Journal of Environmental Management 215 (2018) 32–39

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

Ecosystem-based management of coastal zones in face of climate change impacts: Challenges and inequalities

Gerson Fernandino [a,*], Carla I. Elliff [a], Iracema R. Silva [b]

[a] Graduate Program in Geology, Núcleo de Estudos Hidrogeológicos e do Meio Ambiente – NEHMA, Instituto de Geociências, Universidade Federal da Bahia, Rua Barão de Geremoabo, s/n, Campus Federação, CEP 40170-290, Salvador, Bahia, Brazil

[b] Department of Oceanography, Núcleo de Estudos Hidrogeológicos e do Meio Ambiente – NEHMA, Instituto de Geociências, Universidade Federal da Bahia, Rua Barão de Geremoabo, s/n, Campus Federação, CEP 40170-290, Salvador, Bahia, Brazil

ARTICLE INFO

Article history:
Received 22 November 2017
Received in revised form
3 March 2018
Accepted 9 March 2018
Available online 16 March 2018

Keywords:
Climate change
Coastal zone
Ecosystem-based management

ABSTRACT

Climate change effects have the potential of affecting both ocean and atmospheric processes. These changes pose serious threats to the millions of people that live by the coast. Thus, the objective of the present review is to discuss how climate change is altering (and will continue to alter) atmospheric and oceanic processes, what are the main implications of these alterations along the coastline, and which are the ecosystem-based management (EBM) strategies that have been proposed and applied to address these issues. While ocean warming, ocean acidification and increasing sea level have been more extensively studied, investigations on the effects of climate change to wind and wave climates are less frequent. Coastal ecosystems and their respective natural resources will respond differently according to location, environmental drivers and coastal processes. EBM strategies have mostly concentrated on improving ecosystem services, which can be used to assist in mitigating climate change effects. The main challenge for developing nations regards gaps in information and scarcity of resources. Thus, for effective management and adaptive EBM strategies to be developed worldwide, information at a local level is greatly needed.

Contents

1. Introduction

The 21st century has so far demonstrated a clear trend of increase in both atmospheric and ocean temperature (Semedo et al.,

* Corresponding author.
E-mail address: gerson.fernandino@yahoo.com.br (G. Fernandino).

https://doi.org/10.1016/j.jenvman.2018.03.034
0301-4797/

2013). Greenhouse gas emissions have reached unprecedented atmospheric concentrations due to human activities, as shown in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5). Increases in carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) combined to other human-originated factors have been labeled as extremely probable causes for the global warming phenomenon observed since the mid-20th century (IPCC, 2014).

The upper 75 m of the global ocean has warmed 0.11 °C per decade over the period between 1971 and 2010 (IPCC, 2013). IPCC projections also indicate that oceans will continue to warm until the end of the century, affecting the deep ocean and altering ocean circulation. Moreover, human alterations in atmospheric composition can lead to a series of impacts, such as the heat waves and floods recently experienced in Europe (2003), Pakistan and Russia (2010), and Texas (2011) (Mann et al., 2017).

Since the 1990s, studies such as that by Nicholls and Leatherman (1995) have indicated and alerted to possible impacts caused by climate change to the natural resources of coastal zones. These findings have led to great concern regarding public policies and coping strategies, particularly considering that, as the aforementioned authors also reported, developing countries present incomplete databases on the various aspects of their coastal zones. More than 20 years later, this lack of long-term temporal and spatial data series remains an issue in these countries (i.e. Almeida et al., 2015; Blankespoor et al., 2017), implicating in their ability to understand, predict, evaluate and, therefore, either mitigate or adapt to future conditions. Thus, the decision-makers of the majority of all coastal zones across the globe present inherent difficulties to assess climate change impacts over the coastline and propose adequate management and adaptation strategies. This situation was also observed by Bergillos et al. (2018) regarding the efficiency of nourishment strategies in eroding deltas.

Martínez et al. (2007) identified that 84% of all countries in the world have coastlines, with a large percentage of their population (80–100%) living within 100 km of the shoreline. More recently, Neumann et al. (2015) projected coastal population growth scenarios for 2030 and 2060 and observed a global growth in the population living in low-elevation coastal zones, especially in Asia. Thus, a scenario of rising mean sea level, for example, would imply in a future reallocation of millions of people.

In addition to population growth, population migration is also an important factor contributing towards an increasing coastal population (Martínez et al., 2007). Hugo (2011) shows that human migration may be a reflection of climate change effects. Moreover, during the past few years, civil conflicts and poverty have caused an intense migration of thousands of people from African and Middle Eastern countries towards Mediterranean European countries. Between January 2014 and June 2015 alone, 356,000 refugees and migrants arrived in Europe by sea (Cogolati et al., 2015). This massive short-term population increase may represent an additional pressure to the coastal zones of the countries where immigrants and refugees are settling in. Moreover, refugee settlements have been shown to cause a series of impacts, such as surface and subsurface water depletion and pollution, degradation of agricultural lands, deforestation, etc. (Hoerz, 1995). Thus, effective management of natural resources has become an increasingly pressing matter for countries in this situation.

At the beginning of the 21st century, more than 100 million people were reported to be living in places located merely 1 m above current mean sea level (Douglas and Peltier, 2002). This position would definitely leave these people vulnerable to coastal flooding and to loss of property in ongoing and future climate change scenarios. Inundations are particularly concerning for low lying island countries, which face the risk of disappearing (Albert et al., 2016). Moreover, 13% of the world's population is estimated to live in coastal areas at risk and 75% of this population is located in Asia, in areas between 0 and 10 m above sea level (Smith, 2011). On the other hand, a greater population density could attract more easily financial resources to be used towards management strategies, particularly within an ecosystem-based framework.

The full range of impacts that climate change can impose to coastlines around the world are not fully understood, let alone addressed in coastal management strategies. Thus, the present review has the objective of discussing how climate change is altering (and will continue to alter) atmospheric and oceanic processes, what are the main implications of these alterations along the coastline, and which are the ecosystem-based management (EBM) strategies that have been proposed and applied to address these issues in different contexts.

2. Global climate change effects

2.1. Wind climate

While some consequences of a changing climate have been more deeply explored, such as global warming, less attention has been given to the impact of climate change on wind patterns, for example, despite the great potential for geophysical and societal negative effects (McInnes et al., 2011).

Wind climate is expected to experience either intensification or weakening over various systems in future scenarios. Sydeman et al. (2014) evaluated patterns observed from reanalysis models and identified wind intensification over most latitudes of the Benguela and California systems, as well as for the southern portion of the Humboldt system. However, these same authors observed a weakening in wind intensity in most latitudes of the Iberian system and in the southern half of the Canary system. McInnes et al. (2011) and Gallagher et al. (2016) also observed decreases in wind speeds at 10 m of altitude among most of the models investigated for equatorial ocean regions, and for the North Atlantic, respectively. However, Pryor and Barthelmie (2010) observed that mean wind speeds are unlikely to change more than the current inter-annual variability rate over the majority of Europe and North America during the present century. More recently, Davy et al. (2018) observed a decrease in wind intensity over Europe and an increase over North Africa and Barents Sea, and no negative impact of climate change on wind resources in the Black Sea region. On the other hand, regarding South America, Pryor and Barthelmie (2010) identified that variations may be greater than other regions of the world, but these data were considered uncertain.

Significant variations in wind intensity would imply in changes to the wave climate that is generated by these systems. Wind-generated waves are formed from the transference of momentum from the atmosphere to the ocean surface. Once they are generated, these waves are responsible for the distribution of heat and momentum between these two compartments (Semedo et al., 2013; Dobrynin et al., 2015). Thus, these altered wind-generated waves could propagate across ocean basins and lead to changes in the regional wave climate of places far away from the origin of this alteration.

Nevertheless, wind intensity is not the only wind parameter that can change in future climate scenarios. As described by McInnes et al. (2011), in the case of an intensification of a specific wind directional component (i.e. north component in the Northern Hemisphere), the angle of incidence of this wind system will vary (i.e. clockwise rotation, following the Coriolis Effect). Moreover, these authors also state that changes in the direction of winds are particularly concerning in coastal regions where wind influences hydrodynamic agents. Thus, meteorological tides, waves and the occurrence and intensity of storm surges, for example, can be subjected to changes under these conditions.

Regarding the frequency of extreme events, Mann et al. (2017) stated that weather extremes tend to increase due to climate change. On the other hand, Gallagher et al. (2016), by analyzing wave climate projections for Ireland, found results that indicated that neither intensity nor frequency of wind storms should occur by the end of the current century.

2.2. Wave climate

As exposed in the previous section, changes to wave climate are expected as a consequence to alterations in wind fields. The effects of climate change upon wind climate can lead to alterations in the distribution (direction and intensity) of winds, thus producing new wind-generated wave patterns. Gallagher et al. (2016), for example, modeled wave projections showing overall annual and seasonal decreases. Moreover, as Dobrynin et al. (2015) discuss, there is a cyclic pattern across the globe in which waves are able to modify general wind patterns that, in turn, control the formation and characteristics of waves, in a feedback relationship.

Global oceanographic changes can lead to different responses at regional and local levels. Most projections of wave climate in the literature represent regional scales with several limitations, which make comparisons difficult. However, Hemer et al. (2013) justify that current understanding of the projected changes to wave climate is limited due to the reliance upon other climatological factors such as temperature, rainfall and mean sea level. Moreover, natural variability of the wave climate system should also be taken into consideration. Longshore drift, for example, is a coastal process that would be directly affected in altered wave climate conditions, since it is sensitive to seasonal changes in wave direction due to variations in wind direction (McInnes et al., 2011).

At a regional level, wave climate trends present signals from local patterns, as well as signals from swells that are generated remotely (Dobrynin et al., 2015). These signals are an indication that swell waves strongly influence global wave climate. For example, Hemer et al. (2013) demonstrated that waves generated in the Southern Ocean propagate northwards as a swell, influencing the wave climate of distant locations by increasing mean peak period in over 30%. Increases in wave peak period were also projected for the Southern Ocean, Eastern Pacific and Indian Ocean, and decreases for the North Atlantic Ocean and part of the Western Pacific Ocean (Camus et al., 2017). These conditions could change under a future scenario.

In fact, not only peak periods could change under the expected future scenarios, but also wave heights and wave directions. Camus et al. (2017) projected increases in significant wave height for the Southern Ocean and Eastern Pacific, and decreases for the North Atlantic Ocean, western North Pacific basin, Indian Ocean and Southern Hemisphere mid-latitudes. In fact, Hemer et al. (2013) projected a decrease in the angle of wave incidence particularly for the northern portions of the extratropical storm belts (western regions) of the Southern and Northern Pacific and Atlantic oceans. The same authors also identified that in the southern-equatorial region there will be an increase in the incidence angle of waves that originate from the south, while in the northern-equatorial region, this increase was associated with waves coming from the east.

However, while an increase in storm surge intensity due to wave climate alterations is a worldwide concern, daily wave climate alterations should also be analyzed. Mori et al. (2010) found that regions located at middle latitudes are expected to present lower mean wave height, while areas located at either high latitudes or near the equator will experience an increase in mean wave height.

Finally, wave climate is not altered exclusively by changes in wind patterns. Ice cover expansion and contraction movements in Polar Regions also influence wave climate. However, although the processes are not yet fully understood and not usually incorporated into numerical models, ice melting is associated with wave generation, while marine ice formation prevents this from occurring (Dobrynin et al., 2015).

2.3. Ocean warming and ocean acidification

The effects of a warmer planet have already been observed to affect marine ecosystems, such as coral reefs. There have been three major events of mass coral bleaching (1998, 2002 and 2016) recorded so far. As shown by Hughes et al. (2017), the bleaching event of 2016 was more extensive and more severe, with over 60% of corals from the Great Barrier Reef having experienced extreme bleaching.

In addition to increasing global temperature, higher concentrations of atmospheric CO_2 are being absorbed by oceans and causing a decrease in ocean pH due to the production of carbonic acid. This process is known as ocean acidification. Due to its similar triggering parameter as global warming (increased CO_2), ocean acidification has been referred to as the “other CO_2 problem” (Doney et al., 2009). Nevertheless, the impacts of this alteration to the biogeochemistry of the oceans should not be overlooked.

One of the most concerning aspects of a more acidic ocean regards the reduction in the saturation state of aragonite. As discussed by Spalding and Brown (2015), with a decline in this parameter, coral reef skeletons will become more fragile, prone to erosion and will present lower growth rates. Other marine organisms that rely on biomineralization processes are also threatened by this situation, such as commercially important fish species during planktonic larvae phases (Guinotte and Fabry, 2008; Doney et al., 2009).

Despite clear geological records of coral reefs thriving during periods of higher CO_2 concentrations, the increases observed in the past occurred at a much slower pace than the changes that are currently underway (Pandolfi et al., 2011). Thus, the full scope of the effects that current ocean warming and ocean acidification will impose to marine ecosystems is unprecedented.

2.4. Mean sea level

Mean sea level is considered an important indicator for climate change, since it reflects changes in various parts of the climatic system (Slangen et al., 2014). Signs of sea-level rise can already be observed in several regions of the planet (IPCC, 2013), leading to a series of losses to coastal biota and human population. The relocation of entire coastal communities who live in low-lying areas has already been reported as a consequence of sea-level rise (Albert et al., 2016). However, it is important to note that sea-level rise rates projected at a regional level present significant variations from those calculated at a global scale (Rhein et al., 2013; Carson et al., 2016).

The different rates of sea-level variation due to loss of ice mass from icecaps and the Poles are associated with gravitational, rotational and deformational effects (Slangen et al., 2014). This was made clear in the study by Carson et al. (2016), in which the authors demonstrated that negative gravitational variations near places where ice is melting from icecaps and glaciers (i.e. Western Antarctica and Greenland) have led to a fall in sea level, while more distant regions have experienced a rise in sea level, which was mostly attributed to thermal expansion.

Different projections, considering distinct scenarios of carbon emission, present increase rates of different magnitudes. However, as presented by the IPCC (2013), there is a generalized global trend of increase in mean sea level. As shown in the IPCC AR5 report, the level of the global ocean can reach 0.73 m above current sea level by 2100 in the worst-case scenario of carbon emissions (RCP8.5), in which the mean temperature of the planet would rise 3.7 °C. In the best, though unrealistic, scenario (RCP2.6), in which carbon emissions would be virtually absent – and can no longer be achieved – predictions are of a mean sea-level increase of 0.24 m, with an increase of 1 °C in atmospheric temperature.

Under each of these scenarios, coastal zones across the globe will respond differently according to their individual characteristics. Carson et al. (2016) identified that mean sea level variations at a regional scale in coastal zones for scenario RCP4.5 (moderate mitigation of CO_2 emission) are estimated at 42.4 cm (global mean = 53.5 cm), while the mean sea level increase in coastal zones for scenario RCP8.5 (no mitigation for CO_2 emission) would be 57.8 cm (global mean = 71 cm). Therefore, values of mean sea level variations are lower for coastal zones while the highest values of mean sea level variation are found in offshore locations. However, as also stated by Carson et al. (2016), small oceanic islands, such as those in the Center Pacific region, are subjected to higher projections. Albert et al. (2016) reported that during the past 70 years, five Pacific islands have vanished due to sea-level rise and other six islands are experiencing severe coastal erosion. According to these authors, island disappearance was the result of the combined effect of sea-level rise, tectonic subsidence, and wave incidence, reinforcing the combined and synergic effect of these variables.

Slangen et al. (2014) demonstrated that the human drive is the dominant factor to explain the magnitude of sea level variations, while most of the variability in the models is caused by natural forcings. In addition to altering the concentration of atmospheric CO_2, mankind can also increase vulnerability to sea-level rise locally through human activities, such as causing the subsidence of earth due to the removal of groundwater reserves (Nicholls and Leatherman, 1995). Moreover, the inappropriate development of coastal communities and the construction of coastal engineering structures, such as rip-raps and seawalls, associated with the incidence of extreme events increase vulnerability to shoreline changes (Albert et al., 2016).

Sea level can also be influenced locally by waves. As described by Semedo et al. (2013), wave run-up has an important role in coastal zones since it significantly contributes towards increases in sea level during extreme events and subsequent coastal floods. Moreover, in rising sea-level scenarios, wave run-up is expected to increase and bring important implications to coastal protection designs (Arns et al., 2017).

3. Implications to the coastline

3.1. Coastal ecosystems

The response of each type of coastal ecosystem to climate change will vary according to several aspects, such as type of coastline, environmental drivers, and dominant processes (Ashton et al., 2011). For example, if the area is experiencing a mean sea-level rise or fall, if the ecosystem at hand is relatively sensitive to a warming climate or to a more acidic ocean, if there are other human pressures, etc. Fig. 1 shows various climate change implications to the coastline and the connections between natural and human compartments.

The evolution of coastlines is intrinsically associated with sea-level variations. Thus, there is an important relationship between sea-level rise and coastal erosion: a rise in mean sea level allows more energetic waves to reach the inner continental portions of the beach and redistribute sediment offshore. Even a small increase in mean sea level is able to cause a significant retreat of a beach, which can occur at different time scales. As explained by Leatherman et al. (2000), in a matter of days or even hours, extreme episodic events can cause a transient impact on the position of the shoreline, which intensifies erosion of sandy beaches.

More than 70% of all sandy beaches are currently under erosional processes (Mori et al., 2010). With the expected intensification of storm surges and wave run-up, projected for some locations, beach erosion is likely to increase. Urban beaches are particularly vulnerable, since human constructions have decreased natural wave buffering zones in much of these areas and interfere in longshore sediment transit.

This process of loss of intertidal habitats that are positioned between increasing human pressure landward and rising water level seaward is known as coastal squeeze (Pontee, 2013). Defeo et al. (2009) indicated that this process is in fact the most relevant threat faced by sandy beaches, with no realistic management scenario being able to improve this condition in the short term. In addition to beaches, several other coastal ecosystems are susceptible to coastal squeeze, such as mangroves and deltas. These humid areas present a history of human pressures, with large areas lost to both human and natural changes.

In turn, Woodroffe et al. (2016) affirm that mangrove forest resilience to sea-level rise depends on sediment supply (accretion) and the rate of sea-level variation, with lower resilience observed where human pressure is higher. According to these authors, although paleoenvironmental records indicate the ability of mangroves to adjust to sea-level changes, the idea that mangrove forests can keep up with sea-level rise is misleading, as they are likely to be replaced by terrestrial ecosystems in some locations. Osland et al. (2016) indicated that the replacement of foundation plant species could affect general ecosystem resilience and consequently ecosystem services. Blankespoor et al. (2017) showed that, in addition to loss of habitat, mangrove losses under sea-level rise and more intense storm surge scenarios would represent considerable economic loss to coastal populations in Asia. However, tidal marshes may expand as sea level rises. Raabe and Stumpf (2016), studying the Gulf Coast of Florida, observed a direct loss in salt marsh area of approximately 40 km^2, but a gain in over 80 km^2 as forests were converted into marsh areas over the past 120 years. This result indicates that habitat change due to sea-level rise is not restricted to habitat loss. Some habitats may thrive under new environmental conditions.

In turn, deltas are generally highly vulnerable to sea level rise, but in places where there is a large amount of available sediment, this material can elevate land levels through deposition and counteract the adverse effect of sea level rise (Nicholls et al., 1995). On the other hand, the construction of dams and other human actions can lead to sediment deficit, delta erosion and other important changes to the deltaic environment and morphology (Day et al., 2009; Syvitski et al., 2009; Anthony et al., 2014; Bergillos et al., 2016a). One example of a highly vulnerable delta is the Mekong Delta, in Vietnam, which is threatened by fast sea-level rise associated with local problems such as sediment trapping by river dams, groundwater extraction and accelerated coastal population growth (Allison et al., 2017). Other deltas across the globe are threatened by similar human factors and experience mean relative sea-level rise rates of 6.8 mm/year (Tessler et al., 2017). In addition to sea-level rise, deltas have also been shown to be vulnerable to changes in wave direction. The study conducted by Bergillos et al. (2016b) showed that changes in wave direction, and consequently in longshore drift, combined with river damming played an important role in increasing the vulnerability of a Spanish delta.

Rocky shores, on the other hand, present greater stability and are less likely to suffer a significant impact from sea level rise,

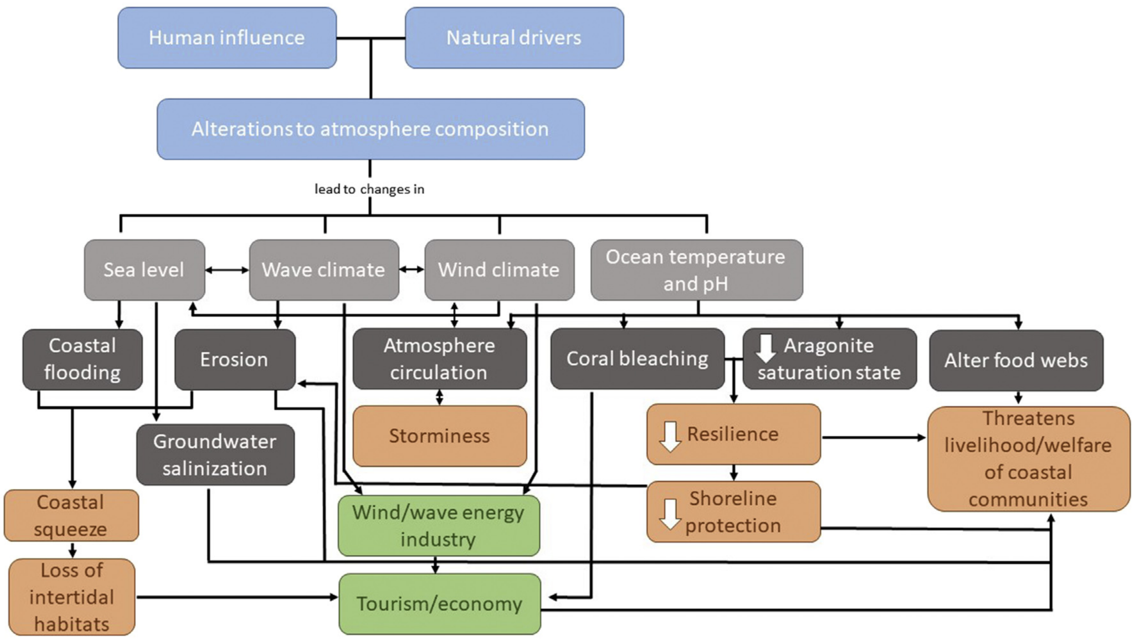

Fig. 1. Climate change implications to the coastline and connections between natural and human compartments.

particularly if they are steep. Moreover, Trenhaile (2011) indicated that an increase in the frequency of storm events will have a minor effect on the erosional efficacy of cliffs.

Coastlines with cliffs usually promote natural protection to adjacent coastal environments against floods and erosion. The response of rocky coasts against sea level change varies according to lithology (IPCC, 2013). There can be several types of feedback to sea level rise (instant, no feedback, negative, inverse) depending on the characteristics of the cliff and the environment (Ashton et al., 2011). A cliff environment with an instant response system is likely to be covered by or consist of sediment that is easily removable and conformable, assuming Bruun-type rules. In a no feedback relationship, there is a constant erosion zone that moves up the cliff profile as sea level rises. In turn, if the sea level remains constant and the erosion rate slows down over time, this would represent a negative feedback system. Finally, the inverse feedback system comprises cliffs where, despite sea-level rise increase, erosion rates decrease.

Nicholls et al. (1995) describe that, generally, the smaller the height of the cliff, the shorter the response time regarding sea level rise. The authors also state that for cliffs composed of muddy substrates, the main mechanism for loss of land is flooding, as opposed to erosion, which most times can be disregarded. However, recession rates of soft-rock coasts depend on the relative change in sea level rise. Ashton et al. (2011) observed that a cliffed coast would directly respond to both total elevation change and rate of sea-level rise. Trenhaile (2011) using a mathematical model, found that sea level rise will trigger faster rates of cliff recession.

Coral reefs are particularly sensitive to climate change effects. Spalding and Brown (2015) emphasize the negative impacts of a warmer and more acidic ocean to these ecosystems. Moreover, as defined by Neumann and MacIntyre (1985), in scenarios of sea level rise, a reef has three options of natural evolution: become a keep-up, catch-up or a give-up reef. Although some reefs may naturally not be able to keep up with a rising mean sea level, healthy and resilient reefs are more likely to thrive and even inhabit new substrates that become flooded (Elliff and Silva, 2017). Moreover, Hughes et al. (2017) also emphasize the importance of recovering reefs that are subjected to recurrent bleaching events through local management actions in marine parks and guaranteeing water quality.

3.2. Natural resources and ecosystem services

Society's reliance on natural resources and ecosystem services is a central point in the discussion of the effects of climate change on coastal environments. Since the classic study conducted by Costanza et al. (1997), the economic value of natural capital and ecosystem services has gained the spotlight in environmental assessments, raising important questions as to how changes to ecosystems could affect human populations from an economic and social perspective.

The effects of climate change encompass several sectors, such as food security, recreation opportunities, energy and coastal development. Moreover, chronic human pressures such as overfishing and pollution interact synergistically and cumulatively with climate change in ways that are still not fully understood (Hernández-Delgado, 2015).

Ruckelshaus et al. (2015) emphasize the challenges imposed by climate change to food security regarding both fisheries and aquaculture. Ocean warming and acidification, for example, threaten current food webs and, consequently, the livelihood of communities that depend on the ocean for a source of protein (Doney et al., 2009).

Tourism represents one of the most highly valued ecosystem services of coastal regions (Principe et al., 2012). The main climate change threats to the delivery of this service are those that affect primarily sandy beaches and coral reefs, two of the most relevant ecosystems for this service. Beaches are an important component for the tourism industry, with significant contribution to the economy (Alexandrakis et al., 2015). According to Defeo et al. (2009), recreational seashore activities are mostly concentrated on sandy beaches, promoting various human stressors on these already impacted ecosystems. As previously mentioned, coastal erosion is expected to increase in several beaches, as are the intensity and frequency of storm surges. Moreover, coral reefs are already experiencing worldwide degradation (Spalding and Brown, 2015), partly due to changes in ocean temperature and pH.

While exploring alternative sources of energy is a way to mitigate climate change, these alternative sources themselves may be susceptible to climate change effects. Pryor and Barthelmie (2010) describe that the main impacts of global changes to the wind energy industry regard alterations in the distribution of winds and their inter- and intra-annual variability. On a positive note, in a more recent study, Pryor and Barthelmie (2013) discuss that the projection for changes in extreme conditions do not pose major risks to structural safety, though research is mostly concentrated in North America and Europe. More recently, Carvalho et al. (2017), using the IPCC CMIP5 scenario, modeled future wind projections for Europe and observed intensification of wind energetic resources for the Baltic Sea region and decreases of this same resource in Southern Europe. However, regarding inter-annual variability, no significant changes are expected for this continent.

Wave, tidal and current offshore renewable energy production may also be affected, but these processes are generally addressed only as an option to mitigate climate change, not as an ecosystem service at risk.

Groundwater, therefore water resources, can be affected by sea-level rise. Nicholls and Leatherman (1995) stated that saltwater intrusions in groundwater reservoirs represent an important threat to the supply of water in coastal municipalities, as reported for Dakar in Senegal and Shanghai in China. The authors also indicated that the efficiency of water drainage is expected to decrease, while floods due to extreme events and rainfall are expected to increase. More recent studies have pointed to the same direction. Masciopinto and Liso (2016) projected saltwater intrusion of over 400 m into the continent and a decrease of approximately 16% in groundwater discharge for the 22nd century in southern Italy. This problem, associated with increasing water use poses serious threats regarding water security in coastal communities. Anderson and Al-Thani (2016) showed that increased groundwater withdrawal was more relevant to groundwater quality deterioration than sea-level rise itself in the Gulf Coast region.

4. Ecosystem-based management strategies and challenges

Environmental management strategies do not always consider the full range of benefits obtained from natural resources or even the multiple users that rely on these benefits. However, the objective of taking an ecosystem-based approach towards the management of coastal zones would be to address the most efficient solutions to make the most of the natural resources available in a broad and flexible manner (Elliff and Kikuchi, 2015).

Long et al. (2015) listed the key principles that guide ecosystem-based management (EBM) strategies as: consideration for ecosystem connections; appropriate spatial and temporal scales; inclusion of adaptive management; use of scientific knowledge; integrated management; stakeholder involvement; taking the dynamic nature of ecosystems into account; ecological integrity and biodiversity; sustainability; recognition of coupled social-ecosystem systems; present decisions that reflect societal choice; distinct boundaries; interdisciplinarity; appropriate monitoring; and acknowledgement of uncertainty.

The fact that adaptive management was included in these principles is a positive sign regarding climate change. As discussed by Ruckelshaus et al. (2015), climate change impacts are often considered as being too distant to be included in coastal management strategies. Thus, by acknowledging the importance of adaptive practices for the management of ecosystem services and human occupation along the coastline, tools and general guidelines can be developed to address site-specific issues.

There are numerous successful case studies on the application of an EBM approach to improve ecosystem services, as reported by Long et al. (2015). However, EBM strategies that are developed specifically to address climate change impacts are less common. Ruckelshaus et al. (2015) describe some examples of ecosystem-based adaptation, which generally involve the recovery of an ecosystem to improve local shoreline protection to erosion and coastal floods (i.e. mangroves, oyster reefs, seagrass beds).

The concept of investing in conservation strategies and habitat restoration instead of only building coastal defenses to improve shoreline protection is becoming increasingly popular. Moreover, as discussed by Spalding et al. (2014), hybrid solutions that involve both habitat restoration and coastal defense interventions can provide a considerable amount of co-benefits. Perkol-Finkel and Sella (2015) demonstrated a successful application of this strategy using two designs of concrete based coastal and marine infrastructure in Israel. The design with greater structural complexity, considered as the ecological design, provided not only shoreline protection at a similar level to its traditional non-ecological counterpart, but also supported a complex biological community. Moreover, using multiple lines of defense formed by complementary ecosystems (i.e. coral reefs and seagrass beds) have also shown great potential (Arkema et al., 2017). Regarding beach nourishment, Gopalakrishnan et al. (2011) emphasize the importance of sand availability to maintain the values of coastal properties and to guarantee beach nourishment as an appropriate strategy.

Considering specifically the impact of sea level rise, the Wellington City Council reported that there are basically five broad paths that coastal management can follow. These paths, which are most likely to be used as combined strategies according to time scale and locations, are: non-intervention, managed retreat, hold the line, accommodate, and expand into the coastal zone (WCC, 2013). *Non-intervention* represents a scenario of "doing nothing", including the normal maintenance of a business-*as*-usual approach. *Managed retreat* represents any strategic action to withdraw, relocate or abandon assets that are threatened by coastal hazards. In turn, a *hold the line* strategy would imply in implementing either a hard or soft protection to the area at risk, such as a seawall or performing beach nourishment. The approach to *accommodate* includes options such as building canals to address inundation issues or even opting for ferry services instead of roads that are constantly under threat. Finally, the strategy of *expanding into the coastal zone* includes actions such as reclamation and adapting homes to survive flood events (i.e. floating homes or house-boats). For example, the WCC (2013) indicated the three main intervention options for the Central Business District of Wellington, New Zealand as: managed retreat, the construction of a seawall and raised reclamation. On the other hand, for the Shelley Bay road to the Karaka Bays Road, the intervention options were: managed retreat and road raising combined with a seawall. These examples show that the interventions chosen depend on the characteristics of each site.

Despite an increasing array of successful applications of an EBM approach towards climate change impacts in coastal environments, planning and implementing adaptation strategies is still a worldwide challenge. For example, Thorne et al. (2017) observed varying levels of preparedness among resource managers for planning and implementing strategies to address climate change, with lower training and access to information among those working in rural estuaries in the USA. This is even more so for developing countries, where information is scarcer and resources less abundant.

As discussed by Hernández-Delgado (2015), the adaptive capacity of a given community depends on its level of wealth, the needs of the population, general education level, infrastructure status, and the vulnerability of the area to hazards. The author emphasizes small island nations as being particularly challenged in this situation of increasing need for preparedness and adaptation. Moreover, as stated by Ban et al. (2011), the science and planning strategies to deal with coral reef management, a critical ecosystem in face of climate change, is derived mostly from developed nations, which present different social, economic and cultural characteristics than the developing nations where most coral reefs occur. Thus, similar to what was observed by Ruckelshaus et al. (2015), local leadership is a key feature for EBM, considering that this group presents greater understanding of both the biophysical and socioeconomic conditions in their communities.

Decision makers need information on location and conditions under which EBM strategies such as nature-based coastal defenses will promote adequate protection (Arkema et al., 2017). Management plans can drive specific human actions that will have measurable outcomes for both the environment and people (Ruckelshaus et al., 2015). Nevertheless, adequate planning requires a level of knowledge that is not always available.

The concept of marine spatial planning (MSP) brings a promising framework to address most of the issues discussed in the present study. Ehler and Douvere (2009) provide an important step-by-step guide on how MSP can be applied and how it can indeed promote improvement in our use of natural capital and ecosystem services.

5. Conclusions

Despite climate model limitations and uncertainties regarding the magnitude of consequences, climate change projections should be incorporated in marine spatial planning and should be considered when devising solutions for ongoing issues in coastal areas. Doing so would provide greater longevity to actions, allowing the mitigation of impacts and reducing the vulnerability of coastal populations.

Moreover, efforts should be increased regarding coastal databases. The lack of long-term sea level measurements and topographic and bathymetric records over long stretches of the world's coastline hinders projections of alterations triggered by climate change.

Potential climate change impacts are projected using computer models, which present their own limitations. These limitations consist of, for example, a lack of data in various temporal and spatial resolutions, downscaling methods, and the complex feedback interactions between input variables. Regardless the fact that models are increasingly more accurate and thorough, feedback between variables tend to not be very well represented, which can lead to differences in the results between models, and between models and the reality. Regarding wind climate projections, for instance, a lack of consensus can be observed between models in the sense of assuring whether there will be significant wind intensity alterations or not.

Finally, while many studies regarding the impacts of climate change focus on global or regional models, decisions need to be made at a local level. Thus, for effective management and adaptive EBM strategies to be developed, information at a local level is greatly needed.

Acknowledgements

G. Fernandino thanks the National Counsel of Technological and Scientific Development (CNPq) for his PhD scholarship. C.I. Elliff thanks the Coordination for the Improvement of Higher Education Personnel (CAPES) for her PhD scholarship. The authors would also like to thank the anonymous reviewers for their time and helpful contributions.

References

Albert, S., Leon, J.X., Grinham, A.R., Chruch, J.A., Gibbes, B.R., Woodroffe, C.D., 2016. Interactions between sea-level rise and wave exposure on reef island dynamics in the Solomon Islands. Environ. Res. Lett. 11 https://doi.org/10.1088/1748-9326/11/5/054011ww, 054011:1–10.

Alexandrakis, G., Manasakis, C., Kampanis, N.A., 2015. Valuating the effects of beach erosion to tourism revenue. A management perspective. Ocean Coast. Manag. 111 (2015), 1–11. https://doi.org/10.1016/j.ocecoaman.2015.04.001.

Allison, M.A., Nittrouer, C.A., Ogston, A.S., Mullarney, J.C., Nguyen, T.T., 2017. Sedimentation and survival of the Mekong Delta: a case study of decreased sediment supply and accelerating rates of relative sea level rise. Oceanography 30 (3), 98–109. https://doi.org/10.5670/oceanog.2017.318.

Almeida, L.R., Amaro, V.E., Marcelino, A.M.T., Scudelari, A.C., 2015. Avaliação do clima de ondas da praia de Ponta Negra (RN, Brasil) através do uso do SMC-Brasil e sua contribuição à gestão costeira. Rev. Gestão Costeira Integr. 15 (2), 135–151. https://doi.org/10.5894/rgci532.

Anderson, F., Al-Thani, N., 2016. Effect of sea level rise and groundwater withdrawal in seawater intrusion in the Gulf Coast Aquifer: implications for agriculture. J. Geoscience Environ. Prot. 4, 116–124. https://doi.org/10.4236/gep.2016.44015.

Anthony, E.J., Marriner, N., Morhange, C., 2014. Human influence and the changing geomorphology of Mediterranean deltas and coasts over the last 6000 years: from progradation to destruction phase? Earth-Science Rev. 139, 336–361. https://doi.org/10.1016/j.earscirev.2014.10.003.

Arkema, K.K., Griffin, R., Maldonado, S., Silver, J., Suckale, J., Guerry, A.D., 2017. Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities. Ann. N. Y. Acad. Sci. https://doi.org/10.1111/nyas.13322.

Arns, A., Dangendorf, S., Jensen, J., Talke, S., Bender, J., Pattiaratchi, C., 2017. Sea-level rise induced amplification of coastal protection design heights. Sci. Rep. 7, 40171. https://doi.org/10.1038/srep40171.

Ashton, A.D., Walkden, M.J.A., Dickson, M.E., 2011. Equilibrium responses of cliffed coasts to changes in the rate of sea level rise. Mar. Geol. 284 (1–4), 217–229. https://doi.org/10.1016/j.margeo.2011.01.007.

Ban, N.C., Adams, V.M., Almany, G.R., Ban, S., Cinner, J.E., McCook, L.J., Mills, M., Pressey, R.L., White, A., 2011. Designing, implementing and managing marine protected areas: emerging trends and opportunities for coral reef nations. J. Exp. Mar. Biol. Ecol. 408, 21–31. https://doi.org/10.1016/j.jembe.2011.07.023.

Bergillos, R.J., Rodríguez-Delgado, C., Millares, A., Ortega-Sánchez, M., Losada, M.A., 2016a. Impact of river regulation on a Mediterranean delta: assessment of managed versus unmanaged scenarios. Water Resour. Res. 52, 5132–5148. https://doi.org/10.1002/2015WR018395.

Bergillos, R.J., López-Ruiz, A., Ortega-Sánchez, M., Masselink, G., Losada, M.A., 2016b. Implications of delta retreat on wave propagation and longshore sediment transport-Guadalfeo case study (southern Spain). Mar. Geol. 382, 1–16. https://doi.org/10.1016/j.margeo.2016.09.011.

Bergillos, R.J., López-Ruiz, A., Principal-Gómez, D., Ortega-Sánchez, M., 2018. An integrated methodology to forecast the efficiency of nourishment strategies in eroding deltas. Sci. Total Environ. 613, 1175–1184. https://doi.org/10.1016/j.scitotenv.2017.09.197.

Blankespoor, B., Dasgupta, S., Lange, G.M., 2017. Mangroves as a protection from surges in a changing climate. Ambio 46 (4), 478–491. https://doi.org/10.1007/s13280-016-0838-x.

Camus, P., Losada, I.J., Izaguirre, C., Espejo, A., Menéndez, M., Pérez, J., 2017. Statistical wave climate projections for coastal impact assessments. Earth's Future 5, 918–933. https://doi.org/10.1002/2017EF000609.

Carson, M., Köhl, A., Stammer, D., Slangen, A.B.A., Katsman, C.A., Van de Wal, R.S.W., Church, J., White, N., 2016. Coastal sea level changes, observed and projected during the 20th and 21st century. Clim. Change 134, 269–281. https://doi.org/10.1007/s10584-015-1520-1.

Carvalho, D., Rocha, A., Gómez-Gesteira, M., Silva Santos, C., 2017. Potential impacts of climate change on European wind energy resource under the CMIP5 future climate projections. Renew. Energy 101, 29–40. https://doi.org/10.1016/j.renene.2016.08.036.

Cogolati, S., Verlinden, N., Schimitt, P., 2015. Migrants in the Mediterranean: Protecting Human Rights. Directorate-general for External Policies, Policy Department, European Parliament. https://doi.org/10.2861/342397.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260. https://doi.org/10.1038/387253a0.

Davy, R., Gnatiuk, N., Pettersson, L., Bobylev, L., 2018. Climate change impacts on wind energy potential in the European domain with a focus on the Black Sea. Renew. Sustain. Energy Rev. 81 (2), 1652–1659. https://doi.org/10.1016/j.rser.2017.05.253.

Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. Nat. Geosci. 2 (10), 681–686. https://doi.org/10.1038/NGEO629.

Defeo, O., McLachlan, A., Schoeman, D.S., Schlacher, T.A., Dugan, J., Jones, A., Lastra, M., Scapini, F., 2009. Threats to sandy beach ecosystems: a review. Estuar. Coast. Shelf Sci. 81 (2009), 1–12. https://doi.org/10.1016/j.ecss.2008.09.022.

Dobrynin, M., Murawski, J., Baehr, J., Ilyina, T., 2015. Detection and attribution of climate change signal in ocean Wind waves. J. Clim. Am. Meteorological Soc. 28, 1578–1597. https://doi.org/10.1175/JCLI-D-13-00664.1.

Doney, S.C., Fabry, V.J., Feely, R.A., Kleypas, J.A., 2009. Ocean acidification: the other CO2 problem. Annu. Rev. Mar. Sci. 1, 169–192. https://doi.org/10.1146/annurev.marine.010908.163834.

Douglas, B.C., Peltier, W.R., 2002. The puzzle of global sea-level rise. Phys. Today 55 (3), 35–40. https://doi.org/10.1063/1.1472392.

Ehler, C., Douvere, F., 2009. Marine Spatial Planning: a Step-by-step Approach toward Ecosystem-based Management. Intergovernmental Oceanographic Commission and Man and the Biosphere Programme. IOC Manual and Guides No. 53, ICAM Dossier No. 6. Paris: UNESCO.

Elliff, C.I., Kikuchi, R.K.P., 2015. The ecosystem service approach and its application as a tool for integrated coastal management. Natureza Conservação 13, 105–111. https://doi.org/10.1016/j.ncon.2015.10.001.

Elliff, C.I., Silva, I.R., 2017. Coral reefs as the first line of defense: shoreline protection in face of climate change. Mar. Environ. Res. 127, 148–154. https://doi.org/10.1016/j.marenvres.2017.03.007.

Gallagher, S., Gleeson, E., Tiron, R., McGrath, R., Dias, F., 2016. Wave climate projections for Ireland for the end of the 21st century including analysis of EC-Earth winds over the North Atlantic Ocean. Int. J. Climatol. 36, 4592–4607. https://doi.org/10.1002/joc.4656.

Gopalakrishnan, S., Smith, M.D., Slott, J.M., Murray, A.B., 2011. The value of disappearing beaches: a hedonic pricing model with endogenous beach width. J. Environ. Econ. Manag. 61, 297–310. https://doi.org/10.1016/j.jeem.2010.09.003.

Guinotte, J.M., Fabry, V.J., 2008. Ocean acidification and its potential effects on marine ecosystems. Ann. N. Y. Acad. Sci. 1134, 320–342. https://doi.org/10.1196/annals.1439.013.

Hemer, M.A., Fan, Y., Mori, N., Semedo, A., Wang, X.L., 2013. Projected changes in wave climate from a multi-model ensemble. Nat. Clim. Change Lett. 3, 471–476. https://doi.org/10.1038/nclimate1791.

Hernández-Delgado, E.A., 2015. The emerging threats of climate change on tropical coastal ecosystem services, public health, local economies and livelihood sustainability of small islands: cumulative impacts and synergies. Mar. Pollut. Bull. 101 (1), 5–28. https://doi.org/10.1016/j.marpolbul.2015.09.018.

Hoerz, T., 1995. Refugees and Host Environments: a Review of Current and Related Literature. Refugee Studies Programme. University of Oxford.

Hughes, T.P., Kerry, J.T., Álvarez-Noriega, M., Álvarez-Romero, J.G., Anderson, K.D., Baird, A.H., Babcock, R.C., Beger, M., Bellwood, D.R., Berkelmans, R., Bridge, T.C., Butler, I.R., Byrne, M., Cantin, N.E., Comeau, S., Connolly, S.R., Cumming, G.S., Dalton, S.J., Diaz-Pulido, G., Eakin, C.M., Figueira, W.F., Gilmour, J.P., Harrison, H.B., Heron, S.F., Hoey, A.S., Hobbs, J.P.A., Hoogenboom, M.O., Kennedy, E.V., Kuo, C.Y., Lough, J.M., Lowe, R.J., Liu, G., McCulloch, M.T., Malcolm, H.A., McWilliam, M.J., Pandolfi, J.M., Pears, R.J., Pratchett, M.S., Schoepf, V., Simpson, T., Skirving, W.J., Sommer, B., Torda, G., Wachenfeld, D.R., Willis, B.L., Wilson, S.K., 2017. Global warming and recurrent mass bleaching of corals. Nature 543, 373–377. https://doi.org/10.1038/nature21707.

Hugo, G., 2011. Future demographic change and its interactions with migration and climate change. Glob. Environ. Change 21S, S21–S33. https://doi.org/10.1016/j.gloenvcha.2011.09.008.

IPCC, 2013. 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.

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.

Leatherman, S.P., Zhang, K., Douglas, B.C., 2000. Sea level rise shown to drive coastal erosion. Eos 81 (6), 55–57. https://doi.org/10.1029/00EO00034.

Long, R., Charles, A., Stephenson, R.L., 2015. Key principles of marine ecosystem-based management. Mar. Policy 57, 53–60. https://doi.org/10.1016/j.marpol.2015.01.013.

Mann, M.E., Rahmstorf, S., Kornhuber, K., Steinman, B.A., Miller, S.K., Coumou, D., 2017. Influence of anthropogenic climate change on planetary wave resonance and extreme weather events. Sci. Rep. 7 (45242), 1–10. https://doi.org/10.1038/srep45242.

Martínez, M.L., Intralawan, A., Vázquez, G., Pérez-Maqueo, O., Sutton, P., Landgrave, R., 2007. The coasts of our world: ecological, economic and social importance. Ecol. Econ. 63 (2007), 254–272. https://doi.org/10.1016/j.ecolecon.2006.10.022.

Masciopinto, C., Liso, I.S., 2016. Assessment of the impact of seal-level rise due to climate change on groundwater discharge. Sci. Total Environ. 569–570, 672–680. https://doi.org/10.1016/j.scitotenv.2016.06.183.

McInnes, K., Erwin, T.A., Bathols, J.M., 2011. Global climate model projected changes in 10 m wind speed and direction due to anthropogenic climate change. Atmos. Sci. Lett. 12, 325–333. https://doi.org/10.1002/asl.341.

Mori, N., Yasuda, T., Mase, H., Tom, T., Oku, Y., 2010. Projection of extreme wave climate change under global warming. Hydrological Res. Lett. 4, 15–19. https://doi.org/10.3178/hrl.4.15.

Neumann, A.C., MacIntyre, I., 1985. Reef response to sea level rise: keep-up, catch-up or give-up. In: Gabrie, C., Toffart, J.L., Salvat, B. (Eds.), Proceedings of the Fifth International Coral Reef Congress. Symposia and Seminars, Tahiti, pp. 105–110.

Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future coastal population growth and exposure to sea-level rise and coastal flooding – a global assessment. Plos One 10, e0118571. https://doi.org/10.1371/journal.pone.0118571.

Nicholls, R.J., Leatherman, S.P., 1995. The implications of accelerated sea-level rise for developing countries: a discussion. J. Coast. Res. SI 14, 303–323. https://doi.org/10.2112/07A-0003.1.

Nicholls, R.J., Leatherman, S.P., Dennis, K.C., Volonté, C.R., 1995. Impacts and responses to sea-level rise: qualitative and quantitative assessments. J. Coast. Res. SI 14, 26–43.

Osland, M.J., Enwright, N.M., Day, R.H., Gabler, C.A., Stagg, C.L., Grace, J.B., 2016. Beyond just sea-level rise: considering macroclimatic drivers within coastal wetland vulnerability assessments to climate change. Glob. Change Biol. 22, 1–11. https://doi.org/10.1111/gcb.13084.

Pandolfi, J.M., Connolly, S.R., Marshall, D.J., Cohen, A.L., 2011. Projecting coral reef futures under global warming and ocean acidification. Science 333 (6041), 418–422. https://doi.org/10.1126/science.1204794.

Perkol-Finkel, S., Sella, I., 2015. Blue is the new green – ecological enhancement of concrete based coastal and marine infrastructure. Ecol. Eng. 84, 260–272. https://doi.org/10.1016/j.ecoleng.2015.09.016.

Pontee, N., 2013. Defining coastal squeeze: a discussion. Ocean Coast. Manag. 84, 204–207. https://doi.org/10.1016/j.ocecoaman.2013.07.010.

Principe, P., Bradley, P., Yee, S., Fisher, W., Johnson, E., Allen, P., Campbell, D., 2012. Quantifying Coral Reef Ecosystem Services. U.S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, Durham.

Pryor, S.C., Barthelmie, R.J., 2010. Climate change impacts on wind energy: a review. Renew. Sustain. Energy Rev. 14, 430–437. https://doi.org/10.1016/j.rser.2009.07.028.

Pryor, S.C., Barthelmie, R.J., 2013. Assessing the vulnerability of wind energy to climate change and extreme events. Clim. Change 121, 79–91. https://doi.org/10.1007/s10584-013-0889-y.

Raabe, E.A., Stumpf, R.P., 2016. Expansion of tidal marsh in response to sea-level rise: Gulf of Florida, USA. Estuaries Coasts 39 (1), 145–157. https://doi.org/10.1007/s12237-015-9974-y.

Rhein, M., Rintoul, S.R., Aoki, S., Campos, E., Chambers, D., Feely, R.A., Gulev, S., Johnson, G.C., Josey, S.A., Kostianoy, A., Mauritzen, C., Roemmich, D., Talley, L.D., Wang, F., 2013. Observations: ocean. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (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 and New York, pp. 255–297.

Ruckelshaus, M., McKenzie, E., Tallis, H., Guerry, A., Daily, G., Kareiva, P., Polasky, S., Ricketts, T., Bhagabati, N., Wood, S.A., Bernhardt, J., 2015. Notes from the field: lessons learned from using ecosystem service approaches to inform real world decisions. Ecol. Econ. 115, 11–21. https://doi.org/10.1016/j.ecolecon.2013.07.009.

Semedo, A., Weisse, R., Behrens, A., Sterl, A., Bengtsson, L., Gunther, H., 2013. Projection of global wave climate change toward the end of the twenty-first century. J. Clim. Am. Meteorological Soc. 26, 8269–8288. https://doi.org/10.1175/JCLI-D-12-00658.1.

Slangen, A.B.A., Church, J.A., Zhang, J.A., Monselesan, D., 2014. Detection and attribution of global mean thermosteric sea level change. Geophys. Res. Lett. 41, 5951–5959. https://doi.org/10.1002/2014GL061356.

Smith, K., 2011. We are seven billion. Nat. Clim. Change 1, 331–335. https://doi.org/10.1038/nclimate1235.

Spalding, M.D., Brown, B.E., 2015. Warm-water coral reefs and climate change. Science 350 (6262), 769–771. https://doi.org/10.1126/science.aad0349.

Spalding, M.D., McIvor, A.L., Beck, M.W., Koch, E.W., Möller, I., Reed, D.J., Rubinoff, P., Spencer, T., Tolhurst, T.J., Wamsley, T.V., van Wesenbeeck, B.K., Wolanski, E., Woodroffe, C.D., 2014. Coastal ecosystems: a critical element of risk reduction. Conserv. Lett. 7 (3), 293–301. https://doi.org/10.1111/conl.12074.

Sydeman, W.J., García-Reyes, M., Schoeman, D.S., Rykaczewski, R.R., Thompson, S.A., Black, B.A., Bogard, S.J., 2014. Climate change and wind intensification in coastal upwelling ecosystems. Clim. Change Rep. 345 (6192), 77–80. https://doi.org/10.1126/science.1251635.

Syvitski, J.P., Kettner, A.J., Overeem, I., Hutton, E.W., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. Nat. Geosci. 2 (10), 681–686. https://doi.org/10.1038/ngeo629.

Tessler, Z.D., Vörösmarty, C.J., Overeem, I., Syvitski, J.P.M., 2017. A model of water and sediment balance as determinants of relative seal level rise in contemporary and future deltas. Geomorphology. https://doi.org/10.1016/j.geomorph.2017.09.040.

Thorne, K.M., Elliott-Fisk, D.L., Freeman, C.M., Bui, T.V.D., Powelson, K.W., Janousek, C.N., Buffington, K.J., Takekawa, J.Y., 2017. Are coastal managers ready for climate change? A case study from estuaries along the Pacific coast of the United States. Ocean Coast. Manag. 143 (1), 38–50. https://doi.org/10.1016/j.ocecoaman.2017.02.010.

Trenhaile, A.S., 2011. Predicting the response of hard and soft rock coasts to changes in sea level and wave height. Clim. Change 109 (3), 599–615. https://doi.org/10.1007/s10584-011-0035-7.

WCC – Wellington City Council, 2013. Sea Level Rise Options Analysis. Tonkin & Taylor Ltd, Wellington.

Woodroffe, C.D., Rogers, K., McKee, K.L., Lovelock, C.E., Mendelssohn, I.A., Saintilan, N., 2016. Mangrove sedimentation and response to relative sea-level rise. Annu. Rev. Mar. Sci. 8, 16.1–16.24. https://doi.org/10.1146/annurev-marine-122414-034025.