Plans are being formulated to upgrade the Thames Barrier to protect London from rising sea levels and storm surges.

Source: Environment Agency, UK

Sea Change Threatened by Climate Change

John Church and colleagues warn that sea level rise will have serious consequences during the 21st century and beyond, and will impact the lives of tens of millions of people.

"Sea change" is a modern phenomenon. For many reasons, many people have moved or are moving to the coast. The rapidly growing populations of the Gold and Sunshine coasts in south-east Queensland and the northern New South Wales coast are examples of the impact of this sea change.

The result is billions of dollars of development, with coastal regions having the highest population density in Australia. About half of Australia's population lives within 7 km of the coast, with as many as 30%, or about six million people, within 2 km of the coast.

Juxtaposed with this rush to the coast is a changing climate.

Our Changing Climate

Climate has changed throughout Earth's history but our modern society has only evolved in the relatively stable climate of the past 10,000 years. Since the start of the industrial revolution in the mid-1700s, carbon dioxide levels in the atmosphere have risen from about 280 parts per million (ppm) to about 380 ppm in 2006. This is well outside the range of about 180–280 ppm experienced through the six glacial cycles of the past 750,000 years.

Carbon dioxide concentrations are continuing to rise, primarily as a result of our burning of fossil fuels, and are likely to reach more than double pre-industrial levels during our children's lifetime. There is now a clear consensus among the world's leading climate scientists that this rise in concentrations of carbon dioxide and other greenhouse gases, which trap long-wave radiation in the Earth's atmosphere, is a result of human activities and is resulting in global warming and other changes in the Earth's climate.

Rising Sea Levels

One of the consequences of this increase in greenhouse gas concentrations and subsequent warming is rising sea levels.

Since the time of the last ice age about 20,000 years ago, sea levels rose by over 120 metres, with major impacts on coastal boundaries. Most of this rise occurred before 6000 years ago, and there was little net change over the 2000 years prior to the start of the 19th century.

Since the early 1800s, sea levels have been rising at an increasing rate. This is now beginning to impact on coastal regions and low-lying islands that have been occupied and developed during the period of relatively stable sea levels of the previous 2000 years or so.

A 20th Century Increase in the Rate of Rise

A combination of sea level measurements from coastal tide gauges and satellite altimeters has recently been used to estimate globally averaged sea levels from 1870 to 2005. Over this period, global-averaged sea levels rose by almost 20 cm. During the 20th century the average rate of rise was about 1.7 mm/year, with rates increasing towards the end of the 20th century, consistent with simulations of an increase in the rate of sea level rise computed with climate models.

Sea level data from satellites and tide gauges show that since 1993 the rate of sea level rise was about 3 mm/year. This is more than 50% larger than the average over the 20th century. Whether this recent increase is part of the expected acceleration in the rate of sea level rise or part of natural decadal variability is not yet clear.

The rate of sea level rise *relative* to the nearby land at particular locations may be smaller or larger than the global average as a result of land movements

Coastal erosion results in the landward movement of the coastline, typically at rates of tens to hundreds of times the rate of sea level rise. Photo: Bruce Miller

and changes in atmospheric and oceanic conditions.

21st Century Sea Level Rise

Climate modelling projections for a range of possible greenhouse gas emission scenarios are for a 9–88 cm rise in sea level between 1990 and 2100.

The two main factors contributing to sea level rise are the increase in the amount of water in the ocean, principally from the melting of grounded ice stored in glaciers and the polar ice sheets, and from thermal expansion due to warming of the oceans.

Higher sea levels and more frequent coastal flooding are already occurring in Australia. We estimate that the average *relative* sea level around the Australian coastline rose by about 100 mm between 1920 and 2000.

This rate of sea level rise is less than the global average because of uplift of the continent and decadal climate variations. However, for some regions this "relative" sea level rise has been larger as a result of compaction of sediments and other land movements that cause the land surface to sink.

The impacts of sea level rise are felt through changes in the average sea level and changes in the height or frequency of extreme sea level events. These extreme sea level events are driven by strong winds and the low pressure of tropical cyclones and mid-latitude storms. These storms generate storm surges and severe wave conditions and, particularly on vulnerable coastlines, cause coastal erosion and flooding.

The frequency and height of coastal flooding events will increase as sea level rises, and would also increase if the intensity of storms increases through stronger winds, lower atmospheric pressures and larger waves.

Analyses of Australia's two longest sea level records, Fremantle in Western Australia and Fort Denison in Sydney (NSW), indicate that there has already been a change in the frequency of extreme sea level events during the 20th century. At these two locations, extreme sea level events of a given height occurred about three times more frequently during the second half of the 20th century than they did during the early part.

This trend will continue. Coastal flooding events that currently occur roughly once every 50 years might occur as frequently as once or more per decade by the end of the 21st century.

A recent study examining worst-case conditions of sea level and wind speed increases for the eastern Victorian coast found that by 2070 a one-in-100-year storm surge event would be almost 50 cm higher due to sea level rise and another 10–20 cm higher due to increases in wind speed.

Eroding Beaches and Loss of Wetlands

Over the past century about 70% of the world's sandy shorelines have been retreating, about 20–30% have been stable, and fewer than 10% have been advancing. Continued coastal erosion is expected as a result of ongoing sea level rise, resulting in the landward movement of the coastline at rates tens to hundreds of times the rate of sea level rise.

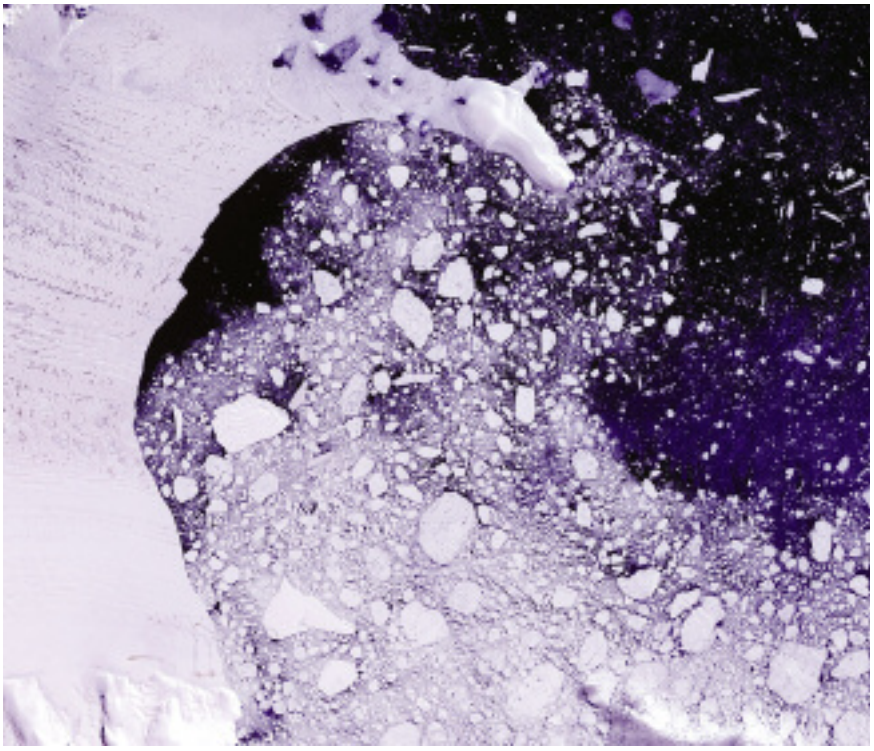
In natural environments this would result in landward movement of the beaches and coastal sand dunes. However, this landward progression is impossible for beaches backed by major developments, such as on the Gold Coast. The result could be the loss of tens of metres of our most popular beaches as they are squeezed between the advancing ocean and coastal developments. This threatens coastal properties and the very features that attract many people to the coast, unless protective measures such as increased beach nourishment and dune revegetation are undertaken.

It is not only modern urban developments and their related beaches that are threatened. Coastal wetlands, intertidal zones and mangroves are areas of environmental significance and biodiversity. These regions can also be damaged or lost as sea levels rise, especially when there is no possibility of their landward movement because they are backed by coastal developments.

The Longer Term

The slow response to global warming of the oceans and the ice sheets means that sea levels will continue to rise for decades to centuries after greenhouse gas concentrations are stabilised in the atmosphere. For a doubling of greenhouse gas concentrations, which is likely to occur during the 21st century unless emissions are significantly reduced, warming of the ocean alone is likely to

Photo: Landsat 7 Science Team and NASA GSFC



The Larsen B Ice Shelf on the Antarctic Peninsula photographed in 2000 before its collapse. The West Antarctic Ice Sheet contains enough ice to raise sea level by 5–6 metres.

result in a sea level rise of metres over hundreds of years.

Perhaps of greatest concern is melting of the Greenland Ice Sheet, which currently contains the equivalent of about 7 metres of sea level rise. Surface melting of the Greenland Ice Sheet has been increasing in recent years. For a warming of about 4.5°C over Greenland (equivalent to a global average temperature rise of about 3°C because high northern hemisphere latitudes are projected to warm more than the global average), surface melting alone is expected to exceed snow fall on Greenland, leading to a decrease in volume of the ice sheet.

We could approach this tipping point late in the 21st century if a significant reduction of global greenhouse gas emissions is not achieved. This would lead to an ongoing and virtually complete and essentially irreversible melt of the Greenland Ice Sheet. Once this tipping point is exceeded for any significant time, surface melting alone would lead to the eventual elimination of the Greenland Ice Sheet and a sea level rise of up to 7 metres over 1000 years or so.

In addition, surface melt water is making its way to the base of the Greenland Ice Sheet, lubricating it and potentially allowing the glaciers to slide more rapidly into the ocean and raise sea level more rapidly than would occur from surface melting alone. Indeed, observations over the past few years have shown increased glacier flow during the summer melt season. This mechanism has not yet been incorporated in models of the Greenland Ice Sheet, and thus the implications are not yet clear.

Concern about the future of the West Antarctic Ice Sheet has also increased over the past 5 years. This increased concern follows the rapid collapse of the Larsen B Ice Shelf on the Antarctic Peninsula in 2002 and the acceleration of glaciers previously restrained by the ice shelf. Significant melting at the base of the ice shelves fringing the West Antarctic Ice Sheet could lead to accelerated decay of these ice shelves and a more rapid movement of glaciers into the ocean. Our current understanding and models are too incomplete to predict the fate of the West Antarctic Ice Sheet, which contains enough ice to raise sea level by 5–6 metres.

In summary, over the coming centuries, sea level rise will be measured in metres unless a significant reduction of greenhouse gases emissions is achieved. Furthermore, it is possible that due to our incomplete understanding of glaciers and ice sheets, current climate models may have underestimated the rate of future sea level rise.

Global Consequences

Around the world, about 100 million people or more live within 5 km of the coast and within 5 metres of current sea levels. As in Australia, populations in coastal regions around the world are increasing significantly.

There has been significant loss of life from storm surges during the 20th century. In the Bay of Bengal, the 1970 storm surge alone led to in excess of 300,000 deaths and there have been at least 23 surges with over 10,000 people killed in each surge since 1737.

By 2100, tens of millions of people are likely to have to respond to coastal flooding events every year unless appropriate adaptation measures are implemented. The cost of stabilisation of coastal regions and protection of coastal infrastructure for a number of western countries is estimated to be tens to hundreds of billions of dollars.

Regions at greatest risk include low-lying deltaic nations such as Bangladesh as well as low-lying tropical islands. But western nations with their coastal cities and developed coastlines are also likely to feel the impacts of sea level rise and extreme events. Many of the world's mega-cities in both the developed world (e.g. New York) and the developing world (e.g. Dhaka) would be threatened by a sea level rise of several metres.

No single coastal flooding event can be blamed on climate change and associated sea level rise alone. However, increasing sea levels, potentially reinforced by increases in the number of

intense tropical cyclones, means that the likelihood of major flooding events and loss of life in the future is increasing.

Hurricane Katrina resulted in the loss of about 1300 lives and a financial loss in excess of US$100 billion. While the New Orleans disaster was not primarily a result of sea level rise, this single event gives an idea of the magnitude of future impacts. It is not so much a question of "if" there is a major event but rather a matter of "when and where, and how will we respond?" Increasing numbers of environmental refugees, including from regions such as the South Pacific where Australia has particular responsibilities, will be an inevitable consequence of continued sea level rise.

Need for Adaptation

While actions to mitigate emissions can slow the degree of sea level rise, some further increase is inevitable. Even if atmospheric concentrations were stabilised at today's levels, sea levels would continue to rise for decades; that is, past greenhouse gas emissions commit us to ongoing sea level rise during the 21st century. Hence adaptation strategies will be essential to accommodate 21st century sea level rise.

Appropriate strategies and investment in coastal adaptation, if implemented early enough, can dramatically reduce the potential for economic loss and human tragedy during the 21st century. Strategies include:

- forward planning (e.g. to ensure that escape and emergency routes are available for future flooding events and to increase the resilience of coastal developments and communities);
- appropriate use of low-lying coastal regions;
- development set-backs for regions susceptible to flooding and erosion;
- increased beach nourishment;
- protection measures such as sea walls for valuable locations; and
- retreat and abandonment of some regions.

One example of an adaptation strategy currently being planned is the investment of billions of pounds to upgrade the Thames Barrier to protect London from rising sea levels and storm surges. Adaptation plans need to not only consider modern urban development but also allow for the protection of historical sites and sensitive environmental areas and ecosystems. With appropriate planning we can substantially lessen the impact of 21st century sea level rise.

Need for Mitigation

The rate and magnitude of sea level rise, particularly later in the 21st century and beyond, depends on future emissions of greenhouse gases. Indeed, 21st century greenhouse gas emissions could commit the world to a sea level rise of several metres over hundreds of years as a result of ongoing ocean thermal expansion and contributions from the Greenland and West Antarctic Ice Sheets. Such a sea level rise would put huge pressures on society and would result in many millions of environmental refugees.

If we are to avoid this large sea level rise, a significant reduction in greenhouse gas emissions, such as the United Kingdom's national goal of a 60% reduction in emissions by 2050, is essential. Achieving a major reduction in emissions such as this will be challenging and requires urgent and sustained commitment.

There is no *single* silver bullet capable of delivering the necessary emission reductions in a sufficiently short time frame. Instead, it will be necessary to develop plans that utilise the full spectrum of options. These include reductions in energy use through better and more efficient designs, renewable energies (e.g. biomass, wind, solar thermal and solar voltaic), geothermal energy, expanded use of gas, and carbon capture and storage.

A portfolio of approaches is essential to:

- enable an early start on emission reductions;
- deal with technical and economic uncertainties in new technologies;
- build resilience into our energy options;
- gain community support; and
- achieve the necessary level of emission reductions in an appropriate timeframe.

Conclusion

There is clear scientific agreement that sea level is rising in response to past emissions of greenhouse gases. Sea levels will continue to rise during the 21st century.

The rate and magnitude of sea level rise, particularly later in the 21st century and beyond, depends on future emission of greenhouse gases. Significant and urgent reductions in emissions are essential if we wish to avoid a sea level rise of metres over coming centuries.

Sea level rises are an international and a national issue. Development of both adaptation and mitigation plans requires partnerships between nations and between all levels of government, private industry, the research community and non-governmental organisations. Planning for a changing climate, including sea level rise, is a mainstream issue in need of informed consideration.

"Increasing numbers of environmental refugees... will be an inevitable consequence of continued sea level rise."

John Church, Neil White, John Hunter and Kathleen McInnes are specialists in sea level rise and coastal impacts research at CSIRO Marine and Atmospheric Research and the Antarctic Climate and Ecosystems Cooperative Research Centre.