

# Chapter 19

## Impact of Climate Change and Loss of Habitat on Sirenians

Helene Marsh, Eduardo Moraes Arraut, Lucy Keith Diagne, Holly Edwards, and Miriam Marmontel

**Abstract** Although the impacts of climate change on the welfare of individual manatees and dugongs are still uncertain, the effects are likely to be through indirect interactions between meteorological and biotic factors and the human responses to climate change. We divided the potential impacts into (1) those that will potentially affect sirenians directly including temperature increases, sea-level rise, increased intensity of extreme weather events and changes in rainfall patterns and (2) indirect impacts that are likely to cause harm through habitat loss and change and the increase in the likelihood of harmful algal blooms and disease outbreaks. The habitat modification accompanying sea-level rise is likely to decrease the welfare of sirenians including increased mortality. Many species of tropical seagrasses live close to their thermal limits and will have to up-regulate their stress-response systems to tolerate the sublethal temperature increases caused by climate change. The capacity of seagrass species to evoke such responses is uncertain, as are the effects of elevated carbon dioxide on such acclimation responses. The increase in the intensity of extreme weather events associated with climate change is likely to decrease the welfare of sirenians through increased mortality from strandings, as well as habitat loss and change. These effects are likely to increase

---

H. Marsh (✉)

College of Science and Engineering, James Cook University,  
Townsville, QLD 4811, Australia  
e-mail: [helene.marsh@jcu.edu.au](mailto:helene.marsh@jcu.edu.au)

E.M. Arraut

Remote Sensing Division, National Institute for Space Research, São José dos Campos, SP, Brazil  
Wildlife Conservation Research Unit, The Recanati-Kaplan Centre, Oxford University,  
Tubney House, Abingdon Road, Tubney OX13 5QL, UK

L.K. Diagne

African Aquatic Conservation Fund, Chilmark, 2535 MA, USA

H. Edwards

Marine Mammal Department, Florida Fish and Wildlife Conservation Commission,  
St Petersburg, FL, USA

M. Marmontel

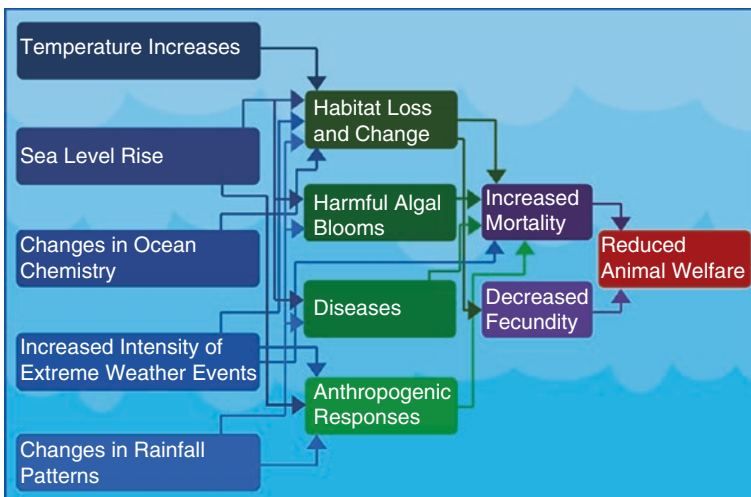
Instituto de Desenvolvimento Sustentável Mamirauá, Tefé, AM, Brazil

the exposure of sirenians to disease and their vulnerability to predators, including human hunters. Climate-related hazards will also exacerbate other stressors, especially for people living in poverty. Thus the risks to sirenians from climate change are likely to be greatest for small populations of dugongs and manatees occurring in low-income countries. The African manatee will be particularly vulnerable because of the high levels of human poverty throughout most of its range resulting in competition for resources, including protein from manatee meat.

## 19.1 Introduction

The impacts of climate change on the welfare of individual manatees and dugongs have not been well explored and are still uncertain (Marsh et al. 2011). The effects are likely to be through indirect interactions between meteorological and biotic factors and the human responses to climate change. Consequently, the impacts of climate change and resultant shift in habitats are likely to be significant for sirenian species.

A simplistic view of the effects of human-induced climate change on sea levels and water temperatures is that they may be beneficial to sirenians. Increased water levels and temperatures could likely allow extension of the ranges of all extant species (e.g. see Lawler et al. 2007). With the exception of the extinct Steller's sea cow, sirenians have typically been restricted to tropical and subtropical waters throughout their evolutionary history (Marsh et al. 2011). Climate changes during the Pleistocene resulted in a northward expansion of manatees in North America (Marsh et al. 2011). However, our analysis of the available literature and data indicates that the impacts will be complex (Fig. 19.1), and on balance, we think climate



**Fig. 19.1** Diagrammatic representation of the direct and indirect effects of climate change on the welfare of sirenians. The impact of these changes is likely to be spatially heterogeneous. In some areas, climate change could have a beneficial effect on sirenians (*Image credit: Elizabeth Collier and Helene Marsh*)

change is likely to have adverse effects on the welfare of manatees and dugongs by increasing mortality and reducing fecundity, hence increasing the likelihood of local extinctions.

In this brief review, we divide the potential impacts into (1) those that will potentially affect sirenians directly, including temperature increases, sea-level rise, increased intensity of extreme weather events and changes in rainfall patterns, and (2) indirect impacts that are likely to cause harm through habitat loss and change and the increase in the likelihood of harmful algal blooms and disease outbreaks. The anthropogenic responses to such changes will likely exacerbate these impacts on manatees and dugongs and have adverse effects on the welfare of individual animals (Fig. 19.1).

## 19.2 Direct Effects of Climate Change on Sirenians: Temperature Increases

According to the Intergovernmental Panel on Climate Change (IPCC, Church et al. 2013), each of the last three decades has been warmer than any preceding decade since 1850. The current estimates of globally averaged land and ocean surface temperature show a warming of 0.85 °C. Over the next 35 years, global mean surface temperatures will likely increase by 0.3 to 0.7 °C and are likely to exceed 1.5 °C by the end of the twenty-first century (Church et al. 2013). Warming of the oceans dominates the increase in energy stored in the climate system and accounts for more than 90% of the energy accumulated between 1971 and 2010 (Church et al. 2013). Worldwide, surface ocean waters have warmed by about 0.1 °C per decade over the last 45 years. Since the 1950s, areas of high surface salinity, where evaporation dominates, have become more saline and areas of low salinity, where precipitation dominates, have become fresher (Church et al. 2013). These regional trends in ocean salinity provide indirect evidence for changes in evaporation and precipitation over the oceans (IPCC 2014). These changes will in turn lead to alterations in ocean currents, mixing and ventilation (Doney et al. 2012). On a broad scale, rising sea surface temperatures are contributing to numerous changes, including sea-level rise, increased ocean stratification, altered patterns of ocean circulation, precipitation and freshwater input (Doney et al. 2012), resulting in loss of the habitat needed for the survival of manatees and dugongs.

The capacity of climate change models to predict changes at local scales is improving but is still limited and geographically uneven, a situation exacerbated by the variable longevity and quality of temperature records. For example, although long-term water temperature records are difficult to find for any region in Africa, it is clear that rising air temperatures and other factors associated with climate change such as deforestation leading to erosion will increase water temperatures as well. Temperatures in Africa are projected to rise faster than the global average increase during the twenty-first century (IPCC 2014). In the Sahel, air temperatures reach 42 °C at the hottest time of the year, and water temperatures of 33 °C have been recorded in African manatee areas (L. Keith Diagne unpublished data).

The temperatures of the freshwater ecosystems of the Amazon are also expected to increase with climate change (Killeen and Solórzano 2008). Higher temperatures stimulate algal growth, bacterial metabolism, nutrient cycling rates and macrophyte growth, resulting in an increase in trophic status. The release of nutrients from the death of this increased biomass, in turn, is expected to cause a feedback loop in which lake trophic status in general and macrophyte growth in particular are further increased (Ficke et al. 2007). Although it is unlikely that the current Amazonian manatee population is limited by food availability, the above scenario suggests that forage will be more abundant, widespread and, possibly, of better quality. The survival of Amazonian manatees might thus have the potential to improve, but the situation is likely to be very complex and geographically heterogeneous, as explained below.

Manatees and dugongs have limited morphological and physiological capacity to regulate their body temperatures without considerable metabolic cost (Elsner 1999). For example, Florida manatees (Irvine 1983), and likely other sirenians (but see Lanyon et al. 2006 for dugongs), have low metabolic rates. Dugongs have a limited blubber layer but well-developed dermis (Horgan et al. 2014). As a result of morphological and physiological limitations, the thermo-neutral zone (the temperature range within which the animal does not require to make regulatory changes in metabolic heat production or loss) of Amazonian manatees is estimated to be from only 23 to 32.5 °C (Gallivan et al. 1983), whilst the lower limit of the thermo-neutral zone of the Florida manatee is only 20 °C (Irvine 1983). The thermal-neutral zone of the other extant sirenians is not known, but their geographic distributions suggest that their thermal tolerances are also likely to be narrow and less than those of pinnipeds and cetaceans (Costa and Williams 1999).

Most of the work on the effects of water temperature on the welfare of sirenians has been on the effects of temperatures cooler than their thermo-neutral zone (see Marsh et al. 2011 for summary). Environmental temperatures that exceed the upper boundary of the thermo-neutral zone also result in an increase in metabolic rate as a consequence of the additional work required to rid the body of excess heat (Costa and Williams 1999). The direct effects of and risks from warmer water on the welfare of sirenians warrants further investigation. The indirect effects are considered below.

### 19.3 Sea-Level Rise

Sea levels are expected to rise by 8–16 mm/yr by the year 2100 as a result of ocean thermal expansion and glacier melting (IPCC 2014). It is virtually certain that sea-level rise will continue for many centuries past 2100. The capacity for sirenian habitats to expand with rising water levels, and at local scales, will depend on the coastal and riparian (the interface between land and river) infrastructure.

Many coastal low-lying regions that support manatees and dugongs are at risk. For example, Florida is extremely vulnerable to sea-level rise and could lose as

much as 10% of its land area under future climate conditions. With a 1–2 m rise predicted in the next 88 years (Rahmstorf 2010; Parris et al. 2012), many of the thermal refuges (see Fig. 19.6) used by Florida manatees will be inundated, including six of the seven most widely used industrial sites, several smaller power plants and the largest passive thermal refuge. Many of these industrial sites are likely to be moved or have their operations limited in response to sea-level rise. Loss or reduction of the warm-water discharge produced at these sites as a byproduct of their cooling systems will inevitably reduce their carrying capacity for Florida manatees during the colder months when thousands of manatees seek refuge in these industrially warmed waters. This increased mortality due to loss of warm water could potentially limit the size and growth of the Florida manatee population (Edwards 2013).

Saltwater intrusion from sea-level rise, or from storm surges, can have significant negative impacts on sirenian species. Intrusion along with lower spring flows could reduce or eliminate the viability of natural springs as warm-water refuges for manatees. Nonetheless, some spring flows may increase due to sea-level rise and saltwater intrusion. In addition, lower stream spring flows could reduce the dilution of streams and rivers, concentrating salts and other pollutants (Bloetscher et al. 2009) or dry up spring runs altogether, isolating manatees from these much needed resources (Edwards 2013). In West Africa, rising sea levels would increase salinity intrusion in coastal lagoons and lakes, including very important manatee habitats in the extensive coastal lagoons of Gabon, Ivory Coast and Nigeria (Lucy Keith Diagne pers. comm.)

Arora and Boer (2001) predict a decrease in runoff and annual discharge of the Amazon River of approximately 34% by the end of this century. In association with sea-level rise, this decrease may cause saltwater intrusion and changes in water chemistry in the Amazon's lowland and delta regions (Ficke et al. 2007). Sea-level rise also increases the severity and area of impact of surges associated with severe coastal storms (Hamilton 2010). These changes would affect manatee distribution in the mouth of the Amazon, an area of sympatry (coexistence in a shared area) of Amazonian and West Indian manatees, and could result in habitat alteration, loss of food resources, episodes of separation of mother and calf pairs and eventual death of animals.

Thus we predict that the net effect of sea-level rise will decrease the welfare of sirenians through habitat modification leading to increased mortality.

## 19.4 Changes in Ocean Chemistry

The accumulation of carbon dioxide in the atmosphere is increasing carbon dioxide concentrations in seawater. Roughly half of all anthropogenic carbon dioxide emitted since the industrial revolution has dissolved into ocean water leading to a decrease in pH (acidification) and a change in the water chemistry (Errera et al. 2014). Koch et al. (2013) reviewed relevant literature and concluded that the

photosynthetic and growth rates of seagrasses are likely to increase under elevated carbon dioxide. However, as discussed below, many species of tropical seagrasses live close to their thermal limits and will have to up-regulate their stress-response systems to tolerate the sublethal temperature increases caused through climate change. The effects of elevated carbon dioxide on the capacity of various species of seagrass to acclimate to increased sea temperatures are unknown. For these reasons, the impacts on the welfare of dugongs and manatees from the changes in ocean chemistry, and on seagrasses, resulting from climate change are, as yet, impossible to predict.

## 19.5 Increase in the Intensity of Extreme Weather Events

Global climate change is also likely to result in increased intensity of severe storms (Webster et al. 2005; Florida Oceans and Coastal Council 2010; Bender et al. 2010, Geophysical Fluid Dynamics Laboratory/NOAA 2015). Such storms are likely to be associated with higher rainfall rates than the present day, and these events may cause runoff into coastal regions smothering seagrasses, flushing toxins into waterways and altering the local habitat through increased water flow. These factors are all associated with creating stressors for sirenian species.

Records of Atlantic hurricane activity show that there is a correlation between local tropical Atlantic sea surface temperatures and the Power Dissipation Index (a measure of Atlantic hurricane activity which combines frequency, intensity and duration of hurricanes). Both sea surface temperatures and the Power Dissipation Index have risen sharply since the 1970s, and there is evidence that in recent years, the levels of the Power Dissipation Index are higher than in the previous active Atlantic hurricane era of the 1950s and 1960s (Geophysical Fluid Dynamics Laboratory/NOAA 2015). This evidence suggests that there may be a large anthropogenic influence on Atlantic hurricanes, which could have profound implications, since big increases in tropical Atlantic sea surface temperatures projected for the late twenty-first century would translate to substantial increases in hurricane destructiveness (~300% increase in the Power Dissipation Index by 2100; Geophysical Fluid Dynamics Laboratory/NOAA 2015).

As a result of climate change, the coastal United States is expected to experience more intense storms and possible changes in the El Niño cycle (Scavia et al. 2002; Emanuel 2005). Since 1996, the frequency of hurricane landfalls in the Southeastern United States has increased, and this pattern of elevated hurricane activity could continue (Goldenberg et al. 2001; Webster et al. 2005; Mallin and Corbett 2006). Under climate change, higher sea levels coupled with more intense storms could impact Florida manatee mortality both indirectly through impacts to habitats (see below) or directly through storm effects. Florida manatees have lower survival during years with intense storms or hurricanes (Langtimm and Beck 2006). The mechanisms that caused mortality are unknown but likely vary with timing, intensity and duration of the storms.

Global models indicate that similar patterns will be seen in other parts of the ranges of sirenians. It is believed that the increase of category 4–5 storms (Bender et al. 2010) will outweigh the effects of the overall decreasing number of storms, and it is estimated that there will be a 30% increase in potential damage. However, these climate change increases in storm intensity are not projected to occur for several decades. Coupling this change with sea-level rise, the impacts to coastal areas used by sirenians are expected to increase over time. Direct mortality of dugongs due to tropical cyclones has been documented (Heinsohn and Spain 1974) including strandings in receding high waters after a storm surge (Marsh 1989). Such direct impacts from extreme weather events are expected to increase along with the indirect impacts on the habitats of manatees and dugongs explained below.

Meager and Limpus (2014) point out that there are several lines of evidence to suggest that the health of dugongs (like Florida manatees) is limited by cooler temperatures at the southern limits of their range. Not only do dugongs move in response to water temperature (Allen et al. 2004; Sheppard et al. 2006), but cold stress syndrome has been described in dugongs in Moreton Bay (Owen et al. 2013), at the southern limit of their temperature range in Australia. Nonetheless, lagged minimum air temperature also explained mortality of dugongs in the tropical Townsville region suggesting that impacts on health may result from the associated impacts of freshwater discharge on seagrass rather than temperature per se (Meager and Limpus 2014), although the change in water temperature may be a contributing factor.

Some models also predict an increase or persistence in wintertime cold-air outbreaks with climate change (Easterling et al. 2000; Walsh et al. 2001). Manatees in Florida occur at the northern limit of the species' range in the temperate and subtropical regions of the Southeastern United States. Manatees are poorly adapted to the cold and have a relatively narrow thermo-neutral zone, as explained above. Chronic exposure to water less than  $\sim 18^{\circ}$ – $20^{\circ}$ C can lead to cold stress, a condition that can, for example, result in emaciation, dehydration, skin lesions, gastrointestinal disorders and death (Bossart et al. 2003). Under current climatic conditions, water temperatures in much of Florida periodically drop below thresholds that manatees can tolerate for extended periods (Laist and Reynolds 2005). Climate scenarios for Florida predict that these events will continue in the future. A significant number of cold-related mortalities of Florida manatees have been documented (1130 deaths from 1986 to 2015; Florida Fish and Wildlife Conservation Commission unpublished data). The cold-related die-off in the winter of 2010 was the most notable, due to its geographic extent and the number of related manatee mortalities (Edwards 2013). Two-hundred and eighty (280) manatees died of cold stress during a 3-month period; for 197 others, the cause of death could not be determined, but the timing of the deaths and the location of the carcasses suggest that most were also a result of the cold. An additional 49 manatees were rescued for treatment of cold stress during that period (Barlas et al. 2011).

The Amazon basin experiences an extreme flood or drought at approximately 10-year intervals, and as recently as 2005 and 2010, two droughts heavily affected riverine life (Marengo et al. 2011). During extreme drought periods, river water levels decrease, lakes become shallow or even dry up, and manatees become more vulnerable



**Fig. 19.2** Amazon basin in a severe drought showing the fragmentation of the water courses inhabited by manatees. Such fragmentation can result in an increase in hunting (*Image credit: Eduardo Arraut*)

to hunting (Miriam Marmontel and Eduardo Moraes Arraut, pers. obs.) as discussed below (Fig. 19.2). Under prolonged drought conditions, aquatic plants do not survive, and manatees resort to ingesting organic matter from the bottom, and consuming sediment in large quantities, a practice which may cause death by obstruction of the intestine (Miriam Marmontel pers. obs.). One of the scenarios for the hydrological cycle in the Amazon basin associated with climate change (Sorribas et al. 2016) predicts that extreme droughts will become more frequent and recurrent in the region. If this scenario prevails, not only will there be more frequent years in which manatee forage is extremely scarce, but manatees will also suffer from more frequent and prolonged periods of vulnerability to predation, especially hunting as discussed below.

Thus the increase in the intensity of extreme weather events associated with climate change is likely to decrease the welfare of sirenians through increased mortality.

## 19.6 Changes in Rainfall Patterns

Patterns of precipitation are expected to change in intensity and variability as a result of climate change. Some areas will get wetter, others drier, as explained by Christensen et al. (2013). The global monsoon is likely to strengthen in area and intensity, and the likelihood of precipitation extremes is likely to increase. The El



Niño-Southern Oscillation (ENSO) will remain the dominant mode of interannual variability, and the associated precipitation variability that comes with El Niño will likely intensify. Severe tropical storms are expected to increase in intensity as mentioned above, with an increase in precipitation rates.

About 20% of Florida, manatees use natural sites as sources of warm water in winter (e.g. natural springs and warm-water seeps). A major concern is that climatic variation may alter the hydrological cycle that replenishes the Florida aquifers that feed these natural springs (Bloetscher et al. 2009; Edwards 2013) causing them to cease operating.

The African manatee occupies the widest range of habitats of any sirenian. The waterways used by manatees range from lagoons within equatorial rainforests in Central Africa to rivers at the edge of the Sahara Desert, to coastal mangrove channels and islands in the Atlantic Ocean. Throughout their range, African manatees migrate seasonally, based upon changes in water levels, moving up flooded rivers during annual rainy seasons to exploit food resources that are unavailable during dry seasons (Powell 1996; Keith Diagne 2015). Climate change in West and Central Africa is predicted to make dry areas drier and wet areas wetter, with longer and more frequent dry periods (Christensen et al. 2013). Therefore, manatee habitat in Central Africa may increase, but habitat loss due to drying and desertification will likely occur in the northern part of the species' range. Manatee populations in Mali, Niger, Senegal, Mauritania, Chad and Northern Nigeria are likely to be the most affected by desertification (Figs. 19.3).



**Fig. 19.3** The Senegal River is the boundary between Senegal, Mauritania and Mali, and its flow is now controlled by the Manantali Dam. This view of the river in the dry season shows the greatly reduced habitat for manatees that could become more severe with increasing desertification (*Image credit: Lucy Keith Diagne*)

There has been a well-documented decrease in rainfall in the Sahel since the late 1960s (IPCC 2014), coupled with an increasing human demand that draws more and more water from rivers. Over timescales measured in decades, rainfall in the Sahel is also affected by sea surface temperatures, with rising ocean temperatures leading to decreased rainfall (IPCC 2014). Climate models predict an increase 1.0–1.9 °C in mean air temperature by 2050, and evaporation rates across Africa are projected to increase 5–10% during the same timeframe (Gaye et al. 2013). Rainfall in West and Central Africa is also known to be influenced by the El Niño-Southern Oscillation (ENSO), the Atlantic Niño and the Mediterranean Sea (Wade et al. 2015). The impact of climate change on African manatees is expected to be exacerbated by the anthropogenic response to increasing human population and human activity changes resulting from climate change (as discussed below).

The main influence of changes in the Amazon's rainfall pattern on Amazonian manatees will come via effects on the dynamics of the Amazon River's flood pulse. Although predictions of such impacts are still controversial, some general trends are emerging. Overall, greater precipitation levels are foreseen for the northern part of the basin, whilst the southern part is expected to experience lower rainfall levels (IPCC 2014). According to Langerwisch et al. (2013), this exchange will result in an increase of about one third in total inundation area and in a decrease in the number of extremely dry years (and in the probability of occurrence of three consecutive extremely dry years). Moreover, though the total number of extremely wet years is not expected to change, the probability of three consecutive wet years decreases by 30% in the east and increases by 25% in the west. Although an alternative hydrological scenario on the impacts of climate change on the dynamics of flooding in the Amazon basin supports the abovementioned increase in duration and extent of the high-water season, it also predicts an increase in the frequency of extreme low-water seasons for Central and Eastern Amazon.

The changes in rainfall patterns associated with climate change are likely to decrease the welfare of sirenians through changes in habitat. The impacts are likely to be geographically uneven.

## **19.7 Indirect Effect of Climate Change on Sirenians: Habitat Loss and Change**

Sirenians are mostly herbivores (Marsh et al. 2011), foraging on a variety of marine, estuarine and freshwater plant species, although all species will eat some animal matter. According to Domning (1981, 2001), seagrasses have played a key role in sirenian life history and evolution, and they are a major dietary component of both dugongs and Antillean and African manatees. Seagrasses are therefore intrinsically linked to the well-being and survival of sirenian species and are an essential component of any environment which they inhabit. Seagrass beds are already among the most threatened of the world's ecosystems (Waycott et al. 2009), with 29% of global seagrasses lost or degraded and with the rate of loss accelerating (at a rate of

110 km<sup>2</sup> yr<sup>-1</sup>; Waycott et al. 2009). Impacts of climate change, including elevated atmospheric carbon dioxide, increased variability in sea temperatures, sea-level changes and alterations in levels of ultraviolet radiation, will alter the conditions for growth of seagrasses (Watson et al. 1996). These effects are likely to be geographically variable.

According to Short and Neckles (1999), the climate change impact that will have the greatest direct effect on seagrasses will be sea-level rise. Increased sea levels will impact the amount of light available to the plants for photosynthesis. A rise in sea level may alter the structure of some seagrass beds by reducing their distribution and productivity and ultimately reducing their functional value (Short and Neckles 1999).

Temperature is a critical factor controlling seagrass growth, survival and reproduction (Poloczanska et al. 2007). Seagrass tolerance to changes in temperature varies by species, and, for species living at the upper limit of their thermal tolerance, mean sea temperature increases of up to 2 °C may have a severe impact (Ralph 1998). Extreme or prolonged thermal stress (Collier and Waycott 2014) and the effect of poor water quality can be synergistic in causing seagrass mortality. Increasing the duration (i.e. more days in a row) of thermal events above 40 °C is likely to negatively impact the ecological function of tropical seagrass meadows (Collier and Waycott 2014). The loss of seagrass species and changes in species dominance as a result of climate change are likely to have significant ramifications for sirenians, as well as for the other species that use seagrass communities (Campbell et al. 2006).

In many parts of the world, severe storms have been a significant cause of disturbance to seagrasses (Steward et al. 2006), as a result of wind, erosion from wave action, storm surge, shifting substrates, torrential rains and changes in salinity, etc., along with increased water turbidity (Short and Neckles 1999; Fourqurean and Rutten 2004). Although not all storms cause damage to seagrass meadows, hurricanes, tropical cyclones and other major weather events have all resulted in the decline of seagrasses. Individual storm characteristics play a role in determining the type and extent of the damage that occurs (Greening et al. 2006).

The dugong is more dependent on seagrass than any other sirenian (Marsh et al. 2011). Loss of available seagrass reduces dugong abundance through temporary migration, increased mortality and negative effects on dugong body condition and female reproductive rates (Marsh and Kwan 2008; Meager and Limpus 2014; Fuentes et al. 2016). Meager and Limpus (2014) used a 17-year data set to investigate the drivers of natural dugong mortality across a subtropical-tropical latitudinal gradient of 13° (>2000 km of coastline). Peak mortality followed sustained periods of low air temperature (lagged by 3 months) and elevated freshwater discharge associated with extreme rainfall events (lagged by 9 months). At a regional scale, these results translated into a strong relationship between annual mortality rates and an index of El Niño-Southern Oscillation, mortality being higher following La Niña events (Meager and Limpus 2014). Meager and Limpus (2014) considered that the two most parsimonious functional explanations for the relationship between freshwater discharge and dugong mortality were (1) reduced food availability and (2)

direct impacts on health. There is strong support for the first hypothesis for dugongs. Elevated flood-linked discharge reduces photosynthetic available radiation (PAR), exported sediment can smother seagrasses, and flood discharges can scour seagrass beds and seed banks (Campbell et al. 2006).

A study of Amazonian manatee feeding ecology identified 49 species of aquatic plants as food items, mostly from the Poaceae (a grass) family (Guterres-Pazin et al. 2014). As grasses with a C4 photosynthetic pathway tolerate high temperatures better than C3 plants (Hamilton 2010), global warming may result in lower plant diversity available to Amazonian manatees. Nutrient quality may also be affected, as C4 grasses have lower nitrogen contents (Hamilton 2010).

On the basis of the strong relationship between inundation duration and predominant vegetation type and structure class (Ferreira-Ferreira et al. 2014; Junk et al. 2012), the Amazonian floodplain in general, and particularly its western part, is expected to gradually shift towards larger areas being covered by vegetation classes associated with longer flooding times, such as herbaceous vegetation. Vegetation associated with shorter inundation times, such as high várzea (seasonal floodplain) forests, is expected to decrease under this scenario. Less forest would result in decreased filtering of the huge amounts of sediment that are brought from the Andes during the high-water season, which in turn would result in greater siltation of open water and herbaceous areas (Ficke et al. 2007). This situation would create a positive feedback loop, in which, as the lakes became shallower, the overall inundation extent would increase, further promoting an increase in the size of the areas dominated by open water and herbaceous vegetation. Overall, this scenario would, on the one hand, result in increased food availability (aquatic macrophytes) for manatees, but, on the other hand, would also increase their vulnerability to predators, including human hunters, as discussed below, owing to the decrease in the depth of floodplain lakes.

## 19.8 Algal Blooms

Species of phytoplankton are important components of the aquatic food chain and over 4000 species of phytoplankton inhabit our oceans (Davidson et al. 2014). Although most species are benign, some species can cause a variety of deleterious effects to the environment and to the organisms that live in it. Some algal species are capable of producing toxins that can kill or sicken birds, fish, humans and marine mammals including some sirenians. Other phytoplankton species can produce high biomass by blooming to excess (Davidson et al. 2014), and such blooms can result in oxygen depletion in bottom waters (hypoxia/anoxia) or can reduce the amount of light that reaches the benthos leading to the death of light-dependent benthic seagrass.

Globally, algal blooms appear to be increasing as a result of increased nutrient loads from human activity (Sellner et al. 2003; Gilbert and Burkholder 2006; Heisler et al. 2008). The relationship is complex, and the link is not universal, but regard-



**Fig. 19.4** Algal blooms are capable of smothering underlying sea grasses and persisting for days to weeks under the right climatic conditions (*Image credit: Tom Reinert*)

less, algae blooms can critically alter ecosystems, disrupt food webs, stimulate the growth of pathogens and have other ecological consequences (Wells et al. 2015; Fig. 19.4). Increasingly there is concern that climate change will result in changes in the phytoplankton community, which will increase the prevalence and geographical spread of algae blooms (Wells et al. 2015). Some harmful species are likely to become more successful under future climate conditions, whilst other species may diminish (Hallegraeff 2010).

Several studies have indicated there may be a relationship between the frequency, duration and magnitude of algal blooms and climate (Moore et al. 2008). Temperature increases from climate change are predicted to increase the range and duration of blooms of some harmful algal species (Moore et al. 2008; Hallegraeff 2010). The warmer upper ocean temperatures predicted under climate change scenarios will reduce vertical mixing of the water column, which will impact phytoplankton growth (Doney 2006). As ocean water warms, blooms will begin earlier and last longer (Moore et al. 2008), and algal blooms will expand their range and the period of time they occur (Gessner and Middaugh 1995). Increases in ocean acidity are also likely to influence phytoplankton in ways that favour algal blooms. Studies show that there is generally a positive relationship between increasing pH and growth and toxin production in algae blooms; however, it is unknown if this relationship will be maintained under the more acidic ocean conditions that will result

from climate change. Although scientists are still uncertain about the impact of climate change on algae bloom species in general, the potential for interaction between the two factors is high. The predicted impacts of climate change on tropical and subtropical habitats are likely to increase the probability of negative impacts on sirenian species from algae blooms as discussed below.

Climate changes can influence red tides over huge spatial scales. Large amounts of African dust are carried by wind to the western Atlantic, including Florida's coast and the Caribbean. The amount of dust being transported is highly negatively correlated with the amounts of rainfall in Africa (Prospero and Lamb 2003). Saharan minerals from this dust are thought to be used by diazotrophic, or nitrogen fixing, bacteria to fuel the nitrogen economy of red tides (Walsh and Steidinger 2001), thus triggering larger algal blooms. Local drier conditions also can create more favourable conditions for red tides nearshore. As the toxic dinoflagellate, *Karenia brevis*, favours areas of higher salinity, changes to Florida's climate, including more episodic storms and changes in the amount of precipitation and runoff, are likely to increase the probability of manatees' exposure to red tide which could increase future mortality of the species (Edwards 2013).

The impact of algal blooms on the welfare of sirenians is well documented for Florida manatees where poison from potent neurotoxins (brevetoxins) produced by *K. brevis* have resulted in the death or suspected death of over 669 manatees since 1984. Such brevetoxicosis can release inflammatory mediators that can result in fatal toxic shock (Bossart et al. 1998). Large die-offs of manatees from red tide occurred in 1996, 2002, 2003, 2005, 2007 and 2013 (highest on record at 277 deaths; Edwards 2013). Sublethal exposure to harmful algal blooms may have long-lasting impacts on a manatee's immune system, which could impact the overall health of a manatee population (Walsh et al. 2015).

According to Landsberg and Steidinger's review (1998), Florida manatees are at high risk of being impacted by red tide blooms in the late winter and spring when salinities are greatest, and when large numbers of manatees move through, or forage in, red tide-affected areas in Florida (Edwards 2013). Pathways of exposure to red tide can occur from consumption of toxin-sequestering seagrass and attached epiphytes, inhalation of toxic aerosols or ingestion of toxic seawater (Landsberg and Steidinger 1998). As the toxins can be retained in some organisms from weeks to months after a red tide has dissipated, exposure can be delayed, and manatees can be affected long after the bloom has subsided. In 2012–2013, an overgrowth of a protistan alga (*Resultor* sp.) caused unusually high manatee mortality in the Indian River Lagoon system in Florida (Edwards 2013). More than 100 manatees died, and more than 50% of seagrass in the lagoon was lost as a result of the bloom (Lori Morris pers. comm).

Most harmful algal species are dinoflagellates that are capable of moving through the water column. Since mobile forms are expected to prevail over other species, it is likely that blooms of motile alga like *K. brevis* will increase as a result of climate change. In addition, under predicted future climate conditions, blooms of *K. brevis* may have the potential to produce higher cell and toxin concentrations (Errera et al. 2014).

Although high mortality due to harmful algal blooms has to date been restricted to the Florida manatee, it is possible that global climate change could alter ecosystems in a way that could increase the negative impact on other sirenian populations. For example, toxic dinoflagellates, which make tumour-producing okadaic acid, and blooms of toxic *Lyngbya* are all found in dugong habitats (Marsh et al. 2011). Although no deaths have been attributed to their occurrence, changes to these ecosystems, from changes in temperature, salinity, light, carbon, nutrients and others, could increase the probability of negative impacts of harmful algal blooms on dugongs.

## 19.9 Disease

Host-parasite dynamics may be altered by climate change, through changes in transmission rates and host susceptibility (Ficke et al. 2007). Environmental and climatic changes may alter biogeochemical cycles, which may increase the incidence of infectious diseases, especially waterborne diseases, such as leptospirosis and cryptosporidiosis (Barcellos et al. 2009; Costello et al. 2009; Lau et al. 2010). Manatees under environmental stress become immunocompromised and susceptible to infectious agents (Bonde et al. 2004). Antibodies anti-*Toxoplasma gondii* and anti-*Leptospira* spp. have been identified in Amazonian manatee samples in Brazil and Peru (Mathews et al. 2012; Delgado et al. 2013, 2015). Freshwater discharge associated with the increased number of extreme rainfall events expected under climate change may also impact the health of dugongs and manatees by increasing their exposure to infectious pathogens such as toxoplasmosis and faecal coliform bacteria (derived from human and animal sewage) or to contaminants with immunosuppressive effects (see Marsh et al. 2011 for review).

Thus climate change is likely to decrease the welfare of sirenians by increasing their exposure to disease.

## 19.10 Anthropogenic Responses

Climate change is already inducing adaptive human responses, and such responses will increase as the biophysical impacts of climate change become more evident. Climate-related hazards exacerbate other stressors, especially for people living in poverty (IPCC 2014). The African manatee will be particularly vulnerable because of the high levels of human poverty throughout most of its range resulting in competition for resources, including protein from manatee meat. Thus the risks to sirenians from climate change are likely to be greatest for small populations of dugongs and manatees occurring in low-income countries (see Marsh et al. 2011 for details).

## 19.11 Fishing and Hunting Pressure

Climate change will increase food insecurity, which in turn is projected to increase pressure on the world's fisheries. As Marsh et al. (2011) point out, 21 of the 33 countries where the impacts of climate change on fisheries are projected to have the greatest national economic impacts (Allison et al. 2009) are in the ranges of dugongs and manatees. The potential national economic impacts of climate change on fisheries could not be assessed in a further 21 countries in the range of sirenians; 17 of these are classified as Least Developed Countries or Small Island States or both and are thus potentially especially vulnerable to climate change.

Both marine and freshwater fisheries in Africa are already in serious decline (Atta-Mills et al. 2004; Allan et al. 2005). The climate change effects of desertification in North Africa and potential shifts in oceanic species throughout Africa will further exacerbate the problem of overfishing (IPCC 2014). A negative correlation between the catches of subsistence fishers and 'wild meat' has already been established for West Africa (Brashares et al. 2004; Rowcliffe et al. 2005). The African manatee is already heavily hunted throughout its range, and its meat is more costly than fish. As fish stocks continue to decline, it is expected that hunting pressure on African manatees will increase, possibly leading to extinction in some parts of its range.

These projected changes in human population resulting from climate change are significant to the sustainability of manatee and dugong populations, because the population growth rate of all sirenians is highly sensitive to changes in adult survival rate (Marsh et al. 2011), and most local populations of sirenians cannot withstand a human-induced mortality of even a few animals per year. These changes are also likely to be important to the welfare of sirenians because the effectiveness of cultural norms and regulations designed to protect them are hampered by weak governance, as illustrated by the following example.

The Torres Strait region between Australia and Papua New Guinea supports the largest dugong population in the world (Marsh et al. 2011). Anthropologists have documented the cultural values of dugongs since the European colonisation of Torres Strait (see Haddon 1912; Nietschmann and Nietschmann 1981). Dugongs are fundamental in the culture of Torres Strait Islanders (Beckett 1987; Johannes and MacFarlane 1991; Marsh et al. 2011). Dugong meat has been an important component of the seafood harvested by the indigenous peoples of Torres Strait for at least 4000 years (Crouch et al. 2007). The Torres Strait dugong harvest, which currently appears to be sustainable (Marsh et al. 2015), has significant provisioning value, particularly for residents of the Western Province of Papua New Guinea. This region is one of the poorest regions in the world (Butler et al. 2015) and has significant food insecurity (Omot 2012).

Climate change is expected to alter the biological productivity of the Torres Strait marine environment and the adjacent terrestrial environments, particularly that of Papua New Guinea (Butler et al. 2015). In addition to the effects of climate changes on the dugong habitats of Torres Strait, the rate of sea-level rise is also expected to accelerate the impacts of inundation on the island communities (Duce



et al. 2010). Some islanders may be forced to relocate by 2100. Much of the coastal area around the Papua New Guinea coastal villages is low lying and flat. Some of this region is also likely to be inundated, necessitating relocation. Nonetheless, the strategic deep-water port, Daru Island, may be deemed too important to evacuate and may be instead protected by sea walls.

Overall, the human population of the coastal areas of Western Province is expected to increase. Stoeckl et al. (in press) predict that this growing population, along with the impacts of extreme weather on subsistence gardens and the degradation of coastal habitat through mining and logging, will increase pressure on Torres Strait dugong stocks. Due to the poor governance systems in place in Papua New Guinea, these changes are likely to result in the increased use of unsustainable gear such as large mesh nets. This change in fishery practice is likely to be more significant than reductions in hunting that might otherwise come about from (i) the relocation of people from islands prone to inundation and (ii) the relocation of animals to deeper waters because of the loss of shallow-water seagrass. Regulation of the Torres Strait dugong harvest is likely to deteriorate wherever Papua New Guinea villagers take a greater proportion of catch, in areas with food shortages, and where regulatory effectiveness is hampered by weak governance or low levels of resourcing for enforcement. These factors are expected to be especially pertinent in regions experiencing limited capacity and the breakdown of cultural norms caused by migration. Thus the animal welfare impacts associated with the dugong harvest in this region are expected to increase.

Some of the climate scenarios described above for the Amazon basin predict lower water levels during the time of seasonal manatee migrations and extreme low-water seasons, trapping manatees between impassable stretches of low water. When trapped, manatees are usually slaughtered for food by local inhabitants. This was the case in the 2016 drought in Mahates wetland, Bolívar, northern Colombia, when an estimated 90 manatees became trapped in a 300 m long, 60 cm deep remnant bed of the river, with their food resources dried out. At least 25 of them were killed by hunters (El Espectador 2016). More extreme low-water seasons would result in shallower refuges, which, again, would likely be associated with increased slaughter of manatees by local inhabitants. This situation occurred, for example, in the 1996, 2005 and 2010 extreme droughts, when mass slaughter occurred in the *rias* Tefé, Manacapurú, Coari, Badajós, Monte Alegre and Jari areas of the Amazon basin (Thornback and Jenkins 1982; Arraut et al. 2010; and personal observations by Eduardo Moraes Arraut, and Miriam Marmontel).

## 19.12 Infrastructure

Forty-four percent (44%) of people live within 150 km of a coast (UN Atlas 2010), and many coastal marine ecosystems are already significantly degraded (Halpern et al. 2008). The impacts of climate change are likely to cause shoreline erosion, coastal flooding and water pollution and affect man-made infrastructure and coastal

ecosystems (IPCC 2014). Addressing the additional stress of climate change is likely to result in new approaches to managing land, water, waste and ecosystems. The examples below illustrate some of the resultant likely problems for sirenians.

As discussed in an earlier chapter (Chap. 17), engineered and technological options are commonly implemented adaptive responses to climate change (IPCC 2014). Dams are a significant threat to the welfare of African manatees, both through entrapment and through crushing in gates (Keith Diagne 2015). Manatees in Sahelian countries are already permanently isolated in the Niger and Senegal Rivers by dams. Major hydroelectric and minor agricultural dams block the ability of manatees to move out of river systems as their habitat and food resources decrease. Three major new dams are already under construction on the Niger River in Guinea, Mali and Niger, and as water scarcity increases with climate change, further dams will trap riverine manatees into smaller and smaller habitat areas making it less likely that they will survive long term.

The threats from hydroelectric damming on Amazonian manatees will be significant if the current massive dam-building plan for the Amazon basin is realised (Arraut and Marmontel 2016). The plan is to build dams or dam cascades across all large- and most medium-sized Amazon rivers to provide energy for aluminium extraction in the region and for industries elsewhere (Castello and Macedo 2015; Brazil 2016; Winemiller et al. 2016). If implemented, this dam-building plan would partition the Amazonian manatee into many small, confined populations, each of which would suffer from inbreeding with resultant reduction in evolutionary potential (Frankham et al. 2014) and increased vulnerability to slaughter, especially during natural or dam-induced extreme droughts. As explained above, in addition to this direct population impact, manatee survival is also expected to decrease even further owing to the intense degradation of the floodplain habitat. In combination, these effects are likely to result in local extinctions of small and confined Amazonian manatee populations and a second species-level population collapse. (The first collapse was driven by commercial over-exploitation for meat and hide over two centuries (Domning 1982).) Local human socio-economic-environmental conditions are also expected to deteriorate further as a result of the dam building (Fearnside 2006, 2014, 2016a, 2016b), resulting in an increase in the hunting pressure on manatees. As manatees are slow-breeding animals, recovery from a second collapse associated with the expected increase in hunting pressure would be highly unlikely. These cumulative impacts have led to calls for the plan for extensive dam building to be reconsidered.

In Florida, manatees rely on both natural and industrial sources of warm water for refuge, when water temperatures drop below approximately 20 °C, as explained above. About 60% of Florida manatees, counted during statewide surveys conducted after cold fronts, were using an industrial source of warm water as a winter refuge (Fig. 19.5). Including ~3% of the total population which were using a single passive thermal refuge (Florida Fish and Wildlife Commission unpublished data). An estimated 93% of the state's human population relies on groundwater for their needs (SFWMD 2001). Florida's human population is putting ever-increasing



**Fig. 19.5** Manatees overwintering at an industrial warm-water refuge in Florida (*Image credit: Stacie Koslovsky*)

stress on already compromised systems, and future water withdrawals are expected to increase by 21% by 2030 (Florida Department of Environmental Protection 2014). Loss of these refuge sites or reduction in their carrying capacity has been identified as a significant threat to the long-term viability of the population (Runge et al. 2007).

We conclude that the anthropogenic responses to climate change are likely to decrease the welfare of sirenians, through human responses to food insecurity and through modifications to rivers as a result of increased dam building.

### 19.13 Conclusions

This review indicates that climate change has considerable potential to negatively impact the welfare of dugongs and manatees. The effects are likely to be particularly serious in the low-income countries (IPCC 2014), which make up most of the ranges of all four sirenian species (Marsh et al. 2011). Given the uncertainties as to how climate change will affect sirenians and their habitats at local scales, the best precautionary actions are likely to be: (1) control factors known to increase mortality and reduce fecundity, as pointed out by Lawler et al. (2007) and Marsh et al. (2011), and (2) adopt an adaptive management approach as outlined in Fuentes et al. (2014). There is increasing global interest in a relatively newly appreciated

ecosystem service provided by aquatic plants, including seagrasses, through their capacity to sequester carbon (Macreadie et al. 2014). The imperative to maintain wetlands as global greenhouse gas sinks has some potential to reduce the otherwise, mainly negative, impacts of climate change on the welfare of sirenians.

## References

- Allan JD, Abell R, Hogan Z et al (2005) Overfishing of inland waters. *Bioscience* 55:1041–1051
- Allen S, Marsh H, Hodgson A (2004) Occurrence and conservation of the dugong *Sirenia: Dugongidae* in new South Wales. *Proc Linnean Soc NSW* 125:211–216
- Allison EH, Perry AL, Badjoc MC et al (2009) Vulnerability of national economies to the impacts of climate change on fisheries. *Fish Fish* 10:173–196. doi:10.1111/j.1467-2979.2008.00310.x/full
- Arora VK, Boer GJ (2001) Effects of simulated climate change on the hydrology of major river basins. *J Geophys Res* 106(D4):3335–3348
- Arraut EM, Marmontel M (2016) Amazonian manatee threatened with extinction by massive dam-building plan in the Amazon. *Science*. eLetter: <http://science.sciencemag.org/content/351/6269/128.e-letters>. Accessed 6 11 16
- Arraut EM, Marmontel M, Mantovani JE et al (2010) The lesser of two evils: seasonal migrations of Amazonian manatees in the western Amazon. *J Zool* 280:247–256. doi:10.1111/j.1469-7998.2009.00655.x
- Atta-Mills J, Alder J, Sumaila UR (2004) The decline of a regional fishing nation: the case of Ghana and West Africa. *Nat Res Forum* 28:13–21
- Barcellos C, Monteiro AMV, Corvalán C, Gurgel C, Gurgel HC, Carvalho MS, Artaxo P, Hacon S, Ragoni V (2009) Mudanças climáticas e ambientais e as doenças infecciosas: cenários e incertezas para o Brasil. *Epidemiol Serv Saúde (Brasília)* 18(3): jul-set 2009
- Barlas ME, Deutsch CJ, de Wit M et al. (2011) Florida manatee cold-related unusual mortality event, January–April 2010. Final report to USFWS (grant 40181AG037). Available via Florida Fish and Wildlife Conservation Commission [http://myfwc.com/media/1536184/2010\\_Manatee\\_Cold\\_related\\_UME\\_Final.pdf](http://myfwc.com/media/1536184/2010_Manatee_Cold_related_UME_Final.pdf). Accessed 30 April 2016
- Beckett J (1987) *Torres Strait islanders: custom and colonialism*. Cambridge University Press, Cambridge
- Bender MA, Knutson TR, Tuleya RE et al (2010) Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science* 327:454–458
- Bloetscher F, Meeroff DH, Heimlich BN (2009) Improving the resilience of a municipal water utility against the likely impacts of climate change—a case study: city of pompano beach water utility. Florida Atlantic University, USA
- Bonde RK, Aguirre AA, Powell J (2004) Manatees as sentinels of marine ecosystem health: are they the 2000-pound canaries? *EcoHealth* 1:255–262
- Bossart GD, Baden DG, Ewing R et al (1998) Brevetoxicosis in manatees (*Trichechus manatus latirostris*) from the 1996 epizootic: gross, histologic and immunohistochemical features. *Toxicol Pathol* 26:276–282
- Bossart GD, Meisner RA, Rommel SA et al (2003) Pathological features of the Florida manatee cold stress syndrome. *Aquat Mamm* 29:9–17
- Brashares JS, Arcese P, Sam MK et al (2004) Bushmeat hunting, wildlife declines, and fish supply in West Africa. *Science* 306:1180–1183
- Brazil (2016) Programa para Aceleração do Crescimento - PAC-II, Eixo Energia (Program for the Acceleration of Growth). In: Minist. Plan. <http://www.pac.gov.br/infraestrutura-energetica>. Accessed 30 April 2016
- Butler JRA, Bohensky E, Skewes T, Maru Y et al (2015) Drivers of change in the Torres Strait region: status and trends. Report to National Environmental Research Program. Reef & Rainforest Research Centre Limited, Cairns, p 60

- Campbell SJ, McKenzie LJ, Kerville SP (2006) Photosynthetic response to seven tropical seagrasses to elevated seawater temperature. *J Exp Mar Biol Ecol* 330:455–468
- Castello L, Macedo MN (2015) Large-scale degradation of Amazonian freshwater ecosystems. *Glob Chang Biol* 3:990–1007. doi:[10.1111/gcb.13173](https://doi.org/10.1111/gcb.13173)
- Church JA, Clark PU, Cazenave A, Gregory JM et al (2013) Sea level change. In: Stocker TF et al (eds) *Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge University Press, Cambridge, pp 1137–1216
- Christensen JH, Krishna Kumar K, Aldrian E et al (2013) Climate phenomena and their relevance for future regional climate change. In: Stocker TF et al (eds) *Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge University Press, Cambridge, pp 1217–1308
- Collier CJ, Waycott M (2014) Temperature extremes reduce seagrass growth and induce mortality. *Mar Pollut Bull* 83:483–490
- Costa DP, Williams TM (1999) Marine mammal energetics. In: Reynolds JE, Rommel SA (eds) *Biology of marine mammals*. Smithsonian Institution Press, USA, pp 218–286
- Costello A, Abbas M, Allen A, Ball S, Bell S, Bellamy R, Friel S, Grace N, Johnson A, Kett M, Lee M, Levy C, Maslin M, McCoy D, McGuire B, Montgomery H, Napier D, Pagel C, Patel J, Oliveira JAP, Redclift N, Rees H, Rogger D, Scotte J, Stephenson J, Twigg J, Wolff J, Patterson C (2009) Managing the health effects of climate change. *Lancet* 373:1693–1733
- Crouch J, McNiven IJ, David B et al (2007) Berberass: marine resource specialisation and environmental change in Torres Strait over the past 4000 years. *Archaeol Ocean* 42:49–64
- Davidson K, Gowan RJ, Harrison PJ et al (2014) Anthropogenic nutrients and harmful algae in coastal waters. *J Environ Manag* 146:206–216
- Delgado PM, Perea NS, Delgado JPM, Garcia CB, Malheiros AF, Davila CRG (2013) Detection of infection with *Toxoplasma gondii* in manatees (*Trichechus inunguis*) of the Peruvian Amazon. *Acta Biologica Colombiana* 18:211–216
- Delgado PM, Perea NS, Garcia CB, Davila CRG (2015) Detection of infection with *Leptospira* spp. in manatees (*Trichechus inunguis*) of the Peruvian Amazon. *Lat Am J Aquat Mamm* 10:58–61
- Domning DP (1981) Sea cows and sea grasses. *Paleobiology* 7:417–420
- Domning DP (1982) Commercial exploitation of manatees *Trichechus* in Brazil c. 1785–1973. *Biol Conserv* 22:101–126
- Domning DP (2001) Sirenians, seagrasses, and Cenozoic ecological change in the Caribbean. *Palaeogeogr Palaeoclimatol Palaeoecol* 166:27–50
- Doney SC (2006) Plankton in a warmer world. *Nature* 444:695–696
- Doney SC, Ruckelshaus M, Duffy JE et al (2012) Climate change impacts on marine ecosystems. *Annu Rev Mar Sci* 4:11–17
- Duce SJ, Parnell KE, Smithers SG, McNamara KE (2010) A synthesis of climate change and coastal science to support adaptation in the communities of the Torres Strait. Synthesis report prepared for the Marine and Tropical Sciences Research Facility (MTSRF). Reef & Rainforest Research Centre Limited, Cairns, p 64
- Easterling DR, Evans JL, Groisman PY et al (2000) Observed variability and trends in extreme climate events: a brief review. *Bull Am Meteorol Soc* 81:417–421
- Edwards HH (2013) Potential impacts of climate change on warmwater megafauna: the Florida manatee example (*Trichechus manatus latirostris*). *Clim Chang* 121(4):727–738. doi:[10.1007/s10584-013-0921-2](https://doi.org/10.1007/s10584-013-0921-2)
- Elsner R (1999) Living in water: solutions to physiological problems. In: Reynolds JE, Rommel SA (eds) *Biology of marine mammals*. Smithsonian Institution Press, USA, pp 73–117
- El Espectador (2016) Medio Ambiente 12 April 2016 Manatíes en ciénaga de Mahates, en riesgo por falta de alimento. <http://www.elespectador.com/noticias/medio-ambiente/manaties-cienaga-de-mahates-riesgo-falta-de-alimento-video-626621>. Accessed 6 11 16
- Emanuel K (2005) Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436:686–688

- Errera RM, Yvon-Lewis S, Kessler JD et al (2014) Responses of the dinoflagellate *Karenia Brevis* to climate change:  $pCO_2$  and sea surface temperatures. *Harmful Algae* 37:110–116
- Fearnside PM (2006) Dams in the Amazon: Belo Monte and Brazil's hydroelectric development of the Xingu river basin. *Environ Manag* 38:16–27. doi:10.1007/s00267-005-0113-6
- Fearnside PM (2014) Impacts of Brazil's Madeira River dams: unlearned lessons for hydroelectric development in Amazonia. *Environ Sci Pol* 38:164–172. doi:10.1016/j.envsci.2013.11.004
- Fearnside PM (2016a) Environmental and social impacts of hydroelectric dams in Brazilian Amazonia: implications for the aluminum industry. *World Dev* 77:48–65. doi:10.1016/j.worlddev.2015.08.015
- Fearnside PM (2016b) Tropical dams: to build or not to build? *Science* 351(80):456–457. doi:10.1126/science.351.6272.456-b
- Ferreira-Ferreira J, Silva TSF, Streher AS et al (2014) Combining ALOS/PALSAR derived vegetation structure and inundation patterns to characterize major vegetation types in the Mamirauá sustainable development reserve, Central Amazon floodplain, Brazil. *Wetl Ecol Manag* 23:41–59. doi:10.1007/s11273-014-9359-1
- Ficke AD, Myrick CA, Hansen LJ (2007) Potential impacts of global climate change on freshwater fisheries. *Rev Fish Biol Fish* 17:581–613
- Florida Oceans and Coastal Council (2010) An update of the effects of climate change on Florida's ocean and coastal resources December 2010. Available at: [http://seagrant.noaa.gov/Portals/0/Documents/what\\_we\\_do/climate/Florida%20Report%20on%20Climate%20Change%20and%20SLR.pdf](http://seagrant.noaa.gov/Portals/0/Documents/what_we_do/climate/Florida%20Report%20on%20Climate%20Change%20and%20SLR.pdf). Accessed 30 April 2016
- Florida Department of Environmental Protection (2014) Water use trends in Florida. Available via <https://www.dep.state.fl.us/water/waterpolicy/docs/factsheets/wrfss-water-use-trends.pdf>. Accessed 30 April 2016
- Fourqurean JW, Rutten LM (2004) The impacts of hurricane Georges on the soft-bottom, back reef communities: site- and species-specific effects in South Florida seagrass beds. *Bull Mar Sci* 75:239–257
- Frankham R, Bradshaw CJA, Brook BW (2014) Genetics in conservation management: revised recommendations for the 50/500 rules, red list criteria and population viability analyses. *Biol Conserv* 170:56–63. doi:10.1016/j.biocon.2013.12.036
- Fuentes MMPB, Chambers LE, Chin A, Dann P, Dobbs K, Poloczanska E, Maison K, Turner M, Pressey RL, Marsh H (2014) Adaptive management of marine mega-fauna in a changing climate. *Mitig Adapt Strateg Glob Chang*. doi:10.1007/s11027-014-9590
- Fuentes MMPB, Beatty B, Delean S, Grayson S, Logan M, Lavender S, Logan M, Marsh H (2016) Spatial and temporal variation in the effects of climatic variables on dugong calf production. *PLoS One*, PONE-D-15-52097R1
- Gallivan GJ, Best RC, Kanwisher JW (1983) Temperature regulation in the Amazonian manatee *Trichechus inunguis*. *Physiol Zool* 56:255–262
- Gaye CB, Diaw M, Malou R (2013) Assessing the impacts of climate change on water resources of a west African trans-boundary river basin and its environmental consequences (Senegal River basin). *Sci Cold Arid Reg* 5:0140–0156
- Geophysical Fluid Dynamics Laboratory/NOAA (2015) Global warming and hurricanes. <http://www.gfdl.noaa.gov/global-warming-and-hurricanes>. Accessed 30 April 2016.
- Gessner BD, Middaugh JP (1995) Paralytic shell fish poisoning in Alaska: a 20-year retrospective analysis. *Am J Epidemiol* 141:766–770
- Gilbert PM, Burkholder JM (2006) The complex relationships between increasing fertilization of the earth, coastal eutrophication and proliferation of harmful algal blooms. In: Granéli E, Turner J (eds) *Ecology of harmful algae*. Springer, New York, pp 341–354
- Goldenberg SB, Landsea CW, Mestas-Núñez AM, Gray WM (2001) The recent increase in Atlantic hurricane activity: causes and implications. *Science* 293:474–479
- Greening H, Doering P, Corbett C (2006) Hurricane impacts on coastal ecosystems. *Estuar Coasts* 29:877–879
- Guterres-Pazin MG, Marmontel M, Rosas FCW, Pazin VFV, Venticinque EM (2014) Feeding ecology of the Amazonian manatee (*Trichechus inunguis*) in the Mamirauá and Amanã sustainable development reserves. *Braz Aqua Mammal* 40:139–149. doi:10.1578/AM.40.2.2014.139

- Haddon AC (1912) Reports of the Cambridge anthropological expedition to Torres Strait. The University Press, Cambridge
- Hallegraeff GM (2010) Ocean climate change, phytoplankton community response and harmful algal blooms: a formidable predictive challenge. *J Phycol* 46:220–235
- Halpern BS, Walbridge S, Selkoe KA et al (2008) A global map of human impact on marine ecosystems. *Science* 319:948–952
- Hamilton SK (2010) Biogeochemical implications of climate change for tropical rivers and floodplains. *Hydrobiologia* 657:19–35. doi:[10.1007/S10750-009-0086-1](https://doi.org/10.1007/S10750-009-0086-1)
- Heinsohn GE, Spain AV (1974) Effects of a tropical cyclone on littoral and sub littoral biotic communities and on a population of dugongs (*Dugong dugon* [Müller]). *Biol Conserv* 6:143–152
- Heisler J, Gilbert P, Burkholder J et al (2008) Eutrophication and harmful algal blooms: scientific consensus. *Harmful Algae* 8:3–13
- Horgan P, Booth D, Nichols C, Lanyon JM (2014) Insulative capacity of the integument of the dugong (*Dugong dugon*): thermal conductivity, conductance and resistance measured by in vitro heat flux. *Mar Biol* 161:1395–1407. doi:[10.1007/s00227-014-2428-4](https://doi.org/10.1007/s00227-014-2428-4)
- Irvine AB (1983) Manatee metabolism and its influence on distribution in Florida. *Biol Conserv* 25:315–334
- Junk WJ, Piedade MTF, Schöngart J et al (2012) A classification of major natural habitats of Amazonian white-water river floodplains (várzeas). *Wetl Ecol Manag* 20:461–475. doi:[10.1007/s11273-012-9268-0](https://doi.org/10.1007/s11273-012-9268-0)
- Johannes RE, Macfarlane JW (1991) Traditional fishing in the Torres Strait islands. CSIRO, Hobart
- IPCC (2014) Climate change 2014: synthesis report contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva
- Keith Dagne L (2015) *Trichechus senegalensis*. In: The IUCN Red List of Threatened Species 2015: e.T22104A81904980. <http://dx.doi.org/10.2305/IUCN.UK.2015-4.RLTS.T22104A81904980.en>. Accessed 15 April 2016
- Killeen TJ, Solórzano LA (2008) Conservation strategies to mitigate impacts from climate change in Amazonia. *Philos Trans R Soc B* 363:1881–1888
- Koch M, Bowes G, Ross C, Zhang X-H (2013) Climate change and ocean acidification effects on seagrasses and marine macroalgae. *Glob Chang Biol* 19:103–132. doi:[10.1111/j.1365-2486.2012.02791.x](https://doi.org/10.1111/j.1365-2486.2012.02791.x)
- Laist DW, Reynolds JE III (2005) Florida manatees, warm-water refuges, and the uncertain future. *Coast Manag* 33:279–295
- Landsberg JH, Steidinger KA (1998) A historical review of *Gymnodinium breve* red tide implicated in mass mortalities of the manatee (*Trichechus manatus latirostris*) in Florida, USA. In: Reguera B, Blanco J, Fernandez ML, Wyatt T (eds) Proceedings of the 8th international conference on harmful algae. Xunta de Galicia and Intergovernmental Oceanographic Commission of UNESCO, Paris, pp 97–100
- Langerwisch F, Rost S, Gerten D, Poulter B, Rammig A, Cramer W (2013) Potential effects of climate change on inundation patterns in the Amazon Basin. *Hydrol Earth Syst Sci* 17:2247–2262
- Langtimm CA, Beck CA (2006) Lower survival probabilities for adult Florida manatees in years with intense coastal storms. *Ecol Appl* 13:257–268
- Lanyon JM, Newgrain K, Alli TSS (2006) Estimation of water turnover rate in captive dugongs (*Dugong dugon*). *Aquat Mamm* 32:103–108
- Lau CL, Smythe LD, Craig SB, Weinstein P (2010) Climate change, flooding, urbanisation and leptospirosis: fuelling the fire? *Trans R Soc Trop Med Hyg* 104:631–638
- Lawler IR, Parra G, Noad M (2007) Vulnerability of marine mammals in the great barrier reef to climate change. In: Johnson JE, Marshall PA (eds) Climate change and the great barrier Reef, a vulnerability assessment. Australia, Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, pp 498–513
- Macreadie PI, Baird ME, Trevathan-Tackett SM, Larkum AWD, Ralph PJ (2014) Quantifying and modelling the carbon sequestration capacity of seagrass meadows – a critical assessment. *Mar Pollut Bull* 83:430–439

- Mallin MA, Corbett CA (2006) How hurricane attributes determine the extent of environmental effects: multiple hurricanes and different coastal systems. *Estuar Coasts* 29:1046–1061
- Marengo JA, Tomasella J, Alves LM, Soares WR, Rodriguez DA (2011) The drought of 2010 in the context of historical droughts in the Amazon region. *Geophys Res Lett* 38:L12703. doi:10.1029/2011GL047436
- Marsh H (1989) Mass stranding of dugongs by a tropical cyclone. *Mar Mamm Sci* 5:75–84
- Marsh H, Kwan D (2008) Temporal variability in the life history and reproductive biology of female dugongs in Torres Strait: the likely role of sea grass dieback. *Cont Shelf Res* 28:2152–2159
- Marsh H, O'Shea TJ, Reynolds JE III (2011) Ecology and conservation of the Sirenia: dugongs and manatees. Cambridge University Press, Cambridge
- Marsh H, Grayson J, Grech A et al (2015) A re-evaluation of the sustainability of an indigenous marine mammal harvest using several lines of evidence. *Biol Conserv* 192:324–330
- Mathews PD, da Silva VMF, Rosas FCW, d'Affonseca Neto JA, Lazzarini SM, Ribeiro DC, Dubey JP, Vasconcellos SA, Gennari SM (2012) Occurrence of antibodies to *Toxoplasma gondii* and *Leptospira* spp. in manatees (*Trichechus inunguis*) of the Brazilian Amazon. *J Zoo Wildl Med* 43:85–88
- Meager JJ, Limpus C (2014) Mortality of inshore marine mammals in eastern Australia is predicted by freshwater discharge and air temperature. *PLoS One* 9(4):e94849. doi:10.1371/journal.pone.0094849
- Moore SK, Trainer VL, Mantua NJ et al (2008) Impacts of climate variability and future climate change on harmful algal blooms and human health. *Environ Health* 7:S4. doi:10.1186/1476-069X-7-S2-S
- Nietschmann B, Nietschmann J (1981) Good dugong, bad dugong: bad turtle, good turtle. *Natural History Magazine* 90, New York
- Omot N (2012) Food security in Papua New Guinea. AARES 56th Annual Conference – Fremantle, Western Australia, February 07–10, pp 17
- Owen HC, Flint M, Limpus CJ, Palmieri C, Mills PC (2013) Evidence of sirenian cold stress syndrome in dugongs *Dugong dugon* from Southeast Queensland, Australia. *Dis Aquat Org* 103:1–7. doi:10.3354/dao02568
- Parris A, Bromirski P, Burkett V et al. (2012) Global sea level rise scenarios for the United States National Climate Assessment. NOAA. Available via [http://www.cpo.noaa.gov/sites/cpo/Reports/2012/NOAA\\_SLR\\_r3.pdf](http://www.cpo.noaa.gov/sites/cpo/Reports/2012/NOAA_SLR_r3.pdf). Accessed 30 April 2016
- Poloczanska ES, Babcock RC, Butler A et al (2007) Climate change and Australian marine life. *Oceanogr Mar Biol Annu Rev* 45:407–478
- Powell JA (1996) The distribution and biology of the west African manatee (*Trichechus senegalensis*, link 1795). United Nations Environmental Program, Regional Seas Programme, Ocean and Coastal Areas, Nairobi, Kenya
- Prospero JM, Lamb PJ (2003) African drought and dust transport to Caribbean: climate change implications. *Science* 302:1024–1027
- Rahmstorf S (2010) A new view on sea level rise. *Nat Rep Clim Chan* 1004:44–45. doi:10.1038/climate.2010.2
- Ralph PJ (1998) Photosynthetic response of laboratory-cultured *Halophila ovalis* to thermal stress. *Mar Ecol Prog Ser* 171:123–130
- Rowcliffe JM, Milner-Gulland EJ, Cowlshaw G (2005) Do bushmeat consumers have other fish to fry? *TREE* 20:274–276
- Runge MC, Sanders-Reed CA, Langtimm CA et al (2007) A quantitative threats analysis for the Florida manatee (*Trichechus manatus latirostris*). Available at U.S. Geological Survey <https://pubs.er.usgs.gov/publication/ofr20071086>. Accessed 30 April 2016
- Scavia D, Field JC, Boesch DF et al (2002) Climate change impacts on U.S. coastal and marine ecosystems. *Estuaries* 25:149–164
- Sellner KG, Doucette GJ, Kirkpatrick GJ (2003) Harmful algal blooms: causes, impacts and detection. *J Ind Microbiol Biotechnol* 30:383–406
- SFWMD (Southwest Florida Water Management District) (2001) Hydrology and water quality of select springs in the Southwest Florida Water Management District. Available at Friends of



- mineral springs <http://friendsofwarmineralsprings.org/wp-content/uploads/2013/09/Hydrology-Water-quality-SW-Fla.pdf>. Accessed 30 April 2016
- Sheppard J, Preen AR, Marsh H, Lawler IR, Whiting S, Jones RE (2006) Movement heterogeneity of dugongs, *Dugong dugon* Müller over large spatial scales. *J Exp Mar Biol Ecol* 334:64–83
- Short FT, Neckles HA (1999) The effects of global climate change on seagrasses. *Aquat Bot* 63:169–196
- Sorribas MV, Paiva RCD, Melack JM et al (2016) Projections of climate change effects on discharge and inundation in the Amazon basin. *Clim Chang*. doi:[10.1007/s10584-016-1640-2](https://doi.org/10.1007/s10584-016-1640-2)
- Steward JS, Virnstein RW, Lasi MA et al (2006) The impacts of the 2004 hurricanes on the hydrology, water quality and seagrass in the Central Indian River lagoon, Florida. *Estuar Coasts* 29:954–965
- Stoeckl N, Larson TM, Hicks C, Pascoe S, Marsh H (in press) Socioeconomic impacts of changes to marine fisheries and aquaculture that are brought about through climate change. In: Phillips B (ed) *The impact of climate change on marine fisheries and aquaculture and their adaptations*. Wiley, USA
- Thornback J, Jenkins M (1982) *The IUCN mammal red data book part 1: threatened mammalian taxa of the Americas and the Australasian zoogeographic region (excluding Cetacea)*. The International Union for Conservation of Nature (IUCN) and United Nations Environment Program (UNEP), Gland, Switzerland
- UN Atlas (2010) UN Atlas: 44 percent of us live in coastal areas <https://coastalchallenges.com/2010/01/31/un-atlas-60-of-us-live-in-the-coastal-areas/>. Accessed April 30 2016
- Wade M, Mignot J, Lazar A, Gaye AT, Carré M (2015) On the spatial coherence of rainfall over the Saloum delta (Senegal) from seasonal to decadal time scales. *Front Earth Sci* 3:30. doi:[10.3389/feart.2015.00030](https://doi.org/10.3389/feart.2015.00030)
- Walsh JJ, Steidinger KA (2001) Saharan dust and Florida red tides: the cyanophyte connection. *J Geophys Res Oceans* 106:11,597–11,612
- Walsh JE, Phillips AS, Portis DH, Chapman WL (2001) Extreme cold outbreaks in the United States and Europe, 1948–99. *J Clim* 14:2642–2658
- Walsh CJ, Butawan M, Yordy J et al (2015) Sublethal red tide toxin exposure in free-ranging manatees (*Trichechus manatus*) affects the immune system through reduced lymphocyte proliferation response, inflammation, and oxidative stress. *Aquat Toxicol* 161:73–84
- Watson RT, Zinyowera MC, Moss RH (1996) *Climate change 1995: impacts, adaptations, and mitigation of climate change. Scientific-technical analysis. Contribution of working group II to the second assessment report of the intergovernmental panel on climate change*. Cambridge University Press, New York
- Waycott M, Duarte CM, Carruthers TJB et al (2009) Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proc Natl Acad Sci U S A* 106:12377–12381
- Webster PJ, Holland GJ, Curry JA et al (2005) Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309:1844–1846
- Wells ML, Trainer VL, Smayda TJ et al (2015) Harmful algal blooms and climate change: learning from the past and present to forecast the future. *Harmful Algae* 49:68–93
- Winemiller KO, McIntyre PB, Castello L et al (2016) Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* 351(80):128–129. doi:[10.1126/science.aac7082](https://doi.org/10.1126/science.aac7082)