CLIMATE COMMISSION

THE CRITICAL DECADE

Climate science, risks and responses

Contents

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Preface

With critical decisions to be made in 2011 on responses to climate change, I hope that this report provides useful information from the scientific community to a wide range of audiences – our political leaders, the general public, the private sector, NGOs, and the media. More specifically, the aim of this report is to provide up-to-date information on the science of climate change and the implications of this knowledge for societal responses, both for mitigation strategies and for the analysis of and responses to risks that climate change poses for Australia.

Over the past two years, a large number of excellent reviews and syntheses of climate change science have been produced by academies of science, by groups of experts, and as outcomes of major international meetings. Much of this information is still current, and I have drawn heavily on it for this report; a list of these documents is given below. Scientific knowledge on climate change is continuously evolving, however, and I have also included information from key papers published in recent months.

I have tried to be as brief as possible in treating the various topics covered in this report, with the aim of providing the key points only. For interested readers, further information on the topics covered can be found in the reports listed below, and, of course, from the original sources of information in the peer-reviewed literature. These are presented in the reference list at the end of this report and in similar lists at the end of the reports below.

At several places in this report, I have made my own syntheses and judgements based on large bodies of work where there is no clear consensus in the peer-reviewed literature. As an example, on my reading of the literature to date and on discussions with experts, I expect the magnitude of global average sea-level rise in 2100 compared to 1990 to be in the range of 0.5 to 1.0 metre. For this and other such judgements, I take full and sole responsibility.

This report has been extensively reviewed by 15-20 colleagues from CSIRO, the Bureau of Meteorology and the university sector. They are all widely recognised experts in their fields of climate science, and I am grateful for the care and thoroughness with which they read and commented on earlier drafts of the report.

I also thank my colleagues on the Science Advisory Panel of the Climate Commission, who critically reviewed drafts of the report.

During the preparation of this report, I have worked closely with Professor Ross Garnaut and his team as they have undertaken their update of climate science. I appreciated the availability of earlier drafts of their update, and for the opportunity for frequent discussions on particularly topical and contentious areas of climate science.

I am grateful to many colleagues in the Department of Climate Change and Energy Efficiency for many useful discussions and for ongoing support of various kinds.

Will Steffen
Climate Commissioner
Canberra
May 2011

THIS UPDATE REVIEWS WHAT THE SCIENCE IS TELLING US ABOUT THE NEED TO ACT ON CLIMATE CHANGE, AND THE RISKS OF A CHANGING CLIMATE TO AUSTRALIA.

Sources that were drawn upon in the compilation of this report

Australian Academy of Science (AAS). (2010). *The Science of Climate Change: Questions and Answers*. August 2010. www.science.org.au/policy/climatechange2010.html

Canadell, J. (ed). (2010). Carbon sciences for a new world. *Current Opinion in Environmental Sustainability* (special issue) **2**: 209-311.

Garnaut, R. (2008). *The Garnaut Climate Change Review: Final Report*. Cambridge, UK: Cambridge University Press, 634 pp.

Garnaut, R. (2011). *Garnaut Climate Change Review – Update 2011. Update paper five: The science of climate change*. www.garnautreview.org.au

Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, (eds). Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M. M. B., Miller, Jr H. L., and Chen, Z. Cambridge, UK and New York, NY: Cambridge University Press, 996 pp.

Richardson, K., Steffen, W., Schellnhuber, H.-J., Alcamo, J., Barker, T., Kammen, D.M., Leemans, R., Liverman, D., Munasinghe, M., Osman-Elasha, B., Stern, N. and Waever, O. (2009). *Synthesis Report. Climate Change: Global Risks, Challenges & Decisions*. Summary of the Copenhagen Climate Change Congress, 10-12 March 2009. University of Copenhagen, 39 pp.

Richardson, K., Steffen, W., Liverman, D., Barker, T., Jotzo, F., Kammen, D., Leemans, R., Lenton, T., Munasinghe, M., Osman-Elasha, B., Schellnhuber, J., Stern, N., Vogel, C., and Waever, O. (2011). *Climate Change: Global Risks, Challenges and Decisions*. Cambridge: Cambridge University Press, 501 pp.

Royal Society (UK). (2010). *Climate change: a summary of the science*. London: The Royal Society, September 2010, 17 pp.

Steffen, W. (2009). *Climate Change 2009: Faster Change & More Serious Risks*. Department of Climate Change, Australian Government, 52 pp.

The Copenhagen Diagnosis. (2009). *Updating the World on the Latest Climate Science*. Allison, I., Bindoff, N.L., Bindschadler, R.A., Cox, P.M., de Noblet, N., England, M.H., Francis, J.E., Gruber, N., Haywood, A.M., Karoly, D.J., Kaser, G., Le Quéré, C., Lenton, T.M., Mann, M.E., McNeil, B.I., Pitman, A.J., Rahmstorf, S., Rignot, E., Schellnhuber, H.J., Schneider, S.H., Sherwood, S.C., Somerville, R.C.J., Steffen, K., Steig, E.J., Visbeck, M., Weaver, A.J. Sydney, Australia: The University of New South Wales Climate Change Research Centre (CCRC), 60 pp.

WBGU (German Advisory Council on Global Change). (2009). *Solving the Climate Dilemma: The Budget Approach*. Special Report. Berlin: WBGU Secretariat, 54 pp.

Over the past two or three years, the science of climate change has become a more widely contested issue in the public and political spheres. Climate science is now being debated outside of the normal discussion and debate that occurs within the peer-reviewed scientific literature in the normal course of research. It is being attacked in the media by many with no credentials in the field. The questioning of the Intergovernmental Panel on Climate Change (IPCC), the "climategate" incident based on hacked emails in the UK, and attempts to intimidate climate scientists have added to the confusion in the public about the veracity of climate science.

By contrast to the noisy, confusing "debate" in the media, within the climate research community our understanding of the climate system continues to advance strongly. Some uncertainties remain and will continue to do so, given the complexity of the climate system, and the impossibility of knowing the future pathways of human political, social and technological changes. Meanwhile there is much climate change science that is now well and confidently understood, and for which there is strong and clear evidence.

THE EVIDENCE THAT THE EARTH'S SURFACE IS WARMING RAPIDLY IS NOW EXCEPTIONALLY STRONG, AND BEYOND DOUBT. EVIDENCE FOR CHANGES IN OTHER ASPECTS OF THE CLIMATE SYSTEM IS ALSO STRENGTHENING. THE PRIMARY CAUSE OF THE OBSERVED WARMING AND ASSOCIATED CHANGES SINCE THE MID-20TH CENTURY – HUMAN EMISSIONS OF GREENHOUSE GASES – IS ALSO KNOWN WITH A HIGH LEVEL OF CONFIDENCE.

However, the behaviour of several important components or processes of the climate system, including some associated with serious risks such as sea-level rise and changes in water resources, are much less well understood and are the subject of intense scientific research and debate.

The purpose of this update is to review the current scientific knowledge base on climate change, particularly with regard to (i) the underpinning it provides for the formulation of policy and (ii) the information it provides on the risks of a changing climate to Australia.

The first chapter of the update focuses on the fundamental understanding of the climate system, which is an important element in framing and informing the formulation of policy. The analysis starts with observations of the climate system and how it is changing, followed by the reasons for these observed changes. It then focuses on the behaviour of the carbon cycle, which is the primary process in the climate system that policy aims to influence. Finally, the often confusing issue of certainty in climate science is explored, with an emphasis on what is known with a high degree of certainty but also where considerable uncertainty remains about important features of the climate system.

Chapter 2 describes some of the most significant risks that are associated with a changing climate. The section is focussed strongly on the implications of our understanding of the climate system for risk assessments, but does not attempt to undertake the sector-by-sector risk assessments themselves. While it is clear that climate change has potential impacts on a wide range of sectors – human health, agriculture, settlements and infrastructure, tourism, biodiversity and natural ecosystems, and others – many other non-climatic factors affect the risks that these sectors face and the outcomes that eventually occur.

For example, there is little doubt that extreme weather events such as bushfires and floods have significant impacts on human health and well-being. The 2011 Queensland floods have led to long-term, mental health and related problems, such as depression, bereavement, post-traumatic stress disorders and other mood and anxiety disorders; and the 2009 Victorian bushfires also led to considerable psychological distress, some of it prolonged, to those who experienced the fires and survived (A.J. McMichael, personal communication). Such extreme weather events have occurred before the advent of human-induced climate change, and the degree to which climate change affects risks associated with extreme events is a very active area of research.

In addition to the intensity of the weather event itself, the severity of the Queensland floods were affected by several other factors, many of which are not related to climate. These include the land cover and condition of catchments and the efficacy of protective structures such as dams. The ultimate health outcomes were additionally influenced by the vulnerability of individuals and communities and the effectiveness of warnings and of emergency management actions.

The Great Barrier Reef, an oft-cited example of an iconic natural ecosystem vulnerable to the potential impacts of climate change, illustrates the importance of considering multiple, interacting stresses and not climate change in isolation. While climate-related risks for coral reefs, such as temperature extremes and increasing ocean acidity, have been widely documented and some are well understood (e.g., Hoegh-Gulberg et al. 2007), other non-climatic factors are also critical for maintaining coral reefs as well-functioning ecosystems. These include overfishing and declines in water quality (Bryant et al. 1998), as well as pollutants, low salinity, turbidity, sedimentation and pathogens, which put further pressure on reefs (Anthony et al. 2007). Thus, risk assessments for particular sectors, such as human health and natural ecosystems, are best undertaken by experts for the particular sector, drawing on the insights that climate science can offer as well as on non-climate knowledge and information.

This chapter aims to provide an up-to-date synthesis of our scientific understanding of five major aspects of the climate system that are important for risk assessments across many sectors. These are: (i) sea-level rise; (ii) ocean acidification; (iii) the water cycle; (iv) extreme events; and (v) abrupt, non-linear and irreversible changes in the climate system.

Finally, Chapter 3 provides a link between the science of climate change and the policy options for reducing emissions of greenhouse gases, particularly carbon dioxide (CO_2). The approach taken here circumvents the complexity and confusion of the targets/timetables/baselines approach by turning to a much simpler budget – or aggregate emissions – analysis. The approach directly relates the further amount of emissions, in billions of tonnes of CO_2, that global society can emit to achieve a particular temperature limit, such as 2 °C above the pre-industrial level.

Each chapter opens with a brief introductory paragraph presenting the main thrust of the section, followed by a series of short bulleted statements. These are brief, summary statements without references. Each of these statements is supported by more detailed text, with references and figures, in the main body of each section.

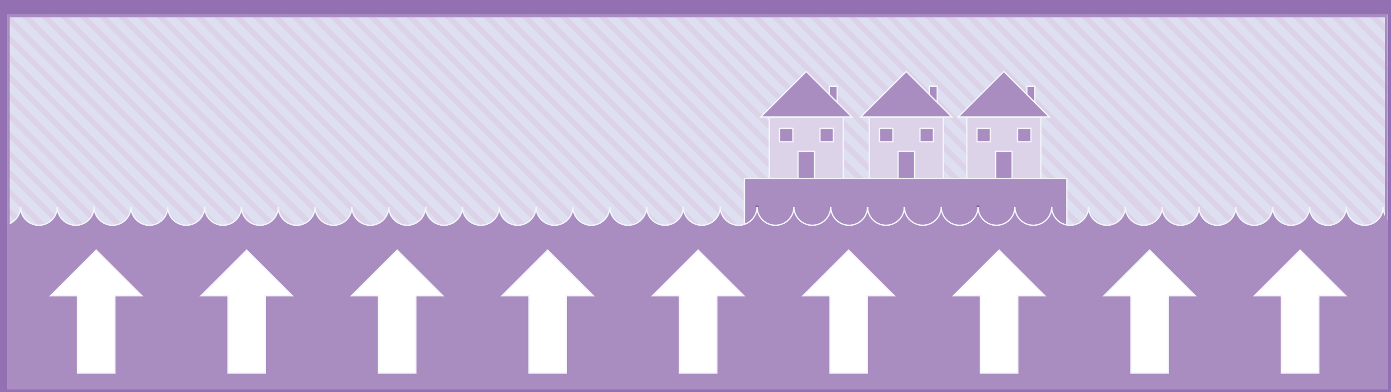
CHAPTER 1: DEVELOPMENTS IN THE SCIENCE OF CLIMATE CHANGE

DID YOU KNOW...

FOR THE MOST RECENT 10-YEAR PERIOD (2001-2010), GLOBAL AVERAGE TEMPERATURE WAS 0.46 °C ABOVE THE 1961-1990 AVERAGE, THE WARMEST DECADE ON RECORD.

85%

MORE THAN 85% OF THE ADDITIONAL HEAT DUE TO THE ENERGY IMBALANCE AT THE EARTH'S SURFACE IS ABSORBED BY THE OCEAN (IPCC 2007a).



GLOBAL SEA LEVEL HAS RISEN BY ABOUT 20 CM SINCE THE 1880s, WHEN THE FIRST GLOBAL ESTIMATES COULD BE MADE.

1.1 Observations of changes in the climate system

Recent observations of changes in the climate system strengthen the conclusions of the IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report (2007a) and the Garnaut Review (2008) that contemporary climate change is indeed real, and is occurring at a rapid rate compared with geological time scales. From a human perspective, the rate of climate change is already discernible to the present generation, and will be even more prominent in the lives of our children and grandchildren. It is leading to significant risks today, and more serious risks in the coming decades, as described in Chapter 2.

In this section the focus is on evidence for the long-term warming trend, while other changes in the climate system – extreme events, the water cycle and abrupt changes, for example – are treated in the discussion of climate risks in Chapter 2. The main conclusions of this section are:

- The average air temperature at the Earth's surface continues on an upward trajectory at a rate of 0.17 °C per decade over the past three decades.
- The temperature of the upper 700 m of the ocean continues to increase, with most of the excess heat generated by the growing energy imbalance at the Earth's surface stored in this compartment of the system.
- The alkalinity of the ocean is decreasing steadily as a result of acidification by anthropogenic CO_2 emissions.
- Recent observations confirm net loss of ice from the Greenland and West Antarctic ice sheets; the extent of Arctic sea ice cover continues on a long-term downward trend. Most land-based glaciers and ice caps are in retreat.
- Sea-level has risen at a higher rate over the past two decades, consistent with ocean warming and an increasing contribution from the large polar ice sheets.
- The biosphere is responding in a consistent way to a warming Earth, with observed changes in gene pools, species ranges, timing of biological patterns and ecosystem dynamics.

Surface air temperature

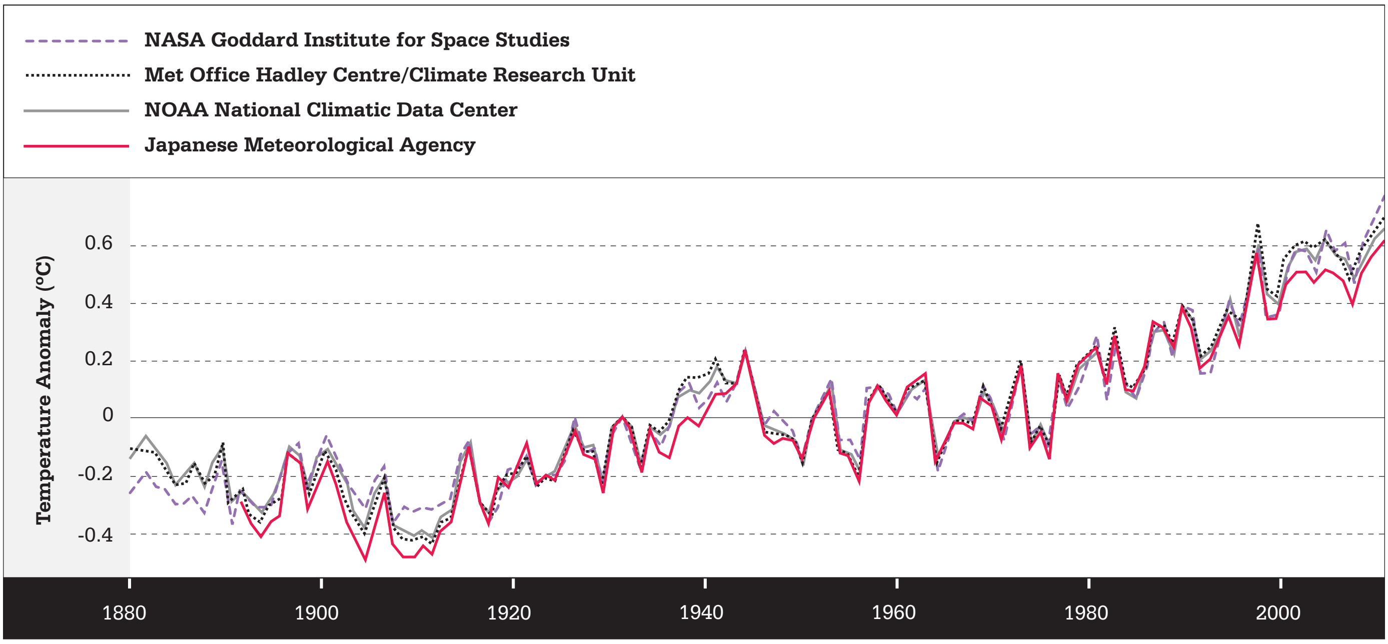
The average temperature at the Earth's surface has continued to increase. The global combined land and sea surface temperature (SST) for 2010 was 0.53 °C above the 1961-1990 average (WMO 2011) and thus 2010 ranks amongst the three warmest years on record.

FOR THE MOST RECENT 10-YEAR PERIOD (2001-2010), GLOBAL AVERAGE TEMPERATURE WAS 0.46 °C ABOVE THE 1961-1990 AVERAGE, THE WARMEST DECADE ON RECORD.

However, time series of at least three decades – and preferably much longer – are required to differentiate with confidence a long-term climatic trend from shorter term variability. Figure 1 shows the global average temperature record from the late 19th century to the present. Over the last three decades, the rate of warming has been 0.17 °C per decade, a very high rate from a geological perspective.

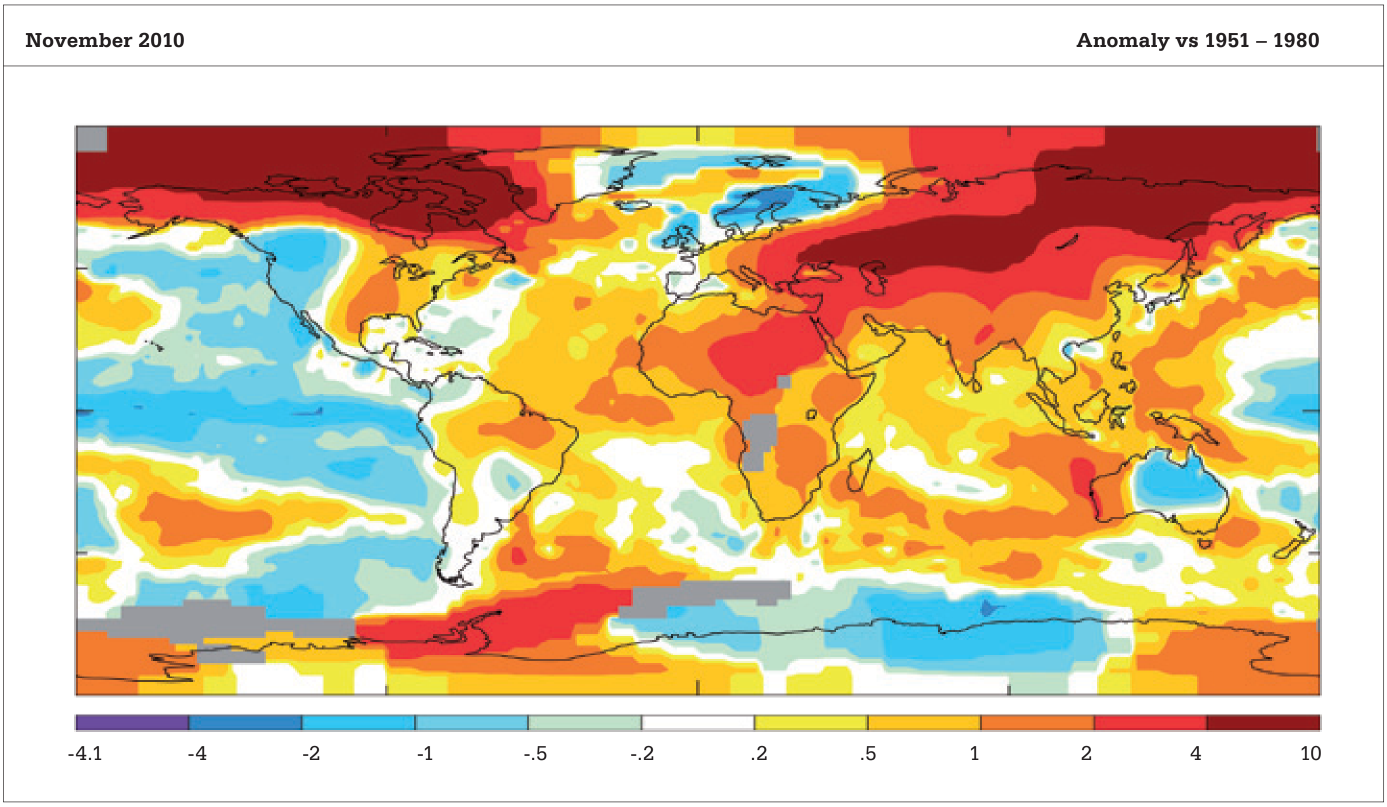
There has been considerable confusion in the media and in the public between shorter term patterns of variability in climate and weather and longer term (multi-decadal) trends in climate. The problem is the inappropriate tendency to expect weather patterns and changes over short time periods and in particular regions to always follow changes in global trends over long periods of time. An example is the extremely cold and snowy weather experienced by parts of Europe and North America in the November-December 2010 period. Does this signal an end to global warming? Absolutely not. As noted above, 2010 was one of the three warmest years on record. Furthermore, the month of November 2010 was exceptionally warm, with extremely high temperatures around the northern high latitudes more than compensating for the cold, snowy weather in western Europe and parts of North America (Figure 2).

Figure 1. Surface air temperature trend from the 1880s to the present. The baseline for the analysis is the 1951-1980 average.



Source: NASA GISS Surface Temperature Analysis.

Figure 2. Global map of surface temperature anomalies for November 2010 showing the unusually cold conditions in parts of Europe and North America but the extreme warmth in other parts of the northern hemisphere.



Source: NASA GISS Surface Temperature Analysis.

Ocean temperature

Although there is a very strong focus on air and sea surface temperature in both the climate research community and the general public, ocean temperature is a better measure of changes in the climate system.

MORE THAN 85% OF THE ADDITIONAL HEAT DUE TO THE ENERGY IMBALANCE AT THE EARTH'S SURFACE IS ABSORBED BY THE OCEAN (IPCC 2007a).

Since the 1960s measurements of the heat content of the upper 700 m of the ocean have been available, and since 2004, measurements to lower depths (up to 2 km) have become widely available with the deployment of Argo floats (Gould and the Argo Science Team 2004).

Figure 3 shows the record of ocean thermal expansion from 1950 through 2008, showing the clear long-term trend of warming (Domingues et al. 2008, and updates). The Domingues et al. updated curve in this figure, which uses the carefully checked and corrected Argo data of Barker et al. (2011), indicates that multi-decadal warming has continued to the end of the record in December 2008 (Church et al. 2011). This record is quantitatively consistent with the observed rate of sea-level rise over the past half-century. Although most of the additional heat stored in the ocean is found in the upper 700 m, recent observations show that warming of the deeper ocean waters in both the Southern and Atlantic Oceans is now occurring (Purkey and Johnson 2010).

Ocean acidification

Increasing the atmospheric concentration of CO_2 leads to more dissolution of CO_2 in surface ocean waters, increasing their acidity (decreasing their alkalinity) via the formation of carbonic acid. Through a series of chemical reactions, increasing the concentration of carbonic acid reduces the concentration of carbonate ions in seawater (Kleypas et al. 2006). This process has implications for marine organisms that form calcium carbonate shells (see Section 2.2). Observations of the acidity of the ocean's surface waters show the expected decrease of about 0.1 pH unit since the pre-industrial era (Guinotte et al. 2003).

Sea ice and polar ice sheets

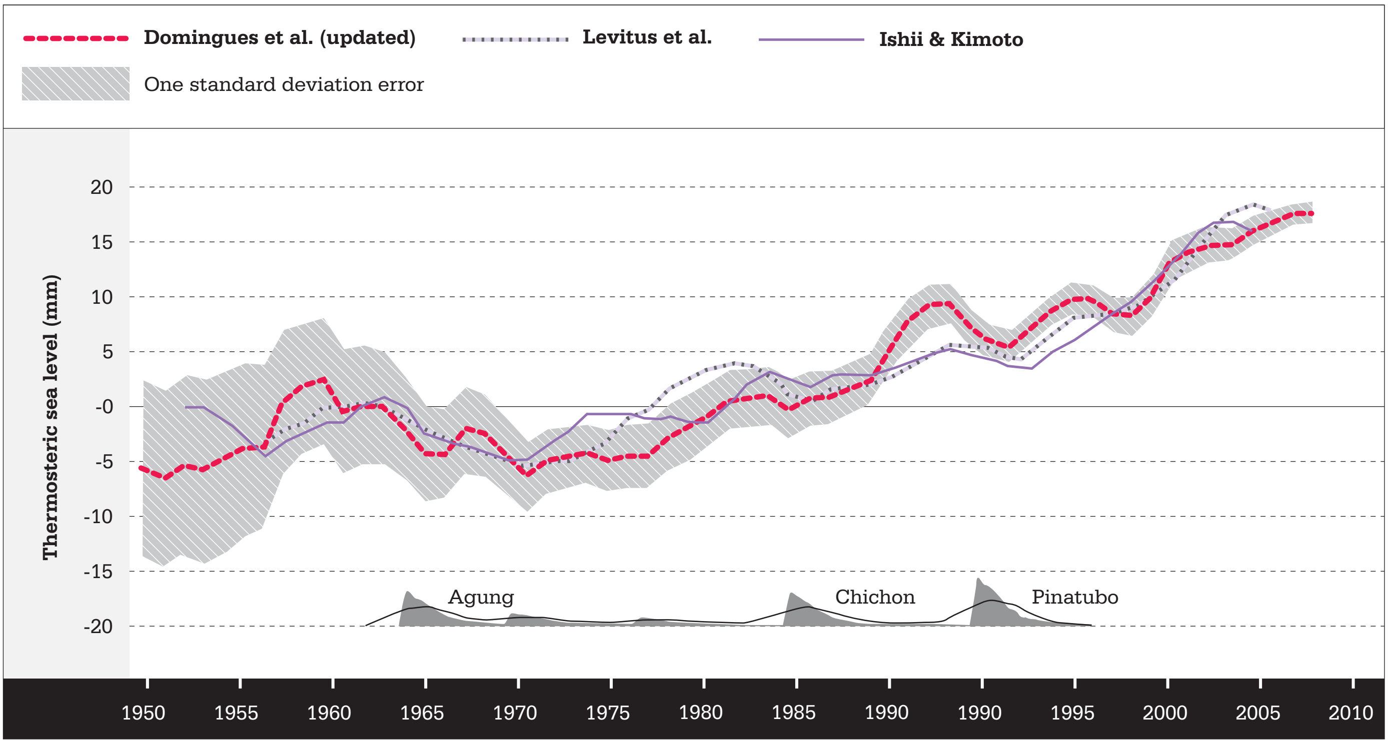
Evidence from the cryosphere (snow, ice and frozen ground) is consistent with the warming of the surface of the Earth. The most striking evidence comes from the northern high latitudes, where the sea ice covering the Arctic Ocean has decreased significantly over the last several decades (Figure 4). Changes to the sea ice surrounding Antarctica are more complex, with no appreciable change in overall extent over the past several decades.

The large polar ice sheets on Greenland and West Antarctica, which are important factors influencing sea-level rise, are currently losing mass to the ocean through both melting and dynamical ice loss; that is, by break-up and calving of blocks of ice. However, there is considerable uncertainty about the rate at which the latter process is occurring. In addition, these trends are often based on shorter term observational records (often the last 10-15 years), and it is not entirely clear whether these are long-term trends that will be maintained into the future or are at least partly the result of natural decadal-scale variability (e.g., Rignot et al. 2008).

Over the past decade one of the most common observational tools for estimating changes in ice mass is the GRACE satellite gravity technique, which estimates the loss of mass from changes in the gravity field. GRACE measurements have been prominent in confirming a trend of ice loss from polar ice sheets, especially Greenland (Figure 5). However, the GRACE observational technique itself is complex with significant uncertainties; a recent re-analysis of the Greenland gravity change data suggests that the rate of ice loss has been overestimated by a factor of two (Bromwich and Nicolas 2010; Figure 6).

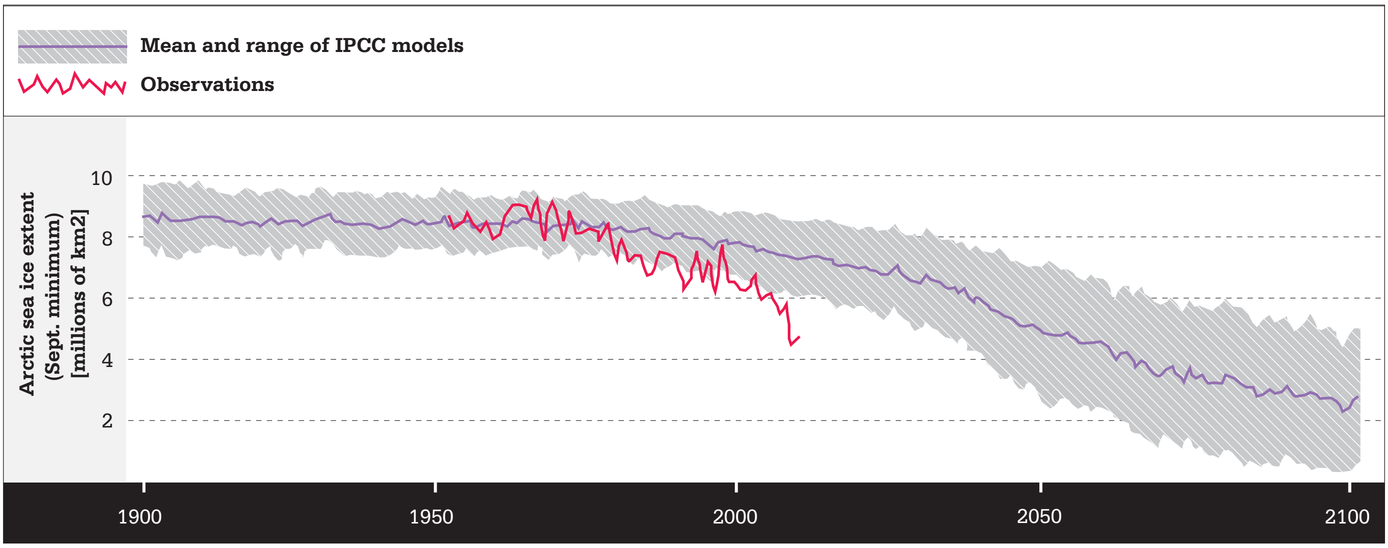
Nevertheless, a synthesis of all observations shows that there is a net loss of mass from the Greenland (and West Antarctic) ice sheets; the uncertainty refers to the rate at which this ice loss is occurring, with some evidence that this rate of loss may be accelerating (Rignot et al. 2011).

Figure 3. Updated estimates of ocean thermal expansion relative to 1961. The updated Domingues et al. (2008) time series is shown as a red broken line, and one standard deviation uncertainty estimates are indicated by the grey shading. The estimates for Ishii and Kimoto (2009) and Levitus et al. (2009) are shown as purple and broken purple lines respectively. The estimated stratospheric aerosol loading (arbitrary scale) from the major volcanic eruptions is shown at the bottom.



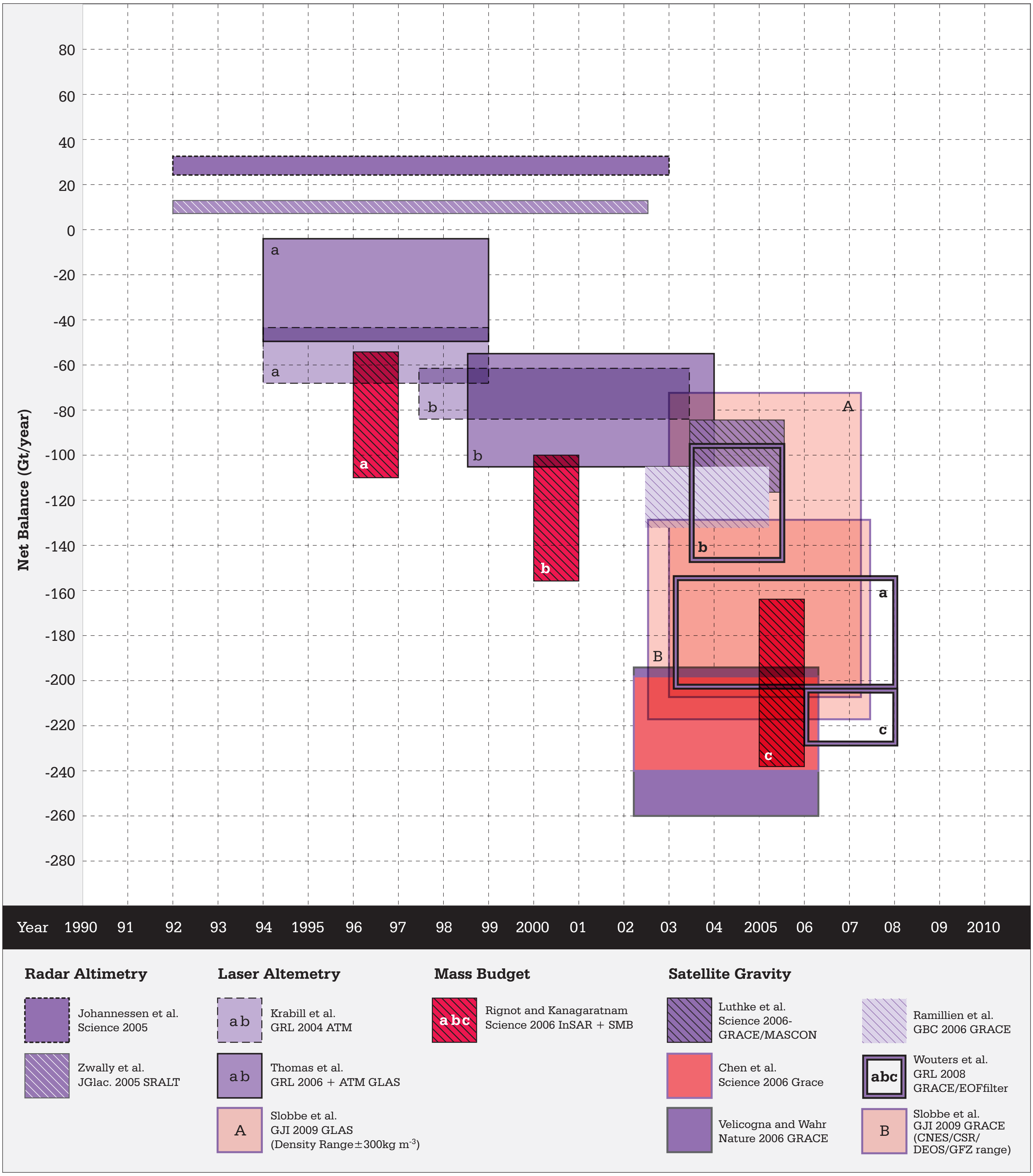
Source: Church et al. (2011).

Figure 4. Observed (red line) and modelled September (end of summer) Arctic sea ice extent in millions of square kilometres. The solid purple line is the ensemble mean of the 13 IPCC AR4 models and the edges of the grey shaded area represent the range of model projections.



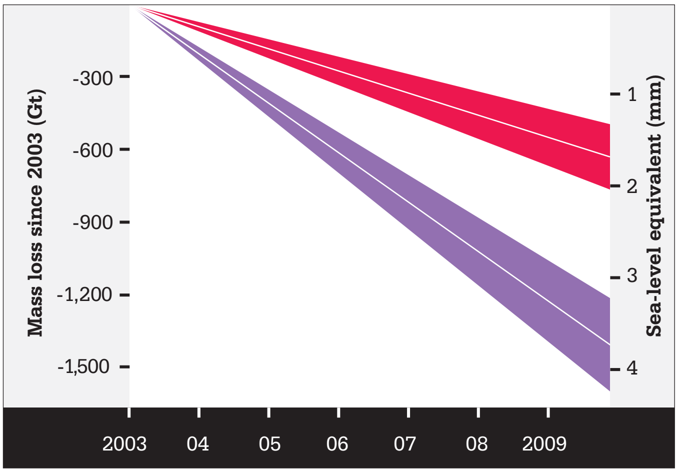
Source: Stroeve et al. (2007), updated to include data for 2008.

Figure 5. Results from the recent large area total mass balance measurements of the Greenland ice sheet, placed into common units and displayed versus the time intervals of the observations. The heights of the boxes cover the published error bars or ranges in mass change rate over those intervals.



Source: AMAP (2009), which includes references to the individual data sets shown in the figure.

Figure 6. Cumulative mass loss of the Greenland ice sheet. The estimate by Wu et al. (2010) of mass loss since 2003 (red) is considerably lower than an earlier predicted value (Velicogna 2009) (purple), owing in part to larger than previously estimated subsidence rates of underlying bedrock. The curves and their differences can thus be interpreted in terms of contribution to global mean sea level (right-hand vertical axis). The shaded areas reflect uncertainties.



Source: Bromwich and Nicolas (2010).

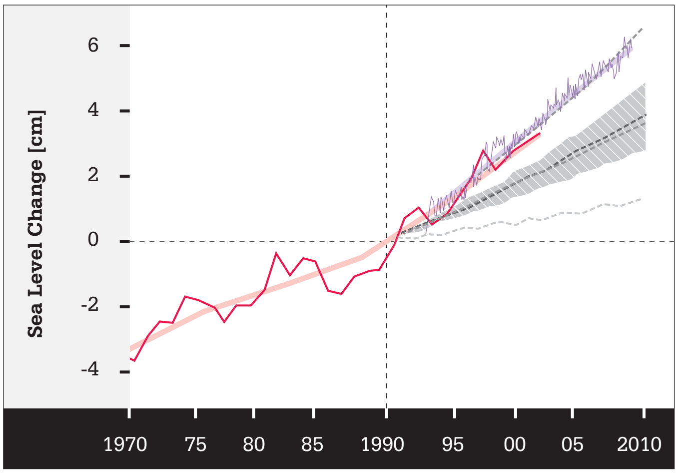
Land-based glaciers and ice caps

Most glaciers and mountain ice-caps around the world have been in retreat the past century and are estimated to be contributing about 0.8 mm per year to sea level rise at the beginning of this century (IPCC 2007a). Glaciers and ice caps are not yet in equilibrium with the present climate, and that adjustment would lead to a mass loss equivalent to another 18 cm sea-level rise (Bahr et al. 2009). However, the climate is still warming and will almost surely continue to warm through this century, with current warming trends leading to an estimated mass loss equivalent to about 55 cm of sea-level rise by the end of the century (Pfeffer et al. 2008).

Sea-level rise

Global sea level has risen by about 20 cm since the 1880s, when the first global estimates could be made. The rate of increase has risen to about 3.2 mm yr^{1} for the 1993-2009 period, based on satellite altimeter data (Cazenave et al. 2009; Domingues et al. 2008; Church and White 2011), compared to a rate of 1.7 mm yr^{1} for the 1900-2009 period (Church and White 2011). Figure 7 shows a comparison of the observed sea-level rise to projections from climate models, which first became available in 1990 and were summarised in the two most recent IPCC reports (2001; 2007a). Observed sea level since 1993 is tracking near the upper end of the model projections, pointing towards significant risks of sea-level related impacts in the 21st century (see Section 2.1).

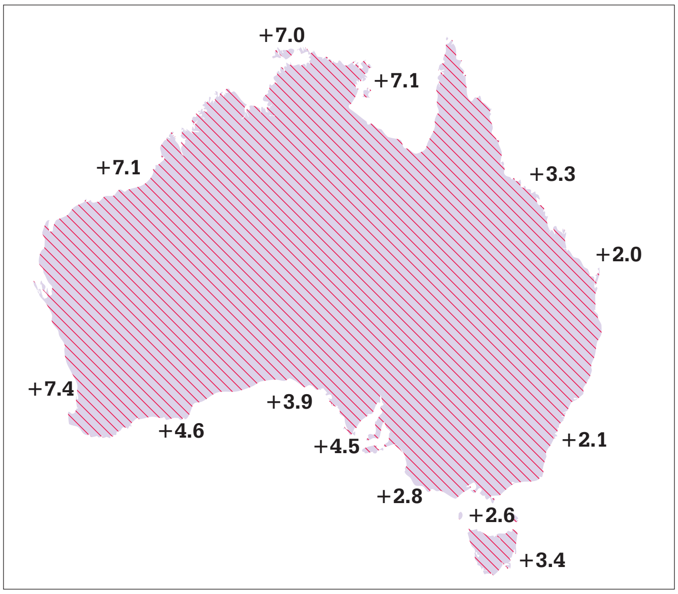
Figure 7. Sea-level change from 1970 to 2008. The thin red line from 1970 to 2002 is based on tide gauge data, and the jagged purple line from 1993 to 2008 is based on satellite data. The thick purple and red lines are running means. The envelope of IPCC projections (broken lines from 1990) are shown for comparison.



Source: after Rahmstorf et al. (2007), based on data from Cazenave and Narem (2004); Church and White (2006), Cazenave (2006) and A. Cazenave for 2006–08 data.

Several processes contribute to sea-level rise, and a quantitative budget of their relative contributions for the 1961-2003 period has been generated (Domingues et al. 2008). The budget shows that about 40% of the rise over this period can be attributed to the thermal expansion of the ocean as it warms, about 35% to the melting of continental glaciers and ice caps (e.g., the Andean and Himalayan mountain glaciers) and about 25% from the large polar ice sheets on Greenland and Antarctica. Estimates of these individual terms aggregate to a total of 1.5 +/- 0.4 mm yr^{1}, which is not significantly different from the observed rate for the same period of 1.6 +/-0.2 mm yr^{1}.

Figure 8. Local sea-level rise (mm/year) around Australia from the early 1990s to 2010.



Source: National Tidal Centre 2010

Global average values of sea-level rise mask large regional differences. For example, around Australia (Figure 8) recent sea level rise (from the early 1990s to 2008) has been below the global average along the east coast, near the global average along the much of the southern coast, but at least double the global average along much of the northern coastline. Such regional differences are important in assessing the risks posed by sea-level rise at particular locations.

Terrestrial and marine biosphere

The biosphere responds to significant changes in the abiotic environment, so the long-term increase in temperature should be evident in biospheric responses.

INDEED, A CLIMATE CHANGE (WARMING) SIGNAL IS NOW CLEAR IN AN INCREASING NUMBER OF AUSTRALIAN AND GLOBAL OBSERVATIONS OF THE RESPONSES OF BIOLOGICAL SPECIES AND ECOSYSTEMS (E.G., PARMESAN 2006; ROOT ET AL. 2005; IPCC 2007b).

Australian observations that show a clear response to a climate signal, distinguishable from the responses to other stressors on ecosystems, include genetic shifts in the populations of fruit flies (Umina et al. 2005), migration of both native and feral mammals to higher elevations in alpine regions (Green and Pickering 2002; Pickering et al. 2004), the southward expansion of the breeding range of black flying foxes (Welbergen et al. 2007), earlier arrival and later departure times of migratory birds (Chambers 2005, 2008; Chambers et al. 2005) and the earlier mating and longer pairing of the large skink *Tiliqua rugosa* (Bull and Burzacott 2002).

In the marine realm responses to a warming climate have also been observed. These include southern range extension of the barrens-forming sea urchin from the mainland to Tasmania (Ling et al. 2008, 2009), significant changes in the growth rates of long-lived Pacific fish species (Thresher et al. 2007), and a southward shift in the distribution of over half of the intertidal species along the east coast of Tasmania (Pitt 2008).

Perhaps the best known marine example of response to climate change is the increase in bleaching events on the Great Barrier Reef; there have been nine mass bleaching events on the GBR since 1979 with no known such events prior to that date (Done et al. 2003; GBRMPA 2009).

1.2 Why is the climate system changing now?

The evidence for a long-term warming trend in Earth's climate is overwhelming. The critical question is: what is causing this warming trend, and the associated changes in the climate system?

This section explores the possible reasons for the observed warming trend by first placing contemporary climate change in a longer term perspective and then examining the various potential causes for the warming. The main conclusions are:

- There is no credible evidence that changes in incoming solar radiation can be the cause of the current warming trend.
- Neither multi-decadal or century-scale patterns of natural variability, such as the Medieval Warm Period, nor shorter term patterns of variability, such as ENSO (El Niño-Southern Oscillation) or the North Atlantic Oscillation, can explain the globally coherent warming trend observed since the middle of the 20th century.
- There is a very large body of internally consistent observations, experiments, analyses, and physical theory that points to the increasing atmospheric concentration of greenhouse gases, with carbon dioxide (CO_2) the most important, as the ultimate cause for the observed warming.
- Improved understanding of the sensitivity of the climate system to the increasing atmospheric CO_2 concentration has provided further evidence of its role in the current warming trend, and provided more confidence in projections of the level of future warming.

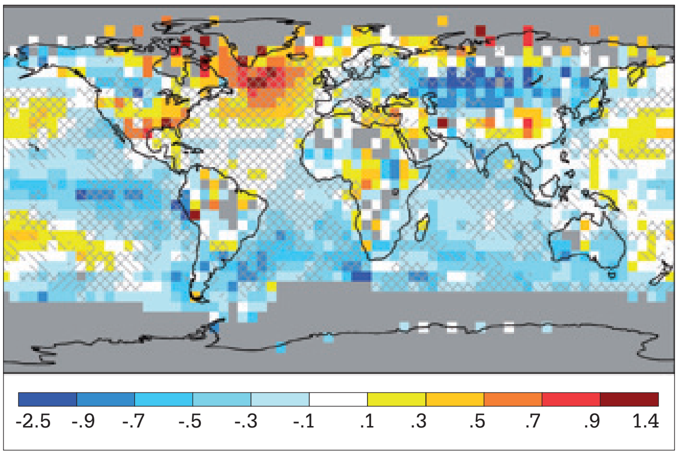
The longer-term context

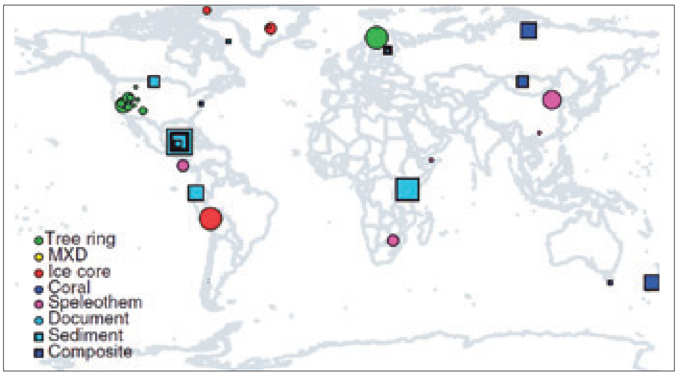
Earth has been much warmer and much colder in the distant past, but for humans the period of relevance is the last half-million years, during which fully modern humans evolved. In particular, the last 12,000 years – the Holocene – is important; during this period agriculture, villages and cities, and more complex societies and civilisations, including our current civilisation, have developed. Compared to the pattern of long ice ages and much shorter interglacial periods over the past 420,000 years (Petit et al. 1999), the Holocene has been an unusually long and stable warm period, facilitating the development of human society beyond the hunter-gatherer stage. The behaviour of the climate system during the Holocene provides a useful, human-relevant baseline against which to test possible explanations for contemporary warming.

Changes in solar radiation

Variation in the amount of solar radiation reaching the Earth has been implicated in temperature fluctuations earlier in the Holocene, for example, as a possible factor in the Medieval Climate Anomaly, often called the Medieval Warm Period (Mann et al. 2009). Variations in solar radiation have been known with better accuracy since the late 1800s, and especially in the last three to four decades, and could have contributed at most 10% to the observed warming trend in the 20th century (Lean and Rind 2008). In particular, there has been no significant change in solar radiation over the past 30 years (IPCC 2007a), when global average temperature has risen at about 0.17 °C per decade. Furthermore, *patterns* of warming over recent decades are inconsistent with solar forcing. In particular, solar forcing would produce a warming of the stratosphere, in addition to that of the troposphere. In fact stratospheric *cooling* has been observed, inconsistent with solar forcing but consistent with CO_2-dominated forcing (IPCC 2007a).

Figure 9. Reconstructed surface temperature pattern for the Medieval Climate Anomaly (MCA, 950 to 1250 C.E., sometimes called the Medieval Warm Period). Shown are the mean surface temperature anomaly (left) and associated relative weightings of various proxy records used (indicated by size of symbols) for the low-frequency component of the reconstruction (right). Anomalies are defined relative to the 1961-1990 reference period mean. Statistical skill is indicated by hatching (regions that pass validation tests at the p=0.05 level with respect to RE (CE) are denoted by / (\) hatching). Grey mask indicates regions for which inadequate long-term modern observational surface temperature data are available for the purposes of calibration and validation.





Source: Mann et al. (2009), which contains further information on methodology.

Modes of natural variability

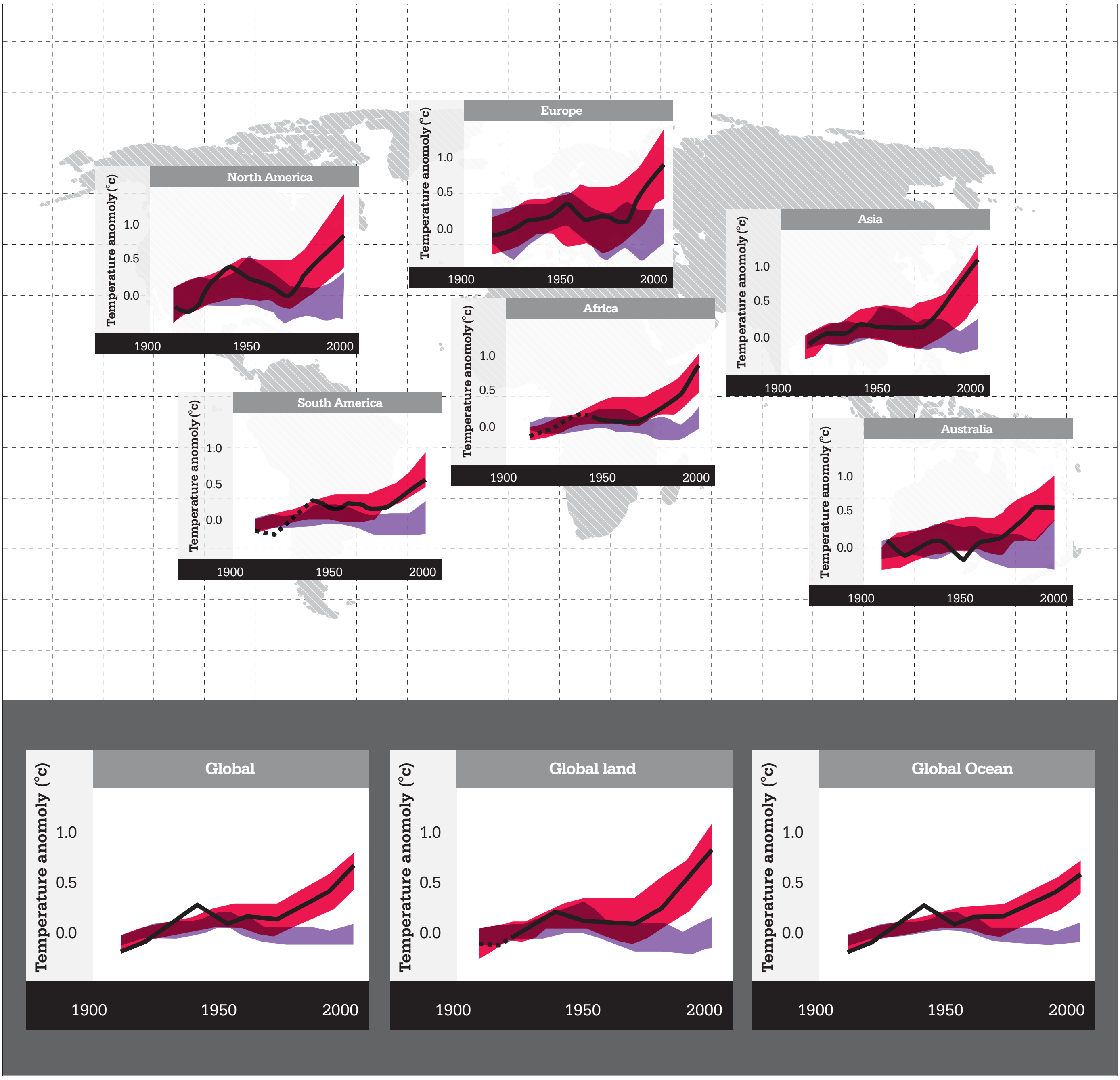
The Medieval Climate Anomaly (MCA), a somewhat warmer period from about 1000 to about 1250 or 1300 AD, has sometimes been invoked to infer that the contemporary warming is nothing unusual in the Holocene and that it is thus likely due to natural variability. However, the bulk of evidence for the MCA comes from the northern hemisphere, which makes it difficult to determine whether the MCA was truly global in scale. Furthermore, a spatially explicit synthesis of all available temperature reconstructions around the globe suggests that the MCA was highly heterogeneous, even in the northern hemisphere, with globally averaged warming much below that observed over the last century (Mann et al. 2009; Figure 9). Thus, the MCA is different in magnitude and extent from contemporary warming (Figure 10).

Shorter-term modes of natural variability, such as ENSO and the NAO (North Atlantic Oscillation), are very important influences on the weather that people experience from year to year, but they cannot explain recent multi-decadal, globally synchronous trends in temperature. Rather, such modes of natural variability are driven by changes in coupled oceanic and atmospheric circulation; in general, they redistribute heat between ocean and atmosphere as well as redistribute it geographically around the planet.

Greenhouse gas forcing

The physics by which greenhouse gases influence the climate at the Earth's surface is now very well established and accepted; it was first proposed in 1824 by Joseph Fourier, experimentally verified in 1859 by John Tyndall (Crawford 1997) and quantified near the end of the 19th century by Svante Arrhenius (Arrhenius 1896). Much research in the 20th century (e.g., Weart 2003; Fleming 2007; Revelle and Suess 1957) has strengthened the scientific basis for the theory as well as sharpened our understanding of it. For example, the very large differences in surface temperature among Earth, Venus and Mars can only be explained by the very different amounts of CO_2 in their atmospheres (Lacis et al. 2010). Also, the difference in globally averaged temperature between an ice age and a warm period, about 5-6 °C, can only be explained by changes in greenhouse gas concentrations and in the reflectivity (albedo) of the Earth's surface that amplify the original modest changes in temperature due to variations in incoming solar radiation caused by cyclical changes in the Earth's orbit around the sun (Rahmstorf and Schellnhuber 2006).

Figure 10. Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Purple shaded bands show the 5–95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings.



Source: IPCC (2007a)

As knowledge of the greenhouse effect improves, changes in the climate system more subtle than globally averaged temperature yield patterns of change consistent with the influence of CO_2 and other greenhouse gases, and inconsistent with changes in solar radiation. Such "fingerprints of greenhouse gas forcing" include, for example, the observation that winters are warming more rapidly than summers and that overnight minimum temperatures have risen more rapidly than daytime maximum temperatures (IPCC 2007a). An apparent inconsistency between observations with greenhouse theory was the alleged failure to find a so-called "tropical hot spot", a warming in the tropical atmosphere about 10-15 km above the Earth's surface. In reality, there was no inconsistency between observed and modelled changes in tropical upper tropospheric temperatures, allowing for uncertainties in observations and large internal variability in temperature in the region. Furthermore, recent thermal wind calculations have indeed shown greater warming in the region (Allen and Sherwood 2008), confirming that there is no inconsistency and providing another fingerprint of enhanced greenhouse forcing.

Climate sensitivity

The rise in globally averaged temperature at equilibrium due to a given change in radiative forcing is known as the "climate sensitivity". In the context of human-driven climate change, climate sensitivity usually refers to the equilibrium temperature rise resulting from a doubling of CO_2 concentration (from 280 to 560 ppm; ppm = parts per million). With no other responses of the climate system (e.g. changes in water vapour, albedo or clouds), a doubling of CO_2 alone would result in around 1 °C warming – a number easily derived from well established radiation calculations. Importantly, water vapour amounts are closely tied to temperature, increasing with warming, and trapping extra heat. Theory, modelling studies and observations all strongly support there being a strong positive (reinforcing) water vapour feedback, which roughly doubles the initial warming from CO_2. Other feedbacks, due to responses from surface albedo (positive), temperature 'lapse rate' (negative) and clouds also contribute, with cloud feedbacks being the most uncertain.

SOME OF THE MOST IMPORTANT RESEARCH IN RECENT YEARS HAS REDUCED THE UNCERTAINTY SURROUNDING ESTIMATES OF CLIMATE SENSITIVITY.

Multiple simulations by climate models driven by a 560 ppm CO_2 atmosphere have generated a probability density function with most of the values for sensitivity falling between 2 and 4.5 °C and a peak near 3 °C (IPCC 2007a). An analysis of the transition of the Earth from the last ice age to the Holocene, which infers climate sensitivity from the observed change in temperature and the corresponding changes in the factors that influence radiative forcing, also estimates a value of about 3 °C (Hansen et al. 2008). Much of the uncertainty on the magnitude of climate sensitivity is associated with the direction and strength of cloud feedbacks. Recent observational evidence from short-term variations in clouds suggests that short-term cloud feedbacks are positive, reinforcing the warming, consistent with the current model-based estimates of cloud feedbacks (Clement et al. 2009; Dessler 2010).

A recent model study comparing the relative importance of various greenhouse gases for the climate estimates a sensitivity of approximately 4 °C for a doubling of CO_2 (Lacis et al. 2010). In addition, the study points to the importance of CO_2 as the principal "control knob" governing Earth's surface temperature. Although CO_2 accounts for only about 20% of Earth's greenhouse effect (other long-lived greenhouse gases account for 5% and water vapour and clouds account for 75% via their fast feedback effects), it is the one that effectively controls climate because of its very long lifetime in the atmosphere. Water vapour amounts are determined by atmospheric temperatures, which in turn are governed by concentrations of the long-lived greenhouse gases such as CO_2. In fact, without these long-lived greenhouse gases, the Earth's temperature would drop rapidly and drive the planet into an ice-bound state.

1.3 How is the carbon cycle changing?

The analysis in the previous two sections shows that (i) the Earth's surface is warming at a relatively rapid rate, and (ii) the primary reason for this warming, at least since the middle of the 20th century, is the increase in CO_2 in the atmosphere. These conclusions focus attention strongly on the carbon cycle – both how the natural carbon cycle operates and how human activities are modifying the cycle.

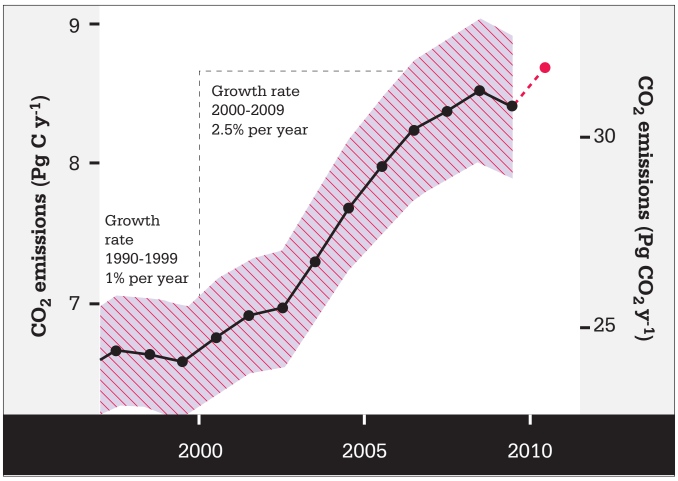
This section summarises the most recent research on changes in the behaviour of the carbon cycle and potential changes to the cycle in the future:

- Despite the dip in human emissions of greenhouse gases in 2009 due to the Global Financial Crisis, emissions continue on a strong upward trend, on average tracking near the top of the family of IPCC emission scenarios.
- Ocean and land carbon sinks, which together take up more than half of the human emissions of CO_2, appear to be holding their proportional strengths compared to emissions, although some recent evidence questions this conclusion and suggests a loss of efficiency in these natural sinks over the past 60 years.
- If global average temperature rises significantly above 2 °C (relative to pre-industrial), there is an increasing risk of large emissions from the terrestrial biosphere, the most likely source being methane stored in permafrost in the northern high latitudes.

Human emissions of CO_2

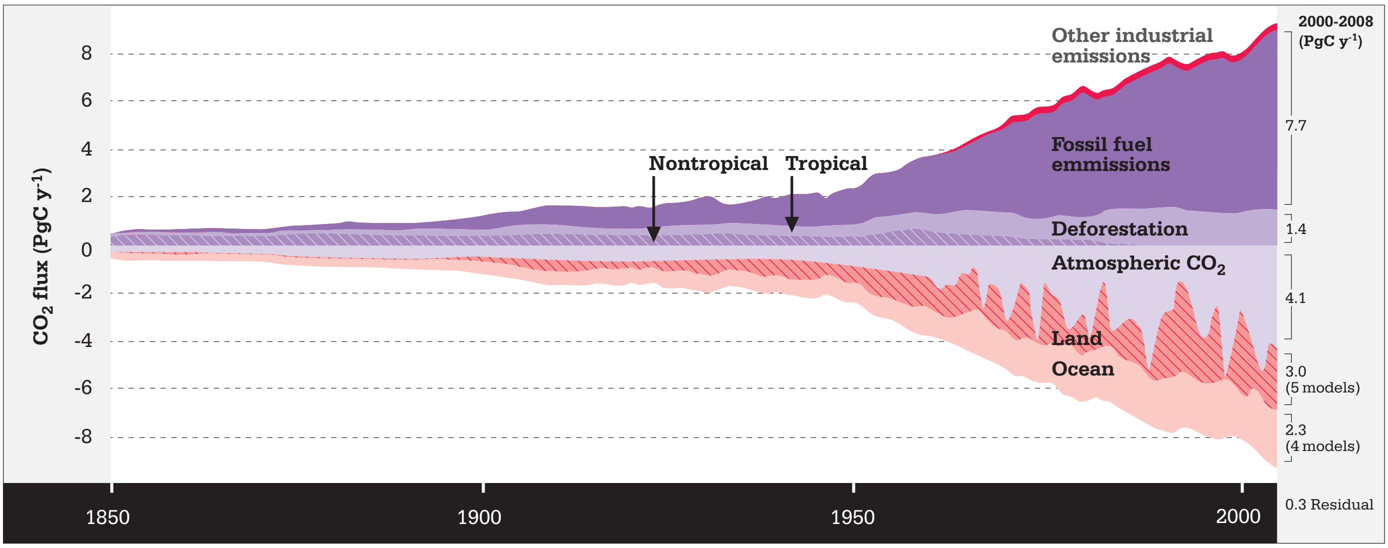
The Global Financial Crisis led to a drop in 2009 of 1.3% in the global emissions of CO_2 from fossil fuel combustion, in sharp contrast to the average annual rise in fossil fuel CO_2 emissions of 3.2% for the 2000-2008 period (Friedlingstein et al. 2010). The growth rate of emissions is expected to resume its upward trend of 3% or greater in 2010 and subsequent years, barring a further sharp economic downturn or rapid and vigorous reductions in emissions in response to climate change (Figure 11; Raupach and Canadell 2010). Given the strong rise in emissions over the past decade, current emissions are about 37% larger than those in 1990, sometimes used as the baseline against which to measure emission reductions. The current rate of emissions lies near the top of the envelope of IPCC projections (Raupach and Canadell 2010). Over the last few years, coal has overtaken oil as the largest source of CO_2 from fossil fuel combustion (Le Quéré et al. 2009: CDIAC 2010). Despite the drop in the absolute amount of emissions in 2009, the atmospheric concentration of CO_2 still rose by 1.6 ppm during the year, compared to an average growth rate of 1.9 ppm per year for the 2000-2008 period (Tans and Conway 2010).

Figure 11. Global CO_2 emissions since 1997 from fossil fuel and cement production. Emissions were based on the United Nations Energy Statistics to 2007, and on BP energy data from 2007 onwards. Cement CO_2 emissions are from the US Geological Survey. Projection for 2010 is included in red.



Source: Friedlingstein et al. (2010), and references therein.

Figure 12. Terms in the global CO_2 budget for the period 1850-2008 inclusive. Anthropogenic CO_2 emissions, shown as positive fluxes into the atmosphere, comprise contributions from fossil fuel combustion and other industrial processes, and land use change, mainly deforestation. The fate of emitted CO_2, including the accumulation of atmospheric CO_2, the land CO_2 sink and the ocean CO_2 sink, is shown by the balancing negative fluxes. Values of average fluxes for 2000-2008 (shown at right) include a small residual because all terms were estimated independently from measurements or models, without a priori application of a mass-balance constraint.



Source: Raupach and Canadell (2010), based on Le Quere et al. (2009).

Ocean and land carbon sinks

Natural sinks of carbon on land and in oceans (e.g., uptake of CO_2 by growing vegetation; dissolution of CO_2 in seawater) have historically removed over half of the human emissions from the atmosphere – for example, 57% for the 1958-2009 period (Le Quéré et al. 2009). The carbon is taken up in approximately equal proportions by land and ocean (Raupach and Canadell 2010; Figure 12), although there is considerable variability in the strength of these natural sinks from year to year, largely in response to climate variability. Over the past half-century the capability of these natural sinks has generally kept pace with the increasing human emissions of CO_2. However, there is evidence that the efficiency of these sinks is declining (Canadell et al 2007; Raupach et al. 2008; Le Quéré et al. 2009), particularly in the Southern ocean (Le Quéré et al. 2007). There are uncertainties with some of these results, and some scientific controversy over the declining trend particularly in recent years (Francey et al. 2010; Knorr 2009; Poulter et al. 2011).

The ongoing strength of these natural sinks is crucially important for the level of effort that will be required to limit climate change to no more than a 2 °C rise above pre-industrial, often referred to as the 2 °C guardrail (Council of the European Union 2005; IPCC 2007a; Copenhagen Accord 2009). This target, often quoted as defining the boundary of "dangerous" climate change, is based on value judgements, informed by scientific understanding, and has been developed through a political process. There is considerable scientific evidence (e.g., Smith et al. 2009; Richardson et al. 2011) that values of temperature rise above 2 °C are "dangerous" by most definitions, but this evidence also shows that there are significant risks of serious impacts in various sectors and locations at temperature increases of less than 2 °C. Nevertheless, the 2 °C guardrail has been a widely accepted and quoted political goal.

Vulnerable new sources of carbon

In addition to the potential weakening of the current natural carbon sinks as temperature increases, there is the potential for activating new natural sources of carbon emissions from pools that are currently inactive. Examples include methane hydrates stored under the sea floor, organic material stored in tropical peat bogs and organic material stored in permafrost in the northern high latitudes and the Tibetan plateau. Of these potential sources, the permafrost carbon is generally considered to be the most important.

> **THERE ARE OVER 1,700 BILLION TONNES OF CARBON STORED IN PERMAFROST (TARNOCAI ET AL. 2009), WHICH IS ABOUT TWICE THE AMOUNT STORED IN THE ATMOSPHERE AT PRESENT.**

There is uncertainty about the vulnerability of this potential new source of carbon (e.g., Lawrence and Slater 2005; Lawrence et al. 2008), but there is already evidence of some loss of methane from the northern high latitudes (e.g., Dorrepaal et al. 2009). One analysis of future vulnerability assesses that about 100 billion of the 1,700 billion tonnes are vulnerable to thawing this century (Schuur et al. 2009).

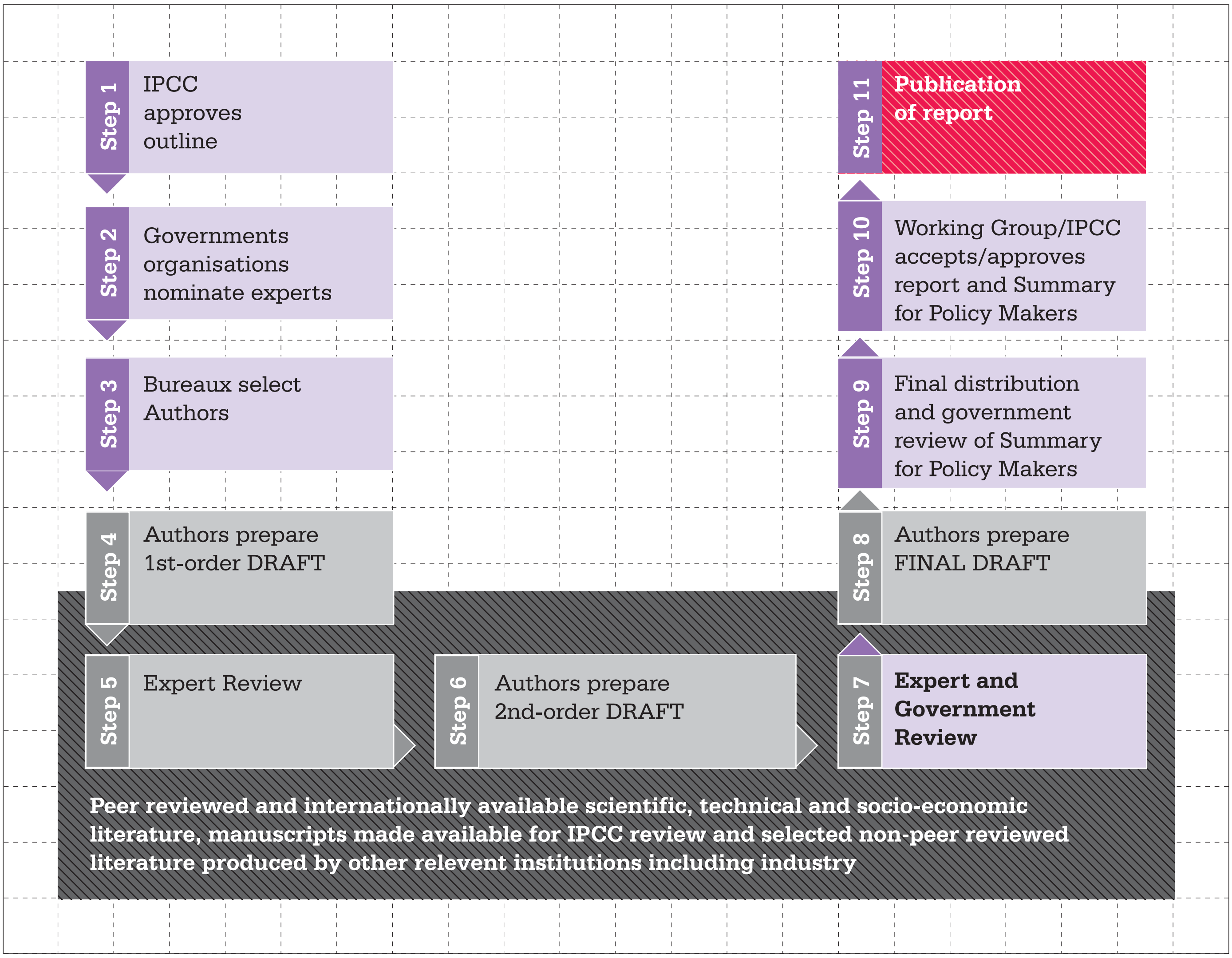
1.4 How certain is our knowledge of climate change?

Following criticisms of the IPCC, the so-called "climategate" incident in the UK (the hacking of emails of climate scientists at the University of East Anglia), and numerous attacks in the media and elsewhere on climate science, there has been much focus on the veracity of climate science and on the level of certainty or uncertainty surrounding knowledge of climate science. The key question is: Are we confident enough about (i) our understanding of the climate system, (ii) the human influence on climate, and (iii) the consequences of contemporary climate change for societies and ecosystems to provide a reliable knowledge base on which to base policy and economic responses?

This section will briefly explore the level of certainty and uncertainty surrounding the knowledge base on which scientific understanding of contemporary climate change rests. The main messages are:

- The IPCC's Fourth Assessment Report has been intensively and exhaustively scrutinised and is virtually error-free.
- The Earth is warming on a multi-decadal to century timescale, and at a very fast rate by geological standards. There is no doubt about this statement.
- Human emissions of greenhouse gases – and CO_2 is the most important of these gases – is the primary factor triggering observed climate change since at least the mid 20th century. The IPCC AR4 (2007a) report attached 90% certainty to that statement; research over the past few years has strengthened our confidence in this statement even more.
- Many uncertainties surround projections of the particular risks that climate change poses for human societies and natural and managed ecosystems, especially at smaller spatial scales. However, our current level of understanding provides some useful insights: (i) some social, economic and environmental impacts are already observable from the current level of climate change; (ii) the number and magnitude of climate risks will rise as the climate warms further.

Figure 13. The process by which the IPCC carries out an assessment, including the careful and exhaustive, two-tiered review process.



Source: IPCC (2011).

The IPCC

As the primary source of information on climate change for the policy community, the IPCC produces periodic assessments of the literature by scientific experts approximately every six years, as well as interim special reports. There are three working groups – one each for the fundamental climate science; impacts, adaptation and vulnerability; and mitigation of climate change. The Fourth Assessment Report (AR4), published in 2007, involved about 1,250 expert authors and 2,500 reviewers, who produced about 90,000 comments on drafts, each one of which was addressed explicitly by the authors. This exhaustive, thorough process is shown schematically in Figure 13.

The IPCC AR4 has been intensively and exhaustively scrutinised, including formal reviews such as that by the InterAcademy Council (2010), and only two peripheral errors, both of them in the WG 2 report on impacts and adaptation, have yet been found (in a publication containing approximately 2.5 million words!). No errors have been found in any of the main conclusions, nor have any errors been found in the 996-page WG 1 report, which describes our understanding of how and why the climate system is changing. The IPCC AR4 WG 1 report provides the scientific input to the development of climate policy. Several official "assessments of the assessment" have concluded that the conclusions of the AR4 are sound (InterAcademy Council 2010; Royal Society 2010; National Research Council 2010).

In summary, despite intensive, and ultimately unsuccessful, attempts to find important errors in the assessments, the IPCC has been confirmed as a source of reliable scientific information on climate change.

Certainty of warming

The evidence that the Earth is warming on a multi-decadal timescale, and at a very fast rate by geological standards, is now overwhelming. Some of this evidence has been presented above. The IPCC used the word "unequivocal" to describe our confidence in the observations of a warming Earth. Observations since 2007 have strengthened our confidence in this statement.

Human causation

Based on its thorough assessment of the evidence, the IPCC in 2007 stated that:

> "MOST OF THE OBSERVED INCREASE IN GLOBAL AVERAGE TEMPERATURES SINCE THE MID-20TH CENTURY IS VERY LIKELY DUE TO THE OBSERVED INCREASE IN ANTHROPOGENIC GREENHOUSE GAS CONCENTRATIONS".

The term *very likely* in the IPCC definitions of uncertainty is associated with a greater than 90% certainty that the statement is correct (IPCC 2007a). Research over the past few years has further strengthened our confidence in the IPCC's assessment of attribution. Such research, described earlier, includes better estimates of climate sensitivity, more observations of the patterns of climatic changes – "fingerprints" characteristic of greenhouse gas forcing, and improved understanding of the long-term role of CO_2 in the climate system.

Large uncertainties

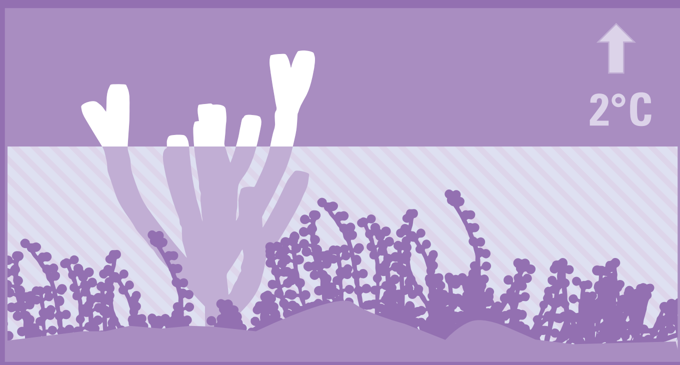
Although the fundamental features of climate change, as described above, are very well known, significant uncertainties surround our understanding of the behaviour of important parts of the climate system. For example, the ways in which the large polar ice sheets on Greenland and Antarctica are responding and will respond in future to warming are not well known, and are generating intense discussion and further research in the scientific community. Similarly, although considerable evidence points toward an acceleration of the hydrological cycle as the climate warms – increased evaporation, more water vapour in the atmosphere, and increased precipitation – this trend is still being debated in the research community, as is the influence of climate change on spatial patterns of precipitation across the Earth's surface and on the temporal patterns of precipitation – droughts and intense rainfall events. These uncertainties, however, in no way diminish our confidence in the observation that the Earth is warming and in our assessment that human emissions of greenhouse gases are the primary reason for this warming.

Many uncertainties also surround our understanding of the risks that climate change poses for human societies and natural and managed ecosystems. These uncertainties stem from several factors: (i) uncertainties in the projections of potential impacts from future climate change; (ii) uncertainties associated with the dynamics of systems being impacted by climate, such as agricultural systems, natural ecosystems, or urban systems; and (iii) uncertainties in the ways in which humans will respond to the threats of climate change by reducing their vulnerability or increasing their adaptive capacity. Despite these seemingly daunting uncertainties, a number of social, economic and environmental impacts can be observed that are consistent with what is anticipated from the current level of climate change. The number and magnitude of climate-related risks will rise considerably as the climate warms towards 2 °C above the pre-industrial level; and above the 2 °C guardrail, the risks may rise dramatically (Smith et al. 2009; Richardson et al. 2011). The most serious risks are associated with potential abrupt or irreversible changes in large features of the climate system, such as the switch to a dry state of the Indian Summer Monsoon (Lenton et al. 2008). Decision-making in the face of such uncertainties will remain a big challenge for the policy and management communities.

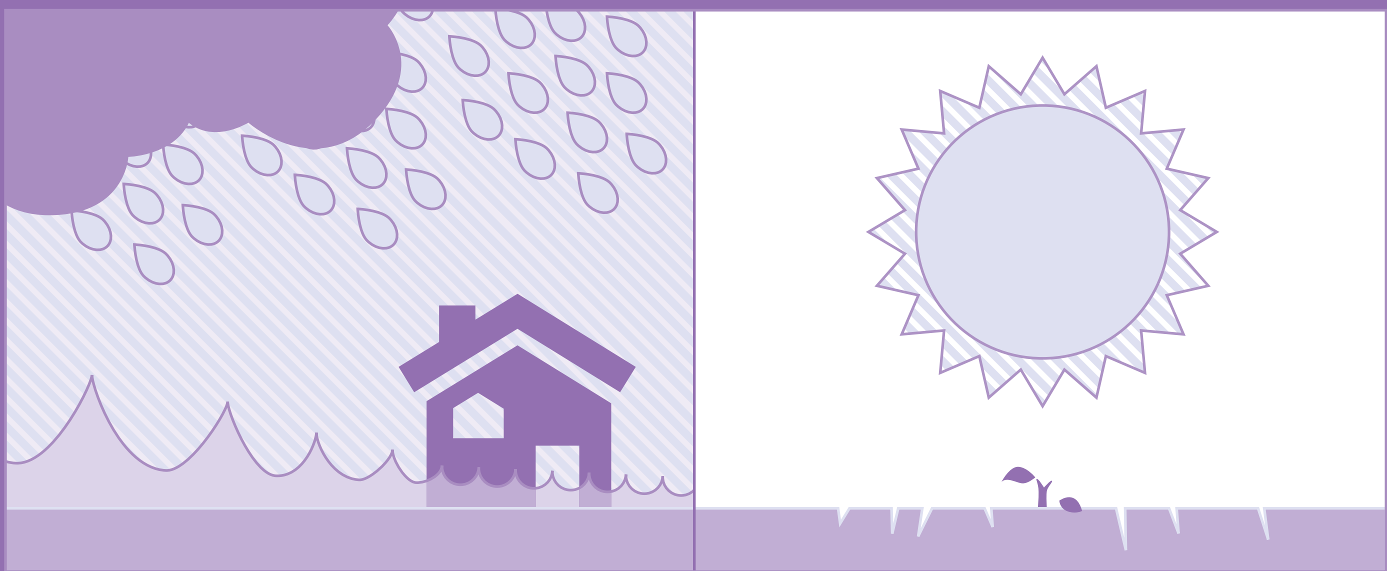
CHAPTER 2: RISKS ASSOCIATED WITH A CHANGING CLIMATE

DID YOU KNOW...

CORAL-DOMINATED ECOSYSTEMS ARE SENSITIVE TO SMALL RISES IN THE TEMPERATURE OF THE WATER IN WHICH THEY RESIDE. WHEN THE SEA TEMPERATURE RISES 1-2°C ABOVE NORMAL FOR A SIX-EIGHT WEEK PERIOD THE CORALS ARE "BLEACHED".



WHAT WE CAN SAY WITH CERTAINTY IS THAT RAINFALL PATTERNS WILL CHANGE AS A RESULT OF CLIMATE CHANGE AND OFTEN IN UNPREDICTABLE WAYS, CREATING LARGE RISKS FOR WATER AVAILABILITY.



TEMPERATURE INCREASES OF 1 OR 2 °C MAY SEEM MODEST, BUT THEY CAN LEAD TO DISPROPORTIONATELY LARGE CHANGES IN THE FREQUENCY AND INTENSITY OF EXTREME WEATHER EVENTS.

2.1 Sea-level rise

With much of our population and a high fraction of our infrastructure located close to the coast, Australia is vulnerable to the risks posed by sea-level rise. Although sea level will continue to rise for many centuries (Solomon et al. 2009), the more immediate concern is the level of risk associated with sea-level rise out to 2100, when some of our existing infrastructure and much new infrastructure will be at risk. The rate at which sea level will rise through this century is a critical factor in determining the degree of exposure to risk.

This section builds on Section 1.1 on observations of sea-level rise to explore the range of rates at which sea-level could rise this century and the implications of such rises for the inundation of parts of our coastline.

The key messages are:

- A plausible estimate of the amount of sea-level rise by 2100 compared to 1990 is 0.5 to 1.0 m. There is significant uncertainty around this estimate, the largest of which is related to the dynamics of large polar ice sheets.
- Much more has been learned about the dynamics of the large polar ice sheets through the past decade but critical uncertainties remain, including the rate at which mass is currently being lost, the constraints on dynamic loss of ice and the relative importance of natural variability and longer-term trends.
- The impacts of rising sea-level are experienced through "high sea-level events" when a combination of sea-level rise, a high tide and a storm surge or excessive run-off trigger an inundation event. Very modest rises in sea-level, for example, 50 cm, can lead to very high multiplying factors – sometimes 100 times or more – in the frequency of occurrence of high sea-level events.

Projections of future sea-level rise

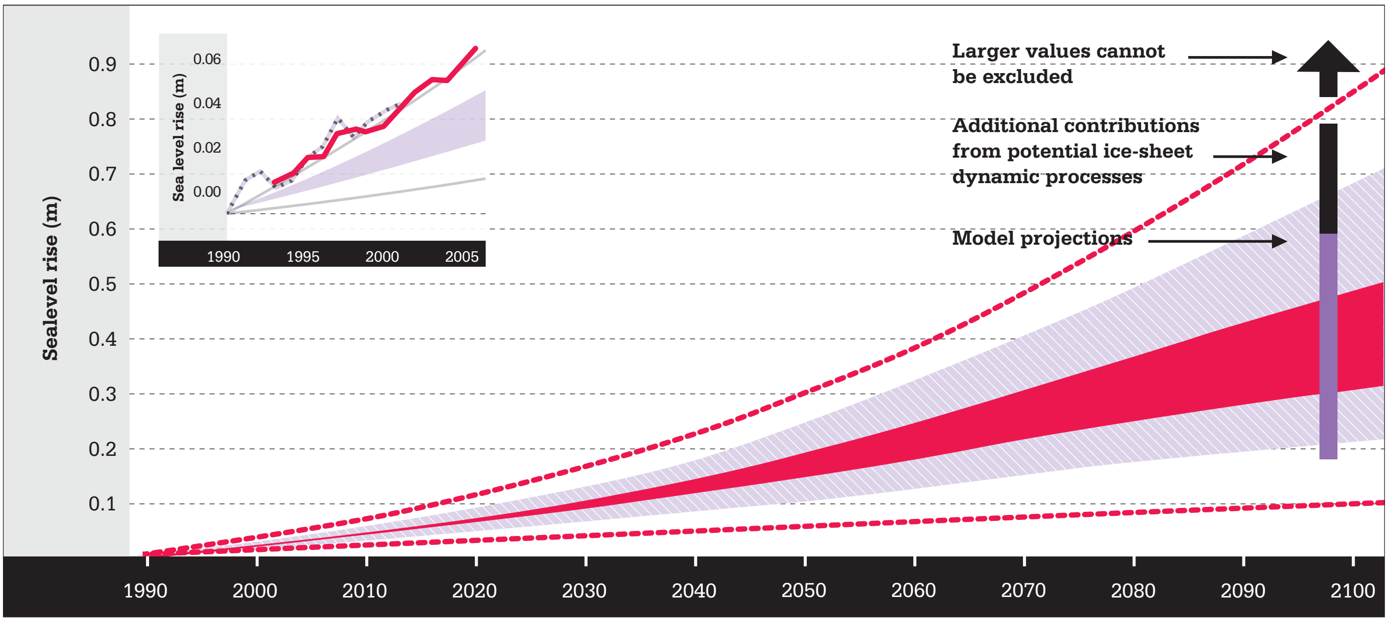
PROJECTIONS OF SEA-LEVEL RISE FOR THE REST OF THE CENTURY VARY WIDELY, FROM THE OFT-QUOTED RANGE OF 0.19-0.59 M BASED ON THE IPCC AR4 (2007a) TO NEARLY 2 METRES (VERMEER AND RAHMSTORF 2009).

The IPCC projections are often misquoted as they do not take into account the loss of ice due to dynamical processes in the large polar ice sheets.

When estimates for this process are included, the range changes to 0.18 – 0.76 m, and the IPCC is careful to note that higher values cannot be excluded (IPCC 2007a; Figure 14). By comparison, the Third Assessment Report of the IPCC (2001) projected a sea-level rise of 0.11 – 0.88 m for this century.

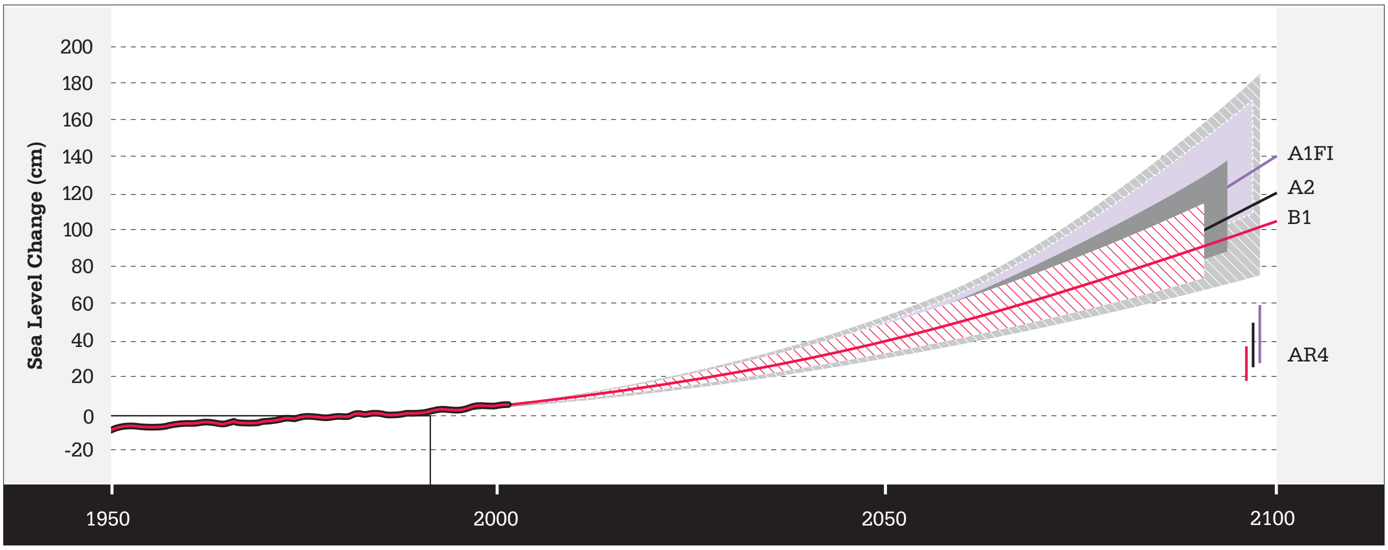
The projections yielding higher ranges of sea-level are often based on statistical or semi-empirical models that relate the observed sea-level rise over the past 120 years to the observed temperature rise over that period (e.g., Rahmstorf 2007; Horton et al. 2008; Grinsted et al. 2009). The approach is to use projections of temperature rise to 2100 to estimate the corresponding rise in sea-level based on the observed relationship. The range of temperature increases then yields a range of projected sea-level changes. Projections using semi-empirical models are generally higher than those of the IPCC because they incorporate the observed acceleration of sea-level rise during the 1990-2009 period and project that further acceleration will occur as the climate warms. Figure 15 shows an example of projected changes in sea level based on a semi-empirical model (Vermeer and Rahmstorf 2009).

Figure 14. Projections of sea-level rise from 2100 from the IPCC Third Assessment Report (TAR) and the Fourth Assessment Report (AR4). The TAR projections are indicated by the shaded regions and the broken red lines are the upper and lower limits. The AR4 projections are the bars plotted in the 2090-2100 period. The inset shows sea level observed with satellite altimeters from 1993 to 2006 (red) and observed with coastal sea-level measurements from 1990 to 2001 (purple dashes).



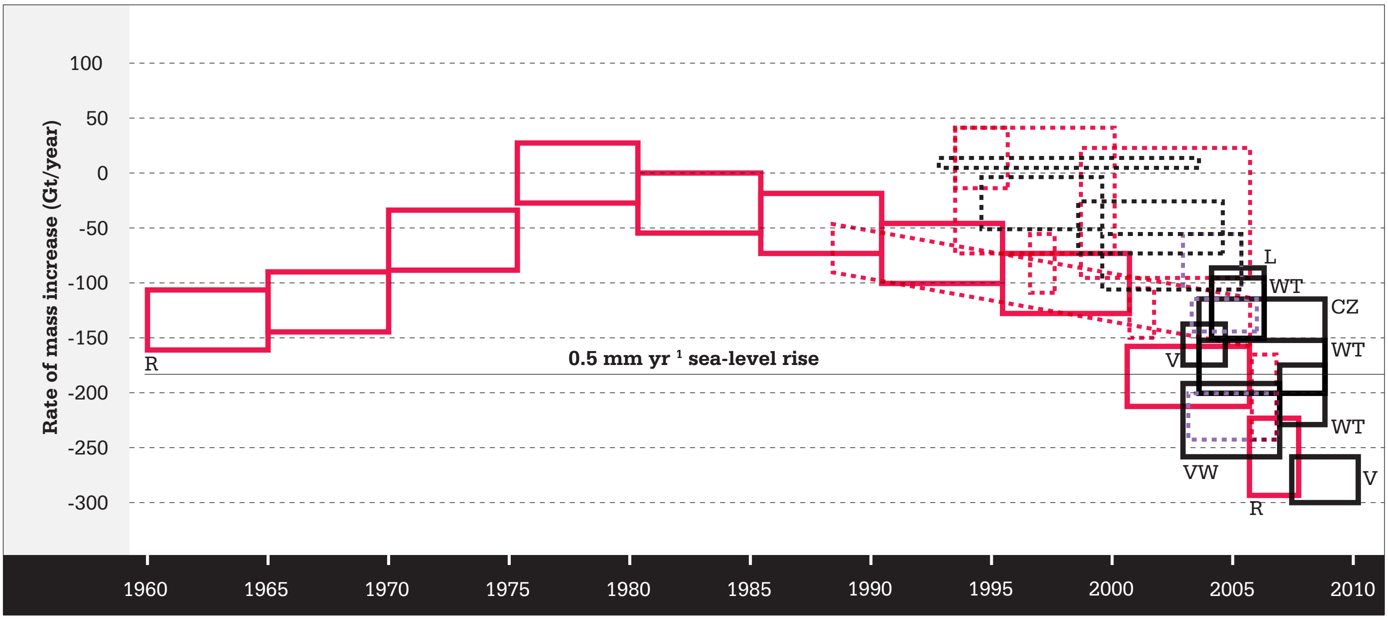
Source: ACE CRC 2008.

Figure 15. Projection of sea-level rise from 1990 to 2100, based on IPCC temperature projections for three different emission scenarios (labelled on right, see Vermeer and Rahmstorf (2009) for explanation of uncertainty ranges). The sea-level range projected in the IPCC AR4 (2007a) (excluding contributions from ice-sheet dynamic processes) for these scenarios is shown for comparison in the bars on the bottom right. Also shown is the observations-based annual global sea-level data (solid red line to 2003) including artificial reservoir correction.



Source: Vermeer and Rahmstorf (2009), and references therein.

Figure 16. Estimates of the net mass budget of the Greenland ice sheet since 1960. A negative mass budget indicates ice loss and sea-level rise. Dotted boxes represent estimates used by the IPCC (2007a). The solid boxes are post-IPCC AR4 assessment (R=Rignot et al. 2008b; VW=Velicogna and Wahr 2006; L=Luthcke et al. 2006; WT=Wouters et al. 2008; CZ=Cazenave et al. 2009; V=Velicogna 2009).



Source: The Copenhagen Diagnosis (2009).

An estimate of the likely magnitude of sea-level rise this century is useful information for risk assessments. A continuation of the currently observed rate of 3.2 mm yr^{1} would give a rise of about 0.32 m by 2100, about the mid-range of the IPCC scenarios. However, sea level is currently tracking near the upper range of the scenarios, and it seems unlikely that the rate of sea-level rise will remain fixed for nearly a century at its current level as the temperature continues to rise. On the other hand, projections of 1.5 or 2.0 metres seem high in light of recent questions surrounding estimates of the current rate of mass loss from polar ice sheets (see Figure 6).

An estimate for the most likely magnitude of sea-level rise in 2100 relative to 2000 taking polar ice sheet dynamics into account is about 0.8 m (Pfeffer et al. 2008), and an expert assessment of Greenland ice sheet dynamics suggests that it will contribute about 20 cm to global sea-level rise by 2100 (Dahl-Jensen and Steffen 2011). These are both consistent with an estimate of a 0.5–1.0 m rise in sea level by 2100.

Dynamics of large polar ice sheets

The largest uncertainty in the projections of sea-level rise discussed above is the behaviour of the large masses of ice on Greenland and Antarctica. Projections at the upper levels of the ranges of sea-level rise assume a much greater contribution from these polar ice sheets, and, in particular, from dynamical processes that discharge large blocks of ice into the sea. Observations over the past 20 years, either by satellite or aircraft altimeters that measure changes in the height of the ice sheets or by satellite gravity measurements that infer changes in mass, show accelerating decreases in the mass of the Greenland ice sheet over the past 15 years (Figure 16) and in the mass of the Antarctic ice sheet over the past decade. Such observations appear to support higher estimates of sea-level rise by 2100.

However, the measurements are for very short periods of time and so are difficult to extrapolate to longer time scales. For example, Figure 16 includes only one record of mass change in the Greenland ice sheet that is longer than 20 years, the record of Rignot et al. (2008b) from 1958. That observational record shows considerable variability on a decadal time scale, making it more difficult to extrapolate the observations of the last 10-15 years into the future with a high degree of certainty. Furthermore, a recent analysis of the gravity measurement methodology (Bromwich and Nicolas 2010) argues that estimates of the cumulative mass loss of the Greenland ice sheet are too large by a factor of two or so (Figure 6). The study of Pfeffer et al. (2008) of the kinematic constraints on rapid ice discharge from the large polar ice sheets suggests an absolute maximum sea-level rise of 2 metres by 2100, but only under extreme climatic forcing.

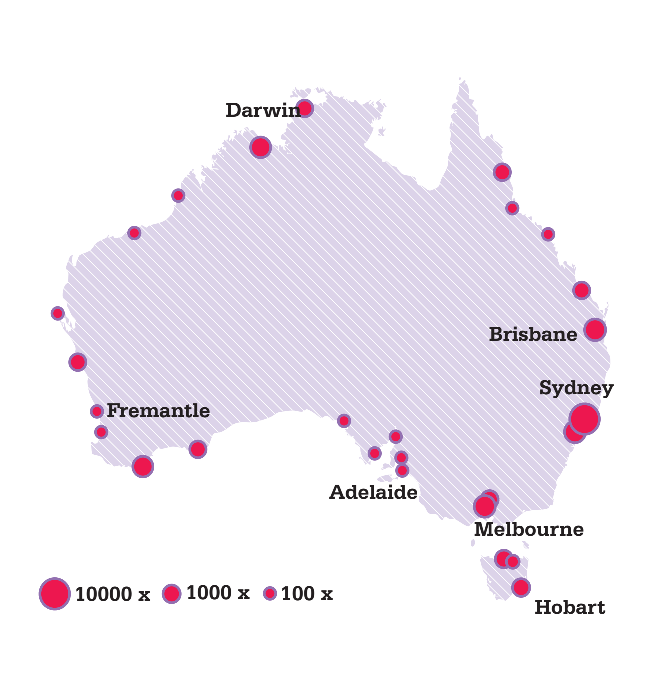
GIVEN THE IMPORTANCE OF THE LARGE POLAR ICE SHEETS FOR THE RATE OF SEA-LEVEL RISE TO 2100 AND BEYOND, THESE ONGOING UNCERTAINTIES ABOUT THE BEHAVIOUR OF THE ICE SHEETS UNDER FURTHER GLOBAL TEMPERATURE INCREASES COMPRISE ONE OF THE MOST PRESSING SCIENTIFIC RESEARCH CHALLENGES THAT REQUIRE URGENT RESOLUTION.

High sea-level events (inundation)

Many of the risks due to sea-level rise are associated with inundation events, which damage human settlements and infrastructure in low-lying coastal areas, and can lead to erosion of sandy beaches and soft coastlines. While a sea-level rise of 0.5 m – less than the average waist height of an adult human – may not seem like a matter for much concern, such modest levels of sea-level rise can lead to unexpectedly large increases in the frequency of extreme high sea-level events. These are defined as inundation events associated with high tides and storm surges, amplified by the slow rise in sea level. Such events are very sensitive to small increases in sea level, and the probability of these events rises in a highly nonlinear way with rising sea level.

Figure 17 shows the results of an analysis exploring the implications of sea-level rise for extreme sea-level events around the Australian coastline (Church et al. 2008). A sea-level rise of 0.5 m, at the lower end of the estimates for 2100, was assumed in the analysis shown in the figure, and leads to surprisingly large impacts. For coastal areas around Australia's largest cities – Sydney and Melbourne – a rise of 0.5 m leads to very large increases in the incidence of extreme events, by factors of 1000 or 10,000 for some locations. A multiplying factor of 100 means that an extreme event with a current probability of occurrence of 1-in-100 – the so-called one-in-a-hundred-year event – would occur every year. A multiplication factor of 1000 implies that the one-in-a-hundred-year inundation event would occur almost every month.

Figure 17. Estimated multiplying factor for the increase in the frequency of occurrence of high sea-level events caused by a sea-level rise of 0.5 metres. High sea-level events are very sensitive to small increases in sea level.



Source: ACE CRC 2008.

The observed sea-level rise of about 20 cm from 1880 to 2000 should already have led to an increase in the incidence of extreme sea-level events. Such increases have indeed been observed at places with very long records, such as Fremantle and Fort Denison, where a 3-fold increase in inundation events has occurred (Church et al. 2006). This is consistent with the methodology used to produce Figure 17.

A more detailed assessment of the potential impacts of sea-level rise has been carried out by the then Department of Climate Change (DCC 2009), providing estimates of areas of inundation for a sea-level rise of 1.1 m, just above the upper end of our projection range for 2100. The Department has recently released more detailed maps to highlight low-lying coastal areas vulnerable to inundation from sea-level rise.

2.2 Ocean acidification

Changes in the alkalinity/acidity of the ocean represent a change in a fundamental environmental condition for marine ecosystems. In particular, those marine organisms that form calcium carbonate shells are at risk from decreasing alkalinity of the ocean, which reduces the concentration of carbonate ions in seawater. Corals are probably the most well-know of these organisms, but other calcifying organisms are important for the marine carbon cycle and play fundamental roles in the dynamics of marine ecosystems.

This section provides information on the projected magnitude and rate of change of ocean alkalinity/acidity through this century, and on observations of the impacts of increasing acidity on marine ecosystems. The key messages are:

- The contemporary rate of increase in ocean acidity (decrease in alkalinity) is very large from a long-time perspective.
- The effects of increasing acidity are most apparent in the high latitude oceans, where the rates of dissolution of atmospheric CO_2 are the greatest.
- Increasing acidity in tropical ocean surface waters is already affecting coral growth; calcification rates have dropped by about 15% over the past two decades.
- Rising SSTs have increased the number of bleaching events observed on the Great Barrier Reef (GBR) over the last few decades. There is a significant risk that with a temperature rise above 2 °C relative to pre-industrial levels and at CO_2 concentrations above 500 ppm, much of the GBR will be converted to an algae-dominated ecosystem.

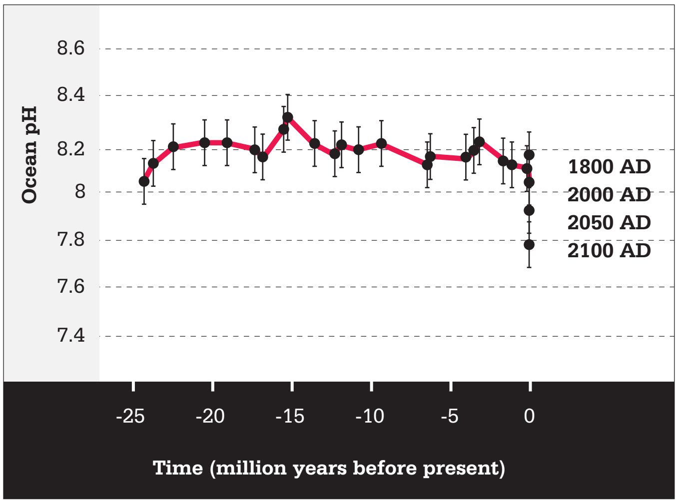
Ocean acidity in a long-time context

The rate at which ocean acidity is increasing is important, especially from an evolutionary perspective. Figure 18a shows the change in ocean acidity over the past 25 million years and projected to 2100 (Turley et al. 2006; 2007).

Ocean acidity has varied considerably over that period, but the level of acidity today is as high as it was 25 million years ago, the previous most acidic state in the record.

MORE STRIKING IS THE RATE OF CHANGE IN ACIDITY THAT HAS ALREADY OCCURRED FROM 1800 TO 2000 AND THAT WHICH IS PROJECTED TO 2100. THIS IS AN EXCEPTIONALLY RAPID RATE OF CHANGE, LIKELY UNPRECEDENTED IN THE 25 MILLION YEARS OF THE RECORD, AND WOULD NO DOUBT PLACE SEVERE EVOLUTIONARY PRESSURE ON MARINE ORGANISMS. (FIGURE 18b)

Figure 18a. Ocean acidity (pH) over the past 25 million years and projected to 2100. The lower the pH, the more acidic the ocean becomes. Prehistoric surface-layer pH values were reconstructed using boron-isotope ratios of ancient planktonic foraminifera shells. Future pH values were derived from models based on IPCC mean scenarios.

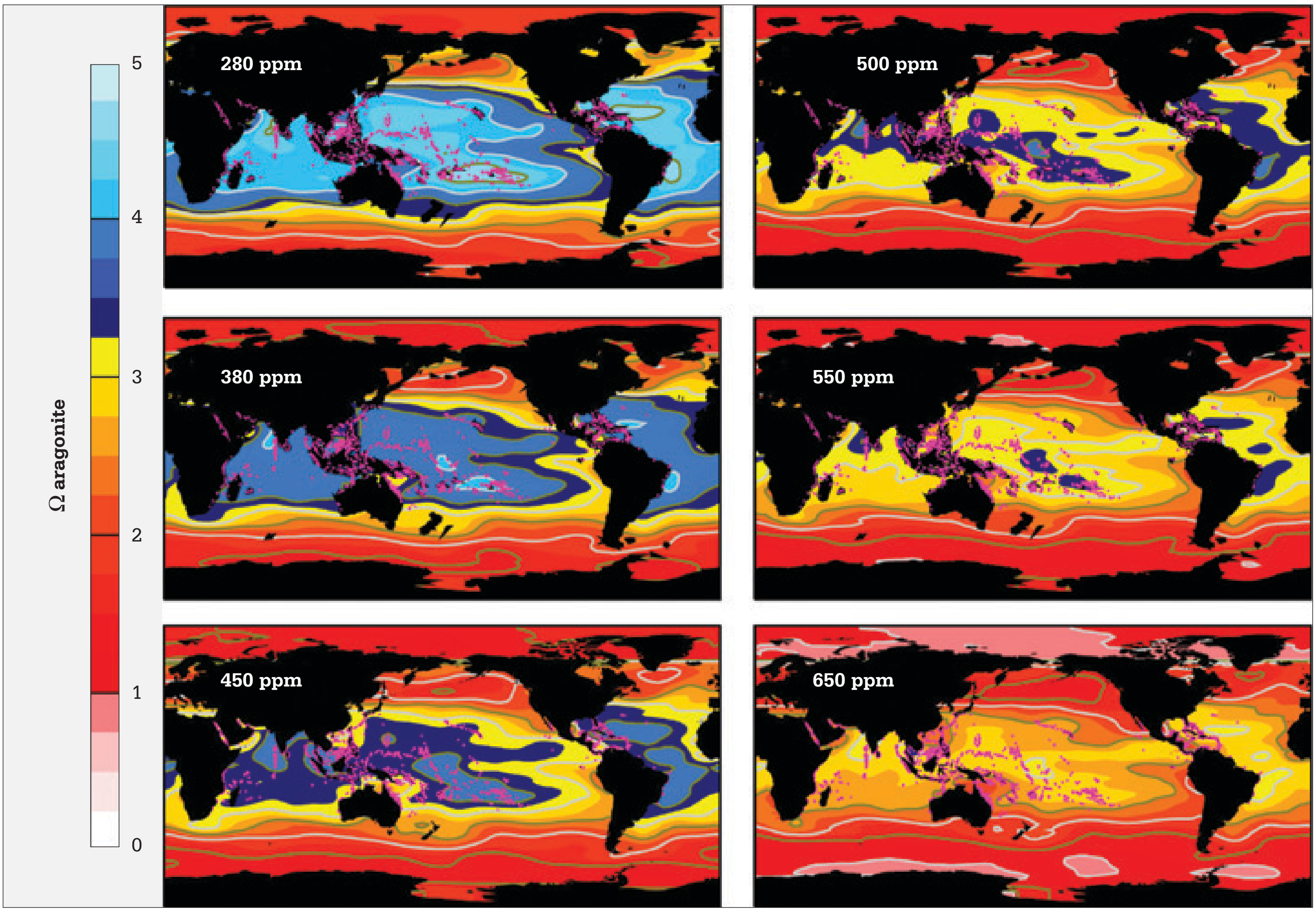


Source: Turley et al. (2006).

Marine ecosystems

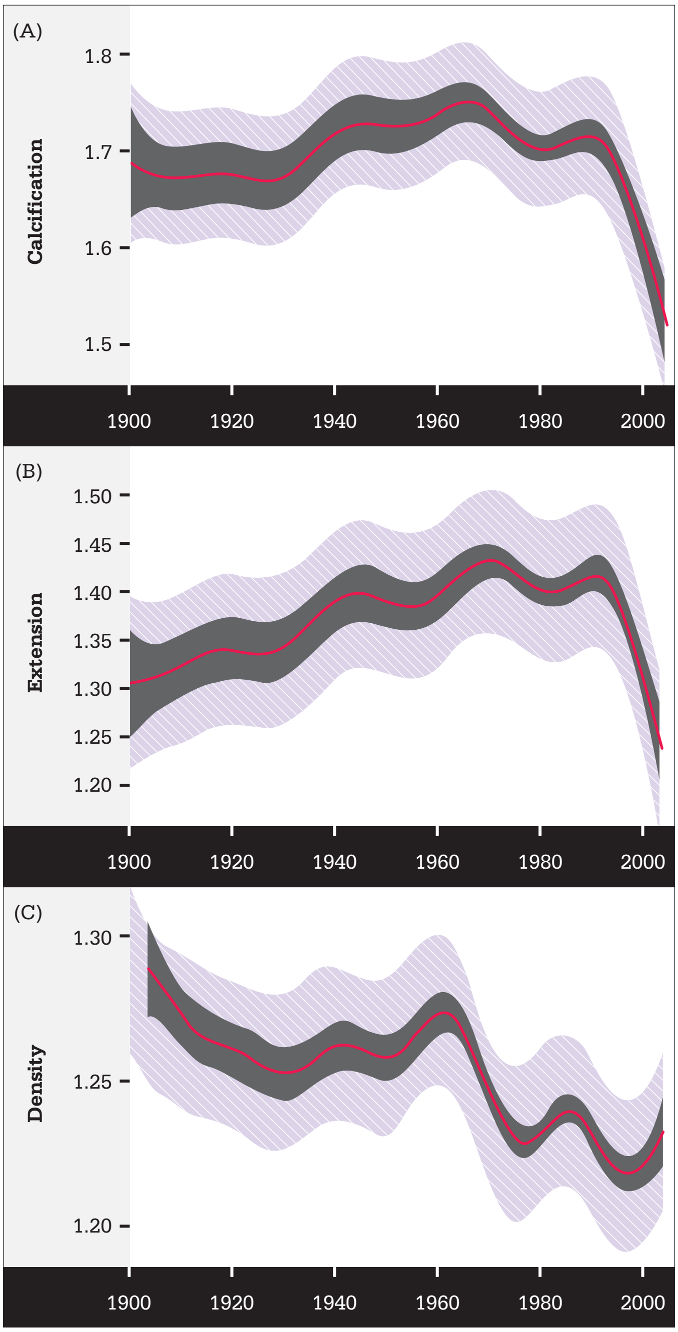
The impacts of increasing ocean acidity are already evident in some marine species (Moy et al. 2009). Many of the earliest impacts are expected in polar or sub-polar waters, as CO_2 is more soluble in cold water than warm and so acidification is expected to proceed more rapidly there. Observational studies in the Southern Ocean of acidity and carbonate ion concentration show strong seasonal minimums in winter; conditions deleterious for the growth of calcifying plankton species could occur as early as 2030 in winter (McNeil and Matear 2008). Experiments in sea water with the acidity level expected in 2100 have shown a 30% reduction in calcification rates for a common pteropod (pelagic marine snail), an important component of marine food chains (Comeau et al. 2009). Even larger reductions in calcification rates of around 50% have been found in experiments with a deepwater coral (Maier et al. 2009). Impacts of acidification further up marine food chains, including fish, are largely unknown as yet (Turley and Findlay 2009). Previous ocean acidification events are likely to have been significant factors in mass extinction events in marine ecosystems (Veron 2008).

Figure 18b. Changes in relative aragonite saturation predicted to occur as atmospheric CO_2 concentrations (ppm – upper left of panels) increase over shallow-water coral reef locations (pink dots).



Source: Hoegh-Guldberg et al. (2007), which gives more information on the figure. See also Figure 20a for the connection between aragonite saturation and coral reef state.

Figure 19. Variation of (a) calcification (grams per square centimetre per year), (b) linear extension (centimetres per year) and (c) density (grams per cubic centimetre) in *Porites* over time. Dark grey bands indicate 95% confidence intervals for comparison between years, and purple bands indicate 95% confidence intervals for the predicted value for any given year.



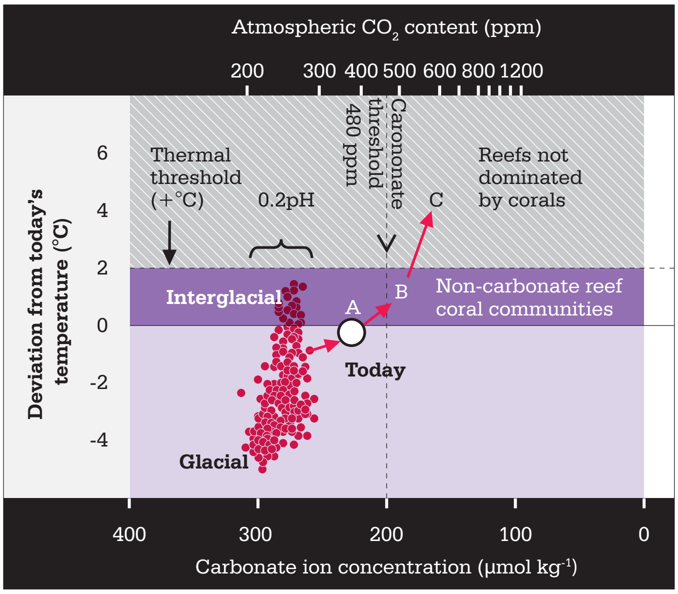
Source: De'ath et al. (2009).

Coral reefs

The risks of climate change for coral reefs are particularly important for Australia, given the iconic status and economic importance of the Great Barrier Reef (Oxford Economics 2009).

There is evidence that shows a possible impact of the increase in acidity that has already occurred, based on a study of changes in the calcification rate of the coral *Porites* (De'ath et al. 2009). The observational study was carried out using 328 sites on 69 reefs and showed a precipitous drop in calcification rate, linear extension and coral density, all indicators of coral growth, in the last 15-20 years of a 400-year record (Figure 19). These data are suggestive of a highly nonlinear response of corals to ocean acidity (in combination with other stressors), perhaps taking the form of threshold-abrupt change behaviour (cf. Section 3.5).

Figure 20a. Temperature, atmospheric CO_2 concentration and carbonate ion concentrations reconstructed for the past 420,000 years. Carbonate concentrations were calculated from Vostok ice core data. Acidity of the ocean has varied by +/- 0.1 pH units over the past 420,000 years. The thresholds for major changes to coral communities are indicated for thermal stress (+2 °C) and carbonate ion concentration (200 micro-mol kg^{-1}); the latter corresponds to an approximate aragonite saturation of 3.3 and an atmospheric CO_2 concentration of 480 ppm. Red arrows pointing towards the upper right indicate the pathway currently followed towards atmospheric CO_2 concentration of more than 500 ppm.



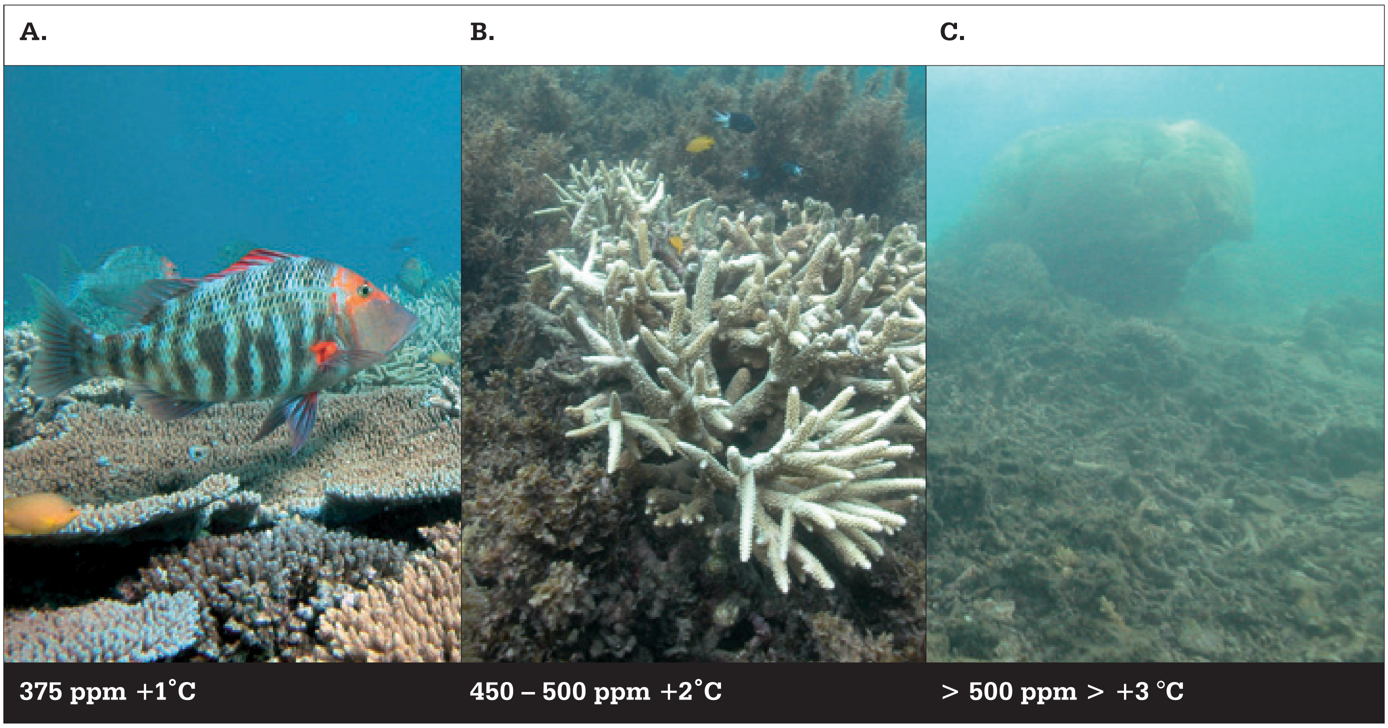
Source: Hoegh-Guldberg et al. (2007), including details of the reconstructions and the location of the photos in part (b).

Corals are also affected by extremes in SSTs (cf. Section 3.4), which can lead to coral bleaching. A 21st century risk analysis for coral reefs emphasises the importance of both SST and acidity/carbonate ion concentration for their future viability. Figure 20 combines the temperature and acidity/carbonate ion concentration influences in a two-dimensional environmental space diagram that contrasts the past, present and future environments for coral reefs (Hoegh-Gulberg et al. 2007).

The cluster of red dots represents the envelope of natural variability that reefs have experienced over the past 420,000 years. Present conditions of carbonate ion concentration – but not temperature – have pushed reefs outside of this envelope.

MOST EMISSIONS AND CLIMATE SCENARIOS FOR THE REST OF THIS CENTURY (IPCC 2007a) PREDICT THE CONVERSION OF CORAL REEFS INTO ALGAE-DOMINATED ECOSYSTEMS (THE UPPER RIGHT QUADRANT OF FIGURE 20a AND THE RIGHT-HAND PANEL OF FIGURE 20b).

Figure 20b. Extant examples from the Great Barrier Reef as analogs for the reef states anticipated for the environmental conditions marked A, B and C in part (a) of the figure.



Source: modified from Hoegh-Guldberg et al. (2007).

2.3 The water cycle

Australia is the driest of the six inhabited continents, and experiences a high degree of natural climatic variability – the proverbial "land of droughts and flooding rains". Thus, the link between climate and water resources has been a dominant theme in the lives of all Australians, from the arrival of the first people about 60,000 years ago to the present. The risks of climate change for water resources, and especially the ways in which the longer term trends of human-induced climate change interact with modes of natural variability, is a hotly debated topic, both within and outside of the research community.

ACHIEVING A BETTER UNDERSTANDING OF THE NATURE OF THIS RISK IS AN URGENT RESEARCH CHALLENGE, THE RESULTS OF WHICH WILL INFORM MANY MANAGEMENT AND POLICY DECISIONS NOW AND INTO THE FUTURE.

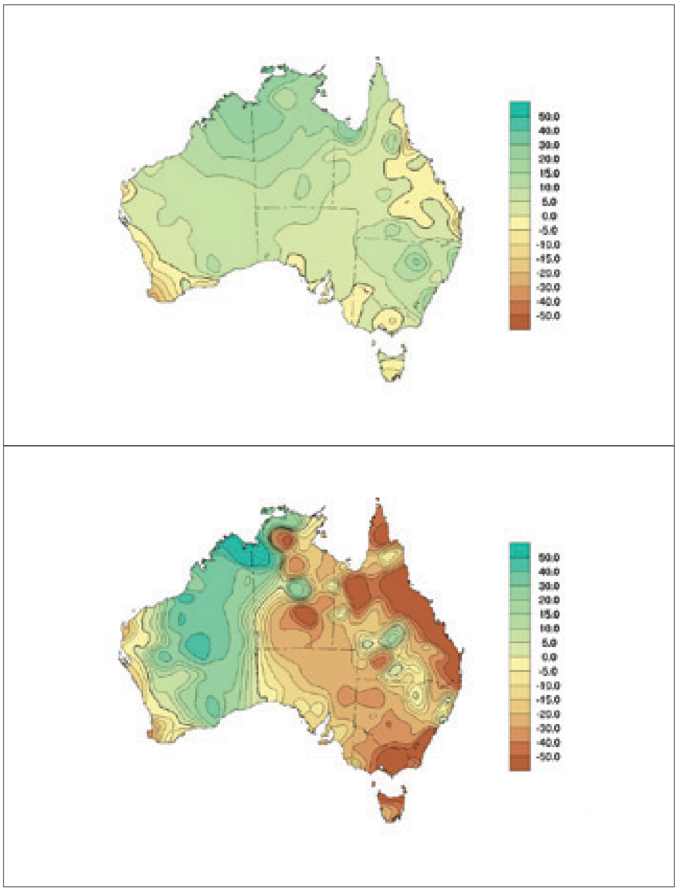
This section explores our current level of knowledge about the climate change-variability relationship and the consequent risks for water resources. The key messages are:

- Observations since 1970 show a drying trend in most of eastern Australia and in southwest Western Australia but a wetting trend for much of the western half of the continent.
- Given the high degree of natural variability of Australia's rainfall, attributing observed changes to climate change is difficult. There is no clear trend, either in observations or model projections, for how the major mode of variability, ENSO, is responding to climate change. Evidence points to a possible climate change link to observed changes in the behaviour of the Southern Annular Mode (SAM) and the Indian Ocean Dipole (IOD).
- Improvements in understanding of the climatic processes that influence rainfall suggest a connection to climate change in the observed drying trend in southeast Australia, especially in spring. In southwest Western Australia, climate change is likely to have made a significant contribution to the observed reduction in rainfall.
- The consensus on projected changes in rainfall for the end of this century is (i) high for southwest Western Australia, where almost all models project continuing dry conditions; (ii) moderate for southeast and eastern Australia, where a majority of models project a reduction; and (iii) low across northern Australia. There is a high degree of uncertainty in the projections in (ii) and (iii), however.
- Rainfall is the main driver of runoff, which is the direct link to water availability. Hydrological modelling indicates that water availability will likely decline in southwest Western Australia, and in southeast Australia, with less confidence in projections of the latter. There is considerable uncertainty in the projections of amounts and seasonality of changes in runoff.

Observations of rainfall change

Although the continent of Australia has become slightly wetter in terms of total annual rainfall over the past century, a pronounced pattern has developed since 1970, with drying in much of eastern Australia and in the southwest corner of Western Australia and increasing rainfall in much of the west (Figure 21). The development of this pattern has coincided with the sharp increase in global average temperature, raising the question of possible links with climate change. However, Australia naturally has a high degree of variability in rainfall, with long periods of intense droughts punctuated by heavy rainfall and flooding, so it is difficult from observations alone to unequivocally identify anything that is distinctly unusual about the post-1950 pattern (apart, perhaps, from the drying trend in southwest Western Australia, see below). While the instrumental record goes back little more than a century, not long enough to clearly discern multi-decadal patterns of variability that are repeated on century timescales, palaeo studies could offer some insights into the severity of the recent drought in a longer time perspective. For example, a recent study (Gallant and Gergis 2011) states that the very low streamflow in the River Murray for the 1998-2008 period is very rare – about a 1-in-1500 year event.

Figure 21. Trend in annual total rainfall (mm/10 years) for (a) 1900 – 2010; and (b) 1970 – 2010.



Source: Bureau of Meteorology.

The climate change-variability interaction

Rainfall patterns across Australia are influenced in complex ways by several modes of natural variability, the most important of which are ENSO (El Niño – Southern Oscillation), SAM (Southern Annular Mode) and IOD (Indian Ocean Dipole).

These modes are a manifestation of changes in oceanic and atmospheric circulation and, in particular, their coupling.

Therefore, their behaviour may change as oceanic and atmospheric circulation change in response to the changing energy balance at the Earth's surface. However, for ENSO there is no clear pattern of change in behaviour that can be observed in the observational record over the past several decades and can be linked clearly to climate change, nor is there a strong consensus in climate model projections of the future behaviour of this mode of variability (Collins et al. 2010)

For the IOD, the number of "positive" events, which induce a reduction in rainfall over southern Australia in winter and spring, has been increasing since 1950, reaching a record high frequency over the past decade (Abram et al. 2008; Ihara et al. 2008; Cai et al. 2009a). By contrast, the number of negative IOD events has been decreasing. The majority of climate models assessed by the IPCC in their 20th century simulations produce an upward trend in the frequency of positive IOD events (Cai et al. 2009b). The projected pattern of the mean ocean-atmosphere circulation change in the Indian Ocean in the future is similar to that of a positive IOD phase, implying an increase in positive IOD frequency and/or intensity and thus a reduction in rainfall over southern Australia in winter and spring (Cai et al. 2011a).

The situation is even clearer for the SAM.

THERE IS GOOD EVIDENCE THAT A SOUTHWARD SHIFT OF THE SAM (SOUTHERN ANNULAR MODE), WHICH BRINGS RAIN-BEARING FRONTS IN AUTUMN AND WINTER TO SOUTHWEST WESTERN AUSTRALIA, IS AN IMPORTANT FACTOR IN THE OBSERVED DROP IN RAINFALL THERE OVER THE PAST SEVERAL DECADES (TIMBAL ET AL. 2010; NICHOLLS 2009).

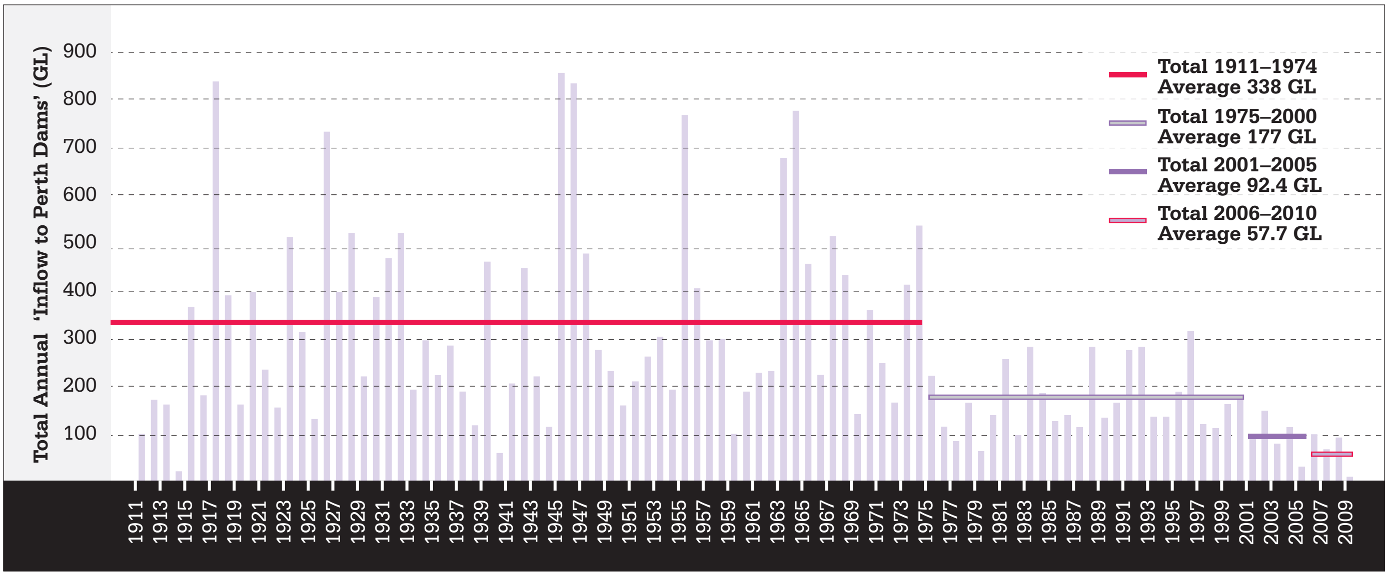
Cai and Cowan (2006) estimate that about 50% of the rainfall reduction is attributable to climate change. This explanation is consistent with our understanding of how atmospheric circulation is changing in response to global warming, and is consistent with model simulations of present climate and of future changes in the SAM (Frederiksen and Frederiksen 2007; Yin 2005; Arblaster et al. 2011).

Furthermore, the drying trend in the southwest has continued into 2011 (Figure 22), consistent with the dominant role of the SAM there, in contrast to the much wetter period in the east, where the other modes of variability are more important.

Understanding hydrometeorological processes

Given the short observational record, the importance of natural variability for Australia's rainfall, and the lack of consensus in climate model simulations at regional scales, a process-level understanding of the factors that influence Australian rainfall patterns offers one way to cut through the complexity and uncertainty and explore possible links between observed changes and climate change. The link between the SAM and the decrease in rainfall in southwest Western Australia, explored in depth by the Indian Ocean Climate Initiative (Cai et al. 2003; Cai and Cowan 2006; Hendon et al. 2007), is an example of the success of this approach.

Figure 22. Trend in total annual stream flow into Perth dams 1911-2010.



Source: Western Australian Water Corporation.

Progress has also been made in understanding recent changes to rainfall in southeast Australia, with the SEACI (South Eastern Australian Climate Initiative, www.seaci.org) playing a major role in this research. Several aspects of the observed decrease in rainfall, especially in Victoria and southern South Australia, are now better understood. First, the proximate cause of the rainfall decline is an increase in the surface atmospheric pressure over much of the continent (Nicholls 2009), although the cause of the rising pressure is not clear. In addition, the subtropical ridge, an east-west zone of high atmospheric pressure that often lies over the southern part of the continent, has strengthened considerably since 1970 (Timbal et al. 2010; Figure 23a). Furthermore, this strengthening of the pressure system correlates very well with the rise in global mean temperature (Timbal et al. 2010; Figure 23b), and is consistent with expectations from the basic physics of the climate system. In another effort to understand changes at the process level, research on changing southern hemisphere circulation patterns, linked to anthropogenic increase in CO_2 concentration, has shown a connection to a reduction in winter storm formation and a consequent reduction in winter rainfall in southern Australia (Frederiksen et al. 2011).

Additional research has shown that, while rainfall variability on year-to-year timescales is strongly associated with changes in tropical SSTs, this relationship explains little of the observed rainfall decline in the southeast (SEACI; Watterson 2010). Furthermore, there is no evidence of a strong land cover-rainfall signal over southeast Australia (Narisma and Pitman 2003), but the methodologies used to explore this relationship are weak and require further development.

Stratifying the observed southeast Australia rainfall changes into seasons, the reduction in autumn is largest (Cai and Cowan 2008), followed by that in spring. Outputs of 20th century simulations by 24 climate models show that only one or two were able to reproduce the observed autumn rainfall reduction. In this season, even the changes in the sub-tropical ridge are unable to account for the rainfall reduction (Cai et al. 2011b). The majority of these models reproduce a reduction in spring rain, as a consequence of an upward trend in the frequency of positive Indian Ocean Dipole events (Cai et al. 2009b).

Figure 23a. Relationship between the May-June-July (MJJ) rainfall in the southwest part of eastern Australia and the sub-tropical ridge intensity during the same three months. The slope of the linear relationship and the amount of explained variance (R^2) is shown in the upper right corner.

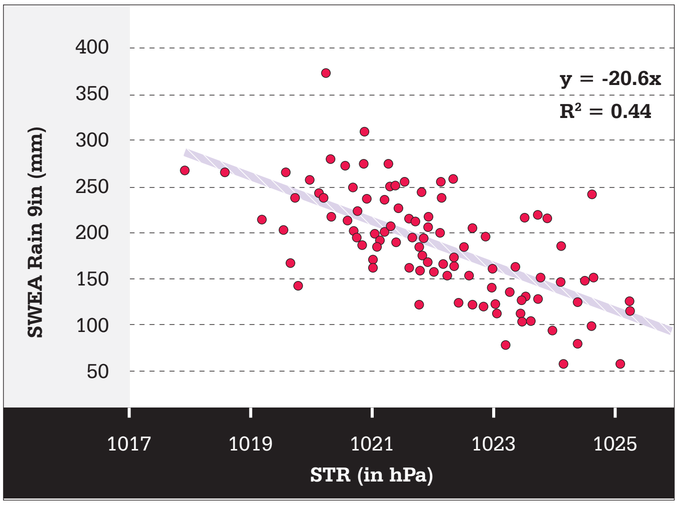
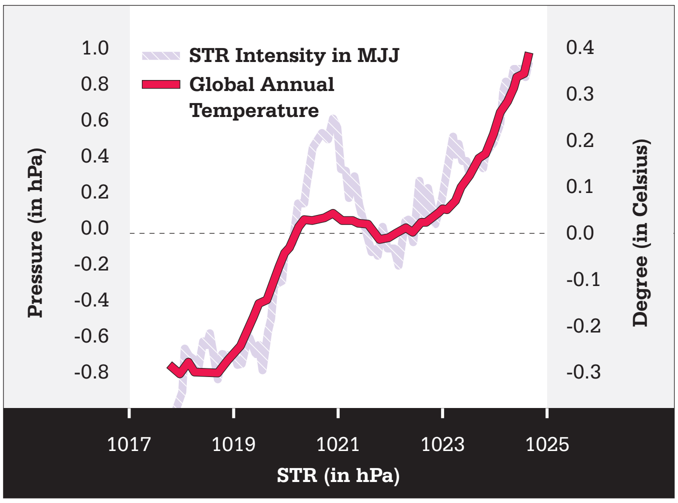


Figure 23b. Long-term (21-year running mean) evolution of the sub-tropical ridge MJJ mean intensity (anomalies in hPa shown on the left-hand Y-axis) compared with the global annual surface temperature.



Source: Timbal et al. (2010), including further details on methodology.

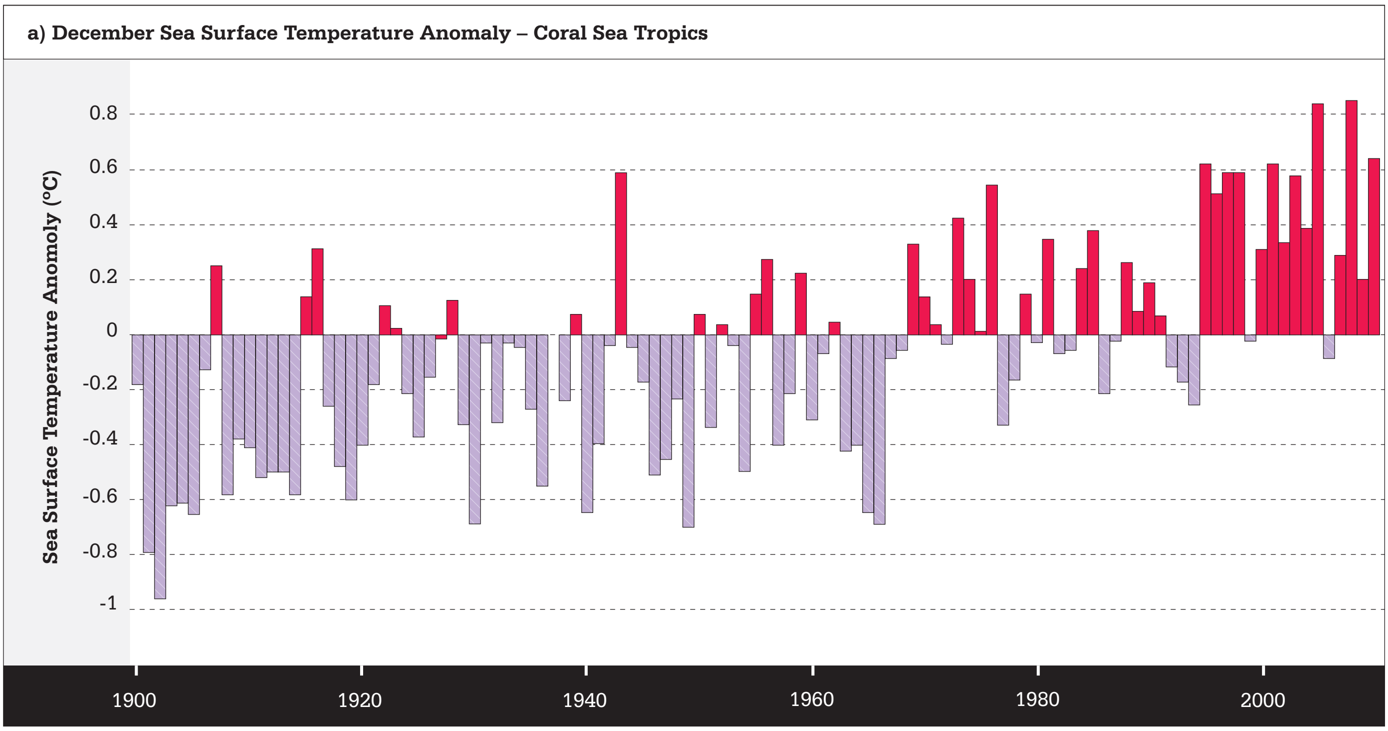
Projecting changes in water availability

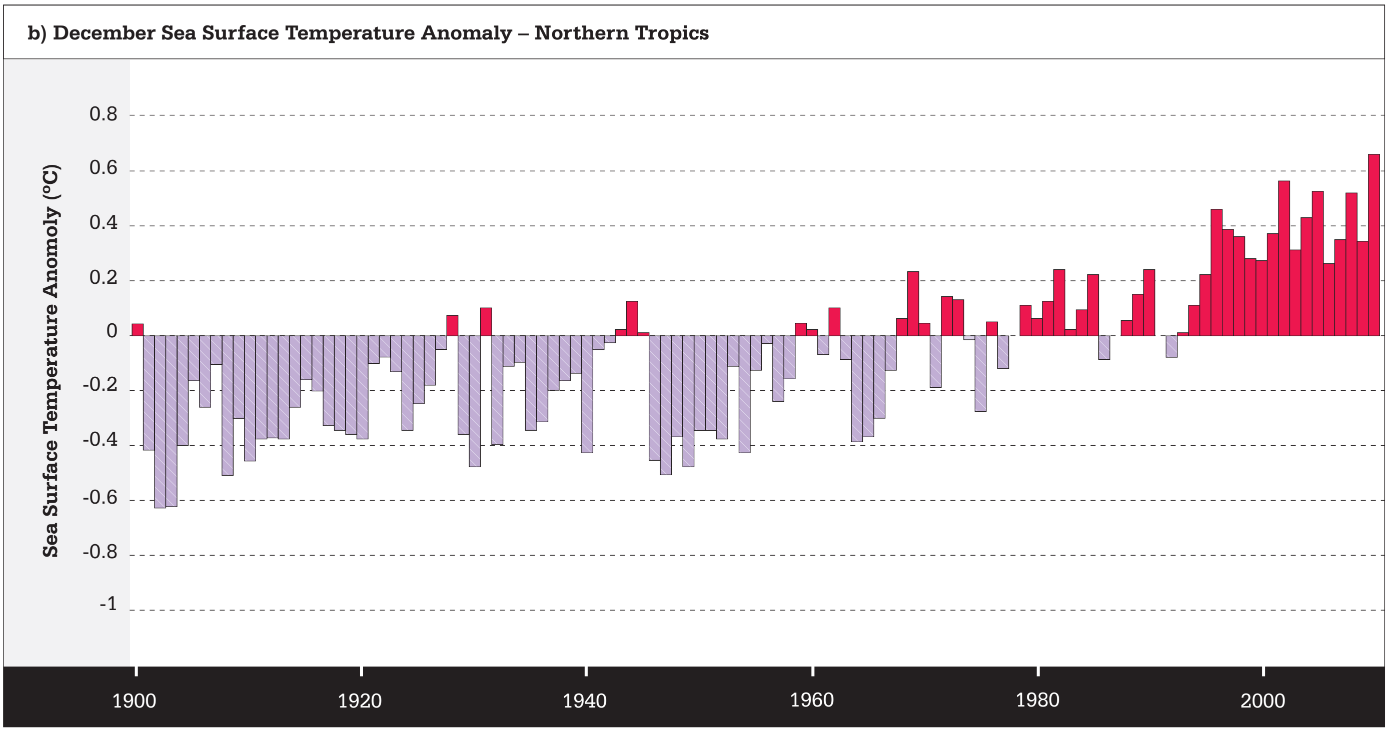
Although there has been progress in unravelling some of the linkages between climate change and observed shifts in rainfall patterns, our capability to project future changes to rainfall patterns, apart from the drying trend in southwest Western Australia, remains uncertain. Does the 2010-2011 extremely wet period across eastern Australia represent a brief interruption in a multi-decadal drying trend, or is it a shift to a multi-decadal wet regime, as one analysis emphasising the Pacific Decadal Oscillation (PDO) asserts (Cai et al. 2010)?

Model projections of future rainfall change do not add much clarity to the situation. Based on the models assessed by the IPCC (2007a), for much of Australia there is no strong consensus across models on the direction of change (increase or decrease in rainfall), or on the magnitude or seasonality. A recent assessment of climate science by the Australian Academy of Science (2010) noted that many aspects of climate change remain difficult to foresee, and, in particular, stated that "how climate change will affect individual regions is very hard to project in detail, particularly future changes in rainfall patterns, and such projections are highly uncertain."

Improving projections of future rainfall patterns is important, as rainfall is the main driver of runoff, which is the link to river flows and water availability. A change in annual rainfall is typically amplified by two or three times in the corresponding change in average annual runoff (Chiew 2006). Downscaled projections of rainfall change from climate models can be translated into changes in water availability through use of hydrological modelling based on point and catchment scale estimates of rainfall and potential evaporation (Chiew et al. 2009). The results of the hydrological modelling reflect the uncertainty in the larger scale rainfall projections by the climate models, but indicate that river flows in southwest Western Australia and in southeast Australia are likely to decline in the future, with higher confidence in the projections for the former. The hydrological models can also project changes in other aspects of water availability that are important for risk assessment, such as variability in reservoir inflows and floods and low flows that affect ecosystems and the environment.

Figure 24. Time series of Sea Surface Temperature (SST) for the month of December from 1900 to 2010 for (a) the Coral Sea and the (b) northern tropical Australian oceanic region.





Source: Bureau of Meteorology.

A possible link between climate change and water availability is via the rise in SST (Figure 24). Based on the strong role of periodic changes in ocean-atmosphere coupling, such as ENSO, for Australia's rainfall, there is a plausible connection between the rising trend in SST and the behaviour of natural modes of variability. As noted in section 3.5 (Figure 32), observations in the eastern Pacific Ocean have shown a link between increasing SSTs, water vapour content in the atmosphere, and heavy precipitation events. The very high temperatures in the Coral Sea and the Northern Tropics in late 2010 (Figure 24) may have contributed to the very strong La Niña event in late 2010 and early 2011 and thus to the record high rainfall across eastern Australia in December 2010 (BoM 2011a). However, the extent of such an influence, and even the direction of the influence (towards stronger or weaker La Niña events) is unknown at this time. No clear trend has been seen in indices of the ENSO, or in eastern Australia rainfall over the past century, suggesting that any link between climate change, ENSO, and Australian rainfall is subtle, at least up to the present time.

The bottom line is that significant uncertainties still surround the relationship between climate change and shifts in Australian rainfall patterns, both in observations over the past several decades and in projections for the future.

It is likely that the drying trend in southwest Western Australia is linked to climate change and will continue. For much of the rest of the country, there is no strong consensus on even the direction of change – more or less – of rainfall. Climate change could, in fact, lead to more extremes in general – both in drought and in rainfall.

APART FROM THESE INSIGHTS, WHAT WE CAN SAY WITH CERTAINTY IS THAT RAINFALL PATTERNS WILL CHANGE AS A RESULT OF CLIMATE CHANGE, AND OFTEN IN UNPREDICTABLE WAYS, CREATING LARGE RISKS FOR WATER AVAILABILITY.

This daunting uncertainty not only challenges attempts at adaptation, but also enhances, not diminishes, the imperative for rapid and vigorous global mitigation of greenhouse gas emissions.

2.4 Extreme events

Many of the impacts of climate change are due to extreme weather events, not changes in average values of climatic parameters. The most important of these are high temperature-related events, such as heatwaves and bushfires; heavy precipitation events; and storms, such as tropical cyclones and hailstorms. The connection between long-term, human-driven climate change and the nature of extreme events is both complex and controversial, leading to intense debate in the scientific community and heated discussion in the public and political arenas.

This section explores our current level of understanding about the relationship between climate change and extreme events, with a focus on types of extreme events that have already occurred in Australia and are likely to occur in future. The key messages are:

- Modest changes in average values of climatic parameters – for example, temperature and rainfall – can lead to disproportionately large changes in the frequency and intensity of extreme events.
- On a global scale and across Australia it is very likely that since about 1950 there has been a decrease in the number of low temperature extremes and an increase in the number of high temperature extremes. In Australia high temperature extremes have increased significantly over the past decade, while the number of low temperature extremes has decreased.
- The seasonality and intensity of large bushfires in southeast Australia is likely changing, with climate change a possible contributing factor. Examples include the 2003 Canberra fires and the 2009 Victoria fires.

- There is little confidence in observed changes in tropical cyclone activity in the past because of problems with the lack of homogeneity of observations over time. The global frequency of tropical cyclones is projected to either stay about the same or even decrease. However a modest increase in intensity of the most intense systems, and in associated heavy rainfall, is projected as the climate warms.
- On a global scale, several analyses point to an increase in heavy precipitation events in many parts of the world, including tropical Australia, consistent with physical theory and with projections of more intense rainfall events as the climate warms.

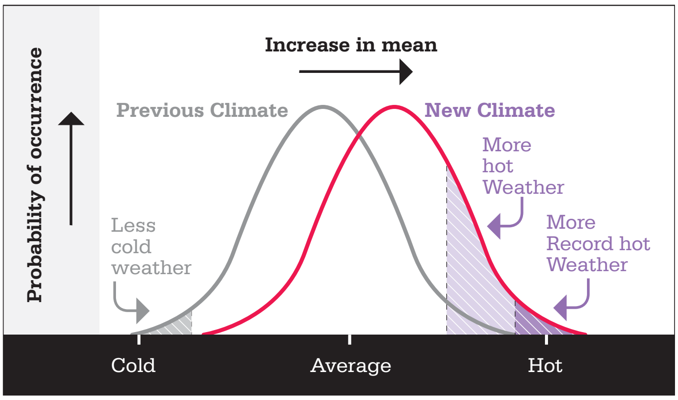
Average-extreme relationship

Temperature increases of 1 or 2 °C, or equivalent changes in other climatic parameters, may seem modest, but they can lead to disproportionately large changes in the frequency and intensity of extreme weather events.

Figure 25 shows the relationship between a change in average temperature and the incidence and severity of extreme events (IPCC 2007a). A modest shift to higher average temperatures leads to a disproportionately large increase in the number of extreme high temperature events, the area under the curve to the right of the dashed vertical line. In addition, the most extreme events become much more intense – the long "tail" at the right of the distribution. Correspondingly, extreme cold events become fewer and less extreme, as shown in the left-side of the figure. This simple picture assumes that there will be no change in the variability of temperature distribution. If variability were also increasing, then this would lead to a much larger impact in the tails.

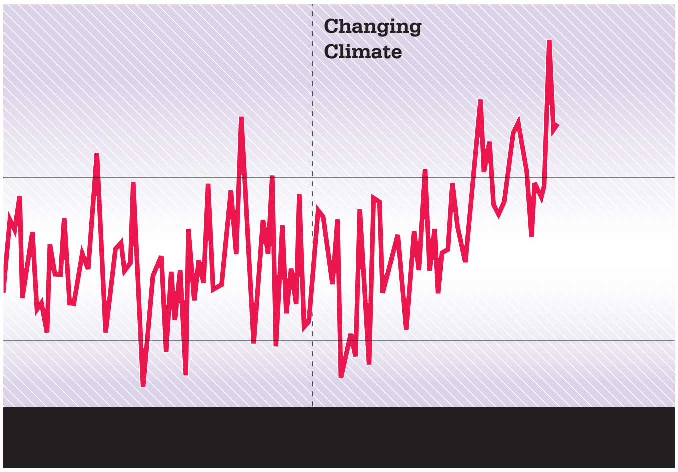
Another way to visualise the relationship between averages and extremes is shown in Figure 26, where the left-hand side of the figure shows variability around a long-term average temperature that does not change. The horizontal lines above and below the long-term average temperature show the limits above and below which extreme events are defined to occur. The right-hand side of the figure shows a rising average temperature with the same shorter-term variability imposed upon it. The figure again shows that the number of extreme high temperature events increases and the intensity of the most extreme of these events also increases.

Figure 25. Relationship between means and extremes, showing the connection between a shifting mean and the proportion of extreme events, when extreme events are defined as some fixed threshold related to a significant impact (e.g., heatwave leading to excess deaths).



Source: IPCC (2007a).

Figure 26. The increase in frequency and intensity of extreme events when an underlying, long-term trend is imposed on an existing pattern of natural variability.



Source: Adapted from Jones and Mearns (2004).

Because extreme events are, by definition, relatively rare, long time series and large spatial areas are required to obtain enough observations to determine statistically whether a change in their frequency and intensity is actually occurring. In most parts of the world, the instrumental record is at most a century or so long, and dense spatial coverage of many areas has only been achieved for a few decades, so determining from observations, with a high degree of confidence, whether any change in the frequency and intensity of extreme events is occurring is very difficult.

Temperature extremes

As described in Section 2.1, the Earth as a whole, including the Australian continent, has been warming strongly since the middle of the 20th century. Thus, it might be possible from observations to discern the beginnings of shifts in extremes that are consistent with what is expected. This is indeed the case for Australian temperature extremes (Alexander et al. 2007).

THE NUMBER OF HIGH TEMPERATURE EXTREMES (E.G. HEATWAVES) IN AUSTRALIA HAS INCREASED SIGNIFICANTLY OVER THE PAST DECADE, WHILE THE NUMBER OF LOW TEMPERATURE EXTREMES HAS DECREASED (FIGURE 27).

An increase in warm nights has also occurred across most of the continent and this is consistent with anthropogenic climate change (Alexander and Arblaster 2009; Figure 27). Changes in Melbourne temperatures provide a good example of the shifts in the frequency and intensity of extremes depicted schematically in Figure 25. The long-term average in the number of days per year 35 °C or above is 10 (BoM 2011c). During the decade 2000-2009, the number of such days per year rose to 13 (BoM 2011c). Furthermore, the increased intensity of extreme events – the long tail to the right in Figure 25 – is clearly evident in Melbourne with the record high temperature of 46.4 °C in February 2009, and the three consecutive days of 43 °C or above in late January.

Sea surface temperature

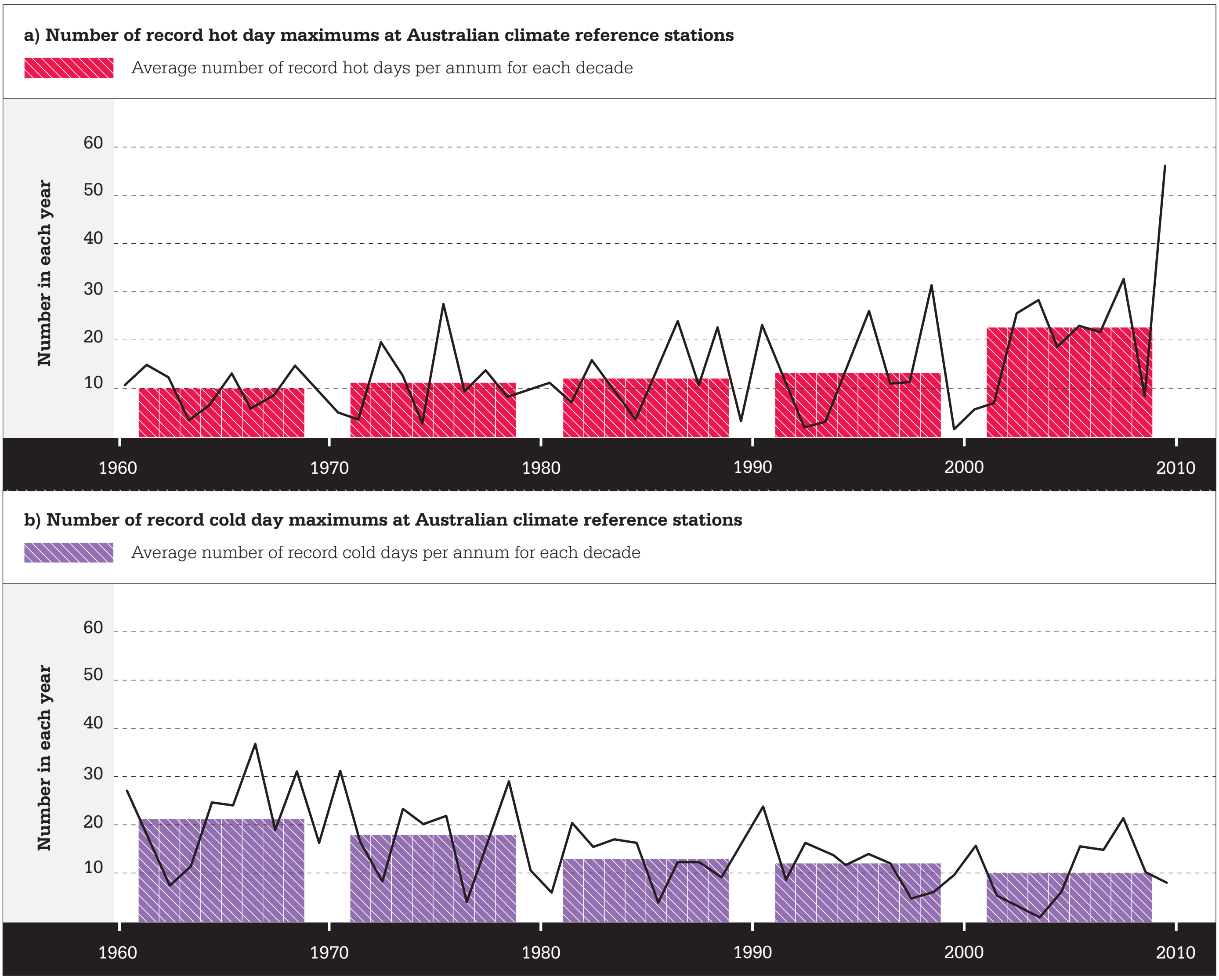
Coral-dominated ecosystems are sensitive to small rises in the temperature of the water in which they reside. This sensitivity results from the breakdown of a symbiosis between corals and tiny organisms called dinoflagellates, which are photosynthetically active and provide corals with organic carbon. When the sea temperature rises 1-2 °C above normal for a six to eight week period, this symbiosis breaks down, the dinoflagellates are expelled, and the corals are "bleached". Corals can recover from a bleaching event, but sustained or repeated bleaching can lead to starvation, disease and death (Hoegh-Guldberg 1999).

Rising sea surface temperature (Figure 24) has increased the number of bleaching events that have been observed on the GBR over the last few decades, consistent with global trends showing increasing incidence of bleaching events since 1979 (Hoegh-Guldberg 1999; Wilkinson 2008). The GBR has fared better than many reefs around the world, although parts of the reef have experienced bleaching events in 1980, 1982, 1983, 1987, 1992, 1994, 1998, 2002 and 2006 – with the 1998 and 2002 events the worst on record for the GBR (Berklemans et al. 2004). In these events over 50% of the GBR bleached in the exceptionally warm conditions, with an estimated loss of 5-10% of corals in each event (GBRMPA 2009).

Bushfire intensity and frequency

Extreme events that are closely related to temperature are also showing changes consistent with what is expected. The intensity and seasonality of large bushfires in southeast Australia appears to be changing, with climate change a possible contributing factor (Cai et al. 2009c). Bushfires have long been a feature of ecosystems in the southeast; the 1939 fires in Victoria are an often-quoted example of large and intensive fires. However, in the first decade of the 21st century, two very large and extremely intense fires occurred – the 2003 Canberra fires, which destroyed 500 houses in suburban Canberra and killed three people, and the 2009 Victoria fires, which killed 173 people in rural areas of the state.

Figure 27. Number of (a) record hot day maximums and (b) record cold day maximums at Australian climate reference stations.



Source: Bureau of Meteorology.

Climate change affects fire regimes in at least three ways (Williams et al. 2009; Lucas et al. 2007). First, changing precipitation patterns, higher temperatures and elevated atmospheric CO_2 concentrations affect the biomass and composition of vegetation, the fuel load for fires. Second, higher temperatures tend to dry the fuel load, making it more susceptible to burning; drought conditions can significantly exacerbate these conditions. Third, climate change increases the probability of extreme fire weather days – conditions with extreme temperature, low humidity and high winds.

The severity of bushfires in southeast Australia is strongly pre-conditioned by low rainfall and high temperature induced by the positive phase of the Indian Ocean Dipole. Since 1950, the majority of large bushfires in southeast Australia, including the Ash Wednesday, Canberra, and Black Saturday bushfires, occurred following a positive IOD event in the preceding spring season, which led to warm and dry conditions (Cai et al. 2009c). Since 2002, the Indian Ocean has experienced five positive IOD events (2002, 2004, 2006, 2007, 2008), with climate change a contributor to the increasing frequency of these events (Cai et al. 2009b).

Tropical cyclones

The relationship between tropical cyclone behaviour and climate change is a particularly complex one, with a high degree of uncertainty in our current understanding. Observational records show no changes beyond natural variability in either the frequency of cyclones or their storm tracks. With the advent of satellite measured intensities of tropical cyclones in 1980, some studies have found a possible link between cyclone intensity and higher sea surface temperatures (e.g. Elsner et al. 2008). However, some of the satellite data is questionable (e.g. over the Indian Ocean), and time period is too short to separate out decadal patterns of natural variability from the underlying trend of rising SST (Knutson et al. 2010). In short, given the short observational period and the changing observational capability through time, it is not yet possible to attribute any aspect of changes in cyclone behaviour (frequency, intensity, rainfall, etc.) to climate change; all observations currently remain within the envelope of natural variability (Knutson et al. 2010).

Heavy precipitation events

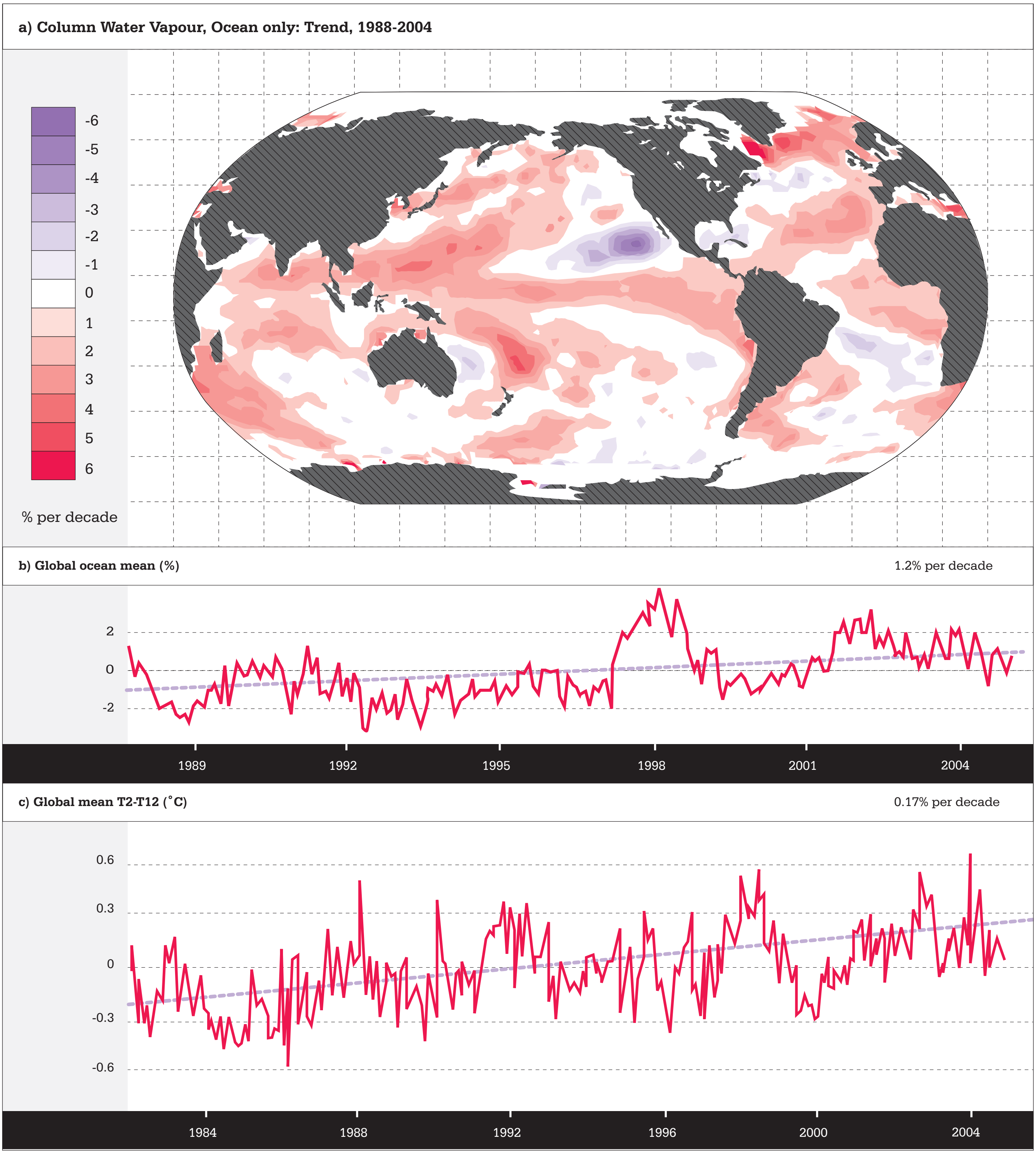
THE SEVERE FLOODING IN QUEENSLAND AND VICTORIA IN EARLY 2011 HAS RAISED THE QUESTION OF A POSSIBLE LINK BETWEEN THE FLOODS AND HUMAN-INDUCED CLIMATE CHANGE.

The severity of the floods is related to several factors, including the intensity of the rainfall event(s) that triggered the floods, the condition of the catchments upstream of and within the flooding area, the effectiveness of structures such as dams designed to ameliorate flooding, and the vulnerability of people and infrastructure to flooding. Here we deal only with the possible connection between climate change and the frequency or severity of extreme rainfall events.

The floods across eastern Australia in 2010 and early 2011 were the consequence of a very strong La Niña event, and not the result of climate change. That is, the underlying cause of the floods is a natural part of climate variability, which is part of the reason why Australia has always been a "land of droughts and flooding rains". The extent, if any, of the influence of the warming planet on the intensity of these heavy rains and floods is simply unknown at this time. There is no evidence that the strength of La Niña events is increasing due to climate change.

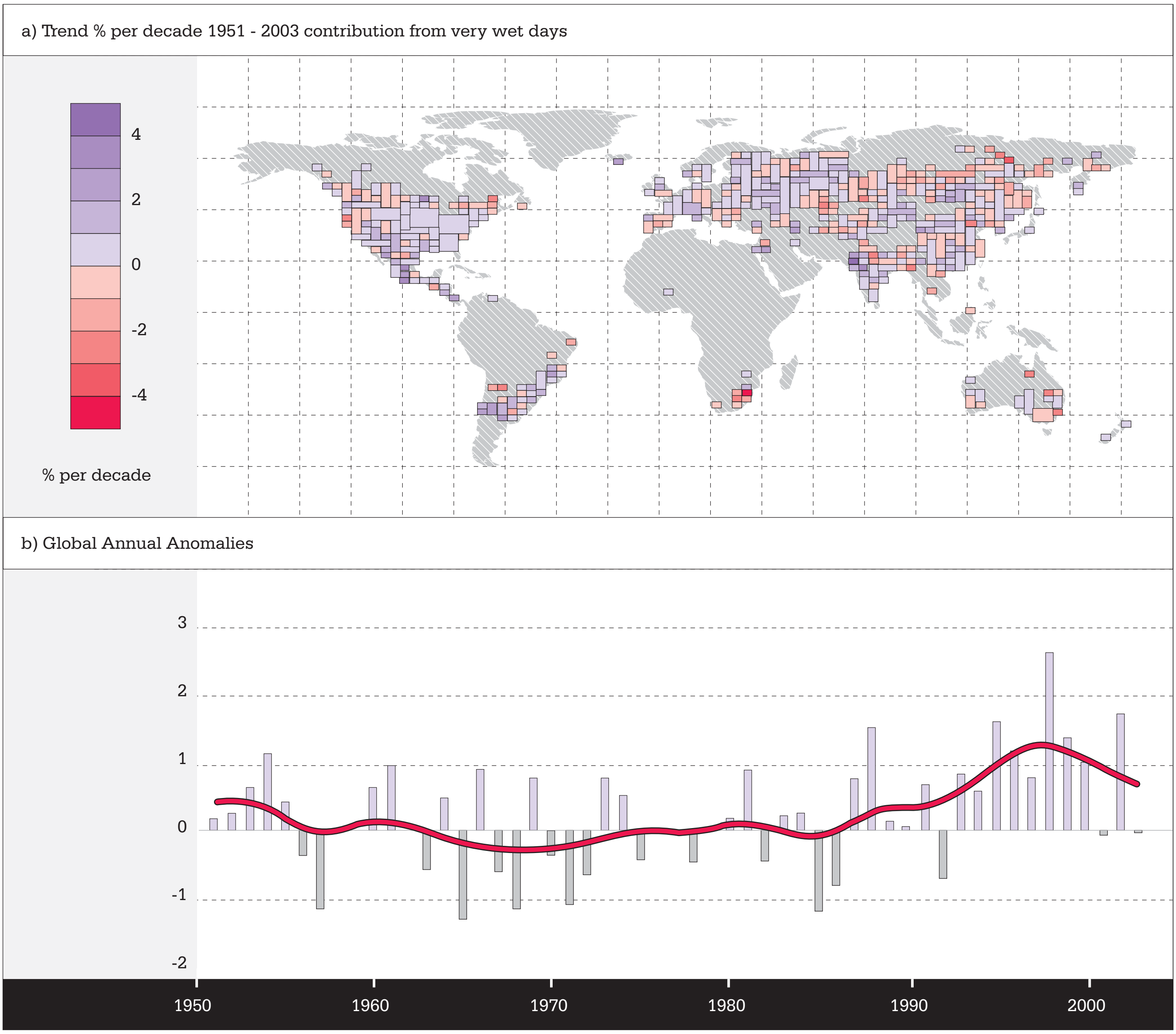
The physical connection between a warming climate and more rainfall is relatively straightforward. Higher temperatures, especially of the surface ocean, lead to more evaporation; this leads to higher water vapour content in a warmer atmosphere (which can hold more water vapour); and this in turn induces more precipitation.

Figure 28. (a) Linear trends in precipitable water (total column water vapour) in % per decade; (b) monthly time series of anomalies relative to the 1988 to 2004 period in % over the global ocean plus linear trend (broken purple line); and (c) monthly time series of global mean (80 °N to 80 °S) anomalies of T2-T12 (an atmospheric radiative signature of upper-trophospheric moistening) relative to 1982 to 2004.



Source: IPCC (2007a), updated from Trenberth et al. (2005) and Soden et al. (2005).

Figure 29. (a) Observed trends (% per decade) for 1951-2003 in the contribution to total annual precipitation from very wet days (95th percentile). Trends were only calculated for grid cells where both the total and the 95th percentile had at least 40 years of data during this period and had data until at least 1999. **(b) Anomalies (%) of the global annual time series (relative to 1961-1990) defined as the percentage change of contributions of very wet days from the base period average (22.5%).** The smooth red curve shows decadal variations.



Source: IPCC (2007a), based on Alexander et al. (2006).

The IPCC assessment (2007a) of observations on a global scale shows an increase in atmospheric water vapour from 1988 to 2004 (Figure 28) as well as increases in precipitation in many parts of the world, with a substantial increase in heavy precipitation events (Figure 29). A recent study (Min et al. 2011) comparing observed and model-simulated patterns of extreme precipitation events found that over the Northern Hemisphere land area with sufficient data coverage (about two-thirds of the total area), human-driven increases in greenhouse gas concentrations have contributed to the observed intensification of heavy precipitation events. However, there is no consistent evidence of an observed increase in heavy precipitation events over most parts of Australia at this time.

At the continental scale a 100-year record from the United States shows a sharp increase in the area of the U.S. experiencing very heavy daily precipitation events (Gleason et al. 2008; Figure 30). A recent analysis of temperature and rainfall extremes in Australia using a combined climate extremes index shows, over the whole continent and for all seasons, an increase in the extent of hot and wet extremes and a decrease in the extent of cold and dry extremes annually from 1911 to 2008 at a rate of between 1% and 2% per decade (Gallant and Karoly 2010). These trends are primarily driven by changes in tropical regions during summer and spring. While such continental-scale analyses in both the U.S. and Australia show trends consistent with a warming planet, it is difficult to attribute them unequivocally to climate change because of the considerable natural variability in rainfall patterns.

Determining a link between climate change and extreme events becomes even more difficult for single extreme events, such as the heavy rainfall event that triggered the floods in southeast Queensland in January 2011. This is especially difficult for eastern Australia in general, where modes of natural variability, such as ENSO and the Indian Ocean Dipole (IOD), play a very important role in influencing rainfall patterns.

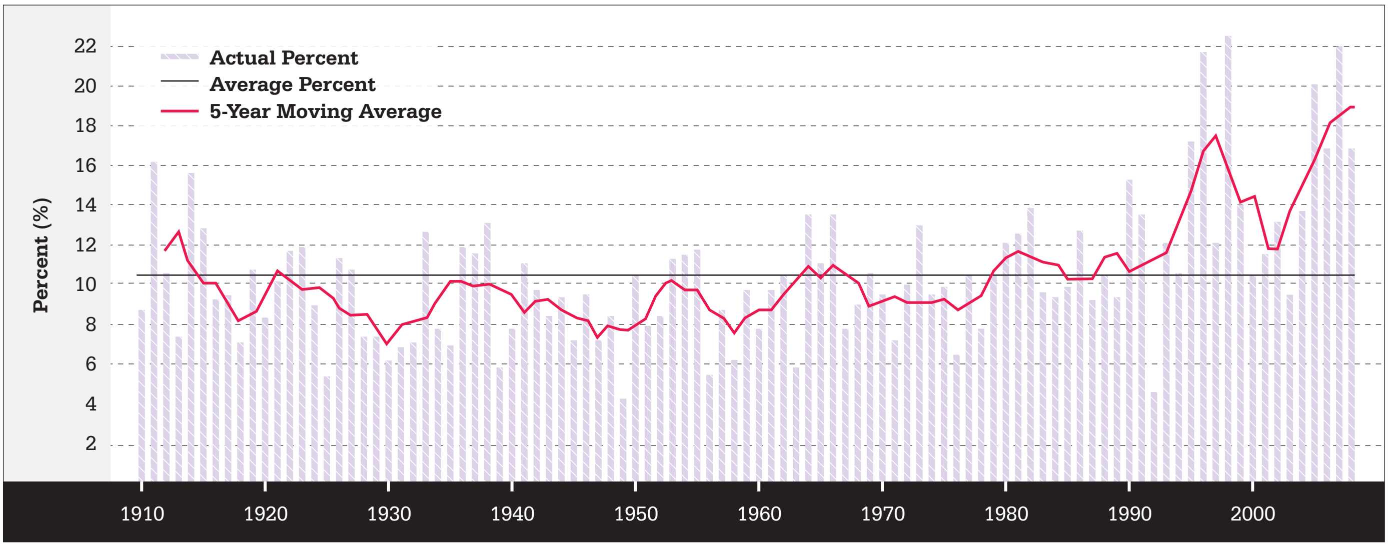
During the second half of 2010 a strong La Niña event developed across the Pacific, with the SOI (Southern Oscillation Index) - an indicator for the state of the ENSO system - showing record positive values for October and December 2010 (BoM 2011b). La Niña events normally bring heavy rainfall to eastern Australia. In the present case the strong La Niña event was accompanied by a positive phase of the IOD, which is associated with unusually warm ocean waters around Indonesia. The combination of a La Niña event and a positive IOD is relatively rare, but they reinforce each other to bring wetter-than-usual conditions across much of Australia. Thus, these two modes of natural variability alone could have generated the heavy precipitation events that occurred in eastern Australia in December 2010 and January 2011.

However, long-term human-induced climate change may also be a factor.

SEA SURFACE TEMPERATURES (SST) HAVE WARMED NEARLY EVERYWHERE OVER THE PAST CENTURY, INCLUDING AROUND AUSTRALIA (FIGURE 31).

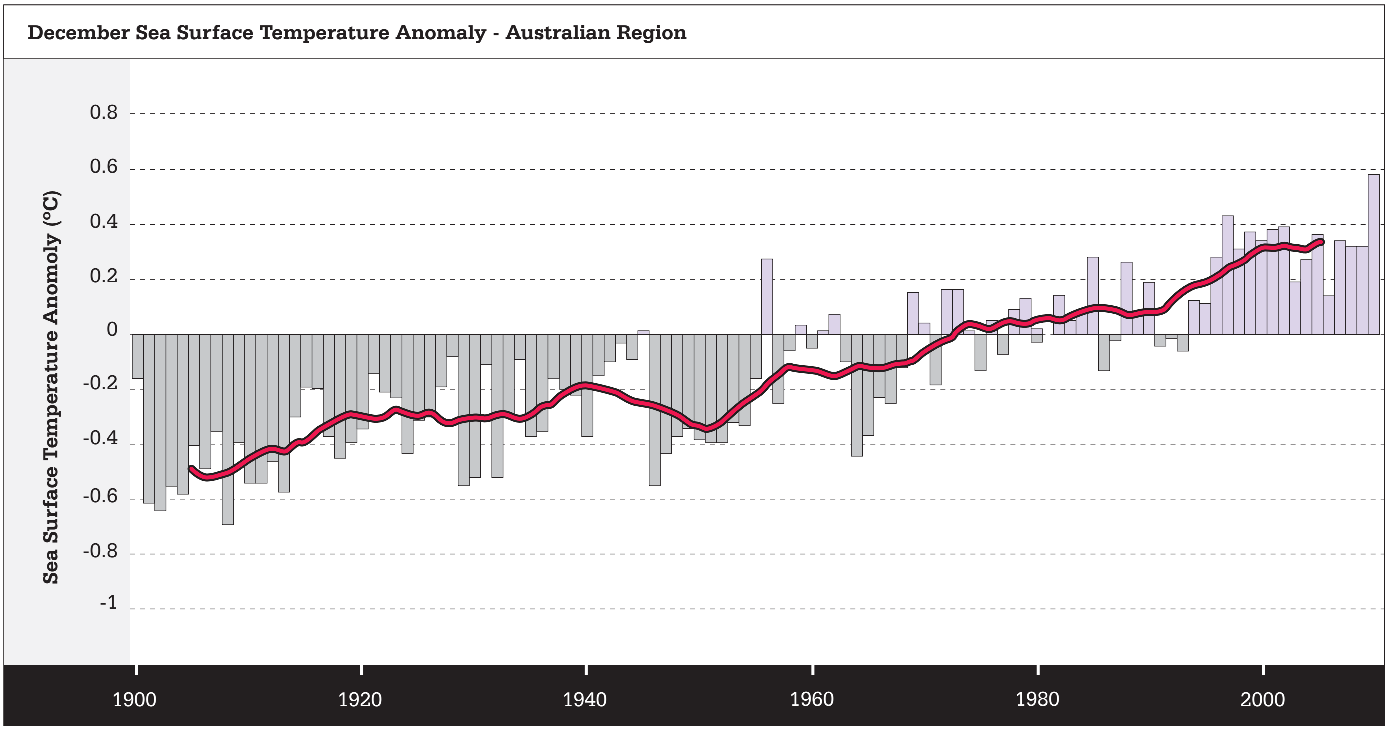
This *additional* warmth in the upper ocean – SSTs in the northern Australian region are currently at or near record levels and are much warmer for this La Niña event than for previous strong La Niña events (Figure 24) – may possibly have enhanced precipitation and led to an even more intense precipitation event than would otherwise have occurred, although such enhancement has yet to be demonstrated.

Figure 30. Time series of the annual values of the percentage area of the United States with a much greater than normal proportion of precipitation originating from very heavy (equivalent to the highest tenth percentile) 1-day precipitation amounts.



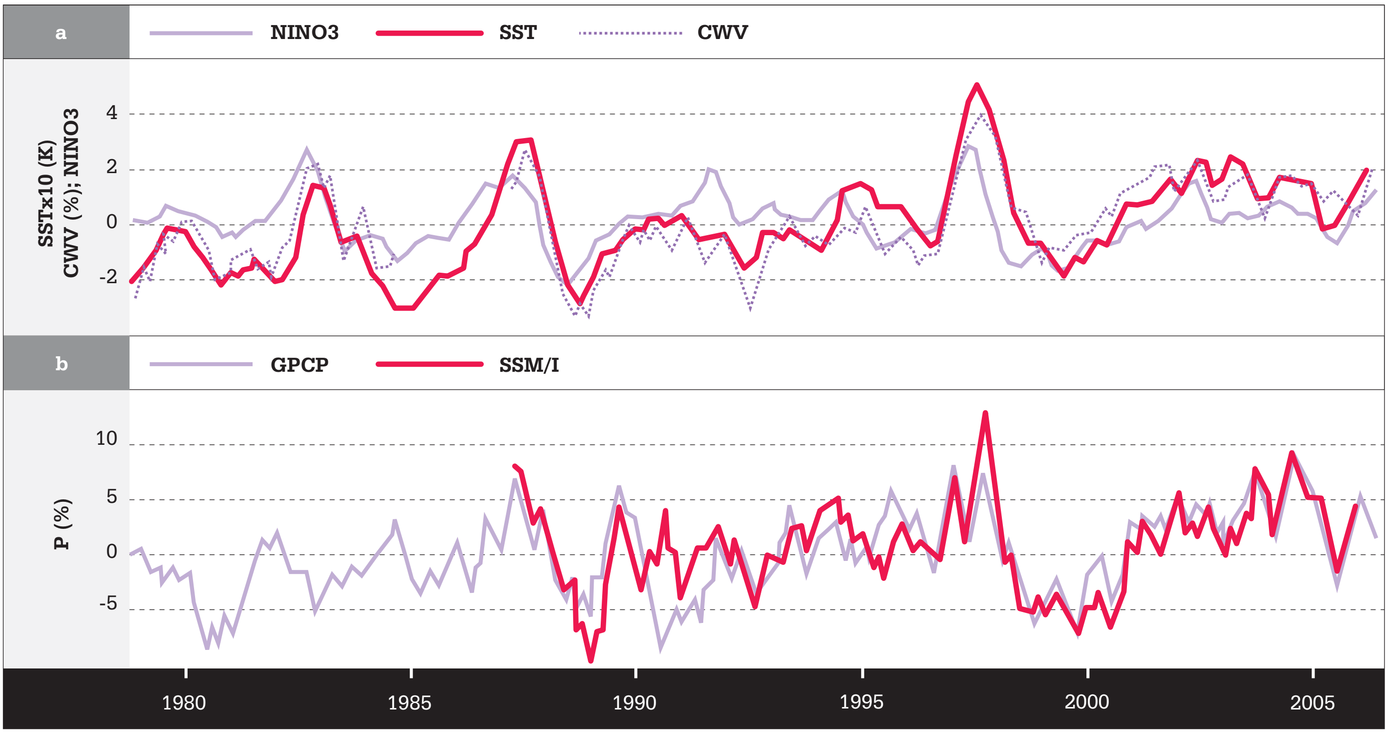
Source: Gleason et al. (2008), updated by NOAA at www.ncdc.noaa.gov/oa/climate/research/cei/cei.html

Figure 31. Times series of SST for the month of December from 1900 to 2010 for the oceanic region around Australia.



Source: Bureau of Meteorology.

Figure 32. Time series of (a) Niño-3 ENSO index (SST anomalies for 90° to 150 °W, 5 °S – 5 °N region, deseasonalised tropical ocean (30 °S to 30 °N) mean anomalies of SST, and column-integrated water vapour (CWV); and (b) precipitation (P).



Source: Allan and Soden (2008).

There is observational evidence that shows a link between SST and rainfall extremes (Figure 32). The top panel of the figure shows a 28-year record of an ENSO index, the sea surface temperature and the column-integrated water vapour in the tropical atmosphere. The three are closely related, with ENSO dominating the interannual variability. The bottom panel shows two observations of precipitation, again showing the prominent ENSO pattern, and also showing the strong correlation between heavy rainfall events and periods of high SSTs. However, despite a substantial warming of the ocean around northern Australia (Figure 24), there is no evidence yet of a trend towards increased precipitation in eastern Australia over the past 50 years, although, as noted above, Gallant and Karoly (2010) found an increase in the extent of hot and wet extremes in the tropical regions of Australia from 1911 to 2008 at a rate of between 1% and 2% per decade.

Looking towards the future, Rafter and Abbs (2009) used extreme value theory to examine changes in the intensity of extreme rainfall as simulated by climate models. Their results showed increases in all regions for 2055 and 2090 for most models considered. The spatial patterns were consistent with previous studies, with smaller increases in the south of Australia and larger increases in the north. Fine-scale regional climate modelling (e.g. Abbs *et al.*, 2007; Abbs and Rafter, 2009) suggests increases in daily precipitation extremes on average, although with large fine-scale spatial variability. The study found short duration (sub-daily) rainfall will change more rapidly than longer duration (daily and multi-day) rainfall.

The bottom line is that although a conclusive link between the southeast Queensland rainfall events and climate change cannot be made, such a link is plausible even if it is not discernible yet. From a risk perspective, this is useful knowledge, and suggests that it would be prudent to factor in a climate change-induced increase in intense rainfall events in urban and regional planning, the design of flood mitigation works, and any reviews of emergency management procedures.

2.5 Abrupt, non-linear and irreversible changes in the climate system

Many projections of future changes in climatic variables are simulated and presented as smooth curves from present values to an altered state at some future point in time. The temperature projections to 2100 highlighted in the IPCC reports are a good example of this. However, smooth changes are not the norm in the climate system. Often the system seems unresponsive to forcing agents until a threshold is reached, after which the system rapidly changes or reorganises into an alternate state. The abrupt drop in rainfall in the mid-1970s in southwest Western Australia is a well-known Australian example. Some changes in the climate system can be irreversible in any timeframe relevant to human affairs, such as the loss of the Greenland ice sheet.

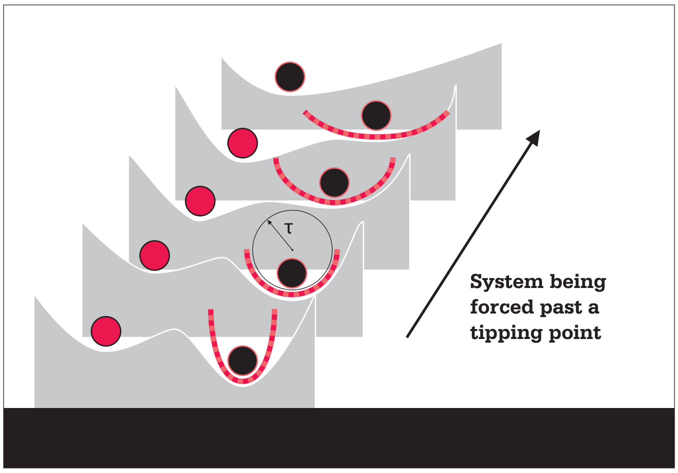
In this section we present a brief summary of the current knowledge base on the potential for abrupt, irreversible changes in the climate system:

- A number of potential abrupt changes in large sub-systems or processes in the climate system – so-called "tipping elements" – have been identified largely through palaeo-climatic research. Many of these, if triggered, would lead to catastrophic impacts on human societies.
- Examples of tipping elements include abrupt changes in the North Atlantic ocean circulation, the switch of the Indian monsoon from a wet to a dry state or vice versa, and the conversion of the Amazon rainforest to a grassland or a savanna.
- Very large uncertainties surround the likelihood, or not, of human-driven climate change triggering any of these abrupt or irreversible changes. Experts agree that the risk of triggering them increases as temperature rises.
- Abrupt shifts in atmospheric circulation can occur very quickly and can have large impacts on regional climates. The recent cold, snowy winters in northern Europe, and their possible link to climate change, comprise a good example of this risk.

The science of abrupt change

While it is common, even in many parts of the scientific community, to employ cause-effect logic and linear thinking (a change in a causal agent drives an appropriately scaled response), the growth of complex system science has brought a new perspective to observing and interpreting changes in the climate system. The phenomenon of abrupt, highly nonlinear changes, which often occur when an apparently small change in a forcing agent triggers an unexpected, large, complex response in the system, has recently been reviewed in the context of the climate system (Lenton et al. 2008; Figure 33).

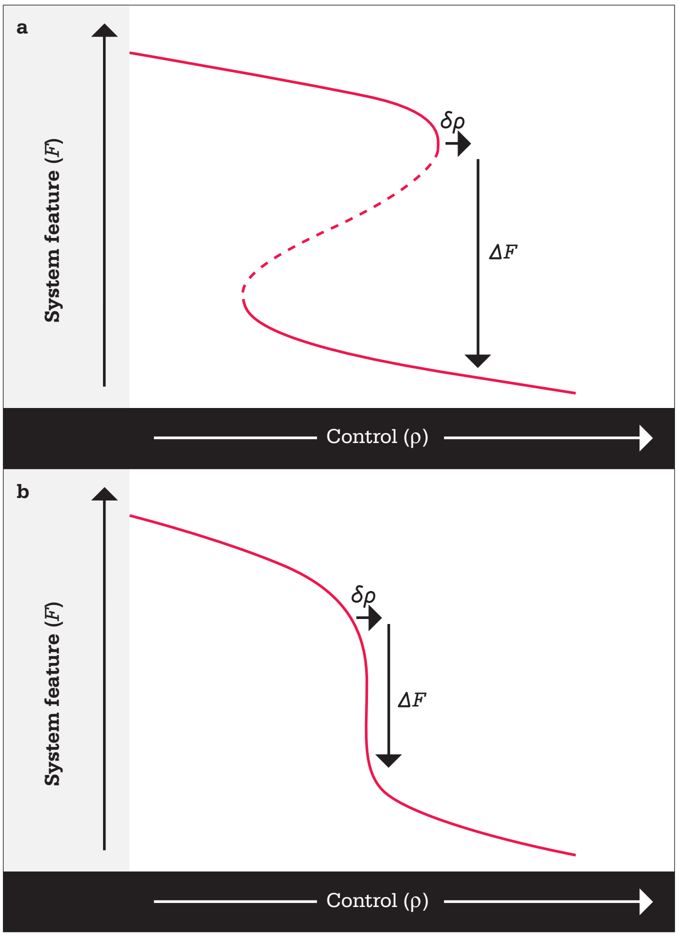
Figure 33. Schematic representation of a system being forced past a tipping point. The system's response time to small perturbations, τ, is related to the growing radius of the potential well.



Source: H. Held, from Lenton et al. (2008).

Figure 34 is a schematic of two types of abrupt change in a complex system such as climate – so-called "tipping elements" – one a mono-stable system showing threshold, abrupt change behaviour and the other showing bistability when a threshold is crossed. An important feature of a tipping element is that it must contain a strong positive (reinforcing) feedback process in its internal dynamics. In addition, tipping elements can have varying degrees of irreversibility. For example, although the large polar ice sheets on Greenland and Antarctica have waxed and waned in geological timescales, they are essentially irreversible on timescales of relevance to human affairs.

Figure 34. Schematic of two types of tipping element that can exhibit a tipping point where a small change in control (δρ) results in a large change in a system feature (ΔF), illustrated here in terms of the time-independent equilibrium solutions of the system: (a) A system with bi-stability passing a true bifurcation point. (b) A mono-stable system exhibiting highly non-linear change.



Source: T.M. Lenton, published in Richardson et al. (2011).

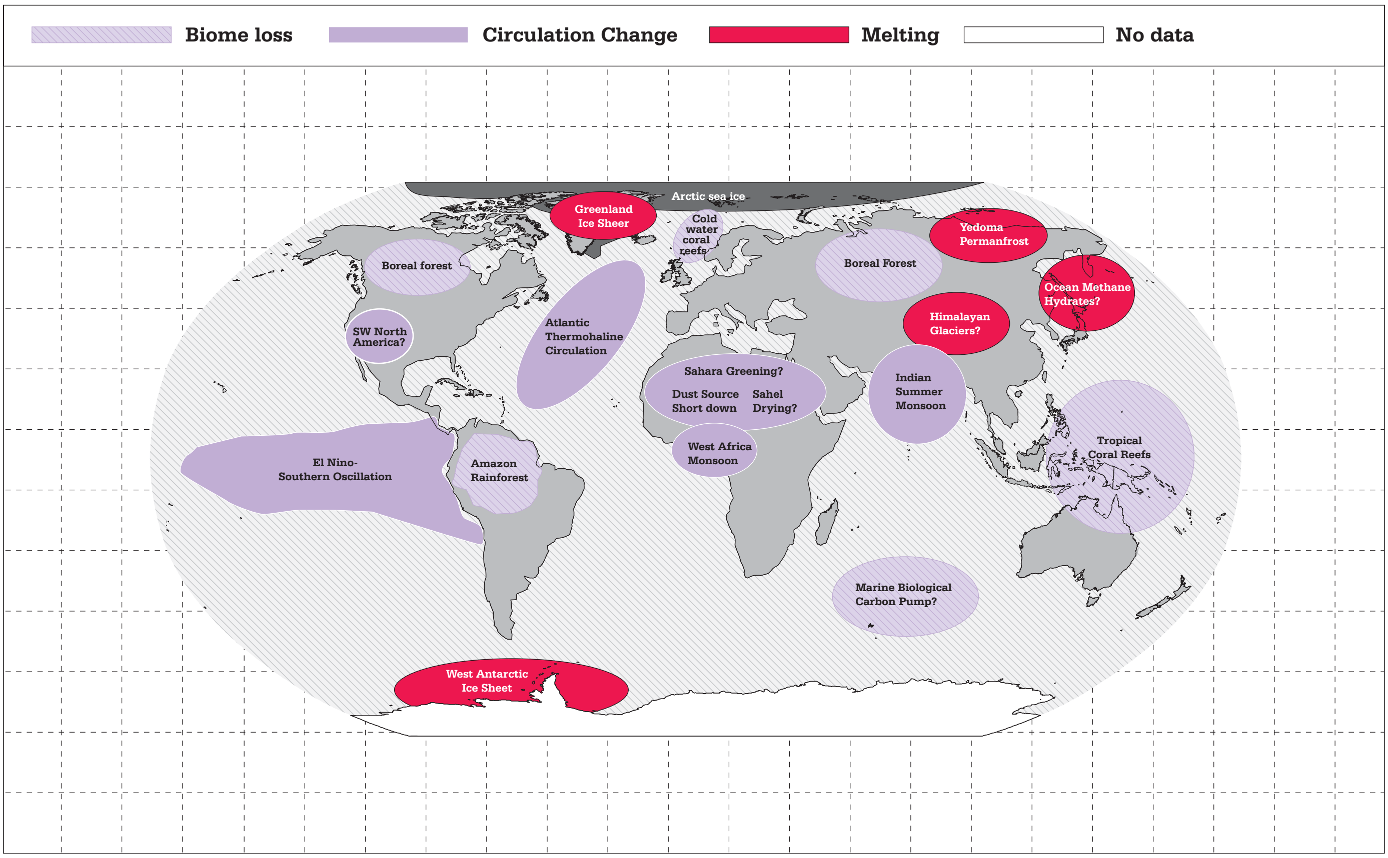
Examples of tipping elements in the climate system

There are many examples of tipping elements in the climate system (Figure 35); it is useful to classify them into those associated with the melting of large masses of ice, those involving significant changes to unique biomes, and those associated with large-scales changes in the circulation of the atmosphere and the ocean (Richardson et al. 2011).

THE GREENLAND AND ANTARCTIC ICE SHEETS MAY NOT SEEM LIKE CANDIDATES FOR TIPPING ELEMENTS AS THEIR RATE OF CHANGE IS NOT "ABRUPT" FROM A HUMAN PERSPECTIVE, BUT THEY ARE DEFINITELY TIPPING ELEMENTS IN THAT BEYOND A RATHER NARROW RANGE OF TEMPERATURE CHANGE, THEY WILL BE COMMITTED TO IRREVERSIBLE MELTDOWN (HUYBRECHTS AND DE WOLDE 1999).

The accelerating downward trend in the loss of Arctic sea ice is indicative of threshold-abrupt change behaviour in which the threshold may already have been crossed (Perovich 2011), although the loss of summer sea ice is not irreversible and could quickly recover with a return to a colder climate.

Figure 35. Map of potential policy-relevant tipping elements, adjusted from Lenton et al. (2008) based on further analysis by T.M. Lenton reported in Richardson et al. (2011). Question marks indicate systems whose status as policy-relevant tipping elements is particularly uncertain.



Source: V. Huber, T.M. Lenton and H.J. Schellnhuber, published in Richardson et al. (2011).

The Amazon rainforest is the most widely quoted example of a large biome at risk of abrupt change from a warming climate. The climate-related forcing factors include both rising temperature and a potential increase in the length of the dry season and the intensity of droughts. A prominent feedback is the way in which a rainforest stores and recycles water. Ecological disturbance processes, such as fires and insect infestations, may also become important feedback processes. Simulations that incorporate these ecological processes suggest that a threshold exists around a 2 °C temperature increase, beyond which the area of the Amazon forests committed to dieback rises rapidly from 20% to over 60% (Jones and Lowe 2011). Severe droughts in the Amazon Basin in 2005 and 2010, along with the observation that such droughts co-occur with peaks of fire activity, support this risk assessment (Lewis et al. 2011).

Perhaps the archetypal example of a tipping element is the Atlantic thermohaline circulation (THC), which in its current mode contributes significantly to the mild climate experienced by western Europe and Scandinavia but which has shown threshold-abrupt change behaviour in the past (e.g., Dansgaard-Oeschger events, Ganopolski and Rahmstorf 2001). A collapse of the THC could lead to a reduced level of warming in the north Atlantic region compared to the global average. Current understanding of the THC system suggests that the threshold for collapse is still rather remote (IPCC 2007a), but that a weakening of the strength of the circulation is likely through this century (Weber and Drijfhout 2011). The THC is an example of a circulation-related tipping element. Others include the El Niño Southern Oscillation (ENSO) and the West African Monsoon, both examples of coupled ocean-atmosphere circulation.

Likelihood of triggering abrupt changes

Much of the interest in tipping elements derives from the very large risks for human well-being associated with activation of many of the tipping elements. For example, loss of significant amounts of the Greenland and Antarctic ice sheets would lead to metres of sea-level rise. The Asian monsoon, or more precisely the Indian Summer Monsoon, is a tipping element whose behaviour is influenced by both the warming of the Indian Ocean and the presence of an "atmospheric brown cloud" over much of the sub-continent. Some models suggest a tipping point related to changes in regional albedo, leading to sudden switches in the strength and location of monsoonal rains (Zickfeld et al. 2005; Levermann et al. 2009). Given that over a billion people directly depend on the reliable behaviour of the Indian Summer Monsoon for their food production, rapid changes in rainfall could have catastrophic consequences for large numbers of people.

Table 1 gives an example of how a risk assessment on tipping elements might be carried out (Richardson et al. 2011). The assessment is based on the combination of the likelihood of the tipping element being activated and the impact on human well-being of a change of state of the tipping element. Of the tipping elements considered, it is interesting that the highest risks are associating with the loss of ice from the large polar ice sheets. Risks associated with the Atlantic thermohaline circulation and the behaviour of ENSO are considered to be rather low primarily because of the small likelihood that a tipping point will be passed.

Abrupt shifts in atmospheric circulation

Tipping elements associated with changes in atmospheric circulation, or coupled ocean-atmosphere circulation, are especially important because of the short time scales on which they can operate. The bi-stability of the Indian Summer Monsoon, noted above, is an example of a large shift in atmospheric circulation that can happen very quickly, even on an annual basis. The recent cold, snowy winters (2005-06, 2009-10, 2010-11) in parts of northern Europe and North America (Figure 2), and their possible link to climate change, comprise another good example of risks associated with this type of tipping element.

Although it sounds counter-intuitive, such cold weather may be linked to the overall warming of the planet. More specifically, a possible link is via the loss of Arctic sea ice in winter and the consequent formation of a high pressure cell over the polar region (Petoukhov and Semenov 2010). This cell changes pressure gradients in the north Atlantic region, rearranging Northern Hemisphere atmospheric circulation and generating cold, easterly airflows over much of western Europe. This change represents an abrupt transition between two states of the circulation. Interestingly, the threshold for the abrupt shift in circulation lies near 40% reduction in sea ice, but another transition, flipping the circulation back to the earlier regime, is projected to exist at about 80% reduction in sea ice.

Table 1. A simple 'straw man' example of tipping element risk assessment, by Timothy M. Lenton

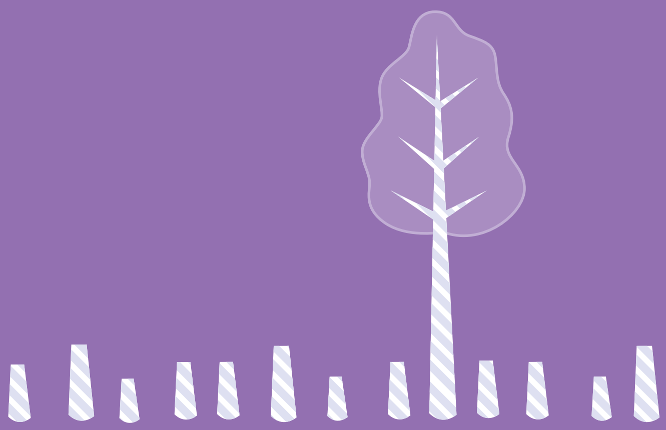
Tipping element	Likelihood of passing a tipping point (by 2100)	Relative impact** of change in state (by 3000)	Risk score (likelihood x impact)	Risk ranking
Arctic summer sea-ice	High	Low	3	4
Greenland ice sheet	Medium-High*	High	7.5	1 (highest)
West Antarctic ice sheet	Medium*	High	6	2
Atlantic THC	Low*	Medium-High	2.5	6
ENSO	Low*	Medium-High	2.5	6
West African monsoon	Low	High	3	4
Amazon rainforest	Medium*	Medium	4	3
Boreal forest	Low	Low-Medium	1.5	8 (lowest)

* Likelihoods informed by expert elicitation

** Initial judgment of relative impacts is the subjective assessment of T.M.L.

CHAPTER 3: IMPLICATIONS OF THE SCIENCE FOR EMISSION REDUCTIONS

DID YOU KNOW...



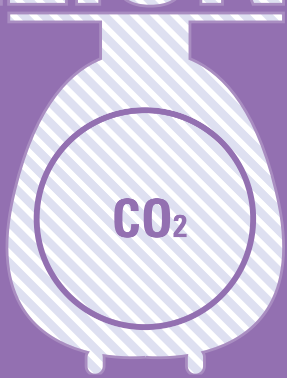
ABOUT 15-20% OF NET CO_2 EMISSIONS GLOBALLY HAVE ORIGINATED FROM LAND ECOSYSTEMS, PRIMARILY FROM DEFORESTATION.

2020

THE PEAKING YEAR FOR EMISSIONS IS VERY IMPORTANT FOR THE RATE OF REDUCTION THEREAFTER. THE DECADE BETWEEN NOW AND 2020 IS CRITICAL.

ONE TRILLION TONNES

2000



2050

HUMANITY CAN EMIT NOT MORE THAN 1 TRILLION TONNES OF CO_2 BETWEEN 2000 AND 2050 TO HAVE A 75% CHANCE OF LIMITING TEMPERATURE RISE TO 2 °C OR LESS.

3.1 The budget approach

Although the targets-and-timetables approach (e.g. an agreed percentage reduction in greenhouse gas emissions by 2020) remains the most common approach to defining trajectories for climate mitigation, the budget, or cumulative emissions, approach is rapidly becoming the favoured approach in analyses in the scientific community. It offers a much simpler, easier-to-understand, transparent and powerful framework to estimate what level of emission reductions is required to meet the 2 °C guardrail.

This section outlines the conceptual framework for the budget approach and its implications for mitigation strategies:

- The budget approach directly links the projected rise in temperature to the aggregated global emissions in Gt CO_2 or Gt C for a specified period, usually 2000 to 2050 or 2100. For example, humanity can emit not more than 1 trillion tonnes of CO_2 between 2000 and 2050 to have a probability of about 75% of limiting temperature rise to 2 °C or less.
- Given an overall carbon budget between 2000 and 2050, the approach does not stipulate any particular trajectory, so long as the overall budget is respected. This allows a strategy that delivers least cost to the economy over time in making the transition to a low- or no-carbon economy.

Conceptual framework.

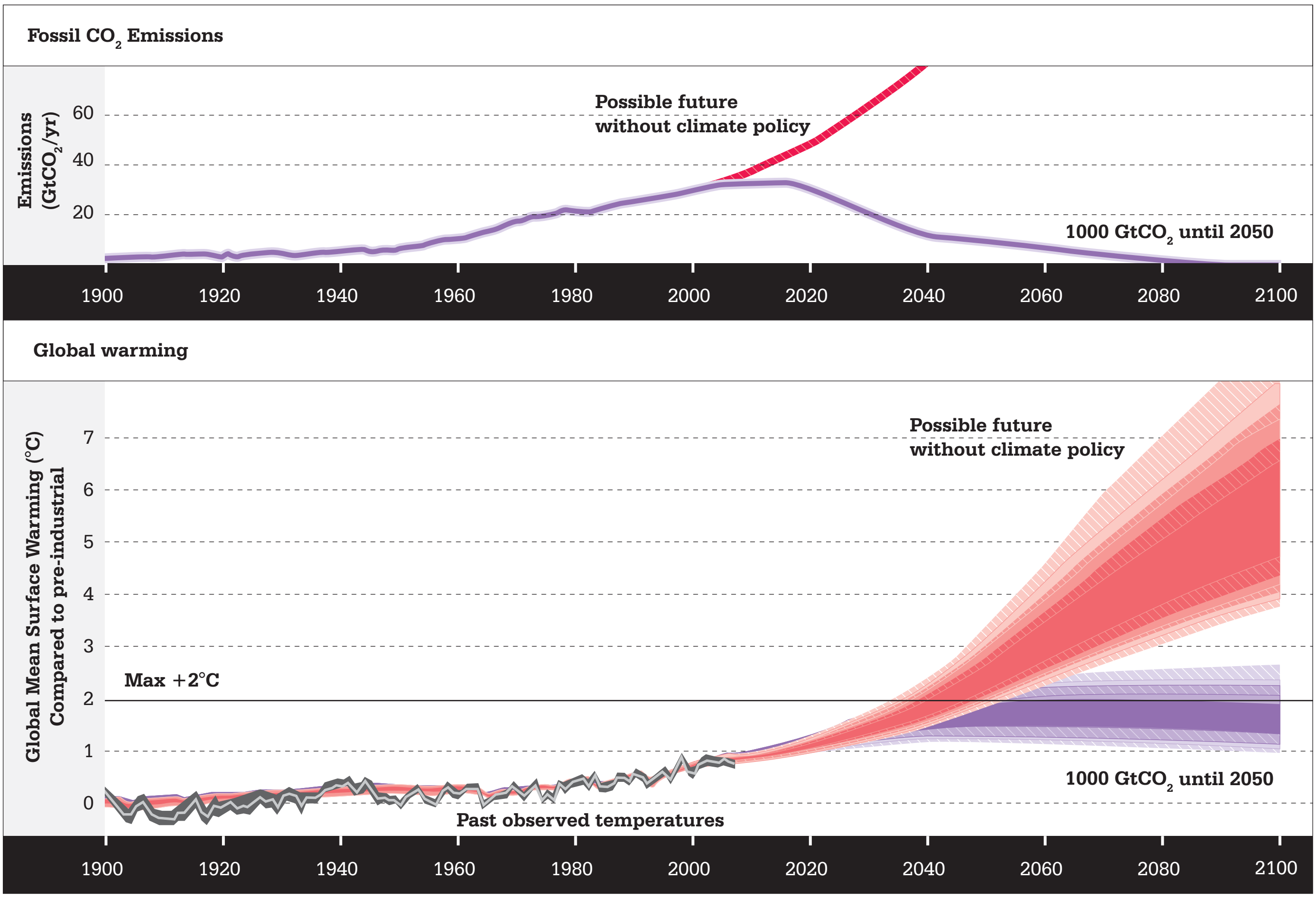
The budget approach avoids the explicit use of targets for the stabilisation of atmospheric CO_2 or CO_2-equivalent concentrations by directly linking the projected rise in temperature to the aggregated global emissions (in Gt CO_2 or Gt C) for a specified period, usually 2000 to 2050 or 2100. That is, it is based on the degree of climate change that we can expect in future estimated directly from the sum of additional greenhouse gases that are emitted to the atmosphere (e.g., Allen et al. 2009; Meinshausen et al. 2009; Figure 36). The relationship is not deterministic but rather probabilistic, given uncertainties in our understanding of the sensitivity of climate to a particular increase in the amount of greenhouse gases in the atmosphere.

To apply the concept, if we wish to have a 75% chance of observing the 2 °C guardrail, we can emit no more than 1000 Gt (one trillion tonnes) of CO_2 in the period from 2000 to 2050. If want to achieve a 50:50 chance of observing the guardrail, then we can emit 1440 Gt in the period. In the first nine years of the period (2000 through 2008), humanity emitted 305 Gt of CO_2, over 30% of the total budget in less than 20% of the time period.

Strategic implications.

Given an overall budget between now and 2050, the approach does not stipulate any particular trajectory, so long as the overall budget is respected. This approach allows, in making the transition to a low- or no-carbon economy, a flexible approach that delivers least cost to the economy, not only across sectors in the economy at any particular time, but also through time from the present to mid-century and beyond. As it is the cumulative emissions over time that must be limited, rather than a series of interim emission reduction targets that must be met, many emission reduction trajectories are possible. However, the later emission reduction trajectories are initiated, the more difficult and costly they become (Garnaut 2008).

Figure 36. Top: Fossil fuel CO_2 emissions for two scenarios: one "business as usual" (red) and the other with net emissions peaking before 2020 and then reducing sharply to near zero emissions by 2100, with the cumulative emission between 2000 and 2050 capped at 1 trillion tonnes of CO_2 (purple). Bottom: Median projections and uncertainties of global-mean surface air temperature based on these two emissions scenarios out to 2100. The darkest shaded range for each scenario indicates the most likely temperature rise (50% of simulations fall within this range).



Source: Australian Academy of Science (2010), adapted from Meinshausen et al. (2009).

3.2 Implications for emission reduction trajectories

Although the budget approach allows more flexibility in the economic and technical pathways to emissions reductions than does a targets-and-timetables approach, the fact that we have already consumed over 30% of our post-2000 budget means that much of that flexibility has been squandered if we wish to avoid the escalating risks associated with temperature rises beyond 2 °C. Thus, there is no room for any further delay in embarking on the transition to a low- or no-carbon economy.

The key messages of this section are:

- Reducing emissions of CO_2 does not reduce or stabilise its concentrations in the atmosphere; it slows the rate of increase of CO_2 concentration. To stabilise the concentration of CO_2 requires emissions to be reduced to very near zero.
- The peaking year for emissions is very important for the rate of reduction thereafter. The decade between now and 2020 is critical.
- Targets and timetables are, in principle, less important in the budget approach, but the urgency of bending emission trajectories downwards this decade implies that more ambitious targets for 2020 are critical in preventing delays in the transition to a low- or no-carbon economy.

Emissions trajectories

Figure 37 (WBGU 2009) shows three of the multitude of trajectories for global emissions that are possible under the budget approach to have a 67% probability of meeting the 2 °C guardrail. It is clear from the figure that global emissions will need to be reduced to very close to zero by 2050 to meet this challenge, that is, to stabilise the CO_2 concentration at a value compatible with the 2 °C guardrail. Less ambitious emission reductions will slow the accumulation of CO_2 in the atmosphere, but its concentration will continue to rise.

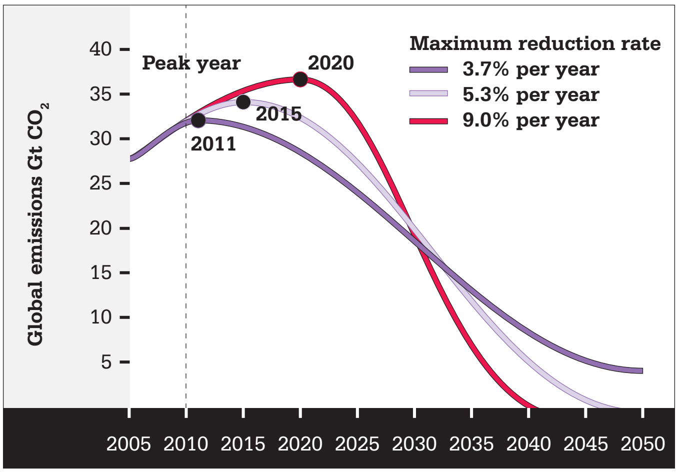
Figure 37 also shows that the peaking year for emissions is especially important for the rate of reduction thereafter. For example, delaying the peaking year by only nine years, from 2011 to 2020, changes the maximum rate of emission reduction from 3.7% per annum, which is very challenging but perhaps achievable, to 9.0% per annum, which is impossible on anything but a wartime footing.

IN SUMMARY, IN TERMS OF MEETING THE 2 °C GUARDRAIL, THE DECADE BETWEEN NOW AND 2020 IS CRITICAL.

Targets and timetables

The more familiar approach of constricting the emissions trajectory to a timetable with a set of interim targets becomes less important in the budget approach. The strategic challenge changes from whether the 2020 target is a 5%, 25% or 40% reduction against a particular baseline to how do we implement the transition to a low- or no-carbon economy by 2050 with the least economic and social cost while staying within the budget? For example, the middle trajectory of Figure 37, with a peaking year of 2015, has a global emissions level for 2020 of about 32 Gt CO_2, which is about the same as for 2010, and much higher than for 1990, the Kyoto baseline. The curves of Figure 37 are for global emissions, though, and industrialised countries would be expected to have much larger emission reductions than the global average.

Figure 37. Three emission trajectories based on the budget approach and giving a 67% probability of meeting the 2 °C guardrail.



Source: WBGU (2009).

The connection between the budget approach and the more familiar targets and timetables approach is clear once a desired trajectory is established based on a nation's overall carbon budget. The trajectory to stay within the budget, in effect, sets a series of targets within a specific timetable that define the trajectory. The flexibility is associated with the determination of the trajectory itself.

THE BUDGET APPROACH ALSO HAS A SUBTLE BUT IMPORTANT PSYCHOLOGICAL ADVANTAGE OVER THE TARGETS-AND-TIMETABLE APPROACH IN THAT IT FOCUSES ATTENTION ON THE END GAME – ESSENTIALLY DECARBONISING THE ECONOMY.

Thus, investment decisions can be taken from a long-term perspective, knowing that a limited budget is most efficiently allocated to invest in new infrastructure that eventually delivers very low or no emissions by mid-century, rather than to invest in shorter-term measures aimed at meeting an interim target that are perhaps less effective in delivering longer-term emission reductions.

Perhaps the biggest challenge to implementing the budget approach is allocating the global budget to individual countries, where equity issues become important. This is a political rather than a scientific question, whereas the overall global budget is more directly related to the science. The problem is not unique to the budget approach, but also bedevils negotiations under the targets-and-timetables approach and has perhaps been the single most difficult issue to resolve to achieve an international agreement on a global emission reduction plan.

3.3 Relationship between fossil and biological carbon emissions and uptake

Carbon "offsets", in which emitters of CO_2 from fossil fuel combustion can meet their emission reduction obligations by buying an equivalent amount of carbon uptake by ecological systems, are often proposed as a way of achieving rapid emission reductions at least cost. However, although the immediate net effect on the atmospheric concentration of CO_2 is the same for both actions, the nature of the carbon cycle means that the uptake of CO_2 from the atmosphere by an ecosystem cannot substitute in the long term for the reduction of an equivalent amount of CO_2 emissions from the combustion of fossil fuels. In fact, the offset approach, if poorly implemented, has the potential to lock in more severe climate change for the future.

Although it is very important to sequester atmospheric CO_2 into land ecosystems, this section outlines the reasons why is not a good idea to consider such biological sequestration as an offset for fossil fuel emissions. The key messages are:

- About 15-20% of net CO_2 emissions globally have originated from land ecosystems, primarily from deforestation. This represents the removal of carbon from a stock in the active atmosphere-land-ocean carbon cycle. It does not introduce any additional carbon into the atmosphere-land-ocean system, but simply redistributes it.
- The combustion of fossil fuels represents the injection of additional carbon from an inert, underground stock into the active atmosphere-land-ocean cycle. This additional carbon is redistributed among the three main stocks in the active carbon cycle, thus adding to the amount of atmospheric CO_2.
- Avoiding emissions by protecting ecosystem carbon stocks is a necessary part of a comprehensive approach to mitigation. Sequestering CO_2 into degraded ecosystems is also an important mitigation activity because it reverses an earlier emission. However, sequestering CO_2 into land ecosystems does not remove it from the active atmosphere-land-ocean cycle. Therefore, the sequestered carbon is vulnerable to human land use and management, which can rapidly deplete carbon stocks, and to major changes in environmental conditions, which can change the amount of carbon stored in the long term.
- The only way that CO_2 sequestered into land ecosystems can permanently "offset" fossil fuel combustion is if the sequestered carbon is subsequently removed from the land ecosystem and stored in an inert state or in a stable geological formation, thus locked away from the active atmosphere-land-ocean cycle. Another approach to offsetting is to replace fossil fuels with biofuels.

Carbon from land ecosystems

Over the past century about 15%-20% of CO_2 emissions globally originate from land ecosystems, primarily from deforestation (Raupach and Canadell 2010). This fraction has decreased over the past decade to about 11% in 2009 (Friedlingstein et al. 2010) due primarily to the large increase in fossil fuel emissions. Emissions from land ecosystems represent the removal of carbon from a stock in the active atmosphere-land-ocean carbon cycle. In essence, deforestation is a human-driven redistribution of carbon among the three active stocks – from land to the atmosphere, and then, in part, to the ocean. It does not introduce any *additional* carbon to the atmosphere-land-ocean cycle. Natural processes such as climate variability also redistribute carbon among these three stocks. A strong La Niña event, for example, redistributes carbon from the atmosphere to the land through increased productivity due to above-average precipitation in some parts of the world. However, averaged over decades, and in the absence of human perturbation or long-term changes in climate, land carbon stocks are relatively stable.

Fossil fuel combustion

The combustion of fossil fuels represents the injection of *additional* carbon from an inert, underground stock into the active atmosphere-land-ocean system. This additional carbon is redistributed among the three main stocks in the active carbon cycle, thus adding to the amount of atmospheric CO_2. A little less than half of the additional, inert carbon activated by the combustion of fossil fuels remains in the atmosphere; the rest is redistributed about equally to the land and ocean (Canadell et al. 2007; Raupach et al. 2007). So the combustion of fossil fuel is fundamentally different from deforestation because fossil fuel combustion introduces additional carbon to the active cycle, rather than redistributing the existing amount of carbon in the active cycle among the three major stocks.

Replacing the legacy carbon on land

Sequestering CO_2 into land ecosystems does not remove it from the active atmosphere-land-ocean system. It returns the original carbon, sometimes called "legacy carbon", lost from land-use change back into the land stock, and the amount that can be sequestered is limited by the prevailing environmental conditions. That is, atmospheric carbon cannot be sequestered into land ecosystems indefinitely.

However, it is very important that this legacy carbon be returned to land ecosystems as soon as possible for a number of reasons. First, such sequestration is indeed a rapid way to begin reducing the anthropogenic burden of CO_2 in the atmosphere. Thus, it yields some quick gains while the slower process of transforming energy and transport systems unfolds.

FURTHERMORE, IF DONE CAREFULLY, SEQUESTRATION OF CARBON INTO LAND ECOSYSTEMS CAN LEAD TO MANY OTHER CO-BENEFITS, SUCH AS ENHANCED SOIL CONDITION, MORE PRODUCTIVE AGRICULTURAL SYSTEMS, AND BETTER BIODIVERSITY OUTCOMES.

Some general principles provide a guide for designing and implementing an appropriate land carbon mitigation scheme:

1. The size of the stock is the important factor in the carbon cycle, not the rate of flux from one compartment (e.g. atmosphere) to another (e.g. a land ecosystem). These two different aspects of the carbon cycle are often confused. Although a fast-growing, mono-culture plantation forest may have a rapid rate of carbon uptake for the years of vigorous growth, it will store less carbon in the long term that an old growth forest or a secondary regrowth forest on the same site (Diochon et al. 2009; Brown et al. 1997; Nepstad et al. 1999; Costa and Wilson 2000; Thornley and Cannell 2000).

2. Natural ecosystems tend to maximise carbon storage, that is, they store more carbon than the ecosystems that replace them after they are converted or actively managed for production (Diochon et al. 2009; Brown et al. 1997; Nepstad et al. 1999). An observational study of temperate moist forests in southeast Australia identified the world's most carbon dense forest and developed a framework for identifying the forests that are the most important for carbon storage (Keith et al. 2009). In general, forests with high carbon storage capacities are those in relatively cool, moist climates that have fast growth coupled with low decomposition rates, and older, complex, multi-aged and layered forests with minimal human disturbance. This framework underscores the importance of eliminating harvesting of old-growth forests as perhaps the most important policy measure that can be taken to reduce emissions from land ecosystems. Recognition of the need to protect primary forests has helped to catalyse formulation of the REDD (Reduction of Emissions from Deforestation and forest Degradation) agenda item under the UNFCCC negotiations (http://unfccc.int/methodsandscience/lulucf/items/4123.php).

3. If designed carefully, a bio-sequestration approach can yield significant co-benefits. These are especially important for deforested, degraded and intensively cropped lands where the potential for sequestering carbon is large. Well-conceived and implemented bio-sequestration schemes in these landscapes can improve the productivity of cropping systems through the replacement of soil carbon that was lost in tillage, can deliver additional ecosystem services such as improved water quality on landscapes, and can maintain or enhance biodiversity. The relationship between bio-sequestration and biodiversity is particularly important, as well-designed sequestration schemes have the potential to yield positive outcomes for biodiversity (Steffen et al. 2009). In fact, a synthesis of the interplay among forest biodiversity, productivity and resilience argues that more diverse forests have higher productivity, store more carbon, and are more resilient towards disturbance than those with impoverished biodiversity (Thompson et al. 2009).

There are some cautions associated with bio-sequestration into land ecosystems, however. As shown in Figure 12, the land sink is highly variable on time scales of a few years, varying by as much as 2-3 Pg C in those timeframes. The strong fluctuations are driven largely by modes of climate variability such as ENSO and by volcanic activity, which induce rapid changes in soil respiration and plant growth through changes in solar radiation, rainfall/drought and temperature (Raupach and Canadell 2010; Kirschbaum et al. 2007).

IN THE LONGER TERM, CLIMATE CHANGE CAN SIGNIFICANTLY WEAKEN OR EVEN REVERSE THE LAND SINK THROUGH DROUGHTS, INCREASED SOIL RESPIRATION AND DISTURBANCES SUCH AS FIRE AND INSECT OUTBREAKS.

Simulations by dynamic global vegetation models using the IPCC IS92a emissions scenario show a levelling off of the land sink in the second half of the century with two models showing a significant weakening (Cramer et al. 2001). When coupled to a climate model in interactive mode, all vegetation models show a weakening of the land sink by 2100 with a net release of carbon back to the atmosphere corresponding to an additional rise in concentration from 20 to 200 ppm CO_2 (Friedlingtstein et al. 2006).

There are already several observations of the processes in the models that weaken the land sink and ultimately threaten to reduce the size of the land stock. The 2003 drought and heatwave in central Europe triggered a 30% reduction in gross primary productivity over the region, which resulted in a strong net source of 0.5 Pg C yr^{-1} to the atmosphere, undoing four years of a net carbon sink for the region (Ciais et al. 2005). A multi-decadal study of the carbon balance of Canadian forests has demonstrated that since 1970 they have become a weaker carbon sink despite a longer growing season, owing to a sharp increase in disturbances such as fire and insect outbreaks triggered by a warming climate (Kurz and Apps 1999). As cited earlier, the Amazon rainforest, an important stock of carbon on a global level, has suffered severe droughts and fires in 2005 and 2010, leading to estimated losses in carbon storage of 2.2 and 1.6 Pg C for the two drought events, respectively (Lewis et al. 2011). This analysis suggests that the two droughts have offset a decade of carbon sink activity, estimated to be about 0.4 Pg C uptake per annum; such observations support the assessment that, at temperatures above the 2 °C guardrail, the Amazon rainforest is at risk of extensive dieback and conversion to a savanna, with consequent loss of carbon to the atmosphere (cf. Section 2.5). If this occurs, then Amazonian ecosystems will continue to hold significant carbon stocks but at lower than current levels.

In summary, for many reasons increasing carbon storage in land ecosystems is a necessary and desirable component of a comprehensive approach to greenhouse gas mitigation. However, it is not equivalent to storing carbon in a secure geological formation, locked away from the influences of climate variability and change or from the direct impacts of human management. The relative vulnerability of carbon stored in land ecosystems to perturbations compared to inert geological fossil fuel is sometimes called the "permanence" issue in the design of economic instruments to reduce emissions.

Geosequestration as an offset

In principle, CO_2 sequestered into land ecosystems can fully offset the emissions of CO_2 from fossil fuel combustion if the sequestered carbon is subsequently made inert to the impacts of human land management, environmental disturbances or changing environmental conditions. It is theoretically conceivable that bio-sequestered carbon could be removed and stored in a stable geological formation, locked away from the active atmosphere-land-ocean system.

Another approach, equivalent to geosequestration, is to replace fossil fuel combustion with biofuel combustion to produce energy. The growth and then combustion of biofuels is potentially carbon-neutral as it represents a cyclical processes of shifting carbon between the land and the atmospheric compartments in the fast atmosphere-land-ocean carbon cycle. The fossil fuels thus replaced would leave the carbon in fossil fuels in the ground and thus away from the atmosphere.

Care must be taken, however, in the generation of the biofuels to limit the emissions associated with the production process to low levels relative to the amount of energy produced, and avoid undesired side effects such as competition with food production, loss of natural ecosystems and thus generation of large carbon emissions (see point 2 on page 60) and losses of biodiversity. In general, biofuels made from 'waste' biomass from plantation forests or from perennial vegetation grown on abandoned agricultural land offer the most advantages and avoid the undesirable side effects.

Focussing on the end game

The budget approach to mitigation described above, which is becoming more widely used for analyses in the research community, offers some scientifically based insights into mitigation approaches. Perhaps most importantly, it focuses strongly on the "end game" rather than interim targets.

PUT SIMPLY, IF THE 2 °C GUARDRAIL IS TO BE ACHIEVED, THEN THERE IS NO TIME FOR DELAY IN INVESTING IN LOW AND NO-CARBON TECHNOLOGIES FOR ENERGY GENERATION, BUILT INFRASTRUCTURE AND TRANSPORT.

Responsibly implemented bio-sequestration schemes offer some early gains; they can remove carbon quickly from the atmosphere and also offer a number of important co-benefits. The challenge is to ensure that linking bio-sequestration to the fossil fuel emissions sectors does not lead to any delays in the investment or deployment of low- or no-carbon technologies in those sectors.

As you've read in this report, we know beyond reasonable doubt that the world is warming and that human emissions of greenhouse gases are the primary cause. The impacts of climate change are already being felt in Australia and around the world with less than 1 degree of warming globally. The risks of future climate change – to our economy, society and environment – are serious, and grow rapidly with each degree of further temperature rise. Minimising these risks requires rapid, deep and ongoing reductions to global greenhouse gas emissions. We must begin now if we are to decarbonise our economy and move to clean energy sources by 2050. This decade is the critical decade.

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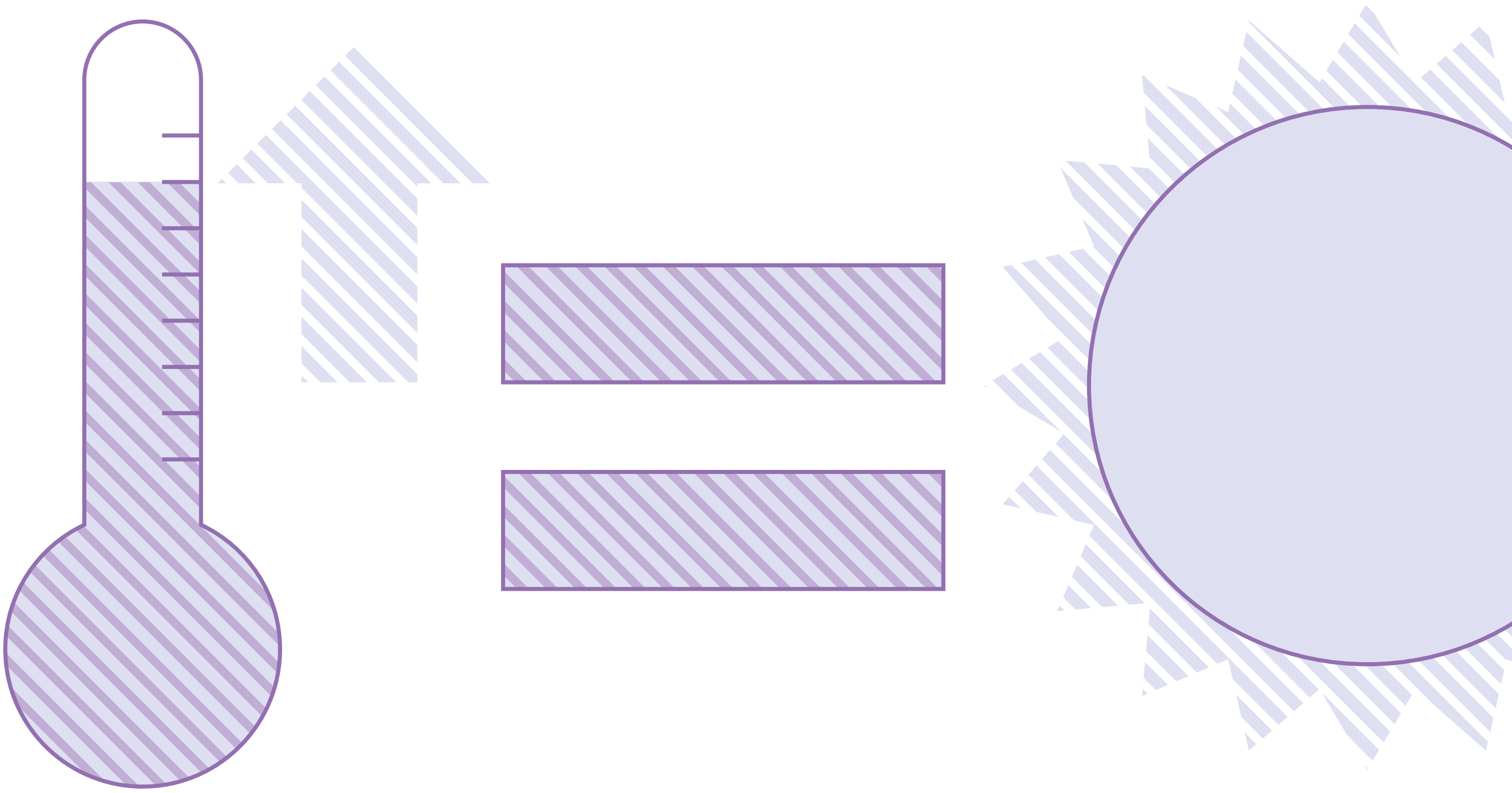

NATIONAL CARBON OFFSET STANDARD CONSUMER

The Climate Commission uses National Carbon Offset Standard certified Tudor RP Carbon Neutral paper
An Australian Government Initiative