Chapter 24

Coastline Degradation as an Indicator of Global Change

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1. INTRODUCTION

Coastal degradation has been widely reported around the world's coasts over the past century, and especially in recent decades as discussed later in this chapter [1,2]. This degradation can be attributed to the intensification of a wide range of drivers of coastal change that are linked directly and indirectly to an expanding global population and economy. The twentieth century was also characterised by recognition of human-induced climate change and sea-level rise, which constitutes an additional set of coastal drivers [3]. This chapter explores the relative contribution of climate change to observed coastal changes, focusing particularly on the extent to which climate change can be attributed as a significant driver of the change.

Climate Change: Observed Impacts on Planet Earth

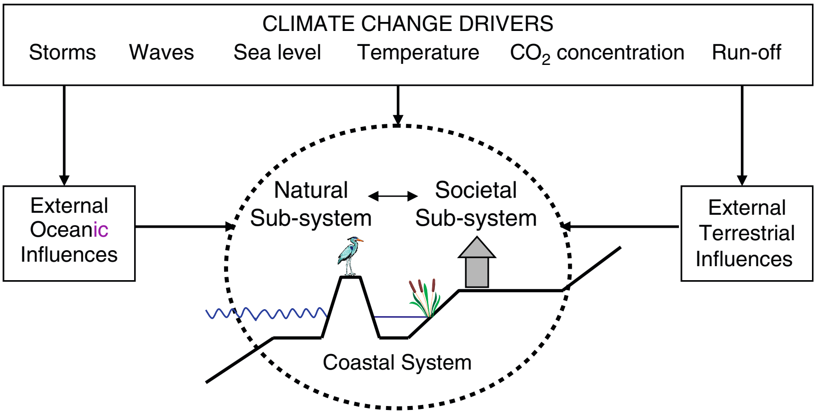

FIGURE 1 The coastal system showing how it is impacted by climate change. The natural environment and coastal inhabitants interact directly, and are affected by external terrestrial and marine issues. Climate change, including sea-level rise, can directly or indirectly effect the coastal system (as can non-climate drivers of change). (Adapted from Ref. [3]).

An analytical framework is adopted, based on a systems view of coasts as defined in Fig. 1. Comprising the narrow interface between land and sea, coastal systems are influenced by both marine and land surface processes. Coastal systems include intertidal zones and adjacent coastal lowlands and bays, lagoons, estuaries and nearshore waters. The connectivity of coasts with both marine and terrestrial systems is responsible, in part, for the high variability and complexity among coastal system types. In contrast to terrestrial systems that have physical gradients that can stretch over tens or thousands of kilometres, coastal biotic and abiotic gradients are often relatively short, particularly along steep rocky shores. Many coastal areas support large and growing populations and high economic activity [4,5], which are changing coastal environments. River catchments feeding to the coast are increasingly modified, such that coastal systems are also influenced by these external changes [6]. Hence, few of the world's coastlines are now beyond the influence of human pressures [7], with many being dominated by human activities [8] and most coastal systems include elements of human development that interact with environmental changes associated with a warming climate.

Global warming through the twentieth century has caused a series of changes with important implications for coastal areas (Fig. 1). These include rising temperatures (both air and sea surface temperatures), rising sea level, increasing CO_2 concentrations with an associated reduction in seawater pH, and more intense precipitation on average (with substantial regional variation). It has also been argued that tropical storms have become more intense [9]. The tragic impacts of Hurricane Katrina on the Gulf of Mexico coast of the United States in 2005 and of Cyclone Nargis on Myanmar in 2008 emphasise the enormous devastation that these events cause, but it cannot be shown that these individual events were more intense as a result of climate change, and no firm conclusions on intensification of storms can be drawn at present.

Sea-level rise is one of the most widely cited outcomes of global warming. Rising global sea level due to thermal expansion and the melting of land-based ice is already being observed with a global-mean rise of 17 ± 5 cm during the twentieth century [9] and a slow accelerating trend [10]. Higher sea level will directly impact coastal areas, including some of the most densely-populated and economically active land areas on Earth.

In this chapter, we outline historical climate and sea-level change and discuss how this impacts coasts, but we also recognise that coastal systems are subject to many other drivers, most especially the impacts of human development. We further discuss the need to discriminate whether coastal degradation can be attributed to the effects of climate or to what degree they are related to non-climate drivers.

2. SEA-LEVEL RISE AND COASTAL SYSTEMS

Since the peak of the last glacial maximum about 20 000 a (years) ago, sea level has risen ~125 m [11]. Geologic evidence indicates inundation of coastal lowlands and retreat of shorelines during periods of rapid sea-level rise, such as major meltwater pulses (Fig. 2). This pattern of sea-level rise was experienced around the world, driven by the melt of the large ice sheets

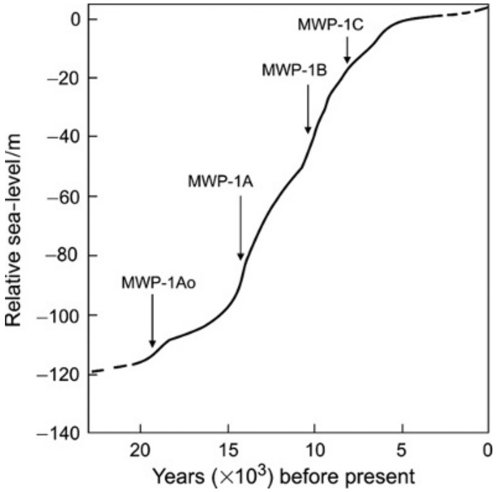

FIGURE 2 Sea-level history since the peak of the last glacial maximum with arrows indicating the timing of meltwater pulses. Abbreviations: MWP = meltwater pulse. MWP-1A0, c. 19 000 a ago, MWP-1A, 14 600–13 500 a ago, MWP-1B, 11 500–11 000 a ago, MWP-1C, ~8200–7600 a ago (Source: Ref. [12]).

which appears to have ceased 7500–6000 a ago. The level of the sea has risen less than 3 m over the past 6000 a and regional variations of sea level on time scales of a few 100 a or longer are likely to have been less than 0.3–0.5 m [13]. As sea level stabilised extensive coastal plains were formed, and the first evidence of early civilisations appeared on the plains [14,15].

Coastline location and stability is intimately linked with changes in mean sea level. However, even under conditions of relatively stable mean sea level, coasts are extremely dynamic systems, involving co-adjustment of form and process at different time and space scales, termed morphodynamics [16,17]. Hence, erosion and deposition of coasts are naturally occurring due to short-term wave and tide conditions, as well as seasonal and longer-term climatic variability. The El Niño phenomenon, for example, has been shown to influence wave processes that shape beaches in the southwest Pacific [18] and cliffs in the eastern Pacific [19].

3. CLIMATE CHANGE AND GLOBAL/RELATIVE SEA-LEVEL RISE

The impacts and responses of coasts to sea-level rise are a product of relative (or local) sea-level rise rather than global changes alone. Relative sea-level rise takes into account global-mean sea-level rise, regional trends in the absolute elevation of the ocean surface, and geological uplift or subsidence and related processes which change the position of the land/sea boundary. Relative sea-level rise is only partly a response to climate change and can vary significantly among coastal systems (Fig. 3). Abrupt changes may occur, for example, where an earthquake causes rapid vertical displacement of a part

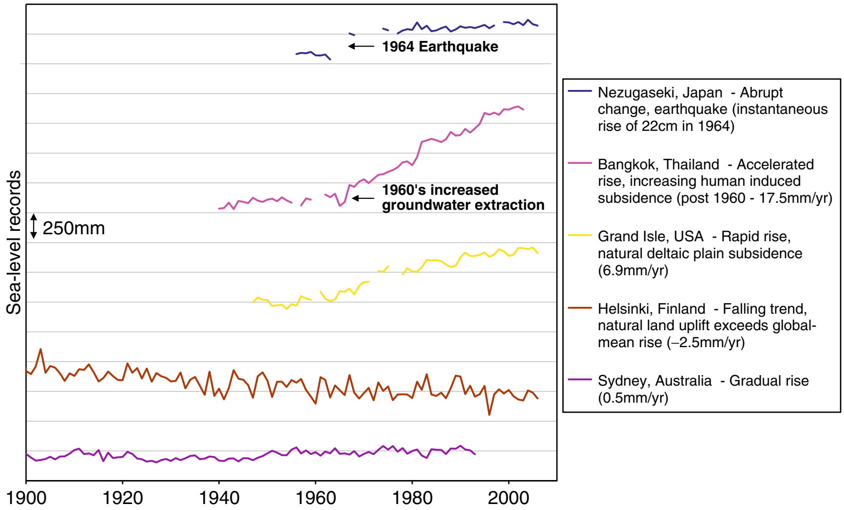

FIGURE 3 Selected relative sea-level records for the twentieth century, illustrating different types of trend. The records are offset for display purposes. Source: http://www.pol.ac.uk/psmsl/.

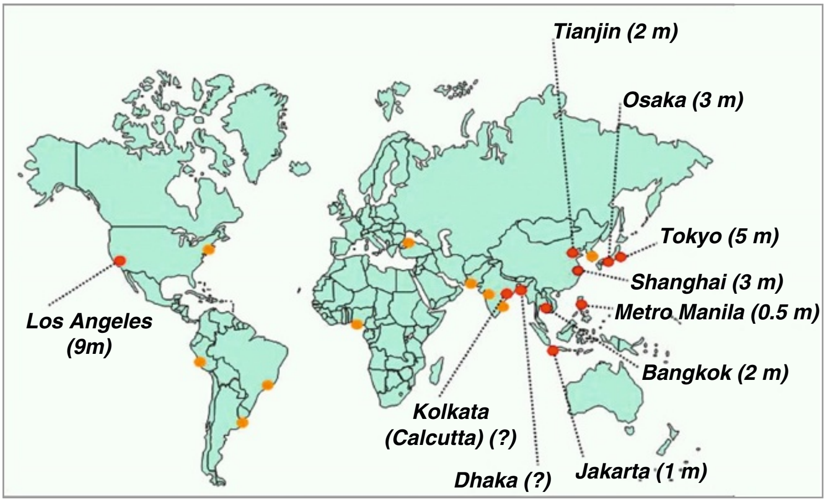

FIGURE 4 Subsiding coastal megacities with the maximum observed subsidence (in m) (adapted from Ref. [23]). Subsidence in Los Angeles was very localised (about 1 km^2) and due to oil extraction. Dhaka and Kolkata are thought to be subsiding, but data is limited.

of the Earth's surface (see Nezugaseki; Fig. 3). Sea level is presently falling due to ongoing glacial isostatic adjustment (rebound) in some high-latitude locations that were formerly sites of large (kilometre-thick) glaciers, such as Hudson Bay and the northern Baltic (see Helsinki, Fig. 3). In contrast, sea level is rising more rapidly than global-mean trends on subsiding coasts, including deltas such as the Mississippi delta (see Grand Isle, Fig. 3), the Nile delta, and the large deltas of south and east Asia [20,21]. Most dramatically, human-induced subsidence of susceptible areas due to drainage of organic soils and withdrawal of groundwater can produce dramatic rises in relative sea level, especially in susceptible coastal areas and cities built on recently-deposited deltaic landforms [22]. Four noteworthy examples over the twentieth century are parts of Tokyo and Osaka which subsided up to 5 and 3 m, respectively, most of Shanghai which subsided up to 3 m, and nearly all of Bangkok which subsided up to 2 m (see Bangkok; Figs. 3 and 4). As a management response to human-induced subsidence, stopping shallow sub-surface fluid withdrawals can reduce subsidence.

4. INCREASING HUMAN UTILISATION OF THE COASTAL ZONE

Human use of the coast increased dramatically during the twentieth century. It has been estimated that 37% of the world's population lives within 100 km, and 49% lives within 200 km, of the coast [24]; the greatest number of people live at low elevations and population densities in coastal regions are about

3 times higher than the global average [4]. Almost two-thirds of urban settlements with populations greater than five million occur at low elevations in the coastal zone (less than 10 m above mean sea level). A disproportionate number of the countries with a large share of their population in low elevation coastal zones are small island countries. Most of the human population in this zone, however, resides in large countries with densely populated deltas, and migration of people to coastal regions is widespread [5].

The expansion of human settlements and associated infrastructure (roads, buildings, ports, etc.) has directly altered land cover and land surface processes in large parts of the world's tropical and mid-latitude coastal landscapes. This rapid urbanisation has many consequences; for example, enlargement of natural coastal inlets and dredging of waterways for navigation, port facilities and pipelines exacerbate saltwater intrusion into surface and ground waters. Increasing shoreline retreat and consequent risk of flooding of coastal cities in many parts of the world have been attributed in part to the degradation of coastal ecosystems by human activities, as well as subsidence as already discussed [3]. As a result of this, cities often progressively move to artificial defensive and drainage systems as they develop/expand and their influence on their environs increases.

The natural ecosystems within watersheds have been fragmented and the downstream flow of water, sediment and nutrients to the coast disrupted [25]. Land-use change and hydrological modifications have had downstream impacts, in addition to localised influences, including human development on the coast. Hillslope erosion has increased the sediment load reaching the coast; for example, suspended loads in the Huanghe (Yellow) River have increased 2–10 times over the past 2000 a [26]. In contrast, damming and channelisation has greatly reduced the supply of sediments to the coast on other rivers through retention of sediment in dams [6], and this effect has dominated through the twentieth century [27,28].

The structure and ecological functions of natural systems are altered as a result of population growth, and ecological services provided by coastal systems are often disrupted directly or indirectly by human activities. For example, tropical and subtropical mangrove forests provide goods and services because they accumulate and transform nutrients, support rich ecological communities of fish and crustaceans, attenuate waves and storm surge impacts, and their root systems trap and bind sediments [29,30]. Large-scale conversions of coastal mangrove forests to shrimp aquaculture have occurred during the past three decades along the coastlines of Asia and Central America [31], and the decline or loss of mangrove forests reduces all of these ecosystem services [32]. Similar reductions of temperate salt marshes and wetlands in deltas are often linked to direct land use change [33,34]. Hence, on those developed coasts that have experienced disproportionately rapid expansion of settlements, urban centres, and tourist resorts, the direct impacts of human activities on the coastal zone are profound, with more widespread indirect effects of human activities.

5. CLIMATE CHANGE, SEA-LEVEL RISE AND RESULTING IMPACTS

Relative sea-level rise has a wide range of effects on the natural system; the main effects are summarised in Table 1. Flooding/submergence, ecosystem change and erosion have received significantly more attention than salinisation and rising water tables. Rising sea level alters all coastal processes. The immediate effect is submergence and increased flooding of coastal land, as well as saltwater intrusion into surface waters. Longer term effects also occur as the coast adjusts to the new environmental conditions, including

TABLE 1 **The main natural system effects of relative sea-level rise, including climate and non-climate interacting factors**

			Interacting factors	
Natural system effect			**Climate**	**Non-climate**
1. Inundation (including flood and storm damage)	a. Surge (from the sea)		Wave/storm climate, erosion, sediment supply	Sediment supply, flood management, erosion, land reclamation
	b. Backwater effect (from rivers)		Run-off	Catchment management and land use
2. Morphological Change	a. Wetland loss (and change)		CO_2 fertilisation of biomass production, sediment supply, migration space	Sediment supply, migration space, land reclamation (i.e., direct destruction)
	b. Erosion (of beaches and soft cliffs)		Sediment supply, wave/storm climate	Sediment supply
3. Hydrological change	a. Saltwater intrusion	i. Surface waters	Run-off	Catchment management (over-extraction), land use
		ii. Groundwater	Rainfall	Land use, aquifer use (over-pumping)
	b. Rising water tables/impeded drainage		Rainfall, run-off	Land use, aquifer use, catchment management

Some interacting factors (e.g., sediment supply) appear twice as they can be influenced both by climate and non-climate factors.

wetland loss and change in response to higher water tables and increasing salinity, erosion of beaches and soft cliffs and saltwater intrusion into groundwater. These lagged changes interact with the immediate effects of sea-level rise and generally exacerbate them. For instance, coastal erosion will tend to degrade or remove natural protective features (e.g. saltmarshes, mangroves and sand dunes) that in turn increase extreme water levels and hence the risk of coastal flooding.

A rise in mean sea level also has a net effect of intensifying flooding during extreme storm events [35]. Changes in storm characteristics could have also influenced extreme water levels. Increases in tropical cyclone intensity in the North Atlantic over the past three decades are consistent with the observed changes in sea surface temperatures [9] and wave data in the North Atlantic support this observation [36]. However, it is difficult to prove if this is a systematic change or a component of cyclic variations in the frequency and intensity of tropical storms. Changes in storm tracks might also result from global climate change; in this context, Cyclone Catarina was the first documented hurricane in the South Atlantic, striking the coast of Brazil in March 2004 as a Category 2 storm on the Saffir–Simpson Hurricane Scale [37,38]. The cyclone killed at least three people and caused an estimated US \$350 $\times$ 10^6 in damage in Brazil, and it is unclear whether this indicates an extremely unusual event, or the beginning of a new trend under global warming.

Changes in the natural system due to sea-level rise have many important direct socio-economic impacts on a range of sectors with the effect being overwhelmingly negative. For instance, flooding can damage key coastal infrastructure, the built environment, and agricultural areas, and in the worst case lead to significant mortality as occurred in 2008 when Cyclone Nargis devastated southern Myanmar. Erosion can lead to losses of the built environment and related infrastructure and have adverse consequences for sectors such as tourism and recreation. In addition to these direct impacts, there are indirect impacts such as negative effects on human health. For example, mental health problems increase after a flood [39], or the release of toxins from eroded landfills and waste sites which are commonly located in low-lying coastal areas, especially around major cities (e.g. Ref. [40]). Thus, sea-level rise has the potential to trigger a cascade of direct and indirect human impacts.

6. RECENT IMPACTS OF SEA-LEVEL RISE AND CLIMATE CHANGE

Sea level was relatively stable in the sixteenth to eighteenth centuries; it started to rise in the nineteenth century and rose about 20 cm by the end of the twentieth century, with a global rise of 17 ± 5 cm rise in that century [9,41]. Although this change may seem small, it has had many significant effects, most particularly in terms of the return periods of extreme water levels [35,42]. Worldwide there are many coasts that have been observed to be eroding [43]. However, attributing particular impacts such as erosion to sea-level rise is difficult as erosion can be promoted by processes other than sea-level rise (Table 1). As already discussed, many of these non-climate drivers of change operated over the twentieth century. While sea-level rise is often inferred as an underlying cause of widespread retreat of sandy shorelines [44], negative sediment budgets also lead to erosion [17]. Human reduction in sediment supply to the coast has contributed to observed changes through activities such as construction of levees, dikes and dams on rivers that drain to the coast [6,45]. Equally, changes in flooding and flood risk are difficult to attribute to global sea-level rise. For instance, flood defences have often been upgraded substantially through the twentieth century, especially in those (wealthy) places where there are sea-level measurements. Most of this defence upgrade reflects expanding populations on the coastal plains and changing attitudes to risk. In many places, relative sea-level rise has rarely even been considered in the design of past coastal infrastructure.

The accelerated rate of sea-level rise observed since the late 1800s has been accompanied by coastal erosion and rapid wetland losses in many low-lying coastal regions. On the US east coast, relative sea levels have risen at rates of between 2 and 4 $\mathrm{mm \cdot a^{-1}}$ over the twentieth century due to varying patterns of subsidence caused by glacial isostatic adjustment. Both rates of sea-level rise and coastal retreat have been measured, providing the opportunity to explore shoreline response to sea-level rise. Away from inlets and engineered shores, the shoreline retreat rate is 50–100 times the rate of sea-level rise, as might be anticipated using the concept of the Bruun Rule [46]. Near inlets, the indirect effects of sea-level rise which cause the associated estuary/lagoon to trap beach sediment can have much larger erosional effects on the neighbouring open coasts than predicted by the Bruun Rule [47]. So, whereas a simple heuristic like the Bruun rule describes the relationship for some shores, more general relationships are required to fully understand coastal change, taking account of sea-level change, sediment supply and coastal morphology [17].

In coastal Maryland and Louisiana, for example, wetland losses and shoreline retreat have led to a rapid restructuring of coastal ecosystems [33,48,49]. In Florida, a decline in coastal cabbage palm forests since the 1970s has been attributed to salt water intrusion associated with sea-level rise [50,51]. Due to extensive human development along these coastlines, it is not possible to quantitatively isolate climate change effects versus changes due to other human development activities.

Human responses to sea-level rise are even more difficult to document. A rare example is human abandonment of low-lying islands in Chesapeake Bay, USA, during the late nineteenth/early twentieth century which seems to have been triggered by the acceleration of sea-level rise and resulting land loss [52].

There have certainly been impacts from relative sea-level rise resulting from large rates of subsidence, such as the Mississippi delta where relative

FIGURE 5 A line of telegraph poles south of Bangkok, Thailand: built on subsiding land, they are now up to 1 km out to sea.

sea-level rise approaches 1 $cm \cdot a^{-1}$! (see Grand Isle, Fig. 3). Between 1978 and 2000, 1565 km^2 of intertidal coastal marshes and adjacent lands were converted to open water, due to sediment starvation and increases in the salinity and water levels of coastal marshes as a result of human development activities coupled with high rates of relative sea-level rise [53]. The flooding in New Orleans during Hurricane Katrina was significantly exacerbated by subsidence compared to earlier flood events such as Hurricane Betsy in 1965 [54]. Coastal retreat has occurred due to subsidence, such as south of Bangkok where shoreline retreat has been more than 1 km (Fig. 5). However, all the major cities that were impacted by relative sea-level rise have been defended, even when the change in relative sea-level rise was several metres.

Hence, while global sea-level rise has been a pervasive process, it is difficult to unambiguously link it to impacts, except in some special cases; most coastal change in the twentieth century was a response to multiple drivers of change. However, changes in two contrasting environments, polar coasts and tropical reefs, do appear to be directly exacerbated by warmer temperatures.

7. GLOBAL WARMING AND COASTS AT LATITUDINAL EXTREMES

Global warming poses a particular threat to coasts at the latitudinal extremes, polar coasts and coral reefs. Polar coasts are experiencing permafrost melt and a decrease in the extent of sea ice as result of warming which is leading to a significant acceleration in erosion rates. Rapid shoreline erosion has been occurring on parts of the Arctic coast over recent decades, attributed in part to reduced sea ice cover allowing more wave activity to reach the shoreline [55]. Reduction in thickness of near-coastal ice, more rapid ice movement and retreat of the glacier fronts in Greenland appears related to warmer temperatures [56,57]. Similar trends to Greenland have been reported from the Antarctic Peninsula [58,59].

Parts of the Alaska coastline on the Beaufort Sea have retreated as much as 0.9 km in the past 50 a (Fig. 6). This coastal region is exposed to a combination of factors relating to climate change – sea-level rise, the thawing of permafrost and the reduction in sea ice that protects that coastline from

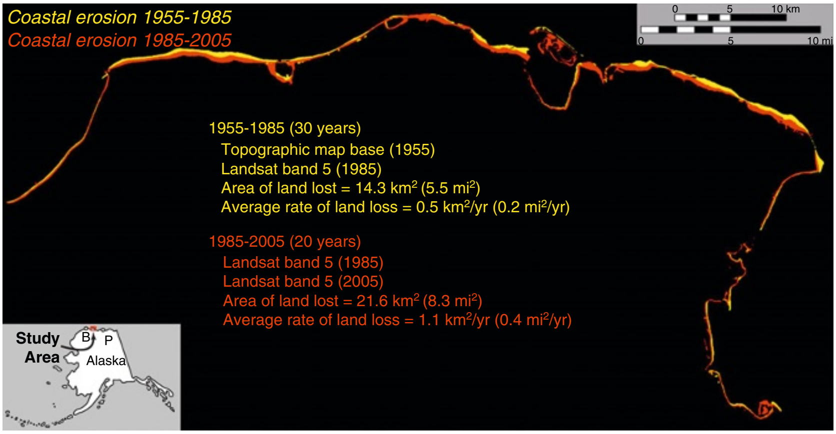

FIGURE 6 An example of land loss due to coastal erosion in northern Alaska over 50 years (1955–1985 and 1985–2005) based on ground survey and satellite (Landsat) measurements (Source: J.C. Mars and D.W. Houseknech, Unpublished work, U.S. Geological Survey, Reston, VA, USA, 2007) (see Ref. [60]).

erosion during part of the year – all of which are contributing to rapid shoreline retreat. Erosion at the coastline has led to the breaching of thermokarst lakes, causing initial draining followed by an increase in marine flooding that alters plant and animal community structure [60]. Similar retreat is occurring at sites in Arctic Canada [61], and evidence documented from traditional ecological knowledge also points to widespread change of coastlines across the North American Arctic from the Northwest Territories, Yukon and Alaska in the west to Nunavut in the east [62]. However, the impacts associated with human settlement along polar coasts are relatively very low due to the low population in these regions.

Within the tropics, widespread coral bleaching was detected on an unprecedented scale around the globe in response to El Niño-related warming in 1998 [63,64]. Further bleaching occurred across much of the Great Barrier Reef off northeastern Australia in 2002 [65] and in the Caribbean in 2005 [66]. Bleaching occurs when warmer than usual sea surface temperatures lead to expulsion of the symbiotic zooxanthellae from within the coral tissue; the coral surface becomes pale, in many cases leading to mortality. It seems that temperatures ~1 °C above the monthly maximum experienced by the coral result in bleaching, and that persistently high temperatures, or temperatures more than 2 °C above this threshold, can cause the coral to die. Threshold temperatures above which corals bleach have evidently been occurring more frequently [67–69], and the prospect of further global warming implies that reefs may bleach with a frequency that exceeds their ability to recover between events.

Coral reefs are also susceptible to many other stresses, and there are many reefs that are severely degraded as a consequence of human activities, particularly overfishing and pollution [70]. As with other considerations of coastal degradation it is difficult to disentangle the effects of human-induced pressures from those that result directly from climate change. The synergistic effects of various pressures combine to affect reefs, but the occurrence of bleaching on remote reefs well away from direct human development, and its incontrovertible association with increased sea surface temperature provides a salutary warning of the likely consequences should global warming continue unabated. Human impacts, such as overfishing, appear to be exacerbating the stresses on reef systems and, at least on a local scale, exceeding the thresholds beyond which coral is replaced by other organisms [71]. Nevertheless, as with polar coasts, it is difficult to avoid the conclusion that these remote coastlines are changing for the worst as a consequence of rising sea surface temperatures.

8. THE CHALLENGE TO UNDERSTAND CONTEMPORARY IMPACTS

While significant coastal degradation has occurred over the twentieth century it is difficult to unambiguously attribute the relative role of climate change. Most degradation has occurred on coasts that are influenced by one or more non-climate related drivers such as ongoing tectonic or isostatic adjustments, or, increasingly often, as a result of human activities. Further, the magnitude of climate change to date remains relatively small. In the next few decades, global warming will continue and is expected to accelerate, resulting in climate-induced impacts becoming more apparent.

In some coastal regions it is possible to discriminate between those effects that can already be attributed to climate change. Rising air and sea surface temperatures have resulted in detectable impacts on polar and tropical coasts. There is an emerging consensus that the increased frequency of bleaching on coral reefs is related to higher sea surface temperatures. Melting of sea ice and permafrost in high latitudes results from increased temperatures, and this is related to rapid erosion of polar coasts. However, these coasts were already experiencing extensive erosion, and there is no clear procedure for differentiating how much erosion would have been occurring because of ongoing factors, such as isostatic adjustments of the land, and how much additional retreat has occurred because of climate change.

A significant component of global-mean sea-level rise also results from global warming, primarily because of thermal expansion, but with a component from ice melt. Discriminating the impacts of the global-mean sea-level component at regional and local scales where other contributions to relative sea-level change are of variable importance remains problematic. This presents a challenge to further test and refine our understanding about the impacts of climate on coasts, so that better predictions can be made and management plans put in place to respond to the anticipated impacts.

To meet this challenge, it will be necessary to continue and expand monitoring of coastlines, including both the climate and non-climate drivers, and the responses of coastal systems. Climate change is a global phenomenon, and therefore this monitoring and analysis needs to consider changes over broad scales. There will be an increasing role for more sophisticated remote sensing which will be an important tool [34,60]. Comparative studies offer the opportunity to assess sensitivity, comparing those coasts with intense human pressures with more pristine counterparts in less densely populated regions. However, as indicated above, the indirect effects of human modification of the Earth are leaving a pervasive signal in even these remote places; global sea-level change effects those coasts that are uninhabited as well as those that are intensively developed. Studies of analogues of climate change and sea-level rise are also relevant, such as relative sea-level rise on subsiding coasts which can provide insights into outcomes expected more widely in response to global warming induced sea-level rise.

9. CONCLUDING REMARKS

Finding a climate change signal on coasts is more problematic than often assumed. Coasts undergo natural dynamics at many scales, with erosion and recovery in response to climate variability such as El Niño, or extreme events such as storms and infrequent tsunamis. Additionally, humans have had enormous impacts on most coasts, overshadowing most changes that we can presently attribute directly to climate change.

Using the geographic examples cited in this paper, various impacts can be inferred on coasts as a consequence of changes in climate. However, each area of coast is experiencing its own pattern of relative sea-level change and climate change, making discrimination of the component of degradation that results from climate change problematic. The best examples of a climate influence are related to temperature rise at low and high latitudes, as seen by the impacts on coral reefs and polar coasts, respectively. Observations through the twentieth century demonstrate the importance of understanding the impacts of sea-level rise and climate change in the context of multiple drivers of change; this will remain a challenge under a more rapidly changing climate.

Nevertheless, there are emerging signs that climate change provides a global threat – sea ice is retreating – permafrost in coastal areas is widely melting – reefs are bleaching more often – and the sea is rising, amplifying widespread trends of subsidence and threatening low-lying areas. From this analysis some important lessons about the response to these challenges become evident. To devise successful response strategies for coastal degradation it will be important to understand coastal changes in the context of integrated assessment and multiple drivers of change, with climate only being part of the problem [72]. To enhance the sustainability of coastal systems, management strategies will also need to address this challenge, focusing on the drivers that are dominant at each section of coast.

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