

Chapter 2

The Vulnerability of Coastal Zones Towards Climate Change and Sea Level Rise

Abstract Natural and human systems of the coastal zone are vulnerable to climate change and its various consequences. One of the main impacts of climate change is sea level rise which affects coasts world wide. Ecosystems are also vulnerable to changes in water temperature and acidity, both of which have already changed notably in the world's oceans. In many, but not all regions, the intensity of extreme weather events has increased. In addition to these, local conditions, especially winter conditions in the Gulf of Saint Lawrence, are evolving and altering the natural dynamics of the coastline. All taken together, these factors lead to a generalized increase in coastal erosion rates, in added stresses for ecosystems and ultimately threats to properties, infrastructures and the livelihood of communities.

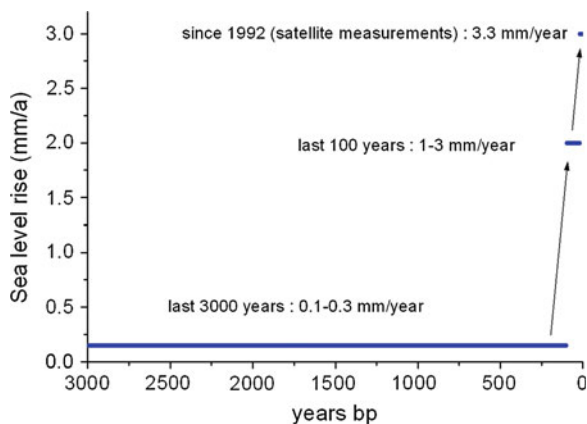
Keywords Sea level rise • Climate change • Coastal zone • Exposure • Coastal erosion

2.1 Sea Level Rise—Causes and Future Outlook

2.1.1 *What Causes Sea Levels Rise?*

Sea levels have fluctuated throughout the Earth's history in response to climate changes and geological events. In the course of the last deglaciation, between 20,000 and 8000 years ago, the sea level rose at a rate of about 10 mm per year, for a total of 130 m (Alley et al. 2005). The presence of land bridges at the end of the Pleistocene allowed population movements across areas nowadays covered by water such as the British channel, the straight of Tasmania or the Bering bridge. Over the last hundred years, sea level rise, which had flattened out over the previous millennia, picked up at an increasing rate, which can only be attributed to the effects of climate change (Fig. 2.1). More precise data obtained from satellite measurements from 1992 on indicate an even faster rate for that period than that extrapolated

Fig. 2.1 Rates of sea level rise over the last 3000 years.
Source S. Weissenberger, 2013



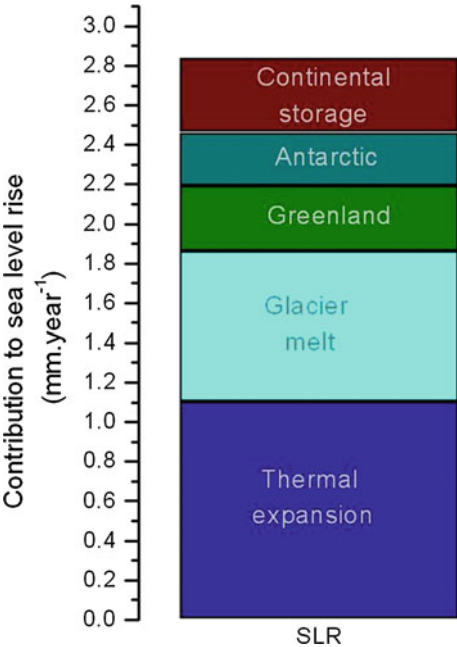
for the last century from other measurements, mainly tidal gauges. Since 1850, the sea level rose by about 19 cm worldwide (IPCC 2013).

Recent sea level rise has two main causes. One is the melting of continental glaciers and polar ice sheets; the other is the thermal expansion of the warming ocean. The numbers involved are small compared to the size of the ocean. The ocean covers roughly 71 % of the Earth's surface, equivalent to $3.6 \times 10^8 \text{ km}^2$. It contains 1.3×10^{21} (sextillion) litres of water, which represents 97 % of all water on Earth. In comparison, glaciers and icecaps represent only a tiny fraction, 1.74 %, of the Earth's water. The thermal expansion coefficient of water, $2.07 \times 10^{-4}/^\circ\text{C}$ is also quite small. Thus, the 19.5 cm of sea level rise that occurred between 1870 and 2004 (Church and White 2006) represent only $5.15 \times 10^{-6} \%$ of the mean depth of the ocean of 3790 m. But for the world's 1,634,701 km of coastline (WRI 2012),¹ this increase in sea level has very real and tangible effects, however small it may be at the scale of the ocean. Earlier modelling efforts reflected among others in the third assessment report (IPCC 2001) were not able to match observed sea level rise with known contributions. That gap has however since been closed, such that the individual contributions from thermal expansion, glacier and ice sheet melt and continental water storage account for the 2.8 mm year^{-1} of sea level rise observed between 1993 and 2010 (IPCC 2013) (Fig. 2.2).

The two main causes of sea level rise have contributed almost equally to recent sea level rise. Thermal expansion (or thermosteric sea level rise) has been estimated at $0.40 \pm 0.09 \text{ mm year}^{-1}$ between 1955 and 1995, $1.6 \pm 0.5 \text{ mm year}^{-1}$ between 1993 and 2003 (Antonov et al. 2005) and $1.1 \pm 0.3 \text{ mm year}^{-1}$ between 1993 and

¹Due to their fractal dimension, the length of coastlines vary according to the scale. The smaller the scale, the longer the coastline, as Benoît Mandelbrot explained in 1967 in his seminal article "How Long Is the Coast of Britain? Statistical Self-Similarity and Fractional Dimension" (*Science* 156, 636–638). Thus, with a scale of 200 km, the coast of Great-Britain measures 2400 km, with a scale of 50, 3400 km.

Fig. 2.2 Contributions to sea level rise from 1993 to 2010. *Source* S. Weissenberger with data from IPCC (2013)



2010 (IPCC 2013). The contribution from glacier melt, excluding the Greenland and Antarctic ice sheets, has been estimated at $0.50 \pm 0.18 \text{ mm year}^{-1}$ between 1961 and 2003, $0.77 \pm 0.22 \text{ mm year}^{-1}$ between 1993 and 2003 (IPCC 2007) and $0.76 \pm 0.18 \text{ mm year}^{-1}$ from 1993 to 2010 (IPCC 2013). The rate of glacier melt has increased in both hemispheres and remains subjected to some level of uncertainty, especially for the Greenland and Antarctic ice sheets (Bindschadler 2006) (Table 2.1).

Some human activities also influence sea levels. Thus, the increase of reservoir area behind the world’s dams has caused a drop of sea level of $0.5\text{--}0.7 \text{ mm year}^{-1}$ over the previous decades (IPCC 2001). On the contrary, groundwater extraction for agriculture or human consumption contributes to sea level rise. Although the estimate of $0.77 \text{ mm year}^{-1}$ between 1961 and 2003 (Pokhrel et al. 2012) is likely exaggerated, groundwater extraction might add 5–8 cm of sea level rise by the end of the 21st century (Konikow 2013; Rahmstorf et al. 2011; Wada et al. 2012).

2.1.2 How Far Will Sea Levels Rise in the Future?

The estimation of future sea level rise has been the subject of many discussions during recent years. IPCC estimates have often been considered too conservative, in that they do not take into account a possible acceleration of ice sheet melt.

Table 2.1 Contribution to sea level rise from selected glaciers and ice sheets

Region	Period	Sea level rise (mm year ⁻¹)	Source
All glaciers excluding Greenland and Antarctic	1961–1990	0.33 ± 0.17	Kaser et al. (2006)
	1961–2003	0.50 ± 0.18	IPCC (2007)
	1993–2003	0.77 ± 0.22	IPCC (2007)
	2001–2004	0.77 ± 0.15	Kaser et al. (2006)
	1993–2010	0.76 ± 0.18	IPCC (2013)
Alaska	1950–1990	0.14 ± 0.04	Meier and Dyurgerov (2002)
	1990–2000	0.27 ± 0.10	Arendt et al. (2002)
	1962–2006	0.12 ± 0.02	Berthier et al. (2010)
Patagonia	1968/ 1975–2000	0.042 ± 0.002	Davies and Glasser (2012)
	1995–2000	0.105 ± 0.011	
Rwenzori mountains	1987–2003	0.03	Taylor et al. (2006)
Greenland	1996–2005	0.5	Rignot and Kanagaratnam (2006)
	1961–2003	0.05 ± 0.12	IPCC (2007)
	1993–2003	0.21 ± 0.07	IPCC (2007)
	1993–2010	0.33 ± 0.08	IPCC (2013)
	1992–2011	0.39 ± 0.14	Shepherd et al. (2012)
Antarctica	2002–2003	>0.2	Thomas et al. (2004)
	2002–2006	0.2–0.6	Velicogna and Wahr (2006b)
	1961–2003	0.14 ± 0.41	IPCC (2007)
	1993–2003	0.21 ± 0.35	IPCC (2007)
	1993–2010	0.27 ± 0.11	IPCC (2013)
	1992–2011	0.20 ± 0.23	Shepherd et al. (2012)
	2010–2013	0.32	McMillan et al. (2013)

Semi-empirical models based on correlation analysis of historic temperatures or radiative forcing generally yield higher rates of sea level rise than mechanistic models, which are the base of IPCC estimates (Table 2.2). Mechanistic models have however improved greatly and are now able to account for all sea level rise over the last twenty years (IPCC 2013). Therefore, over time, a convergence of mechanistic and semi-empirical models can be expected. The main reason for the ranges in projected sea level rises in IPCC reports are the emission or CO₂ scenarios, followed by model ranges for a given scenario. Possible rapid changes in ice sheet dynamics resulting in faster sea level rise are not included, due to a lack of knowledge about those processes (IPCC 2013). Therefore, those estimates are not necessarily worst-case scenarios.

Table 2.2 Some estimates of sea level rise in the 21st century

Sea level rise in the 21st century (cm)	Details	Source
9–88	Likely ranges according to the different emission scenarios	IPCC (2001)
18–59	Likely ranges according to the different emission scenarios	IPCC (2007)
26–82 (98)	Likely ranges according to the 4 scenarios (assuming a higher rate at the end of the century for the RCP8.5 scenario)	IPCC (2013)
50–140	Semi-empirical model, correlation with paleoclimatic temperatures yielding a proportionality constant of $3.4 \text{ mm}^{-1} \text{ year}^{-1} \text{ }^{\circ}\text{C}^{-1}$	Rahmstorf (2007)
74–190	Semi-empirical model, correlation with paleoclimatic data, addition of rapid response term	Vermeer et al. (2009)
60–160	Semi-empirical model, correlation with radiative forcing over the past 1000 years	Jevrejeva et al. (2010)
90–130	Semi-empirical model, correlation with temperatures over the last 2000 years	Grinsted et al. (2009)

The main sources of uncertainty in estimates of future sea level are the Greenland and Antarctic ice sheets, which contain two thirds of all freshwater and 95 % of ice on the planet. The Greenland ice sheet contains the equivalent of 6 m of sea level rise, the Antarctic 23 m, seven of which are in the more unstable West Antarctic Ice Sheet (WAIS). The future behaviour of the ice sheets remains uncertain. An increase of melting rates has been observed over the first decade of the 21st century for the Greenland ice sheet (Joughin 2006; Rignot and Kanagaratnam 2006). The melt rate has increased from $0.13 \text{ mm year}^{-1}$ SLR equivalent² between 1994 and 1999 (Krabill et al. 2000) to $0.5 \pm 0.1 \text{ mm year}^{-1}$ between 2002 and 2006 (Velicogna and Wahr 2006a; Murray 2006). Both rates are higher than the -0.02 to $0.09 \text{ mm year}^{-1}$ from the Third IPCC report for the period 1961–2003 (IPCC 2001). In the Antarctic, the western part (WAIS) is losing ice, at a rate of $0.4 \pm 0.2 \text{ mm year}^{-1}$ between 2002 and 2005 (Velicogna and Wahr 2006b), while the interior of the continent has gained $0.12 \pm 0.02 \text{ mm year}^{-1}$ between 1992 and 2003 (Davis et al. 2005).

Both ice sheets have substantially melted in the past and will indeed continue to melt for several centuries or millennia in response to current climate change. During the last interglacial, sea levels were about 6 m higher than present, which is attributed to a partial melt of the Greenland and West Antarctic ice sheets (Schøtt Hvidberg 2000; Cuffey and Marshall 2000; Otto-Bliesner et al. 2006). And during

²Volumetric ice losses can be converted into equivalents of sea level rise via the surface of the ocean. This nomenclature is adopted in IPCC reports.

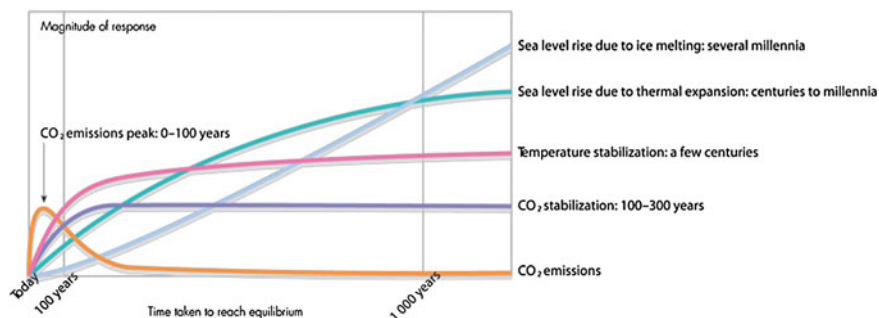


Fig. 2.3 Evolution of the different components of sea level rise over time. *Source* IPCC (2001), UNEP/GRID-Arendal, 2006

the Pliocene, around three million years ago, the last time atmospheric CO₂ concentrations were around or in excess of 400 ppm, sea levels were 22 ± 5 m higher than today; neither the Greenland nor the West Antarctic Ice Sheets existed (Miller et al. 2011).

It is important to consider that sea level rise, although often expressed as expectations for the end of the 21st century, will extend far beyond that deadline, for several hundred years after stabilization of atmospheric CO₂ concentrations for thermal expansion, equivalent to the ocean overturning period, and even several millennia for ice sheets to find a new equilibrium as function of new atmospheric conditions (Fig. 2.3).

2.1.3 Is Sea Level Rise Uniform?

Sea level rise is not uniform in time and space, as it depends on a number of variables, such as ocean currents, dominant wind patterns, climate oscillations, continental crust movements or punctual events like volcanic eruptions. Thus, the centres of the large oceanic gyres are elevated by 20 cm. El Niño creates similar sea level differences between Australia and South America. The Krakatau volcanic eruption of 1883 caused a temporary drop in sea levels by cooling surface water for several decades (Gleckler et al. 2006). The El Niño event of 2010–2011 caused massive rainfalls over South America leading to a temporary continental storage of all that water and a concomitant drop of sea levels by a centimeter during that period (Boening et al. 2012). In the northern hemisphere, isostatic rebound leads to an elevation of the continental crust in certain areas, at the center of the former ice sheets, and a subsidence of others, at the edges of those ice-sheets. In certain regions, changes in salinity can lead to sea level changes. For example, in the subpolar gyre of the North Atlantic, increasing salinity and the resulting halosteric sea level drop cancels out part of the thermosteric sea level rise (Bindoff et al. 2007).

2.1.4 Sea Level Rise Gulf of St. Lawrence and Coast of New Brunswick

Over the past hundred years, an acceleration of sea level rise could be observed on the coasts of the southwestern part of the Gulf of Saint Lawrence, as evidenced by tidal gauges measures (Forbes et al. 2006) (Fig. 2.4). Differences in the rate of relative sea level rise at the three gages stem from different rates of isostatic

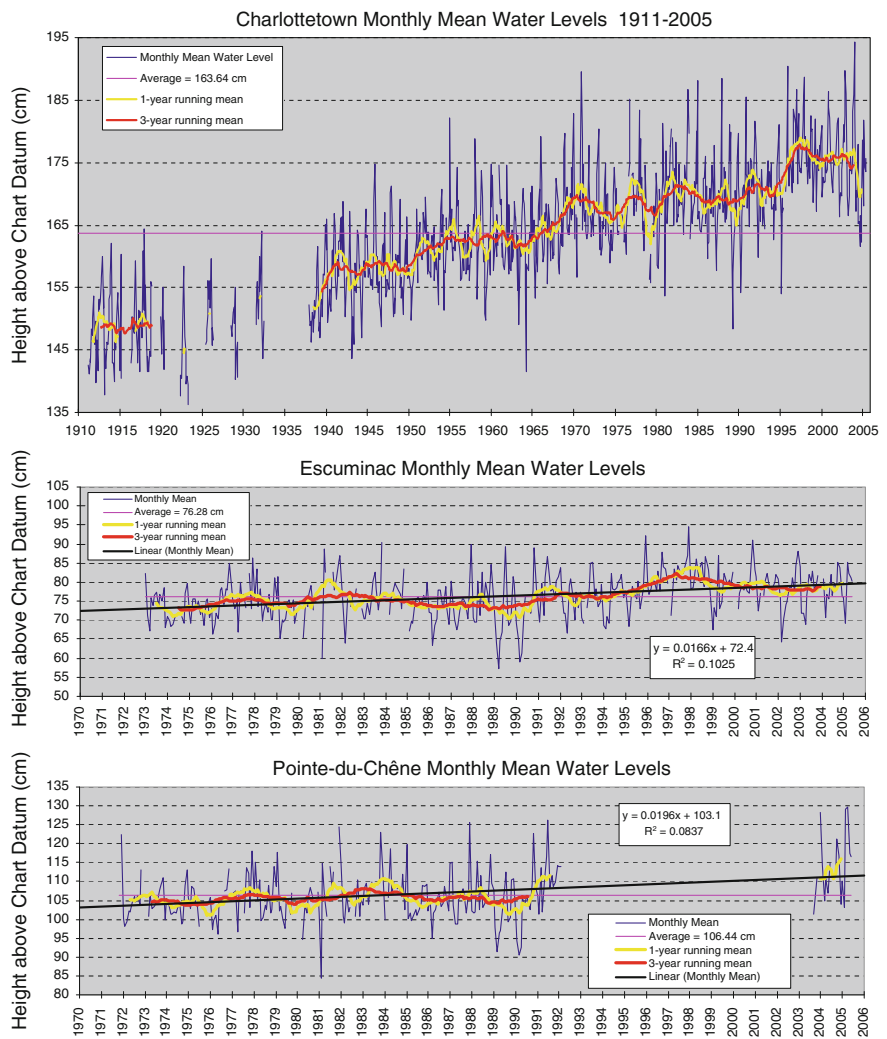


Fig. 2.4 Monthly mean water levels for three tidal gauges in the Gulf of Saint Lawrence. Source Forbes et al. (2006)

Table 2.3 Extrapolated rates of sea level rise for different parts of the Acadians coast in southeastern New Brunswick using a value of 44 cm for global sea level rise according to IPCC IS92A scenario (from Forbes et al. 2006)

Site	Vertical motion (cm) 2000–2100	Relative sea level rise (cm) 2000–2100
Cape Jourimain	15 ± 5	59 ± 35
Shemogue	13 ± 5	57 ± 35
Cap-Pelé	12 ± 5	56 ± 35
Shediac	10 ± 5	54 ± 35
Bouctouche	9 ± 5	53 ± 35
Kouchibouguac	7 ± 5	51 ± 35
Escuminac	6 ± 5	50 ± 35

adjustment. The exact rates of isostatic adjustment are still subject to debate (Forbes et al. 2006, Daigle 2012). Glaciers have retreated from the southwestern part of the Gulf of Saint Lawrence around 14,000 years ago (Forbes et al. 2006). At this point, large areas around the Northumberland Strait were submerged. Between 9000 and 7500 years ago, those areas emerged (Forbes et al. 2006). Subsequently, water levels rose at a decelerating rate until the 19th century.

Based on tidal gauge measurements up to 2005 and crustal motion derived from those measurements, and from sea level rise scenarios from IPCC's third assessment report, Forbes et al. (2006) extrapolate the following relative sea level rise for different points of the Acadian coast in New Brunswick (Table 2.3).

2.2 Increase in Extreme Weather Events and Changes in Winter Conditions

2.2.1 Increase in Storm Frequency and Intensity

The impact of climate change varies from region to region. In the northern mid-latitudes, a strengthening of westerly winds has been observed between the 1960s and the 1990s³ paired with a northward migration of storm tracks, explaining the increase in storm intensity, winds speed and wave heights observed in the North Sea or in Atlantic Canada (Trenberth et al. 2007; Lefebvre 2000; Daigle 2006). Since periods of strong storm activity have occurred in the past, for example at the end of the 19th century (Alexandersson et al. 1998, 2000) and barometric measurements only started in 1880, it is difficult to extrapolate current trends for the middle and far future. However, the observations are in agreement with climate model results (Fischer-Bruns et al. 2002, 2005) and according to likely climate

³For a representation of the evolution in significant wave height between 1950 and 2002, see Gulev and Grigorieva (2004) in IPCC (2007), http://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-3-25.html.

scenarios, storm surges in the North Sea could increase by 20 cm in 2030 and 70 cm in 2085 (Helmholtz Gesellschaft 2007).

Hurricanes seldom reach the Gulf of Saint Lawrence and if they do, it is only as tropical storms. Hurricane activity in the north Atlantic is influenced by the Atlantic multi-decadal oscillation (AMO), whose warm phase (e.g. 1930–1960) corresponds to a higher, and its cold phase (e.g. 1905–1925, 1970–1990) to a reduced hurricane activity. The increase in strong hurricanes since the 1970s is however mostly attributed to higher water temperatures as a result of climate change, as indicated amongst others by the strong correlation between the energy dissipation index and water temperatures (Emanuel 2005; Goldenberg et al. 2001; Trenberth et al. 2007; Webster et al. 2005). In contrast, the overall number of hurricanes has decreased during the period 1957–2004 (Ren et al. 2006).

The Gulf of Saint Lawrence is characterized by a highly variable storm activity. Storm surges can exceptionally reach a height of 10 m, but 99 % of waves do not exceed 4 m. On the southeast coast of New Brunswick, an increase in overall storm frequency is not discernable, but instrumental records suggest an increase in high intensity events in the years 2000–2004 (Fig. 2.5). The data also shows the presence of underlying multidecadal cycles (Parkes et al. 2006). It must be noted that strong storms that occurred in recent years, especially in 2005 and 2010, are not yet included in the graphs below. Several tidal gauges, including Québec, Charlotte-town and Pointe-du-Chêne have recorded historic maxima during the last decade. Climate models predict an increase in wave heights over the 21st century, despite a possible decrease in the total frequency of storms (Savard et al. 2008).

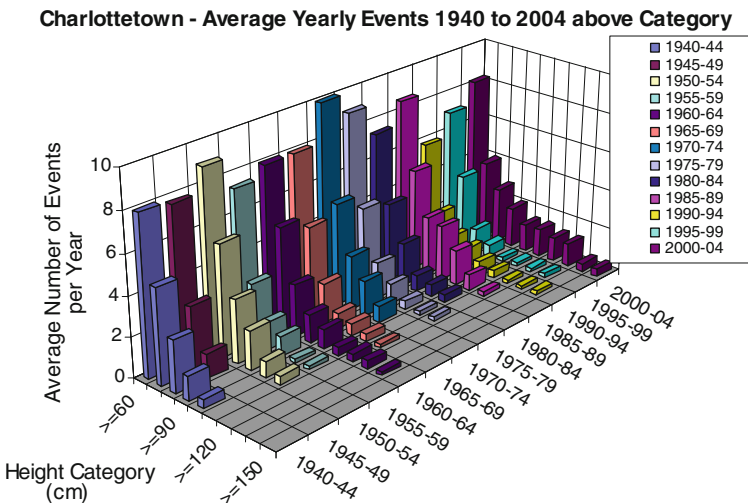


Fig. 2.5 Evolution of storm surge amplitudes by decade from 1940 to 2004. *Source* Parkes et al. (2006)

2.3 Changes in Winter Conditions

As in most northern regions, a change in winter conditions has been observed in Atlantic Canada over the past decades. Sea ice cover has been reduced in size and duration (Fig. 2.6) and thaw-frost cycles have become more frequent. In the Gulf of Saint Lawrence, the ice-covered period has decreased by about one third between 1969 and 1995 and could disappear entirely by the end of the 21st century (Savard et al. 2008). As sea ice protects the coasts from winter-storm surges, this contributes to an increase in erosion rates.

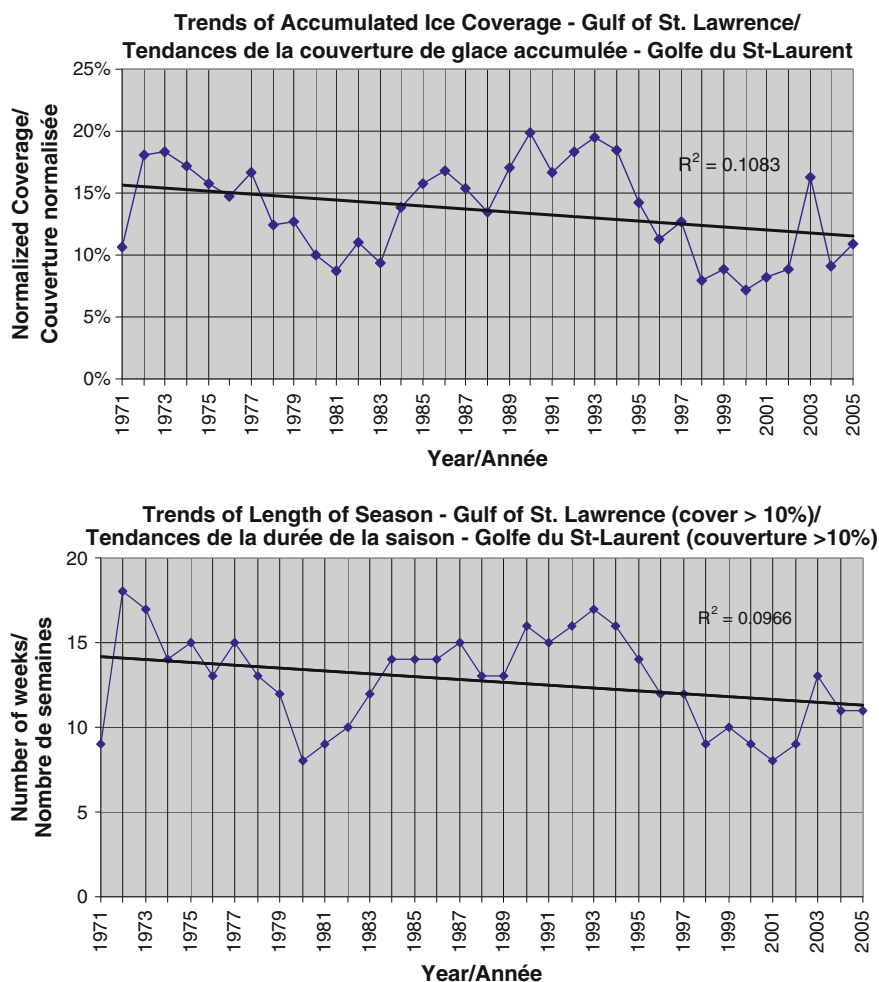


Fig. 2.6 Decrease of the duration and extent of ice cover in the Gulf of Saint Lawrence. *Source* Parkes et al. (2006)



Fig. 2.7 Cliff erosion caused by frost-thaw cycles, Carleton, Quebec, Canada. *Source* S. Weissenberger, 2012

The increase in frost-thaw cycles has a severe impact on erosion rates of friable shores, especially cliffs made out of glacial tills, as are very frequent in Atlantic Canada (Fig. 2.7).

2.4 Ocean Warming and Acidification

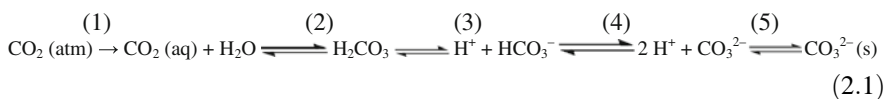
Ocean warming and acidification are two consequences of human CO₂ emissions which have the potential to greatly disrupt marine and coastal ecosystems, in addition to sea level rise and extreme weather events. Because of its roughly one thousand times higher heat capacity, the ocean warms more slowly than the atmosphere, while absorbing 20 times more heat (Levitus et al. 2005). Thus, oceans have absorbed over 90 % of all the energy accumulated in the Earth's surface due to increased radiative forcing since 1970, two thirds of which in the first 700 m (IPCC 2013). During the last ten years, during which the atmosphere has warmed at a slightly slower rate, the upper (0–700 m) and middle (700–2000 m) ocean has kept accumulating heat without discernable slowing down in comparison to the previous decade (IPCC 2013).

Water temperatures in the Gulf of Saint Lawrence have increased by 0.9 °C for the yearly average and 1.6 °C for winter temperatures during the 20th century (Savard et al. 2008). A recent analysis of NOAA satellite data indicates a rapid warming of 1.8 °C between 1985 and 2009, which is probably in part due to local circumstances (Galbraith et al. 2010, 2012).

Increased water temperatures affect species and ecosystems, possibly leading to (1) migration of species, (2) alteration of ecosystems, (3) adaptation of species and assemblages, or (4) deterioration of ecosystems. The possible impacts of ocean warming, and in the long term ocean acidification, on American lobster (*Homarus americanus*) include physiological effects (Camacho et al. 2006; Dove et al. 2005), activity and catchability (McLeese and Wilder 2011), reproduction (Tlustý et al. 2008), the spread of diseases (Cawthorn 2011) and other indirect effects resulting from ecosystems alterations (Parsons 1996; Scheibling 2012; Wharton and Mann 2011). Ocean warming will also significantly influence cod population, leading to a change in seasonal cycles, a northwards expansion and a further reduction in stocks in some traditional cod fishing areas such as Celtic and Irish seas, the Baltic, the Scotian shelf or the Gulf of Maine (Clark et al. 2003; Drinkwater 2005; Drinkwater et al. 2010; Fogarty et al. 2008).

Ocean acidification has often been referred to as the “other” CO₂ problem (Doney et al. 2009). Since preindustrial times, ocean acidity has increased by about 30 %, from pH 8.2 to pH 8.1 as a response to increased atmospheric CO₂ concentrations (Eq. 2.1), and might increase by a further 0.14–0.35 pH units in the course of the 21st century (Solomon et al. 2007; Orr et al. 2005). Ocean acidification is faster in high latitudes, due to the higher solubility of CO₂ in colder waters. Acidification has the potential to affect all calcifying organisms, such as crustaceans, including copepods, an essential component of zooplankton, foraminifera and molluscs. Several of those species, including lobster, snow crab, shrimps, oysters and mussels are mainstays of local fisheries and aquaculture. It has also been found that elevated acidity can disrupt physiological processes in several aquatic species that lack adaptation mechanisms towards it (Doney et al. 2009).

Carbonic acid equilibrium reactions



Legend (1) Atmospheric CO₂ dissolves in sea water, (2) dissolved CO₂ transforms into carbonic acid H₂CO₃, (3) and (4) carbonic acid dissociates as function of pH, bicarbonate HCO₃[−] being the main species under oceanic conditions, (5) dissolved carbonate ions CO₃^{2−} are in equilibrium with carbonate in inorganic and organic particulate matter, as calcite or aragonite.

Locally, water properties such as temperature, salinity and pH can also change as a result in hydrodynamics. Thus, in the Gulf of Saint Lawrence, a 4–24 % decrease in freshwater inflow from the Saint Lawrence River is expected by the mid 21st century (Savard et al. 2008). On the other hand, an increase in cold water inflow from the Labrador Sea across the Strait of Belle Isle has been observed since 1996 (Starr et al. 2002). The pH has decreased by 0.2–0.3 units since 1934 in the deep

waters of the Gulf of Saint Lawrence, while remaining almost unchanged in surface waters, which is due to a stronger inflow of anoxic and CO₂ rich water masses rather than to an uptake of atmospheric CO₂ (Benoît et al. 2012).

2.5 Coastal Erosion and Its Impact on Infrastructure

2.5.1 *Erosion as an Accelerated Natural Process*

Erosion is a natural process by which beaches and cliffs are shaped over time. It can give rise to surprising shapes such as the Hopewell Rocks on the Bay of Fundy shore (Fig. 2.8). Natural beaches and cliffs are in a steady state, also termed as dynamic equilibrium. Material stemming from the erosion of the cliffs or dunes behind the beach replenishes the beach at the same time as wave action carries sand and other materials out to the sea. Thus, the structure of the beach remains preserved as it moves backwards into the land. Additionally, lateral currents known as the littoral drift cause a sideways movement of sand and sediments, which explains that certain spits or dunes “move” along the beach. In reality, they decrease through erosion on one side and increase through accretion on the other side. In estuaries and lagoons, the dynamics of shore evolution can be quite complex.

Climate change has lead to an increase in erosion rates in the majority of sectors of the New Brunswick coastline because of sea level rise, increased wave activity and more frequent frost-saw cycles. There are however also sectors which are in net growth, in which littoral drift carries eroding material from neighbouring sectors to. Erosion rates are particularly high on the east coast of New Brunswick, somewhat lower in the Chaleur Bay and lowest in the Bay of Fundy.

Fig. 2.8 Hopewell Rocks, Fundy Bay, New Brunswick, Canada. *Source* S. Weissenberger, 2011



2.5.2 Coast Type and Rate of Coastal Retreat

Bruun's formula from 1962 predicts a coastal retreat rate of 1.0–1.5 m per centimetre of sea level rise (Heberger et al. 2009). This is of course a very rough approximation, since the coastal retreat rate will strongly depend on the coastal substrate and the exposure to erosion agents such as wind and waves. Hard cliffs (granite, gneiss, basalt, etc.) erode much more slowly, at rates of a few millimetres per year, than soft cliffs (limestone, shale, etc.), which have retreat rates of the order of centimetres per year, or friable and loose cliffs (soft limestone, till, etc.). Unfortunately, harder substrates like granite are also more difficult and costly to build on, so that houses and infrastructure are often located on more rapidly eroding substrates. Dunes and beaches erode more quickly than cliffs. Vegetated shores are usually more erosion-resistant than sandy shores.

Insert: common types of costal substrate around the Gulf of St. Lawrence

Granite is a hard impermeable igneous rock of plutonic origin, formed by the slow cooling of magma, during which it acquires a crystalline structure. The main minerals of granite are quartz, feldspath and mica, but there are numerous variations of granite with different colours. Most of the Earth's crust, and in particular of the Canadian shield, is formed by granite, which can be over 4 billion years old.

Slate (Shale) (Fig. 2.9) is a clastic sedimentary rock formed in two stages, first by compaction in shallow waters (diagenesis) and then by metamorphosis. Depending on the degree of metamorphosis, slate, phyllite, schist and gneiss are distinguished. Slate can be made of silt, quartz, calcite or clays and can have various colours from red to black.

Fig. 2.9 Slate cliffs at Meat Cove Beach, Cape Breton, Nova Scotia, Canada. *Source* S. Weissenberger, 2013



Fig. 2.10 Phyllite cliffs in Cape Breton, Nova Scotia, Canada. *Source* S. Weissenberger, 2013



Phyllite (Fig. 2.10) is a foliated metamorphic rock formed by metamorphosis of slate. It is intermediate between slate and schist. Phyllite is commonly black, grey or light greenish with a silvery sheen (phyllic luster).

Gneiss is a metamorphic rock originating from granite (orthogneiss) or from clay (paragneiss). Flattening and stretching during the metamorphosis generate the typical banded or bedded structure, often with altering colours. Gneiss is found at the base of highly eroded mountain ranges. The St. John region in Southern New Brunswick has granite and biotite gneiss formations.

Basalt is a grey-black very hard rock of volcanic origin. Basalts are formed by rapid cooling of lava flowing to the surface during volcanic eruptions of along ocean ridges. The several hundred feet deep North Mountain basalt of the Early Mesozoic Fundy extends in the Fundy Bay between New Brunswick and Nova Scotia and is visible in places such as Grand Manan and other locations in New Brunswick, Nova Scotia and

Fig. 2.11 Banded red sandstone and black shale from the Mississippian (old carboniferous) at Cape Saint Lawrence, Cape Breton, Nova Scotia, Canada. *Source* S. Weissenberger, 2013



Fig. 2.12 The Roché Percé in Gaspé is a 433 m long, 90 m wide and 88 m high siliceous limestone formation weighing 5 million tons. The second arch (*on the right*) collapsed in 1854. *Source* D. Ménard, 2001, in Wikipédia



Maine. They are part of the central Atlantic magmatic province (CAMP) which covered 11 million km² shortly before the breakup of Pangea.

Sandstone (Fig. 2.11) is a detrital rock formed by the aggregation of sand and sometimes quartz in lake, river or desert sediments. Under the pressure of overlying sediments, the sand particles are cemented by silicates or carbonates to form a yellow, red or brown rock.

Limestone (Fig. 2.12) is a white sedimentary rock made of calcite (70 %) and aragonite, two carbonates of marine origin, mostly formed by plankton. It is a popular building material since antiquity. Over geological periods, limestone is water-soluble leading to erosional landforms like karsts and caves. Chalk, Travertine, Tufa and Coquina are various forms of limestone.

Till (Fig. 2.13) is a heterogeneous assemblage of glacial deposits of various sizes formed during the last glaciation. Primary deposits consist in rock carried by the glaciers. Deformation till denotes primary deposits which have been reworked and homogenized through fluvial transport or other events.

Fig. 2.13 Cliff with glacial till overlying sandstone cliff in Trout Brook, Nova Scotia, Canada. *Source* S. Weissenberger, 2013



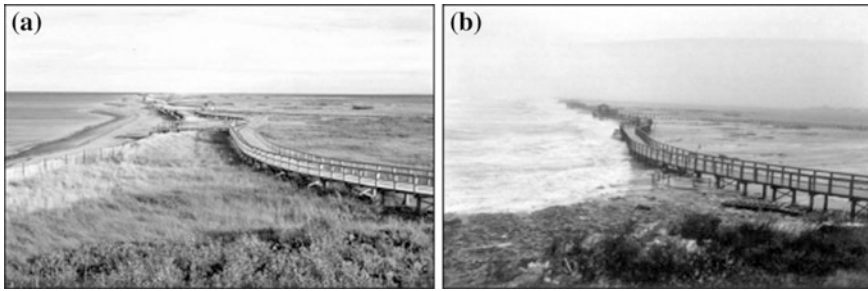


Fig. 2.14 The Bouctouche dune **a** in the summer 2000 and **b** during the storm of October 2000. *Source* Jolicoeur et al. (2010)

Tillite is a sedimentary rock formed from till that has been buried into solid rock and lithified.

Erosion is a gradual process over long time periods, but often occurs in a dramatic fashion during storms, when strong waves carry away large quantities of substrate. The accumulation of strong storm events in recent years in the Gulf of Saint Lawrence is therefore a contributing factor to high erosion rates in exposed shore segments. In the Sept-Îles area on the north shore of the Saint Lawrence estuary and in the Magdalen Islands in the middle of the Gulf of Saint Lawrence, erosion rates of up to 7 m have been measured following the storm of October 2005 (Bernatchez et al. 2008). The Bouctouche dune has been repeatedly flooded in recent years and lost considerable amounts of sand (Fig. 2.14). During the storm of December 2010, half of the walkway and 8 m of beach were lost.

2.5.3 Coastal Retreat in New-Brunswick

Most of the coast of New Brunswick has little elevation and relief. The coastal plain consists mainly of glacial deposits (till, moraines) overlying older bedrock. Rock cliffs can be found to a small extent on the southern part of the Acadian peninsula or on the Bay of Fundy shore. Most of the hinterland is not well drained, accounting for the strongly meandering rivers and the presence of numerous coastal wetlands. A large part of the coast is protected by dikes (Table 2.4), which have their origins in the Acadian dykes of the 17th century. The scarcity of forested coastlines is also attributable to the deforestation which occurred initially during the Acadian occupation of the land in order to create agricultural land and procure firewood and construction materials, later through English settlers and, especially in the 19th century, for shipbuilding at a time where New Brunswick accounted for up to one quarter of Canada's registered tonnage (New Brunswick Museum 2003).

Table 2.4 Constitution of the coasts of New Brunswick

Type of land	Surface area	
	Area (ha)	Percentage
Salt marshes	14,622	47.6 %
Diked lands	125,954	41.0 %
Sand dunes	2580	8.4 %
Beaches	829	2.7 %
Rock platforms	93	0.3 %

Source Authors, after data from Bérubé (n.d.)

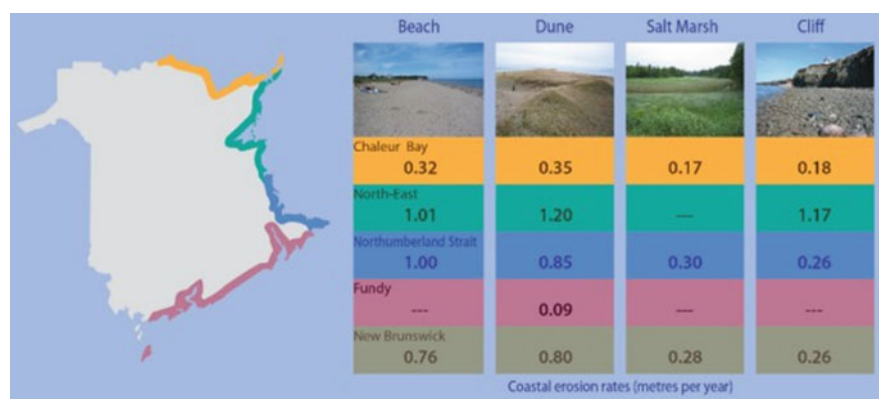


Fig. 2.15 Erosion rates measured in different sectors of the New Brunswick coast. Source New Brunswick Department of Natural Resources (n.d.)

In New Brunswick, average erosion rates observed are 0.26 m year⁻¹ for cliffs, 0.28 m year⁻¹ for coastal wetlands, 0.76 m year⁻¹ for beaches and 0.80 m year⁻¹ for dunes. They are higher on the east coast (North–East and Northumberland strait) than in the Chaleur or Fundy bays (Fig. 2.15).

Like large tracts of the coastal zones of the Gulf of Saint Lawrence, most of the coast of New Brunswick can be considered as moderately to highly vulnerable according to Natural Resource Canada’s assessment, based on a sensibility index adapted from Gornitz (1990), which includes seven variables: relief, geology, morphology, relative sea level rise, coastline movement, wave height, amplitude of tides.



Fig. 2.16 Damages on road 113 on the island of Miscou, New Brunswick, Canada. *Source* S. Weissenberger, 2012



Fig. 2.17 Abandoned road due to coastal erosion at Richibuctou Head (Cap Lumière). *Source* New Brunswick Department of Environment/Paul Jordan

2.5.4 Impact of Coastal Erosion on Buildings and Infrastructures

Coastal erosion puts houses, properties, roads and infrastructure at risk. Besides an increasing risk of flooding during storm events, a receding coastline can undermine the foundation of houses, necessitating an evacuation, demolition or relocation.

Fig. 2.18 The camping ground l'Étoile Filante in Shediac, New Brunswick, Canada, flooded during the storm of December 2010.
Source S. Doiron, 2010



Roads and railways are often built near the coast, linking villages and urban centers. In recent years, in New Brunswick, and more generally in the Gulf of Saint Lawrence, considerable damages has occurred to coastal roads and railways, necessitating costly repairs and consolidation, in some instances even landward displacement (Figs. 2.16 and 2.17).

2.5.5 Impact of Climate Change and Coastal Erosion on Tourism

Tourism, mainly situated on the coast, is a rapidly growing industry in New Brunswick and a considerable source of revenue and employment for the province. In 2010, tourism contributed about 1.1 billion dollar in revenue, 738 million dollars of which from non residents, representing 3.5 % of provincial GDP, and 34,700 jobs for an equivalent of 19,600 full-time jobs, representing 9 % of provincial labour force (Province of New Brunswick 2012). However, the tourism sector is particularly vulnerable to the impacts of climate (WTO 2009; Scott et al. 2012), through its effect on ecosystems, on the coastline, damage to tourism infrastructure mainly situated in coastal areas and indirectly through the visual impact of coastal protections. Extensive damage has been caused by storms in the last decade to camping sites, beach infrastructure or educational infrastructure (Fig. 2.18). On the positive side, an increase in air and water temperatures might represent an additional argument for tourists to visit New Brunswick, which bases part of its publicity strategy on having “the warmest waters north of Maine”, but only if water quality, popular beaches and often visited ecosystems remain unaffected by climate change. Winter activities, such as skiing, skating or snowmobiling would suffer in equal measure as summer activities potentially benefit from a warmer climate.

2.6 Conclusion

Even after an eventual stabilization of atmospheric CO₂ concentrations and in term of the Earth's climate, sea level rise will continue for many centuries. Therefore, coastal erosion and flood risk will remain a growing problem in the world's coastal zones. When warming and increasingly acid oceans, changes in the patterns of extreme weather events and altered winter conditions are added to the equation, it becomes clear that considerable challenges lie ahead for many coastal areas. The sensitivity of New Brunswick's coasts is already becoming apparent as erosion rates and the frequency of severe flooding increase. Climate change can therefore not be ignored when the future development of the coast is considered.

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