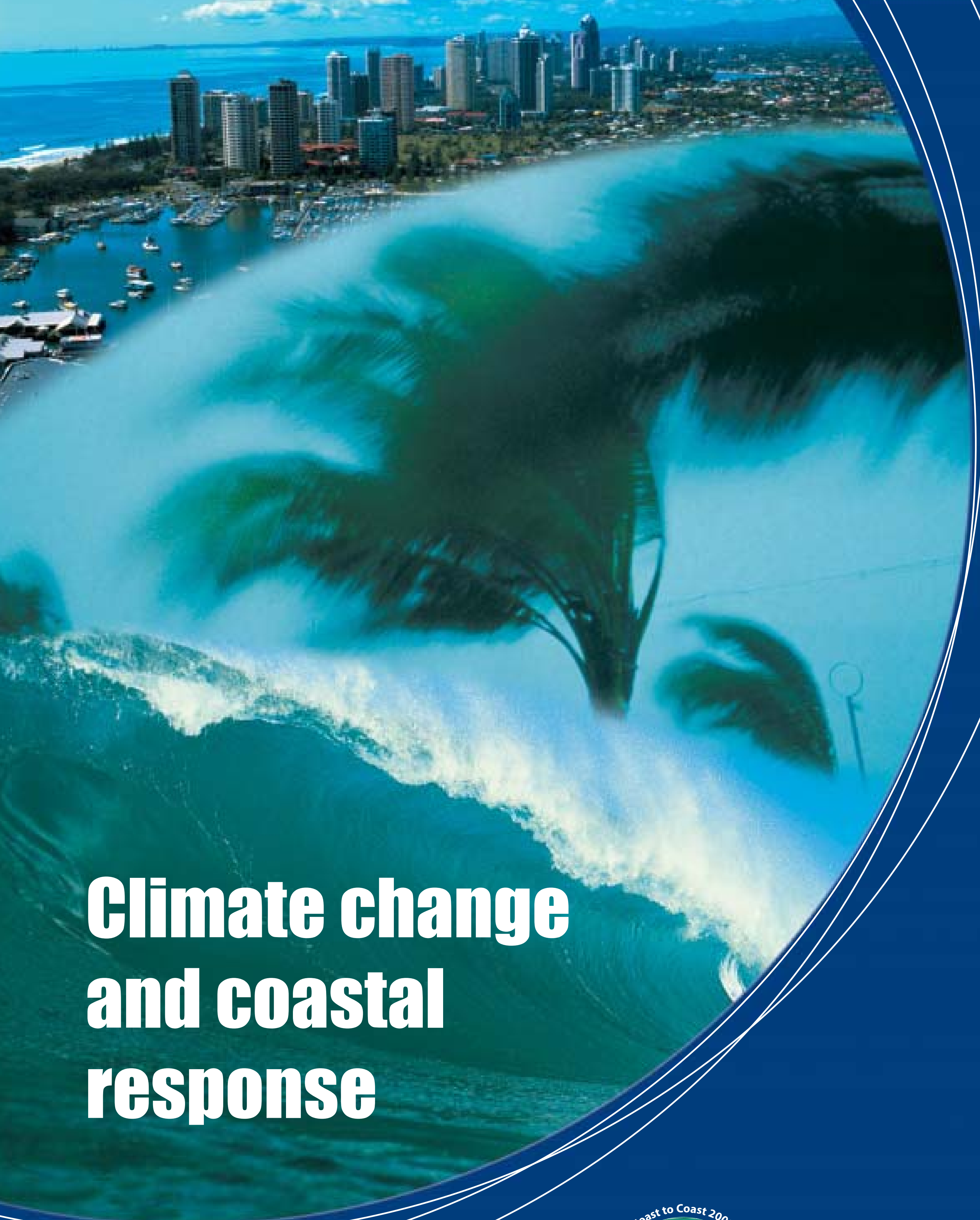

Climate change and coastal response

Coast to Coast 2003 "Source to Sea"

Coastal CRC

A report from the Coast to Coast 2002 Conference, Tweed Heads Australia • published April 2004

Climate change and coastal response

A theme report from the Coast to Coast 2002 National Conference, Gold Coast, November 2002

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Executive Summary

Climate change caused by global warming has a number of implications for coastal management. Even though the effects of global warming may take several decades to become apparent, this is within the design lifetime of much coastal infrastructure. Moreover, the economic and cultural value of the Australian coastline is such that long-term planning and adaptation is necessary to preserve it, or at least to avoid unacceptable changes.

Sea level rise

On average, the sea level in coastal Australia is rising. Globally, it is believed this observed rise has been caused mostly by the warming and thereby expansion of the ocean during the 20th century, along with a smaller contribution from the melting of ice caps and glaciers. Global mean sea level is expected to rise by 3–30 cm by 2040, and 9–88 cm by 2100. The range in the projections arises from uncertainties about future greenhouse gas concentrations and also scientific uncertainties regarding the magnitude of the various components.

Despite the large range of projections, this is perhaps one of the more confident projections of climate change science in the sense that it is quite likely to occur. Nevertheless, its effects will be noticed only slowly. In contrast, most coastal damage due to elevated sea level is caused by extreme events, those rare floods or storms that increase the height of the sea and, when combined with wave action, erode the coastline in a short period of time. The interaction between chronic, incremental sea level rise and these acute events is important, as small changes in average conditions can lead to large changes in the frequency of extremes. In addition, other local factors, such as land subsidence and geological processes, can cause rapid sea level change in certain locations.

Coastal erosion

The main projected impact of sea level rise is increased coastal erosion. Short-term events such as storms do cause erosion, but recovery then occurs afterwards. Sea level rise would cause more permanent changes: depending on the slope of the beach, coastline recession could be 150 times the rate of sea level rise. There has been a general retreat of sandy coastlines world-wide in the 20th century. The cause is unclear but may be related to the observed sea level rise.

Extreme erosion events along the Australian coastline are associated with tropical cyclones, east coast lows and mid-latitude low pressure systems, and their resulting impacts on winds and waves. Current trends in winds and waves are difficult to estimate: for waves, the reliable Australian data record in the 20th century is too short. For wind climate, at first glance the situation is rather better, as wind data has been recorded in Australia for at least a century. However, data before the 1950s consists mostly of Beaufort scale estimates, which are not accurate enough for climate change studies.

For the northern half of the country, erosion-causing extreme wind and wave events in most coastal regions are associated with tropical cyclones. There has been a downward trend in tropical cyclone numbers off the Australian coast since the late 1960s. For the southern part of the country, numbers of mid-latitude low pressure systems south of Australia decreased since 1970, while at the same time they have become larger and deeper. There are also well-known associations between variations in the El Niño/Southern Oscillation (ENSO) phenomenon and coastal erosion.

Future projections of changes in mid-latitude low pressure systems indicate slight increases in their intensities in a warmer world in this region, although this projection is not of high confidence. For tropical cyclones, a number of studies have suggested that tropical cyclones are likely to become slightly more intense, perhaps 5–10% by around 2050. A big remaining uncertainty here is

that the numbers of tropical cyclones affecting Australia depend heavily on whether there is a La Niña or El Niño occurring, yet the effect of global warming on ENSO is not yet well understood.

Floods and sediment

Over the past three decades, the cost of all flooding in Australia has ranged between $2.5 and $4 billion per decade. High rainfall associated with storms can cause flooding in coastal locations, leading to runoff events that may have an impact on coastal ecosystems. While there is substantial uncertainty regarding rainfall changes in a warmer world, it appears likely that the amount of rainfall per storm will increase, perhaps even if overall precipitation decreases at a location. Thus a combination of river flooding and high ocean levels seems more likely under a warmer climate. It also is likely that average streamflow in southern Australia will decrease due to reductions in rainfall and increases in evaporation due to higher temperatures, while streamflow in northern Australia is more likely to increase.

Streamflow transports sediment to the coast, and this can determine whether the coastline at a location is eroding or not. Measurement and simulation of sediment transport and erosion processes is very difficult. For climate change, if the change in rainfall is large enough, some regions may receive an increased supply of sediments from greater river flow, thus decreasing erosion in some locations sharply, despite sea level rise. Additionally, more intense extreme rainfall events may lead to higher sediment transport in rivers, particularly if accompanied by periodic drought conditions, which would cause reduced land cover and thereby more inland erosion. The maintenance of existing beaches will depend partly on whether future natural conditions favour an increased transport of sediments towards them along the shoreline.

Coastal ecosystems

Climate change may also have a number of impacts on coastal ecosystems. Temperature increases in estuaries could conceivably change nutrient concentrations, affecting the ecology of these valuable marine habitats. Coastal ecosystems in Australia include estuaries, saltmarshes, mangroves and seagrass. Each of these could be affected by global warming. Estuary ecosystems are sensitive to sea surface temperatures: in a warmer world, this may lead to changes in the biota of estuaries or other coastal bodies of water. As mentioned above, in many regions of Australia, increases in extreme runoff events may occur. This would cause an increase in nutrients and pollution in coastal waters and estuaries. To date, the impact of these changes on Australian estuaries has not been systematically evaluated. For mangroves, as sea levels become higher mangroves should move inland, but whether this occurs will be governed by the local topography, the tidal range, sediment supply and the adaptability of particular mangrove species. In the large tidal regions of northern Australia, a slight sea level rise could lead to big impacts on the low-lying wetlands in these regions. There is a high probability that increased sea surface temperature would lead to more frequent episodes of coral bleaching, eventually leading to death of corals.

The value of the coast

The coast, and in particular the beach, plays an important role in Australian culture. Therefore it has an intrinsic value in addition to that associated with land and property prices along the coast. Any changes that might threaten these amenities would be opposed for reasons that are not directly related to economic considerations. Climate change thus has the potential to cause significant conflicts.

The coast is also a tremendous generator of revenue for Australia. Under a changing climate, where coastal amenities may be under threat in some locations, the economic value of the assets would provide a strong impetus for coastal protection that may, in principle at least, potentially conflict with best practice environmental management.

While coastal impacts are highly specific to locations, in general the demographic pressures on the coast will act to exacerbate the issues of coastal stability that are associated with climate change. The main reason is that increased infrastructure along the coast will require adaptations to changes in the coastal erosion environment that are more extensive than they would be in the case of stable or declining infrastructure.

Planning and scientific uncertainty

Scientific uncertainty is a fact of life. No conclusions in science are 100% certain. Yet, as we know, many scientific results have very small uncertainty, which means that we can use them with confidence. In the science of climate change, one of the challenges is to estimate the uncertainty of a projection and then decide whether this uncertainty is small enough for decisions to be made. No projection of climate change science will ever be free of uncertainty, but projections can still be used to minimise risk in specific circumstances.

Despite uncertainty, planning can and does take place. For sea level rise, planners would ideally prefer a projection of a certain sea level rise to be associated with a specific probability. This projection could then be used in a risk assessment of the impact. Crucial in this assessment is the use of Geographical Information Systems, which provide spatial information on land elevations and infrastructure. Risk management in this context takes on a number of guises. Because coastal assets often have perceived societal and cultural values beyond their strictly economic valuation, risk management is sometimes not so much a cost-benefit analysis as a means of preventing outcomes that would be unacceptable to the community. Valuation of assets at risk may not only include infrastructure. Estimates of the value of cultural and biological resources along the coast can and should be made.

Adaptation

Accelerated coastal erosion due to sea level rise is the main coastal issue associated with climate change. As such, a number of strategies have been suggested to adapt to a coastal environment with a higher average sea level:

- accommodation / no protection – for example, in the case of unpopulated coastlines containing no unique ecosystems;
- protection – for regions of very high commercial or community value;
- adaptation – such as raising the height of infrastructure (where possible) or raising the height of the beach (beach nourishment); and
- retreat – by progressively restricting land use further and further inland with time.

Reasonable construction setbacks, combined with elevation of vulnerable properties above expected storm surge heights, can protect property effectively. Engineered structures along the coastline also may be useful, but these are only recommended where there is a clear understanding of the potential impact of the structures on coastal processes such as sediment transport. Setback buffers may be and have been integrated into planning schemes. Without setbacks, the risk is that inappropriate zoning may lead to infrastructure being built in vulnerable locations, making the zoning too expensive to revoke in the future and leading to demands to protect the existing infrastructure.

Engineered structures can have unintended effects. Experience in California has shown that once substantial sections of the coast are armoured with sea walls, there is less sand available for beaches, creating a need for further sea wall construction. As an alternative, the use of salients and breakwaters may be a way of protecting the coastline without resorting to sea walls. Artificial reefs are an example of such techniques, which usually have low environmental impact.

An integrated approach to coastal management is required, involving all stakeholders in decisions that reflect current best practice, recognise the precautionary principle and have sustainability as a primary goal. Because of the possible negative impacts of some adaptations, “no regrets” adaptations should have priority.

Policy

Australia is signatory to several international conventions that are relevant to climate change. With regard to coastal issues, there currently exists no official national policy on coastal issues, and a national response to the vulnerability of the coast to climate change issues has not occurred. State coastal strategies vary in their content and application to local issues. A recent change in the planning environment is the adoption of statutory coastal plans (i.e. plans with the force of law) in many States. Even given this added legal protection, enforcement of these plans at the local level is not guaranteed. Despite recent advances in the legislative environment, not all local councils in Australia have included climate change issues in their planning. Often this is the result of lack of resources to do so: for every well-equipped council with ample access to technical expertise, there are numerous coastal councils with far fewer resources. Ultimately, though, because local government often lacks resources, State and National governments need to step in to provide local support for implementing State and National Policy initiatives.

Future monitoring

Measuring systems are now in place that will give good measurements of Australian sea level trends (the SEAFRAME network). While sea level rise and erosion go hand-in-hand, the future rate of erosion at a specific location will not bear a simple relationship to sea level rise. Ongoing monitoring of erosion rates at very local levels will be required. Likewise, data on coastal ecosystems is very fragmentary and will need to be monitored more closely.

Recommendations

The Australian coastline is heterogeneous but faces common issues in all jurisdictions. A national coastal policy should be constructed that provides an effective coastal planning and management framework. There should be a national review of available data sources related to coastal stability, combined with an efficient means of cataloguing and delivering data to users. There should be improved funding for regional and local assessment of climate change risks as part of a national coastal policy, including scientific, risk management, economic and social issues. These assessments can then be incorporated in regional and local planning.

There is a clear need for the reduction of scientific uncertainties, especially for issues related to coastal processes. Through research, education and technical assistance, the Federal and State governments should aid this process. The effectiveness of coastal management strategies can only be assessed by future monitoring of outcomes, including a national strategy for doing so. Vital monitoring systems, such as the SEAFRAME high precision sea level measuring network, should be retained.

Beyond these largely adaptive responses in reaction to climate change, bodies with an interest in coastal sustainability have an interest, whether recognised or not, in the global question of measures to reduce the extent of climate change and sea level rise, essentially through reductions in the emissions of greenhouse gases.

Introduction

Climate change caused by global warming has a number of implications for coastal management. Even though the effects of global warming may take several decades to become apparent, this is within the design lifetime of much coastal infrastructure. Moreover, the cultural value of the Australian coastline is such that long-term planning and adaptation is necessary to preserve it.

There is still some uncertainty regarding what the effect of climate change will be on natural systems on Earth. While there remain disagreements on the timing and magnitude of global warming, there is now little dispute that it will occur and that it will have an impact on climate, on ecosystems and on human society. Observed global average air temperatures reached record levels in the 1990s, and this trend has continued into the early part of the 21st century (IPCC 2001; NCDC 2003). This has been accompanied by similar increases in Australian temperatures (Bureau of Meteorology 2003).

Possible effects of climate change on the coastal environment in Australia have been summarised in CSIRO (2002). The most likely effects are those associated with temperature increases. These include sea level rise, caused largely by the expansion of the oceans as they warm, as well as increases in ocean temperatures and the resulting impacts on coastal ecosystems. Some changes in the strength of storm systems are also likely, with tropical cyclones expected to have slightly higher maximum wind speeds. Less certain are changes in large-scale rainfall patterns, as in many parts of Australia these tend to be associated with changes in the El Niño/Southern Oscillation phenomenon, whose future state in a warmer world is still controversial. It is likely that extreme daily rainfall amounts will become greater, causing extreme runoff events in the coastal region to become larger also, with downstream effects on nearshore marine ecosystems.

This paper briefly summarises the science of climate change and the latest observed trends. Coastal management strategies are listed, relevant regulations are reviewed and recommendations are made.

1) Issues and background

a) Sea level change as an aspect of global change

On average, the sea level in coastal Australia is rising. In the context of climate change, sea level rise is a relative term in that it indicates either a rise in the ocean level or a fall in the land level. Globally, it is believed this observed rise has been caused mostly by the warming and thereby expansion of the ocean during the 20th century, along with a smaller contribution from the melting of ice caps and glaciers. Note that there is not an exact correspondence between rates of global warming and sea level rise. For instance, Antarctica is so cold that global warming of a few degrees will only cause more snow to fall over most of the continent, rather than melting. More accumulation of snow in Antarctica would therefore contribute to a sea level fall, as would interruptions to streamflow into the ocean caused by man-made structures such as dams. Despite these effects, future sea level change is projected to accelerate, due to a general predicted rise in temperature associated with global warming.

This is perhaps one of the more confident projections of climate change science in the sense that it is quite likely to occur, although there is a wide range of estimates of its magnitude (Fig. 1). This slow projected change might be described as “incremental” in that its effects may be slow to be noticed. In contrast, most damage due to elevated sea level is caused by extreme events, those rare floods or storms that increase the height of the sea and, when combined with wave action, erode the coastline in a short period of time and significantly affect the hydrodynamics of estuaries and coastal lagoons, thereby exacerbating flooding. Extreme events may be defined as those events that occur above a certain threshold: for instance, the 1 in 100 year flood event (1% annual exceedance probability – AEP) would be defined by the estimated flood height reached during this event. The interaction between chronic, incremental sea level rise and these acute events is important, as small changes in average conditions can lead to large changes in the frequency of such events (Figure 2). Thus, extreme events need to be considered separately. These issues are dealt with in more detail in Section 2.

b) Erosion as a natural process

Coastal erosion may be defined in terms of the retreat of the coastline over hundreds of years. Short-term events such as storms do cause erosion, but recovery then occurs afterwards. In contrast, long-term coastal erosion has been occurring ever since the formation of the continents billions of years ago. It is a natural process but one that is in increasing conflict with the needs of human society. Because of the high monetary and cultural value of coastal infrastructure, efforts continue to be made to counteract erosion.

Erosion affects all kinds of coastal structures, from rocky cliffs to sandy beaches, although erosion proceeds at greatly differing rates depending on the type of coastline in question (e.g. Woodroffe 2002). In general, major erosion events occur during storms, largely from the impact of waves. On rocky coasts, the cliff base is undercut by the waves and by the impact of rocky debris in the water. Eventually, the cliff is undercut so much that the overhanging section breaks off and falls into the sea.

Beaches are also eroded by wave activity, but here the drift of sediments along the coast (the longshore transport) is an important factor in the changing shape of the coast, as the beach can be replenished after erosion events by sediment transported from elsewhere. Such sediment sources include river outflows and eroded cliffs. In some locations, the longshore transport of sediments, combined with a favourable shoreline configuration, could be large enough to offset or reverse the tendency of beaches to erode that has occurred in the 20th century. In addition, some beaches undergo alternating periods of erosion and accretion, depending on whether significant erosion events (usually storms) have occurred recently or not, or depending upon the seasonal and year-to-year variation of the prevailing wind direction (Harvey and Caton 2003). Erosion is not the only possible response to sea level rise, as the sediment released by erosion in one place along the coastline can accumulate at another, causing the coast in that location to accrete.

Links between the level of the sea and the resulting increased erosion of the land led Bruun (1962) to propose a simple relationship between sea-level increase and landward erosion, based on the concept of the re-establishment of an equilibrium beach profile after sea level rise as a result of conservation of mass. Known as Bruun's rule, this relationship is highly simplified compared with real coastal processes, but it provides a rough estimate of the potential for erosion. Typically, a value of 100 m of erosion for every 1 m of sea level rise is employed. For instance, using observed historical data, Leatherman et al. (1999) suggest that for sandy beaches on the east coast of the U.S., the distance of the retreat of the land is 150 times the rate of sea level rise.

Along the Australian coastline, extreme erosion events are associated with tropical cyclones, east coast lows and mid-latitude low pressure systems. Tropical cyclones affect the northern half of the continent and cause high winds, often accompanied by storm surge, a dome of water pushed onshore by winds. Sea level can also be raised by the low atmospheric pressures of the storms themselves. Cyclones may cause high wave events as far south as northern New South Wales or Perth. East coast lows are intense weather systems that form largely off the coast of New South Wales in the winter half of the year, and can cause high winds, extreme rainfall and waves in that State, as well as in southern Queensland and eastern Victoria (Hopkins and Holland 1997). Mid-latitude low pressure systems, while mostly travelling south of the country, occasionally cause serious coastal erosion in Western Australia, South Australia, Victoria and especially Tasmania.

Extreme events can cause massive erosion in a short period of time, due to high wave activity. There are a number of locations in Australia that are vulnerable. Perhaps best known in Australia is the regular beach erosion that affects the Gold Coast, an area of high infrastructure, commercial and recreational value. High waves from both tropical cyclones and east coast lows have caused significant damage to beaches and infrastructure along the Gold Coast in the recent past (Boak et al. 2001). This has motivated the construction of extensive engineering-based solutions to this problem. Overseas, similar efforts are being undertaken by the State government of Florida, where a number of coastal regions are designated as critically at risk from erosion (State of Florida 1999).

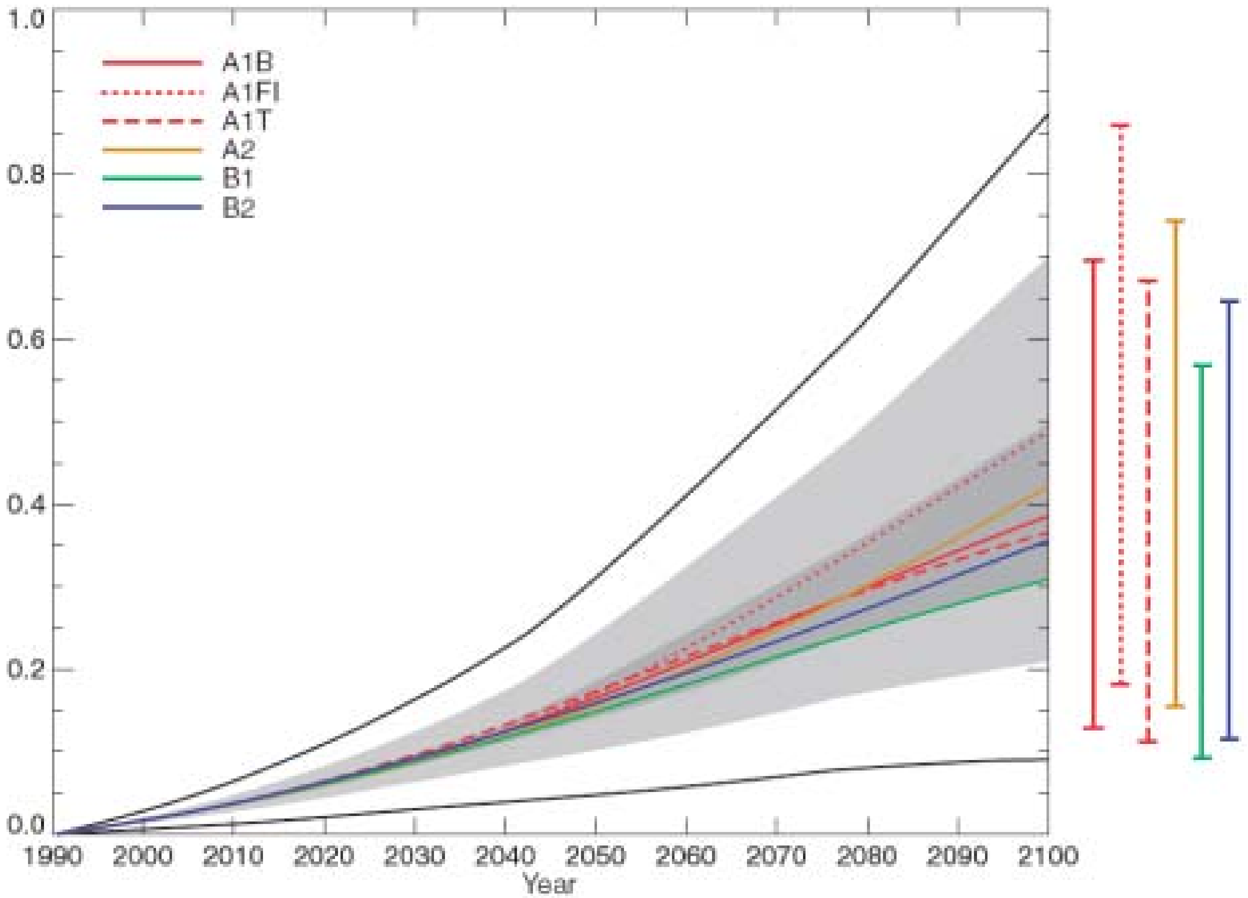

Figure 1. Projections of future sea level change. Black bold lines indicate extreme range of projections, including all uncertainties. The grey area shows the range of model projections only. The coloured lines indicate the average of all model projections for one assumption ("scenario") about future greenhouse gas concentrations; these greenhouse gas scenarios are indicated in the legend. The coloured bars on the right hand side of the graph show the range of model projections for each scenario. From Church et al. (2001).

c) Impact of erosion on built and non-built infrastructure

There has been a general retreat of sandy coastlines world-wide in the 20th century (Bird 2000). The cause is unclear but may be related to the observed sea level rise, based upon known relationships between sea level changes and erosion, such as Bruun's rule. Inevitably, this has the potential for impacts on infrastructure. The largest effects will likely occur in regions that are already vulnerable to erosion events. A rise in sea level would exacerbate these effects. Impacts could include the undermining and damaging of structures, increased maintenance costs, salt water intrusion into agricultural regions, and so on.

In addition to affecting sandy coastlines, in some locations sea level rise may be sufficient for more storms to attack the dune fields behind the beach, or breech dunes separating the ocean from

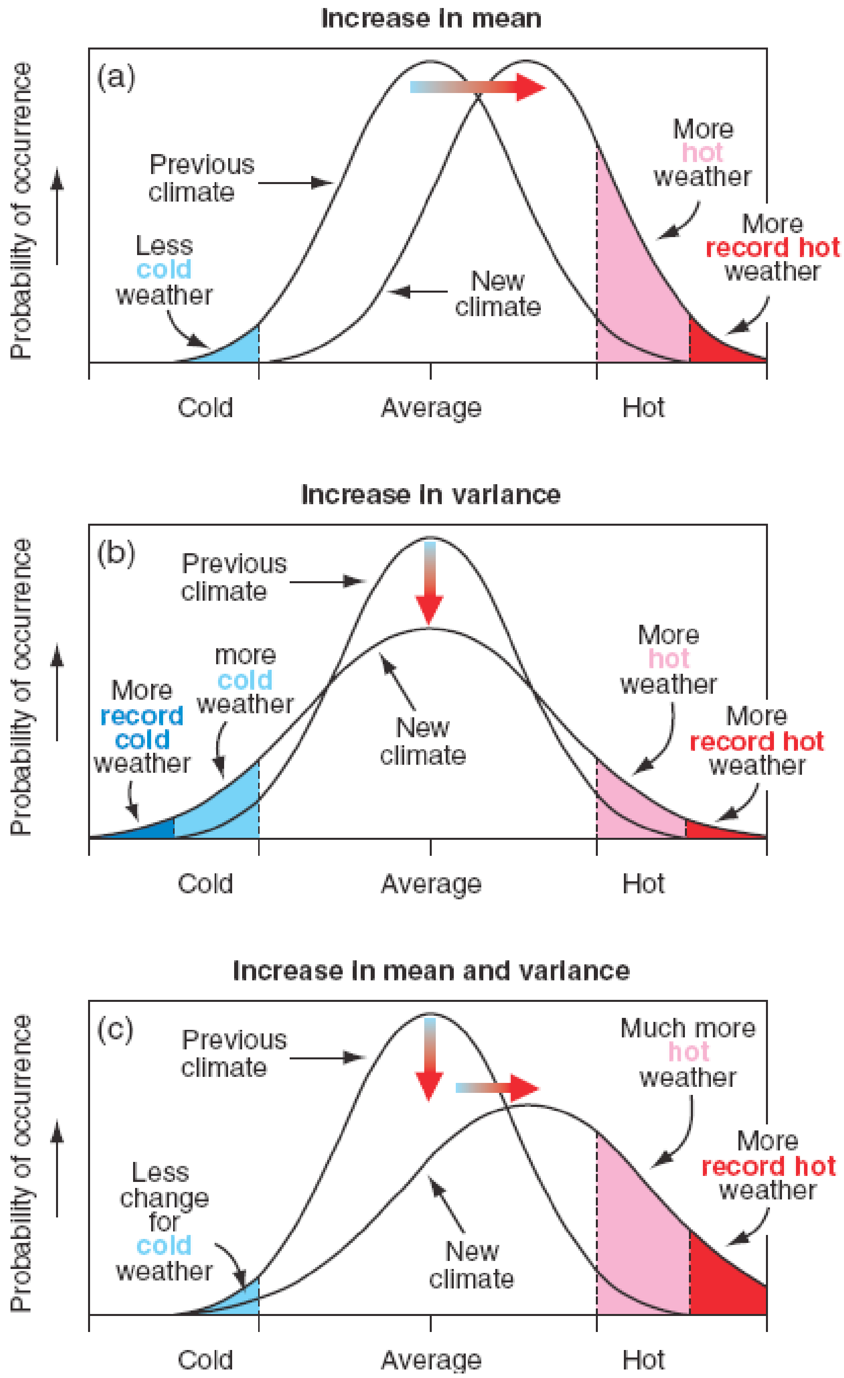

Figure 2. Diagram indicating the concept of a small change in the mean leading to a large change in the occurrence of extremes. Extremes are defined as events greater than a given threshold. In the changed climate, the area under the curve above a temperature threshold is much greater than in the previous climate, and thus the frequency of high temperatures is also much greater. Also, incidences of unprecedented temperatures (record hot) weather occur in the new climate. From Folland et al. (2001).

coastal lagoons (e.g. Gippsland Lakes in Victoria). Note that recent work (Nott and Hubbert 2003) suggests that dune fields do not survive overtopping by high-intensity storm surge events. This may be relevant to the evaluation of risk to coastal developments. Nevertheless, whether this would occur or not is very location-dependent: dune overtopping would be much more of a problem in north Queensland, where wave-built dunes developed in current sea level conditions are vulnerable under present-day conditions. Wind-built dunes that are higher, such as those on the Gold Coast, are less vulnerable.

d) Impact of climate change on coastal ecosystems

Climate change may have a number of impacts on coastal ecosystems. Temperature increases in estuaries could conceivably change nutrient concentrations, affecting the ecology of these valuable marine habitats. Along the coastline of northern Australia, where tidal excursions are large, a slight sea-level rise could lead to substantially increased inundation of coastal wetlands (Harvey and Caton 2003). Similarly, sea level rise could have large impacts on saltmarsh areas, which support a variety of crustaceans, molluscs and birds. Mangroves, coral reefs and other sensitive coastal ecosystems may be similarly affected. Possible impacts are reviewed in Section 3.

e) Coastal flooding and effects on infrastructure

High rainfall associated with storms can cause flooding in coastal locations, leading to runoff events that may have an impact on coastal ecosystems and infrastructure. There are often interactions between flooding and storm surge: a storm surge may increase the impact of a flooded river system, for instance. While there is substantial uncertainty surrounding rainfall changes in a warmer world, it appears likely that rainfall intensity per storm will increase, perhaps even if overall precipitation decreases at a location. Moreover, if the ground is drier on average in a warmer world (which seems likely), more intense rainfall will lead to greater runoff, as dry ground is not easily infiltrated. Thus a combination of river flooding and high ocean levels seems more likely under a warmer climate. Increased rainfall intensity may also have an impact on storm water drainage, with shorter return periods of intense events causing design drainage capacity to be exceeded in some locations (Smith 1998; Abbs et al. 2000). Increases in sea level will cause more frequent events of high storm surge: for Cairns, McInnes et al. (2003) estimated that higher sea levels, combined with more intense tropical cyclones, could lead to more than a doubling of high surge events in a warmer world.

Over the past three decades, the cost of all flooding in Australia has ranged between $2.5 and $4 billion per decade (Bureau of Transport and Regional Economics 2001). Rising sea levels, combined with increased storm intensities and storm surge heights, along with increases in the value of buildings in the vulnerable regions, will likely increase these losses (CSIRO 2002).

f) Water resources

While projections of rainfall changes in a warmer world remain substantially uncertain, it is likely that average streamflow in southern Australia will decrease due to reductions in rainfall and increases in evaporation due to higher temperatures (Chiew and McMahon 2002; CSIRO 2002). This will have implications for water resources in coastal communities in these regions. Extreme runoff events have the potential to increase in most regions, even in some locations where the average streamflow decreases in the future. In northern Australia, increases in average rainfall and streamflow are more likely, as are more frequent extreme rainfall events.

Another possible impact of sea level rise is the intrusion of salt water into coastal aquifers (Ghassemi et al. 1996), with implications for the quality of coastal water supply and for ecosystems.

g) Cultural value of coastal amenities

The coast, and in particular the beach, plays an important role in Australian culture. Therefore it has an intrinsic value in addition to that associated with land, ports and property prices along the coast. Any changes that might act to threaten these amenities would be opposed for reasons that are not directly related to economic considerations. Climate change has the potential to cause significant conflicts. As the sea level rises, for instance, some hard choices may need to be made between the maintenance of culturally important coastal facilities and the economic realities of coastal management.

h) Beach protection

The intrinsic cultural value of the beach and the monetary value of associated infrastructure have inevitably led to protection strategies for the beach. In Queensland, the Beach Protection Act of 1968 was the first legislation introduced specifically to protect beaches (subsequently amended by the Coastal Protection and Management Act 1995). Other States have legislation that aims to preserve and maintain the beach environment. In Western Australia, the perceived value of the beach is such that public ownership of coastal foreshores is the fundamental principle of coastal policy.

Under future climate conditions, where beach erosion may become more frequent in some locations, strategies for beach protection (or for avoiding the need for protection) will become even more important. Note that even if the beach still survives along an eroding coastline at a location inland of the current position, the presence of infrastructure behind the beach may necessitate strategies to maintain the beach in its current configuration.

i) Equity issues (paying for other's problems)

The costs of beach protection can be large and, at least in terms of infrastructure protection, would disproportionately benefit a small sector of society, namely owners of beachfront property. On the other hand, Harvey and Caton (2003) point out that if council rates are inadequate to cover the costs of maintaining the beach infrastructure because of the impacts of a large number of visitors, there is often resistance to the imposition of a levy on local ratepayers.

Another issue involves access to beaches. Under some titles, owners have the right to protect their property regardless of public access considerations. Thus, in an eroding coastline, it is possible that public access to the beach would be lost (Gordon 2000).

Under conditions where the beach infrastructure may be under threat from climate change, these issues will become more important as the cost of maintaining the beach environment and infrastructure increases. The issue of dividing responsibilities for paying for these costs between various levels of government is already one that causes difficulties: Harvey and Caton (2003) gives the example of Adelaide Beach, where sand renourishment is paid for by the State because agreement on allocating costs could not be reached among the five relevant councils. Similarly, the State government of Western Australia provides funds for local governments to assist with coastal planning and management. As beaches of cultural and economic significance may well experience increased management costs because of global warming, this issue may become even more fractious.

j) Economic considerations

The coast is a tremendous generator of revenue for Australia. Under a changing climate, where coastal amenities and infrastructure may be under threat in some locations, the economic value of the assets would provide a strong impetus for coastal protection that may, in principle at least, potentially conflict with best practice environmental management. For instance, "hard" protection measures such as sea walls may give the impression of providing a permanent solution to an erosion problem, yet their impact on the surrounding coastline may be deleterious. For instance, sea walls inevitably cause beach loss (FEMA 1999). This issue is discussed further in Section 4.

In addition to the costs of protection due to sea level rise, there may be costs associated with other types of adaptation measures. Moreover, costs of maintenance have to be balanced against the potential costs of doing nothing to adapt to climate change. Detailed cost-benefit analyses are needed, such as those made for coastal protection strategies in the present-day climate, but in general these have not yet been attempted for changed climate conditions.

2) Trends

a) Current sea level trends in Australia

Global average sea level in the 20th century rose 10-20 cm (Church et al. 2001). More recently, Church et al. (2004) used satellite altimeter data, combined with tide gauge records, to estimate sea level rise over the period 1950-2000. The global average rise was estimated at 1.8 ± 0.3 mm per year. There was also a clear regional pattern of sea level rise, with a maximum in the eastern off-equatorial Pacific and a minimum along the equator.

In Australia, reliable long-term records of sea level are few. The only genuinely long-term record that we have is from tide gauges, in some locations for longer than 100 years. Nevertheless, these data needed to be examined carefully. Many tide gauges are located either in geologically active regions or in locations where land subsidence is occurring, thus making them unsuitable for measuring oceanic sea level rise. For example, tide gauges at Port Pirie and Port Adelaide show very different sea level trends since 1940, due to local land subsidence near Port Adelaide (Belperio 1993). To take these land movements into account, sea level rise should be measured at locations that are geologically stable, where any relative vertical movement of the land and sea can be interpreted as due to changes in the sea level alone.

In Australia, there are a number of tide gauges with long records (Mitchell et al. 2000), but only a few satisfy the above conditions (Lambeck 2002). The tide gauges at Fort Denison and Fremantle are generally considered reliable, due to the geological stability of the locations where they are sited, which implies little change in the level of the land. Sea level rises at these stations are generally similar to the global estimates. Also consistent with these is a longer record recently discovered in Tasmania. Pugh et al. (2002) and Hunter et al. (2003) compared current sea level with 19th century records at Port Arthur, establishing a rate of sea level rise of about 1 mm per year (10 cm per century), consistent with the previous results listed above and towards the low end of the Church et al. (2001) estimates. There is also network of high-precision, calibrated sea level gauges maintained in the Pacific (SEAFRAME; www.pacificsealevel.org), but these data have only been collected since the early 1990s and are thus not yet suitable for assessment of long-term changes.

b) Trends in wind and wave climate

There have been a number of studies assessing trends in wave climate at various locations in Australia, but in general the reliable data record has been too short to consider the impact of global warming on wave climate in the 20th century in this country. Reliable waverider buoy data has been available in Australia for only 30 years (Allen and Callaghan 1999). Earlier work (NSW Public Works Department 1985) examined wave climate for the coast of New South Wales over the period 1880-1980, using a combination of data sources. Subsequent analysis of these data suggests that there may be trends, but the reasons for these trends have not been fully established.

Studies in the North Atlantic have shown an increase in wave heights over the past 30 years (Guley and Hasse 1999), and similar results have been found for the northwest Pacific (Komar et al. 2000), although again both of these records are not long enough. The essential problem is that there are well-known patterns of oscillation in the atmosphere that occur over periods of 10-30 years. Known as decadal variability, these oscillations make it difficult to ascribe trends to climate change for records of less than 30 years length. Currently, only Queensland and New South Wales have a baseline wave climate monitoring program (Wyllie and Kulmar 1995). Lord and Kulmar (2000) found no significant trends in analysis of New South Wales waverider buoy data.

For wind climate, at first glance the situation is rather better, as wind data has been recorded in Australia for at least a century. However, data before the 1950s consists mostly of Beaufort scale estimates, which are not accurate enough for climate change studies (B. Trewin, Bureau of Meteorology, personal communication, 2003). Pressure gradients can also be used to represent wind speeds, and an analysis of these showed generally insignificant trends over most of Australia for the period 1962-1996.

For coastal erosion, it is trends in extreme wind events that are important. Erosion-causing events tend to be associated with large weather systems such as tropical cyclones or intense mid-latitude systems. For the northern half of the country, erosion-causing extreme wind and wave events in most coastal regions are associated with tropical cyclones. There has been a downward trend in tropical cyclone numbers off the Australian coast since the period of fully reliable records began (since about 1968, the advent of weather satellite monitoring). This has been largely due to more El Niños during this period, which cause fewer tropical cyclones to form in the Australian region (Nicholls et al. 1998).

For mid-latitude lows, Simmonds (2003) found that numbers between 50^{o}S and 70^{o}S decreased since 1970, while at the same time they have become larger and deeper. The number of east coast lows shows an upward trend over the past 40 years (Hopkins and Holland, 1997).

c) Erosion trends

Methodologies for assessment

Erosion trends can be estimated in a number of ways. They can be simply extrapolated from current observed trends (e.g. Thom and Hall 1991; State of Florida 1999), although most studies have been of insufficient duration to determine long-term patterns of change (Woodroffe 2002). Erosion can also be simulated using modelling techniques (see Woodroffe, 2002 for a recent review). On the time scales of climate change, it is often difficult to discern trends and estimate the impacts of extreme events, as long periods of monitoring are required. Bruun's rule can also be used to estimate the direction of changes, although it appears to be a less than accurate predictor of the amount of change (Komar 1998).

Current status and projections

As stated earlier, coastlines world-wide have been receding in the 20th century. In Australia, there are well-known associations between variations in the El Niño/Southern Oscillation phenomenon and coastal erosion (Bryant 1983; Short et al. 2000; Ranasinghe et al. 2001). For example, at Narabeen Beach in the Sydney region, when the Southern Oscillation Index is positive, the northern end of the beach is eroded while the southern end is built up. The opposite occurs when the Index is negative. Indeed, small changes in wind and wave climate can lead to large changes in beach profile. There is also some evidence of longer-term changes in beach erosion associated with decadal variability (Goodwin 2004).

d) Demographic trends

Coastal population

Trends in coastal population are covered in detail in the accompanying report by Lisa Intemann on this topic. While coastal impacts are highly specific to locations, in general the demographic pressures on the coast will act to exacerbate the issues of coastal stability that are associated with climate change. The main reason is that increased infrastructure along the coast will require adaptations to changes in the coastal erosion environment that are more extensive than they would be in the case of stable or declining infrastructure.

3) Science

a) Future sea level change

The current global average sea level rise is likely to continue into the future, and projections are that it will accelerate. Church et al. (2001) provide a summary of this topic. Global mean sea level is expected to rise by 3-30 cm by 2040, and 9-88 cm by 2100. The range in the projections arises from uncertainties about future greenhouse gas concentrations and also scientific uncertainties regarding the magnitude of the various components contributing to project future sea level rise: warming and thereby thermal expansion of the oceans, melting of glaciers, the future contribution of surface water storage in lakes and reservoirs, and so on.

Note that just because the global sea level is projected to rise, this does not necessarily mean that the relative level of the sea and land is also changing in the same way. There are also significant local sea level effects that need to be taken account in many regions of the globe. In most locations in Australia, land-level changes are relatively small except in locations affected by subsidence: for example, the Port Adelaide region mentioned earlier, or the Gippsland Lakes region, where subsidence due to oil and gas extraction may exacerbate local sea level rise (Sinclair Knight Merz 1995). Local land subsidence can cause changes in the land level than can be faster than any predicted sea level rise. Subsidence rates can differ even within a single municipality or local government region, so they must be estimated very locally.

Changes in extreme sea levels will largely depend on change in the meteorological conditions that cause them.

b) Future meteorological conditions

Future projections of changes in return periods of intense mid-latitude lows have been performed by Whetton et al. (2002) for the Victorian region, using a numerical climate simulation model. These results indicated slight increases in storm intensities (i.e. higher wind speeds) in a warmer world in this region, although this projection is not of high confidence due to the inadequate model simulation of the storm intensities. McInnes et al. (2002), also using a simulation technique, found that while the numbers of mid-latitude lows off southern Australia decreased in a warmer world, the intensities of the most extreme lows were about the same. In general, more work needs to be done on this issue.

For tropical cyclones, a number of studies have suggested that tropical cyclones are likely to become slightly more intense in a warmer world (IPCC 2001; Walsh 2004). All other things being equal, this would lead to an increased frequency of erosion events along the tropical and sub-tropical coasts. One difficulty in making such a projection is that numbers of tropical cyclones in the Australian coastal region strongly depend upon whether there is an El Niño or a La Niña under way, and projections of the effect of climate change on the El Niño/Southern Oscillation phenomenon do not give a clear-cut answer. Nevertheless, increased wind speeds from tropical cyclones may have some implications in tropical Queensland for building design standards, as current standards may not be adequate in a warmer world (Walsh et al. 2001).

For winds in general in Australia, McInnes (2003) uses numerical models to suggest that increases in extreme winds in northern Australia may occur, while slight decreases may occur in the mid-latitude regions of coastal Australia, although there is some seasonal dependence of these predictions. Increases in extreme winds off the New South Wales coast in winter are also suggested.

There have been few studies performed on the effect of global warming on east coast lows. Earlier studies (Katzfey and McInnes 1996; McInnes et al. 1998) used numerical simulation techniques to show that east coast lows may be fewer but more intense in a warmer world; however, the study used a relatively coarse-resolution model and thus the results are not of high confidence.

For rainfall, both modelling studies and theoretical arguments suggest that rainfall events should be more intense in a warmer world. Nevertheless, such predictions would have to be both accurate and site-specific to be useful. As a step in this direction, fine-resolution model simulations are needed, with good simulations of the distribution of rainfall in the current climate. Some progress towards this goal is being made (e.g. Abbs 2002).

c) Erosion

Erosion is occurring continually but excess erosion can be caused by both extreme wave events and gradual sea level rise. Measurement and simulation of these processes, particularly sediment transport, is very difficult. If the change in rainfall is large enough, some regions may receive an increased supply of sediments from greater river flow, thus decreasing coastal erosion in some locations sharply, despite sea level rise (Bird 2000; Bell et al. 2001). Additionally, more intense extreme rainfall events may lead to higher sediment transport from rivers, particularly if accompanied by periodic drought conditions, which would cause reduced land cover and thereby more inland erosion (Australian Greenhouse Office 2003).

The impact of rising sea levels or changes in worsening meteorological conditions would vary depending upon the existing characteristics of the beach. Bird (2000) has summarised various scenarios. Erosion in general will increase: beaches that are already eroding will do so at an accelerated rate, while beaches that are stable or accreting may begin to erode instead. Where the beach fringe is narrow and backed by high ground, beaches will quickly disappear unless the sea level rise increases nearby cliff erosion to the point where sufficient extra sediment is generated, or additional sediment is transported from elsewhere. Beaches bordering salt marshes or mangroves are likely to be removed as the sea invades the land behind them. If sea walls have been constructed to protect the coast, the beaches in front of them will be either reduced in size or removed by increased wave activity.

The maintenance of existing beaches will depend partly on whether future natural conditions favour an increased transport of sediments towards them along the shoreline. Bruun's rule suggests that the distance that a typical beach would recede would be 50 to 100 times the sea level rise. For beaches about 30 m wide, this would imply the beach would disappear with a sea level rise of some 30-60 cm, or towards the later part of the 21st century, although as mentioned earlier changes in sediment transport rates could negate this change. Additionally, the supply of sediment that is important to maintain the equilibrium of the beach system may be disrupted by sea level rise. Under higher sea conditions, sediment may become trapped in creek mouths and tidal flats, thus reducing the amount available for replenishment of the beach.

d) Biological effects of global warming

Coastal ecosystems in Australia include estuaries, saltmarshes, mangroves and seagrass (e.g. Harvey and Caton 2003). Each of these could be affected by global warming. For Australia, Pittock and Wratt (2001) have reviewed the possible impacts of climate change on coastal ecosystems.

Estuaries are inlets or bays that have both saltwater and freshwater inflow (Harvey and Caton 2003). They are productive ecosystems and are often important fishing grounds. Moreover, many of the most productive estuaries are also located adjacent to large population centres, which places a further strain on their ecosystems. These ecosystems are sensitive to sea surface temperatures: in a warmer world, this may lead to changes in the biota of estuaries or other coastal bodies of water. For example, the phytoplankton growth rate is highly sensitive to temperature, which would also affect algal growth rates. Runoff changes due to increases or decreases in mean rainfall could also affect biota growth rates. Most predictions call for a decrease in mean runoff rates in most Australian rivers (Pittock and Wratt 2001), with the exception of rivers in tropical Australia. Even so, in many regions of Australia, increases in extreme runoff events may occur, as mentioned in Section 1. This would cause an increase in sediment flow to the coastal regions, including nutrients and pollution. To date, the impact of these changes on Australian estuaries has not been systematically evaluated. Nevertheless, climate change effects may be secondary to effects caused by changes in effluent rates due to demographic effects or technological improvements in the treatment and discharge of waste water from urban areas.

There may also be changes in coastal ecosystems due to differences in coastal currents in a warmer world. However, there has been little detailed work done on this issue to date.

Saltmarshes are flat regions that extend between the high water neap and high water spring tide levels. Saltmarsh is often found immediately landward of mangroves, as well as in flat coastal areas of South Australia and Western Australia. Since they lie on flat ground, they could be extensively inundated as sea level rises. To our knowledge, there has been little scientific work done on the impact of sea level rise on saltmarshes in Australia, although management plans have addressed this issue (for example, at Mutton Cove on the South Australian coastline).

Mangroves are forests situated at the edge of the land in regions of the tropics and subtropics where wave energy is low (Alongi 2002). These are located extensively in many tropical and subtropical coastal regions of Australia. Future higher carbon dioxide concentrations may lead to complex effects, with different responses between species (Ball 1998). Higher temperatures and changed precipitation are also likely to lead to changes in distribution and species composition, but these effects will be highly location-specific. In general, as sea level becomes higher, landward progression should take place, but this will be governed by the local topography, the tidal range, sediment supply and tree species (Alongi 2002). Overall, global warming is likely to cause increased risks of flooding and erosion, but the magnitude of the effects will vary considerably from location to location. Pittock and Wratt (2001) note that mangroves have moved landward during past periods of rising sea level, so they may prove highly adaptable to climate change, provided that such landward movement is not restricted by topography or coastal development.

There is little or no observational evidence of changes in seagrass distribution in the 20th century, despite a sea level rise over that time that should have led to shoreward movement in seagrass bed locations (Duarte 2002). Thus it is hard to determine whether sea level rise will cause landward migration of seagrasses. In addition, increased carbon dioxide will lead to an increase in photosynthesis that will be balanced against a decrease in calcification. A study in the Mediterranean (Glémarec 1997) indicated a relationship between temperature rises and seagrass decline. Some poleward movement of seagrass species may occur, but overall, Duarte (2002) claims that there are too many uncertainties regarding the processes that govern seagrass habitats at present to make quantitative predictions of the effects of climate change.

In the large tidal regions of northern Australia, a slight sea level rise could lead to big impacts on the low-lying wetlands in these regions. It is possible that wetlands in Kakadu National Park could become saline as a result of sea-level rise (Pittock and Wratt 2001). In these regions, coastal monsoon vine thickets could also be affected. These regions contain high biodiversity and are of high recreational and ecological value. Predicted increases in extreme events may alter the disturbance regime of these ecosystems and lead to a significant change in the species composition and physical structure of these coastal systems. Wetlands in the Gippsland region may also be under threat (Gippsland Coastal Board 2002).

Coral reefs may not be strictly considered to be coastal ecosystems, but because of their importance in Australia, a considerable amount of work has been performed to evaluate the impact of climate change on them. In their summary, Pittock and Wratt (2001) concluded that there was a high probability that increased sea surface temperature would lead to more frequent episodes of coral bleaching, eventually leading to death of corals (see also Done et al. 2003).

Due to generally warmer conditions, it is likely that species distributions could change in the coastal environment. This could also lead to changes in marine pest distribution. For coastal fisheries, little work has been done on the criteria that determine species distribution in the current climate, let alone in a warmer world. Tolerances for aquaculture species are better known, and the effects of climate change would then be easier to estimate.

Interactions between changes in meteorological conditions and coastal ecosystems need to be considered. Changes in local wind patterns could conceivably cause differences in coastal upwelling and thus nutrient supplies. Changes in flood intensities would also have an impact on nutrient supplies.

e) Scientific uncertainties

Scientific uncertainty is a fact of life. No conclusions in science are 100% certain. Yet, as we know, many scientific results have very small uncertainty, which means that we can use them with confidence. In the science of climate change, one of the challenges is to estimate the uncertainty of a projection and then decide whether this uncertainty is small enough for decisions to be made. No projection of climate change science will ever be free of uncertainty, but projections can still be used to minimise risk in specific circumstances.

Global warming

Much has been written about the scientific uncertainties associated with projections of the effects of global warming. It is clear, though, that when the confidence of projections of climate change is assessed, there is what could be termed a hierarchy of uncertainty: projections of some effects are considerably more confident than others. For example, global average temperature has clearly been rising this century and this increase has accelerated in the past decade or so. Moreover, this acceleration has been predicted by climate models (with varying degrees of accuracy) since the 1970s. Global average temperature is a robust variable that can be simulated by climate models with some accuracy. Thus projections of effects that are based largely on global average temperature have relatively high confidence. Sea level depends to a large degree on global average temperature and so projections of sea level increases are also relatively confident, despite a wide range of future global sea level projections. In contrast, rainfall has a very variable distribution in space and time and also is difficult to simulate in numerical models. Thus projections of rainfall changes tend to have lower confidence.

Wind and wave climate

Similarly, future changes in wind and wave climate are harder to project than changes in sea level. Changes in wind and wave climate are just as important for coastal erosion processes as changes in sea level. Indeed, as mentioned earlier, Bell et al. (2001) showed that plausible alterations to wind and wave climate could reverse increased coastal erosion trends caused by rising sea levels.

Extreme events

The evaluation of the effect of climate change on extreme events is a particularly important issue, as damage to coastal infrastructure in Australia is largely caused by extreme events such as tropical cyclones or other intense low-pressure systems. Coastal assets may be damaged by high winds and/or waves and the resulting erosion. In some coastal locations, storm surge may cause significant damage. The viability of coastal infrastructure would depend upon how frequently these extreme events occurred on average, known as the return period. Here, an "extreme" event might be defined as one that causes damage greater than a certain critical threshold (Jones, 2001). These thresholds would vary from location to location: an example of a threshold might be the wave height at which a particular sea wall would be overtopped. Frequent occurrence of such events would imply a short return period and may lead to this infrastructure becoming unviable.

Techniques continue to advance for the estimation of recurrence intervals for extreme events. In the context of climate change, major uncertainties arise from the difficulty of estimating these return periods in the current climate with a limited time series of historical data. Without knowledge of the precise state of current conditions, it is often difficult to detect a climate change when it occurs. One way around this issue would be to find data from previous centuries that could be analysed to determine the "real" return period of an extreme event. An example is the use of coral debris fields to estimate the intensity and dates of past cyclones (e.g. Nott and Hayne 2001). Nevertheless, the techniques involved in these studies often rely upon assumptions regarding processes in coastal geomorphology, where knowledge of many processes remains incomplete. In addition, in some cases damage is caused by a combination of effects each of which may be differently affected by climate change. For instance, flooding in estuaries is affected by river discharge, wind and coastal ocean level, all of which are separately expected to change in the future, but so too may their joint probabilities.

f) From science to adaptation

Thus it is clear that there are a large number of issues to be addressed regarding the effect of climate change on the coast. It is also clear that many of the projections remain highly uncertain, limited by both our lack of knowledge of scientific processes and our inability to project with complete accuracy future economic conditions. Nevertheless, even with projections of some uncertainty, planning can and does take place. The next section reviews the strategies and tools used to plan for climate change along the Australian coast.

4) Strategies and tools

a) Scientific tools for better assessment of hazard and vulnerability

In risk management, the hazard is typically defined as the phenomenon with the potential to cause damage: in a meteorological context, hazards might include tropical cyclones and storm surges. The vulnerability is defined as the likelihood that infrastructure (or individuals) would suffer damage for a given intensity of hazard. The risk is then defined as the expected loss of infrastructure or life within a given period of time. Other risk management definitions are possible, notably the use of critical thresholds discussed above (Jones 2001), whereby the probability of damage greater than a threshold is given, thus better defining the risk in terms of the number of events that exceed the unacceptable level indicated by the threshold.

Hazards can be mapped. For example, there are various methods for calculating the 1 in 100 year (1%AEP) flood level in a coastal location. One difficulty with these estimates, of course, is that often there is less than 100 years of good observed water level data to establish this return period. Thus there is a range of uncertainty associated with them. In some locations, there is a longer meteorological data record, so modelling techniques using this meteorological data as input may be employed to calculate AEP flood levels (e.g. Tan et al. 2001). Even so, it can be argued that much more data than 100 years would be required to accurately estimate the 100 year return period. These techniques may also be used for future climate change scenarios, but this assumes that the relationships between the relevant forcing factors remain the same.

Likewise, for tropical cyclone occurrence, there is significant uncertainty regarding whether tropical cyclone occurrence can be reliably estimated from the data that are readily to hand, which in many locations in Australia comprises not more than 100 years. Standard techniques for estimating return periods may be found in Institution of Engineers (1999).

For sea level rise, planners would ideally prefer a projection of a certain sea level rise to be associated with a specific probability. This projection could then be used in a risk assessment of the impact (e.g. Jones 2001).

GIS/mapping

Crucial in this assessment is the use of Geographical Information Systems, which provide spatial information on land elevations and infrastructure, which can then be used for assessment of risk. An example is a study performed for Collaroy/Narrabeen Beach in Sydney (Greve et al. 2000). Here the costs of sea-level rise and the resulting inland effects of storm damage were calculated. The results showed a very fast increase in the cost of damage as storm effects penetrated further inland. Cowell and Zeng (2003) used a GIS model to estimate the landward erosion at Fingal Beach, New South Wales that could be caused by sea level rise.

GIS elevation data needs to be very accurate to be useful for assessment of vulnerability to sea level rise. Either extensive surveys need to be performed (e.g. Wealands et al. 2002) or new technology such as laser altimetry must be employed.

Risk management

In the context of climate change, risk management takes on a number of guises. Because coastal assets often have perceived societal and cultural values beyond their strictly economic valuation, risk management is sometimes not so much a cost-benefit analysis as a means of preventing outcomes that would be unacceptable. Abbs et al. (2000) give an example of the application of a sophisticated modelling system, combined with a damage assessment model and GIS, to estimate the impact of climate change on an historic flood in south-east Queensland (the Australia Day floods of 1974). Assuming reasonable increases in sea level, they estimate that between 3 and 18% more dwellings would have been affected had the same flood occurred with a higher sea level.

Valuation of assets at risk may not only include infrastructure. Estimates of the value of cultural and biological resources along the coast can and should be made (e.g. Costanza et al. 1997).

b) Adaptation

The selection of the most appropriate adaptation strategy for a particular location depends somewhat on the assessment process. Coastal regions often divide themselves logically into areas known as littoral cells, parts of the coast within which sediment is circulated (e.g. Woodroffe 2002). The meaning is similar to that of beach compartments except that compartments are more appropriate to coastlines where headlands interrupt the alongshore flow of sediment. Cells can be bounded by river mouths, submarine canyons and headlands. The littoral cell concept is useful for management in that cells act as closed regions for the supply of sand.

It is clear that coastal adaptations usually have unintended side effects. Under some circumstances, these can outweigh benefits of the adaptation (United Nations 1999). As stated before in assessments of this kind, “no regrets” adaptations should have priority.

Managing erosion

Accelerated coastal erosion due to sea level rise is the main coastal issue associated with climate change. A number of strategies have been suggested to adapt to a coastal environment with a higher average sea level. Titus (1990) defines the following strategies (see also Townshend 2002):

accommodation / no protection

This is defined as not protecting existing infrastructure or amenities in any way from natural erosive processes. This strategy is appropriate for regions of little or no infrastructure, or of little cultural or other value. It may also be appropriate if the costs of protecting existing infrastructure are prohibitive.

The land abandoned becomes unusable. In this scenario, there may also be possible compensation claims from owners of abandoned infrastructure.

protection

This means to build coastal engineering structures that will reduce landward erosion. Examples include the use of levees, groynes and sea walls. This can often be costly: sea wall costs have been estimated at about US$3000 (1998 dollars) per linear metre, with maintenance costs of 4-10% per annum, depending on exposure to wave action (Neumann and Livesay 2001). Such engineering structures can also appear unsightly and may negatively affect the appearance of the relevant coastal region, leading to a decrease in recreational use. Groynes may affect the coastal alongshore transport of sand and therefore can affect sand deposition in other areas. Because of the significant cost of this approach, it is only practical on coastal regions of high infrastructure cost.

Newer technology may provide a more cost-effective solution. Artificial reefs can provide some protection to shoreline regions, by controlling the flow of sediment (eg. Jackson et al. 2000).

adaptation

This is defined by Titus (1990) as modifying existing infrastructure to adapt to sea level rise. Examples include raising the height of existing buildings and raising beach height (beach nourishment). Other adaptations may include the creation of land setbacks and the provision of Government insurance.

Costs associated with this approach include the cost of modifying existing infrastructure, the expense of finding and putting sand on the beach, and the cost of Government insurance.

retreat

This is a strategy that involves gradually restricting the use to which land can be put over time; Titus (1998) used the term “rolling easements” to describe this process. This zoning approach prohibits expensive development in risk areas but allows lower cost usage that can economically be abandoned over time (such as grazing or recreational use). Many areas that are currently vulnerable would be appropriately managed by this response.

Another set of adaptation strategies is listed in Kay et al. (1996):

event protection
- hard: sea walls
- soft: beach nourishment

damage prevention
- avoidance – prevent development
- mitigation – building codes, flood proofing

loss distribution
- individual – insurance
- community – insurance / relief / cost sharing

risk acceptance
- includes doing nothing

Adaptation measures to combat erosion may take different forms. In a region where the economy depends upon the maintenance of an aesthetically pleasing beach, beach nourishment may be needed to raise the level of the beach. In locations where infrastructure needs to be protected from rising sea level but where aesthetic considerations are secondary, a sea wall could be employed. In the section on management options, some of the advantages and disadvantages of these approaches are given.

Some lessons may be learned from the current strategies in place to deal with extreme events (FEMA 1999). Major storms may cause permanent changes in the coastline, but a great deal of the erosion caused represents a shift of sand to offshore regions. Much of this sand eventually returns to the beaches. Reasonable construction setbacks, combined with elevation of vulnerable properties above expected storm surge heights, can protect property effectively.

A recent study has examined the management options for coastal erosion in the Gippsland lakes region (Gippsland Coastal Board 2002). For this work, a planning horizon of 100 years is set. Consistent with State guidelines, doing nothing is the recommended option for most regions of the coastline, other than for key infrastructure. Much of the Gippsland coastline consists of National or Coastal Parks and reserves that do not contain large infrastructure or biologically sensitive regions. In some locations, setback buffers are recommended, with setback specified both with and without allowance for sea level rise. Revegetation is also recommended to inhibit further erosion. Engineered structures are also considered. These are only recommended where there is a clear understanding of the potential impact of the structures on coastal processes such as sediment transport. Beach nourishment is currently undertaken at high-use beaches in the region, but cheap offshore supplies of suitable sand have not yet been identified. Planning approvals should consider the impact on the coastline of proposed engineering structures. Ongoing reassessment of erosion rates should take place every 15 to 20 years. A project to assess the impacts of climate change on the Gippsland coast is currently under way.

In the same report, Bird (2002) gives an evaluation of the effect of climate change and sea level rise on the Gippsland coast. The main effects of climate change are likely to be as follows:

- landward expansion of the Gippsland Lakes, leading to increased erosion on the bordering shores;
- submergence of river deltas and lower parts of rivers;
- increased salinity of the Gippsland Lakes, leading to changes in species distribution;
- landward migration of saltmarsh and seagrass regions;
- exacerbation of short-term riverine flooding events; and
- the need for modification of coastal structures to adapt to the new sea level.

While applying adaptation measures to coastal ecosystems may be problematic, one example is making an allowance for the landward migration of mangroves and wetlands through the establishment of vegetation corridors (CSIRO 2002). Another strategy that could be interpreted as an adaptation would be to remove the other environmental stresses on ecosystems (such as pollution), which would enable them to deal more effectively with climate change.

Controls and zoning

Implicit in the provision of good management options are allowances for controls and zoning. Sea level rise and other effects of climate change can be very costly in the future if substantial infrastructure is erected in locations where it is likely to become unviable. Inappropriate zoning may lead to infrastructure being built in vulnerable locations, making the zoning too expensive to revoke, leading to demands for measures to protect the existing infrastructure. Controls that have been put into place to date include regulations regarding the height of buildings so that there is a clearance above the 1-in-100 year flood height return period. Variations on such regulations are incorporated into the planning schemes of many state government bodies and municipalities (see below for a review).

An additional control mechanism is through the declaration of marine protected areas, such as the Great Barrier Reef World Heritage Area or the recently-created Marine National Parks in Victoria. In the context of climate change, the importance of these would be to decrease other stresses on the ecosystems.

Other approaches

Experience in California has shown that once substantial sections of the coast are armoured with sea walls, there is less sand available for beaches, creating a need for further sea wall construction. Progressive protection of the coastline through the use of salients and breakwaters may be a way of protecting the coastline without resorting to sea walls. Artificial reefs are an example of such techniques, which usually have low environmental impact.

Application of this technique has been undertaken in many locations. In Egypt, the coastal resort town of Ras-El-Bar has faced the loss of sediment transported by the Nile after the construction of the Aswan High Dam in 1964 (Dabees and Kamphuis 1998). Significant coastal erosion has occurred since then due to wave activity in the Mediterranean. A series of breakwaters were built in 1990; since then, the coastline has widened.

An innovative approach has currently been suggested for a beach close to Newcastle. This beach is backed by an eroding cliff face. It has been suggested that the cliff be excavated back to a stable profile and the excavated area replaced with suitable armouring structures.

Innovative engineering alternatives that provide benefits for all sectors of society should be investigated for vulnerable locations, but only if there is a clear understanding of the consequences of such structures.

5) Policy and planning

Policy and planning for coastal issues in Australia have been influenced by the concept of Integrated Coastal Management (ICM). In broad terms, ICM involves an integrated approach to coastal management, involving all stakeholders in decisions that reflect current best practice, recognise the precautionary principle and have sustainability as a primary goal (e.g. Harvey and Caton 2003; Belfiore 2003). For instance, Victoria's coastal management strategy incorporates a number of these elements. An even clearer example is given by the management of the Great Barrier Reef, which needed an Act of Parliament to establish the Great Barrier Reef Marine Park Authority (GBRMPA) to integrate the policies of different government agencies and to incorporate the latest technical advice into management decisions for the reef.

a) National coastal strategies

Australia is signatory to several international conventions relevant to climate change. With regard to coastal issues, there is currently no official national policy on coastal issues, and a national response to the vulnerability of the coast to climate change issues has not occurred. Internationally, coastal climate change planning is often informed by reference to the Common Methodology for Coastal Vulnerability (IPCC 1992). Harvey and Caton (2003) consider this methodology inappropriate for coastal Australia because of the dominance in the methodology of economic considerations, whereas for the coast, as already mentioned, societal or cultural values often outweigh these. In general, Australian national policy recommendations do not ensure an integrated approach to coastal issues, nor are there national systems and databases to provide benchmarks for coastal management.

The Commonwealth Coastal Policy (1995) makes reference to climate change issues, stating that it should be taken into account to "ensure that consequences arising from the dynamic nature of coastal environments are recognised", and in the context of regional cooperation with South Pacific nations vulnerable to sea level rise. In addition, it recommends the adoption of the IPCC Common Methodology to deal with climate change issues. Glanznig (2002) details some of the changes that have occurred in the policy environment since then, most notably the introduction of Australia's Ocean Policy, in which regional planning is used to manage marine natural resources. He points out that any future coastal policy must include measurable goals to be successful.

National guidelines on responses in coastal engineering to climate change were published by the Institution of Engineers, Australia (1991). While many of these strategies remain valid, Engineers Australia is currently preparing new guidelines that will be released in early 2004. Institution of Engineers (2000) identified the effect of climate change on the coast as the most important research priority for coastal engineering in Australia.

b) State coastal strategies

State coastal strategies vary in their content and application to local issues (Harvey and Caton 2003; Walsh et al. 2004). A recent change in the planning environment is the adoption of statutory coastal plans in many States (i.e. plans with the force of law). Even given this added legal protection, enforcement of these plans at the local level is not guaranteed.

Tasmania faces serious issues with respect to planning for climate change. Tasmania's coastal legislation was recently overturned by a legal challenge regarding the accepted definition of a coastal zone, but has since been reinstated. Initiatives to incorporate climate change into local planning are limited by funding needed to implement the conclusions of planning agencies. Moreover, the enforcement provisions of previous policies were flawed (Rees 2002). Issues that are perceived as peripheral, including climate change, face a hard road to acceptance in local planning schemes.

In the Northern Territory, coastal policy is currently under review, with a new coastal and marine management policy being developed.

In 2003, Western Australia released its State Coastal Statement of Planning Policy. This takes sea level rise into account in calculating setbacks, which are designed to ensure the continuity of a public foreshore area. The delineation of the setback to development includes consideration of a suitable area to conserve landforms and biodiversity and provide for public recreational needs as well as allowing for coastal processes. Setbacks are calculated by assessing the erosion or accretion trend on that section of coast, modelling of the influence of a severe storm (using the SBEACH model; Larson and Kraus 1989) and including a component to allow for global sea level rise (using Bruun's Rule and a mid-range estimate of global sea level rise from the latest IPCC assessment). For an undeveloped sandy shore, a setback of about 100 m is expected (e.g. Jones and Hayne 2002). The State has considerable involvement in helping local authorities to keep their local plans up-to-date. More than 97% of the coastal foreshores in this State are in public ownership, so the State has a very limited liability for providing protection to development on the coast.

In addition to the previous coastal buffer zone policy of the Queensland Beach Protection Authority, Queensland has new legislation and a statutory policy, the State Coastal Management Plan. The plan lists the standard adaptation options to sea level rise and requires local governments and other planning agencies to take these into account in local planning. Regional Coastal Management Plans are also being formulated (Maher 2002) to deal with the implications of climate change through risk assessment and planning processes. Nevertheless, there are also numerous restrictions on the powers available under statutory planning in Queensland: for instance, there are a number of exemptions from development assessment, including land under agricultural use. Land use allocations from previous eras restrict councils from changing current land use. As a result, local planning for sea level rise along the coast in Queensland has varied considerably. Regional responses to date do not indicate significant changes to the local planning environment. In addition, there are strong and continuing pressures to develop coastal areas further to service the tourism industry. These issues are not limited to this State alone.

Victoria also has a new statutory coastal policy, the Victorian Coastal Strategy. Coastal planning and management bodies are required to take a long-term approach to decision making, including climate change. Nevertheless, specific management initiatives to take climate change into account at the local level have been limited. Beach nourishment works are active and have recently been coordinated with dredging (James 2002). Monitoring of ecosystems continues, and the recent establishment of marine national parks and reserves may aid this process.

In New South Wales, there is a strong coastal policy with legislative powers. Virtually all local councils have included a setback of 10 to 20 m over a 50-year planning horizon to allow for possible sea level rise – although one could argue that this might not be conservative enough. Indeed, Thom (2002) indicates that global change science is driving an improved understanding of coastal zone management.

Despite a long history of coastal planning, South Australia has no statutory integrated coastal policy, although, for instance, all local council development plans incorporate sea level rise in their planning schemes. Harvey (2002) summarises planning for sea level rise in South Australia. Planning for sea level rise includes an allowance for a 0.3 m sea level rise by 2050, on top of the 100-year storm tide, with an allowance for wave run-up. On top of this, a 0.25 m freeboard is imposed. Infrastructure must be capable of being protected against a further 0.7 m of sea level rise, either by use of a levee bank or by raising the building. In terms of active measures to combat erosion, the renourishment of Adelaide beaches continues, but sand sources for this are now becoming harder to find (Caton 2002). The State Coastal Protection Board is currently formalizing its existing policies into a policy statement.

A related question is the design of the optimum framework for coastal plans, one that considers the linkages between plans and has appropriate consideration of scales and coverage. Obviously, partnerships between State and local authorities are crucial. More details may be found in Harvey and Caton (2003) and Walsh et al. (2004).

c) Local government plans and implementation

Despite recent advances in the legislative environment, not all local councils in Australia have included climate change issues in their planning. Often this is the result of lack of resources to do so: for every well-equipped council with ample access to technical expertise (e.g. Betts 2001), there are numerous coastal councils with far fewer resources. This limits their ability to plan for climate change. In addition, some councils are simply resistant to implementation of plans that are perceived to disadvantage certain sectors of the community (Thom 2002).

Townshend (2002) has suggested an approach whereby local governments could address the issue of climate change:

1. Identify vulnerable areas with the relevant likelihood and type of hazards
2. Assess extent of vulnerability and potential consequences to current or potential development for each vulnerable area
3. Evaluate adaptation options and implications for each vulnerable area
4. Select the adaptation options for each area and combine into a planning and management strategy for the Municipal area
5. Incorporate the strategy into the Municipal strategic plan, planning scheme, emergency plan, etc.
6. Provide community education to increase awareness of the risks and the reasoning behind the management strategy
7. Implement the strategy
8. Continue key research to reduce local and regional uncertainty
9. Monitor the rate of the local impacts of climate change and the success of the implementation of the strategy
10. Update the planning and management strategy and its implementation (see 4 above)
11. Continue this cycle into the future for as long as necessary

Again, cost limitations would make it difficult for some coastal councils even to address stage 1 of this approach, let alone conduct the kind of comprehensive management plan indicated.

Selection of appropriate adaptation

Adaptation selection is highly dependent upon location and upon the available technical expertise, and yet is crucial to the successful response to climate change. For instance, protection of a beach using a sea wall will invariably lead to total loss of the beach through scouring in front of the wall. There are numerous examples of coastal engineering works that have led to negative impacts on the coastline, partly because of our lack of detailed knowledge of coastal processes. On the other hand, coastal modification could be instrumental in preservation of precious coastal assets in the future, as the sea level rises and if extreme events become more common.

For ecosystem changes caused by effects other than sea level rise, adaptation issues are more problematic. Not only is there less fundamental understanding of the complicated biological processes involved, but data is also even less available than for issues like erosion. Furthermore, in some cases there may be no obvious adaptation options available: for instance, it is hard to imagine how human intervention can stop higher ocean temperature causing persistent bleaching of the Great Barrier Reef corals from occurring in the future, other than by reducing man-made stresses on the reef such as pollution.

Responsibility

Responsibility deals with the legislative and common law duties of National, State and local governments. In the context of climate change, National and State governments play a role in improving the knowledge and understanding of possible climate change impacts. They also support the development of planning tools for regional and local government planners so that they may undertake assessments of hazards, vulnerability and risks. Ultimately, though, because local government often lacks the resources to address technical planning issues, State and National governments need to step in to provide local support for implementing State and National policy initiatives.

d) Unresolved issues

Lack of financial resources at the local level

For climate change issues, this is one of the major stumbling blocks. Local municipalities may make reference to the strategic plans or other documents produced by the States, but along the coastline many of the issues are quite local in nature. Certainly the nature of the coastal environment in a local government region is often heterogeneous and the effects of climate change would need to be examined at specific sites. Resources to perform these detailed technical evaluations are often lacking.

Equity issues

The impact of climate change will not be equitable. Moreover, even if it were, there are wide differences in the ability to pay. Again, the role of government in addressing this issue is crucial.

6) Implementation

The ability to implement climate change adaptations is limited by the availability of funding. Moreover, the legislative framework needs to be in place to support the assessments carried out at the local level. Training and assistance will be needed to ensure that assessments are scientifically justifiable.

a) Vulnerability and risk assessments

Assuming that resources are available, vulnerability assessments can be carried out, preferably at the littoral cell level. The spatial extent and types of risks within this region should be delineated and appropriate adaptation strategies designed.

b) Adaptation strategies

Protection/adaptation recommendations

It is difficult to give general guidelines in the dynamic and varied coastal environment. Guidelines were previously compiled by the Institution of Engineers (1991) and are currently being revised (Engineers Australia, 2004). These include consideration of a host of variables and provide a ready reference to possible impacts.

Planning regulations (including rezoning)

Considerable planning has already taken place, as detailed above. A significant issue that in general has yet to be addressed is the translation of IPCC estimates of global sea level rise down to regional and local levels, through the inclusion of land movements caused, for example, by subsidence (e.g. Bell et al. 2001). In addition, the planning process should be made flexible enough to incorporate future improvements in scientific understanding, both of global warming and of coastal processes.

7) Monitoring and evaluation

a) Future sea level trends

Measuring systems are now in place that will give good measurements of Australian sea level trends (the SEAFRAME network). The sea level has been rising in the 20th century and will continue to rise in the 21st. For the sea level to rise as much as the projected amount by 2050, some acceleration in the present sea level rise rate will have to occur. If this does occur, it should be measurable by the SEAFRAME gauges. Thus monitoring of Australian-average sea levels will be relatively straightforward provided that the SEAFRAME network continues to measure data into the next few decades. Survival of this network is not guaranteed, however, and needs to be made a priority consideration.

Measuring of local sea level at locations without robust sea level gauges is more problematic. As mentioned earlier, many locations are affected by subsidence, which is measured by local tide gauges whose data is sometimes less than reliable. Useful monitoring requires gauges whose relative elevation is measured to an absolute standard on a regular basis, through GPS observations, for instance. This should certainly be part of any future SEAFRAME network. There also needs to be an effort to reanalyze current tide gauge data to obtain a more accurate picture of sea level change around Australia.

Since most erosion events are caused by extreme events, changes in these should to be a particular emphasis of future studies. In addition, the current range of projections of global sea level rise needs to be narrowed through further work, particularly at the regional level. As noted above, there will always be a considerable range of predictions.

b) Future erosion trends

While sea level rise and erosion go hand-in-hand, the future rate of erosion at a specific location will not bear a simple relationship to sea level rise. Ongoing monitoring of erosion rates at very local levels will be required.

c) Future ecosystem changes

Indicators of changes in ecosystems as a result of climate change also need to be monitored. Here the impact of confounding factors, such as the demographic pressures caused by human population growth in the coastal region, becomes very great. Certainly, though, large-scale variables such as ocean temperatures can be monitored relatively easily. Likewise, changes in wind climate can also be monitored using standard meteorological networks, provided that processes are in place to ensure that instrumentation and site changes do not affect the observations. Changes in wave climate are more difficult to monitor, given the current sparse network of wave observations.

d) Rate of implementation of adaptation strategies

The uptake of informed adaptation strategies is a key indicator of the progress of adaptation to climate change. This would need to be periodically monitored by national agencies to measure the success of any national policy initiative on addressing issues associated with coastal climate change.

8) Recommended actions

a) National coastal framework that aids the development of cooperation on coastal issues between National, State and local governments.

b) National review of available data sources related to coastal stability

c) Improved funding for regional and local assessment of climate change risks as part of a national coastal policy

- i) Scientific assessment
- ii) Risk management assessment
- iii) Economic impact assessment
- iv) Social impact assessment

d) Incorporation of local assessments of climate change impacts into regional and local planning

- i) Consistency with State statutory and non-statutory plans

e) Reduction of scientific uncertainties, especially coastal geomorphology issues

- i) Federal government funding initiative

f) Education and technical assistance

- i) Capacity building within the planning profession

g) Future monitoring of outcomes

- i) National strategy for monitoring coasts
- ii) Continuation of high-precision sea level baseline network (SEAFRAME)

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