CHAPTER 2

VULNERABILITY OF SEMI-ENCLOSED MARINE SYSTEMS TO ENVIRONMENTAL DISTURBANCES

MICHAEL MACCRACKEN, ELVA ESCOBAR BRIONES, DENIS GILBERT, GENNADY KOROTAEV, WAJIH NAQVI, GERARDO M.E. PERILLO, TIM RIXEN, EMIL STANEV, BJØRN SUNDBY, HELMUTH THOMAS, DANIELA UNGER, AND EDWARD R. URBAN JR.

2.1 Introduction
Semi-enclosed marine systems (SEMS) are impacted on time scales ranging from the very short (days or less) to the very long (decades and beyond) by many of the same forces and stresses as other components of the Earth system. Like the open ocean, SEMS are linked to large-scale anthropogenic disturbances through climate change, acidification from increasing levels of atmospheric carbon dioxide (CO₂), and atmospheric deposition of contaminants. The restricted flushing of SEMS makes them vulnerable to land-based disturbances. Locally, SEMS are affected by agricultural runoff, urbanization, and pollution. Changes in freshwater runoff and precipitation, cloudiness, winds, and upwelling can modify sedimentation and erosion patterns and the productivity and health of these systems. Atmospheric motions, especially sea and land breezes, connect SEMS with neighboring land areas. These motions transport gaseous and particulate matter and nutrients, buffer diurnal and seasonal temperature variations over land, and amplify them over the ocean.

While SEMS are more vulnerable to human influences than coastal environments that are fully connected to the open ocean, the diversity of SEMS, in terms of location, size, depth, and coupling to adjacent land areas and the open ocean precludes a simple, generalized description of their vulnerability. This chapter presents an overview of the most important drivers of change, the processes that are likely to be most affected, and the most important implications for SEMS.

2.2 Significant Climatic Forcing Factors
Worldwide emissions of CO₂, other greenhouse gases, and aerosols are forcing significantly larger changes in the global climate than previous extremes and fluctuations caused by natural phenomena such as solar radiation and volcanic eruptions. Natural oscillations of the ocean-atmosphere system, such as the El Niño/Southern Oscillation, are becoming less effective in obscuring the regional manifestations of human-induced climate change. Such oscillations, which are likely to be affected by the changing climate, will continue to result in fluctuations around the changing mean climatic conditions, increasingly leading to new extremes. IPCC’s Fourth Assessment Report (IPCC, 2007a,b) projects an increase in the global average surface temperature of about 0.2 to 0.4°C/decade over the 21st century, compared to an average rate of roughly 0.06°C/decade over the 20th century. As a result, the switchover from a naturally dominated to a human-dominated world will occur at an accelerating pace, amplified further as the efficiency of the ocean carbon sink decreases.

Because the ocean will warm less rapidly than continents, the land-sea contrast will increase, which will affect atmospheric circulation, cloud distributions, precipitation, and freshwater availability in coastal regions. In addition, changes in the north-south temperature gradient will alter atmospheric circulation and storm tracks on larger scales, changing precipitation patterns, river runoff, wetness of soils, and duration and extent of snow and ice cover. These globally forced changes will be augmented at the regional scale by changes in land cover, water and soil management, agriculture and forest
management, urban and coastal development, energy use and development, and other factors that alter
the surface albedo, soil permeability, heat capacity of the surface, and supply of freshwater and
sediment to the coastal environment.

Global warming is also accelerating the rate of sea level rise, both by increasing ocean heat content,
which leads to thermal expansion of ocean waters, and by increasing the rate of loss from the world’s
glaciers. Over the past decade, increasing deterioration of the Greenland and West Antarctic ice sheets
has accelerated the rate of sea level rise. Over the next few decades, if strong controls of greenhouse
gas emissions are not implemented soon, the rate of sea level rise will likely increase from the average
20th century value of almost 20 mm/decade to 60-100 mm/decade, or even more; indeed, the recent rate
is already near 40 mm/decade. Higher sea level will cause significant impact along the low-lying
coastlines that surround many SEMS.

Higher temperatures and the elevated atmospheric CO2 concentration are also increasing the intensity
of the hydrologic cycle, with higher rates of evaporation leading to a net increase in global
precipitation. However, changes in the timing and amount of runoff are uncertain because evaporation
from land regions will also increase and because changes in atmospheric circulation will alter
precipitation patterns, causing increases in some locations (particularly in high latitudes) and decreases
in others (particularly in the subtropics). More rapid drying of land areas is likely to amplify any initial
temperature increase, and, if precipitation does not simultaneously increase by a sufficient amount, the
result will be higher temperatures and salinities in estuaries and coastal waters. In some regions, wind
changes could also amplify or diminish upwelling of colder waters.

In addition to changing mean conditions, global warming is very likely to lead to new climatic
extremes. With higher atmospheric water vapor mixing ratios, heavy rain and snow events will become
more common. Tropical cyclones (variously also known as hurricanes and typhoons) are projected to
become more powerful, leading to significantly higher precipitation rates and wind speeds. These
changes will in turn lead to higher storm surges and waves, which will greatly increase coastal damage
and shore erosion, especially because of sea level rise and reduced extent and duration of sea ice.

The manifestations of large-scale changes in particular regions are likely to shift as atmospheric and
oceanic circulations change and are affected by the local coastline, coastal landforms, and bathymetry.
The complexity and uniqueness of the influences and driving forces in each region make it important
to carefully evaluate the consequences for each semi-enclosed marine system.

The following sections describe the primary processes and characteristics affected by human-induced
climate change and their potential influence on SEMS; the boxes provide specific examples from
around the world.

2.3 Physical Responses to Climate Forcing
Climate change will cause a wide range of changes in the physical environment. While climate change
is often described in terms of the amount of warming, the largest impacts on SEMS are likely to result
from changes in the components of the hydrologic cycle that move water through the system and from
changes in the supply and distribution of sediment which, along with changes in sea level and, in some
regions, sea ice, affect erosion and induce changes in the coast.

Changes in hydrodynamics: Circulation in regional seas is dominated by regional wind patterns.
These patterns are likely to shift in response to global warming as mid-latitude storm tracks shift
poleward. Such shifts are likely to cause changes in the location and intensity of upwelling, ice cover
extent and duration, and ocean stratification, and, by affecting regional weather, including the balance of precipitation, evaporation and runoff. As the hydrologic cycle intensifies, the depth and strength of ocean currents will also be affected.

The temperature of the upper ocean’s mixed layer is strongly affected by latent and sensible heat fluxes at the sea surface, short-wave radiation (modulated by cloudiness, atmospheric aerosol, and seawater transparency), the surface long-wave radiation budget, and the effects of water transport and mixing. Heat fluxes caused by inflowing rivers and melting and freezing of ice can have regional- to global-scale impacts on ocean ecosystems. Horizontal mixing conditioned by mesoscale processes, vertical mixing caused by winds, shear or convective instability, and large-scale or local upwelling phenomena can affect temperature distributions.

Because the coastal ocean is significantly impacted by freshwater fluxes, warming and changes in precipitation and evaporation can alter salinity and affect important hydrologic features. These features include river plumes, salt wedges, and fresh water and thermal fronts that can alter not only vertical exchanges of heat, but also ecological and sedimentary systems. In addition, salinity in the mixed layer is directly dependent on the amount of precipitation relative to evaporation, river runoff, and sea ice formation and melting.

Regional weather will also be affected. Changes in land and ocean surface temperature resulting from human activities will affect the atmospheric coupling between land and ocean, intensifying the daytime sea breeze and weakening the evening land breeze. Generally, the warm season will lengthen and the cool season will become shorter. Changes in climate will generally be larger over land areas than over ocean areas, greater at night than during the day, and greater during the cold season than during the warm season, except where land areas dry out. However, the responses of particular SEMS are likely to vary. Where the water is relatively shallow or stratified, changes could be more closely related to warming over land.

The observed trend toward more intense precipitation events is likely to continue, which could make runoff more variable and even episodic, especially as warmer temperatures increase evaporation and reduce runoff between storms. In regions exposed to tropical cyclones, the warmer ocean temperatures are projected to lead to increases in the average intensity of storms (a change already evident in the Atlantic basin), causing higher storm surges and wind-whipped waves that will penetrate further inland. Greater duration of hurricane level winds is likely to extend the domain and increase the frequency of exposure of various coastal regions, leading to increased inundation and erosion of coastal lands.

**Changes in fresh water runoff and salinity:** Changes in the amount of fresh water reaching estuaries will alter temperature, salinity and nutrient concentrations, shifting the position of the salt intrusion boundary. Decreasing runoff will cause landward displacement of organisms that are adapted to fluctuating salinities, an increase in the frequency and severity of salt-water contamination events in low-lying coastal regions, and an increase in the extent of salt transport into coastal aquifers and groundwater, impacting municipal water supplies (Nicholls and Wong, 2007).

**Changes in the supply of sediments:** River input is the major source of sediment in most coastal regions (Wang et al., 1998 and Chapter 7, this volume), although atmospheric transport of dust, along-shore transport of sediments, and coastal erosion can also be important. Observations of baselines and trends reveal significant regional variations in sediment supply due to natural variations of relief and erosion, and human influences such as damming, water treatment, and flood control (Restrepo and
Kjerfve, 2000a,b; Kjerfve and Restrepo, 2002; Syvitski et al., 2005a). Both flood control measures and land use and land cover modification have affected sediment delivery (Syvitski et al., 2005b, Syvitski and Milliman, 2007). The sediment source term has increased by an estimated 2.3 ± 0.6 billion tonnes per year (Gt y⁻¹) because of deforestation, soil mismanagement, and other causes, but about 60% of this increase (1.4 ± 0.3 Gt y⁻¹) is retained by reservoirs. An estimated 100 Gt of sediment have been sequestered in reservoirs built over the last 50 years, depriving the coastal zone of a substantial source of sediments.

Severe storms and tropical cyclones can have devastating effects on sediment transport. For example, Hurricane Agnes (1972), with its particularly strong rains, flushed out large amounts of sediment that had built up in the drainage basin over previous decades, carrying the sediment into Chesapeake Bay and wiping out the benthic ecosystem in estuaries and on the shelf (Meade and Trimble, 1974; Gross et al., 1978). Observations already indicate that a larger fraction of the precipitation is coming in heavy rainfall events (Trenberth and Jones, 2007), and projections are that climate change will lead to more powerful tropical cyclones that drench coastal regions with substantially increased precipitation (Meehl and Stocker, 2007). As one example, Box 2-1 describes interactions that are likely to result as the Gulf of Mexico and Caribbean Sea warm.

**Box 2-1: Gulf of Mexico and Ocean-Atmosphere Interactions**

The Gulf of Mexico provides an example of the interactions of regional circulation patterns with climate. The region’s weather is influenced by trade winds, with differences in ocean and atmospheric temperatures resulting in cyclogenesis from June through October that, when the tropical storms become hurricanes, poses a severe threat to humans (Escobar, 2006). Although these systems cause extensive damage as a result of high wind speeds and flooding, these cyclonic systems contribute vital rainfall over an extensive area of the southern and eastern United States. Warming of the Gulf of Mexico and Caribbean Sea is likely to increase regional warming and lead to additional intensification of nascent tropical cyclones, exacerbating both the positive and negative influences of these SEMS over the adjacent land areas. For example, as a result of the powerful hurricanes that struck the central coast of the Gulf of Mexico in 2005, roughly 300 square kilometers of coastal wetlands were lost (Barras, 2006), increasing the exposure of urban and industrial infrastructure in the Mississippi River delta region to future hurricanes.

At the ocean interfaces of the Gulf of Mexico, climate change will also exert influences. The interaction of ocean eddies with the continental slope (Muller-Karger, 2000; Toner et al., 2003) and the confluence of along-shelf currents generate cross-shelf transports near- and off-shore (Cochrane and Kelly, 1986; Zavala-Hidalgo et al., 2003). As a result, cross-shelf transports of chlorophyll-rich waters have a seasonal cycle that is largely modulated by the wind field and its timing and linkages to marine life could be affected by climate change.

**Increase in sea level and higher storm surges:** Thermal expansion of ocean waters, melting of mountain glaciers, and changes in snow accumulation and melting on the surfaces of the Greenland and West Antarctic ice sheets are projected to cause an increase in global sea level of 0.18 to 0.59 m by 2100 (IPCC, 2007a). Significant additional contributions from the Greenland and West Antarctic ice sheets are likely as a result of rapid dynamical changes in ice flow that are already becoming evident in some glacial streams. Although sea level rose about 120 m as the last glacial period ended, relative constancy of sea levels over the past several thousand years allowed development of mangroves, corals, seagrass beds, and other coastal features that have tended to stabilize the existing coastline. The
dynamic state of equilibrium that came to exist is being disturbed by human activities, including by climate change, cutting of mangroves, and building of dams (Syvitski et al., 2005b). In some areas, dredging of channels for sand and to improve navigation channels has altered riverbeds, and waves from ship traffic have caused erosion. Increased tourism, attracted by sandy beaches, has also accelerated coastal erosion, especially in locations where increased tourism has led to loss of coastal vegetation and increased construction on beaches and foredunes. With coastal resistance to the sea weakened, rising sea level is likely to significantly impact many low-lying areas, particularly those exposed to storm surges and wind-whipped waves.

**Reductions in sea-ice cover:** Global warming scenarios for high latitudes predict amplified warming due to positive feedbacks from loss of sea ice and allocation of the additional energy to warming rather than to increased evaporation. Loss of coastal ice cover increases the exposure to surface waves, especially during winter storms, and increases the risk of accelerated coastal erosion. In areas of coastal permafrost, shoreline erosion can be several meters per year. Sea ice melting and increased arctic river input are also likely to lead to stronger thermohaline stratification and reduced deep-water formation in high-latitude regions, reducing the efficiency of ocean carbon sequestration, and further amplifying global warming. Reduced ice cover is also likely to disrupt reproduction and feeding of seals, which depend on ice for reproduction, and polar bears, which prey on the seals. Changes in ice cover are already disrupting the livelihood of the humans who hunt seals and depend on other marine resources.

Reduction in sea ice can affect climatic conditions in downwind regions. For example, reduced ice cover over Hudson Bay and the Arctic Ocean will lead to sharply warmer temperatures in the fall and early winter over much of eastern North America. Similar effects will be seen as a result of diminished ice cover and reduced ice thickness, and of later formation and earlier melting of seasonal sea ice in areas such as the Sea of Okhotsk, Baltic Sea, Hudson Bay, and Gulf of St. Lawrence (Box 2-2).

### Box 2-2: Changes in Gulf of St. Lawrence Stratification and Hypoxia

Throughout the 20th century, the hydrologic regime of the Gulf of St. Lawrence was modified by construction of major dams along the St. Lawrence, Saguenay, Manicouagan and several smaller rivers. Changes in the seasonal patterns of river flow caused by these dams altered the seasonal cycle of surface salinity and stratification in the Gulf of St. Lawrence, although the effects have not yet been quantified. With further construction of dams planned over the next few decades, changes in freshwater flows are likely to have further impacts, especially near the mouths of the newly harnessed rivers.

Additional changes are likely as warmer winter temperatures reduce the extent and duration of the seasonal ice cover. These reductions will likely benefit marine transportation by lengthening the ice-free navigation season, but adversely impact wildlife. Further nutrient enrichment and increased eutrophication of the St. Lawrence River and estuary over the coming decades appear likely as the human population continues to grow, as more farmers turn to row-crop cultures of corn to produce ethanol for fuel, and as the construction of new and bigger animal farms and the associated manure disposal continue to stress the nutrient-accepting capacity of agricultural land.

Global warming will also cause changes in ocean currents in the northwest Atlantic Ocean. A continuing decrease in the western transport of Labrador Current Water along the southern edge of the Grand Banks of Newfoundland is likely to cause warmer, saltier, and lower-oxygen waters from the
Gulf Stream to enter the mouth of the Laurentian Channel and then propagate landward toward the heads of the three major deep channels of the Gulf of St. Lawrence (Laurentian, Anticosti, and Esquiman channels). Entrance of low-oxygen water from the open ocean would further exacerbate the oxygen deficit in the bottom waters of the Gulf of St. Lawrence (Gilbert et al., 2005).

**Accumulated impacts on erosion, coastal stability and the coastal edge:** The natural coastline is a result of dynamic processes acting over geological time scales. These processes include changes in sea level, uplift or subsidence of continental land masses, erosion by waves, tides and currents, and sediment supply. About 70% of the world’s sandy coast, occupying ~20% of the global coastline, has been retreating over the last century; 20-30% has been stable and less than 10% has been advancing (Bird, 1993; Syvitski et al., 2005a); sea level rise will cause more rapid retreat of the coastline (Leatherman, 2001).

Experience has shown that attempts to protect sandy beaches from erosion by constructing barriers such as jetties and wave breakers to limit wave action and reduce littoral sediment transport has only shifted the problem to other locations with unintended consequences such as complete loss of beaches and destruction of property (Perillo, 2005). With projected changes in winds, temperature, precipitation, frequency and intensity of extreme events, and sea level, the risk is high for dramatic changes to sedimentary systems in ways that are yet to be understood.

**2.4 Biological and Chemical Responses to Climate Forcing**

In addition to the many physical responses to climate forcing, significant chemical and biological responses are expected in SEMS. Projected changes in the hydrological cycle will certainly alter fluxes and distributions of nutrients, CO$_2$, and contaminants and, as a consequence, the ecology of SEMS.

**Changes in fluxes and distribution of nutrients:** Increasing amounts of nitrogen and phosphorus compounds are being released to coastal waters due to the use of fertilizers, disposal of sewage, and production of manure (e.g., Cloern, 2001). The phosphorus loading in runoff has been reduced in many places as a result of improved wastewater treatment and elimination of phosphate from detergents, but the dissolved inorganic nitrogen (DIN) load is still high and even increasing. Indeed, modern sewage treatment is not designed to remove nitrogen compounds. Atmospheric inputs of nitrogen to SEMS can be important, and in densely populated regions, atmospheric nitrogen inputs can exceed riverine inputs.

Paradoxically, the flux of dissolved silica (DSi) to the coastal zone has diminished, apparently because of removal by algal growth in the increasing numbers of reservoirs and in eutrophic rivers (Humborg et al., 1997; Garnier et al., 2002). Because DIN consumption by algae tends to be outweighed by anthropogenic DIN additions downstream, the DSi/DIN ratio in river water has been shifting from “pristine values” of ~30 to 40 (typical in the Amazon or Zaire rivers) to < 2 (typical of the heavily impacted Changjiang, Mississippi, and Scheldt rivers, each of which empties into a semi-enclosed marine system; e.g., Chou and Wollast, 2006). A full review of the effects of human perturbations on the silicon cycle is provided by Ittekkot et al. (2006).

Organic nitrogen compounds from natural and anthropogenic sources can comprise a significant proportion of total nitrogen in coastal seas (see Chapters 8 and 9, this volume). Organic nitrogen compounds serve as nutrients for heterotrophic bacteria and phytoplankton (Seitzinger et al., 2002). Adverse shifts in plankton species composition and development of harmful algal blooms are potential consequences of an imbalance between nitrogen and phosphorus.
In addition to the nutrients supplied by runoff, the ocean is a major source of nutrients (and other constituents of sea water) for SEMS. For example, the primary production in the North Sea, amongst the highest in marine areas, is fuelled to a large extent by nutrients from the North Atlantic Ocean and to a lesser extent by riverine or atmospheric nutrient sources. In return, the North Sea exports inorganic carbon taken up from the atmosphere to the North Atlantic Ocean via the continental shelf pump (Box 2-3). Land-use change can also affect riverine inputs in ways that can alter the alkalinity of coastal seas, which in turn can determine the capacity of the water to take up atmospheric CO₂ (Raymond and Cole, 2003).

Box 2-3: The Baltic Sea and the North Sea: Connected but Different

While the Baltic Sea and the North Sea are connected through the Skagerrak, their physical and biogeochemical characteristics differ substantially. The Baltic Sea is a brackish environment, with the river runoff into it being three times larger than the inflow of water from the North Sea. The biogeochemical characteristics of the freshwater inputs to the Baltic are controlled by its drainage area, which includes parts of the Scandinavian Peninsula and parts of continental Europe. The Baltic’s deep waters are anoxic, with only occasional oxic periods induced by the inflow of oxygenated waters from the North Sea. The stagnant conditions make this sea very sensitive to eutrophication and other human impacts. Over recent decades, international efforts to limit pollution and nutrient flows have improved the health of the Baltic Sea, which has allowed reestablishment of the codfish stock after depletion by overfishing.

The characteristics of SEMS that are not strongly coupled to the open ocean are primarily controlled by river runoff and in-situ forcing, which significantly increases the vulnerability of the systems to human-induced disturbances. In the Baltic Sea, for example, anoxic conditions dominate unless sporadic events deliver oxygen into anoxic deep waters and temporarily reestablish oxic conditions. In the Black Sea (Box 2-4), which is only minimally ventilated vertically or by exchange with the Mediterranean Sea (Stanev et al., 2002), stagnant anoxic conditions prevail in the bottom waters (Stanev et al., 2004).

The North Sea is made up of a shallower southern region exhibiting shelf-like characteristics, and deeper central and northern regions having ocean-like conditions (see Plate 1). The flushing time scale for North Atlantic Ocean water to circulate through the North Sea is on the order of one year, which resets North Sea conditions on annual time scales. Despite deleterious impacts of eutrophication on its northernmost ecosystem during the second half of the 20th century, the relatively strong mixing has prevented spreading of the anoxic conditions characterizing the German bight and other near-shore areas. International management efforts have led to improvement of water quality over recent decades, although pelagic and benthic fauna are still under severe pressure from exploitation. On the other hand, the relatively good ventilation makes the North Sea susceptible to disturbances originating in or experienced by the North Atlantic Ocean, including the declining pH due to the rise in atmospheric CO₂ concentration.

Box 2-4: The Black Sea: A Nearly Closed, Freshwater-dominated Basin

The Black Sea is a deep basin with a broad shelf zone in its northwestern area. Although its maximum depth exceeds 2200 m, it is fresh-water dominated. Eighty percent of the total river discharge of about 300 km³ y⁻¹ enters the northwestern shelf. The exchange with the Atlantic Ocean via the Mediterranean Sea is restricted to narrow straits, creating a nearly enclosed environment with a surface salinity that is
about half that of the Mediterranean Sea. The extremely strong vertical stratification restricts ventilation and encourages accumulation of hydrogen sulfide (H₂S) in the deep layers.

A permanent feature of the upper layer circulation is the encircling Rim Current, which forms a sharp (40-80 km wide) salinity front over the continental slope and dynamically decouples the coastal and open sea waters. Permanent and transient mesoscale anticyclonic circulations develop between the jet current and the coast, providing a mechanism for coastal-open sea exchange.

The Black Sea’s continental shelf hosts a biodiverse ecosystem that is, however, heavily affected by a massive influx of nutrients and pollutants from the surrounding coastal areas. From the 1970s to the 1990s, the delivery of nitrogen and phosphorus to the northwestern Black Sea increased by factors of 3 and 10, respectively, mostly as a result of more intensive agriculture, while silica decreased by a factor of ~4, leading to significant modification of inorganic nutrient ratios. Eutrophication and enhanced oxygen deficiency as a result of human intervention in river flow, introduction of a ctenophore (Mnemiopsis leidyi) that achieved dominance, overfishing, uncontrolled sewage discharge and dumping of wastes, have all added to the Black Sea’s ecological problems (e.g., see Lancelot et al., 2002a and references therein).

Environmental monitoring during the last several years has indicated a perceptible and gradual improvement in the state of some biotic components of the ecosystem in the western coastal waters (Black Sea Environment Programme, 2002; Chapter 3, this volume). One of the most noticeable improvements was the reduction in the nutrient input, reducing the frequency and intensity of algal blooms (Petranu et al., 1999). During 1995 and 1996, the mesozooplankton biomass was observed to be more abundant than in previous years, which is also reflective of a gradual improvement in the ecosystem. However, the effects of high zooplankton mortality in past decades are still evident in the reduced benthos.

The recent availability of reliable computational tools for the Black Sea ecosystem (Lancelot et al., 2002b; Beckers et al., 2002) has opened the road to predictions based on the integration of up-to-date data and numerical models (Stanev, 2005). Results indicate that future improvement of environmental conditions will depend on further reductions of riverine nutrient input (Black Sea Environment Programme, 2002).

**Climatic effects on vertical stratification:** By changing temperatures and freshwater fluxes, climate change will affect the stratification of the water column. Stratification controls the vertical exchange of heat and dissolved elements, hence the supply of nutrients to the photic zone. Stronger stratification, resulting from warming of the upper ocean, will reduce upward mixing of nutrients from the subsurface layers and reduce the depth of oxygen penetration from the atmosphere. Episodic cooling, for example after volcanic eruptions or from unusual weather regimes, can also affect the formation of intermediate water masses in regional seas and contribute to transport of nutrients from deeper layers into the photic layer. This occurred in the Black Sea during the first half of the 1990s (Stanev et al., 2003).

**Increased occurrence of phytoplankton blooms:** Increasing runoff, to the extent that it occurs, is expected to increase the likelihood and intensity of phytoplankton blooms in coastal areas (Rabalais et al., 2002). This can occur because fresh water can increase stratification and inputs of the macronutrients that lead to phytoplankton blooms, although the end result will depend on changes in the ratios of the individual nutrients (Anderson et al., 2002; GEOHAB, 2005). In high-latitude regions,
changes in the timing of sea-ice formation and breakup, combined with changes in timing and amount of river runoff, are also likely to impact the timing of plankton bloom formation and related events involved in the marine food web. One of the best-known examples is the northern Gulf of Mexico, where seasonal hypoxia and plankton blooms are sustained by nutrient inputs provided by the Mississippi River (Turner and Rabalais, 1994). Mixing of the water column during hurricanes only relaxes the hypoxic conditions temporarily because large hurricanes draw additional nutrients into the water column from the sediments, and because increased freshwater inflow from rivers carry with them increased amounts of nutrients (see Chapter 11, this volume).

Officer and Ryther (1980) hypothesized that if a Si:N ratio of 1:1 for diatoms was not maintained, then a phytoplankton community of non-diatoms might become competitively enabled. The alternative community would be more likely to be composed of flagellated algae such as dinoflagellates, including noxious bloom-forming algal communities. This has been observed in various SEMS, including the East China Sea (Gong et al., 2006; Jiao et al., 2007), the Baltic Sea (Radach et al., 1990), the North Sea (Lancelot et al., 1987), and the Northern Adriatic (Granéli et al., 1999).

Changes in nutrient rations also cause the fisheries web to switch to less desirable species. This actually happened in the continental shelf waters near the Mississippi River delta (Turner et al., 1998); when the Si:N ratio dropped below 1:1, the copepod abundance of the zooplankton dropped from 80% to 20%. The fecal pellet production of copepods and the relative proportion of carbon carried from the upper to the lower water column via fecal pellets also declined. Because copepod fecal pellets contain many partially decomposed diatoms, they sink much more rapidly than individual phytoplankton cells, and there is relatively less decomposition enroute to the bottom. For this reason, more of the sinking organic material is respired in the bottom layer if copepods dominate the zooplankton community than when the Si:N ratio is < 1:1 and copepods are relatively scarce. These findings are affected when eutrophication occurs in the presence of higher diatom production (i.e., when Si:N > 1:1). Under these conditions, there is greater fecal pellet production, more carbon sedimentation to the bottom layer, higher respiration rates in the lower water column, and development of hypoxia throughout the stratified water column.

**Altered size distribution of organisms:** The size distribution of phytoplankton and zooplankton can also change if the copepod density is decreased for a period longer than their generation time. For these conditions, Turner (2001) projected that a reformed phytoplankton community of smaller cells would be grazed by a new community of smaller prey of different escape velocities, growth rates, aggregation potential, and palatability, or by filter feeders, such as salps.¹ A sequence of events leading to reduced productivity of different trophic levels has been documented on the northwestern shelf of the Black Sea as nitrogen and phosphorus loads increased and silica decreased (Zaitsev, 1992; Lancelot et al., 2002a).

**Biogeochemical cycling of elements:** Alterations of nutrient inputs and nutrient speciation and organic matter input influence primary production and respiration processes, which in turn play a significant role in determining the system’s trophic state. While organic matter inputs can play a direct role in creating anoxic conditions that kill off the marine life on which society depends, inorganic nutrients play a more complicated role because primary production supplies not only organic matter,

---

¹Salps are gelatinous barrel-shaped marine animals that have a free-floating life at sea. Salps filter feed on the smallest phytoplankton fraction. Like other tunicates, salps contribute to the carbon cycle by aggregating the carbon into fecal pellets that sink to the ocean floor.
but also oxygen, to offset anoxia. If the water column is shallow and/or poorly ventilated, sinking or settled organic matter will be remineralized over short time scales, promoting anoxic conditions.

The balance between oxygen consumption via remineralization of organic matter and oxygen supply determines the concentration of dissolved oxygen. The supply of oxygen is controlled by advection and mixing, both within the basin and with the open ocean. The residence time of water is largely determined by the exchange with the open ocean. The residence time of water within the oxygen minimum zone (OMZ) of the central Gulf of Mexico is less than a year, resulting in a high oxygen concentration (>100 µM). Basins that have long residence times (thousands of years), such as the Black Sea, are essentially anoxic below the pycnocline. Oxygen concentrations within the OMZ in the Bay of Bengal are as low as ~2-3 µM. This implies that minor changes in oxygen consumption or supply could make the water column of this region denitrifying (Box 2-5).

**Box 2-5: Bay of Bengal: Very Open, But Very Vulnerable to Change**

The Bay of Bengal, including the Andaman Sea, is strongly influenced by monsoonal seasonality and by inputs from surrounding landmasses. As a result of the high monsoonal precipitation over the Bay and runoff from a number of major rivers, reduced surface salinities are found over most of this large semi-enclosed marine system. Consequently, the upper water column here is among the most strongly stratified in the world, affecting nutrient replenishment from deeper waters and gas exchange between the ocean and atmosphere.

The basin receives enormous quantities of dissolved and particulate matter. The dissolved inorganic nitrogen (DIN) input from the Ganges-Brahmaputra river system alone is estimated to contribute about 10% of the global total (Dumont et al, 2005); nonetheless, the region is still considered nitrogen-limited. The supply of suspended sediment by this river has led to the formation of one of the world’s largest deltas and is essential for stabilizing the low-lying coastline of Bangladesh. The surrounding regions are among the most densely populated on Earth, making this oceanic region highly vulnerable to human-induced changes.

In this region, disturbances from climate change in combination with other human influences are likely to lead to a number of ecological and socioeconomic impacts:

1. Changes in monsoon precipitation and reductions in snow cover in the Himalayas, coupled with enhanced water utilization, will alter freshwater inputs to the Bay of Bengal, affecting both stratification and dissolved silica loading. Any relaxation of the stratification is likely to bring about enhanced emission of CO₂. Addition of nutrients from subsurface waters via mixing and upwelling would enhance productivity and most probably affect local food web structures (e.g., reducing the presently high diatom contribution to primary production).

2. Eutrophication caused by enhanced inputs of nutrients from both river runoff and atmospheric deposition triggers primary production and related organic matter input to the water column, altering oxygen demand. This is especially important because the Bay of Bengal’s subsurface waters are presently close to suboxic. Therefore, any disturbance to the delicate biogeochemical balance between organic matter supply, regeneration and oxygenation has the potential to bring about large changes in regional biogeochemistry and functioning of the ecosystem (e.g., onset of water column denitrification, emission of N₂O).

3. A rise in sea level of a meter or more, along with associated coastal erosion, would very likely lead to a huge loss of land, with serious socioeconomic implications, especially for Bangladesh. This
effect would be likely to be compounded by projected increases in the strength of the tropical cyclones that frequently cause enormous loss of life and property.

(4) Sea level rise is a severe threat to the extended mangrove forests of the Sundarbans, and would add to the intense human pressure on these forests. With a pace of change that is expected to be too rapid for this complex ecosystem to adjust, the Sundarbans might face partial or even complete disappearance. Thus, the natural functions of the mangroves, including provision of nursery grounds for fish, stabilization of the coastline, and modulation of land-ocean fluxes, as well as related services provided to the coastal population, would be heavily impacted.

**Increased emission of greenhouse gases:** Production and release to the atmosphere of the greenhouse gases nitrous oxide and methane (N₂O and CH₄, respectively) are expected to increase with increasing oxygen deficiency. This holds for the Bay of Bengal, where production of greenhouse gases is large. However, recent studies of N₂O in the Black Sea did not find it to be a strong source (Westley et al., 2006). Methane accumulates in the Black Sea and the Cariaco Trench to ~15 µM (Reeburgh, 2007), which is four orders of magnitude higher than in surface waters of the open ocean. CH₄ concentrations in surface layers can be supersaturated with respect to the atmosphere in spite of the presence of methane oxidizing bacteria in the water column.

**Acidification of the ocean:** The oceanic carbonate system involves a complex balance among individual carbonate species (CO₂, H₂CO₃, HCO₃⁻, CO₃²⁻). However, the overall response of the carbonate system to perturbations is predictable: higher atmospheric CO₂ concentration will shift the pH of the surface ocean to lower values and lower the concentration of CO₃²⁻. The CO₃²⁻ concentration, in turn, controls the saturation state of carbonates (Zeebe and Wolf-Gladrow, 2001). The decreasing carbonate saturation level during the next 100 years is likely to have multiple impacts. Changes to the carbonate system by acidification of the ocean are likely to make carbonate precipitation more difficult for calcifying organisms (Kleypas et al., 1999) and will interfere with the biological pump, which transfers organic matter produced in the surface waters to the deep ocean (Armstrong et al., 2002; Klaas and Archer, 2002). Changes in the biological pump are likely to affect the distribution of nutrients and oxygen in the water column and the burial rate of organic matter in sediments (Volk and Hoffert, 1985; Jahnke, 1996; Rixen et al., 2000; Rixen and Ittekkot, 2005).

For SEMS, the most important effect is likely to be on the marine species they host. The effects of the decrease in ocean pH on pelagic and benthic calcifying organisms will be larger in the colder waters of high latitudes, and the resulting impacts on the food web and fish stocks are also likely to be greatest there. In lower latitudes, corals will be disproportionately affected. In particular, the aragonite saturation state is decreasing. In the Bay of Bengal the saturation state has decreased from between 4.0 and 4.5 to between 3.5 and 4.0 since the beginning of the Industrial Revolution (Kleypas et al., 2006) and is projected to drop below 3 by the year 2100. This would threaten coral reefs and disrupt their ability to sustain the diversity of SEMS and their ability to deliver ecosystem services (Box 2-6).

---

**Box 2-6: Impacts on Coral Reefs Fringing Tropical SEMS**

Coral reefs are among the most diverse ecosystems in the world. They also function in ways that provide ecosystem services to tropical peoples and tourists from around the world. Their largest threats come from overexploitation, eutrophication, and sediment loading. Global surveys of the status of reefs around the world indicate conditions are serious, and many countries have programs to protect their reefs. In addition to local stresses, however, global warming is also impacting reefs, contributing, for example, to acidification and to the extensive coral bleaching during El Niño events (e.g., 1997-1998).
Ocean acidification caused by the rising concentration of atmospheric CO₂, especially given projected levels in the future, suggests a catastrophic future. Laboratory and model results indicate that coral calcification will be reduced by 30-40% during the 21st century. Algal replacement and competition will also be more evident. Dissolution of reefs will result in loss of their ability to function and provide services, making tropical coastal areas even more vulnerable to extreme events such as tropical storms and tsunamis/floods.

Concluding Remarks
The intention of this chapter has been to provide an overview of examples of how human-created disturbances are affecting and foreseeably could affect SEMS. Our purpose has been to illustrate the wide variety of processes active in these highly diverse oceanic regions. The description of the physical and chemical impacts given here provides a foundation for the three following cross-cutting chapters which, in turn, focus on thresholds and key drivers of accelerated or even abrupt change (Chapter 3), the implications for sustaining ecosystem services (Chapter 4), and the best tools for assessing the present condition and future states of SEMS (Chapter 5).

Climate change will affect many of the characteristics of SEMS, including average and extreme temperatures, precipitation intensity and patterns, runoff intensity and timing, salinity distribution, circulation, stratification, mixing, and chemical properties. We recommend regional assessments to evaluate the state of understanding of SEMS, identify important questions that need to be investigated, and take measures to increase the resilience of the system and reduce the potential for adverse consequences. These assessments must be made jointly by the scientific community and local and regional managers and decision makers.

References


Geophysical Union