This online textbook provides free access to a comprehensive education and training package that brings together the knowledge of how countries, specifically Australia, can adapt to climate change. This resource has been developed formally as part of the Federal Government’s Department of Climate Change’s Climate Change Adaptation Professional Skills program.

Chapter 1: Understanding the Risks and Adapting to Climate Change

Lecture 1.4: Adapting to Sea-level Rises – Coasts and the Built Environment
The Natural Edge Project ('TNEP'), 2009

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Acknowledgements

The Work was produced by The Natural Edge Project funded by the Australian Government Department of Climate Change under the Climate Change Adaptation Skills for Professionals Program, with in-kind hosting provided by Griffith University and the Australian National University. The development of this publication has been supported by the contribution of non-salary on-costs and administrative support by the Science, Engineering, Environment and Technology Division (SEEET) of Griffith University, under the supervision of Professor Brendan Gleeson, and both the Fenner School of Environment and Society and Engineering Department at the Australian National University, under the supervision of Professor Stephen Dovers.

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Educational Aim

Adapting to sea-level rises is one of the greatest climate change related challenges that will face humanity in the coming centuries. In the short term, even very small increases in sea level will amplify storm surge damage, and in the longer term anticipated rises in sea level stand to threaten inundation of coastal development across the world. This lecture will explain how climate change is causing sea-level rises, and discuss the associated risks (including amplification of storm surges) as well as providing an overview of the adaptation options (which will be covered in more detail in Module C). It is important also for built environment professionals and planners to realise that the scientific understanding of sea-level rises induced by climate change is evolving rapidly. This lecture summarises some of the most important recent developments that will affect the likely scale and rate of sea-level rises, so as to help better inform planning decision making processes. Practitioners in the field should continue to stay up-to-date with the climate science which relates to sea-level rises.

Learning Points

1. Global warming, caused by rising levels of greenhouse gas emissions, is causing sea levels globally to rise, through a combination of thermal expansion of the oceans, and the melting of glaciers, ice caps, and large ice sheets into the oceans. The average temperature of the global ocean at depths of up to 3000 m has been increasing since 1961, and this additional heat provides the water molecules with more energy to vibrate, so the volume taken up by the molecules increases, leading to rising sea levels. This is known as thermal expansion. Thermal expansion results from the ocean absorbing the heat that has been added to the atmosphere, and it is estimated that the world’s oceans have been absorbing more than 80 per cent of this heat. Widespread melting of glaciers, ice caps and ice sheets have also contributed to sea-level rise. The melting of the Greenland and Antarctic ice sheets, for example, have very likely contributed to the sea-level rise between 1993 and 2003.

2. The IPCC has found that ‘The global sea-level rose at an average of 1.8 mm/year from 1961 to 2003, and the rate of increase was faster (about 3.1 mm/year) from 1993 to 2003.’ It is anticipated that the global average sea level will rise at least between 9 and 88 cm between 1990 and 2100, and if it rises 88 cm, the IPCC 4th Assessment warns that coastal flooding could...

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2 Ibid
3 Ibid
4 Ibid.
6 It is important to note that local factors will mean that for any specific region sea levels will rise slightly higher or slightly lower than the average global sea-level rise.
'grow tenfold or more by the 2080s, to affect more than 100 million people/yr'.

While the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment projected a sea-level rise of between 9 and 88 cm between 1990 and 2100, the assessment also cautioned that due to significant levels of ice melt in the northern summer of 2007, the estimate of 88 cm could actually be an underestimate. Rahmstorf has shown that the observed rate of sea-level rise is tracking at or near the upper limits of the envelope of IPCC projections.

3. Given the uncertainties inherent in long-term sea-level rise prediction, a risk management approach – which weighs the probability of certain changes happening against the magnitude of the impact if they do – is recommended for decision makers to underpin efforts to reduce the risks of damage from sea-level rises as cost-effectively as possible. When assessing risks and adaptation strategies, it is important that decision makers, planners, and local and state governments look at the short, medium, and long term risks from sea-level rises.

4. The main risk of damage from sea-level rises in the short term comes through the potential for sea-level rises to combine with storm surges from extreme weather events, such as cyclones in the tropics, and large cold fronts in the middle and lower latitudes. The IPCC 4th Assessment found that the greatest hot spots at risk of damage from sea-level rising is North and South East Queensland, where there are risks of cyclones creating storm surges, which at a high tide can inflict severe damage. This coastline has many sandy beaches and dunes, and also includes Fraser Island, the world's largest sand island. The region's population is projected to increase rapidly in the short term, with many estuaries and nearby lowlands having already been intensively developed, and thus, as sea-level rises, the risks of damage and flooding of buildings and the built environment Far North and South East Queensland from storm surges and high tides will grow. It is important to note that the frequency of extreme events is already increasing in many locations. There is clear evidence for this already in Fremantle and Sydney where the frequency of extreme tidal events has changed upward by between 2 and 3 fold due to sea-level rises.

5. The potential negative risks, in the medium to longer term, from sea-level rise can be divided into five categories: 1) inundation of low-lying areas, 2) erosion of beaches and bluffs, 3) salt intrusion into aquifers and surface waters, 4) higher water tables, and 5) increased flooding and storm surge damage. The potential magnitude of impact in these five areas needs to be assessed on a case by case basis to determine the level of risk to different cities, towns and communities along the Australian coast. CSIRO's researchers are working with local

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12 Ibid
13 Ibid
14 Ibid
governments to help understand the nature of these risks. CSIRO’s scientists such as Drs Debbie Abbs and Katherine McInnes have published many studies which have mapped likely sea-level rises and impacts of storm surges for Australia’s major coastal cities and coastal developments.

6. Over the next one hundred years many Australians will be at risk from sea level rises. The IPCC warns that that 1 cm rise in sea level erodes beaches about 1 m horizontally. Therefore, even the lower end of the IPCC predictions, 9 cm is likely to result in as much as 9 m of eroded beach and coastline. Hence by the year 2100, significant coastal erosion is anticipated and sandy beaches could have receded by up to 88 m. Eighty per cent of Australian’s population lives in the coastal zone. Longer term, if the global sea level rise is not stopped in coming centuries, about 711,000 Australian household addresses will be threatened, which are located within 3 km of the coast and less than 6 m above sea level.

7. When assessing risk, one key factor to take into account, when determining the potential magnitude of the damage is whether or not insurance is available. Sea level rises will pose a significant risk to many Australians over the coming decades because currently most insurance companies are not willing to provide insurance for damages from storm surges. Karl Sullivan from Insurance Council of Australia recently stated that “There is very limited cover available for this particularly inundation risk and it is one of many different flooding risks that you can have. It is viewed as an extreme risk for a large number of Australians and consequently there’s not a huge appetite to insure that risk because we don’t understand how far and how expensive that could be. The first thing that needs to happen there is mapping that risk right across Australia and making policy decisions in a planning sense about avoiding the risk into the future.”

8. The next step in a risk assessment approach is to identify the best way to reduce risks in this case from sea level rises. The best and most cost effective adaptation measures for sea level rises are related to urban planning or infrastructure. Since these decisions have very long time horizon, it is vital that planning decisions made today take likely sea level rises into account. This is why the Victorian Government Coastal Strategy (2008) requires local government to incorporate sea-level rises of no less than 0.8 m by 2100 into all planning decisions and bans any further canal residential development. Local government must assume sea-level rises of 80 cm by 2100 when considering any new developments for approval. The strategy also urges local government councils to consider other climate change effects, including storm surges, erosion and landslides, when approving developments. Similar new coastal strategies should be adopted by all state and local governments in Australia, not just because it is the wisest course of action, but also because it will help governments avoid legal liability for any damages from

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rising sea-level rises. With the likely prospect of increasing extreme weather events being exacerbated by sea level rises, legal experts argue local government is at increasing risk of incurring liability if they ‘unreasonably fail to take into account the likely effects of climate change’.  

9. A sound risk management approach to sea level rises also needs to factor in the risk that the IPCC 4th Assessment predictions for sea level rises may be too conservative. There is concern that sea levels may rise more quickly and higher than originally expected and even could exceed 1 m by 2100. NASA Scientist, Dr James Hansen, argues that the slow melting of ice sheets used for the current IPCC Sea-level Rise estimation is does not match up well with the historic climate change record. Hansen points out that the geological record suggests that when temperatures increased to 2-3 degrees above today’s level 3.5 million years ago, sea levels rose not by 59 cm but by 25 m.

10. Also, there is concern that the IPCC’s latest predictions on the speed of sea level rises may also be too conservative. The IPCC 4th Assessment predicted that significant melting of the Greenland and West Antarctica ice sheets would not happen for over 100 years. However, scientific evidence in late 2008, a year after the publication of the IPCC 4th Assessment report, shows that sea levels could rise faster than scientists had previously predicted, due to a number of environmental side effects feeding back on the overall system and accelerating the trend known as “positive feedbacks”. Hence, there is a need for decision makers, planners and government officials involved in planning to monitor these ‘feedbacks’ over time to reassess potential sea-level rises and factor this information into planning and development decisions and risk assessment.

11. These “positive” feedbacks could lead to sea-level rises higher than 1 m by 2100 and include:
   - The melting of the North Arctic Sea ice, which is particularly dangerous as the ice has a high ‘albedo’ effect, meaning that it reflects light well, and when it is melted it is replaced by water, with a lower albedo, which absorbs much more heat, hence accelerating the ocean’s warming even further.
   - Rapid melting of the North Arctic Sea ice and a reduction in albedo will result in more rapid warming of the permafrost and other substrates in the northern hemisphere. This, in turn, will increase the rate of release of methane from peat deposits, wetlands and thawing permafrost. With increasing temperatures methane is released from a range of storages in the environment, hence increasing the global greenhouse gas emissions levels.

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- A study published in January 2009\textsuperscript{31} argued that most of the Antarctic continent was warming, up half a degree over the past half-century, and that ice shelves which hold the large Antarctic glaciers from the sea are weakening.

- The weakening of the natural land carbon sinks, reducing the amount of greenhouse gas that can be absorbed, sometimes to the point that greenhouse gases are released.\textsuperscript{32} This is due mainly to deforestation and loss of vegetation combined with agricultural practices affecting the ability of soil to absorb carbon dioxide.

- Ocean acidification is happening faster than predicted, spelling disaster for coral reefs and resulting in the ocean diminishing as a carbon sink — it will absorb less carbon dioxide, leaving more in the atmosphere to trap heat. The weakening of the natural ocean carbon sinks reducing the amount of greenhouse gas that can be absorbed.\textsuperscript{33} As the temperature of the oceans increase, its ability to absorb carbon dioxide decreases.

12. The following three possible coastal adaptation response options are recommended by the IPCC to reduce the risks of damage from sea level rises (discussed in the Brief Background Information).\textsuperscript{34}

- Protect: Protect the land and cities from the sea so that existing land occupation can be maintained by constructing hard structures (such as seawalls) and using soft measures (such as beach nourishment).

- Accommodate: The land is still occupied but some modifications are made (such as elevating buildings on piles such as using the old Queenslander house design and growing flood- or salt-tolerant crops).

- Retreat: The coastal region is abandoned.\textsuperscript{35}

**Brief Background Reading**

**Climate Change and Sea-level Rises**

Current Intergovernmental Panel on Climate Change (IPCC) 4th Assessment projections are for a sea-level rise of between 9 and 88 cm between 1990 and 2100 but the 4th Assessment final Synthesis Report has stated that larger values for the upper bound cannot be excluded. As seen in Figure 1.4.1, at the global scale, ocean temperatures and sea level will continue their rising trends.\textsuperscript{36} Observations since 1961 show that the average temperature of the global ocean has increased at


\textsuperscript{35} Ibid

depths of at least 3000 m, and that the ocean has been absorbing more than 80 per cent of the heat added to the climate system.37

![Figure 1.4.1 Projected sea-level rise for the 21st Century](image)

Source: CSIRO38

Such warming causes seawater to expand, contributing to sea-level rise. As Table 1.4.1 shows, climate change causes sea-level rises due to thermal expansion of the oceans. Thermal expansion is just one factor causing sea levels to rise. Sea-level rise is also due to the melting of glaciers, ice caps and large ice sheets into the oceans as shown in Table 1.4.1.

**Table 1.4.1:** Observed rate of sea-level rise and estimated contributions from different sources

<table>
<thead>
<tr>
<th>Source of sea-level rise</th>
<th>Average annual sea-level rise (mm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal expansion</td>
<td>0.42 ± 0.12</td>
</tr>
<tr>
<td>Glaciers and ice caps</td>
<td>0.50 ± 0.18</td>
</tr>
<tr>
<td>Greenland ice sheet</td>
<td>0.05 ± 0.12</td>
</tr>
<tr>
<td>Antarctic ice sheet</td>
<td>0.14 ± 0.41</td>
</tr>
<tr>
<td>Sum of individual climate contributions</td>
<td>1.1 ± 0.5</td>
</tr>
<tr>
<td>Observed total sea-level rise</td>
<td>1.8 ± 0.5</td>
</tr>
<tr>
<td>Difference (Observed minus sum of estimated climate contributions)</td>
<td>0.7 ± 0.7</td>
</tr>
</tbody>
</table>


Note: Data prior to 1993 are from tide gauges; those from 1993 onwards are from satellite altimetry. 

Source: IPCC (2007) 39

The global sea level rose at an average of 1.8 mm/year from 1961 to 2003, and the rate of increase was faster (about 3.1 mm/year) from 1993 to 2003, as shown in Table 1.4.1. 40 It is important to note that locally sea level rise will be slightly higher or lower than the global average for sea-level rises. This is because sea-level rise also depends on a number of factors such as where the heat penetrates the oceans, how this changes circulation patterns and how local geography interacts which the mean flow.

During the 21st Century, on average, sea levels will continue to rise due to warming from both past and future greenhouse gas emissions.

Sea levels will respond more slowly than temperatures to changing greenhouse gas concentrations. Sea levels are currently rising globally at around 3 mm per year and the rise has been accelerating. According to the IPCC, sea levels are projected to rise by 9-88 cm by 2100, mainly due to expansion of the warmer oceans and melting glaciers on land. However, because warming only penetrates the oceans very slowly, sea levels will continue to rise substantially more over several centuries. On past emissions alone, the world has built up a substantial commitment to sea-level rise.

Sir Nicholas Stern, The Stern Review, 2006 41

Risks and Costs of Inaction on Sea-level Rises

Many developed locations in Australia are lower than 1m above sea level and are thus vulnerable to sea-level rises this century. These locations include Broome, Perth and its surroundings, Mandurah and its surroundings, Busselton, parts of most capital cities and, in particular, the Gold Coast, which is built on sand and has many canal developments. Approximately 700,000 Australian homes face flood risks from the combination of rising sea levels and storm surges. 42 The IPCC warns that that 1 cm rise in sea level erodes beaches about 1 m horizontally. 43 However, depending on the geomorphology, coastal flooding can be between 50 - 200 times the sea-level rise. 44 The coastal property owners of insured buildings may lose millions of dollars, as whilst the value of coastal buildings may be protected to some extent by insurance, the land value of properties is not insured at all. Thus when land gets inundated or severely eroded and their land loses value they will not be compensated by insurance. 45 It is thus in Australia’s interest to mitigate climate change to avoid this potential future scenario. It is also in the global interest.

44 Ibid.
Globally, tens to hundreds of millions more people will be flooded each year under the business-as-usual greenhouse gas emission scenario.\(^{46}\) According to IPCC 4\(^{th}\) Assessment, coastal flooding could grow tenfold by the 2100, due to sea-level rise alone. Figure 1.4.2 shows the consequences and total costs of a rise in sea level for developing and developed countries, and globally. For coastal cities and towns the potential magnitude of negative impact from these risks can be very high. A 1 m sea-level rise this century would leave 2.2 million square km of land under water, forcing 145 million people to migrate, mostly in Asia, and costing the global economy US$944 billion.\(^{47}\)

**Figure 1.4.2 Causes, Consequences and Total Costs of an Assumed Sea-level Rise**

Sea-level rise will directly impact on millions of people over the next century,\(^{49}\) but this is likely to be overshadowed, particularly in the shorter term, by the impacts of extreme weather events that are

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exacerbated by sea-level rise.\textsuperscript{50} That is, even if the climate conditions that lead to weather events (such as cyclones and storm surges) remain unchanged in terms of intensity and frequency, the higher sea level will make the impacts more intense and more frequently reach ‘extreme’ levels. The frequency of extreme events is already increasing in many locations and, depending on local conditions, 100-year events could occur as frequently as every few years by 2100.\textsuperscript{51}

Coastal erosion or flood risk will affect at least 158,000 people by 2020 in Europe, while 50 per cent of Europe’s remaining coastal wetlands most likely will disappear under rising sea levels.\textsuperscript{52} In 2004, about a fifth of the European Union’s coastline suffered serious erosion. Between 1986 and 2001, expenditure on coastline protection in Europe has risen over 30 per cent to an estimated US$4 billion in 2001.\textsuperscript{53}

\textbf{Sea-level Rises Combine with Storm Surges}

Sea-level rise will cause damage and disruption over the coming centuries. But perhaps more importantly in the short term, the main threat of damage from sea-level rises comes through the potential for it to combine with storm surges from extreme weather events, such as cyclones in the tropics, and large cold fronts in the middle and lower latitudes.

Storm surges occurring on higher mean sea levels will lead to inundation and enable waves to push further inland, increasing damage and erosion of the built environment and natural coastline. CSIRO has found that extreme sea-level events that currently occur once every 100 years could occur as frequently as once every few years by 2100.\textsuperscript{54} Along the east coast of the United States and Canada, sea-level rise over the last century has reduced the period between extreme sea-level events, leading to greater and more rapid damage to fixed structures, compared to the same events a century ago.\textsuperscript{55}

\begin{figure}[h]
    \centering
    \includegraphics[width=\textwidth]{sealevel_rise.png}
    \caption{Effect of a small average sea-level rise on sea-level extremes}
\end{figure}

\begin{footnotesize}
\begin{itemize}
    \item ibid
    \item ibid.
    \item ibid
\end{itemize}
\end{footnotesize}
The IPCC 4th Assessment found that the greatest hot spots at risk of damage from sea-level rising is north and south east Queensland, where there are risks of cyclones creating storm surges, which at a high tide can inflict severe damage. As the IPCC stated, ‘Between 2001 and 2021, the Sunshine Coast population is projected to grow from 277,987 to 479,806, and the Wide Bay-Burnett population is projected to grow from 236,500 to 333,900. Sandy beaches and dunes are key biophysical characteristics of this coastline, including Fraser Island which is the largest sand island in the world. These natural features and the human populations they attract are vulnerable to sea-level rise, flooding, storm surges and tropical cyclones. Many estuaries and adjacent lowlands have been intensively developed, some as high-value canal estates.

Thus a rise in sea level of even a few mm per year, although not threatening spectacular inundation of the coastline, is still extremely important as it can enhance the reach and power of storm surges, as Bird, Warrick et al, and Nicholls and Leatherman emphasise. (Figure 1.4.4)

Sea-level Rise Impacts on Waste Water and Storm Water systems

Urban water supply and urban stormwater and wastewater treatment systems are also vulnerable to sea-level rises. Protecting these systems and the potable fresh water supplies from saltwater

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intrusion is one of the most challenging issues relating to climate change.\(^{66}\) Sea-level rises and storm surges risk leading to an increased level of poor stormwater drainage performance caused by seawater levels backing up drainage systems. Urban coastal sewerage systems depend on gravity to help treated sewerage flow, usually out to sea. Sea-level rises and storm surges threaten to prevent this from happening. This inundation would render gravity drainage systems useless and require modifications to prevent seawater from backing up into the system.

**Sea-level Rises – Is there a Potential for a > 1 m Sea-level Rise by 2100-2200?**

Governments and planners across the world are now becoming increasingly aware of the requirement to consider the risks of sea-level rise in the development of policy and planning, considering options in the event of a rise of up to 1 m by 2100. Many approaches to this challenge emphasise strategies to ensure that future development occurs further inland, and at least 1 m above sea level. But is 1 m sufficient? What if the global average sea-level rise ends up being greater than 1 m over the next one hundred years? Also, since there is a long delay built into sea-level rises, due to the thermal expansion effect, even with strong climate change mitigation in the early decades of the 21\(^{st}\) Century, sea levels may continue to rise well into the next century.\(^{67}\)

Investors in real estate, or other forms of development, need the security of knowing that the site, which they are investing in, will be safe from sea-level rises for at least 50-100 years to ensure land resale values are at least maintained.\(^{68}\)

Whilst it is true to say that the highest probability is that sea levels will rise between 18 cm and 1 m by 2100, it is possible that it could be higher than this. Should the Greenland ice sheet and the Western Antarctic Ice Shelves melt, this would result in up to 7 m,\(^{69}\) and 5-6 m global sea-level rise respectively, significantly greater than the 1 m predicted. One of the reasons why there is such uncertainty about the loss of polar ice sheets is that climate scientists have never witnessed their disappearance. Thus, scientists, led by Anders Carlson,\(^{70}\) have investigated the melting of polar ice sheets using geological evidence from the end of the last ice age, to better understand the phenomenon of ice sheets melting. Around 20,000 years ago, when the last ice age was at its peak, the Laurentide ice sheet covered much of North America. This ice sheet was the most recent large Northern Hemisphere ice sheet to completely disappear. The researchers used geological evidence and computer modelling to reconstruct the demise of the Laurentide ice sheet. Computer simulations based on the geological data showed that that the first ice melt, from around 9,000 years ago, led to sea-level rises of 7 m at a rate of around 1.3 m per hundred years.\(^{71}\) The scientists involved in this study argue that there are strong parallels with this ice sheet and the Greenland ice sheet today. Thus Carlson, lead author of the study, concludes that, ‘For planning purposes, we should see the IPCC projections as conservative. We think this is a very low estimate of what the Greenland ice

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\(^{68}\) This is exacerbated by the fact that locally changes might be more or less than the global average. The kind of work that CSIRO researchers like Deborah Abbs and Kathy McInnes are doing is to try to make these projections of change more realistic at the regional to local level.


sheet will contribute to sea level." This has implications for governments and planning authorities currently grappling with what level of sea rise they should build into their long term planning. It is important therefore for urban planners and government officials, and those working in the built environment, to understand the most recent developments in climate change which will affect the scale and rate of sea-level rises. We consider these recent developments next.

Understanding the Latest Climate Science and the Risks of > 1 m Sea-level Rises by 2100

The concern over the conservative estimate of the IPCC arises because of the complexity of the climate system, and in particular, how a range of associated environmental changes and impacts will affect the rate of melting. The following environmental changes and impacts stand to have direct effects on the scale and rate of sea-level rise.

The Melting of Polar Sea Ice and Implications for Greenland Ice Melt and Sea-level Rise

The first important trend to consider is the rate of thawing of Arctic sea-ice into water. This is particularly important as ice floating in water reflects a much higher percentage of incoming sunlight back into the atmosphere than water, down from around 80 per cent to 10 per cent. This is known as the ‘albedo’ effect, where the replacement of highly reflective sea ice with darker open water greatly increases heat absorbed from sunlight.72 Greater absorption of the Sun’s heat leads to an increase in water temperatures, resulting in further thermal expansion, faster melting of remaining sea ice, and local increases in air temperature that increases melting of land based ice in the area. NASA climate change expert Dr James Hanson asks the question: ‘Could the Greenland ice sheet survive if the Arctic were ice-free in summer and fall? It has been argued that not only is the ice-sheet survival unlikely (under this circumstance), but its disintegration would… proceed rapidly. Thus an ice-free Arctic Ocean, because it may hasten melting of Greenland, may have implications for global sea level, as well as the regional environment, making Arctic climate change centrally relevant.…’74

If you had asked most climate scientists at the start of 2007 when they thought the Arctic would be free of sea ice in summer, most would have said by 2100 or perhaps 2070 at the earliest. Now respected climate scientists say that the summer arctic ocean could be ice free by as early as 2013-2030.75 The reason for this significantly revised estimation is the September 2007 sea ice levels, which were the lowest ever recorded, beating the old record set in September 2005 by 23 per cent – i.e. additional melting the size of the USA’s states of Texas and California combined.76 Between 1997 and 2002, the ice thickness in the Arctic decreased 35 per cent and the volume by 33 per cent.77 The decrease in both extent and thickness suggests that the summer sea-ice has lost more than 80 per cent of its volume in 40 years. Arctic sea-ice now is unusually thin, making it more likely

to melt in future summers. Combining the shrinking sea-ice area with the thinness of the remaining ice, it has been estimated that the overall volume of ice has fallen by half since 2004.78

Figure 1.4.5: Actual Arctic Summer Sea Ice Loss Compared to IPCC Models

Source: Dr Asgeir Sorteber (2007)79

Following the extraordinarily hot Arctic summers of 2007 and 2008,80 many climate scientists have warned that we are approaching a tipping point of great significance. Hansen,81 for example, has said that the today’s level of CO₂ in the atmosphere is enough to cause Arctic sea-ice cover and massive ice sheets such as on Greenland to eventually melt away leading to greater sea level82 rises. Many other scientists agree.83

**Implications from Recent North Arctic Sea Ice Melt on Rates of Greenland and West Antarctic Ice Melt**

The rapid melting of sea ice in the Arctic in 2007 led to the absorption of enough heat by the ocean to affect the melting of land ice in Greenland. Eric Rignot, a lead author of a paper showing a doubling of loss from the Greenland ice sheet over the last decade,84 has stated that, ‘These results absolutely floored us... The glaciers are sending us a signal. Greenland is probably going to

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emissions and ocean temperatures have gradually increased, the buffering capacity of the oceans
have absorbed nearly half the carbon dioxide produced by human activities. 95 Greenhouse gas with a global warming effect that is 25 times more potent than carbon dioxide. 90
The edges of the ice-sheet are melting up to ten times more rapidly than earlier research had indicated, and the ice sheet height is falling by up to 10 m a year. 88 In addition to these surface processes, there are suggestions of a potential dynamical response (sliding of the outlet glaciers over the bedrock) of the Greenland and Antarctic ice sheets. In Greenland, there was a significant increase in the flow rate of many of the outlet glaciers during the early 21st Century. One potential reason for this is increasing surface melt making its way to the base of the glaciers, lubricating their flow over the bedrock, consistent with increased glacier flow rates. Another effect which may be becoming more important is that, as the ice shelves around Antarctica and Greenland melt or break up they allow the glaciers behind them to flow faster, leading to increased flow into the ocean.

Implications from the Release of Methane from Peat Deposits, Wetlands and Thawing Permafrost
The rate of global temperature and sea-level rise will also be amplified by the potential release of billions of tons of methane from peat deposits, wetlands and thawing permafrost. 89 Methane is a greenhouse gas with a global warming effect that is 25 times more potent than carbon dioxide. 90 Models suggest that up to 90 per cent of the upper layer of permafrost will thaw by 2100, 91 and this, together with the wetland and permafrost soil stores, comprise more than double the total cumulative emissions from fossil fuel burning so far. 92 As the Stern Review recognises, permafrost melting is now another escalating issue to consider with global warming and predictions of rates of Greenland ice sheet melting and sea-level rises. 93

Implications of the Weakening of the Planet’s ‘Carbon Sinks’
Global temperature increases and sea-level rises will also be amplified by the weakening of the ocean and land ‘carbon sinks’ to absorb greenhouse gas emissions. Scientists are warning that levels of carbon dioxide in the atmosphere have grown 35 per cent more quickly than expected since 2000 partly because of a ‘weakening’ of natural carbon sinks. 94 Over the last 200 years, the oceans have absorbed nearly half the carbon dioxide produced by human activities. 95 However, as emissions and ocean temperatures have gradually increased, the buffering capacity of the oceans

have decreased, resulting in ocean acidification, changes to biological processes, increased temperatures and a reduced ability to absorb more carbon dioxide. This is also reflected in land ecosystems through reduced plant growth and the drying and burning of forests (releasing more carbon dioxide).

To conclude, the latest science concerning these ‘positive feedbacks’ is leading many climate experts to review their estimates of the potential speed and scale of sea-level rises for this century and beyond. Dr Graeme Pearman, former head of CSIRO’s Atmospheric and Marine Research Division, summed up the situation well in a report in 2007, stating that,

A recent review of climate observations compared to projections suggests that the IPCC projections may have underestimated sea-level rise. The observed sea-level rise for 1993 to 2006 shows a linear trend of 3.3 +/- 0.4 mm/year, which is higher than the IPCC projected best estimate of 2 mm/year. Rahmstorf estimates a sea-level rise of 0.5 to 1.4 m by 2100, which is much higher than the range of projections in the IPCC Fourth Assessment Report. In its assessment, the IPCC assumed a negligible contribution to 2100 sea-level change from the loss of Greenland and West Antarctic ice. More recent work suggests that this conclusion is likely to be incorrect. Projected warming of 2-3 degrees Celsius would result in increased melt-water during lengthened melt seasons. Multiple positive feedbacks would have a significant impact on accelerated loss of ice sheets. The consequences ‘could yield sea-level rise of several metres per century with eventual rise of tens of metres, enough to transform global coastlines’.

Climate Change Adaptation Strategies to Address Risks from Sea-level Rises, Storm Surges and Flooding

Increasingly national, state and local governments are undertaking the development of serious climate change adaptation strategies to address the risks of sea-level rises. The choice of


the best mix of measures to adapt to sea-level rises depends on many variables, such as the geography, economic, political and environment of the particular part of the coastline. Although such measures could be implemented on a case by case basis there are general patterns. In 1990, the IPCC published a comprehensive guide to governments on the three possible coastal adaptation response options:105

− **Protect:** which aims to protect the land from the sea so that existing land uses can continue, by constructing hard structures (e.g. seawalls) as well as using soft measures (e.g. beach nourishment).

− **Accommodate:** which implies that people continue to occupy the land but make some adjustments (e.g., elevating buildings on piles, growing flood- or salt-tolerant crops).

− **Retreat:** which involves no attempt to protect the land from the sea; in an extreme case, the coastal area is abandoned.

<table>
<thead>
<tr>
<th>Coastal adaptation (IPCC CZMS, 1990)</th>
<th>Adaptation objectives (Klein and Tol, 1997)</th>
<th>Adaptation responses (after Cooper et al., 2002; Defra, 2001)</th>
<th>Example</th>
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<tr>
<td>Protect</td>
<td>Advance the line</td>
<td>Land claim; empowering Estuary closure</td>
<td></td>
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<tr>
<td>Accommodate</td>
<td>Hold the line</td>
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<td>Improved awareness and preparedness</td>
<td>Community focussed adaptation</td>
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<td>Monitoring only</td>
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<td>Flood hazard mapping; flood warnings</td>
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**Figure 1.4.6 Evolution of Coastal Adaptation Strategies**

*Source: IPCC (1990)*

In Figure 1.4.7, the IPCC extends this framework as it is relevant to the protection of island states that are threatened by rising sea levels. The 1990 IPCC report on *Strategies for Adaptation to Sea Level Rise* outlines in detail each of the options engineers and government planners need to consider.107 Other useful resources to guide decision makers, engineers and planners here include:

- The publications pages of CSIRO scientists such as Drs Debbie Abbs108 and Katherine McInnes.109 These pages list many studies which have mapped likely sea-level rises and impacts of storm surges for Australia’s major coastal cities and coastal developments. For instance, they found that in Gippsland, Victoria, by 2070, climate change would increase 1-in-100 year storm

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surge heights by 38-46%. Their modelling indicated that most of this height increase was due to sea-level rise.

- There have been a range of recent conferences which have brought together expertise in this area and experience to-date in making these choices to plan to adapt to sea-level rises.

- There are also studies and economic modelling which seeks to work out the relative cost benefits of the different options, such as retreat versus protection, which can help guide processes to make these decisions.

- Finally, the Australian Government and CSIRO’s ‘Your Development Portal’ provides a list of questions to ask to help guide adaptation to sea-level rises for specific future developments.

We now overview the general strategies to adapting to sea-level rises briefly. A more detailed discussion of these options will be covered in Module C.

**Protection of Coastal Cities and Towns from Sea-level Rises and Storm Surges**

While it will not be economically viable to protect all of the world’s coastlines from sea-level rises and the amplified storm surges, studies show that it is viable to protect highly populated areas, where

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large proportions of national populations are concentrated, even if faced with sea-level rises in the order of 1-2 m. There is a wealth of studies going back twenty years investigating sea-level rises up to 1 m which shows that the costs of protecting highly populated cities - with bulkheads, dikes, levees and pumping - is economically efficient compared to the potential direct losses and costs of relocation and retreat. Hence even a partial defence against sea-level rise can protect much of the world’s coastal population over the coming centuries. A number of cities around the world are gaining important experience in responding to sea-level rises, including:

- Coastal cities such as Tianjin, Shanghai, Tokyo, London, Osaka, and Bangkok presently have large areas below sea-level which are dependent on flood defences and pumped drainage to avoid flooding. Some of these cities have sea protection barriers which are now very famous, such as the Thames River Barrier. London is particularly vulnerable to storm surges and high spring tides and the Thames Barrier was built to protect London from these and other potential flooding scenarios.

- In the case of the Netherlands, half of the country is below sea level. The Netherlands has constructed walls to protect their land and cities from flooding by the sea, nearly two-thirds of which lies below sea level. The Netherlands government intends to spend up to EU1.5 billion (US$2.1 billion dollars) per year during the 21st Century on additional safety measures. The country has already built an elaborate network of dikes, man-made islands and a 1.5 mile stretch of 62 gates to control the entry and exit of North Sea waters into the country's low-lying south-western provinces.

In Australia, local governments like the City of Melbourne are learning from overseas experience to develop their own climate change adaptation strategies to plan for sea-level rises to protect their built environment and infrastructure.

While there is a growing level of experience globally on how to protect coastal cities, towns and coastlines from rising sea levels and the associated increased risks of storm surges, much of this experience is in the range or 1-2 m, and will not be sufficient to deal with a future rapid increase in the range of 5 – 6 m from the potential melting of the remaining massive ice stores as described previously. This is because most have assumed that, if there are extreme sea-level rises, retreat is the only option. Certainly, it will not be economically viable to protect every coastal city and town with

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a 5 m high sea wall, however a recent global cost benefit analysis study\textsuperscript{126} shows that, even with 5 m sea-level rises, it is economically efficient to invest in protecting highly populated major coastal cities.\textsuperscript{127} However, this is unlikely to be true for those mega-cities that are built on river deltas which are already subsiding. Studies show that coastal protection infrastructure like dikes, water gates, pumping and drainage systems, seawalls and breakwater can lose their stability due to sea-level rise.\textsuperscript{128} The reason is that sea-level rise decreases the bearing capacity of the soil foundation.\textsuperscript{129}

Detailed and locally specific studies for the Netherlands,\textsuperscript{130} Thames Estuary, London\textsuperscript{131} and the Rhone delta\textsuperscript{132} suggest that a range of factors will mean that retreat is the most likely option than protection. These studies suggest that, under a 5 m sea-level rise scenario, strategic retreat with a lower level of protection further inland is more likely than further major coastal investment in protection. This is thought to be due to a range of issues, including:

- The fact that decisions are made not just on the basis of cost-benefit analysis, as investing in coastal protection involves opportunity costs. The voting public may overall prefer that money is spent on other priorities such as health and education, and an organised retreat and relocation rather than major coastal protection.

- The risk that inefficiencies in the adaptation process can threaten the success, including indecision and inertia due to the fact that co-ordination is needed across all levels of government.

- The potential for the public to lose confidence that coastal protection will work under such a scenario of abrupt climate change and sea-level rise. Thus, even when cost-benefit analysis suggests that protection should occur, there are a range of reasons why it may not be wise to do so.

**Accommodation by Coastal Cities and Towns to Sea-level Rises and Storm Surges**

A strategy focused on *accommodation* rather than protection accepts that it is not economically viable to seek to protect all of the world’s coastlines and includes a number of key options, including:

- Elevating residential and small commercial buildings on pilings to protect them from sea-level rises and storm surges. This is already done in regions and countries that are low lying or below sea level, such as in the Netherlands. Building codes should be adapted to specify minimum elevations and piling depths in such conditions. In Australia, the traditional “Queenslander home”, which was raised on pilings, is a good example of effective building design to adapt to the risks of sea-level rises and storm surges.

- Storm warning, evacuation and preparedness plans could be instituted to protect communities from extreme events and the amplified storm surges that will be a result of higher sea levels.


Where sea-level rises harms agricultural lands and traditional crops, salt tolerant crops could be used to adapt and accommodate. Long term larger changes to coastal agriculture may be required such as a shifting from agricultural lands to aquaculture farming.

Retreating from Sea-level Rises and Storm Surges

The lowest risk adaptation strategy is that of retreat. Retreating from low lying areas may prove to be the most cost effective way to adapt to rising sea levels. To facilitate such a retreat, coastal zone development plans should be adjusted to discourage development of coastal areas likely to be vulnerable to sea-level rise.133 Such a strategy may restrict future development to areas that are now less than 2-3 m above sea-level over the next 100 years. Government can ensure this happens by limiting development on low lying lands through land acquisition and applying land use restrictions, prohibiting reconstruction of property damaged by storms, and reductions of subsidies and incentives for development in vulnerable areas.

Many nations, including Australia, already require new buildings be set back from the sea. These regulations should be updated to require the consideration of the future impacts from a rising sea level. Increasingly government planners and local government councils are doing this. Byron Bay Council, in New South Wales, for example, has incorporated a requirement for all future development to consider the location in respect to sea-level in order to receive approvals. The Victorian Government through their Victorian Coastal Strategy (2008) now requires local government to incorporate sea-level rises of no less than 0.8 m by 2100 into all planning decisions and bans any further canal residential development. Local government must assume sea-level rises of 80 cm by 2100 when considering any new developments for approval. The strategy also urges local government councils to consider other climate change impacts, including storm surges, erosion and landslides, when reviewing development applications.134 Similar new coastal strategies should be adopted by all state and local governments because it will reduce the risk of legal liability for any damages from rising sea-level rises. Local government is at increasing risk of incurring liability if they ‘unreasonably fail to take into account the likely effects of climate change’.135

As outlined above, another driver for change will be as Australian citizens realise how difficult it is to gain storm surge insurance in Australia. Currently few Australians are aware that the insurance industry sees storm surges as a high risk area and hence is rarely offering insurance to cover it. For all these reasons we recommend that state and local government follow the lead of the Victorian Government136 and councils like the Melbourne City Council137 which are developing clear planning criteria to address the risks of sea-level rises this century.

Key References

Assessing Vulnerability to Sea-level Rises – Australia


Strategies to Adapt to Sea-level Rises, Storm Surges and Flooding


**Best Practice Adaptation Case Studies in Protection Strategies –**


**Other Useful Links**
