Planning for Climate Change Effects on Coastal Margins

A report prepared for the Ministry for the Environment as part of the New Zealand Climate Change Programme

New Zealand Climate Change Programme
Te Hōtaka Rerekētanga Āhuarangi ō Aotearoa

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Executive Summary

This report addresses the impacts of climate change and global warming on coastal margins. It complements the more general overview of climate change impacts on New Zealand published by the Ministry for the Environment/New Zealand Climate Change Programme in July 2001 (MfE, 2001). The report aims to assist resource managers and planners to understand the underlying impacts and issues in climate change and sea-level rise, and to provide guidance in planning and the development of mitigation or adaptation strategies for coastal communities.

Effects of global warming, climate change and sea-level rise

- 'Climate change' is defined as any significant change or trend in climate – natural or human-induced, and includes global warming.
- "There is new and stronger evidence that most of the global warming observed over the last 50 years is attributable to human activities" (IPCC, 2001a).
- The sea level has risen 0.3 m since the mid 1800s and sea temperature by 0.4 to 0.5°C since 1870. This rise is expected to continue and accelerate.
- Relative sea-level rise in New Zealand is most likely to be 0.14 to 0.18 m by 2050 and 0.31 to 0.49 m by 2100.
- Oceans are a vast heat 'reservoir', so it may take centuries for the oceans to cool and for sea-level rise to level out, even after curtailing greenhouse gas emissions.
- Regional New Zealand climate projections for the 2080s by the National Institute of water and Atmospheric Research Ltd (NIWA) are for:
  - a rise in mean air temperature of 1.6 to 2.2°C (winter) and somewhat less in summer will increase sea temperatures in estuaries and coastal waters, affecting aquatic ecosystems
  - extreme storms are unlikely to be more frequent, but may be more intense, especially with regard to rainfall and wind strength
  - a more westerly wind stream over New Zealand (more El Niño-like)
  - sediment supply to the coast to be affected in a number of ways by climate change, such as changes in river flows (and sediment load) after heavy rainfall, winds, wave climate and currents.

  These projections are based on the assumption of continued increase in greenhouse gas emissions and use current global climate model results. Uncertainties are associated with both projected greenhouse gas emissions and model calculations.

Pressures on our coastal areas

- There are huge pressures to develop and occupy the coast (for subdivisions, marinas, roads and drainage). Beach-front property prices continue to escalate in most beach resorts.
- At vulnerable coastal margins, coastal development and global warming are on an eventual collision course (if they have not collided already), which will result in further ‘coastal squeeze’ between the land and the sea.
- Developed areas around the New Zealand coast are usually nestled in or near low-lying coastal margins, such as beaches, estuaries and harbours, and will therefore become increasingly vulnerable to the effects of global warming.

Expected impacts on coastal margins

- Sea-level rise relative to the landmass is the main concern locally, rather than global sea-level rise *per se*. Local effects, such as subsidence and tectonic movements, can cause a departure, up or down, on the global average.
- Parts of the coastline have historically been eroding or retreating, and climate change will exacerbate these trends.
- Sea-level rise will eventually lead to permanent inundation of very low-lying margins, episodic sea flooding of higher margins, increased coastal erosion, salinisation of adjacent freshwater, drainage problems in adjacent low-lying areas, and further coastal squeeze where shorelines are held and constrained by structures such as seawalls and stopbanks.
- Climate change will affect not just sea-level rise, but most physical drivers that shape coastal margins and ecosystems, such as winds, waves, storms, sediment supply and sea temperature.
- Predicting shoreline response as a result of climate change is complex, and simpler conceptual models based solely on sea-level rise are of limited use. Beach response will also depend on factors such as sediment supply, wave climate, storm frequency and alongshore changes in sediment movement.
- Wind and wave changes will alter sediment movement and coastal upwelling of cooler nutrient-rich ocean waters, which are important for coastal productivity, including fisheries.
- Increase in storm rainfall intensities will lead to lowland river flooding and impacts on water quality from increased sediment loads to estuaries, although sediment availability will also depend on catchment land-use and construction practices.
- Aquatic ecosystems will be affected by rising temperatures (air and water), potential loss of habitat from constraining stopbanks in some areas, and increases in sediment loads entering estuaries during storms in other areas.
- The sea level around New Zealand is presently rising at a steady rate. This is projected to accelerate, which will exacerbate coastal erosion, flooding and (for some areas) permanent tidal inundation.

- Impacts on coastal margins will differ between regions and even between localities within regions, depending on shoreline parameters (such as slope, erodibility, sediment type), sediment supply, and potential offshore changes in wave climate and sediment movement.

Assessment of vulnerability and adaptation options

- There is need for education about the unique consequences of global warming for coastal margins. A better informed public should engender a growing acceptance of these consequences and assist buy-in to prudent response options at the local level.
- Diversity of coastal types requires local or regional investigations and solutions.
- The vulnerability and adaptive capacity of ecosystems and human systems (communities, infrastructure, economy, insurance) need assessing before feasible and environmentally appropriate responses to sea-level rise and other climate change impacts are decided.
- In largely undeveloped areas, pre-planned retreat by way of setback hazard zones is the only cost-effective long-term option.
- For communities or infrastructure that are vulnerable, managed retreat and adaptation are the only reasonable long-term options, given that sea level is projected to continue rising for several centuries.
- Continued or new protection options for high-density population beaches, such as beach re-nourishment or holding structures, may be the only palatable solution in the medium term (several decades) because of the large investment in real estate. However, situations that may require new protection measures are complex, particularly if those measures are likely to have significant adverse environmental effects. This is counter to the intent of the Resource Management Act 1991 (RMA) and the New Zealand Coastal Policy Statement.
- A robust planning and policy framework is already in place to manage and mitigate natural coastal hazards, under the umbrella of the RMA. However, the framework needs some fine tuning to ensure that integrated management across coastal margins and long-term (over 100-year) planning occur, possibly through a revised New Zealand Coastal Policy Statement and Building Act 1991. It must also continue to be flexible at regional and local scales.
- Topography and cadastral databases for coastal margins need to be upgraded before the scale of the sea-level rise impacts and feasible response options can be assessed on local, regional, and national scales.

Conclusions

- We have time to plan prudently.
- We have a robust policy framework to deal with coastal hazards and, by inference, any climate change effects.
- We have prior knowledge of climate change impacts, albeit uncertain in scale, timing and local detail.
- Education, discussion and gradual adjustment to sustainable long-term response options are now vital keys to adapt to the effects of global warming on our coastal margins.

> *The challenge is not to find the best policy today for the next 100 years, but to select a prudent strategy and to adjust it over time in the light of new information.*
>
> IPCC, 1996

1 Scope of the Global Warming Problem for Coasts

This report addresses planning for climate change effects on coastal margins. It complements the more general overview of climate change impacts on New Zealand recently published by the Ministry for the Environment (MfE, 2001). The aim of the report is to convey information that will help address two fundamental questions:

- What changes will global warming make in our coastal locality?
- What can be done about these changes?

Socioeconomic pressures to develop and occupy coastal and estuarine margins[1] are growing faster than ever, as more New Zealanders clamour to be near the sea – to live, holiday and play. Many of our major urban areas already encroach on harbours or estuaries. Worldwide, over 20% (some 1.2 billion people) live near a coastline, but this proportion is expected to rise rapidly (IPCC, 2001b). This social pressure for coastal development is largely oblivious to the reality of global warming due to the enhanced greenhouse effect from human activities, and to resulting long-term changes to coastal hazards that will impinge on coastal margins.

New Zealanders have only a moderate knowledge about climate change issues. A survey showed that 51% claimed they knew a “fair amount”, but the survey analysis suggests that these were often fairly generous self-assessments (UMR, 2001). There was even less concern about the impacts of global warming. From our own contacts with the general public, it would appear that few are aware that sea level and sea temperatures around New Zealand have already been rising for some time, with data to confirm this rise going back to the mid 1800s. Projections are for the rise in sea level to accelerate and continue for several centuries. Even a very small acceleration in the rise of sea level during the 21st century could eventually lead to catastrophic situations in some developed areas if mitigation or adaptive plans are not progressively put in place. Coastal erosion, flooding by the sea or backed-up rivers, drainage difficulties and damage to property in coastal margins are expected to progressively worsen as global warming changes the balance of our climate. These hazards pose little risk to undeveloped coastal margins other than loss of land.

Put simply, communities and coastal margins in many localities are on a slow, but sure, collision course. Like the sunbathers on the beach ignoring the encroaching high tide, we have shown little inclination to implement long-term mitigation and adaptation strategies or ultimately plan our retreat from the coastline where this is expected to become necessary. Most existing coastal erosion hazard problems result from development being too close to the sea to accommodate the natural cycles of cut-back and advance of the shoreline. There is little doubt that global warming impacts will exacerbate these same problems in the long term through sea-level rise and other climatic changes which impact on the coastal margin.

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[1] See the Glossary for a definition of ‘coastal margin’.

One of the physical functions of a coastal margin is to absorb the energy generated by waves, any temporary rise in sea level (or storm surge) during storms, and the regular twice-daily dose of tides. In other words, the coast as we see it today is the integrated response of a very dynamic marine environment and a near-static terrestrial environment. In many developed areas this function is compromised by construction of dwellings, roads, seawalls and stopbanks (Figure 1). Such changes constrain the ability of coastal margins to respond dynamically to existing coastal processes, let alone future climate change. These constraints result in 'coastal squeeze' as an outcome of the collision between naturally dynamic coasts and relatively static coastal communities.

Figure 1: *Timber seawalls have been placed to mitigate coastal erosion at Cooks Beach (Coromandel Peninsula). The photo captures the concept of "coastal squeeze", where dwellings are quite close to an eroding beach, leaving little room for natural cycles of cut-back and advance of the shoreline.* [Photo (1996): RK Smith]

Part of the essential message of this report is that climate changes likely to occur over the next 50 to 100 years will aggravate this coastal squeeze in developed coastal areas. Ultimately, it will probably be almost impossible to maintain communities and infrastructure that have been placed too close to the sea to accommodate the projected changes, while also protecting the coastal environmental values critical to our economy and our quality of life, and that draw us to the coast in the first place.

The most serious *physical* impacts of gradual sea-level rise on coastal margins may be:

- coastal inundation, causing landward movement of estuaries, wetlands and marshes
- coastal erosion and shoreline change through sediment movement
- increased vulnerability to coastal storm damage and flooding
- increasing difficulty draining coastal and river lowlands
- the possibility of increased sediment loads to estuaries, with projected increases in rainfall intensity and run-off
- surface water, river water and groundwater in lowlands increasingly becoming saltier from seawater intrusion.

The primary *ecological* impacts will stem from a rise in temperature (air and water), inundation by a higher sea level, and a loss of habitat from increased siltation in some estuaries and harbours, while in others there will be a loss of intertidal areas caused by constraining shoreline protection structures or embankments.

Sea-level rise will obviously cause many of the impacts unique to coastal margins, but other coastal ‘drivers’ or physical forcing agents affected by climate change – such as river flows, winds, waves, storm intensity, and perhaps storm frequency – will create their own impacts, besides exaggerating or mitigating the impacts of sea-level rise.

If the increasing rate at which people are moving to the seaside continues for some time, then educating people about the consequences of global warming on coastal margins is a key to planning and minimising the impacts on society. Underlying this issue are two fundamental questions:

- What changes will global warming make in our coastal locality?
- What can be done about it?

This report addresses these two questions by presenting the latest projections on climate change and how they are likely to affect coastal margins around New Zealand. Sections on long-term planning and response options, human and cultural issues, and information gaps are provided to assist the transformation of climate change information into effective statutory or hazard mitigation plans and public education initiatives. Much of the material is presented by way of case studies or schematic diagrams.

- Sea level around New Zealand is rising. This rise is projected to accelerate, causing more coastal erosion, inundation and episodic flooding from storms.
- There are huge pressures to develop and occupy the coast (subdivisions, marinas, roads, drainage).
- Coastal development and global warming are on a collision course at coastal margins, resulting in 'coastal squeeze'.
- There is a need for education about the unique consequences of global warming for coastal margins, before buy-in will occur to precautionary responses.
- This report aims to assist resource managers and planners to develop mitigation or adaptation strategies for coastal communities.

2 New Zealand's Coastal Scene

New Zealand has about 18,000 km of coastline, indented by some 350 estuaries, harbours, inlets, bays or fiords. Coastal margins are the transition between the ocean and the land, and the place where seawater mixes with freshwater and interacts occasionally with the fringing low-lying land during storms or extreme tides. Climate change impacts will vary locally as a result of local and regional differences in both the physical forcing functions (for example, waves, winds, currents, sea level) and coastal types. A broad-scale distribution of New Zealand coastal types, distinguishing 'bold' (steep, rocky), headland-bay, low-cliffed, depositional (mobile sediments) and beaches is shown in Figure 2. Estuaries and their associated low-lying margins (coastal plains, wetlands, salt marshes) are particularly vulnerable to climate change.

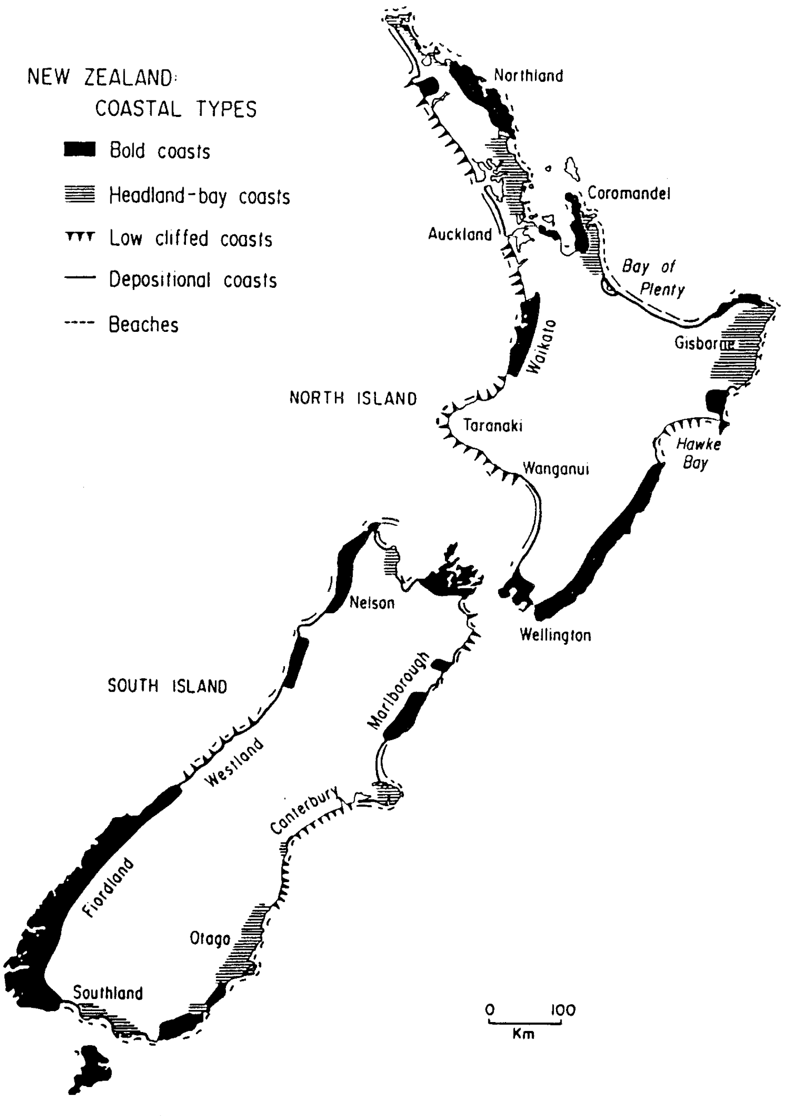


Figure 2: Geomorphic types around the New Zealand open coast (after McLean, 1978). Climate change and sea-level rise impacts would be least on bold coasts and greatest on depositional coasts and beaches.

A quick glance at Figure 2 may suggest that New Zealand's vulnerability to rising sea levels is low, due to the extensive lengths of high rocky or cliffed coast. But there are two types of coastline at risk. Some cliffed coasts are eroding at high rates, such as the unconsolidated alluvial cliffs in the Canterbury Bight, which may worsen with increased storminess and sea-level rise. However, the most vulnerable areas are where our urban centres, ports and holiday resorts cluster around low-lying portions of the coastline, such as harbours, estuaries, beaches, inlets and bays. They are there because these types of coastal environments are attractive aesthetically, places for recreation and access to the sea, or are functional as sheltered vessel moorings and ports.

Coastal environments already vulnerable to erosion or flooding hazards are most at risk from the impacts of global warming, but at least in these localities there is some residual knowledge of the potential hazards. For instance, coastal erosion can result in loss of dunes and beach area when seawalls are built (Cooks Beach, Figure 1), or damage and loss of property (Ohiwa Spit, Figure 3). Many coastal communities in low-lying coastal margins that have little history of erosion or coastal flooding may be more vulnerable in the long term because of greater resistance to precautionary response and adaptation plans. Territorial authorities have had a major struggle to get coastal hazard set-back zones accepted in established communities (for example, Papamoa Beach and even the more erosion-prone Waihi Beach), especially when home-owners find they are located seaward of the proposed set-back boundary.

Figure 3: *Catastrophic erosion at Ohiwa Spit west of Opotiki (Bay of Plenty) in April 1976 showing the futile efforts to defend the shoreline. Over the last two decades, the spit has subsequently built out seaward by around 200 m to cover the railway-iron protection seen offshore.* [Photo: RK Smith]

Maori have a special affinity for both the land (whenua) and the sea (moana), where fish and seafoods (kaimoana) are prized. As a consequence, there will be cultural impacts of global warming for Maori, especially with respect to any loss of land (and associated marae, middens and urupa) from erosion or flooding, and loss of habitat for kaimoana.

The spectrum of marine ecosystem habitat types around New Zealand ranges from exposed and wild cliff-lined or rocky coasts, through to quiescent waters within a mangrove stand or salt marsh at the upper reaches of an estuary. Coastal ecosystems are threatened by sea-level rise because extensive areas of wetlands, salt marsh and intertidal habitats lie at or just above sea level. But in some respects New Zealand is fortunate. Being a steep landmass with relatively narrow coastal margins, we are not vulnerable to the kinds of massive disruptions from global-warming impacts faced by countries such as Bangladesh (where 16% of rice-growing land is lower than 1 m above high tide), the Netherlands (increasingly more land below sea level) and some of our Pacific Island neighbours who live on low-lying atolls.

Along New Zealand's coastal margin the most serious impacts induced by climate change will be sea-level rise (permanent or storm sea flooding) and changes in climate and weather patterns, which may alter coastal sediment budgets ('sand in the bank'). Even minor shifts (positive or negative) in sediment delivered to the coast from the adjacent catchments could create long-term shifts in coastline movement.

Historical rates of erosion and accretion around New Zealand's open coastline are shown in Figure 4. While this nearly 20-year-old database desperately needs updating, it provides a picture of a patchy spatial distribution of shorelines that are advancing and eroding. Sea-level rise and climate change is likely to lead to markedly more eroding areas on the coast, particularly where sand or gravel supplies to the coastline are reduced by changes to rainfall, river flow, windiness, and storm frequency and intensity caused by global warming. There will very likely be areas where sediment supply or availability increases above historical rates, particularly if storm rainfall intensity increases, leading to advancing shorelines. Sea flooding and rising sea and estuary temperatures will also have significant impacts on ecosystems.

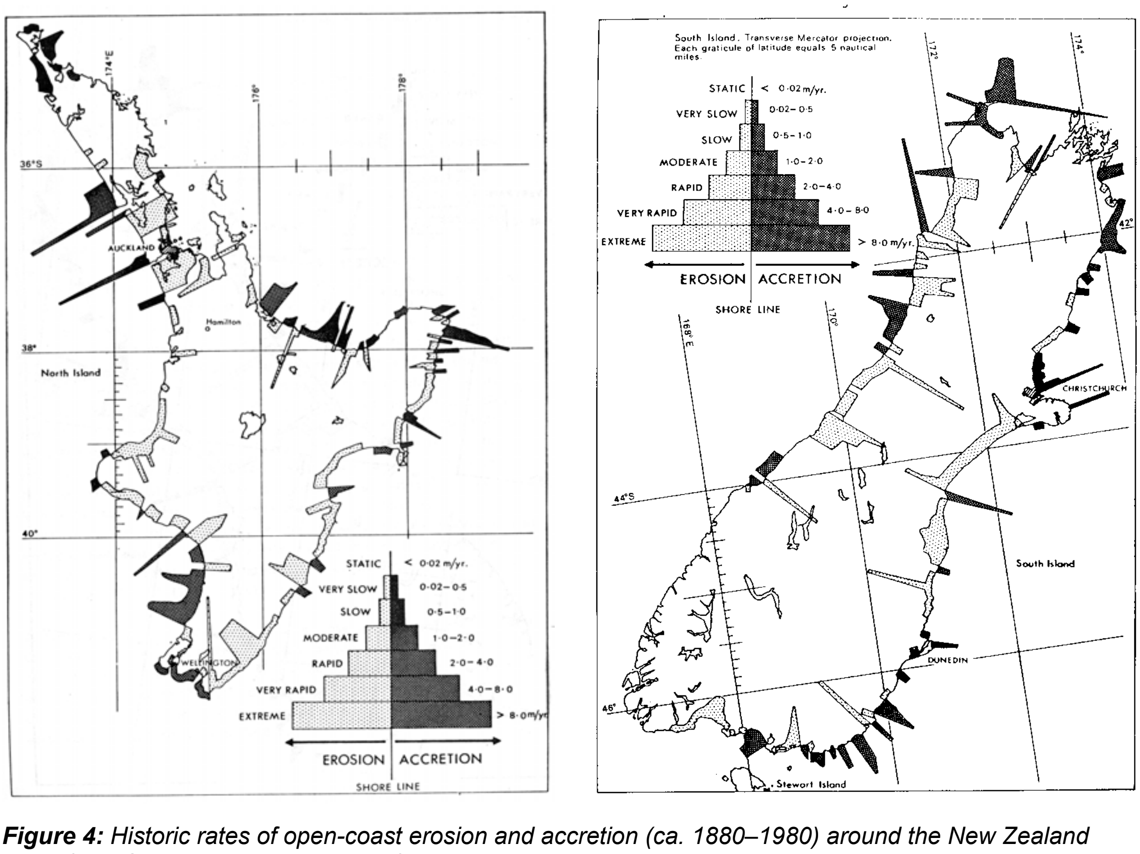


Figure 4: *Historic rates of open-coast erosion and accretion (ca. 1880–1980) around the New Zealand coast from Gibb (1984). (This type of national overview urgently needs updating.)*

The variability of New Zealand coastal types and different exposures to physical forcing functions (such as east versus west coasts) means that mitigating or adapting to the impacts of climate change for such a wide range of environments will entail different local investigations and solutions.

A warming world has already caused changes. Sea level around New Zealand has risen on average around 0.3 m since the mid 1800s (Bell *et al*., 2000), and coastal sea-surface temperatures have risen by around 0.4 to 0.5°C since 1870 (Folland and Salinger, 1995).

- **Developed areas are mostly near desirable beaches, estuaries and harbours, but by their very low-lying, accessible nature are vulnerable to the effects of global warming.**
- **Parts of the coastline have historically been eroding or retreating, and climate change will exacerbate these trends in some locations.**
- **Diversity of coastal and catchment types requires local or regional investigations and solutions.**
- **The sea level has risen 0.3 m since the mid-1800s and the sea temperature by 0.4 to 0.5°C since 1870.**

3 Setting the Scene: Climate Change and Coastal 'Drivers'

3.1 Some key definitions

Some working definitions for terms we use are important to avoid misunderstandings. Other terms are listed in the Glossary.

Climate is the 'average' state of weather in a region over periods of seasons or longer. *Climate change* refers to any significant change or trend in climate over time, either the mean state of climate and/or its variability (for example, extremes of temperature or rainfall, the retreat or advance of glaciers, the El Niño–Southern Oscillation). The Intergovernmental Panel on Climate Change (IPCC), which was formed jointly by the United Nations Environment Programme and the World Meteorological Organisation to regularly assess global climate change, investigates climate change due to both *natural variability* and as a *result of human activity*.

Global warming is often used synonymously with *climate change due to human activity*, the former being an expression the public identify with more readily (UMR Research Ltd, 2001), although climate change will incur more than just a rise in temperature, which is implicit in the term global warming. At times there can be uncertainty on whether climate change of a particular variable has occurred, because a small long-term trend or change must be distinguished from regular natural variability in any set of measurements.

Climate projection is a projection of the response of the climate system to emission scenarios of greenhouse gases and aerosols and other radiative forcing, usually based on simulations by a numerical climate model. Climate projections are distinguished from *climate predictions*, to emphasise that projections depend on model assumptions and the particular scenarios used, which in turn are based on assumptions concerning future socioeconomic trends, emission rates and technological developments, that may or may not be completely realised. Thus every climate projection must be seen as a *plausible* future development that is *consistent with a certain set of assumptions*, not a scientifically stated certainty.

Global sea-level rise refers to the average vertical rise across the world's oceans. *Relative* sea-level rise is the net rise relative to the landmass in a region, which is the sum of the local subsidence (or uplift) of the coastal margin and the *absolute* sea-level contribution in that region (which may in itself depart from the *global average* value in different regions). Tide gauges around the open coast and inside harbours measure *relative* sea level. Why the distinction? Because the long-term projections of sea-level rise made every five years by the IPCC are *global average absolute* rates, but in any particular region or locality it is the *relative* sea-level rise that determines the long-term susceptibility to coastal flooding and erosion. Therefore, the projected IPCC global rates need to be translated into relative rates for each region.

This is made somewhat easier in New Zealand because, by and large, our relative sea-level rates at the major ports are similar to the global average. However, it is unlikely that these relative sea-level rates apply everywhere around New Zealand all the time. Along some New Zealand coasts, seismic events can cause rapid or unsteady changes in relative sea level over localised areas. It is impossible to know when, where, and by how much, but research and monitoring of land movements can usefully pinpoint areas that are more vulnerable to either seismic uplift or subsidence. This irregular or episodic shift in the local landmass is usually impossible to quantify in order to combine with the trend of increasing global sea level to produce a reliable figure for any given area.

3.2 The role of the oceans in climate change

The ocean is a key player in the global climate system, moderating atmospheric temperature rises and absorbing CO_2. Oceans are large reservoirs of heat, and they change their temperature only slowly, but over time the cumulative effects of warmer air temperatures are manifested by thermal expansion of warmer upper-layer seawater and extra water volume from glacier and ice cap melt, causing the sea level to rise. The sheer size of the ocean heat reservoir means, even given a curtailment of greenhouse gas emissions, that several centuries may pass before rising sea level due to thermal expansion slows down (IPCC, 2001a).

Over the past few decades, public awareness raising about the effects of climate change on coastal margins has been entirely focused on the rise in sea level. However, other changes in climate (temperature, rainfall, wind flows, ocean currents and El Niño) and weather (storms, winds and waves) will also pose additional issues for the coast, either directly or indirectly. For example, a change in rainfall patterns in the Southern Alps will affect flows in the main Canterbury feeder rivers, how much is abstracted for irrigation, and therefore how much sand and gravel is supplied to the coast.

3.3 ‘Drivers’ of coastal change

It is important to distinguish the different physical ‘drivers’ or forcing agents (Figure 5) of physical and ecological change in coastal margins. Climate change will eventually affect all these drivers, either directly, or through their interaction with other drivers. For example, global ocean tides will be unaffected directly, but tidal propagation characteristics in shallow estuaries and rivers may be altered by deeper or shallower water depths (caused by changes in sediment supply) and/or a higher sea level.

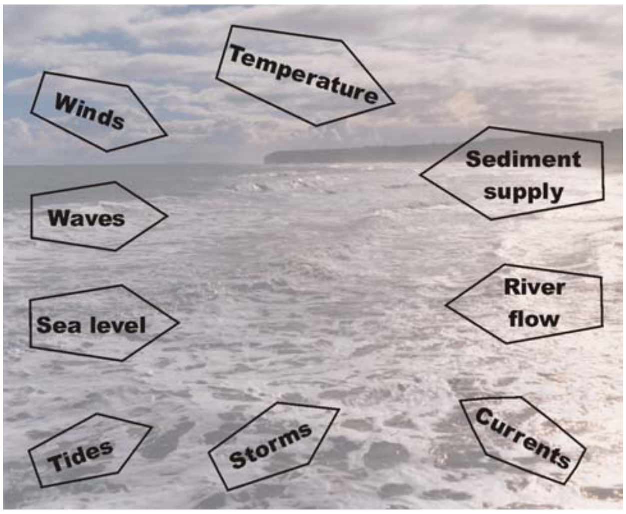


***Figure 5:** The key physical "drivers" or forcing agents that govern change in coastal and estuarine systems. Climate change will eventually affect all these drivers either directly or indirectly.*

Sediment supply can be affected by a myriad of catchment and ocean factors including:

- catchment geology and rainfall
- river flows
- frequency and magnitude of storms
- river controls (for example, dams, abstraction for irrigation)
- sand and gravel extraction for aggregate
- ocean wave climate
- prevailing winds
- alongshore currents
- the type of foreshore and its sedimentary composition.

The next section describes expected changes in some of these physical drivers as a result of global warming, based on historical data and future regional climate projections. Most is known about sea-level rise and temperature; we are less certain about other drivers of coastal change because of complex interactions between drivers and climate changes, and about specific regional variations compared to global or hemispheric averages.

- Climate change is any significant change or trend in climate, natural as well as human-induced, and includes global warming.
- Regional sea-level rise relative to the landmass is what will affect us locally, rather than the average global sea-level rise.
- Oceans are a vast heat reservoir, so that it will take centuries to cool and slow down sea-level rise, even if greenhouse gas emissions are curtailed immediately.
- Climate change – not just sea-level rise – will affect most physical drivers that shape coastal margins and ecosystems.

4 Climate Change Projections for Coastal Drivers

4.1 IPCC assessment process

Every five years since 1990 the Intergovernmental Panel on Climate Change (IPCC), established by the United Nations Environment Programme and the World Meteorological Organisation, has produced an assessment report on the state of global climate change. The main outputs of Working Group I of the IPCC are future climate projections on temperatures, greenhouse gas levels and sea-level rise, along with some general statements on the potential effects on El Niño cycles, extreme events, snow/ice melt, etc. Working Group II assesses the impacts of the projected climate changes on natural and human systems, and how humans can adapt to those changes. Working Group III reports on technological and social mitigation options to reduce future emissions of greenhouse gases, and their expected economic impact (for example, the implementation of the Kyoto Protocol).

The IPCC has developed procedures for the preparation, review and approval of its assessment reports aimed at guarding their objectivity and ensuring all relevant information is considered. Report preparation and review involves large numbers of scientific experts from most countries of the world. Two previous assessment reports were produced in 1990 and 1995. The Third Assessment Report (TAR) for Working Group I was released in Shanghai in January 2001 in the form of a Summary for Policymakers, followed by a more detailed Technical Summary and the full underlying report in June 2001 (IPCC, 2001a). The full report was compiled over 2½ years by 122 lead authors and 515 contributing authors, and subject to 420 reviewers. The draft Summary for Policymakers was adopted line by line at the Shanghai meeting by government officials and scientists from each country to reach a consensus document, with the agreement of the lead authors of the underlying report. The scientific process and questions that Working Group I of the IPCC worked through and then published as its contribution to the Third Assessment Report are summarised in Figure 6. Working Groups II and III went through a similar process to produce their Summaries for Policymakers, Technical Summaries and full underlying reports (IPCC, 2001b, 2001c).

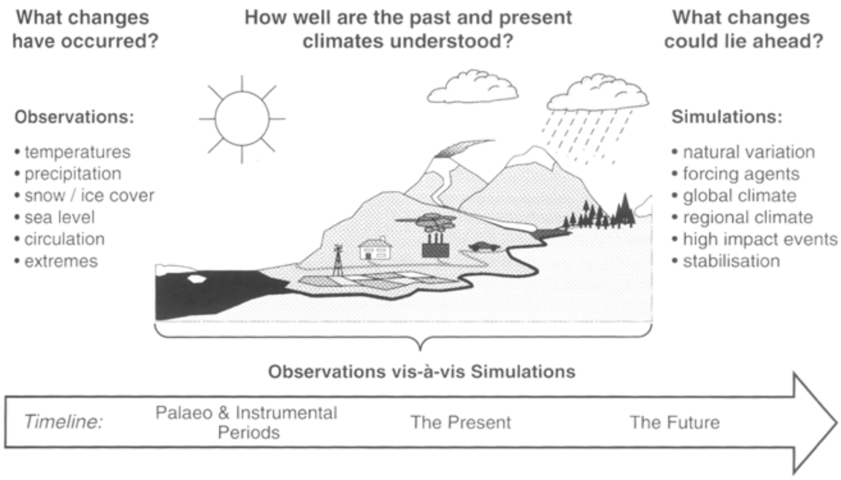


Figure 6: *Key questions posed by Working Group I of IPCC about the global climate system. IPCC (2001a) is a status or assessment report that addresses these questions via the approach outlined.*

Two of the main conclusions of the Third Assessment Report are worth quoting, as for the first time there is a relatively high degree of certainty expressed that human-induced global warming has been demonstrated and is projected to continue. In the previous 1995 Second Assessment Report, the IPCC concluded that "the balance of evidence suggests that there is a discernible human influence on global climate". Since then the evidence has become much stronger, based on the recent record global warmth in the late 1990s, the improved paleo-record (for example, ice cores, tree rings) that provides a longer context, improved modelling and simulation of the past climate, and improved statistical analysis. Thus the headline conclusions of the 2001 Third Assessment Report are:

> There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.
>
> Global average temperature and sea level are projected to rise under all IPCC 'Special Report on Emission Scenarios' or SRES scenarios.
>
> [The SRES scenarios cover a gambit of possible socioeconomic factors including energy use, population growth, technological advances and environmental concerns.]
>
> *Summary for Policymakers (IPCC, 2001a)*

A recent report in June 2001 by the US National Academy of Sciences, commissioned by the White House, has also come out in support of the main conclusions of the 2001 IPCC Third Assessment Report (National Academy of Sciences, 2001).

Because of lag effects, particularly in the ocean, it may take some time for the effects of global warming, such as acceleration in sea-level rise, to filter through. However, the IPCC prognosis is for long-lasting effects in sea-level rise well beyond the 21st century. The take-home messages are that:

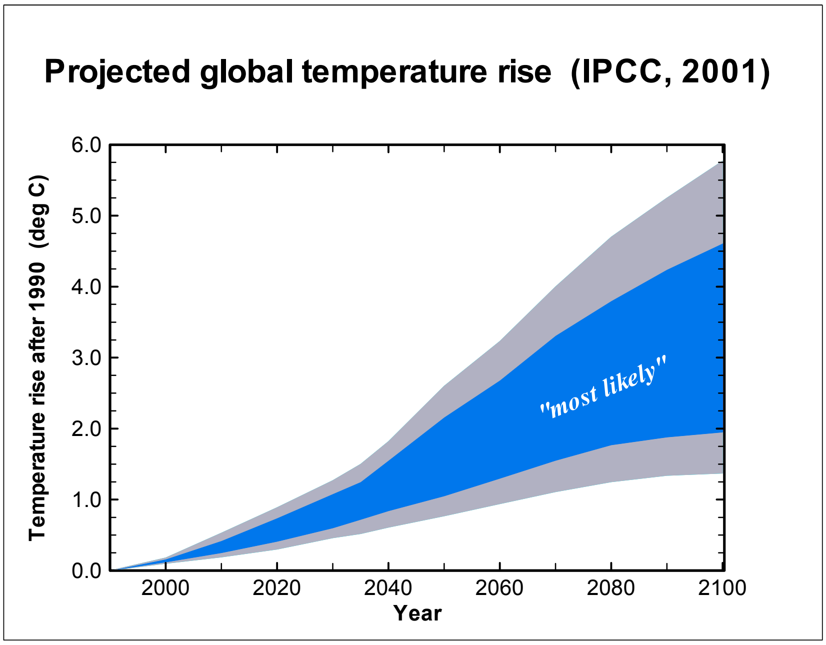
- general agreement has been reached that global warming and accompanying sea-level rise is already a reality
- there will be lingering effects of a sea-level rise for several centuries, even if greenhouse gas concentrations were to be stabilised within this century.

4.2 IPCC climate projections

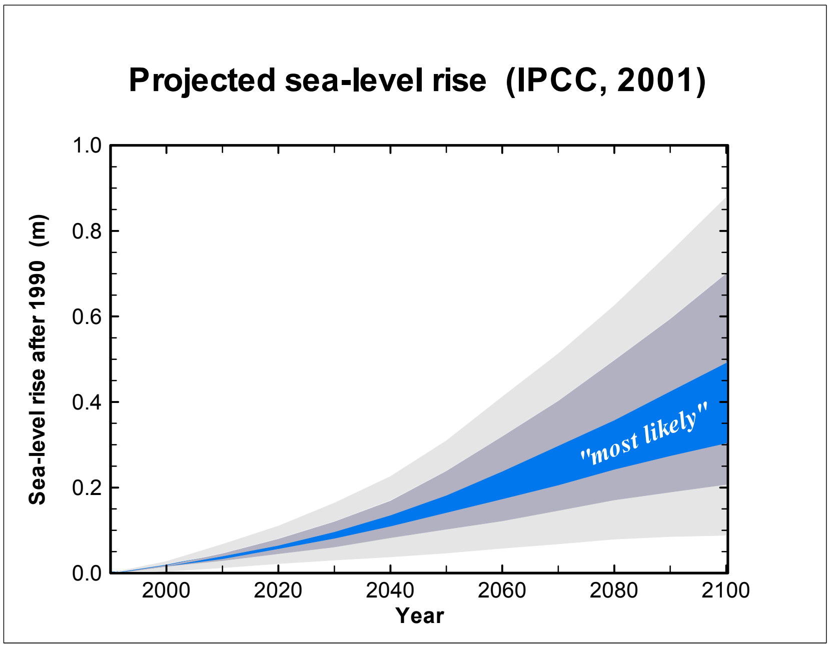
Based on a good match of climate-ocean models with historical data, these same models are then used to generate forward projections at least 100 years ahead using a range of greenhouse gas emission scenarios. The models provide a means to estimate the response of key climate variables, such as global temperature and sea level, to various scenarios of climate forcing, such as fossil-fuel emission rates, other greenhouse gases such as methane, population growth, and economic growth.

Figure 7 shows the various envelopes for *global* temperature and sea-level rise produced by the IPCC in its Third Assessment Report. The darker middle envelope covers the average projections of several climate models for a range of emission scenarios, which we have called the 'most likely' zone in this report. The lightest outer zones for sea level cover the upper and lower range of uncertainty in individual model projections for all the emission scenarios that were evaluated by the IPCC, and include a component of land-ice melt uncertainty.

__Figure 7:__ IPCC (2001a) climate model projections up to 2100 for: (UPPER) global mean air temperature rise, and (LOWER) global mean sea-level rise, both relative to 1990 levels. The "most-likely" zone shows the range of the average of seven ocean-climate model simulations for each of 35 socio-economic/ emission scenarios. The adjacent medium-shaded regions show the range of all seven models for all 35 scenarios. The outer light-shaded zones for sea level show the range of all models and scenarios including uncertainty in land-ice changes,



permafrost changes (e.g., thawing) and sediment deposition, but excludes changes in the Antarctic ice sheet.



4.3 Regional climate change projections

IPCC reports contain projections for *globally averaged climate* change, but it is strongly acknowledged that the range in *regional variation* of climate and ocean response could be substantial. There may be large local and regional departures from the global climate change predictions, which can either reduce or exaggerate the impact of climate change in different parts of the world.

The process of translating IPCC global predictions to likely regional climate and coastal responses is a difficult technical and socioeconomic exercise. It includes making sure that the level of resources that regional and national agencies should put towards this is commensurate with the likely effects on regional environments, communities and economies. The translation process is achieved technically by running more detailed climate prediction models at regional scales (called downscaling), with input from global general circulation models (GCMs) linking the atmosphere with the ocean. But the results must be interpreted in the context of an understanding of New Zealand's climate and historical trends evident in monitoring data.

Figure 8 summarises in schematic form the climate projections for the 2080s in different regions of New Zealand.[2] A collaborative programme called CLIMPACTS also produces climate projections throughout the 21st century for New Zealand, focusing on likely climate effects on primary production sectors.[3] Regional and local climate projections are generally less certain than global average predictions because of the extra layer of complexity that local terrain adds, and because of the limited

2 See also web site: http://katipo.niwa.cri.nz/ClimateFuture/Scenarios.htm

3 Web site: http://www.waikato.ac.nz/igci/climpacts_webpage/index.htm

spatial resolution of global climate models. As a result, global climate models may produce different regional climate projections even if they agree in their global average projections. Evaluation of the impact of climate change on any given region must therefore again adopt a scenario approach, that is, evaluate a range of plausible future changes.

In summary, New Zealand's climate in the 2080s is likely to have the following features if greenhouse gas emissions continue to increase (MfE, 2001).[2]

- *Winds:* overall there will be more winds from a westerly and southwesterly direction across the country (more El Niño-like), with more north to north-east winds for Wellington and Canterbury. This wind pattern arises because the temperate and tropical regions will warm up faster than the Southern Ocean regions.
- *Rainfall:* there is likely to be more average rainfall on the west coasts and central high country of both islands, but less rain in the east (Canterbury, Hawke's Bay and Poverty Bay). The changes in rainfall patterns are expected to be stronger during winter than during summer.
- *Temperature*: there will be higher *mean* temperatures everywhere, with a higher increase in winter (northern: +2.0 to 2.2°C; central: +1.8 to 2.1°C; southern: +1.6 to 1.8°C) than in summer (northern: +1.6 to 1.8°C; central: +1.4 to 1.6°C; southern: +1.0 to 1.3°C). These are on the lower side of the most likely projected global average temperature rise of 1.8 to 3.8°C by 2080. Surface seawater temperatures in inshore waters and estuaries will also rise, but not quite to the same extent as air temperatures, due to the moderating and lag effect of a slower rise in ocean temperatures.
- *Storms and extreme events:* estimates of likely changes in regional climate extremes are even less certain than projections of average conditions. The frequency of extreme storms is unlikely to change significantly, but genesis areas and tracks for tropical cyclones in the South Pacific may vary more between El Niño and La Niña years and with warmer local oceanic temperatures in the 'breeding' grounds of the tropics (Basher and Zheng, 1995). The more El Niño-like mean state of the tropical Pacific may lead to changes in the location-specific frequency of tropical cyclones in the Pacific. What is reasonably clear is that storms are likely to be accompanied by heavier rainfall intensity in a warming world, because a warmer atmosphere can hold a higher moisture content. The intensity of wind in extra-tropical cyclones could increase with global warming, but there is little agreement between current climate models on whether the intensity of mid-latitude storms will increase. Changes in storm intensity, if they do occur, will affect sediment loads delivered to the coast from both offshore and from rivers, and coastal flooding.
- *Sea-level rise*: projected sea-level rise around New Zealand is expected to match the global projections of 0.25 to 0.36 m by 2080, except in areas where significant vertical landmass movements exaggerate or mitigate the absolute rise in sea level.

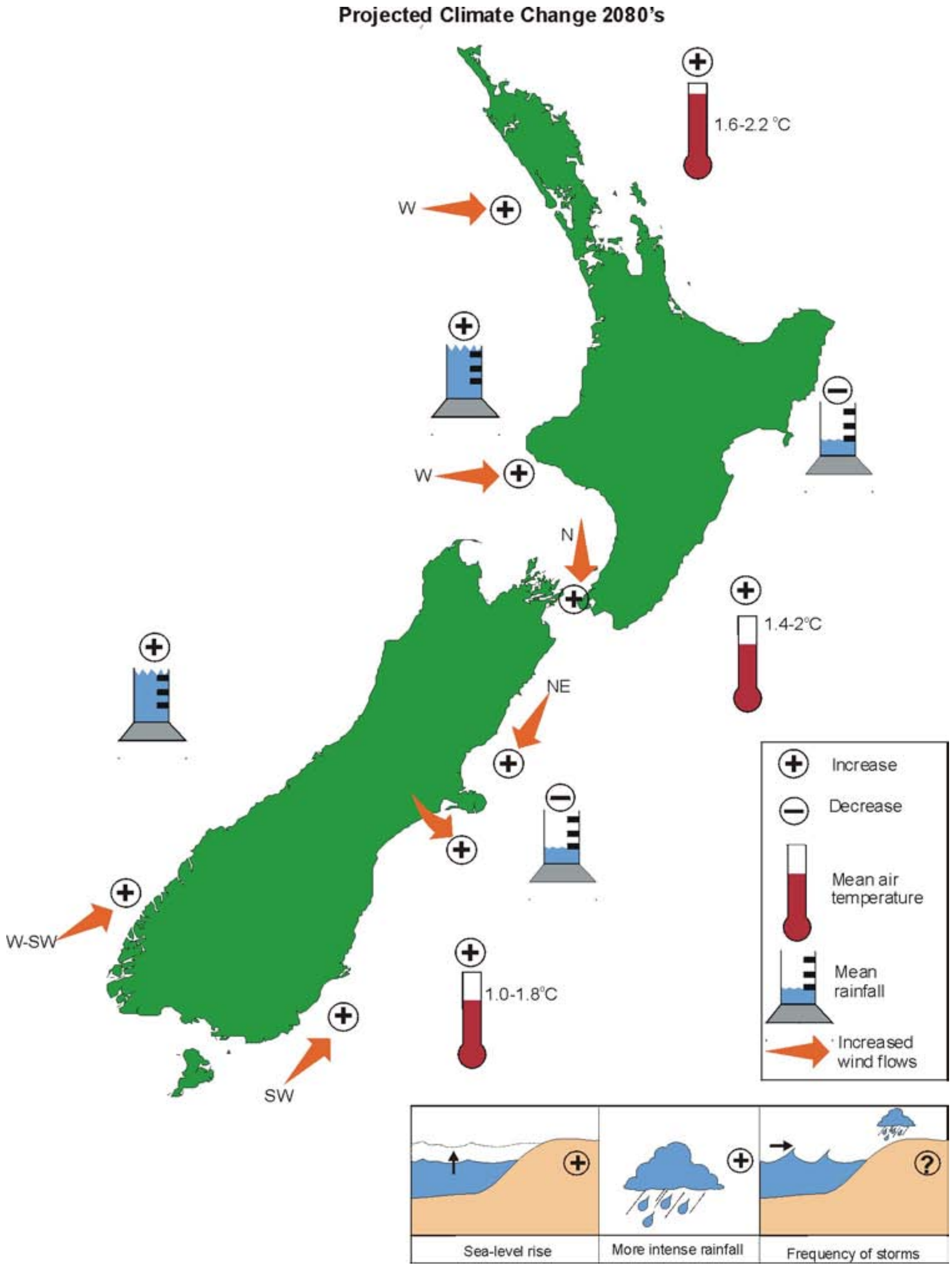


Figure 8: *Schematic of projected changes in regional climates around New Zealand by the 2080s, that have the potential to modify coastal "drivers" and cause impacts on coastal margins. Derived by NIWA from statistical downscaling of global climate model runs (MfE, 2001).* [Graphics: K MacLeod]

As a rule, the overall trends in climate variables on regional scales are considered to be more robust (for example, an overall increase in temperatures and sea level for New Zealand, or a broad shift in rainfall patterns towards less rain in the east and more in the west), than any absolute projections (such as a statement like "there is likely to be 20% more rainfall in region X").

4.4 Role of monitoring

The global-to-regional translation process that downscales climate projections must be backed up by sufficient long-term regional monitoring of key climate and ocean parameters. Such targeted monitoring has three essential uses:

- to calibrate or verify regional climate-ocean models
- to provide more in-depth knowledge and understanding of how regional climates and oceans behave or are likely to respond to patterns of global climate change
- to compare with ongoing IPCC global projections and work back to check the translation process from global to regional climate change.

CASE STUDY 1: Sea-level and Climate Monitoring

An example of climate change monitoring is the network of 11 open-coast sea-level gauges (Figure 9) co-ordinated by NIWA, with support from some regional and district councils, the University of Canterbury, Land Information NZ, Department of Conservation and the Australian National Tidal Facility (Adelaide). These gauges were all deliberately positioned around the open coast, spanning the entire coast, but their recent installation (apart from Moturiki) means the records are too short at this stage to make any assessment on New Zealand-wide relative sea-level rise. In time, they will complement the much longer gauge records from the four main ports (back to 1900), even though sea-level inside ports is modified by harbour entrances, river floods, port dredging and possible instability of the gauge site.

NIWA also co-ordinates the archiving and analysis of a long-term climate database. The data originate from meteorological sites managed by the NZ Meteorological Service around New Zealand, territorial and regional councils, universities, government departments, Crown research institutes, private companies and individuals (see web site: http://katipo.niwa.cri.nz/www_cli.htm). These databases will provide a sound basis

Figure 9: *Open-coast sea-level network of 11 gauges co-ordinated by NIWA. Most sites commenced monitoring from 1997–98, but Moturiki has been recording since 1973.*

4.5 Sea-level rise around New Zealand

Over the past century *global* sea level has been rising at an average rate of 1.8 mm per year. That does not sound much, but it is nearly 0.2 m since 1900, which has been significant for low-lying coastal margins and gently sloping beaches. Analysis of *relative* sea-level trends at New Zealand's major ports since 1900 has produced similar rates of 1.7 ± 0.4 mm per year (Bell *et al*., 2000; 2001b). Given the similarity of global and relative rates of rise, this means that the local landmass is relatively stable at the four main ports.

New Zealand's most accurate long record is from the Port of Auckland. Annual means of sea level from the port since 1899 are plotted in Figure 10, along with the historical trend (1.4 mm per year). These historical data are then blended with the projected IPCC (2001a) sea-level rise envelopes out to 2100 to provide the context. By the end of this century (2100), it is likely that sea-level rise around New Zealand will have more than doubled (over 0.4 m) compared with the 0.2 m rise experienced last century (Figure 10).

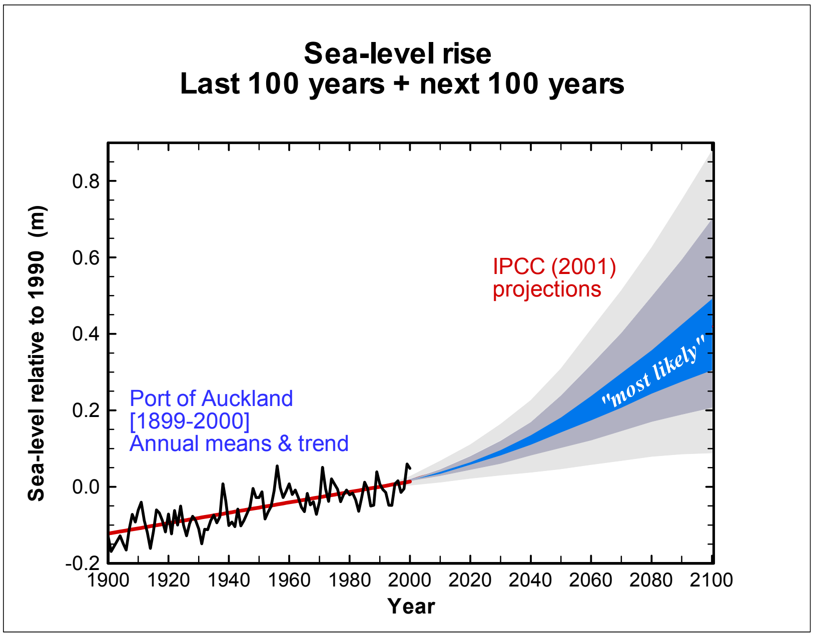


***Figure 10:** The relative sea-level trend for Auckland since 1899 and the annual variability in mean sea level (Hannah, 1990; Bell et al., 2001) is spliced with the predicted IPCC (2001) projections in "global" sea-level rise up to 2100. The middle "most likely" zone spans the range of average estimates produced by a range of climate-ocean models. The least likely estimates (high and low) are the lightest-coloured zones. Note: Sea level has been plotted relative to the 1990 values (which for Auckland is 1.840 m above gauge datum).*

What has caused this rise?

This rise has been caused by a variety of factors, but mainly thermal expansion from higher global air temperatures caused by 'natural' long-term cycles in climate and radiation from the sun, compounded increasingly by greenhouse-related global warming. As water heats up, it expands in volume (recall those boil-overs of the car radiator?). Seawater will expand vertically because it is constrained horizontally by landmasses. Minor contributions have come from melting of glaciers and small ice caps (but so far not the large polar ice sheets). No apparent acceleration in sea-level rise has been detected so far around New Zealand. There is also no evidence globally for an acceleration of sea-level rise during the last century, nor would any necessarily be expected from the observed climate change to date (IPCC, 2001a), because it is masked by the larger annual and decadal variability in sea level, such as El Niño and La Niña effects (see Figure 10). Detection of an acceleration of the rising trend in sea level from tide gauges and satellite measurements may take another few decades to confirm.

Relative sea-level projections for New Zealand

Translating long-term global-average projections from IPCC (2001a) to what is likely to occur along the New Zealand coast is complicated by landmass instability and any regional effects on the absolute rise in sea level caused by changes in ocean currents and wind patterns. Any local landmass uplift will lead to a smaller magnitude of relative sea-level rise at that locality, compared to the absolute sea-level rise, while subsidence will lead to a higher relative sea-level rise. As a result, three main factors need to be considered in assessing the relative rise in sea level.

(1) Gradual deformation

Different parts of the New Zealand landmass are undergoing slow vertical deformation, or 'creep'. The causes are glacial isostatic adjustment, tectonic uplift due to the subduction of the Pacific Plate underneath the Australian Plate (Barnes and Lewis, 1996), and gradual subsidence from historical sediment loading of plains and coastal basins. Parts of New Zealand, mainly the lower South Island, are probably still rising slightly as an after-effect of the removal of glacial ice-caps since the last ice age. The rate of glacial isostatic uplift is uncertain (difficult to measure), and likely to be heavily masked by tectonic and earthquake activity. One estimate using a global crustal-deformation model developed by Peltier (2001) is 4 to 5 cm per century (or –0.4 to –0.5 mm/yr) for New Zealand (negative because uplift reduces the relative rise in sea level). However, because isostatic adjustment is difficult to distinguish, and likely to be small compared to the expected overall rise in sea levels, it could be disregarded until future, more accurate data suggest otherwise.

Maps summarising *average* tectonic uplift and subsidence are available for the North and South Islands after the work by Pillans and Wellman respectively, which is summarised by a diagram in Hicks (1990; Figure 8.2). Other coastal margins in Canterbury and the South Taranaki Bight have experienced minor subsidence from eons of sediment loading on the plains and adjacent coastal basins. For example, estimates of subsidence along the Mid to North Canterbury coastline are +0.1 to +0.2 mm/year according to a 1979 study by Wellman, reproduced in Hicks (1990), but this is again small compared with the current global sea-level rise of 1.8 mm/year.

In most places the average rates of gradual uplift or subsidence are small, and it is also not clear whether any past uplift or subsidence occurred suddenly (seismically) or slowly. There are major information gaps and uncertainties in the landmass stability information pertaining specifically to coastal margins, which are outlined in Appendix A.

(2) Seismic deformation

Earthquakes can result in sudden large local changes in land elevation. Berryman and Beanland (1988) have summarised tectonic activity around New Zealand. Local coastal response to sudden vertical movements accompanying the 1931 Hawke's Bay and 1987 Edgecumbe earthquakes are described in Case Study 5. Some localities suddenly subsided by +0.7 m (effectively a sudden sea-level rise), while other coastal areas have experienced sudden uplift, reclaiming land from the sea (for example, –1.8 m at Westshore, Napier). Such tectonic changes can over a short time frame have a much larger local impact on relative sea level than the gradual sea-level rise expected from global warming.

(3) Regional variations in absolute sea level

Regional differences in oceanic currents and the ocean response to climate change around New Zealand and the southwest Pacific will produce regional differences in absolute sea level that depart from the global average rise predicted by IPCC (2001a). In particular, regional sea-level variability associated with the two- to five-year El Niño–Southern Oscillation and the 20- to 30-year Interdecadal Pacific Oscillation (both evident in Figure 11) may cause differences from the global average rise in sea level. Not enough is known about the magnitude of these differences to provide regional New Zealand projections, but satellite data, meshed with ongoing monitoring of open-coast sea level (Case Study 1), will progressively shed more light on any systematic regional departures from the global average rise.

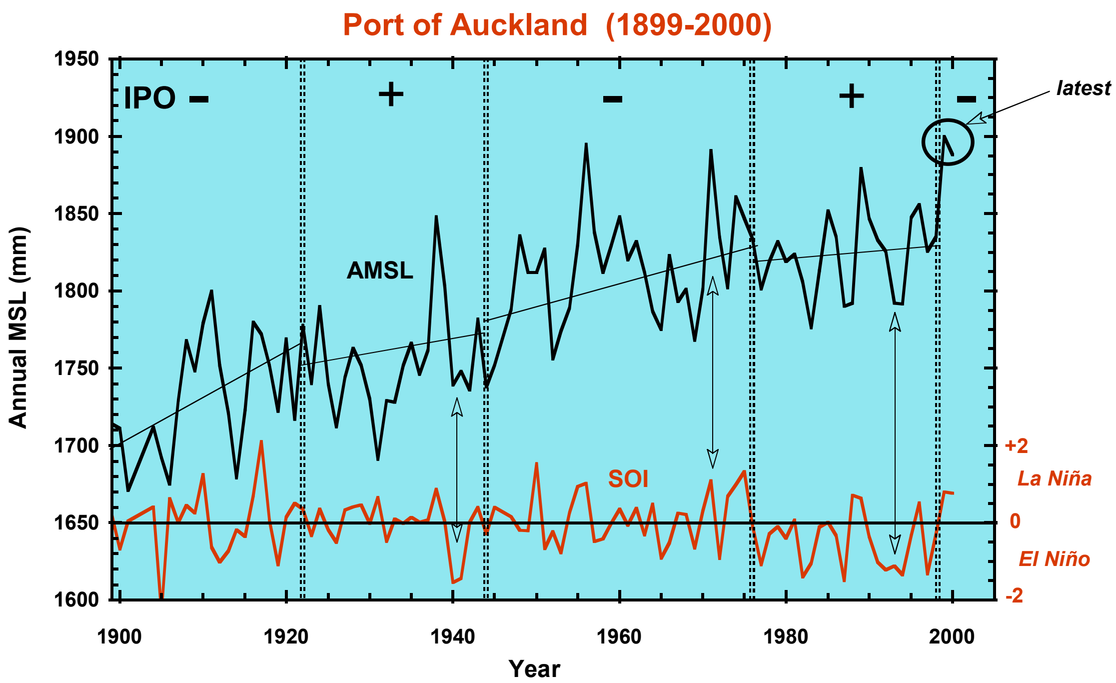


Figure 11: *Annual mean sea-level (AMSL) for the Port of Auckland since 1899 and the annual mean Southern Oscillation Index (SOI). The transitions between phases of the Interdecadal Pacific Oscillation (IPO) are marked by vertical dotted lines. During El Niño events (SOI is negative), sea level is lower than normal, and vice versa for La Niña events. During the negative phase of the longer 20–30 year IPO episodes, sea level rises more steeply compared with episodes when the IPO is positive.* [Data sources: Hannah (1990); Bell et al. (2001a); Ports of Auckland Ltd.; RNZN Hydrographic Office.]

Considering all these factors (and their uncertainty), together with the observation that all four historical sea-level gauges in New Zealand show a rising trend in relative sea-level rise for the 20^{th} century (average +1.7 ± 0.4 mm/year) that is broadly consistent with the global average to date (+1.8 mm/yr), suggests that there seems little practical justification for making any local or regional uplift/subsidence corrections to global projections within the next century, or until more accurate information becomes available on landmass stability.

Therefore, in summary, the 'most likely' band in Figure 10 produced by the IPCC for the global average rise in sea levels is currently also the best estimate of sea-level rise for New Zealand over the next 100 years. The specific projections are listed in Table 1, and compared with the present New Zealand rate if it were to continue without any acceleration.

Table 1: A comparison of projections of future sea-level rises for different scenarios

Scenario	Climate factors	SLR by 2050 (m)	SLR by 2100 (m)
Average linear New Zealand trend continues (+1.7 mm/yr)	Sea-level trend over the 1900s continues	0.09	0.17
IPCC (TAR, 2001) 'Most-likely' mid-range	Average of climate models and socioeconomic greenhouse gas emission scenarios	0.14–0.18	0.31–0.49
IPCC (TAR, 2001) Uncertainty ranges	Intermediate zones Upper and lower limits of entire range of IPCC projections	0.10–0.24 0.05–0.31	0.21–0.70 0.09–0.88

Note: 'Most-likely' projections and uncertainty ranges (Figure 10) for future global sea-level rise (SLR) by 2050 and 2100 are from IPCC (2001), compared with a continuance of the New Zealand-average rise in *relative* sea level from 1900s with no acceleration. Suggested 'most-likely' SLR projections to work with are shaded.

4.6 Dynamic sea-level variability

Existing patterns of short- to medium-term variations in local sea level could be altered by long-term climate change. It is therefore important to be aware of and understand these existing patterns. Alteration of those patterns could occur through changes to the mechanisms generating storm surges, seasonal, interannual (year-to-year) variability and interdecadal (decade-to-decade) variability.

CASE STUDY 2: Measurements of Dynamic Sea-level Variability

Recorded sea-level data at Tauranga, Moturiki and Port of Auckland has shown the following.

- Storm surges around New Zealand appear to have had an upper limit of around 1 m above the predicted tide (excluding surf zone wave set-up and run-up), with the highest recorded being 0.9 m at Port of Tauranga during the 'Wahine' storm in 1968 (Bell *et al.,* 2000). Severe storms usually generate storm surges of 0.5 to 0.7 m.
- The El Niño–Southern Oscillation system governs interannual variations in sea level around New Zealand, being *lower* than normal during El Niño episodes and

higher than normal during La Niña episodes (Figure 11). This variability can be up to ± 0.15 m, which is significantly higher than seasonal winter-to-summer variations of ± 0.05 m.

- Long 20- to 30-year cycles arise from the Pacific-wide Interdecadal Pacific Oscillation (IPO), and can be seen in the Port of Auckland record (Figure 11). It appears that the Pacific entered a new negative phase of the IPO in 1998 (Salinger *et al.*, in press). This means that, for the next few decades, sea level around New Zealand is likely to rise faster than the long-term trend, and already 1999 has seen the highest annual sea level on record at Auckland (Figure 11). We have left behind a positive phase in the IPO (begun 1976), where El Niño episodes dominated, but the new phase is likely to see more of a balance between El Niño and La Niña episodes.

Why are the dynamic sea-level variations shown in Case Study 2 so important? Firstly, any short-term (24 hours to months) or medium-term (1 to 30 years) increase of mean sea level enables drivers such as waves, winds, currents and tides to attack further up shoreline slopes on the coast or in estuaries. Long-term sea-level rise will further compound this effect by elevating them higher still. Secondly, even small modifications to any of these drivers or sea-level cycles by greenhouse-related changes could cause higher than expected storm surges, especially when medium-term sea levels are elevated over certain periods of years. Highest medium-term (1 to 30-year) sea levels occur with a combination of a La Niña cycle during a negative phase of the IPO, which is the current 1999–2001 situation (Bell *et al.*, 2001b).

At this stage changes in regional climate (see Section 4.3) indicate that only general wind patterns will change (there will be more westerlies), but it is uncertain whether El Niño or La Niña magnitudes and the frequency of extreme storms could change significantly by the 2080s. However, rainfall intensity during storms will probably increase by this time, which could exacerbate lowland river and estuary flooding at times of high tides and higher than normal mean sea level. More intense rainfall may, depending on catchment land use, deliver larger ‘slugs’ or doses of sediment to estuaries. This could produce increased siltation of muds and silts, and intertidal flats, in the upper reaches of estuaries with the risk of smothering bottom-dwelling animals and plants.

4.7 Temperature rise

Substantial increases in mean air temperature of up to +2.0 to +2.2°C (northern New Zealand) and +1.6 to +1.8°C (southern New Zealand) in winter are projected to occur by the 2080s, while increases in mean summer temperatures will be somewhat less. This will translate into a temperature rise in shallow estuarine waters and salt marshes or wetlands, but less than the air temperature increase. How much will depend on the water depth and the degree of flushing with coastal water, which will continue to be moderated by a much more slowly warming ocean and any changes in upwelling[4] of cooler deep ocean water by changes in wind patterns. It also means that with

4 Upwelling of cooler bottom waters on the continental shelf occurs during favourable offshore winds or shore-parallel winds with the shoreline on the right; e.g., NE winds down the east coast of the South Island.

increased mean winter temperature, the current trend of a reduction of frost-nights will continue. Air and sea temperature changes will have major implications for coastal and estuarine ecosystem and fringing plant communities.

4.8 Sediment supply

Sediment supply incorporates several physical drivers that can alter the supply and subsequent availability or mobility of sediments (gravel, sand, shell, silt) to the open coast and estuaries or harbours. Open-coast beaches in particular are often sensitive to small changes in sand supply, which means any small climate change effect on the drivers (winds, waves, river flow, currents, sea-level rise) could pose problems for beaches that are presently eroding or are dynamically stable.

CASE STUDY 3: Pegasus Bay shoreline response

Pegasus Bay comprises 30 km of coastline north of Christchurch. It receives around 1 million cubic metres of sand-grade material per year, mainly from the Waimakariri River. The southern end of the bay is sheltered from southerly waves by Banks Peninsula and so receives most wave activity from the northeast, whereas the northern end of the bay is more exposed to the south as the wave shadow effect of Banks Peninsula diminishes. Approximately 50% of the Waimakariri River sand moves south, resulting in accretion of the southern beaches, while the other 50% goes north, but does not linger, being mobilised by the northerly littoral drift fuelled by the southerly swells. Presently, the Waimakariri River has built an elongated delta, with a planform shape in equilibrium with the present wave and wind climates and sediment supply.

Regional climate projections to the 2080s indicate a drier Canterbury Plains, with reduced freshwater runoff apart from heavy rainfall periods in the high country, and higher demands on water for irrigation. However, different rivers along the Canterbury Plains would be affected by these changes to different degrees. Rivers whose catchments lie in the Main Divide may in fact see increased rainfall in their catchment area, while smaller rivers originating in the foothills of the Southern Alps may experience decreases.

Overall, less water in rivers would mean less sediment supply to the coast. Computer modelling of shoreline change (Figure 12) indicates the bulge in the Pegasus Bay shoreline would flatten out in such a case, resulting in erosion of the shoreline to the south of the river. Erosion in the north of the bay will continue. If the wave climate were to change and bring more northeasterly waves and fewer southerly swells, then the shape of the coastline bulge (sediment) will skew towards the south, with increased erosion to the north. A major drop in sand export from the river would cause localised erosion either side of the mouth (Figure 12).

Importantly, these local responses in shoreline to wave climate and sand supply are likely to be larger than a direct landward translation of the shoreline in response to just a rising sea-level. This example illustrates the need to address both coastal and catchment processes, and to understand, address and solve complex local coastal issues in the context of climate change.

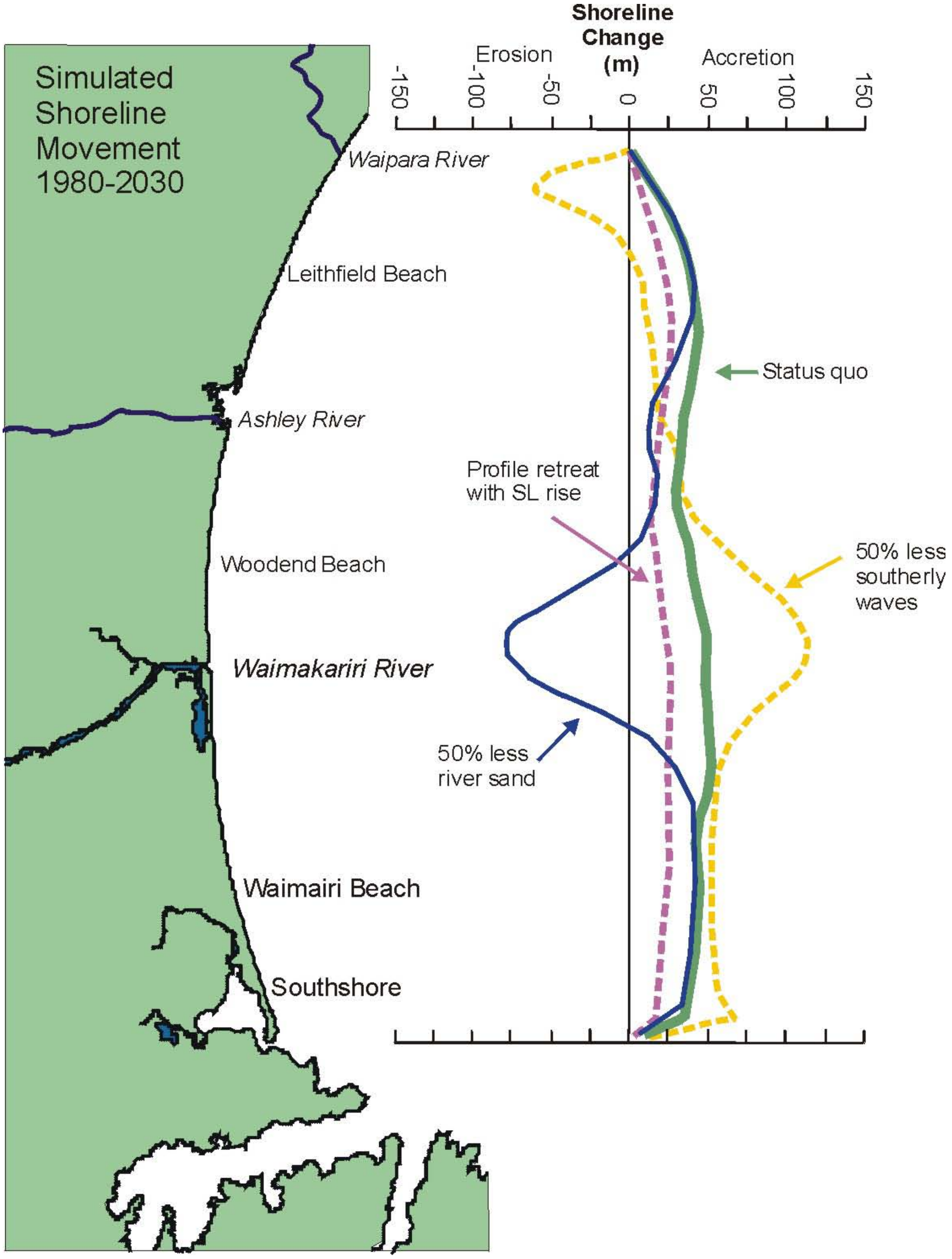


***Figure 12:** Shoreline modelling results using GENESIS to isolate the effect of changing various "drivers" on shoreline movement in Pegasus Bay (North Canterbury) compared with the status quo for the period 1980–2030.* [Graphics: K MacLeod]

- **“There is new and stronger evidence that most of the global warming observed over the last 50 years is attributable to human activities” (IPCC, 2001a).**
- **Relative sea-level rise in New Zealand is most likely to be 0.14–0.18 m by 2050 and 0.31–0.49 m by 2100.**
- **Regional climate projections for 2080s are:**
  - **mean air temperatures will rise by 1.6–2.2°C in winter (less in summer), which will increase estuary and coastal water temperatures**
  - **extreme storms are unlikely to be more frequent, but especially rainfall may be more intense.**
  - **“Sediment supply” to the coast will be affected in several ways by climate change**

5 Climate Change Impacts on Coastal Margins

A comprehensive review of climate change impacts on New Zealand's coast and estuaries was undertaken in 1990 by the Ministry for the Environment (Hicks, 1990; Burns *et al.,* 1990). Much of this information is still relevant today, apart from the magnitudes of climate change projected at that time and a much greater certainty that climate change is a reality. Overall projections of climate change and their relevance for New Zealand were updated by the Ministry for the Environment and New Zealand Climate Change Programme in 2001 (MfE, 2001).

Sea-level rise in itself will obviously cause many of the impacts unique to coastal margins, but other drivers affected by climate change – such as river flows, winds, waves, storm intensity and perhaps frequency – will create their own impacts besides exaggerating or mitigating the impacts of sea-level rise. For coastal and estuarine aquatic ecosystems, changes in water temperatures – caused by changes in ocean currents, winds, upwelling, and air temperature – will cause biological impacts of similar significance to the physical changes caused by sea-level rise.

The range of impacts unique to coastal margins is summarised in Figure 13 and Table 2. The impacts of sea-level rise will vary by location and depend on a range of physical/biological characteristics and socioeconomic factors, including the human response. The primary impacts of sea-level rise will be physical changes to the environment. These changes, in turn, affect human uses of the coast such as tourism, settlement, shipping, commercial and recreational fishing, shellfish gathering, agriculture, and wildlife viewing.

The most serious physical impacts of climate change on coastal margins will be:

- coastal inundation, causing landward displacement of estuaries, wetlands and marshes
- coastal erosion and shoreline change through sediment movement
- increased vulnerability to coastal storm damage and episodic flooding
- increased difficulty draining coastal and river lowlands
- surface water, river water and groundwater in lowlands becoming increasingly saltier from seawater intrusion.

The primary ecological impacts will stem from a rise in temperature (air and water), inundation, and loss of habitat from increased sedimentation of muds/silts on intertidal areas in some areas, and loss of intertidal areas where shoreline protection prevents the sea moving further inland.

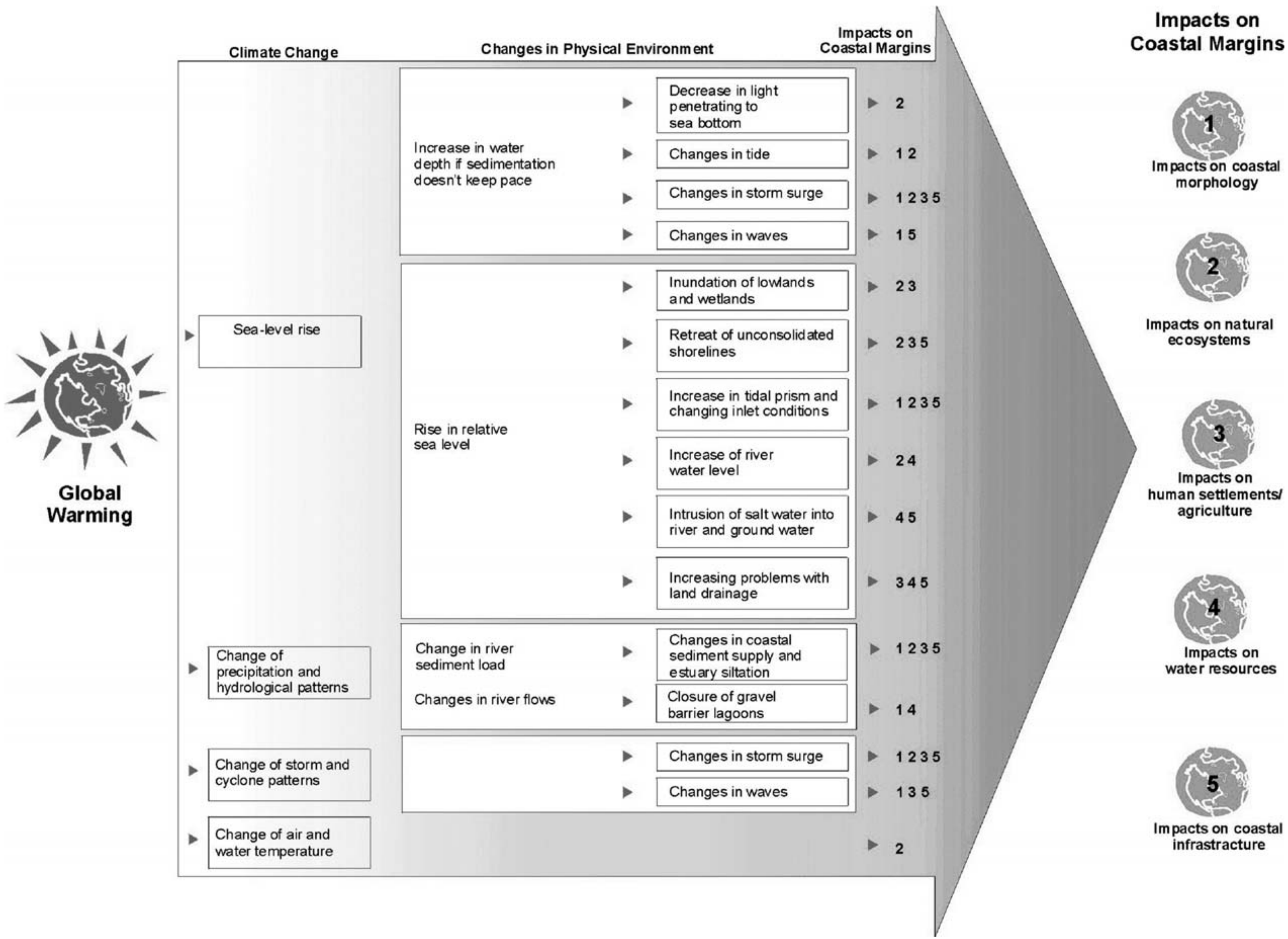


Figure 13: *Summary of changes and impacts for coastal margins as a result of global warming.* [Adapted from CGER, 1996]

Table 2: Potential impacts of climate change and sea-level rise on coastal margins

Biophysical impacts can include: • increased coastal erosion • inhibition of primary production processes • more extensive coastal inundation • higher storm-surge flooding • landward intrusion of seawater in estuaries and aquifers • changes in surface water quality and groundwater characteristics • changes in the distribution of pathogenic micro-organisms • higher sea-surface temperatures.
Related socioeconomic impacts can include: • increased loss of property • increased flood risk and potential loss of life • damage to coastal protection works and other infrastructure • increased disease risk • loss of renewable and subsistence resources • loss of tourism, recreation, and transportation functions • loss of non-monetary cultural resources and values • impacts on agriculture and aquaculture through decline in soil and water quality.

Source: IPCC, 2001b.

5.1 Sea-level rise impacts

There is often confusion over the difference between erosion and inundation under a rising sea level, because both cause a loss of land from the coastal margin. Erosion involves the physical removal or export of sediment from the beach or shoreline by waves and currents, and therefore physical change in the coastline structure. Inundation, by contrast, is merely the permanent intertidal submergence of low-lying land or marsh and doesn't involve sediment movement (Leatherman, 2001). However inundation may facilitate erosion.

Coastal flooding and inundation

A rising mean sea level will initially cause more frequent coastal flooding of peripheral areas of coastal margins by extreme tides and storm surge by the mechanisms shown in Figure 14. Even if storm frequency and intensity remain similar to present-day levels and tides are unchanged, an overall rise in the mean sea level will substantially increase the probability of a given land mark or level being exceeded, and hence causing more damage to housing and infrastructure. For example, using the Moturiki sea-level gauge tidal record, a land level or stopbank height that is currently exceeded by only 0.01% of high tides (or 1 in 14 years) will, under a 0.3 m and 0.4 m rise in sea level, be exceeded by 5% and 9% of high tides respectively (MfE, 2001). Permanent tidal inundation of low-lying coastal margins will progressively take place, on the back of a rise in sea level, as extreme high tides routinely reach margins previously only flooded during storms. However, in some estuary catchments prone to future increased sediment supply, inundation will be slower as sediment build-up around the estuary margins could act to counteract sea-level rise.

On undeveloped coastal margins, the landward migration of an inundated shoreline under a rising sea level depends on the slope of the fringing land, as shown in Figure 15. Shorelines may move much further inland at very gently-sloping fringing areas around some estuaries or river mouths, while cliffed coastlines will only migrate landwards by slow erosion rather than inundation, probably at no faster rate than at present (unless there is more active notch cutting by waves at the base of the cliff).

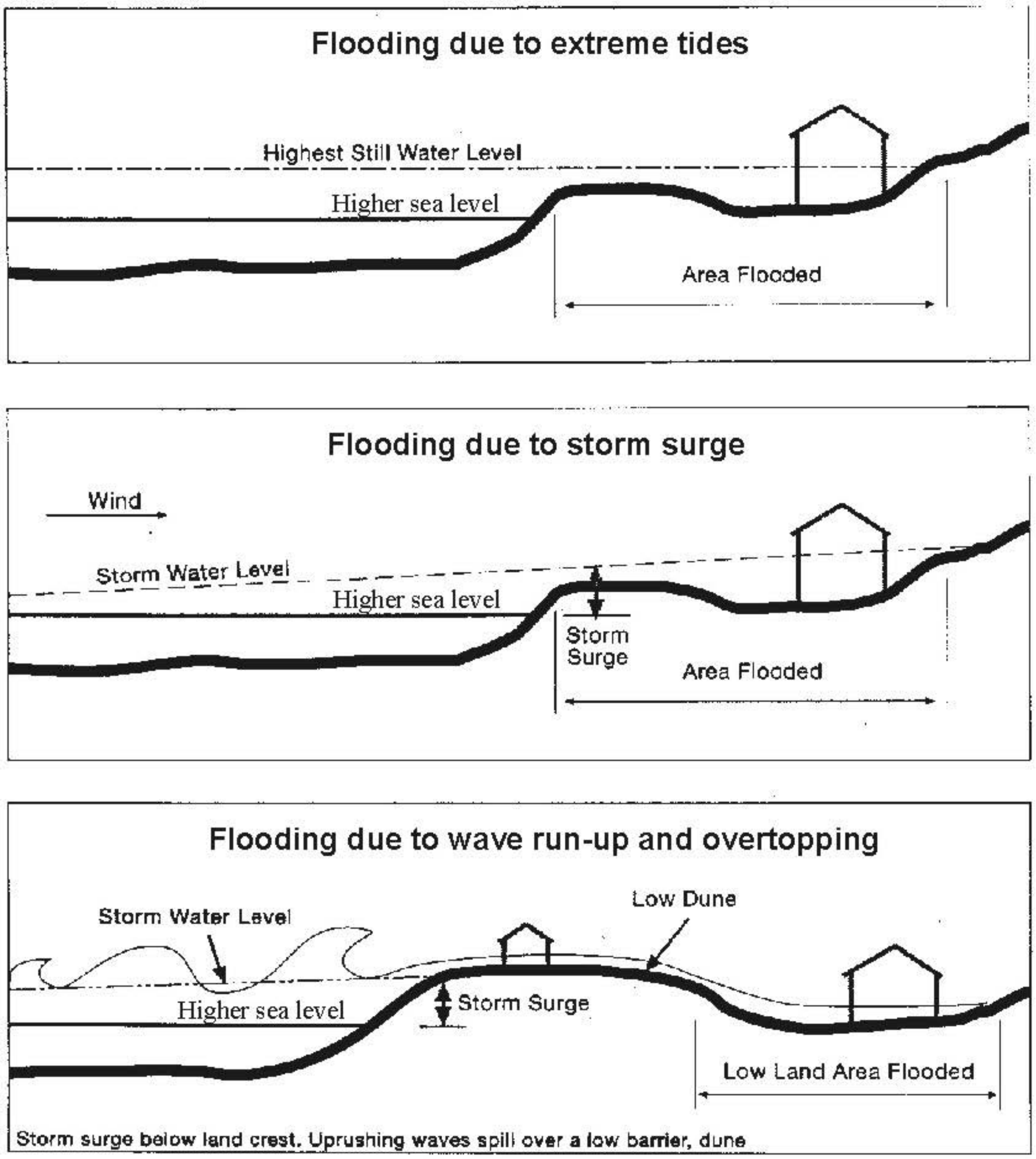


Figure 14: *Mechanisms of coastal flooding by extreme tides, storm surges and wave run-up and overtopping for a higher mean sea level (not to scale).* [Adapted from Keillor, 1998]

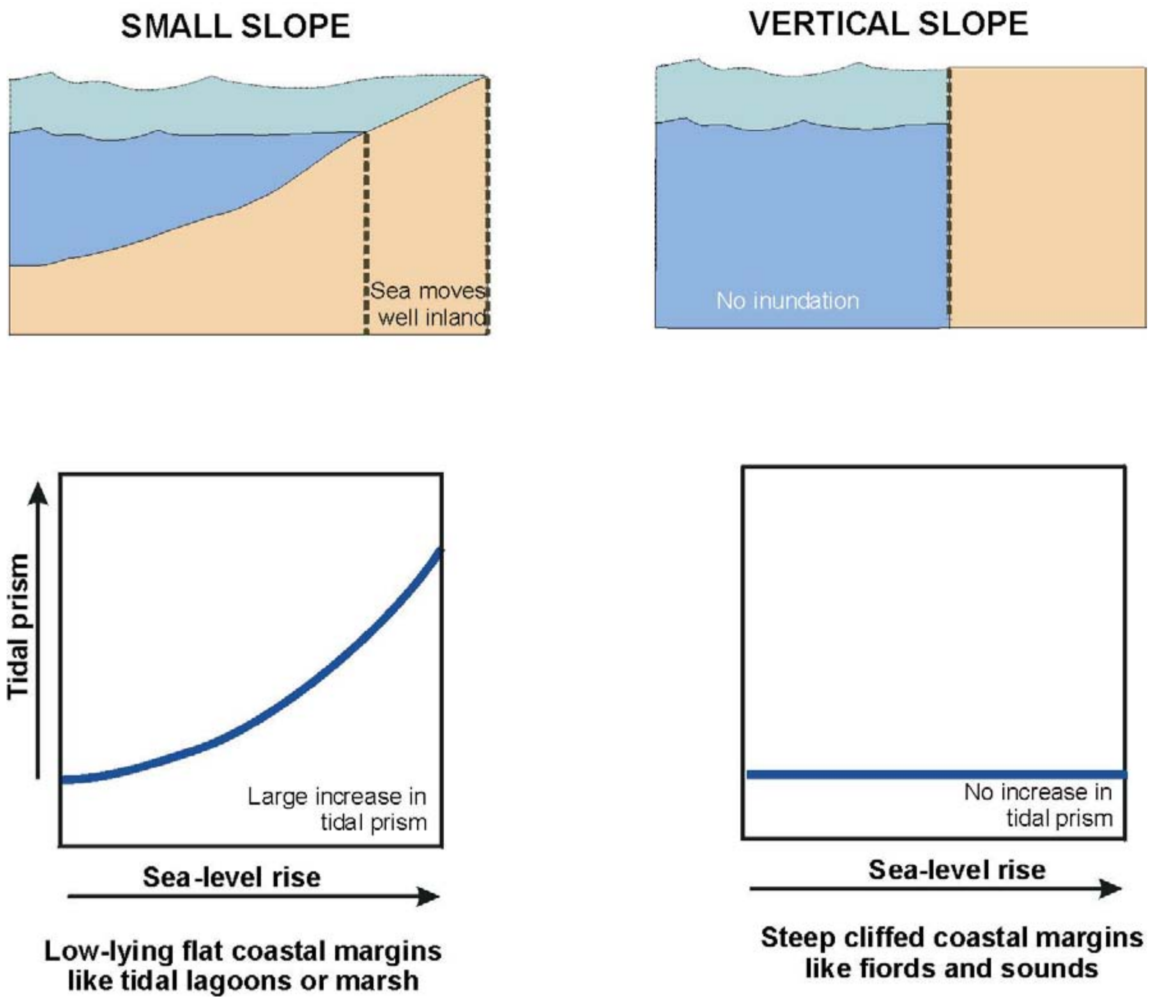


Figure 15: *Loss of peripheral land by inundation and increases in estuary tidal prism volume due to sea-level rise depends on the slope of the marginal land.* [Graphics: K MacLeod]

On developed coastal margins, especially estuaries, sea-level rise may result in a loss of intertidal area and habitat, because present shores are often 'fixed in place' by seawalls, stopbanks and road/rail causeways. With sea-level rise, the present-day low tide mark will be raised higher and will move inland by a distance that depends on how much extra sedimentation occurs from other climate change factors. In contrast, the corresponding high-tide mark may be prevented from moving any further inland in some localities by shoreline constraints such as a stopbank (unless the structure is overtopped occasionally during storms). Consequently, this type of 'coastal squeeze' will mean intertidal areas (and habitats) may be lost, especially where sedimentation rates do not increase along with sea-level rise. Coastal squeeze may also occur on open coast beaches protected by a structure, and where, as the intertidal beach sediment is gradually lost, the capacity of coastal margins to protect the hinterland during storms is reduced.

Loss of intertidal habitats or too much mud/silt material would affect the gathering of kaimoana by Maori and Pakeha alike and have major consequences for estuarine intertidal ecosystems in general. Loss of intertidal areas also poses risks to migratory shorebirds by potentially eliminating foraging habitat. The relevance of these impacts does, however, need to be placed in the context of already existing human impacts on estuaries (Bell *et al*., 2000) that have led to loss of good-quality seabed substrates through overdosing of mud/silt sediments. Examples include catchment land-use changes, altering the river flow regime (for example, Maketu Estuary in the Bay of Plenty), and historical reclamations.

In estuaries and harbours, the 'tidal prism' is the volume of seawater that flows in on each incoming tide. The tidal prism will increase with rising sea level if fringing land is allowed to flood (Figure 15), particularly if the marginal lands or marshes are low-lying with small slopes (National Research Council, 1987). Increased tidal prisms in estuaries will result in physical changes to the entrance channel (through higher tidal velocities and scouring) and in the growth in volume and height of sand shoals inside and outside these entrances (National Research Council, 1987; Hicks and Hume, 1996). These changes will have ramifications on the erosion of adjacent open-coast beaches and navigation. At the other extreme, an estuary/fjord shoreline of steep rock walls and no intertidal areas will experience little change in tidal prism.

To date, sedimentation[5] in New Zealand's estuaries has been keeping up with the present sea-level rise of nearly 2 mm per year (Swales *et al*., in press). However, the overall effect of future global warming on estuaries is uncertain, because we do not have clear answers to several key questions, namely:

- Are catchment exports of sediments likely to reduce over time (while sea level continues to increase), especially with increasing urbanisation, hard paving or better land-use controls?
- Will higher-intensity rainfall during storms increase the frequency of large storm sediment loads of fine muds and silts from a catchment?
- How big an acceleration in sea-level rise is needed before the rate of rise outstrips the sedimentation rate, causing modifications to the estuary?

The conservative assumption is that tidal prism volumes in estuaries will eventually increase, even if sedimentation rates become somewhat higher, because of the extra tidal volume over estuarine marginal land that is progressively inundated.

The characteristics of tides themselves (such as the timing of high water and tide range) may also be modified by deepened estuaries (where sea-level rise outstrips the rate of sedimentation), or estuaries where the tidal prism increases markedly. However, on the open coast, tides will be largely unaffected by sea-level rise.

Shoreline migration by sediment movement

Beach systems are by nature abrupt transitions between the land and a very dynamic ocean environment. Dynamic energy is generated by physical drivers such as waves, currents, winds, tides and fluctuating mean sea level (see Figure 5). Beaches adjust to the changing dynamics of the ocean by continual displacement of the shore and any dune features via sediment movement offshore, onshore or alongshore. Natural shoreline movement (vertical and horizontal) and realignment of a stretch of coast takes place both gradually during calmer sea swell and in jumps during storms, and

[5] Rate at which sediments are permanently laid down, expressed in mm thickness per year.

over timescales of irregular events (such as storms) to a few decades (such as the Interdecadal Pacific Oscillation). For example, a timber seawall built at Bowentown (Figure 16) to protect the shoreline after storms in 1978, was subsequently buried by up to 4 m of sand with the beach foredune advancing seawards of the buried wall by 20 m. The wall was exposed again two decades years later, as shown in Figure 16. This natural to-and-fro movement of the coastline is normally only an issue when it threatens to impinge on coastal developments, infrastructure and dwellings (Pilkey and Hume, 2001).

Figure 16: *Re-emergence and destruction of a timber seawall at Bowentown (Katikati) during storms in 1996. The retaining wall was originally built some 20 years earlier to protect the shoreline from further erosion after storms in 1978. Subsequently the beach experienced an accretion cycle that built out the shoreline by 20 m and covered the wall by up to a 4 m depth of sand.* [Photo (1996): RK Smith]

In this report we have defined 'coastal erosion' as a trend towards shoreline retreat and/or loss of beach sediment volume. However, most shorelines erode to a certain extent anyway, so eroding coastlines are deemed to be those that exhibit a *long-term* erosion trend over timescales of years to several decades (such as shown in Figure 4).

CASE STUDY 4: Examples of long-term erosion

- ***Shoreline retreat:*** North of Timaru, the South Canterbury shoreline has been starved of gravel supply by the port breakwater, which forms a barrier to alongshore sediment movement driven by southerly swells. The coastline was believed to have been eroding naturally prior to the construction of the breakwater, but the erosion rate accelerated after its construction in 1878. Consequently, the shoreline has retreated at rates varying from 2 to 9 m beach loss per year at Washdyke Beach (Kirk and Weaver, 1985; Todd, 1989).
- ***Loss of beach volume:*** Mission Bay is a pocket beach in eastern Auckland. The shoreline was stabilised by a seawall in 1933, but the beach volume diminished over time (particularly during the 1970s and 1980s), leaving a negligible beach at high tide. Reasons for the erosion included the loss of sediment previously supplied by cliff retreat, the wall itself, and a stormwater outflow scouring the beach. The beach was successfully rebuilt in 1992, following renourishment with imported sand, and separation of the stormwater from the beach (Priestley and Consedine, 1991).
- ***Cliffed coastlines:*** Cliffs of *consolidated* rocks and clays erode slowly through frittering, undermining and slumping. Examples of slow erosion of coastal cliffs occur in the Waitemata Group sandstones and siltstones around Auckland and North Shore (Moon and Healy, 1994; ARC, 2000). In contrast, *unconsolidated* alluvial cliffs, such as those in the Canterbury Bight, are eroding much more quickly.

Erosion-resistant rocky *bold* coastlines (Figure 2) will not experience any significant effects associated with sea-level rise.

Sediment is food for beaches. Generally, long-term erosion is caused when there is insufficient sediment supply coming into the nearshore system to keep pace with the sediment transport out of the system by waves and currents (Pilkey and Hume, 2001). Sediment supply, as we have seen, is particularly vulnerable to climate change that could alter any one of the drivers and therefore the supply to beaches from catchments and the continental shelf.

The impact of climate change on coastal shoreline stability at any particular location will depend not only on sea-level rise, but on several other factors that influence the overall sediment budget of beach systems. Despite these complexities, socioeconomic pressures to provide long-term estimates for coastal hazard assessments have prompted engineers and coastal scientists to produce simplified rules or conceptual models to predict coastal erosion arising from sea-level rise. An in-depth analysis of these approaches is beyond the scope of this report, but some example references are: Bruun (1962), Dean (1990), Healy (1991), SCOR Working Group 89 (1991), van Rijn (1998), Komar (1998), Leatherman (2001) and ARC (2000).

However, no single model or tool that can be used to predict erosion is without its limitations – transferability from location to location being a major issue. There are many ways climate change will influence coastal erosion other than just sea-level rise, including:

- the dynamics and variability of sediment transport up and down coastlines
- sediment transport offshore in deeper water during large storms
- any long-term change in the approach angle of the predominant wave action to the shoreline
- the binding effect of dune vegetation
- the all-important driver of the total sediment supply from offshore, rivers and cliff erosion for the specific coastal unit.

Consequently, more research is needed to derive robust sediment-budget three-dimensional numerical models for estimating shoreline response of open-coast and estuary shorelines to climate change and associated sediment supply (not just sea-level rise).

Figure 17 summarises some of the potential impacts of sea-level rise on shoreline movement for different types of coasts. In essence, shorelines that have historically exhibited erosion will continue to erode, but faster, under a rising sea level. Open coasts that have been dynamically stable over time (excluding cycles of minor erosion and accretion over several years) are likely to show a *bias towards erosion* under a higher sea level *unless* the sand supply to the beaches and associated physical drivers under a changed climate can keep pace, which in parts of New Zealand is quite likely. With sea-level rise, accreting open coastline beaches may continue to accrete, but more slowly (Figure 17). As already noted, a possible alteration in sediment supply is a major factor to consider even for accreting beaches.

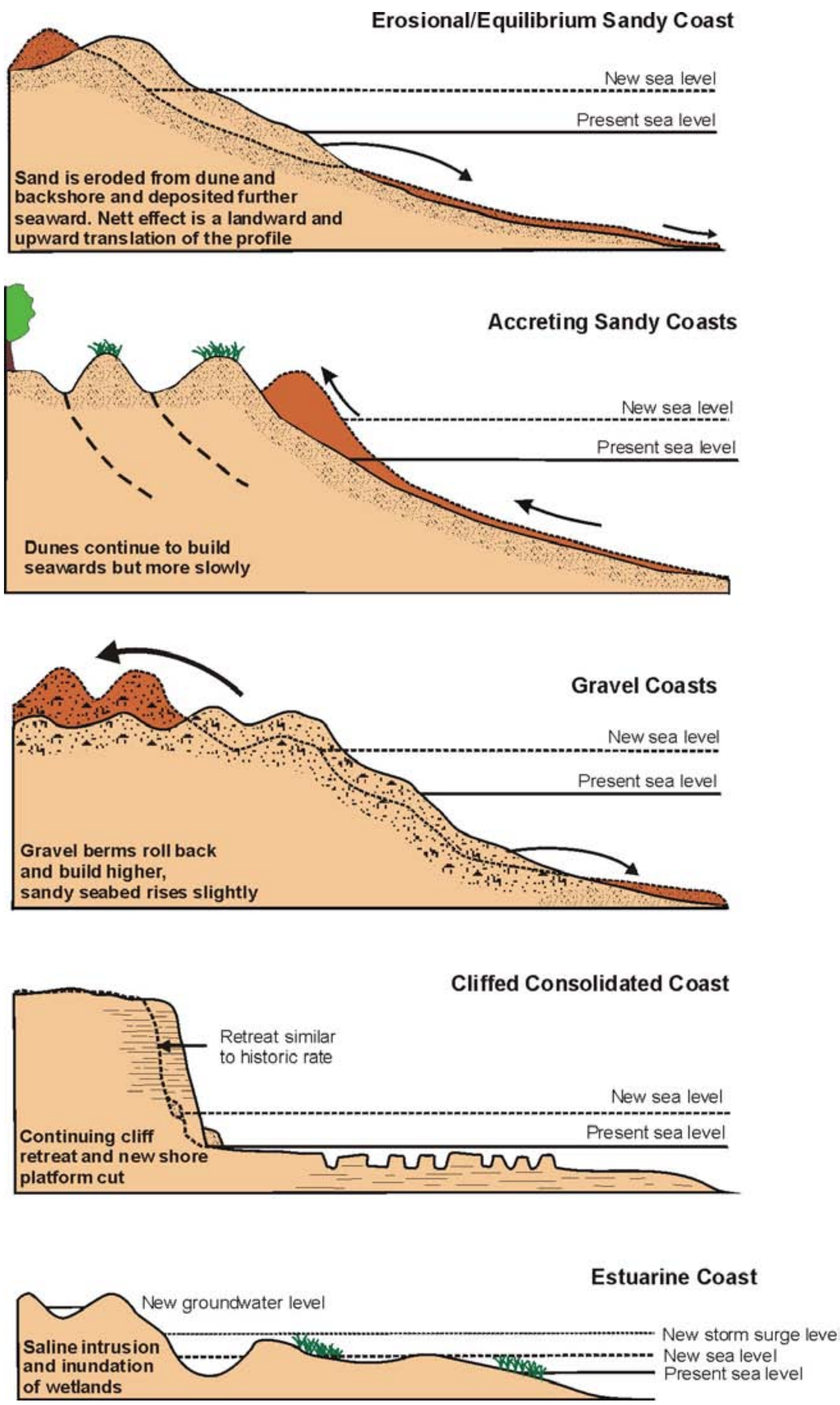


Figure 17: *Generalised shoreline impacts of sea-level rise and coastal "drivers" on different types of coasts. Indicative only as local conditions and "sand supply" may produce different responses.* [Graphics: K MacLeod]

Gravel (including mixed sand and gravel) beaches, which comprise nearly 25% of New Zealand's coastline, will respond differently to sea-level rise, since waves tend to push gravel on to beaches rather than offshore. Gravel beaches would therefore be built higher as storm waves ride-in on a higher mean sea level, and retreat landward more as gravel is rolled up the beach face, with little material deposited offshore (Figure 17). Since gravel beaches maintain a steeper slope, their retreat rate landwards is liable to be much less than for sandy beaches (Hicks, 1990). However the heightened gravel berms at river mouths, such as those draining into the Canterbury Bight, will pose increasing difficulties with flooding and land drainage, particularly if river mouth closures were to occur more often with a drier climate on the Canterbury Plains.

Erosion of cliffs comprising sedimentary rocks and clays/silts is a one-way process that will continue at similar rates (Figure 17). However, on the back of a rise in sea level, energetic waves will form a notch higher up the cliff face and may produce a higher shore platform, depending on the sediment type, rate of sea-level rise, and erosion rate of the cliffs (van Rijn, 1998).

In most of the above cases of exposed coasts comprising loose, mobile sediments, the beach and nearshore seabed elevations will rise to accommodate the average rise in sea level.

Any retreat of open-coast beaches will predominantly occur by erosion (sediment movement). In contrast, shorelines around estuaries will retreat from both inundation (Figure 17), as well as a slower, but steady, contribution from erosion due to the less energetic wave environment and limited exposure time to waves around high water. Sedimentation rates in the main body of North Island estuaries have been 2 to 4 mm/year (Swales *et al.,* in press) and therefore sediment supply has been keeping up with or exceeded the present rise in sea level of ~2 mm/year. Past geological evidence also shows that sedimentation in estuaries may keep up in the future, at least until the acceleration in sea-level rise becomes too great or other effects limit sediment supply (Bell *et al.,* 2001a).

CASE STUDY 5: Response of New Zealand beaches to tectonic land shifts

A window on how the New Zealand coastline might behave with a rise in sea level can be cautiously appraised from examples where the land has subsided suddenly in an earthquake, effectively causing a relative rise in sea level.

- **Thornton Beach (Bay of Plenty):** The Edgecumbe earthquake on 2 March 1987 caused the 9 km coastal margin between the mouth of the Rangitaiki and Tarawera Rivers to subside by about 0.4 m (equivalent to an instantaneous rise in sea level). Sea floor sediments adjacent to the Rangitaiki Plains are sand and silty-sand. Historically the trend has been a coastline advancing seaward (Healy *et al.,* 1977), although the beach was relatively stable from 1977 to 1987. The retreat likely to be caused by the 0.4 m subsidence was 45 m using the Bruun (1962) rule. What took place was quite different, with the lower foreshore (below 2 m elevation above mean sea level) showing a loss of material for the first five years after the earthquake, as expected, followed by accretion to the present, as shown in Figure 18 (RK Smith, NIWA unpublished data). Above 4 m elevation the dune deposit maintained a steady accretion rate throughout. In this case, even though the lower foreshore initially eroded in response to the sea-level change, it appears that sufficient sediment supply was available from offshore and alongshore drift to satisfy the sediment demand of what was effectively a localised rise in sea level, and thereby rectify the perturbation.
- **East Clive (Hawke's Bay)**: On 3 February 1931 an earthquake of magnitude 7.5 on the Richter scale rocked the Hawke's Bay region, causing land at East Clive (south of Napier) to subside by about 0.7 m. The coastline comprises a sand and gravel barrier beach that lies on top of the sediments of the Heretaunga Plains. Originally the height of the beach barrier was built by wave action pushing gravel as high as possible up onto the barrier beach. After the earthquake, the lowered beach barrier meant that waves could now overtop it and swash material from the beach face to the back of the barrier, causing the whole coastline to retreat landwards. This 'roll-over' process occurs naturally on gravel coasts, but will be exacerbated by

a rise in relative sea level (see Figure 17). As this retreat process took place over decades the remains of vegetation that had once been on the back of the pre-earthquake barrier became exposed on the beach face (Figure 19). In this case the effective rise in sea level has hastened the beach retreat, but with little loss in beach volume. In other words, upper beach gravel material was not eroded and deposited offshore as suggested by the Bruun (1962) response to sea-level rise for sandy

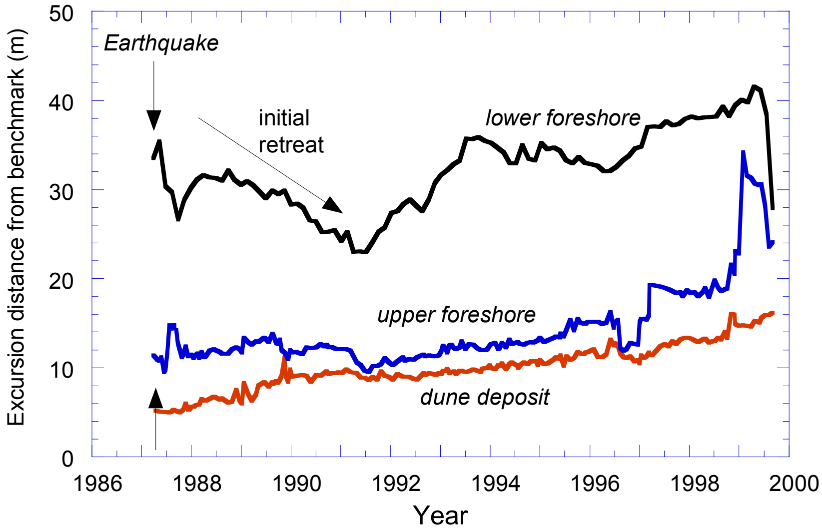


***Figure 18:** Response of a beach profile near Thornton (Bay of Plenty) following the March 2, 1987 Edgecumbe earthquake when the coastal margin subsided by 0.4 m. The upper foreshore and dune deposit lines are 1.5 m and 2 m respectively above the lower foreshore datum.* [Source: RK Smith, unpublished data]

***Figure 19:** Gravel beach at East Clive (Hawke Bay) in 1980 showing the remnants of vegetation on the beach face that once were growing behind the beach barrier prior to the 1931 Hawkes Bay earthquake. Sudden subsidence of 0.7 m has caused the gravel barrier to retreat inland much quicker than before the event.* [Photo: RK Smith]

Drainage and protection of lowland areas

Sea level rise, if accompanied by the projected increases in storm rainfall intensities (Section 4.3), could mean that the drainage and flood protection of low-lying areas around coastal margins will become progressively more difficult and expensive. Low-lying city areas such as the eastern suburbs of Christchurch, areas of Invercargill reclaimed from the New River Estuary, and rural areas such as the Hauraki Plains and Lake Ellesmere could be faced with situations where gravity drainage is increasingly difficult and expensive pumping stations have to be installed. Further strengthening and build-up of impoundment structures such as existing stopbanks may also be necessary to defend against the higher water levels and flooding from extreme tides, storm surges and higher river floods on the back of a rising sea level. Already Moanataiari, a subdivision in Thames, has had its seawall protection strengthened and pumping stations installed to alleviate the present and future risks of flooding from the sea, or rivers draining the hinterland (see Case Study 7). Infrastructure such as roads, railways, airports and oxidation treatment plants in low-lying coastal margins will also be subject to a greater risk of inundation in extreme events, requiring more elaborate drainage systems to mitigate future flooding exacerbated by climate change.

Salinisation of lowland rivers, surface waters and aquifers

Rising relative sea level will progressively affect the quality of freshwater resources in coastal wetlands, lowland river reaches, aquifers and soils by salinisation (more saltiness from incursion up rivers or seepage of seawater). This effect will be particularly marked during drought conditions, which are increasingly likely under climate change in some eastern regions such as Canterbury and Hawke's Bay/Poverty Bay. In New Zealand, with its abundance of freshwater sources for town and city water supply or irrigation, most intakes are located well upstream from the coast, so salinisation is unlikely to have a major impact on bulk water supply. Soils in low-lying agricultural areas may be affected by sporadic overtopping and flooding of saltwater, with effects being cumulative. Coastal aquifers normally flow toward adjacent surface waters, such as estuaries or the sea. Aquifers with low hydraulic heads, such as those in Christchurch, could, however, be induced to flow in the reverse direction with a rise in sea level under excessive pumping rates for municipal water supply. Increasing salinisation of peripheral lands around estuaries will have effects on their flora and fauna, being part of a gradual process that will eventually transform 'land' into salt meadows, then salt marshes, and finally into the estuary proper, provided there are no artificial constraints like bunds or stopbanks.

5.2 Impacts from changes in rainfall and hydrological/oceanographic patterns

Changes in rainfall patterns and increasing storm intensity will probably have a substantial impact on coastal and estuary sediment budgets. The main impacts will be increasing sediment slugs (large doses of sediment) entering estuaries during storms, which will impact the benthic (sea-bed) ecology by smothering and blocking siphons of filter-feeding shellfish (see Case Study 6). Increased sediment run-off during storms will also increase turbidity levels and decrease light levels for plants and animals. Interactions between increased rainfall intensities and sediment loads to estuaries are complex for urban catchments, where progressively soils are stabilised as subdivisions and roads become established, and the trend towards tighter sediment run-off loads continues.

Changes in the flow regime of rivers would also cause modifications to river mouths and bar features, which in turn could impact on river flood control and navigation.

CASE STUDY 6: Sediment slugs and their impact on estuarine benthic ecosystems

Estuaries are rich in structural and biological diversity and play an important role in the functioning of coastal ecosystems. However, changes in land use and the modification of coastlines due to human development have increased rates of sedimentation and changed the areal extent and composition of sediment deposits in estuaries (Edgar and Barrett, 2000). Episodic events such as landslides, extreme rain events and flooding can result in catastrophic deposition of sediments and more turbid waters, with profound affects on the structure and function of benthic communities in estuaries (Ellis *et al.*, 2000).

Experiments were recently carried out in Okura Estuary (North Shore) involving sudden dumps of clay-rich mud, obtained from the catchment, on more sandy estuary sediment in 2 m diameter patches of varying thicknesses (Norkko *et al.*, in press). Results clearly demonstrated the direct negative effects of fine silty/mud sediments from the adjoining land on intertidal benthic communities. When slugs or large doses of clay-rich sediment of more than 2 cm are dumped on intertidal flats, there is almost complete extinction of the fauna in the underlying sediments due to physical smothering and lack of oxygen. Initial response was rapid. After only three days, animal abundance was reduced by around 60%, and after 10 days virtually no animals were found alive under the clay. Recovery following this disturbance over a small patch was slow, and still incomplete after more than 12 months.

Catastrophic, or heavy sedimentation, events in estuaries depositing over 1 to 2 cm thick layers of fine sediments in short time periods can modify habitats over wide areas, affecting resource availability and leading to massive extinctions of benthic animals. Such impacts could occur more often with global warming and increased rainfall intensities, particularly if catchment land use and earthwork practices are not subject to sediment controls.

Coastal and ocean currents could eventually change with global warming, but are unlikely to be affected by sea-level rise alone. Complex ocean–atmosphere interactions such as wind pattern shifts, Pacific-wide temperature distributions and modifications to the El Niño–Southern Oscillation system, are likely candidates for causes for changes in currents. Upwelling of cooler, nutrient-rich bottom ocean waters along our coasts is strongly governed by winds that blow parallel to the shoreline or directly offshore, so any shift in wind patterns will alter the frequency and intensity of these events. Changes in ocean currents and coastal upwelling are likely to affect ocean productivity (nutrients, larval distributions, fish stocks) and the incidence of toxic algae blooms, but predictions about the direction of these changes are highly uncertain.

Most of our open coastline beaches are sensitive to subtle year to decade changes in the height and (particularly) the direction of waves and swell. Again, shifts in wind patterns could significantly alter the coastal wave climate, causing erosion or accretion in areas different to those presently being affected. Waves arriving at an angle to the shoreline can shift large volumes of sediment downcoast; for example, southerly swells cause the northerly drift of gravels and sand along the Canterbury Bight. Possible effects on the Pegasus Bay shoreline of a shift in wind and wave direction with climate change are described in Case Study 3.

Consequently, any shift in prevailing wind and wave patterns will have a substantial effect on alongshore and off/onshore sedi7ment transport and cycles of erosion and accretion, but no general model predictions of resulting changes are available at this stage. Partly, this is because with limited beach profile data on our coasts (that includes the underwater section beyond the surf zone), it is not yet clear what relative effects variations in wind, waves, swell (from a remote ocean source) and currents over El Niño and Interdecadal Pacific Oscillation time scales have on erosion and accretion of our beaches.

5.3 Impacts from changes in storm and cyclone patterns

At this stage, projections are for no significant change in the frequency of *extreme* storms, given the uncertainty among the various models of extreme events (MfE, 2001; IPCC, 2001a). However, extreme rainfall intensity and possibly cyclone wind strength may increase in New Zealand with global warming. Rainfall intensity increases would have most impact on lowland river reaches, where floodwaters could reach high levels more often (a reduced return period for a specified level) and will be exacerbated by higher sea levels. Consequently, the threat to lowland areas like the Hauraki Plains will be compounded by climate change, both from high river levels during extreme storms and from higher sea levels causing a backwater effect. Shorter return periods for high river flows will also alter the sediment supply to the coast.

Wind intensity during extra-tropical cyclones may increase, as increasing sea-surface temperatures could move their genesis areas further south and sustain the cyclone for longer periods than at present. The impact of this scenario, along with the background sea-level rise, would be to increase the incidence of coastal flooding through higher extreme tides, storm surges and wave run-up (Figure 14).

5.4 Impacts from temperature rise

As shown previously, temperature rise is a primary driver of rising sea levels through thermal expansion in the oceans and glacier and ice cap melting. The more direct impacts of a regional rise in air and water temperature (Section 4.3) will mainly impinge on aquatic and adjacent terrestrial ecosystems. Some species are more susceptible to temperature than others, which could mean changes in the make-up of ecological communities and their biodiversity. For instance, naturally occurring mangrove (manawa) presently has a southern limit of Ohiwa Harbour on the east coast, and Kawhia Harbour on the west coast (de Lange and de Lange, 1994). With a mean air temperature rise of at least 1°C, decreases in frosts by 2080s and changes in wind patterns, mangroves could become established by natural means in estuaries south of the current limit, altering estuarine ecosystems.

However, research is needed to show how currents will move early-life stages of estuarine plants and animals further south, and to determine the sensitivity to temperature rise for key species in estuarine, mangrove and salt-marsh ecosystems, before the impacts of higher temperatures on entire ecosystems can be predicted. Besides, climate change will bring several other confounding effects such as altered sedimentation regimes, wave and wind exposure and depth changes from a rising sea level.

Warmer sea and estuary temperatures may also create even more favourable conditions for the explosive growth of overseas invasive species (exotic shellfish, seaweeds, toxic algae) that could venture here by ocean currents, or be transported here via ballast water in cargo vessels.

5.5 Overview

The impacts of climate change, including sea-level rise, will occur in coastal areas that are continually evolving and that already face a wide range of natural and human-induced stresses, including erosion, storms, land subsidence, loss of wetland and marsh, and environmental degradation from recreation and development pressures. 'Coastal squeeze' will increasingly become a problem, as humans interact with and influence the functioning of coastal margins. Responses to sea-level rise and other climate change impacts on coastal drivers at the national, regional and local levels must therefore reflect an understanding of the complex interactions of human, physical and ecological systems in coastal margins. The next section outlines human response options to mitigate those climate change impacts.

- Sea-level rise will lead to inundation, sea flooding, coastal erosion, salinisation of freshwater, drainage problems and coastal squeeze – where shorelines are constrained by structures.
- Shoreline movements predicted by simple models using only sea-level rise are likely to be too simplistic, because shoreline movements also depend on factors such as sediment supply, storm frequency, and wave/wind climate.
- Increasing storm rainfall intensities will lead to lowland river flooding and increased deposition of sediment slugs in estuaries, affecting water quality.
- Wind and wave changes will alter sediment movement and coastal upwelling of ocean waters.
- Estuary ecosystems will be affected by temperature rise, loss of habitat and more deposits of muds.

6 Responses to Climate Change

On the basis that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities" (IPCC, 2001a), planning procedures for coastal margins for the 50 to 100-plus years timeframe will need to allow regular re-assessments of vulnerability, sustainability and response to climate change impacts. Sea-level rise due to the greenhouse effect is generally regarded by the insurance industry as a known impending event, and is likened to the recent Y2K issue. So the industry is unlikely to provide general insurance cover for damage linked to sea-level rise (Chris Ryan, Insurance Council, personal communication). Increasingly, liability issues between territorial authorities and property owners over climate change related damage will arise, which is why authorities are now taking a more precautionary approach.

The management and planning for natural hazards (such as floods, tsunami, landslips and coastal erosion) is primarily conducted within the framework of the Resource Management Act 1991 (RMA),[1] which is now firmly established in New Zealand. The framework, outlined in Figure 20, sits under the umbrella of the RMA and supporting New Zealand Coastal Policy Statement (sections 56–58) and national policy statements (sections 45–55). Within this framework, regional councils and territorial authorities are able to regionally manage and mitigate natural coastal hazards through statutory instruments such coastal, regional and district plans under an overarching Regional Policy Statement (sections 59–62). Under the Act there is an implied hierarchy, whereby a plan or policy must not be inconsistent with those above it (Figure 20). Out of this planning framework flows a variety of 'actions' (Figure

The key planning issues related to climate change effects on hazards are as follows.

- How explicitly or implicitly are additional climate change effects on coastal hazards going to be woven long-term into the resource management framework, given the insidious or slow emergence of these effects?
- How can integration of planning best take place across both the 'coastal marine area' (defined in the RMA) and adjacent land areas in coastal margins that eventually may be impacted by climate change, including sea-level rise?
- The challenge with respect to climate change hazards is to assimilate and promulgate ongoing research findings, climate projections, and monitoring data into such 'actions' (Figure 20) to better prepare communities to respond and adapt to impending climate change impacts.

This section outlines the process of determining vulnerability and the available capacity for humans and ecosystems to adapt to impending climate change hazards, followed by a range of appropriate response options to mitigate or retreat from the coastal frontline. The societal and cultural effects on people are then considered, along with planning issues associated with climate change hazards.

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[1] Online text of RMA: http://www.mfe.govt.nz/management/rma/textrma.htm

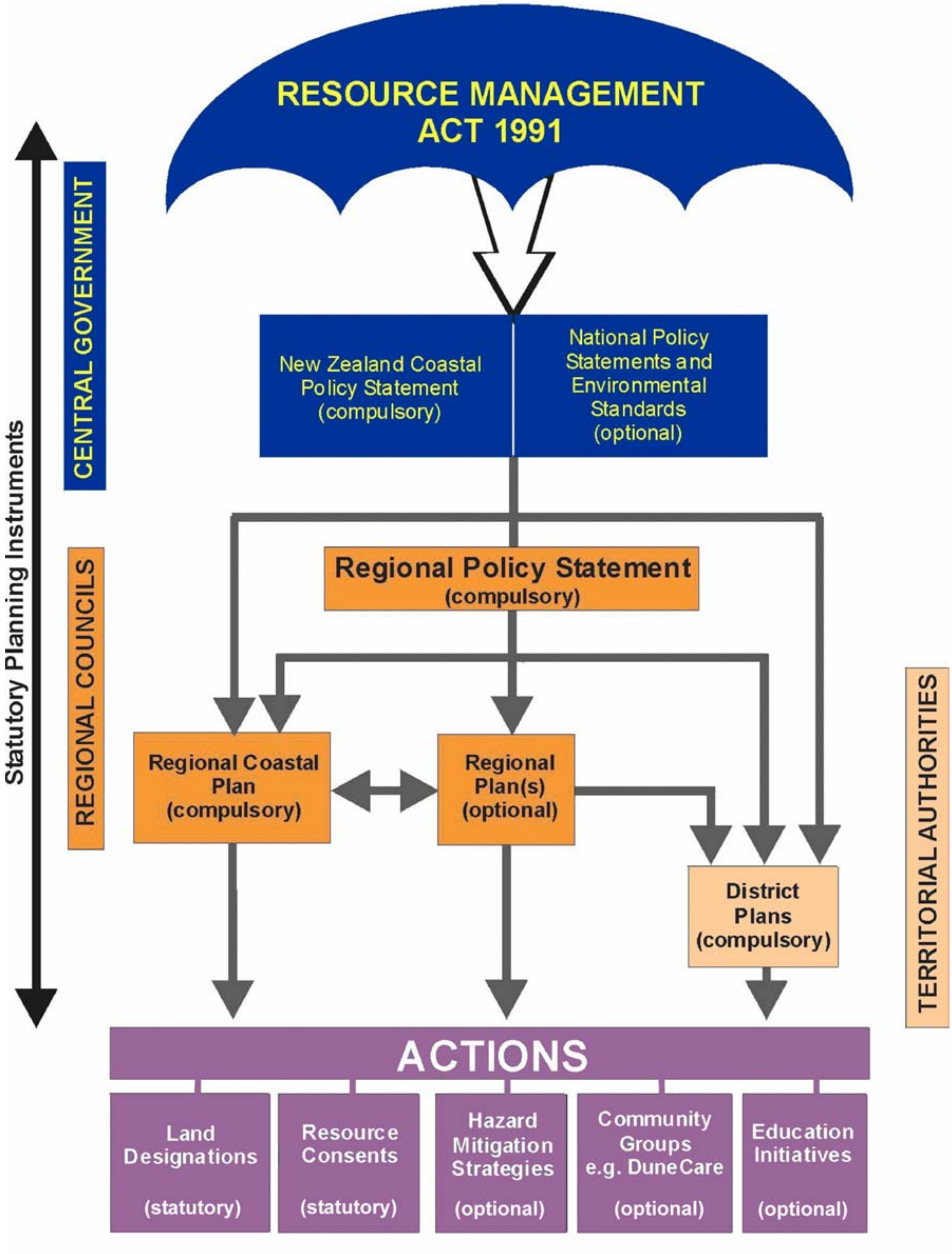

Figure 20: *Hazard planning framework in New Zealand under the umbrella of the Resource Management Act (1991).* [Adapted from Environment Waikato (1999)].

6.1 Vulnerability and adaptive capacity

Most people are familiar with environmental impact assessments of activities that will cause various effects on people and their natural environments. Assessment of human-induced climate change in a region or coastal locality can follow similar principles. So, two questions need to be worked through (Feenstra *et al.,* 1998):

- How important or serious are the various impacts of global warming likely to be nationally, regionally and for different coastal situations (for example, bays, estuaries and harbours)?
- What can and should be done to prevent, modify or avoid these impacts, and when and how should it be done?

Key concepts in the impact assessment and response to climate change impacts on *both* ecosystems *and* human systems (water resources, coastal communities, infrastructure, traditional fisheries, insurance, human settlement) are discussed by the latest IPCC Working Group II report (IPCC, 2001b), in terms of vulnerability and adaptive capacity.

Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate change to which an ecological or human system is exposed, its sensitivity, and its adaptive capacity. *Adaptive capacity* is the ability of a system to adjust or respond to climate change (including variability and extremes such as storms), to reduce potential damages, to take advantage of new opportunities arising from climate change, or to cope with and absorb the consequences.

In assessing climate change impacts, it is imperative to take adaptive capacity into account. Plants, animals and humans will not simply continue on as they do today: they will migrate to more favourable locations. Humans, if necessary can retreat from the coastal ‘frontline’ or try to engineer defences against the sea. For people, successful adaptation requires an acceptance that climate change (or global warming) is happening, followed by education on the impacts that it will create in coastal margins, and assessments of their response options and what behaviour modifications will be needed to cope with the effects.

Impacts, response options and adaptation assessments are necessary to evaluate where and when responses to climate change should be implemented. This will include performing cost-benefit analyses and undertaking social-impact studies to examine the full range of costs associated with available responses. There are real social costs in leaving homes and communities under threat from coastal hazards, just as there are social costs in moving families, and financial costs related to implementing responses and the damages to resources that are not protected. Impact and adaptation assessments will identify those responses that are feasible. Without such assessments, coastal communities run the risk of making uninformed, unwise and perhaps unnecessarily costly decisions. Such assessments take time, particularly where they involves whole communities, so it is important that planning commences now. However, adaptation strategies will need to be consistent with the purpose and principles of the RMA and subsidiary national, regional and district plans, regardless of cost-benefit assessments.

At present, property losses – or the costs to protect property or infrastructure – tend to dominate economic impact assessments. However, there are other significant values that cannot yet be adequately costed using traditional economic analysis. The social costs to communities and property owners will be difficult to assess, and there is a tendency to under-estimate or even ignore the significance of environmental losses. Emerging information from the fields of ecological and environmental economics indicates that the 'cost' to the nation of impacts such as loss of intertidal areas (or their sediment quality), salt marshes, wetlands and beaches, and site damage of culturally and historically significant areas, may be very significant. The RMA and the New Zealand Coastal Policy Statement also give a high priority to the protection of such values. Therefore, as a general rule, adaptation strategies that sacrifice these values are unlikely to provide appropriate long-term solutions.

6.2 Response options

Three main types of response options to climate change impacts in coastal margins are:

- planned retreat
- adaption (or accommodation)
- protection (or defence).

Figure 21 summarises some possible response options for open coasts and estuaries. Response options can vary in scale from quite small structures designed to 'plug a gap', to extensive land rezoning to establish wider coastal buffer zones. Worldwide there has been a strong trend away from hard protection of shorelines (such as seawalls, groynes and rocks) towards 'soft' protection measures (such as beach nourishment), adaptation or managed retreat (Pilkey and Hume, 2001; Council of Europe, 1999). This is also reflected in recent coastal hazard management strategies within New Zealand, such as that adopted for the Waikato Region (Environment Waikato, 1999). Some brief illustrations based on Figure 21 are given below.

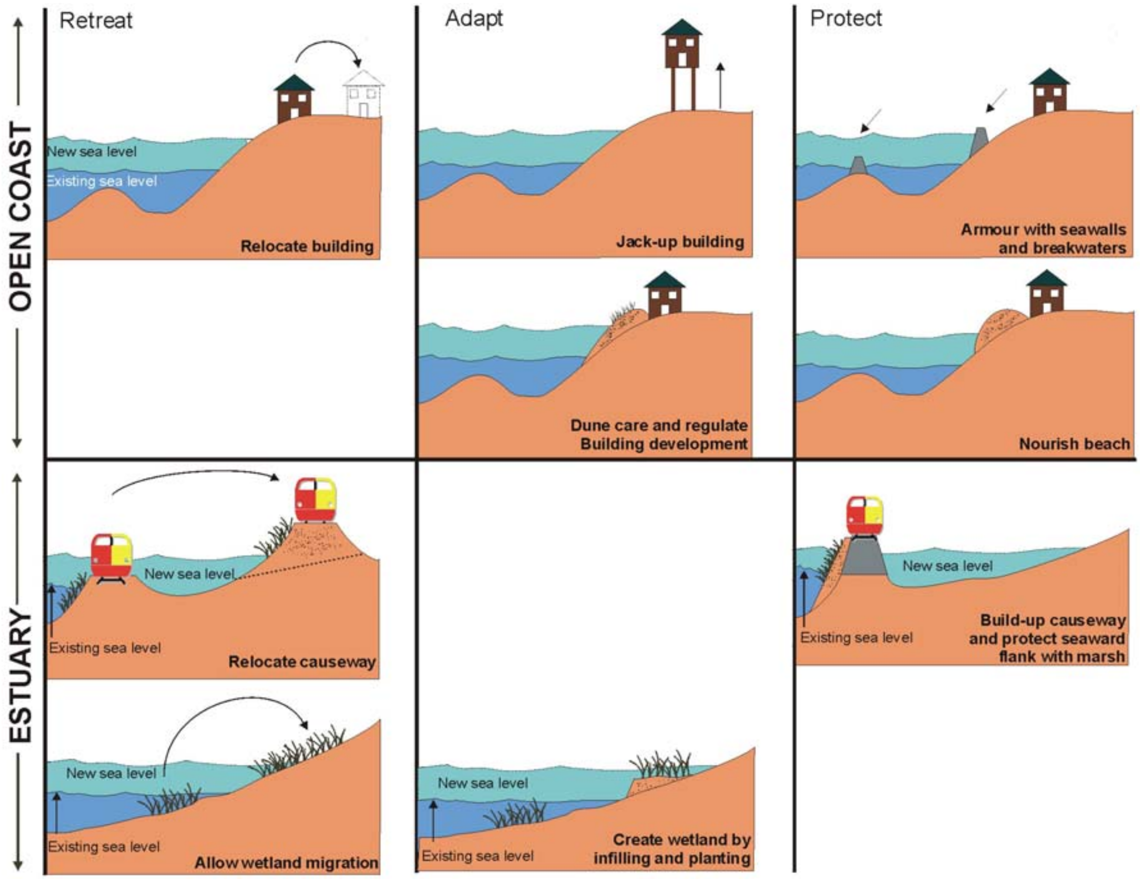

Figure 21: *Response options to sea-level rise for open coasts and estuaries.* [Graphics: K MacLeod]

Planned retreat

This means progressively giving up threatened or vulnerable land by moving away from the coastal frontline, or by preventing future developments along the coast that may be affected by sea-level rise. In largely undeveloped areas (for example, agricultural land, coastal wetlands and salt marshes), allowing the sea to progressively erode or inundate land will be the cost-effective option along large tracts of the New Zealand coast. The alternative of defending hundreds of kilometres of shoreline with stopbanks and seawalls would require enormous capital and maintenance costs. Hard protection can also result in serious environmental losses (to beaches and wetlands, for example) in front of the wall.

Allowing estuaries and marshes to retreat naturally with rising sea level will maintain the integrity of these areas as ecosystems and as sources of kaimoana. Allowing beaches to retreat on sandy shores will maintain a useable beach, which is an icon of the New Zealand lifestyle, especially where the beach is an important community or regional feature (for example, Wainui Beach, Gisborne).

For most coastal communities that have already experienced periods of erosion or inundation, managed retreat is eventually likely to be the *only* long-term option, as alternative protection or adaptation options will increasingly become too expensive. As set out in the following sections, identifying whole threatened communities or enclaves of housing that warrant long-term protection would have to be done with care, taking into account long-term costs in the widest sense, and the environmental effects.

Modern coastal subdivisions now include a prior 'retreat' step by taking a 'greenfields' approach, where a generous coastal buffer against coastal hazards is an integral part of the development. It also meets environmental goals under the RMA of preserving the natural character of the coast. An example is the new coastal subdivision at Omaha South north of Auckland, planned with a generous set-back from the existing shoreline (Dahm, 2001). This contrasts with the older neighbouring subdivision at Omaha North Spit, where rock groynes and beach nourishment were required to stabilise the shore after erosion destroyed the wooden seawall in 1978 (Figure 22).

Figure 22: *Erosion at Omaha North Spit subdivision after a severe storm in July 1978. The remains of a timber seawall can be seen. The wall was originally constructed along 1 km of beach to protect the subdivision. The dune system was levelled to provide better access and views to the beach. Following the erosion, the sand spit and tidal entrance to Whangateau Harbour were stabilised by several rock groynes built between 1979–1981, after an Act of Parliament was passed for emergency remedial work.* [Photo: TM Hume]

Retreat mechanisms are also built into some regional and district plans, whereby any further housing within a coastal hazard zone must be 'removable'. There is the need for caution, however, because stipulating a removable house does not address a raft of financial and social costs on the owner who may be forced to abandon, or retreat within, their property when damage occurs.

In the UK, 'managed retreat' has become increasingly popular, particularly on coastlines that have been subsiding for some time. The British government has a list of 40 areas where, as an experiment, the sea will be allowed to follow nature's directions.

Adaptation (or accommodation)

This strategy involves continued but altered use of land, including adaptive responses such as elevation of buildings, roads, railways and existing stopbanks, modification of drainage systems (such as more pump stations), and land-use change. For natural coastal and estuarine systems, it also includes enhancing the existing natural protection of dunes by vegetation and fencing, or creating and planting upper intertidal areas and salt marshes.

Integrated coastal management of entire coastal units can also provide a way to adapt to hazards. An example is the resource consent granted to the Whitianga canal development. The consent required that large volumes of sand be made available for coastal renourishment if required, to offset the removal of harbour sands by dredging. This was achieved by stockpiling sand excavated from the canal development for future use in beach renourishment of Buffalo Beach (J Dahm, personal communication).

Protection (or defence)

This strategy involves defensive measures and seeks to maintain shorelines in their present position, either by hard options like building or strengthening protective structures, or more natural soft options such as beach nourishment. This strategy has been widely used overseas and to a lesser extent in New Zealand (Figures 1, 3, 22) to protect properties and productive land against existing coastal hazards – with very mixed success. In New Zealand, small budgets, lack of subsidies for coastal works, and poor understanding of coastal processes has left the coastal landscape peppered in places with small ad-hoc structures in various states of disrepair and usefulness.

Protection results in a loss of the natural character of the coast or estuaries and curtailment of public access – two values esteemed in law by the RMA and subsidiary NZ Coastal Policy Statement. Such protection also compromises the natural function of coasts to resist storms, waves and tides, and results in significant beach loss over time. This form of coastal squeeze, otherwise known as passive erosion, occurs because the hard protection works progressively truncate and narrow the beach as the beach profile moves inland. This effect can be further exacerbated during series of erosion events by the effects of wave reflection and sediment loss from in front of hard structures. Because climate change effects will be widespread along New Zealand's 18,000 km coastline, there is unlikely to be a general pragmatic or cost-effective method of holding back the sea, such as exists in the Netherlands, for instance.

Beach renourishment, where similar-sized sediment is placed on or near a beach, is already used in some places around New Zealand as an acceptable soft engineering option to mitigate coastal erosion (for example, at Mission Bay in Auckland, and Westshore in Napier), and its use could increase (at least judging by the trend in the USA). But it requires regular applications of suitable sediment, and it comes with a price. On the major renourished beaches on the east coast of the USA, the cost is about US$10,000 per beachfront lot per year (Pilkey and Hume, 2001).

Protection measures such as seawalls and stopbanks, combined with pumping systems, can protect property for several decades, but these measures are likely to be increasingly ineffective in the long term as sea-level rise continues and likely accelerates and/or if storm intensity and frequency increase. These measures will also result in further loss of salt marshes, estuary intertidal areas and beaches (the coastal squeeze), with detrimental effects on ecosystems, the availability of kaimoana, recreation and tourism.

Councils are often faced with very difficult situations where existing beach resorts or urban subdivisions are seriously threatened, and structures can sometimes be required at these sites. These structures may be medium- to long-term measures. Protection of the Moanataiari subdivision (Thames) by strengthened seawalls and a pumping system is an example (Case Study 7), but at a cost of over $1 million for around 100 households. This site is built on a low reclamation and was already surrounded by a rock wall rather than a natural shoreline. Therefore, the further armouring did not result in serious adverse environmental impacts – as would have occurred had the site been fronted by a natural beach.

The situation is even more complex where a structure is likely to have significant adverse environmental impacts. These areas are likely to become serious problems as a consequence of future climate change, and careful attention needs to be given to their coastal hazard management. Sophisticated hazard management strategies are required and engineering solutions alone will generally not provide socially and ecologically appropriate long-term solutions. For instance, in some parts of the world (for example, South Carolina, USA), hard structures are already prohibited, even in heavily urbanised areas, because of the importance of beaches to the wider community. History is a great teacher and now the challenge is to plan well for the future, given that sea-level rise is projected to continue unabated for at least a few centuries.

The process of identifying and evaluating adaptation and retreat options for a locality are discussed in more detail by Feenstra *et al*. (1998).

CASE STUDY 7: Protection response option at Moanataiari (Thames)

The low-lying Moanataiari subdivision on the Thames foreshore has already suffered from storm-water drainage problems, and the lowest area was almost completely inundated by coastal flooding (high tides combined with a storm surge) in July 1995 and January 1997, with damage to over 30 properties. Given the increased frequency of future sea-flooding events and the withdrawal of insurance cover for property damage, the Thames Coromandel District Council, after a cost-benefit analysis, took action to address the issues and mitigate the health hazard of surcharged foul sewers.

The Moanataiari reclamation was formed progressively from the turn of the century, initially by dumping mine tailings and mullock over intertidal flats. Dumping dredgings from the port further reclaimed the area, which was then capped with a raft of weathered rock and clay from the hills under more controlled conditions in the mid to late 1960s. Housing construction was generally underway in the 1970s. The end result was a 'little Holland' extending 500 m from the line of the coast into the sea (Figure 23).

Moanataiari's existence was threatened by the elements from the start because it lies near the mouth of a large river where floods and storm surges in the Firth of Thames cause coastal flooding of low-lying land. The steep catchment behind the subdivision also delivered stream flood waters during heavy rainfall, besides the acute vulnerability to sea flooding.

Engineers were engaged to rectify the problems of sea flooding and rainfall ponding to a 1 in 50-year design for non-coincident events (Duder *et al.,* 1999). The old seawall was reconstructed, made impermeable, its elevation raised, and a timber parapet added for further protection against wave run-up of the sea over the crest. A pump system was installed to pump catchment rainfall or seawater from the subdivision when it exceeds the capacity of the gravity drainage system. The back-beach 'dune' at the beach immediately north of the subdivision was built up to improve its capacity to absorb the main wave uprush. Swale drainage behind this beach and behind the subdivision was constructed to channel storm water from the upland catchment around the subdivision. The construction works alone cost $1.08 million, for the benefit of about 100 households in the subdivision.

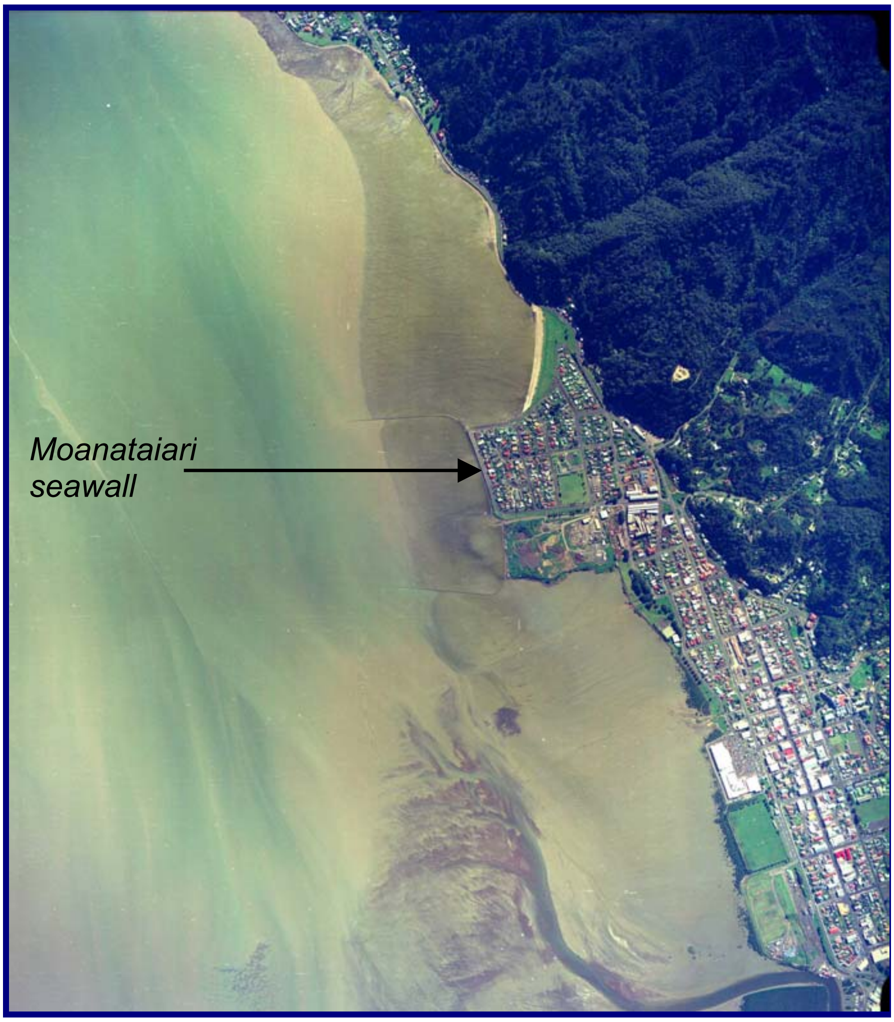

Figure 23: *Moanataiari subdivision at the north end of Thames. Reclaimed over several decades and finished in the late 1960s, the subdivision is now home to just over 100 households. The seawall was strengthened and elevated in 1999 along with a pumping system at the cost of over $1 million.* [Photo courtesy: Environment Waikato]

6.3 Effects on Maori

Traditionally, Maori have had a strong cultural bond with the sea (moana), which provides kaimoana (shellfish and fish). Consequently, historically marae were often established along coastal margins (estuaries or the open coast). The solutions for the mitigation of potential damage from sea-level rise are complex, particularly where they involve special land areas that are culturally significant (such as urupa, middens and marae) and would need protection. Climate change impacts such as increased coastal flooding, possible loss of intertidal areas where landward retreat is constrained by stopbanks or roads, or loss of sediment quality of habitats from too much mud and silt deposition, will have serious implications for Maori in terms of aquatic ecosystems and the integrity of food sources.

It is interesting to note, however, that because Maori have inhabited the coastline of New Zealand for many centuries, they have already experienced a coastal hazard that resulted in a significant change in Maori culture and settlement patterns away from the immediate coastline. This occurred around 1460 AD after the tsunami generated by the Haowhenua ("*land swallower or destroyer*") earthquake on the Wairarapa fault led to widespread abandonment of the prehistoric coastal settlements around New Zealand, particularly central New Zealand coastlines (Goff and Chagué-Goff, 2001).

This should remind us that what we end up doing about coastal hazards is likely to be in response to an amalgam of catastrophic and insidious coastal hazards, with climate change as just another contributor to the total package of hazards at each coastal location.

6.4 Community awareness of climate change hazards

Controversial planning issues over the last few decades have mainly arisen through the process of setting coastal set-back lines or hazard zones to accommodate climate change impacts. Invariably, the most contentious issues occur with dynamically stable coasts, where any temporary erosion after severe storms may only occur once in every generation of homeowners (every few decades).

Coasts subject to long-term erosion more regularly show their hand, and awareness of the hazard is higher, although seldom high enough to be a part of an everyday perception by those living in or near such coastal hazard zones. Individual and collective community memories are short and denial is often strong (see Case Study 8 below). The degree of awareness is also evidenced by the continuing high prices being paid for coastal sections wholly or partly within identified hazard zones; for example, at Raumati, along the Kapiti Coast.

The critical issue with climate change effects on coastal margins is now not 'Will it happen?', but 'How adaptable will humans and socioeconomic systems be to the changes that will inevitably occur?' Depending on the policy options chosen, the impact of rising seas could fall disproportionately on a small number of people or communities in the most vulnerable areas, who previously may have been unconcerned or uninformed about the hazard.

This underlines the importance that should be given to social impact studies, both before coastal development is allowed to occur in marginal cases, and also when existing development areas need to respond to increased hazards on the back of rising sea levels. Such social impact studies would give planners a better idea of the full range of issues and potential impacts, and would also provide a good platform for developing effective public education programmes. Public education about climate change effects and the additional coastal hazards they pose will be the challenge of the next decade if results from a small survey are anything to go by (see Case Study 8).

CASE STUDY 8: Survey of community awareness to coastal hazards (South Brighton Spit)

South Brighton suburb is located at the tip of the Brighton sand spit barrier that encloses the Avon–Heathcote Estuary. The area has been subject to erosion, with several properties threatened by a retreating coastline. A verbal survey was undertaken by Christchurch City Council of 29 South Brighton Spit residents, with 40% of respondents living seaward of the coastal hazard set-back boundary (Ridgen, 2000). While not a large survey, it provides a window on views of coastal dwellers. Following are the main findings.

- 86% said they were aware of coastal hazards, citing erosion most often. However, 83% believed that as a place to live, South Brighton Spit is generally safe from coastal hazards.
- 83% of respondents had moved to their property since the last major erosional event in July 1992. Since then coastal conditions have been predominantly calm, resulting in general shoreline growth.
- Three-quarters (76%) of respondents believed that climate change would cause an increase in the rate of sea-level rise in the next 50 years; four (14%) did not believe this was the case and three (10%) did not know.
- Less than half (45%) of respondents believed their property was completely safe from sea-level rise in the next 50 years, with the remainder ranking the risk as low (24%), moderate (21%) or high (10%).
- From a list of planning methods that might be used in hazard-prone areas, strong support was given for education (90%) and awareness programmes (72%), building restrictions (72%), enhancing natural defences (90%) and limiting development (90%). Moderate support was given for engineering solutions (45%), prohibiting development (41%) and relying on Civil Defence and insurance (38%), while the 'do nothing' approach was least favoured.
- The large majority perceived that the risk to their property is minimal, and some suspicion of the experts' (coastal scientists') evaluation of the risk was evident. The decision-makers (councils) are seen by some to have relied too heavily on the experts and not taken into account the evidence that existing dwellings have survived thus far.

Clearly, there is much to be done in the areas of education, awareness programmes and communication with regard to coastal hazards pertaining to climate change.

6.5 Planning issues

Planning framework under the Resource Management Act

Regional councils and territorial local authorities already have a range of statutory procedures available to plan for, manage and mitigate local natural hazards – which implicitly includes global-warming impacts. The planning hierarchy under the umbrella of the RMA was shown in Figure 20. It is important to outline some of the details of this framework for those not familiar with its workings. If we are to manage whole coastal margins or environments for future climate change impacts, it is important that there is integration across the artificial planning boundary that separates functions and responsibilities in the coastal marine area (below mean high water springs) from those on the adjacent land.

National level

At the national level it is the role of the Minister of Conservation to prepare at least one New Zealand Coastal Policy Statement (NZCPS) (DoC, 1994), approve regional coastal plans and make decisions on restricted coastal activities set out in the NZCPS. The Minister for the Environment can recommend the development of national environment standards, prepare national policy statements on matters of national significance, and monitor the effect and implementation of the Act.

Regional level

At a regional level, it is mandatory for regional councils to prepare a regional policy statement (RPS), which overarches statutory plans prepared by regional councils and territorial authorities. The RPS includes objectives, policies and methods of implementation to manage the significant resource management issues across a whole region. For example, the proposed RPS by Environment Waikato has major objectives in regard to general hazard management of:

- clearly identifying the roles and responsibilities of all relevant agencies for the management of natural hazards in the Waikato region
- minimising the adverse effects associated with natural hazards, including threats to life and property, disruption of essential services and infrastructure, and adverse environmental effects (web site: http://www.ew.govt.nz/policyandplans/ rpsintro/rps/).

A regional coastal plan must be prepared by a regional council to administer the ‘coastal marine area’, and the plan must not be inconsistent with the NZCPS. Regional plans may be prepared (optional) to assist the regional council to carry out its functions under the RMA. Some councils, such as Environment Canterbury and Environment Bay of Plenty, have chosen to combine the regional coastal plan with the regional plan (called a regional coastal environment plan) to promote the integrated management of the coastal marine area and any related part of the coastal environment (section 64, RMA). Other councils, such as Environment Waikato, have chosen to engender integrated management of the coastal environment through clearly defined roles and responsibilities for both the regional council and territorial authorities in the RPS, backed up by non-statutory mitigation strategies for hazards; for example, coastal erosion and coastal flooding (Environment Waikato, 1999).

Local level

District plans, which are mandatory, are prepared by territorial authorities (city and district councils), and apply to the dry land above mean high water spring tide level. A district plan must not be inconsistent with policies and plans above it in the framework (see Figure 20), including the NZCPS, national policy statements, the regional policy statement or any regional plan. While both regional councils and territorial authorities have functions to avoid or mitigate natural hazards, territorial authorities have primary control of the subdivision of land. Territorial authorities also administer the Building Act 1991, which can place controls on the construction of houses within coastal or river flood-plain areas, including the requirement for minimum building floor levels.

Actions

Non-statutory methods (see Figure 20), including use of mitigation strategies for hazards, the development of education and awareness programmes, and help with facilitating local dune care and beach care groups, may also be used by regional councils and territorial authorities to promote sustainable development and hazard mitigation in coastal margins.

More details of the statutory framework are given by Williams (1997).

Planning for climate change hazards

It is important to note that if territorial authorities and regional councils had in place all the measures they considered necessary to deal with their natural hazards, as they currently understand them, New Zealand would have come a long way towards coping with any future variations resulting from climate change. A significant amount of work remains to be done and measures put in place just to cope with present-day natural coastal hazards.

Plans and policy statements (see Figure 20) can either explicitly or indirectly require hazards arising from, or exacerbated by, climate change to be taken into account when permitting new developments and subdivisions, or to be incorporated into minimum building floor levels in low-lying coastal margins and adjacent lowland river floodplains. In fact, section 106 of the RMA[2] expressly prohibits the granting of a subdivision consent by a territorial authority where the land to be subdivided, or any buildings on that land, is likely to be subject to material damage from natural hazards, including coastal hazards that involve erosion, subsidence and inundation. There is clearly scope for taking account of additional hazard from climate change, but there have been no extensive reviews into how this provision is being interpreted and applied by the different territorial authorities.

For coastal margins there is also the added complexity in some regions of differing planning mechanisms and approvals between the coastal marine area (below mean high water spring, or MHWS) and land above MHWS. To any coastal geomorphologist, the concept of using MHWS to define the position of the shoreline boundary is nonsense (Brookes, 2000). On sandy beaches, the MHWS mark fluctuates back and forth by

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2 Online text of RMA: http://www.mfe.govt.nz/management/rma/textrma.htm

metres at event timescales, and up to hundreds of metres at century timescales (for example, Piha, west of Auckland). Further, along the central eastern coast (Banks Peninsula to Hawke Bay), spring tides are not the highest monthly tides, meaning MHWS can be exceeded by higher tides up to 50% of the time (Bell *et al*., 2001b).

Under the planning framework for hazards (see Figure 20) there are a variety of mechanisms under the Act that can circumnavigate this problem, including:

- the ability of regional coastal plans to form part of a regional plan
- identification in the Regional Policy Statement (RPS) of who has responsibility for natural hazards
- joint hearings of consent applications
- the hierarchy between national, regional and district policy statements and plans.

As an example, Environment Canterbury has a Regional Coastal Environment Plan, which extends above the coastal marine area into the coastal environment, and includes regional rules down the whole coastline. District and city councils in Canterbury have agreed that seaward of hazard lines, it is the regional rules that apply to buildings, earthworks and vegetation removal.

In essence, 'coastal' climate change impacts will increasingly affect the entire coastal margin, which lies well landward of the present-day MHWS boundary, thus demanding an increased level of co-operative planning hinged around the mechanisms outlined above. To date, a range of approaches that are specific to climate change hazards have been taken by regional and local authorities (see Case Study 9), from the 'wait-and-see' approach through to specifying, in regional plans, the numerical guidelines on sea-level rise and specific methodologies to be used in the consenting process.

CASE STUDY 9: Regional, coastal and district plans (sea-level rise)

A recent survey of territorial authorities and regional councils was undertaken by DTec Consultants (Derek Todd) and NIWA to assess the degree to which current statutory plans and policies have specifically taken sea-level rise into account.

Some regional coastal plans (Southland, Otago, Bay of Plenty) and regional policy statements (Southland) have specifically included a magnitude of sea-level rise to be used for new developments and consenting, although a range of magnitudes were sourced from either the 1990 or 1995 IPCC assessment reports, the former being markedly higher than current projections. Other regional councils have included a more general statement about using the most recent IPCC projections for sea-level rise impact assessments. Five other councils (Canterbury, West Coast, Waikato, Auckland, and Northland), who have restrictions on structure and reclamation design due to sea-level rise, are less definite in what level of restriction they will apply, using words such as "have regard to", "adequate", "appropriate" in terms of sea-level rise. In theory this allows them to use discretion on a case-by-case basis for what level to allow, but in reality they could be bound by the precedent of their first decision and face Environment Court hearings if they do not use widely accepted rates of sea-level rise. Only two coastal plans (Gisborne and Bay of Plenty) stated that the effects of sea-level rise will be incorporated into hazard zone or area assessments, while Canterbury will include these within five years of its plan becoming operative. We assume this is to allow further information on the effects of sea-level rise to be gathered.

From the small sample of 11 district plans reviewed, it appears that district council plans have less emphasis on sea-level rise than city council plans. The size of the population and value of infrastructure potentially at risk seem to influence how much emphasis there is on sea-level rise in the statutory planning documents. An exception to this is that there appears to be more emphasis on investigations of coastal hazards, which may or may not include sea-level rise, in the district council plans than in the city council plans.

There are two side issues associated with incorporating sea-level rise into planning instruments. One is the inflexibility of plans to be changed regularly (because of the lengthy public process) and how best to regularly incorporate changes in climate and sea-level projections from each five-yearly IPCC climate assessment or regional predictions. There is also the issue of translating IPCC global projections down to the regional level. Further work is needed to establish regional values for relative sea-level rise around New Zealand by monitoring both sea-level and vertical land movements. It may well be that IPCC projections are appropriate, but this needs to be established by monitoring.

In summary:

- all surveyed councils are aware of sea-level rise, but not all have implemented policies and rules to deal with its potential effects
- the wording of some policies and rules does not allow the councils to use the more recent estimates of sea-level rise
- there is no consistency in the planning horizon used to plan for sea-level rise, with some councils choosing 50 years and others 100 years.

Contributors to this report (see Appendix B) and the authors have offered a number of comments and suggestions, and indicated information gaps (see Appendix A) regarding the implementation of planning procedures to address climate change hazards in coastal margins.

New Zealand Coastal Policy Statement (NZCPS)

Promulgated by the Minister of Conservation in 1994, the NZCPS is an integral part of the planning framework for the ‘coastal environment’ – the coastal marine area and a somewhat indeterminate but flexible band of coastal land influenced by the sea (section 58 RMA). This is an important distinction in the context of climate change impacts, as an NZCPS is not limited just to the ‘coastal marine area’ below mean high water spring tide level. In regard to coastal hazards, the NZCPS directs that a precautionary approach should be adopted and reliance on coastal protection works avoided, except “where they are the best practicable option for the future” (Policy 3.4.6; NZCPS). Rather, the emphasis is placed on the protection (and, where appropriate, the enhancement) of natural protective features of the coast (such as beaches, dunes and wetlands), and the planning and design of new subdivisions to avoid the need for hazard protection works (Policies 3.4.1–3.4.5; NZCPS). The NZCPS also directs that:

> *Policy statements and plans should recognise the possibility of a rise in sea level, and should identify areas which would as a consequence be subject to erosion or*

inundation. Natural systems which are a natural defence to erosion and/or inundation should be identified and their integrity protected. [Policy 3.4.2 (DoC, 1994)]

The Department of Conservation is currently preparing for the review of the NZCPS in 2003. Policy 3.4.2 should have more teeth than just 'recognising the possibility' of sea-level rise, given the ongoing rise in sea level since the mid-1800s and the certainty that global warming is already a reality, with projections that sea-level rise will accelerate. In addition, there is a need to review:

- whether coastal and regional plans encourage protection of these 'natural defence' systems that buffer erosion and inundation
- the extent of implementation across coastal margins, particularly land that may in future be subject to coastal climate change effects.

Buildings and liability

A recent report by the Building Research Association of New Zealand (BRANZ) discusses the impact of climate change effects on New Zealand housing (Camilleri, 2000). BRANZ (2001) recommend that new developments take a precautionary approach in low-lying areas and coastal communities, particularly as significant climate changes are predicted to happen within the lifetime of houses being built now.

The purpose of the Building Act 1991 is to provide controls on building work and use, and to ensure that buildings are safe, through a Building Code. The Code is principally concerned with performance-based criteria relating to methods of construction and building safety, while the RMA is concerned with effects on the environment. In short, the RMA is intended to answer the question of whether a structure may be erected on a site, and the Building Act will answer the question of how the structure is erected (Williams, 1997). Nevertheless, there are areas of overlap between planning and building controls, particularly in relation to natural hazards, such as flooding by surface waters.

Currently, the minimum floor level required for residential or communal buildings under the Building Act is equivalent to the 2% annual exceedance probability (1 in 50-year) flood event (with some allowance for freeboard to cover wave effects). Provisions under the Building Act do not currently take into account changes resulting from sea-level rise, nor do they apply to industrial and commercial buildings. This approach should be reviewed for all buildings in coastal margins and adjacent to lowland rivers, and treated as a special case in the light of pending climate change effects that will be unique to coastal margins. Clearly, in coastal margins with sea level likely to increase unabated for a few centuries, this level of protection will not be satisfactory in the long term (100-plus years), especially as newly created subdivisions become more or less permanent (not just for a few decades).

Coastal hazards exacerbated by global warming are a real issue for consultants and local authorities, who could end up wearing the liability for many years to come, especially as the insurance industry is likely to opt out of insurance against the direct effects of sea-level rise (Chris Ryan, personal communication). Such an environment is already resulting in conservative coastal hazard-zone boundaries to limit future liability issues for councils and in recognition of climate change effects that will be around for longer than the minimum 50-year horizon of the Building Act. However, in established coastal communities, this cuts across individual property rights, and is defended vigorously. Therein lies a challenge.

Local issues

The direct effects of sea-level rise and climate change impacts will vary greatly by region and locality. So waiting on a national approach, other than promulgation of guidelines and dissemination of knowledge, is not going to get the job done. For some regions, such as cliffed or bold coastlines without communities, sea-level rise will be a minor issue. In contrast, low-lying coastal areas like the Hauraki Plains, the Kapiti Coast and suburbs of Invercargill and Christchurch are quite vulnerable. Changes in sediment supply to the coast will also vary greatly depending on local and regional changes in climate.

The question of urgency

How urgent is the problem? Many of the changes due to global warming will be insidious: while the changes may not be noticeable on a year-by-year basis, there will probably be increasingly frequent episodes of severe damage, with storms causing excessive erosion and coastal flooding, riding on the back of the sea-level rise, more river floods and changes in coastal drivers such as winds and waves. The challenge, therefore, is to implement strategies that allow timely reactions to the impacts of climate change before major costs are incurred that could have been avoided with prudent planning.

Gaps in supporting datasets

Some potentially useful databases are not currently available to help out with planning, or are deficient. There is a poor definition of areas of potential inundation, coastal flooding and erosion, a lack of information on changes in tidal prisms of estuaries, and areas where intertidal habitat will be lost (or increased intertidal areas where sedimentation increases). These gaps are directly linked to the current lack of an accurate topography of New Zealand's low-lying coastal margins to make such impact and economic assessments in a cost-effective manner.

The present Land Information New Zealand (LINZ) 1:50,000 series topography database and maps only cover topography at 10 to 20 m contour heights, which is much too coarse for planning purposes in coastal margins where climate change effects will only register a few metres above MHWS. Modern techniques such as Light Detection And Ranging (LIDAR), using lasers or aerial photogrammetry, can provide consistent topography of the order of 0.1 to 0.3 m, which would provide an immensely useful database for planners, engineers and scientists working on the impacts of climate change. There are probably many people living in our coastal areas who have not yet been flooded but might actually be living less than 1 to 2 m above mean high water spring and don't realise the potential future risk they face. The present Digital Cadastral Database (DCDB) is also inaccurate and outdated in its boundaries and shorelines at the coast, although a massive exercise is being undertaken by LINZ to produce a full digital cadastral and geodetic database called Land*online*. Definition and updating the position of dynamically changing shorelines remain a challenge for such databases.

Finally, there is a need for regional and national reviews of long-term strategic monitoring of key climate change variables such as waves, sea level, winds and river flows, which can then be compared with 'morphodynamic' monitoring of coastal and estuarine sediment budgets and more regular surveys of nearshore and beach profiles.

- **The vulnerability and adaptive capacity of ecosystem and human systems needs assessing before feasible responses to sea-level rise are decided.**
- **Retreat is the only cost-effective long-term option in largely undeveloped areas.**
- **Managed retreat or adaptation are the only reasonable long-term (100-year) options for most communities or infrastructure at risk.**
- **Education will play a vital role in helping people accept and adapt to climate change effects.**
- **A robust planning and policy framework is in place through the RMA, but needs some changes, and must be flexible at regional and local scales.**
- **Topography and cadastral databases need to be upgraded to assist designing local response options and assessing overall regional response.**

7 Conclusions

After somewhat tentative global assessments of climate change in the 1990s, the latest IPCC (2001a) Third Assessment Report has concluded that human-induced global warming is already a detectable reality. Global average sea level has already risen by 01 to 0.2 m over the 1900s. Most likely projections on global sea-level rise are for a further 0.14 to 0.18 m by 2050 and 0.31 to 0.49 m by 2100. The IPCC projects that sea level will continue to rise for several centuries, even with abatements in greenhouse gas emissions and stabilisation in concentrations.

In New Zealand, western parts are projected to be wetter, but it should be drier in the east. This change in rainfall distribution, coupled with any changes in waves, winds and storms, could well alter the sediment supply to estuaries and the coast. Any reduction in sediment supply, along with storm impacts that ride on the back of a higher sea level, will lead to more coastal erosion.

There will be regional and local differences from the global projections. More targeted research, modelling and monitoring are required to translate global projections to likely regional effects.

Impacts on coastal margins arising from climate change are summarised in Figure 13. Sea-level rise and changes in sediment supply will dominate the effects on the physical environment, while rising sea and estuary temperatures, high doses of silts/muds during storms, and human intervention (such as stopbank protection, which may decrease intertidal flats) will be key drivers of changes in aquatic ecosystems.

Three broad options have been proposed to respond to coastal climate change threats in coastal margins: planned retreat, accommodation or adaption, and protection. Figure 21 summarises the range of response options for open coasts and estuaries.

Protection measures such as seawalls, stopbanks, beach renourishment and pumping systems may protect property for several decades, but these are likely to be increasingly ineffective as sea-level rise accelerates and/or storm intensity and frequency increase. However, some regional councils and territorial authorities will be faced with difficult situations. For instance, existing communities that will be seriously threatened may have capital investment sources available locally to implement protection measures, but the current resource management framework under the RMA focuses on enhancing the natural character of the coast and minimising environmental effects. Hard protection measures usually result in further environmental loss of salt marshes, estuary intertidal areas and beaches – with detrimental effects on ecosystems, sources of kaimoana, recreation, and tourism. Soft protection options, such as raising the elevation of beaches and adjacent land by way of renourishment with additional sand or fill respectively, are more appropriate options. However, they will not be feasible in many locations, and would require extraordinary financial and political commitments into the indefinite future to maintain, in situations where they only benefit a small number of people.

Adaptation or retreat measures – such as elevation of structures, infrastructure (roads, railways) and land surfaces, and land-use designations that only allow shorelines to retreat naturally – are less disruptive response strategies. However, most of these options will require strategic action; few will occur autonomously. They will be challenging to implement in areas already highly developed.

Confronting coastal squeeze and the eventual loss of some beaches, coastal marshes/wetlands and estuary intertidal areas will require better information on the existing and future value of these recreational assets and habitats. Susceptibility of marshes and intertidal areas to future loss to sea-level rise, storms, temperature rise and altered freshwater run-off, and what these mean to ecosystems, will have to be addressed in the context of geomorphic setting, degradation that has already occurred and the extent of physical constraints on further landward retreat, such as bunding, stopbanks, housing estates, and road or rail causeways.

Solutions for mitigating damage caused by sea-level rise are complex, particularly where they involve people's homes and recreation areas, or are culturally significant (for example, marae, urupa, middens, sources of kaimoana). Because climate change effects will be widespread along the coastline, there will be no reasonable or cost-effective method of reversing or holding back the sea along extensive sections of coast. Further, sea-level rise due to the greenhouse effect is generally regarded by the insurance industry as an impending known event, which is likened to the recent Y2K issue, so the industry is unlikely to provide general insurance cover for such follow-on damage (Chris Ryan, Insurance Council, personal communication). Increasingly, liability issues from climate change related damage in developed coastal margins will arise between territorial authorities and property owners.

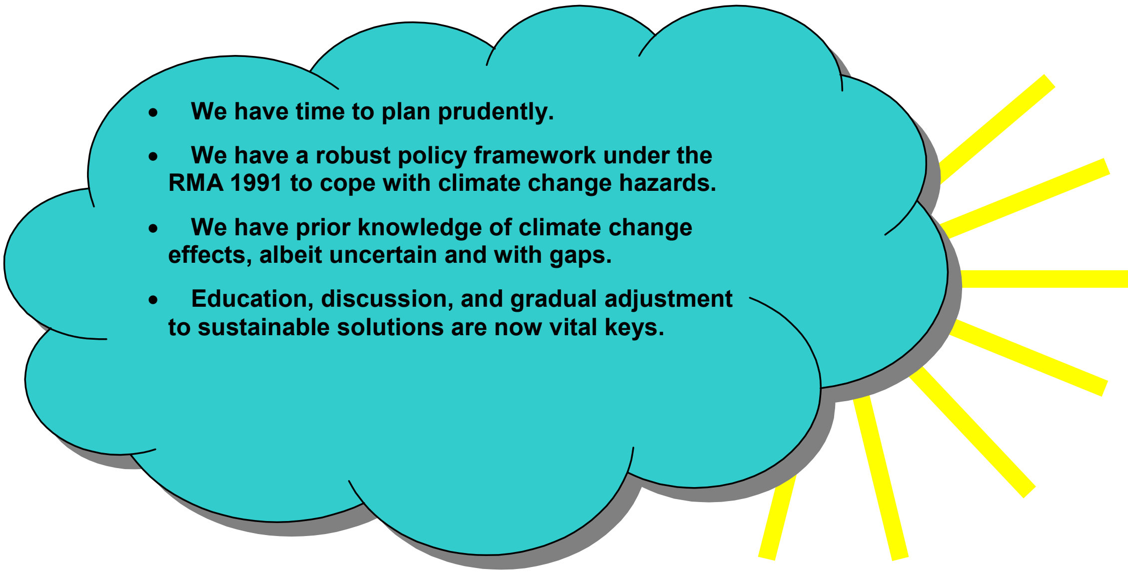
Ultimately, there is no silver lining to the sea-level rise story. The hope is that people and local communities will plan long term for its inevitable consequences, even though the rate of rise is currently small and the impacts likely to take a few decades to materialise. But the rise in sea level is insidious, so it is too easily ignored or forgotten until the problem surfaces during a major storm event. Unfortunately, society is much more prone to respond to a crisis situation with band-aid approaches.

Hopefully, common sense will prevail as long-term hazard mitigation plans and land designations are set in place through existing planning instruments such as regional policy statements, coastal and regional plans, district plans under the umbrella of a soon-to-be revised New Zealand Coastal Policy Statement and the existing Resource Management Act. The proposed changes to the Local Government Act 1974 also signal the need for councils to develop long-term plans that integrate social, environmental, cultural and economic activities, moving beyond the current requirement to look at a long-term financial strategy.

The biggest challenge will be changing the mindsets of New Zealanders: from one of complacency, to one that recognises that coastal margins will increasingly be under threat from climate change (even if it hasn't happened *yet*). Following a change in mindset, the next challenge will be to work through the issues of how humans can adapt and adjust to the changing coastal and estuarine landscape for generations to come.

In essence, climate change decision-making has been, and will continue to be, a sequential process under general, but gradually reducing, uncertainty of the impacts.

> The challenge is not to find the best policy today for the next 100 years, but to select a prudent strategy and to adjust it over time in the light of new information.
>
> *[Source: IPCC 1996]*



Glossary and Abbreviations

adaptive capacity	the ability of a human system or ecosystem to adjust or respond to climate change (including both variability and extremes), to reduce potential damages, to take advantage of new opportunities arising from climate change, or to cope with and absorb the consequences.
climate	average weather patterns over medium to long time scales of seasons, decades and centuries.
climate change	any significant change or trend in climate over time, either in the mean state of climate and/or in its variability (e.g. extremes of temperature or rainfall, retreat or advance of glaciers, El Niño–Southern Oscillation). The IPCC include both ‘natural’ change and that attributable to human activities (e.g. use of fossil fuels).
coastal erosion	a long-term trend of shoreline retreat and/or loss of beach sand volume over several decades. ‘Cutback’ is a more suitable term to use on a dynamically stable shoreline to describe the temporary loss of beach volume or shoreline retreat during a storm, before it gets replenished over ensuing weeks and months.
Coastal margin	in this report, defined as sub-environments such as shallow coastal waters, beaches, dunelands, lowland rivers, estuaries, salt marsh and all adjacent land areas that are affected by potential and actual impacts caused by the dynamic marine environment, including long-term impacts of climate change. The coastal margin includes the coastal marine area.
coastal marine area	(or CMA) is that area of the foreshore and seabed of which the seaward boundary is the outer limits of the territorial sea (12 nautical miles) and the landward boundary is the line of mean high water springs, except that where that line crosses a river, the landward boundary at that point shall be whichever is the lesser of 1 km upstream from the mouth of the river, or the point upstream that is calculated by multiplying the width of the river mouth by five (Resource Management Act 1991).
ENSO	El Niño–Southern Oscillation, the climate system that governs year-to-year climate variability in the Pacific and Indian Oceans.
hazard	a situation with the potential to cause harm or damage; a hazard does not necessarily lead to harm.
intertidal	the areas of an estuary or harbour that are exposed at low tide.
IPCC	Intergovernmental Panel on Climate Change, a group set up by the United Nations Environment Programme and World Meteorological Organisation to regularly assess climate change.
IPO	Interdecadal Pacific Oscillation, a 20 to 30-year climate cycle in the Pacific that modifies the ENSO system.

MHWS	mean high water spring, which is the level of the average spring tides predicted around full or new moon periods.
natural character	the qualities of the coastal environment that together give the coast of New Zealand recognisable character. These qualities may be ecological, physical, spiritual, cultural or aesthetic in nature, whether modified/managed or not.
natural hazard	any atmospheric or earth- or water-related occurrence (including earthquake, tsunami, erosion, volcanic and geothermal activity, landslip, subsidence, sedimentation, wind, drought, fire or flooding), the action of which adversely affects or may adversely affect human life, property or other aspects of the environment (Resource Management Act 1991).
risk	related to both the likelihood (how often it will occur) and the magnitude of an impact. It also has an element of subjective assessment by humans.
sea level	the level of the sea over a certain averaging period (days, weeks, years, decades) after averaging out the tides.
sea-level rise	the trend of annual mean sea level over time scales of at least two to three decades: *global* sea-level rise is the overall rise in absolute sea level in the world's oceans; *relative* sea-level rise is the net rise relative to the local landmass (which may be subsiding or being uplifted).
storm surge	a temporary elevation in sea level above the predicted tide height caused during storms by a combination of both low barometric pressure and on-shore winds that cause a set-up in coastal sea levels.
vulnerability	susceptibility to potential harm or damage, considering factors such as the ability of a system to cope or absorb stress or impacts and to 'bounce back' or recover.

Appendix A: Information Gaps and Monitoring Needs

It is clear from this report that there are considerable uncertainties about how New Zealand's beaches, estuaries and salt marshes will respond to local, regional and global changes in climate caused by global warming. Some of the uncertainties stem from a lack of good-quality information on coastal features and habitats, which could be met by a commitment to strategic information gathering and long-term monitoring. Many other uncertainties would require dedicated additional research to determine how humans, physical environments and ecosystems are likely to respond to climate change, and how that should be managed.

A substantial body of knowledge already exists, with ongoing research funded by the Foundation for Research, Science and Technology and, in some areas, local government. The lists of recommendations for additional research and information gathering were compiled by the authors during the process of writing this report, with additional inputs from contributors and reviewers. The recommendations are provided to assist, amongst others, the National Science Strategy Committee for Climate Change in its development and review of a comprehensive national climate research strategy and its advice to government on the overall balance of climate change research priorities.

Information and technology gaps

Following are some of the most important information and technology gaps that have been identified.

- Planners, engineers, scientists and the public need to have a GIS mapping tool available to identify layers of fundamental coastal-margin properties (for example, sediment type, intertidal areas, vegetation, active or non-active dunes, habitat types, ecology, marshes and wetlands, salt meadows, settlements, areas of cultural significance, planning boundaries and topography). Some of this work is currently being done by the Ministry for the Environment and NIWA to develop a marine and estuary classification system.
- An accurate topography (land and dune heights at many different locations) of the coastal margin is a key requirement for planning and researching the likely impacts of climate change, locally, regionally and nationally. Some city and regional councils have made progress, but it is a daunting task, made easier with the advent of modern remote-sensing techniques. Currently, on a national scale we have little idea of the overall physical, ecological and socioeconomic losses and impacts that would result from various stages of sea-level rise; for example, land areas that would be inundated or occasionally flooded by storms for different sea-level heights. This contrasts with the US, where maps showing vulnerable coastal margins at 1.5 m increments are now viewable on the internet.[3] Topography for New Zealand is currently only available in 10 to 20 m contour

[3] Maps at: http://www.epa.gov/globalwarming/publications/impacts/sealevel/maps/index.html

increments in the LINZ topographic database, which is much too coarse to ascertain coastal hazard impacts. Ideally, a topography database with small height and distance increments of less than 0.3 m and 1 m respectively would be of huge benefit in assessing climate change effects. The technology is available, but it may require both national and regional co-ordination and approximately $1 million to achieve such an outcome.

- The Digital Cadastral Database (DCDB) is a computer register containing data on land parcels throughout New Zealand. It represents the geographic location, shape, area, land appellation and street address for each land parcel and the legal definition of roads, road centrelines, railways and hydrographic features. The DCDB also contains administration boundaries such as local authority and electoral districts. Updating the DCDB (or the replacement LINZ **Land*online*** program) is required in vulnerable coastal margins. Legal boundaries can be out by 20 m in places, and more accurate location of the coastal marine area (as defined by the MHWS) and an updated shoreline would greatly improve its utility for coastal-impact assessments. The DCDB or Land*online* should build in a mechanism to include regular updates of the mean shoreline and MHWS tide mark, utilising modern remote-sensing techniques.
- Mapping on-land and offshore sand supplies could potentially be used for mitigation and beach renourishment. An alternative would be to research methods of better utilisation of dredged materials from ports/marinas.
- There are some gaps in the baseline monitoring of coastal drivers, such as sea level, waves, winds, sea-surface temperature, catchment exports (sediment and flow). Research should be aimed primarily at separating long-term trends and climate change effects from natural variability over years and decades. Present systems would need an injection of capital upgrading to improve their accuracy and put in place robust quality assurance systems.
- Regular updates of the magnitude and direction of predicted climate change are needed for the major regions of New Zealand (as outlined in Section 4.3).
- Lack of knowledge about subsidence and uplift along coastal margins is a major gap in the process of translating IPCC global projections into regional values of relative sea-level rise. The Institute of Geological and Nuclear Sciences (GNS) and the University of Otago are operating a pilot project using global-positioning sensor (GPS) units on top of four sea-level gauges in major ports. Leaving these units recording over long periods yields information on land stability (whether the land is subsiding or being uplifted) and tectonic activity. An allied gap nationwide is the need to establish – or re-establish in some cases – a set of 'bedrock' benchmarks associated with strategic sea-level gauges. Historical benchmarks are in poor condition for our port gauges (for example, located on wharf structures) or non-existent for some of the open-coast gauges (see Case Study 1). These bedrock benchmarks ideally should be surveyed and levelled annually, or at intervals no longer than five years (RJ Beavan, GNS, personal communication).
- There needs to be a regular (every decade) update of a national analysis of the extent of erosion and accretion of coasts (along the lines of Figure 4, but expanded in scope) and remaining areas of estuaries (including intertidal areas) and salt marshes. This could be achieved through co-ordinating the supply of relevant data from regional councils, while plugging any gaps with remote-sensing techniques, databases, aerial photos, etc. It would be important to extend the scope of this analysis to what is happening on sub-tidal beach profiles below the low-tide mark. By updating this every decade or so, it would reveal on a national scale if sea-level rise, sediment supply changes, or engineering protection works were having an overall effect on New Zealand's coastal margins. Local effects will be up or down, and that needs managing locally, but a national sweep would isolate the trend of shoreline movement and estuarine/marsh areas overall across the country.

- There needs to be more concerted effort put into regular monitoring (and developing efficient techniques) of full beach profiles that go beyond the surf zone, and of sedimentation rates in estuaries, including marshes, mangrove areas, and intertidal flats, to benchmark climate change effects.

Research gaps

- Better quantitative methods and models for determining coastal set-back or coastal hazard zones for rising sea-level scenarios are needed that incorporate factors other than sea-level rise (for example, changes in waves and windiness, frequency of storms, impacts on sediment budgets, such as river flows, flood sequencing and catchment contributions).
- Three-dimensional morphodynamic models (driven by hydrodynamics and sediment transport) should be developed to predict the impact on sandy coastlines of sea-level rise, and climate change effects on the various physical drivers (Figure 5), over long time scales covering El Niño/La Niña cycles and the Interdecadal Pacific Oscillation. These types of models would need to be calibrated for particular long sandy shorelines, such as Bay of Plenty, North Island west coast, Poverty Bay, Tasman Bay, Wanganui–Manawatu and Pegasus Bay. Different models would need to be developed for mixed sand/gravel coastlines, such as Canterbury Bight and Hawke's Bay.
- Integrated coastal-impact assessments of climate change need to be trialled for a few particular coastal units, based on consistent databases and scenarios of local and regional effects. We also need to look at analyses across various sectors (research, social, economic, governance), involving outreach to and inputs from the residents, iwi, stakeholders and policymakers in a region.
- The resilience and adaptation capacity of New Zealanders living along the coast needs to be determined. Social-impact studies are needed that will identify and begin quantifying the full range of social impacts on people facing, or likely to face, damage to property, and on communities wrestling with coastal hazards and the impacts of response options on both public and private assets. (Is their home their castle? Do they think they are safe if no previous erosion or flooding event has occurred? What is the effect on the well-being of residents once the threat of coastal hazard damage can no longer be ignored?)
- It would be highly desirable to have a database of the coastal hazard provisions in regional and district plans and policy statements under the Resource Management Act framework. We also need to undertake research into the way councils have implemented section 106 of the Resource Management Act and the coastal hazard provisions of the NZCPS, and regional policies and plans, and how climate change impacts on hazards may be built in to these planning instruments.
- Future impacts on Maori, who treasure the coast for its kaimoana and spiritual significance, need to be assessed. What is the adaptation capacity for Maori, and what response options do they favour, especially if middens, urupa or marae are in vulnerable coastal margins?
- Are New Zealand sandy beaches likely to follow the Bruun (1962) rule, which is so widely relied on, and erode? In particular, what is the likely response of intertidal sand/silt estuary beaches to sea-level rise? Further research could be carried out on sites that may act as surrogate beach systems under a rising sea level, such as large hydro lakes, where lake levels vary slowly with the seasons.

- There needs to be a review of information already available from overseas literature on likely physical and biological responses to climate change in coastal margins and marine ecosystems, including a summary of impact assessment techniques based on available New Zealand data and climate projections. This should also include a compilation of temperature tolerance ranges for species where data exist, and identify significant species (rare or economically important) for which data do not exist.
- We need to begin to devise methods (models) of possible changes in ecological function and diversity, given the difficulty predicting the details of the local ecological response due to uncertainties in the magnitude of change in coastal drivers and the interaction between these drivers and biological processes that produce emergent patterns or trends. Initially it may be better to tackle the simpler shifts in the re-distribution of species associated with new temperature regimes (for example, higher air and sea temperatures and associated decreasing frequency of frost will influence plants in estuarine and coastal fringing habitats).
- We need to identify potential response times to change for ecological systems in different coastal sub-environments (for example, temperature, increase in water depth, sedimentation, loss of intertidal areas, increased tidal prism volumes in estuaries as the waters edge retreats landward).
- Areas where freshwater inflows presently have a significant influence on the structure or functioning of the coastal ecosystem need to be identified, as do significant species and fisheries in these areas, and an assessment made of the risks associated with changes in river inflows or an ingress of seawater.
- We need to assess techniques that could be used to rehabilitate historically reclaimed land back to salt marsh and other fringing habitats to mitigate the likely progressive loss of such habitats in other areas where the shoreline is constrained by structures or geology.
- Salinisation effects on lowland freshwater ecosystem processes, including fringing habitats and vegetation, need additional research.
- The likely changes to continental shelf upwelling zones, and potentially affected coastal areas, need to be identified, as do important species and fisheries that presently depend on upwelling, and an assessment made of the risk from disruption of upwelling on the functioning of these coastal ecosystems, abundance of important species, and fisheries.
- We need to carry out research on sea-level variability on time scales of years to decades, and determine from global sea-surface heights whether there are regional differences in response of the southwest Pacific, compared with the global average rise.
- Robust real-time and forecasting techniques for sea storms and coastal flooding in vulnerable areas are needed.
- A more rational and pragmatic planning boundary for the coastal marine area (other than MHWS?) is needed to facilitate more co-operative planning between regional councils and territorial authorities, especially in the light of projected climate change, which will see the coastal marine area progressively encroach on to adjoining land in the coastal margin.

Appendix B: Contributors and Reviewers

A number of people across a range of sectors provided input through discussions, invitations to contribute comments and case studies, or requests for reviews. The contributions of the following are gratefully acknowledged.

Research sector

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