least are not directly linked to anthropogenic drivers.

Food Web Changes

Atlantic herring has long been a key forage fish, as well as a commercial fish species within the Gulf of Maine. Herring biomass fluctuated greatly during the period 1977–2002, primarily because of chronic overfishing in the 1970s followed by a recovery in the 1990s (Overholtz and Link 2006). Along with the herring recovery there has been a change in food web interactions between species. Marine mammals increased their consumption of herring in the Gulf of Maine to the point where they consumed a roughly equal amount as demersal piscivorous fish (fish that eat fish) (Figure 5). Consumption of herring by these natural predators is now potentially larger than that of the commercial fishery in some areas of the Gulf of Maine. This is a significant change from the early 1990s when fish were the dominant natural predator of herring, accounting for approximately 70% of predation, and nearly three times that eaten by marine mammals. The change is likely to have impacts on energy flow through the ecosystem, and a failure to consider these changes may lead to an over-optimistic picture of how many fish the commercial herring fishery can harvest. If herring were overfished, important trophic interactions would be disturbed, and an important link in the Gulf of Maine food web significantly altered (Overholtz and Link 2006).

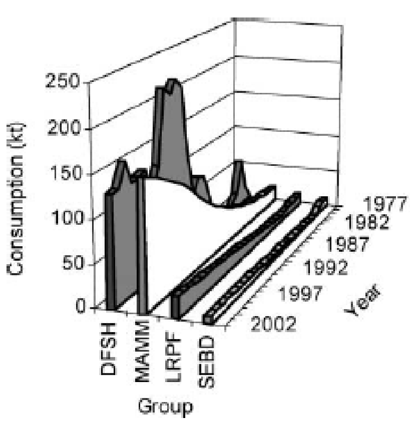


Figure 5. Consumption of Gulf of Maine-Georges Bank herring by the four groups of predators (DFSH - demersal fish; MAMM - marine mammals; LRPF - large pelagic fish; SEBD - seabirds) during the years 1977–2002 (Overholtz and Link 2006).

Although the previous example involves food web impacts at higher trophic levels, impacts at the base of the trophic structure can have potentially far reaching implications for the entire ecosystem. Ottersen et al. (2001) have shown that the North Atlantic and surrounding regions display a biological response not just at the species level, but also at the population and community levels, to NAO-influenced climatic variability (a natural driver). They have demonstrated how NAO-influenced changes ripple through trophic levels of the ecosystem from primary production to herbivores to predators, influencing growth, life history traits, and population dynamics along the way. For example, it has become apparent based on the analysis of 40 years of collected plankton data that plankton abundance and bloom timing within the Gulf of Maine changed significantly around 1991. At that time phytoplankton abundance increased, zooplankton abundance decreased, and the bloom of early stages of important zooplankton species came later in the year. It has been suggested that these changes were related to changes in the Labrador Current (Sameoto 2004), a water mass known to be influenced by the NAO. Similarly, since the late 1970s, the phytoplankton colour index from the western Gulf of Maine continuous plankton recorder data has shown an overall decline in colour (and by proxy larger phytoplankton). Such decline in larger phytoplankton has important implications for food webs in the ecosystem and may indicate a shift to smaller phytoplankton in recent decades (e.g., smaller dinoflagellates) (Ecosystem Assessment Program 2009). The implications include a change in the balance of how energy is transferred by phytoplankton through one of three mechanisms (benthic production, microbial loop, and large zooplankton grazing) to other organisms.

Fitness Consequences

The abundance of a particular species does not alone indicate the health of the population, and natural impacts can affect health of individuals and populations. Fitness of a species, measured in several ways such as health and size of individuals, can have a significant impact on the ecosystem. A recent example of this was apparent after an assessment of fat and oil content of bluefin tuna caught in the Gulf of Maine between 1991 and 2004 indicated a decline in marketable quality. The fat and oil content is reflective of a significant change in the cellular condition of these fish. Northern bluefin tuna are now seasonally arriving in the Gulf of Maine in a leaner condition, and are not increasing their fat stores while here on the feeding grounds as they did during the early 1990s (Golet et al. 2007). Herring are a primary food for tuna in the Gulf of Maine, and herring abundance was at historically high levels during the 1990s, which would suggest food could not be an issue in the decline of fat stores in tuna. Yet, it was determined that herring was experiencing an apparent decline in energy density (joules of energy per gram of fish weight) and condition (weight of a fish at a given length) that is believed to have been associated with limited abundance at that time of the copepod *Calanus finmarchicus* upon which herring feed (Pershing et al. 2012). The deterioration in the condition of tuna in the Gulf of Maine is thought to be related to the lower observed energy density of herring (Diamond and Devlin 2003), meaning the bluefin were getting less energy while eating the same number of fish. A coincident decline in northern bluefin tuna and Atlantic herring condition in the Gulf of St. Lawrence indicates that similar changes are occurring not only in the Gulf of Maine, but also in other Northwest Atlantic shelf systems (Golet et al. 2007).

Since herring is a keystone prey species not just for predator fish species like the bluefin tuna, but also mammals and birds within the Gulf of Maine ecosystem (Overholtz and Link 2006), the variable energy density of Atlantic herring has significant potential to have broad fitness consequences throughout the food web, for example, a number of seabird species feed on herring within the Gulf (Overholtz 2006). During periods when herring have been the dominant prey, the breeding success of both Arctic and Common Tern at the mouth of the Bay of Fundy has been positively correlated with the energy density of juvenile herring (Diamond and Devlin 2003). Younger age classes of herring are also an important food source for Bonaparte's Gull, and have made up >80% of the diet of Razorbills and Puffins in the outer Bay of Fundy (Clarke et al. 2008). Therefore changes in the herring population could be expected to affect not just fish populations, but also a number of seabird populations within the Gulf of Maine.

Spatial Changes

The following example indicates how natural impacts to physical-biological ecosystem linkages can influence spatial changes in where certain organisms are found. Petrie and Yeats (2000) noted that a potentially major influence of decadal variability on marine populations may occur through associated changes in chemical oceanographic properties (an ecosystem driver). Significant changes in nutrients (decreased nitrate) and dissolved oxygen (increased) occurred in the Gulf of Maine region when colder/fresher water entered the Gulf during the 1960s, with potentially important biological implications, some of which were spatial. Such implications included changes in distributions and migrations of various species (Loder et al. 2001). The driving forces that effect such changes in the biological communities of the Gulf of Maine do not have to originate within the Gulf. For example, the NAO and a number of associated physical oceanographic changes have significant biological influence within the Gulf of Maine. Straile and Stenseth (2007) have outlined a wide array of known ecological relationships with the NAO, including the spatial characteristics of location and abundance of different temperature habitats in oceanic waters for Atlantic salmon.

Natural drivers also affect more local spatial changes within the ecosystem. The Gulf of Maine has distinct temperature and salinity characteristics from the adjacent offshore Atlantic Ocean, and a "front" that delineates these differences generally lies along the continental slope east of Georges Bank (Page et al. 2001). An oceanic front is the interface between two water masses of different physical characteristics. There is usually a strong horizontal change of temperature and salinity across a front, and some associated current shear that may mix nutrients and capture and concentrate numbers of small living organisms that are food for other animals. Fronts are important for organisms such as plankton and jellyfish, which tend to collect at a front, and their congregation attracts predators such as sea turtles, whales, and pelagic seabirds (Worcester and Parker 2010). Although other fronts exist in the Gulf of Maine, the most persistent frontal region is at the continental shelf break on the southeastern flank of Georges Bank (Mavor and Bisagni 2001). However, the persistence of this front does not indicate spatial stability. Seasonally, this front moves farthest offshore in winter and farthest onshore in late summer and early autumn. Although this front has closely followed the continental shelf at the southern extent of Georges Bank, it lies slightly further east of the outer continental shelf near the entrance to the Northeast Channel (Page et al. 2001). Another less persistent front on the northeast peak area of Georges Bank has been shown to move as much as 5 km (3 miles) per month and is not a permanent year-round feature (Mavor and Bisagni 2001).

The spatial variability of these oceanic fronts means that the organisms that are drawn to or captured within the fronts often move with the front, or disperse to other areas when the front disappears. For example, the Northwest Atlantic bluefin tuna stock migrates into the Gulf region and distributes throughout the waters of the Gulf of Maine during July to October. During this time, tuna are actively feeding on prey fishes that probably follow temperature frontal zones in areas of high productivity (Schick et al. 2004 cited in Overholtz 2006). The basking shark is a pelagic animal that, although frequently observed in coastal areas, in offshore areas is often found near oceanic fronts where temperatures are between 7–16°C (45–60°F). Within the offshore Gulf of Maine, these sharks are frequently observed along the continental slope southeast of Georges Bank, and along the northwest slope of Georges Bank (Campana et al. 2008), both areas of oceanic fronts (Mavor and Bisagni 2011). The front on southeastern Georges Bank has also been shown to be important to other biological processes such as larval feeding success and survival (Loder et al. 2001).

Some natural ecosystem impacts lead to infrequent spatial changes within the Gulf of Maine. For example, changes in the oceanic environment led to cooling events during the mid-1980s to the mid-1990s, having significant impacts on fish and invertebrate distribution and causing what are known as range shifts. Because each fish species or stock tends to prefer a specific temperature range, long-term changes in temperature can lead to expansion or contraction of distributional range. This is one of the reasons physical oceanography (which includes water temperature) is considered a natural ecosystem driver in the Gulf of Maine. During the cooling events, capelin, a small cold water fish, expanded its range southward to the Gulf. This happened as Gulf water temperatures cooled, approaching temperatures that are preferred by capelin. This range expansion is not unique, but it is infrequent. The arrival of capelin in the Bay of Fundy was also noted following cooling in the 1960s, as was their disappearance when temperatures rose in the 1970s. Reported capelin catches in the Bay of Fundy prior to the 1960s all corresponded with periods of colder-than-normal water (Frank et al. 1996). Natural fluctuations in temperature and salinity, such as those associated with the NAO, or anthropogenic changes tied to climate change can allow species to migrate northward or southward beyond their typical habitats and into the Gulf of Maine.

4.2 ANTHROPOGENIC IMPACTS

Pressures from changing ocean activities such as shipping and fishing result in a number of important impacts to the Gulf of Maine ecosystem. These impacts are anthropogenic—caused by human activities—and may be intentional or unintentional. Because human activity in the offshore marine environment is primarily the result of social and economic drivers such as the need to provide food and acquire financial stability, anthropogenic impacts may be refered to as socio-economic impacts. The following section describes impacts from human activities to the food web structure of the Gulf of Maine and some of the physical habitats found on the ocean floor.

Trophic Structure Changes

Trophic structure is a term used to capture the idea that each organism has a place within the food web. There are several ways in which human activities can alter the trophic structure of an ecosystem. One way is by introducing a species that becomes a dominant predator or prey within the ecosystem, upsetting the natural balance of interactions that previously existed. Commercial shipping has led to the introduction of at least 14 of the 64 marine invasive species identified in the Gulf of Maine through two primary mechanisms: transport by ballast water and fouling on ship surfaces (see *Marine Invasive Species* theme paper; Pappal 2010). However, invasives can also naturally migrate to new areas as changing environmental conditions permit. Although a body of knowledge has been collected on marine introductions in the Gulf of Maine, most of it is for the shallower coastal and estuarine systems rather than the offshore ecosystem. Logistical constraints and identification difficulties, generally associated with the extremely small size of many introduced organisms or their tendency to live within soft sediments, mean only some habitats and groups of organisms have been adequately identified (Pappal 2010). Twenty-two new plankton species have been observed in the Bay of Fundy alone during the last 15 years, although it is unclear whether all of these records represent true introductions (Martine and LeGresley 2008 cited in Pappal 2010). However, these low trophic level organisms have the potential to alter the food web because of the number of higher level organisms that feed on or are supported by plankton.

Introductions of new organisms into the food web can also have an economic impact on the people living and working around the Gulf of Maine. It is believed that the colonial tunicates *Botrylloides violaceus* and *Diplosoma listerianum* were fouling (attached to ships' hulls) introductions to the Gulf of Maine. These tunicate species can displace a wide array of native species by smothering their habitat, growing prolifically over large areas. Some of the displaced species are fished commercially, resulting in an economic impact/loss. The tunicates also coat aquaculture equipment, hulls of vessels, and harbour infrastructure requiring maintenance costs for removal and cleaning. Because modern vessels are faster, have shorter times in port, and are more frequently maintained, the role of hull fouling in more recent transoceanic introductions has been questioned (Pappal 2010).

Another anthropogenic impact to the trophic structure of an ecosystem can occur by direct removal of one or more species from the food web. Within the Gulf of Maine, significant numbers of large benthic groundfish species have been heavily fished over an extended period of time. During the early 1980s there appeared to be a regime shift (response) in the dominant offshore fish community on Georges Bank from these heavily harvested demersal species (cod, haddock, and yellowtail flounder) to small bodied pelagic species (Atlantic herring and mackerel). This shift appears to be a consequence of commercial fisheries harvesting (the driver) (GOMC 2004) and has altered numerous trophic interactions in the Gulf of Maine food web. Adult cod on Georges Bank has supported the most productive cod fishery in the Gulf of Maine, yet even recently adult cod biomass on Georges Bank declined an estimated 80% from 1990 to 1995 (TRAC 2007) and has remained around this lower level despite management measures to decrease catches since 1995 (Wang et al. 2011). Both a significant ecological and economic impact occurred because of the change from large benthic groundfish species like cod to small-bodied pelagic species.

Many of the pelagic fish species that are now dominating fish biomass on Georges Bank are consumers of zooplankton (planktivores) (Gaichas et al. 2009). However, there does not appear to have been a corresponding decrease in zooplankton abundance or changes in the zooplankton species composition that may have been expected (GOMC 2004). Still, shifts in dominant species within the pelagic planktivorous fish community from sand eels to herring may also have been a driver of changes in the distribution patterns of fish-eating whales, dolphins, and porpoises, as well as a driver of changes in the diets of piscivorous fish species (secondary responses) (GOMC 2004). This example further demonstrates how long-term variability at one level (demersal fish community) can influence an assortment of biologically linked species or groups or organisms (sand eels → herring → whales) within the Gulf of Maine through its trophic structure.

Spatial and Benthic Impacts

Human use impacts are not limited to direct biological pressures on the food web. Some impacts are spatial or benthic, effectively competing with marine organisms by occupying or altering physical space and habitat. For example, the distribution of macrobenthic organisms is influenced in part by human activity such as bottom-trawl fishing (GOMC 2004). Physical habitat damage from trawls is visible through side scan sonar of the ocean floor. Corals are susceptible to trawling and have been damaged within the Gulf of Maine by these fishing activities (DFO 2006). It has been estimated that the entire U.S. side of the Gulf of Maine sea floor was impacted annually by mobile fishing gear between 1984 and 1990, based on calculations of area swept by trawl and dredge gear. It was calculated that the Georges Bank sea floor was covered by trawling three to nearly four times annually during the same period (Auster et al. 1996). Studies at three sites in the Gulf showed that mobile fishing gear altered the physical structure of benthic habitats, reduced habitat complexity by direct removal of biogenic (e.g., sponges, hydrozoans, bryozoans, amphipod tubes, holothurians, shell aggregates) and sedimentary (e.g., sand waves, depressions) structures and by removal of organisms such as crabs and scallops that create structures. Reduction in habitat complexity is thought to lead to increased predation on juveniles of some commercial harvested species and ultimately reduce the harvestable stock (Auster et al. 1996). As such, direct benthic impacts from trawl fishing on the ecosystem may also have an indirect economic impact on a variety of commercial fisheries. Further unquantified negative pressure is placed on small fish such as Atlantic herring, silver hake, juvenile cod, haddock, red hake and flounder which are often caught in various quantities as bycatch in shrimp trawls within the Gulf of Maine (He et al. 2007).

As noted previously, a significant decline in adult cod biomass on Georges Bank occurred around 1990, and has remained relatively low since (Wang et al. 2011). Over a 25-year time series study (1973-1998), the majority of North Atlantic cod could be found in three areas: the Gulf of Maine (excluding Georges Bank), Georges Bank, and the Scotian Shelf. This indicates the historic importance of the Gulf of Maine habitat to the entire North Atlantic cod population. During this current period of low abundance on the U.S. continental shelf, fewer cod have been found south of the Gulf of Maine, implying an effective contraction of the distribution of cod over the three decades from the 1970s to the 1990s (Link and Garrison 2002). The contraction of species range for the cod from areas south of the Gulf is indicative of a changing ecosystem even though the driver is not entirely clear.

Another example of a human activity causing impacts on the Gulf of Maine ecosystem is the introduction of an invasive tunicate on Georges Bank. It is thought that the invasive colonial tunicate *Didemnum* sp. was brought to the Gulf of Maine on oysters transferred for aquaculture (Pappal 2010). The tunicate was first noted in an area of gravel habitat on Georges Bank in 2002. Since its discovery there the infested area has spread to an area of 230 km^2 (89 $miles^2$) in two adjacent gravel areas, and at some locations covers nearly 75% of the seabed. *Didemnum* sp. has had a significant impact on the species composition of the benthic community. In particular, the abundance of two polychaete species has increased significantly in areas infested by the tunicate compared to areas not infested. The polychaetes live beneath the tunicate mats, and the increased abundance of these species suggests they are avoiding predation by fish by being under the mats (Lengyel et al. 2012). Although the implications of such changes are not yet understood, there is a direct link between the anthropogenic impact and the biological response.

5. Actions and Responses

"Responses" are societal responses to mitigate negative impacts on the environment and humans, by halting or reversing the damage already inflicted or by preserving and conserving natural resources. These responses can include the development of legislation and policy, which may have legal implications for those not adhering to the prescribed corrective actions, or may include monitoring and research intended to lead to better future decision making and actions.

5.1 LEGISLATION AND POLICY

Both Canada and the United States have a number of acts and policies that pertain to the management of their oceans and the resources associated with those waters. In Canada the *Oceans Act* was enacted in 1997 to provide a framework for modern ocean management that guides such activities as the establishment of economic fishing zones, marine protected areas, and the powers and duties of protection and marine science services. In the United States, a key piece of oceans policy has been the establishment of the National Ocean Policy in 2010 based on recommendations of the Interagency Ocean Policy Task Force (OPTF 2010). The Policy provides principles for management decisions and actions toward achieving sound ocean stewardship for present and future generations. Both countries have also developed legislation for species specific protection and management. The Canadian *Species at Risk Act* of 2002 and the U.S. *Endangered Species Act* of 1973 provide various protections to species that have become rare or endangered, and help guide recovery and management approaches for a larger number of species that are considered at risk.

Along with the overarching national oceans policy and legislation, there are a number of approaches that are specific to the waters of the Gulf of Maine. Legislative and policy response to changes within the Gulf of Maine include resource management approaches such as modification of shipping lanes, limitation of certain activities, and the establishment of protected areas and species' recovery strategies as indicated in the following examples.

Perhaps the most proactive, or protective, actions have been with regard to offshore oil and gas development within the Gulf of Maine. Despite the expectation that a significant resource of oil and gas exists under the seafloor of Georges Bank, Canada has had a moratorium on offshore petroleum activities (i.e., exploration, drilling, and development) on the Canadian portion of the Bank and much of Northeast Channel since 1988. This moratorium has twice been renewed, most recently by the governments of Canada and Nova Scotia in 2010, extending it to December 31, 2015 (NSGOV 2010). In the United States, then-president George H. Bush established an oil and gas moratorium on Georges Bank in 1990 (Oceana 2012). This moratorium was cancelled in 2008; however, current American President Barack Obama announced on March 31, 2010, that offshore petroleum activities in the U.S. North Atlantic region, which includes the U.S. portion of Georges Bank, would not be considered for leasing until 2017 (DFO 2011). Numerous potential interactions between the marine environment and offshore petroleum activities exist, but concern over the potential environmental impacts from offshore petroleum development and production is largely linked to the possible exposure of marine organisms to seismic noise, operational waste discharges (e.g., drill wastes, produced water, and other associated wastes), and accidental oil spills and/or blowouts (DFO 2011).The current moratoria have been established to protect the ecosystem from perceived risk of impacts, rather than existing or created impacts.

Legislation and policy have also been used as a response to help minimize known impacts to individual species of conservation concern within the Gulf of Maine, for example the North Atlantic right whale. The abundance of the endangered right whale is critically low (DFO 2007, DFO 2012a). These whales have been provided legislative protection under the Canadian *Species at Risk Act* and the U.S. *Endangered Species Act*. Within the Gulf of Maine, Grand Manan Basin is an important feeding and aggregation area for the right whale (DFO 2007). It was identified as a Right Whale Conservation Area in 1993 and as critical habitat in the 2009 North Atlantic Right Whale Recovery Strategy (Brown et al. 2009). Activities in these areas are not enforced pursuant to legislation, but rather have been managed through voluntary measures published in the Canadian Coast Guard Annual Notices to Mariners and through government-industry cooperation (DFO 2011). The Great South Channel has also been identified as critical habitat (WWF 2000), limiting certain fishing and shipping activities in that area.

Study and observation have confirmed a significant percentage of right whale mortalities have resulted from ship strikes (IMO 2002). In 2003, the International Maritime Organization (IMO) amended and implemented the Bay of Fundy Traffic Separation Scheme to reduce ship strikes of the highly endangered North Atlantic right whale by shifting the ship traffic lanes from an area with the highest density of right whales to an area where there is a lower whale density (IMO 2002), as shown in Figure 6. The new shipping lanes have had an effect on commercial activities in the region as fishermen now do some of their fishing in the lanes instead of east of them, and ships' passages are longer to ports in Saint John, New Brunswick, and Eastport, Maine. Despite these inconveniences, both industries supported the proposal and their stewardship has contributed to recovery efforts for the species in the Bay of Fundy (Canadian Whale Institute 2012).

A similar response of policy and activity changes has been applied to the Northeast Channel. Although cold-water corals are found in a number of locations across the Gulf of Maine, significant concentrations of corals are not. One location where concentrations of corals have been found is the Northeast Channel. These corals show visual evidence of disturbance, such as broken living corals, tilted corals, and skeletal fragments, indicating that the area was being damaged

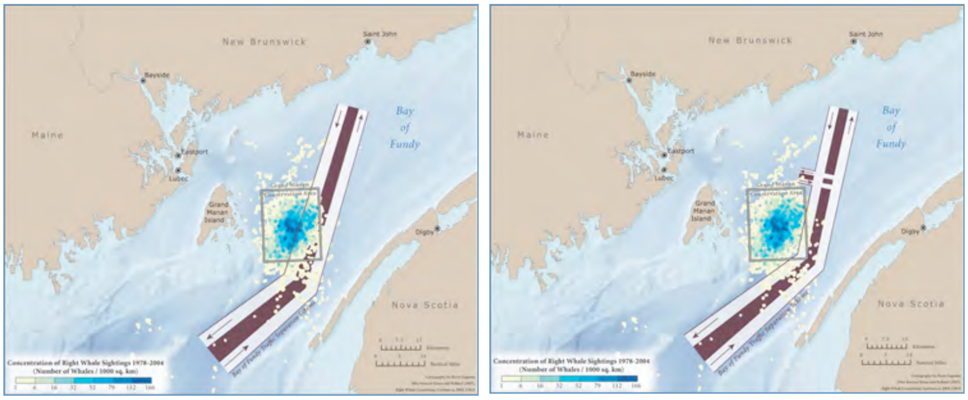


Figure 6. Right whale density in the Bay of Fundy in relation to the old shipping lanes (left) and amended shipping lanes (right) (Canadian Whale Institute 2012).

by bottom fishing activities. To protect the high densities of large, branching gorgonian corals, the Northeast Channel Coral Conservation Area was established by Fisheries and Oceans Canada in 2002 (Mortensen and Buhl-Mortensen 2004 cited in DFO 2011; DFO 2006). Most corals are highly vulnerable to human activities, in particular, bottom-contacting activities such as fishing. Corals are filter feeders and, as such, are also vulnerable to intake of organic and inorganic contaminants in the water column and in bottom sediments. Bottom-contacting gear is restricted in most of the Coral Conservation Area, with the exception of a small zone where groundfish longline fishing may occur with observers on board (DFO 2011).

Some regulations and policy have been developed to manage specific activities within the Gulf of Maine. For example, Transport Canada has focused on ballast water exchange through the Ballast Water Control and Management Regulations that apply to Canadian shipping waterways. These regulations have identified specific Ballast Water Exchange Zones in the Gulf of Maine to help manage the risk of alien invasive species, which can be introduced and spread via transport in ballast water (Worcester and Parker 2010). In addition to the mandatory provisions in the regulations, there are recommendations for ballast water exchange locations for vessels traveling to and from ports in the Bay of Fundy (Transport Canada 2007).

Some policy and legislation is designed to provide protection to specific habitats within the Gulf of Maine. For example, the U.S. Sanctuary Program designated 2200 km^2 (842 mile^2) of shallow bank habitat within the Gulf of Maine as the Gerry E. Studds Stellwagen Bank National Marine Sanctuary. Regulations developed under the National Marine Sanctuaries Program for this area of the Gulf prohibit certain activities, like sand and gravel mining, transferring petroleum products, and taking or harming marine mammals, birds and turtles within the sanctuary. It also dictates when and how traditional activities like commercial fishing may take place (NOAA 2012b).

A number of collaborative U.S./Canada management arrangements exist to protect the Gulf of Maine ecosystem, including mechanisms on acid rain, mercury pollution, climate change, fisheries and shellfish sanitation, and shipping, to name a few (ACZISC 2006). As well, collaborative recovery strategies have been initiated between Canada and the United States for species such as the leatherback turtle, North Atlantic right whale, and Atlantic salmon of the inner Bay of Fundy and Gulf of Maine (Worcester and Parker 2010). Since 1998, the Transboundary Resources Assessment Committee (TRAC) has reviewed fish stock assessments and projections necessary to support management activities for shared resources across the U.S.-Canada boundary in the Gulf of Maine-Georges Bank region. These assessments are necessary to advise decision makers on the status of these resources and likely consequences of policy choices. Recent development of species-specific arrangements for consistent management of individual fish species (cod, haddock and yellowtail flounder) on eastern Georges Bank have also been undertaken as part of international collaborative management (DFO 2012b). A collaborative management and planning body, the Gulf of Maine Council for the Marine Environment (GOMC) is a U.S.-Canadian partnership of government and non-government organizations working to maintain and enhance environmental quality in the Gulf of Maine. The Council has supported numerous initiatives, ranging from bi-national actions to local projects, to improve water quality, conserve land, restore coastal habitats, and enable citizens to be better stewards of the environment around them (see www.gulfofmaine.org).

5.2 MONITORING AND RESEARCH

Monitoring and research are important components of oceans management that allow decision makers to minimize the effects of human activities on the ecosystem. Monitoring involves the systematic collection of data or information over time to track potential changes, while research is focused on finding an answer to a specific predetermined question. As ecological processes and biota function independently of human-established boundaries, such as the Canada-U.S. border, ecosystem management requires transboundary collaborative arrangements and initiatives. These initiatives include sharing collected data sets and ensuring that monitoring and sampling methods within the Gulf of Maine are compatible across the international border. Over 60 monitoring programs have been established within the Gulf of Maine (Chandler 2001). The GOMC maintains a list of many current monitoring programs that are ongoing within the ecosystem, and these are available through their EcoSystem Indicator Partnership (ESIP) website (www.gulfofmaine.org/esip/index.php).

Perhaps the longest running example of transboundary collaboration on monitoring is the consistent sampling methodology within the Gulf of Maine for the collection of plankton data. The United Kingdom's Sir Alister Hardy Foundation for Ocean Science continuous plankton recorder (CPR) program methods have been applied to sample lines across the central Gulf of Maine and Georges Bank since 1961. The CPR is towed from ships of opportunity and collects plankton. Two CPR routes are operated on the United States side of the Gulf of Maine, while portions of another sample line exist on the Canadian side of the Gulf (NOAA 2012a). The same method is used in many of the world's oceans, allowing further collaboration, comparison, and analysis of collected plankton data.

Organisms can also be monitored as indicators of anthropogenic impacts. One genus of mollusc that may be vulnerable to ocean acidification is *Limacina* spp. It is a relatively abundant member of the zooplankton community, and has a thin calcium carbonate shell that is degraded by low pH (high acidity) seawater. These predatory sea snails have been monitored to assess changes in pH and acidification of the Gulf. Based on long term CPR data available for the eastern Gulf of Maine (1961 -2006), no discernible changes in the abundance of this mollusc have been noted (Head and Pepin 2010). The abundances documented to date serve as baselines against which effects of ocean acidification can be judged in the future (Head and Pepin 2010).

Even in areas of the Gulf of Maine that have been extensively studied, such as Georges Bank, there remain many unanswered questions relating to the complex relationships between ecosystem components, trophic dynamics, the interannual variation of populations, and the linkages with physical and chemical characteristics of the system. Predicting the response of the ecosystem to perturbations may be difficult (DFO 2011). For example, across the Gulf there are numerous biological and chemical measurements used to operationally define water quality, but the relationship of these physical parameters to biological integrity is generally only understood qualitatively (GOMC 2004). Table 4 has been developed to highlight our relative knowledge of various Gulf of Maine ecosystem components, and is an indicator of where some knowledge gaps exist.

Table 4. Knowledge matrix for the coastal and deep water areas of the Gulf of Maine (adapted from GOMC 2004).

	LEVEL OF KNOWLEDGE			
REGION	High	Moderate	Poor	None
COASTAL OCEAN				
Biota		X		
Water transport			X	
Water quality		X		
Habitat quality			X	
Offshore linkages		X		
Onshore linkages			X	
OFFSHORE OCEAN				
Biota		X		
Water transport		X		
Water quality		X		
Habitat quality			X	
Offshore linkages			X	
Onshore linkages			X	

Limited understanding of the physical-biological-chemical interactions within the Gulf of Maine leads to observations of ecosystem response that are not always anticipated. Sometimes, critical information gaps are specific to a species, and even a portion of that species' life cycle. For example, since the late 1980s and 1990s, Gulf of Maine salmon populations have diminished at an unprecedented magnitude and have drawn attention to the lack of knowledge of salmon life history during the marine phase. Migration routes, distribution, and abundance for specific stocks are completely unknown. Furthermore, the reason(s) behind the current high mortality rates for Atlantic salmon, which are known to be occurring at sea, have no specific known cause(s) (Reddin 2006). It has been suggested that our poor understanding of ecosystem linkages is particularly true in the offshore, where coupling between the far field ocean forcing/migration and inshore coastal areas is not well understood. These knowledge gaps hinder the development of predictive models of the offshore ecosystem (GOMC 2004).

INDICATOR SUMMARY

INDICATOR	POLICY ISSUE	DPSIR	ASSESSMENT[1]	TREND[2]
NAO Index	Changes in NAO affect temperature and salinity, and thus ecosystems	Driving Force	Fair	/
Total fisheries landings, Georges Bank	Fisheries influence trophic structure and species composition of ecosystem	Driving Force/ Pressure	Fair	?
Community Structure (benthic / pelagic balance)	Change from benthic to pelagic dominated fish community impacts harvestable quotas	State	Unknown	/
Species diversity	Changes in species diversity can affect the structure and function of ecosystem	State	Unknown	?
Disturbance from human activities (fishing, shipping)	Direct and indirect impact to habitats, and trophic interactions	Impact	Poor	/
Number of invasive species	Invasive species may substantially change structure and function of offshore ecosystems	Impact	Fair	/
Total area of habitat protected in the Gulf of Maine	Conservation and management measures protect offshore ecosystems	Response	Unknown	+
Whole Gulf management	International boundary creates duplicate and partial area approaches to management/ research/monitoring.	Response	Poor	+

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

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

Data Confidence

- The NAO is monitored regularly by scientists.
- Fisheries landings are documented regularly by government agencies.
- Study has only recently moved from species-specific and commercial species to broad community assemblages and ecological relationships.

Data Gaps

- Species diversity was recently documented by the Census of Marine Life. While this provides a baseline for future studies, trends in diversity are not presently known.
- While many of the indicators are monitored regularly, implications for the ecosystem may not be documented or are theorized rather than proven.
- Linkages to coastal and open oceanic habitats and processes are known to exist, but not always well understood.
- Gulf-wide data on communities, oceanographic characteristics, and trends are not available; data sets tend to be separated by the international boundary.

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