5 OBSERVATIONS AND PROJECTIONS OF GLOBAL CLIMATE CHANGE

Key points

As a result of past actions, the world is already committed to a level of warming that could lead to high-consequence climate change outcomes.

Extreme climate responses are not always considered in the assessment of climate change impacts due to the high level of uncertainty and a lack of understanding of how they work. However, the potentially catastrophic consequences of such events means it is vitally important that the current knowledge of these outcomes is incorporated in the decision-making process.

Continued high emissions growth with no mitigation action carries high risks. These risks would be reduced by ad hoc mitigation, but remain high for some elements. Ambitious global mitigation would reduce the risks further, but some systems may still suffer critical damage.

There are advantages in aiming for an ambitious global mitigation target in order to avoid some of the high-consequence impacts of climate change.

This chapter looks at changes to the global climate that have been observed to date, and describes possible future changes under a range of assumptions about mitigation. It looks at both the 'best-estimate', projections, the possibility of extreme climate responses, and the likelihood of crossing thresholds that might lead to abrupt or irreversible climate change.

Much of the research literature on observed and projected climate change has been summarised and evaluated in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007). Here the Review summarises the key observations and illustrates some of the main possible changes. Where relevant, the discussion makes use of evidence from research undertaken since the Fourth Assessment Report was compiled and considers alternative views.

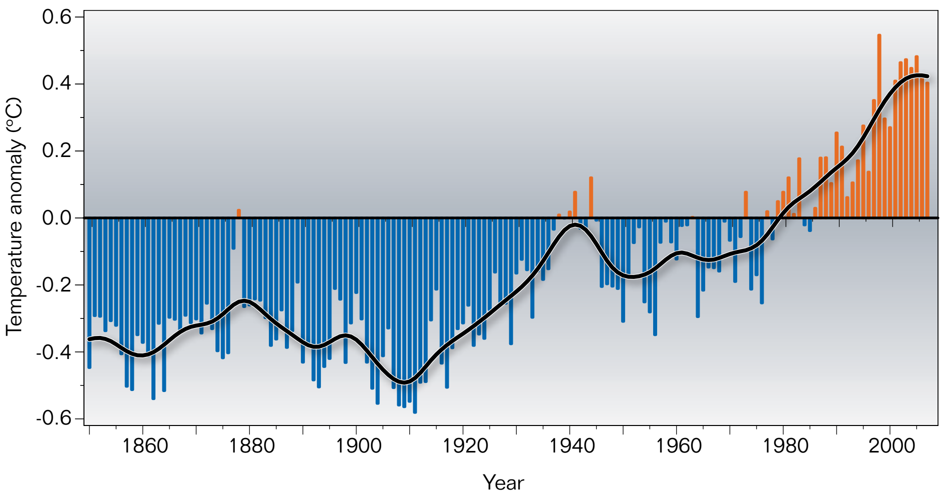
5.1 How has the climate changed?

The IPCC states that 'warming of the climate system is unequivocal', and that this is evident in the measured increase in global average air and surface temperatures, and also in the widespread melting of snow and ice and the rising global sea level (IPCC 2007: 5).

5.1.1 Changes in temperatures

Global average temperatures have risen considerably since measurements began in the mid-1800s, as shown in Figure 5.1. Since early industrial times (1850–1899) the total global surface temperature increase has been estimated at 0.76°C ± 0.19°C.

Figure 5.1 Average global average air temperature anomalies, 1850 to 2005



Source: Brohan et al. (2006, updated 2008).

Note: The data shows temperature difference from the 1961–1990 mean. The black line shows the annual values after smoothing with a 21-point binomial filter.

Since 1979, the rate of warming has been about twice as fast over the land as over the ocean. During the last century, the Arctic has warmed at almost twice the global average rate.

The warming of the ocean since 1955 has accounted for more than 80 per cent of the increased energy in the Earth's climate system (IPCC 2007: 47). Warming in the top 700 m is widespread, with deeper warming occurring in the Atlantic Ocean.

The rate of warming in the lower atmosphere (the troposphere) has exceeded surface warming since 1958, while substantial cooling has occurred in the lower stratosphere. The pattern of tropospheric warming and stratospheric cooling is most likely due to changes in stratospheric ozone concentrations and greenhouse gas concentrations in the troposphere (IPCC 2007: 10). Both the troposphere and the stratosphere have reacted strongly to events that have suddenly increased the volumes of aerosols in the atmosphere (IPCC 2007: 270).

Box 5.1 Is there a warming trend in global temperature data?

Observations show that global temperatures have increased over the last 150 years (Figure 5.1). The data also suggests that the warming was relatively steep over the last 30–50 years. A comparison of three datasets shows that they differ slightly on the highest recorded temperatures—data from the Hadley Centre in the United Kingdom shows 1998 as the highest year, while data from the National Aeronautics and Space Administration and the National Climatic Data Centre in the United States show 2005 as the highest year.* All three datasets show that seven of the hottest 10 years on record have been in the last nine years between 1999 and 2007. There has been considerable debate in recent months on the interpretation of the global temperatures over the past decade. Questions have been raised about whether the warming trend ended in about 1998.

To throw light on this question, the Review sought assistance from two eminent econometricians from the Australian National University to investigate the question. Trevor Breusch and Farshid Vahid have specific expertise in the statistical analysis of time series—a speciality that is well developed in econometrics. They were asked two questions:

- Is there a warming trend in global temperature data in the past century?
- Is there any indication that there is a break in any trend present in the late 1990s, or at any other point?

They concluded that:

> It is difficult to be certain about trends when there is so much variation in the data and very high correlation from year to year. We investigate the question using statistical time series methods. Our analysis shows that the upward movement over the last 130–160 years is persistent and not explained by the high correlation, so it is best described as a trend. The warming trend becomes steeper after the mid-1970s, but there is no significant evidence for a break in trend in the late 1990s. Viewed from the perspective of 30 or 50 years ago, the temperatures recorded in most of the last decade lie above the confidence band produced by any model that does not allow for a warming trend (Breusch & Vahid 2008).

* Three datasets were used in this analysis—1) Hadley Centre Hadcrut3 (Brohan et al. 2006), <www.cru.uea.ac.uk/cru/data/temperature/hadcrut3gl.txt> accessed 7 May 2008; 2) the Goddard Institute for Space Studies, NASA, <http://data.giss.nasa.gov/gistemp/tabledata/GLB.Ts.txt>, accessed 17 May 2008; 3) the National Climate and Data Centre, US Department of Commerce, <ftp://ftp.ncdc.noaa.gov/pub/data/anomalies/annual.land_and_ocean.90S.90N.df_1901-2000mean.dat>, accessed 16 May 2008.

5.1.2 Observed oceans and sea level

The ocean has an ability to store a thousand times more heat than the atmosphere. The heat absorbed by the upper layers of the ocean plays a crucial role in short-term climatic variations such as El Niño (IPCC 2007: 46).

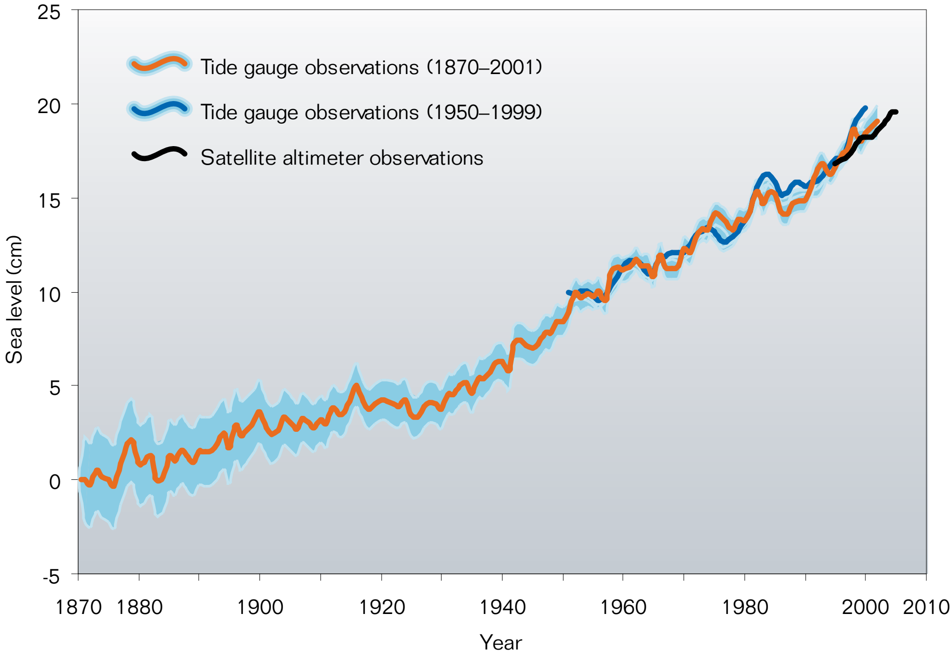
As oceans heat up, they expand, causing the volume of the ocean to increase and global mean sea level to rise. Sea level also rises when mass is added through the melting of grounded ice sheets and glaciers. Measurements show that widespread decreases in non-polar glaciers and ice caps have contributed to sea-level rise. The Greenland and Antarctic ice sheets are also thought to have contributed, but the proportions resulting from ice melt and the instability of the large polar ice sheets have yet to be fully understood (IPCC 2007: 49).

The total sea-level rise for the 20th century, including contributions from thermal expansion and land ice-melt, was 170 mm (Figure 5.2). Measurements show that the average rate of sea-level rise in the period 1961–2003 was almost 1.8 ± 0.5 mm per year. For 1993–2003 it was 3.1 ± 0.7 mm per year (IPCC 2007: 387).

Sea level varies spatially due to ocean circulation, local temperature differences, land movements and the salt content of the water. Regional changes in ocean salinity levels have occurred due to changes in precipitation that affect the inflow of freshwater. Changes in salinity have the potential to modify ocean currents and atmospheric circulation at the global scale. On an inter-annual to decadal basis regional sea level fluctuates due to influences such as the El Niño – Southern Oscillation. Regional changes can lead to rates of sea-level change that greatly exceed the small annual increases in global average sea level (Cazenave & Nerem 2004).

Ocean acidity has increased globally as a result of uptake of carbon dioxide, with the largest increase in the higher latitudes where the water is cooler (IPCC 2007: 405). The oceans are now more acidic than at any time in the last 420 000 years (Hoegh-Guldberg et al. 2007).

Figure 5.2 Global average sea-level rise from1870 to 2005



Note: Observed global average sea-level rise inferred from tide-gauge data (with 95% confidence limits shown as blue shading) and satellite altimeter data.

Source: Church & White (2006); Holgate & Woodworth (2004); Leuliette at al. (2004).

5.1.3 Changes in water and ice

The climate system varies considerably on a local and regional basis, so that consideration of global averages can mask large regional variations (see Figure 5.3).

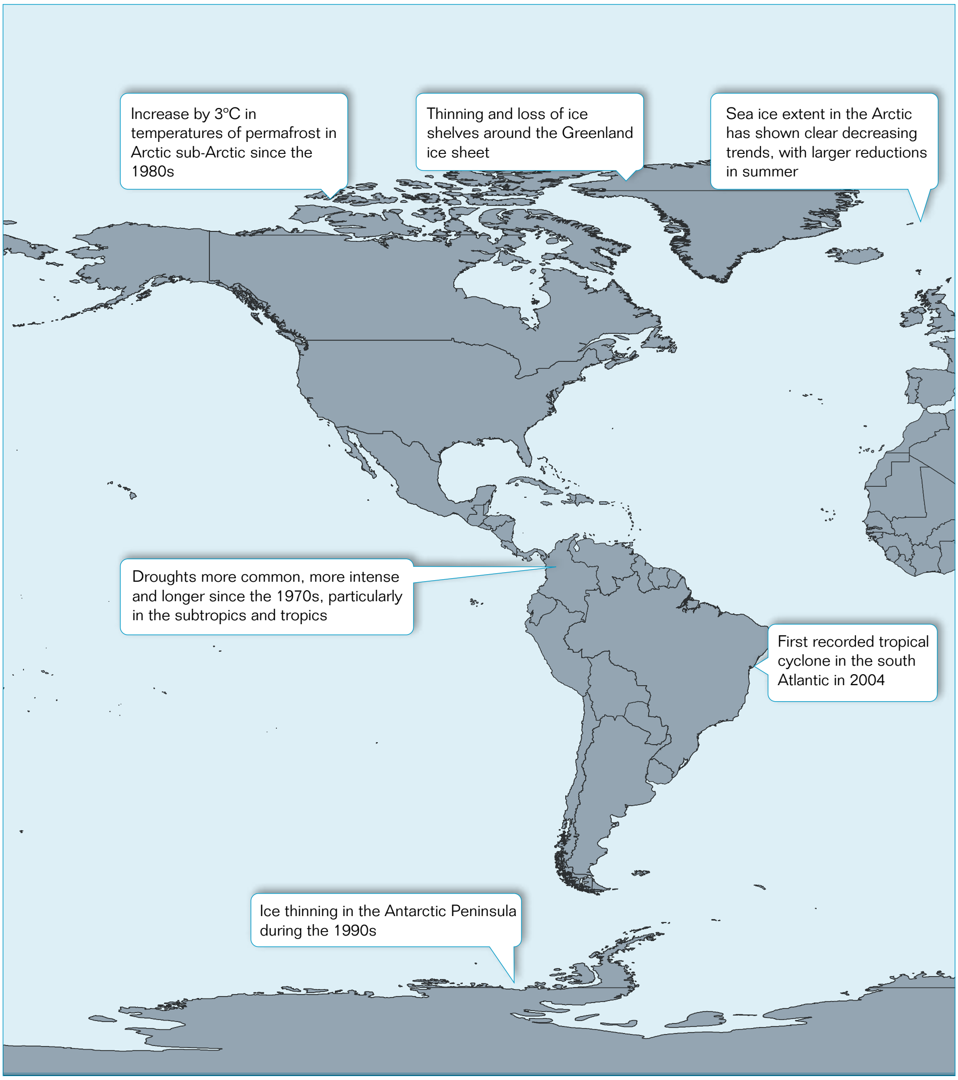
Precipitation

Increases in temperature affect the amount of water vapour that the air can hold and lead to increased evaporation of water from the earth's surface. Together these effects alter the water cycle and influence the amount, frequency, intensity, duration and type of precipitation.

Over oceans and areas where water is abundant, the added heat acts to moisten the air further rather than warm it, which can reduce the increase in air temperature and lead to more precipitation.

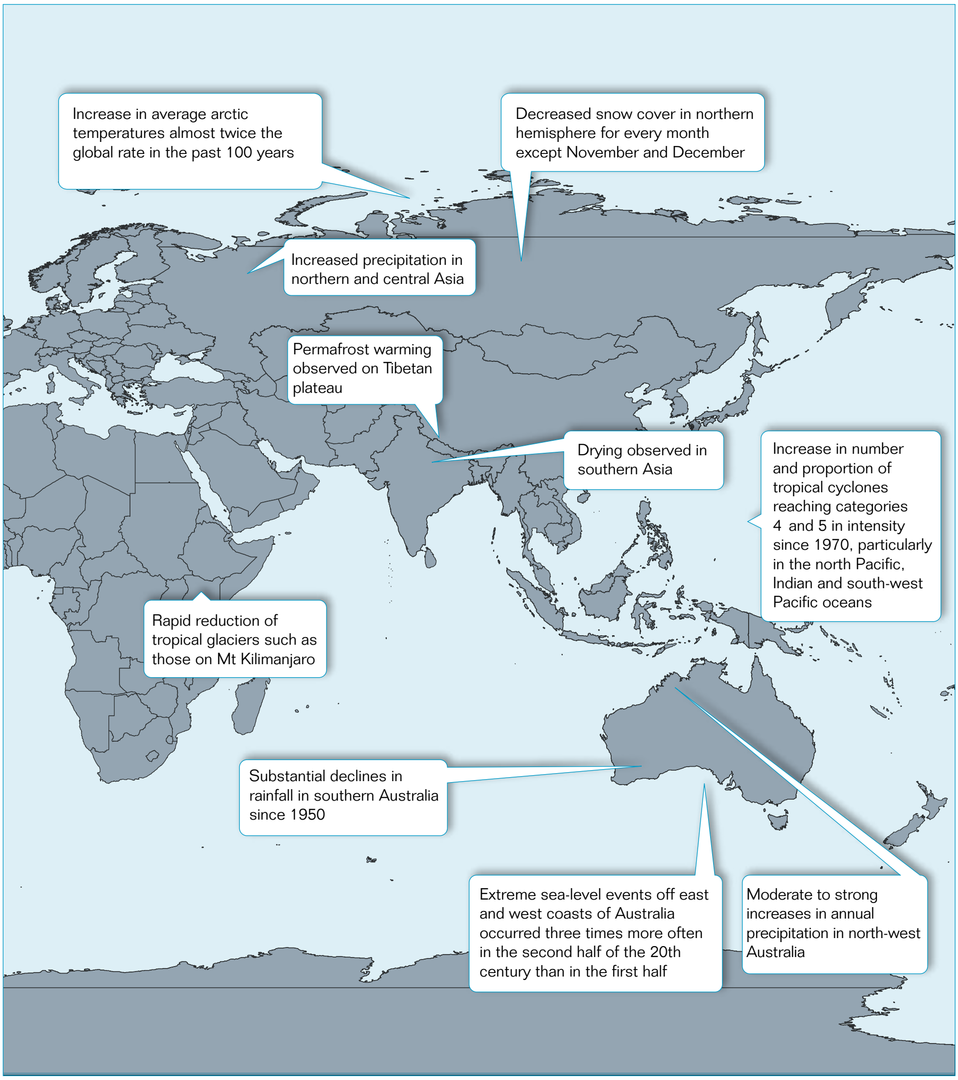
Where the surface is too dry to exchange much water with the atmosphere, increased evaporation can accelerate surface drying without leading to more rainfall. Cloudiness will also fall in the warmer and drier atmosphere, leading to further temperature increases from the higher amount of sunlight reaching the surface (IPCC 2007: 505). These effects can cause an increase in the occurrence and intensity of droughts (IPCC 2007: 262). Local and regional changes in precipitation are highly dependent on climate phenomena such as

Figure 5.3 Selected regional climate change observations



Source: IPCC (2007); Church et al. (2008); CSIRO & BoM (2007).

Figure 5.3 Selected regional climate change observations *(continued)*



the El Niño system, changes in atmospheric circulation and other large-scale patterns of variability (IPCC 2007: 262).

There is high variability in precipitation over time and space, and some pronounced long-term trends in regional precipitation have been observed. Between 1900 and 2005, annual precipitation increased in central and eastern North America, northern Europe, northern and central Asia and south-eastern South America (IPCC 2007: 258). Decreases in annual precipitation have been observed in parts of Africa, southern Asia and southern Australia (IPCC 2007: 256).

In addition to changes in mean precipitation, studies of certain regions show an increase in heavy rainfall events over the last 50 years, and some increases in flooding, even in areas that have experienced an overall decrease in precipitation (IPCC 2007: 316).

Ice caps, ice sheets, glaciers and frozen ground

About 75 per cent of the fresh water on Earth is stored in ice caps, ice sheets, glaciers and frozen ground, collectively known as the cryosphere. At a regional scale, variations in snowfall, snowmelt and glaciers play a crucial role in the availability of fresh water

Ice and snow have a significant influence on local air temperature because they reflect about 90 per cent of the sunlight that reaches them, while oceans and forested lands reflect about 10 per cent (IPCC 2007: 43).

Frozen ground is the single largest component of the cryosphere by area, and is present on a seasonal and permanent basis at both high altitudes and high latitudes (around the poles). Thawing of permanently frozen ground can lead to changes in the stability of the soil and in water supply, with subsequent impacts on ecosystems and infrastructure (IPCC 2007: 369).

Extensive changes to ice and frozen ground have been observed in the last 50 years, some at a rate that is dramatic and unexpected. Arctic sea ice coverage has shown a consistent decline since 1978. The average sea ice extent for the month of September 2007 was 23 per cent lower than the previous record set in 2005 (NSIDC 2007).

There has been a reduction in the mass of glaciers and ice caps everywhere, except in parts of Greenland and Antarctica (IPCC 2007: 44).

5.1.4 Changes to extremes

Changes in the intensity and frequency of certain severe weather events have been observed. Observed changes in temperature extremes have been consistent with the general warming trend—cold days, cold nights and frost have been occurring less frequently in the last 50 years, and hot days, hot nights and heat waves have been occurring more frequently (IPCC 2007: 308).

The area affected by droughts has increased in certain regions, largely due to the influence of sea surface temperatures and changes in atmospheric circulation and precipitation (IPCC 2007: 317). Full assessments of changes in droughts are limited by difficulties in the measurement of rainfall and poor data on soil moisture and stream flow (IPCC 2007: 82).

Tropical storm and hurricane frequency, lifetime and intensity vary from year to year and are influenced by the El Niño – Southern Oscillation, which can mask trends associated with general warming. At the global scale, there is a trend towards storms of longer duration and greater intensity, factors that are associated with tropical sea surface temperatures (IPCC 2007: 308).

5.1.5 Human attribution of observed changes

The climate system varies naturally due to external factors such as the sun's output and volcanic eruptions, and internal dynamics such as the El Niño – Southern Oscillation (Chapter 3). Over the longer term, in geological time, there are changes in climate associated with changes in the earth's orbit and the tilt of its axis (Ruddiman 2008).To establish whether human activities are causing the observed changes in climate, it must be established that the changes cannot be explained by these natural factors.

When only natural factors are included in the modelling of 20th century temperature change, the resulting models cannot account for the observed changes in temperature. However, when human influences are included, the models produce results that are similar to the observed temperature changes (IPCC 2007: 703). Using this technique, the influence of human activities on regional temperatures can be established for every continent except Antarctica, for which limited observed data is available.

Modelling has been used to determine human attribution of a range of observed changes in the climate, including the low rainfall in the south-west of Western Australia since the 1970s (CSIRO & BoM 2007), and the reduction in extent of Arctic sea ice (CASPI 2007).

Apart from modelling exercises, there are other gauges of observed change that suggest a human influence on the climate. These include the measurements of higher rates of warming over land than over sea, which would not be associated with El Niño, and the differential warming in the troposphere and stratosphere, which would be unlikely if caused by increased solar radiation, but can be explained by increases in greenhouse gases in the troposphere and the depletion of the ozone layer in the stratosphere (CASPI 2007).

5.2 Understanding climate change projections

How the climate will change in the future depends on a range of natural changes—'forcings'—as well as human activity, and the way the climate responds to these changes. These forcings are difficult to predict, can occur randomly and may interact in a way that amplifies or reduces the effects of another element. The inherent variability and complexity of the climate system is complicated further by the possibility of a non-linear and unpredictable response to levels of greenhouse gases that are well outside the range experienced in recent history.

The most important direct human forcings are greenhouse gas emissions, a process that humans can control through policy and management. Identifying specific pathways of human-induced greenhouse gas emissions—the dominant mechanism for human influence on the climate—simplifies the projection of climate change. But, of course, future changes in climate will be influenced by the natural factors as well.

5.2.1 Responding to climate change now

The human-induced warming, and the associated changes in climate occurring over the next few decades, will largely be the result of our past actions and is fairly insensitive to our current actions.

An exception is if large changes in emissions of sulphate aerosols occur, where warming (decrease) and cooling (increase) can occur within months of a change in emissions.

Models show that the warming out to 2030 is little influenced by greenhouse gas emissions growth in the future (IPCC 2007a: 68), as a result of lags in the climate system. By 2050, however, different trends in emissions have a clear influence on the climate outcomes, and by 2100 the potential differences are substantial.

To estimate the magnitude of climate change in the future it is necessary to make assumptions about the future level of global emissions of greenhouse and other relevant gases.

The Review takes a different approach to the IPCC in terms of scenario development. While the SRES scenarios show a range of possible outcomes for a world with no mitigation, the Review looks at four futures based on different levels of mitigation.

The four emissions cases

Figure 5.4 shows the emissions and concentration pathways for the four emissions cases considered in this chapter:

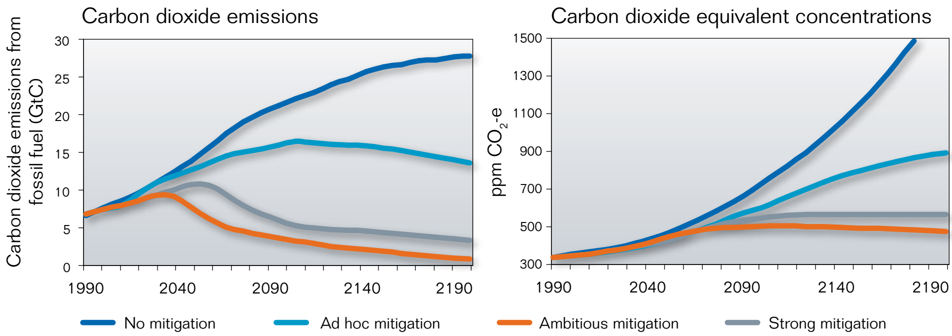
No-mitigation case—A global emissions case with no action to mitigate climate change has been developed as part of this Review. Details of the Garnaut–Treasury reference case are provided in Chapter 4. This emissions case recognises recent high trends in emissions of carbon dioxide and other greenhouse gases; these continue to increase throughout the 21st century.

Ad hoc mitigation case—As concerns rise about climate change, increased mitigation action is likely to occur, but might not be at the scale or speed required to achieve stabilisation, even at a moderate target. The Review therefore models an 'intermediate' emissions case. Current commitments suggest that high emissions growth will continue early in the century, but as developing countries accept mitigation targets, emissions will peak and then decline very gradually.

Strong global mitigation case—In the context of current international discussions, a target is considered that restricts greenhouse gas concentrations to 550 ppm CO_2-e. Emissions peak before 2030 and decline steadily through the remainder of the century.

Ambitious mitigation case—An ambitious target involving emissions reductions that lead to a stabilisation concentration of 450 ppm CO_2-e is considered, with an overshoot to 500 ppm CO_2-e. Carbon dioxide emissions peak before 2020 and decline steadily throughout the century.

Figure 5.4 Carbon dioxide emissions and concentrations of greenhouse gases in the atmosphere for the four emissions cases, 1990–2100



5.2.2 Confidence in the projection of climate change

As discussed in Chapter 3, climate models provide a wide range of estimates of temperature response and changes in climate variables such as rainfall. It is important to understand the uncertainty in the accuracy of model outputs, and how these are reflected in climate change projections.

Confidence in climate models

The ability of climate models to accurately simulate responses in the climate system is dependent on the level of understanding of the processes that govern the climate system, the availability of observed data for various scales of climate response, and the computing power of the model—all of which have improved considerably in recent years (CSIRO & BoM 2007).

Confidence in models comes from their ability to represent patterns in the current climate and past climates, and is generally higher at global and continental scales. For some elements of the climate system, such as surface temperature, there is broad agreement on the pattern of future climate changes. Other elements, such as rainfall, are related to more complex aspects of the climate system, including moisture transport, and are not represented with the same confidence in models.

Using a range of models, the likelihood of a particular outcome can be assessed. However, outcomes at the high or low end of a range of model results may also be plausible, and cannot be excluded from consideration.

There is significant uncertainty associated with the way the atmosphere will respond to a given change in carbon dioxide concentration— the equilibrium climate sensitivity (Chapter 3).

The extent to which the climate warms in response to changes in greenhouse gas concentrations is centrally important to the assessment of projected climate change. Many aspects of projected climate change relate closely to global mean temperature (IPCC 2007: 630). For example, the extent of melting of glaciers and permafrost is ultimately related to the magnitude of temperature increase. However, changes in other dimensions of climate, such as regional variation in rainfall, can not be easily correlated with temperature change; depending on location, the magnitude, spatial pattern and seasonality of rainfall can all change in ways that can not be directly inferred from temperature change. As a general rule, though, the severity of many aspects of climate change are correlated to the magnitude of projected warming.

Confidence in other elements of climate change

To assess the risk of climate change, a good understanding of the different elements that are included or excluded in the model outcomes is necessary, as is the uncertainty associated with these elements based on current knowledge. Elements often are communicated differently to recognise disparities in understanding or certainty, but to gain a comprehensive understanding of potential climate change for a given temperature outcome all these elements should be considered together:

Well-constrained climate outcomes—Some elements of the climate system have a well-established response to increased temperatures or other parameters, and models have a high level of reliability in reflecting the possible outcomes. Examples include the pattern of regional temperature response, sea-level rise from thermal expansion, melting of permafrost and damage to reefs.

Partially constrained climate outcomes—Some elements of the climate system have a relatively well-constrained pattern or direction of change in response to temperature rise, but are known to be poorly represented in models. Some uncertainty is created by disagreement between models. The extent and direction of rainfall change is an example of the latter, although this is becoming well constrained for some parts of Australia.

Poorly constrained climate outcomes—some elements of the climate system have an unknown response to changes in global temperature. An example is the response of the El Niño – Southern Oscillation, where scientists are unsure whether the fluctuations will increase, a permanent El Niño state may form or perhaps decline in influence.

5.2.3 Limitations in the Review's assessment

The uncertainty in projected climate change and the range of model outputs for a given emissions pathway means that there is value in investigating the climate outcomes from a large number of models. The SRES emissions datasets have been publicly available since 1998, and their use as a consistent basis for climate change projections has been extensive. The availability of multiple models allows for a better assessment of the level and sources of uncertainty in climate change projections. This provides more robust results and reduces the influence of individual model bias (IPCC 2007: 754).

An equivalent pool of data is not, however, available for the no-mitigation and mitigation cases being investigated by the Review.

The summary of projected climate change for the four emissions cases in this chapter is based on a range of data from the outcomes of the climate models used in the Review's modelling exercise and interpretation of the 2007 IPCC summary of projected climate change (IPCC 2007), based on the SRES scenarios.

The Review's analysis of the strong and ambitious mitigation cases is still under way. The outcomes will be presented in the supplementary draft and final reports. The emissions profile for the SRES scenario A1B is used a proxy for the ad hoc case. The strong and ambitious global mitigation cases analysed in this draft report were developed using the Simple Model for Climate Policy Assessment (Meinshausen et al. 2006). The global mitigation cases will be updated following more detailed economic modelling for the final report.

The no mitigation case used in this report has been updated to reflect high emissions growth and reductions in aerosols emissions in recent years. The ad hoc, strong and ambitious mitigation cases have not been updated.

5.3 Projected climate change for the no-mitigation and mitigation cases

Quantitative climate change projections for well-constrained elements of the climate system are provided for each emissions case. 'Best-estimate' outcomes are presented along with estimates of the magnitude and possible range of lower-probability outcomes. Severe weather events and changes in variability are considered at a general level.

5.3.1 Changes in temperature

Many of the changes to the climate system are related to changes in global average temperature, and they tend to increase in magnitude and/or intensity as temperature levels rise. As a result, temperature change over time and space is a key indicator of the extent of climate change. This section explores a range of aspects of temperature change under the four emissions cases.

Box 5.2 Temperature reference points

Various reports and studies on mitigation may use different points of comparison for temperature increases. Temperature rise may be framed in terms of the increase from pre-industrial times, or from a given year.

Unless otherwise specified, temperature changes discussed in the Review are expressed as the difference from the period 1980–99, usually expressed as '1990 levels' as per the IPCC Fourth Assessment Report.

Following the same convention, temperatures over the period 1850 to 1899 are often averaged to represent 'pre-industrial levels'. To compare temperature increases from 1990 levels to changes relative to pre-industrial levels, 0.5°C should be added.

Projected changes to the end of the 21st century are generally calculated from the average of 2090–99 levels, but are often expressed as '2100'.

Commited warming

'Committed warming' refers to the future change in global mean temperature from past emissions, even after concentrations are held constant.

The IPCC estimated the warming resulting from atmospheric concentrations of greenhouse gases being kept constant at 2000 levels would result in an increase of 0.6°C by 2100. The increase for each of the next two decades would be 0.1°C from past emissions alone (IPCC 2007: 79).

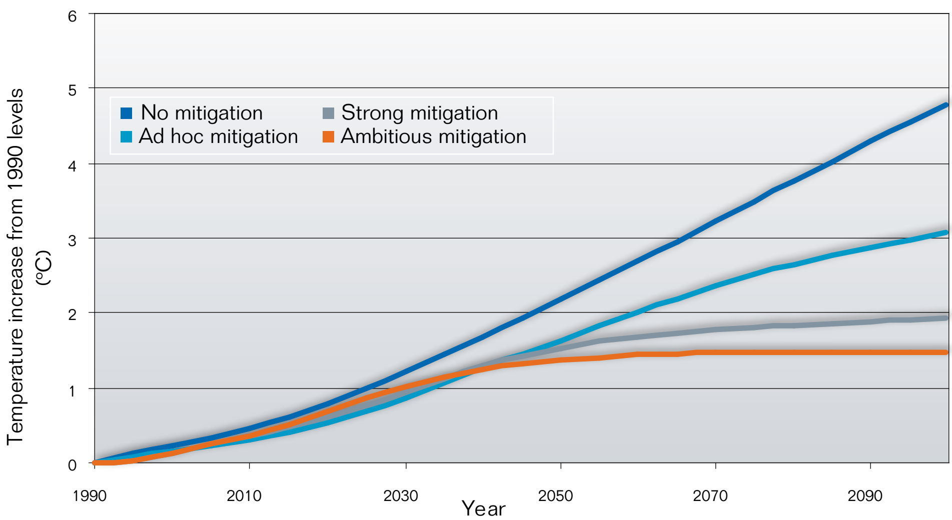
As a result of committed warming, the temperature outcomes for next few decades are minimally affected by the different emissions cases. The average warming for the period 2011 to 2030 for the middle to lower SRES scenarios is in the range 0.64–0.69°C above 1990 levels, with high agreement between models (IPCC 2007: 749).

Global mean temperatures post-2030

Projections of global mean surface air temperature for the 21st century show the increases continuing for all emissions cases. Figure 5.5 shows the projected temperature increases for the four emissions cases for the best-estimate climate sensitivity of 3°C. Temperatures are projected to be slightly higher between 2020 and 2030 under the ambitious global mitigation case than the ad hoc and strong cases as rapid declines in aerosol emissions are expected under strong mitigation which will decrease the cooling influence.

By the end of the century the global average temperature increase under the no-mitigation case is 4.5°C, and still increasing a high rate. The temperature increase under the ad hoc mitigation case is lower, at about 2.8°C and the rate is slowing. The strong and ambitious global mitigation cases reach 1.9°C and 1.5°C respectively, with the rate of increase having fallen to minimal levels in 2100 in both cases.

Figure 5.5 Global average temperature outcomes for four emissions cases with a 'best-estimate' climate sensitivity (3°C)



Note: Temperature increases from 1990 levels are from the MAGICC climate model (Wigley 2003).

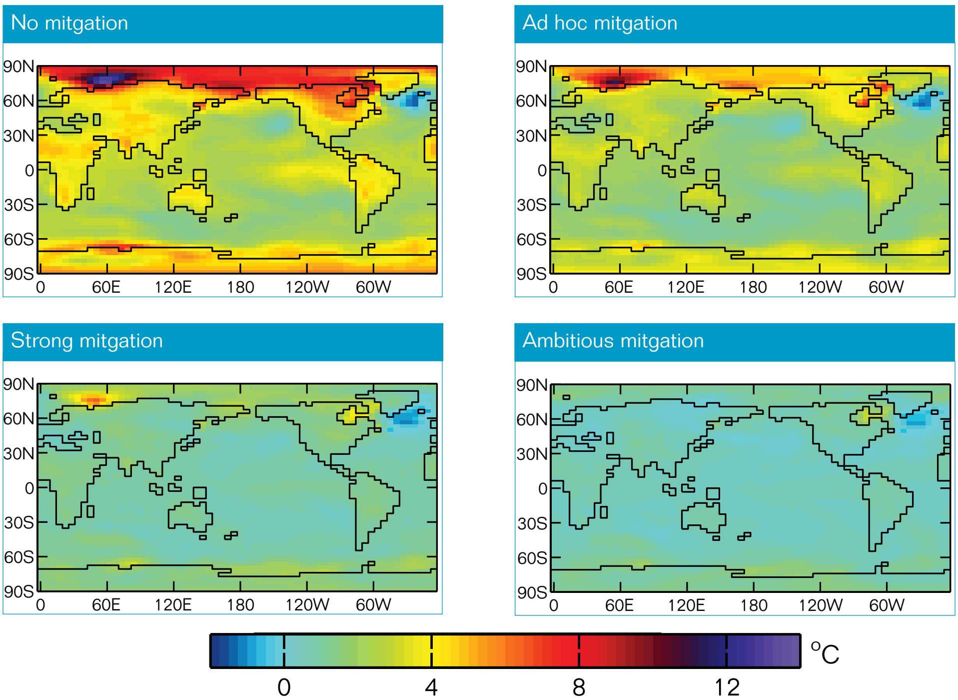
Spatial variation in temperature

Figure 5.6 shows the spatial variation in the simulated temperature changes at the end of the 21st century under the four emissions cases. The greatest warming occurs at the poles and over large land masses, with lesser warming over the oceans. A small region of cooling lies over the north Atlantic ocean.

The strong warming in the polar regions arises from feedbacks caused by changes in the reflection of solar radiation from the loss of ice and snow. Melting ice and snow expose the darker ocean or land surface beneath, which then absorb a greater fraction of incoming solar radiation. In turn, this leads to further warming. By the end of the century in the no-mitigation case, temperatures in parts of the Arctic are more than 10°C above 1990 levels. In the strong and ambitious global mitigation cases, the feedback effects of melting ice are restricted and the temperature response in the Arctic is more subdued.

The north Atlantic region is significantly influenced by oceanic circulation. The Gulf Stream transports warm surface waters northward, warming this region significantly relative to other regions at the same latitude. Climate change is projected to lead to a weakening of the Gulf Stream, resulting in cooler temperatures in the north Atlantic under all emissions cases.

Figure 5.6 Spatial variation in temperature change in 2100 for the four emissions cases



Note: Temperature outcomes are from the CSIRO Mk3L model (Phipps 2006), which demonstrates a lower global average temperature response than the MAGICC model used to calculate the global average temperatures in Figure 5.5. The differences in the response of the two models are discussed in Chapter 9.

Extremes in global mean temperature response

The discussion of climate sensitivity in Chapter 3 outlined the IPCC assessment of a best-estimate climate sensitivity of 3°C, with a likely outcome between 2°C and 4.5°C (IPCC 2007: 12). The lower end of the range of possible outcomes is much better constrained than the upper end—most studies investigating climate sensitivity find a lower 5 per cent limit of between 1°C and 2.2°C, while the upper 95 per cent limit for the same studies ranges from 5°C to greater than 10°C (IPCC 2007: 721).

For the no-mitigation case, the chance of avoiding the 2°C pre-industrial warming threshold, which the European Union has announced as a mitigation goal (1.5 degrees above 1990 levels), is virtually zero. The risk of temperatures above around 6°C ranges from 15 to 40 per cent, according to different distributions of sensitivity.

For the ad hoc and strong emissions cases the chance of avoiding the 2°C threshold is less than 4 per cent and 26 per cent respectively. Only the ambitious global mitigation case has the likelihood of avoiding the 2°C threshold greater than 50 per cent for even one of the selected climate responses.

If a higher temperature response were to occur, the high temperatures evident in the polar regions in the no-mitigation case would be even more extreme. In the mitigation cases, a higher temperature response would lead to positive feedbacks and amplified temperatures in the polar regions.

Temperature outcomes for other mitigation pathways

The strong and ambitious global mitigation cases discussed in this chapter represent a future where the world responds in a coordinated way to a specific target for stabilisation of greenhouse gases in the atmosphere. There are many possibilities for the choice of a global mitigation target, as well as for the pathway to get there (see Chapter 3).

Under the 'likely' range of climate sensitivity, concentrations would need to be stabilised at less than 450 ppm CO_2-e to have at least a 50 per cent chance of keeping long-term warming at below 2°C above pre-industrial levels.

Due to the slow response of the ocean to changes in the energy balance of the climate system, it may be hundreds or even thousands of years before the equilibrium temperature is reached. When considering the impacts of climate change in the future in a policy context, it is relevant as well to consider the transient, or short-term, temperature response. Different models can show a range of short-term temperature outcomes for the same emissions pathway.

The pathway to a given stabilisation target will also be a key factor in the short-term temperature response. As discussed in Chapter 3, to achieve some of the lower concentration targets, an overshoot in concentration may be required, leading to higher temperature responses for a period. This short-term temperature response could lead to greater impacts increasing the risk of reaching key temperature thresholds.

5.3.2 Precipitation

Climate model simulations show that, as temperatures increase, there will be increased precipitation in the tropics and at high latitudes, and decreased precipitation in the subtropics (IPCC 2007: 750). Figure 5.7 shows the percentage change in precipitation in 2100 for the four emissions cases from the average of 1980—99 levels, estimated using a technique based on the outputs of 23 global climate models (Watterson 2008; CSIRO & BoM 2007). The values overlaid by 'stippling' show areas where there is less than 67 per cent agreement on whether the change will be an increase or a decrease.

For the four emissions cases, the pattern of rainfall change in response to temperature generally stays the same, but the change intensifies as temperature increases.

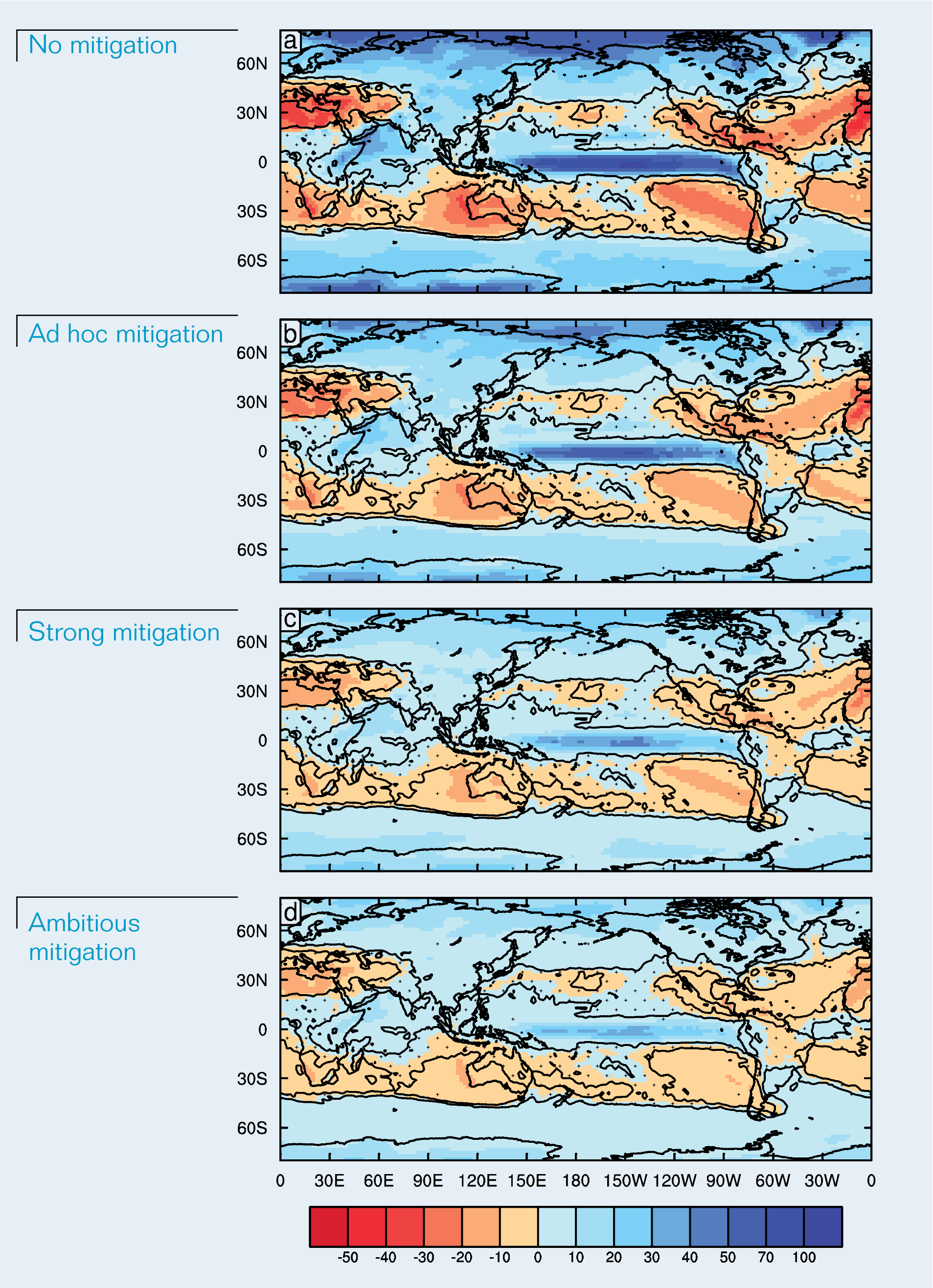
Rainfall is set to increase at high latitudes and over equatorial oceans, where the atmosphere can be rapidly resupplied with moisture after rainfall. In the subtropics, air tends to descend as result of atmospheric circulation patterns, and humidity is relatively low. This process is intensified as the climate warms. Changes in the circulation patterns also push the weather systems that bring rain further towards the poles—the outcome is a decrease in rainfall over many of the subtropical regions. Major regions with substantial decreases in rainfall include Australia, the Mediterranean, Mexico, and north-west and south-west Africa (Watterson 2008).

However, the interactions in the processes that control rainfall in a particular region are complicated, and rainfall changes can vary considerably at the local level. For example, while these projections suggest the likelihood of drying of southern Australia with increases in global average temperature, assessments undertaken at a local scale suggest some possibility of an increase in rainfall. This is discussed in more detail in Chapter 6.

The higher temperatures and lower rainfall in the mid latitudes are expected to lead to an increased risk of drought (IPCC 2007: 782). There is also an increase in the risk of heavy precipitation and flooding, as precipitation will be concentrated into more intense events (IPCC 2007: 782).

Rainfall is expected to increase in the Asian monsoon (although variability is expected to increase season to season), and the southern part of the West African monsoon, and is expected to decrease in Mexico and Central America. Uncertainty about the role of aerosols complicates monsoon projections (IPCC 2007: 750).

Figure 5.7 Percentage changes in precipitation in 2100 for the four emissions cases, based on the mean model outcome



Source: Watterson (2008).

5.3.3 Sea-level rise

Sea-level rise would be greater than was projected by the IPCC if, for any reason, average temperature increases were larger than expected.

Sea-level rise will come from two main sources—thermal expansion and the melting of land-based ice sheets and glaciers. The greater the temperature increase, the greater the increase from thermal expansion and the faster the loss of glacial mass (IPCC 2007: 830). Current estimates show that thermal expansion of the oceans will contribute 70 per cent to 75 per cent of the projected rise. Under the no-mitigation and ad hoc mitigation cases, sea level is expected to continue to rise over the 21st century at a rate that exceeds the observed average rate between 1961 and 2003 (IPCC 2007: 70).

The IPCC estimated sea-level rise in 2100 for a scenario similar to the no-mitigation case at 26–59 cm, and for the ad hoc mitigation case at 21–48 cm (2007: 70). However, melting of some ice sheets on Greenland and the west Antarctic has accelerated in recent decades (IPCC 2007: 44). Observed data suggests that sea-level rise has been at the high end of previous IPCC projections (Rahmstorf et al. 2007).

The level of understanding and uncertainty in the magnitude and timing of contributions to sea level rise from ice melt is low. If the current accelerated rates of ice melt were to increase in the future in proportion to increased globally averaged surface temperatures, the IPCC estimates that it would add between 10 and 20 cm to the upper bound of sea-level rise predicted for the 21st century. A key conclusion of the IPCC sea-level rise projections was that larger values than the upper estimate of 79 cm by 2100 could not be excluded (IPCC 2007:14).

The accelerated response in Greenland may be the result of melt-water from the surface lubricating the movement at the base of the ice sheet and increasing the dynamical flow of solid ice into the sea. The west Antarctic ice sheet is grounded below sea level, which allows warming ocean water to melt the base of the ice sheet making it more unstable (Oppenheimer & Alley 2005).

The sea-level rise projections in the Third and Fourth Assessment Reports of the IPCC in 2001 and 2007 respectively were communicated in a different way in terms of the uncertainty and confidence limits. A key change between the two reports was the revision of the lower estimate of sea-level rise upwards. However, the lower end of the range is still only slightly higher than the sea-level 'committed' rise that would occur if greenhouse gas emissions ceased, and leaves little room for contributions for additional ocean warming and land-ice melt, making such a low outcome unlikely (Rahmstorf 2007; Pew Center 2007).

Ongoing melt of the Greenland and west Antarctic ice sheets

If the Greenland and west Antarctic ice sheets were to melt completely, they would add an estimated 7 m and 6 m to global sea level respectively (IPCC 2007: 752; Oppenheimer & Alley 2005). If a sufficiently warm climate were sustained, the Greenland and west Antarctic ice sheets would be largely eliminated over a long period. The IPCC estimates that the complete melting would take longer than 1000 years (IPCC 2007: 794); Lenton et al. (2008) suggest that a lower limit of 300 years is conceivable if the rapid disappearance of continental ice at the end of the last ice age were to be better simulated in current models.

Current models suggest that once a certain temperature is exceeded, major reduction of the Greenland ice sheet would be irreversible. Even if temperatures were to fall later, the climate of an ice-free Greenland might be too warm for the accumulation of ice (IPCC 2007: 752, 776). Sufficient global temperature rise to initiate ongoing melt of the Greenland ice sheet lies in the range 1.2–3.9°C relative to 1990 (IPCC 2007: 752). Estimates of the warming necessary to melt the west Antarctic ice sheet range from 1°C to 10°C (Oppenheimer & Alley 2005). A simple reading of the scientific literature suggests a high probability that, under business as usual, the point of irreversible commitment to the melting of the Greenland ice sheet would be reached within this century.

Accelerated sea-level rise

While not endorsing outcomes that are not well supported in the published literature, the Review must draw attention to the fact that there is evidence to suggest that future sea-level rise could be much worse.

Sea-level has varied extensively throughout history. Climate records indicate that much faster rates have occurred historically. At the end of the last interglacial when the northern hemisphere ice sheets disintegrated, sea-level rise peaked at a rate of 4 m per century. This indicates that substantially higher rates of sea-level rise than those predicted by the IPCC have occurred historically (Church et al. 2008).

The sea-level rise outcomes of the IPCC (2007) include the effects of thermal expansion of the oceans, and some consideration of ice flow from Greenland and Antarctica. However, they do not show the full effects of ice-sheet flow due to dynamic processes, which are not adequately presented in current models (Oppenheimer & Alley 2005).

Estimating the likelihood of rapid disintegration of ice sheets remains very difficult, but recent evidence and comparison with historical rates suggests it is more likely than previously thought (Hansen 2005; Lenton et al. 2008). If the linear relationship between temperature and sea-level rise observed during the 20th century were to continue, a rise of up to 1.4 m by 2100 for strong warming scenarios could occur (Rahmstorf 2007).

5.3.4 Other climate outcomes

Current limitations in scientific understanding and levels of uncertainty mean that quantifying outcomes under various scenarios is difficult. Box 5.2 summarises the major conclusions relating to the no-mitigation and mitigation cases.

Some climate variables are likely to respond to temperature increase in a nearly linear manner, while change in other variables could occur much faster than the rate of temperature increase. An example of a non-linear relationship is sea-level rise due to the dynamic flow of ice sheets and glaciers, which occurs at an increasing rate as the mass of ice is reduced (IPCC 2007: 70).

5.3.5 Post-2100 outcomes

Beyond 2100, modelling of projected climate change becomes even more uncertain and many emissions pathways and scenarios do not extend into the 22nd century. As part of the Fourth Assessment Report, the IPCC undertook a number of simulations in order to understand the elements of post-2100 climate change better.

If concentrations are stabilised at around 900 ppm, and all other human-induced forcings are also stabilised, current modelling shows that sea-level rise due to thermal expansion in the 22nd century would be similar in magnitude to that of the 21st century, and would continue at a decelerating rate for many centuries. The final magnitude of sea-level rise when equilibrium is reached is estimated at 0.2–0.6 m per degree of temperature increase (IPCC 2007: 752).

If net emissions were reduced to zero in 2100, concentrations could gradually fall over time. Long model runs suggest that temperature and sea level would take more than 1000 years to stabilise, and are projected to remain well above pre-industrial levels even after 3000 years (IPCC 2007: 752).

5.4 Assessing the extremes

The no-mitigation case could generate a greater risk of potentially severe and irreversible impacts on the world's climate, environment and people by 2100 than has been suggested by the focus on 'most likely' or mean outcomes.

5.4.1 Extreme climate outcomes

Extreme climate responses are not always considered or communicated in the assessment of climate change impacts due to uncertainty and lack of understanding about their magnitude and timing.

This section identifies some of the extreme responses within the climate system that could have considerable impact at the subcontinental scale.

Box 5.2 Summary of trends in projected climate change

Temperature extremes

Heatwaves will become more intense, more frequent and last longer as the climate warms. Cold episodes and frost days will decrease (IPCC 2007: 750).

Future increases in temperature extremes generally follow increases in mean (IPCC 2007: 785).

Snow and ice

As the climate warms, snow cover and sea ice extent will decrease. Glaciers and ice caps will lose mass, as summer melting will dominate increased winter precipitation (IPCC 2007: 750).

Snow cover and permafrost area are strongly correlated to temperature, so decreases are expected as warming occurs. In some northern regions where precipitation is expected to increase, snow cover may also increase. This is also true for much of Antarctica.

Some models project that summer sea ice in the Arctic could disappear entirely by 2100 under high-emissions scenarios like the no-mitigation case (IPCC 2007: 750). Comparisons with observed loss in Arctic sea ice suggest that current models underestimate the rate of decline. Between 1953 and 2006, the observed decline in September sea-ice cover is -7.8 ± 0.6 per cent per decade, compared to the multimodel mean trend of -2.5 ± 0.2 per cent per decade (Stroeve et al. 2007).

The extent of sea-ice melting is related to the magnitude of temperature rise, which is amplified in the polar regions due to the warming feedback of melting ice. The small change in global average temperature between the strong and ambitious mitigation pathways could have a relatively large impact on sea-ice extent.

Carbon cycle

As temperatures increase, the capacity of the land and ocean to absorb carbon dioxide will decrease so that a larger fraction of emissions will remain in the atmosphere and cause greater warming (IPCC 2007: 750). The extent of the carbon–climate feedback is dependent on the level of emissions or stabilisation. The higher the temperature increase, the larger the impact on the carbon cycle (IPCC 2007: 750).

Tropical cyclones and storms

Tropical cyclones are likely to increase in intensity and near-storm precipitation. Most models suggest a decrease in the total number of storms. There will be a poleward shift of storm tracks, particularly in the southern hemisphere.

Increased wind speeds will cause more extreme wave heights in these regions (IPCC 2007: 783).

Ocean acidification

As carbon dioxide concentrations increase in the atmosphere, a greater amount is absorbed by the ocean where it reacts with water to create carbonic acid. This increases the acidity of the ocean, which will likely result in carbonate sediments in shallow water dissolving, and may affect marine calcifying organisms.

The level of ocean acidification will depend on the carbon dioxide concentration in the atmosphere. Under the no-mitigation case, carbon dioxide concentrations are more than 1000 ppm in 2100—more than three times pre-industrial concentrations.

Changes to the El Niño – Southern Oscillation

As discussed in Chapter 3, the El Niño – Southern Oscillation ('El Niño' system) is a large-scale pattern of climate variability that leads to climatic effects in both the Pacific region and some other parts of the world (IPCC 2007: 945). Its fluctuations involve a large transfer of heat between the ocean and atmosphere, which has a considerable influence on year-on-year changes in global mean temperature and rainfall patterns.

Palaeoclimatic data suggests that the nature of the El Niño system, and the way it affects the global climate, has changed over time. Some evidence suggests that warmer temperatures in the past were linked to higher El Niño variability, and that the El Niño system may have played an important role in the climatic response to historic changes in radiative forcing (IPCC 2007: 482).

In the 20th century, El Niño system events occurred every three to seven years, but were more intense in the second half of the century (IPCC 2007: 288). There is evidence that this pattern may be significantly different from that exhibited in the 19th century (Steffen et al. 2004).

The far-reaching consequences of the El Niño system, in terms of both its influence on global climate and its consequential impact on human systems, have stimulated intense research into its characteristics. In the last 10 years steady progress has been made in the modelling of El Niño system events, but climate models are still limited in their ability to capture the timescales, amplitude and structure of its variability.

Based on knowledge of the mechanisms behind the El Niño system, as well as historical evidence, it would be expected that changes in ocean temperature and density would change the current pattern of the El Niño system (Lenton et al. 2008). Model outcomes suggest that El Niño system events will continue, but some simulations have shown an increase in its variability, while others exhibit no change or even a decrease.

Based on a survey of available models, the IPCC states that 'there is no consistent indication at this time of discernable changes in projected El Niño – Southern Oscillation amplitude or frequency in the 21st century' (IPCC 2007: 751). However, Lenton et al. (2008) disagree, and based on the available evidence consider there to be 'a significant probability of a future increase in El Niño – Southern Oscillation amplitude', with the potential for the threshold warming to be reached this century. However, the existence and location of any 'threshold' that may result in such a change is highly uncertain.

Climate–carbon feedbacks

As discussed in Chapter 3, there is agreement across climate models that climate change in the future will reduce the efficiency of the oceans and the terrestrial biosphere in absorbing carbon dioxide from the atmosphere. There is large uncertainty regarding the sensitivity of the response. When the impacts of climate change are taken into account in the calculation of carbon dioxide concentrations over time, an additional climate warming of 0.2–1.5°C occurs by 2100 (Friedlingstein et al. 2006).

There are a number of climate–carbon feedback effects that are not well understood, but which could have considerable influences on the temperature response to an increase in carbon dioxide emissions. These include:

- **Release of methane from methane hydrates in the ocean**—Methane hydrates are stored in the seabed along the continental margins in stable form due to the low temperatures and high pressure environment deep in the ocean. It is possible that warming may cause the hydrates to become unstable, leading to the release of methane into the atmosphere (IPCC 2007: 642).
- **Release of methane from melting permafrost**—Methane trapped in frozen soils may be released as temperatures increase and melting occurs.
- **Abrupt changes in the uptake and storage of carbon by terrestrial systems**—The potential for a terrestrial system to change from a sink to a source of carbon dioxide is not well understood, but is beginning to be seriously considered (IPCC 2007: 642). Potential sources could be the increased rate of oxidation of soil carbon and dieback of the Amazon rainforest and high latitude forests in the northern hemisphere.
- **Reduced uptake of CO_2 by oceans.**

All these outcomes are related to the extent of warming and would result in a positive feedback to the climate system, amplifying warming. The thresholds of temperature or emissions that might trigger these outcomes are not well understood, but as the climate warms, the likelihood of the system crossing that threshold increases (IPCC 2007: 642).

5.4.2 High-consequence climate outcomes

Melting of the Himalayan glaciers

After the polar regions, the Himalayas are home to the largest glacial areas. Together, the Himalayan glaciers feed seven of the most important rivers in Asia—the Ganga, Indus, Brahmaputra, Salween, Mekong, Yangtze and Huang Ho.

While localised climate conditions cause different responses, a generalised retreat and reduction in size of glaciers has been observed in the Himalayan glaciers. The trend was strong in the first half of the 20th century, followed by a short period of advance between the 1950s and 1970s. Since the 1980s, however, these glaciers have begun retreating at rates beyond the range of pre-industrial variability. They are receding faster than any other glaciers around the world, and current estimates project that they may disappear altogether by 2035 (WWF Nepal Program 2005).

Unlike many glacial systems, the Himalayan glaciers rely on cool summer temperatures and summer monsoons to accumulate mass in the summer. Under increased temperatures, more precipitation falls as rain rather than snow and the rate of melting increases, which combine to create an increased rate of retreat and risk of downstream flooding.

Rivers fed from glaciers are projected to experience increased stream flows over the next few decades as a result of glacial melt, followed by a subsequent decline and greater instability of inflows as glaciers begin to disappear altogether, leaving only seasonal precipitation to feed rivers (WWF Nepal Program 2005).

Glacial retreat can also result in catastrophic discharges of water from meltwater lakes, known as glacial lake outburst floods, which can cause considerable destruction and flooding downstream.

Failure of the Indian monsoon

The Indian monsoon has been remarkably stable for the last hundred years. The monsoon is central to south Asia's economy and social structure (Challinor et al. 2006). Any change in the monsoon, in timing or intensity, is likely to have significant consequences for the region.

There is limited scientific understanding of the processes underpinning the development of the Indian monsoon (Challinor et al. 2006). The monsoon is the result of the complex interactions among the ocean, atmosphere, land surface, terrestrial biosphere and mountains.

Central to projections of how the Indian monsoon may change with a changing climate is an understanding of the response of El Niño – Southern Oscillation, which is highly uncertain. Some projections indicate a reduction in the frequency of rainfall events associated with the monsoon but an increase in their intensity. The monsoon also exhibits variations within seasons that lead to severe weather events with potentially large consequences. The ability of current climate models to predict these seasonal cycles is limited, but changes in the intensity, duration and frequency of these cycles may constitute the most profound effects of climate change on the monsoon system (Challinor et al. 2006).

Destruction of coral reefs

Coral reefs are highly sensitive to changes in the temperature and acidity of the ocean. As carbon dioxide concentrations increase, a greater amount is absorbed by the ocean where it reacts with the water to create carbonic acid. Higher ocean acidity reduces the availability of calcium carbonate for reef-building corals to create their hard skeletons. The concentration of calcium carbonate in the ocean is a key factor in the current distribution of reef ecosystems.

Long-term records show that sea temperature and acidity are higher than at any other time in the last 420 000 years. The rates of change of these factors in the last hundred years are also two to three times higher than those inferred from records from the same historical period, with the exception of some extremely rare short-lived spikes (Hoegh-Guldberg et al. 2007).

Reef-building corals have already been pushed to their thermal limits by increases in temperature in tropical and subtropical waters over the past 50 years. Many species also have a limited capacity to adapt quickly to environmental change, so the rate at which these changes occur is critical to the level of impact (Hoegh-Guldberg et al. 2007). In combination with other stressors such as excessive fishing and declining coastal water quality, increases in acidity and temperature can push reefs from a coral- to algae-dominated state. If the reef ecosystem is pushed far enough, a tipping point is likely to be exceeded (Hoegh-Guldberg et al. 2007).

Calcium carbonate saturation levels associated with existing coral reefs decrease dramatically under small increases in carbon dioxide concentrations.

Areas with saturation levels suitable for reef development will decrease as ocean acidity increases. The Great Barrier Reef is particularly vulnerable as it is located in an area of ocean with a relatively low concentration of calcium and carbonate ions.

At a carbon dioxide concentration of 450 ppm, the diversity of corals on reefs will decline under the combined affects of elevated temperature and ocean acidity. Atmospheric carbon dioxide concentrations as low as 500 ppm will result in coral communities that no longer produce calcium carbonate to be able to maintain coral reef structures.

Risk of species extinction

The patterns of temperature and precipitation in the current climate are key determinants in the core habitat of a species. These affect the abundance and distribution of species.

Recent research has shown that significant changes in ecosystems are occurring on all continents and in most oceans, and that anthropogenic climate change is having a significant impact on these systems globally and on some continents (Rosenzweig et al. 2008). In Australia these climate-related changes are currently overshadowed as a driver of biodiversity loss by a wide range of existing stressors, the most important of which are landscape modification, fragmentation by land clearance and the introduction of invasive species (Lindenmayer 2007).

However, projected climate change under high-emissions scenarios are expected to exacerbate the effects of existing stressors and lead to even further loss of biodiversity (Steffen et al. in press). Species respond individually to climate change, leading to the formation of novel ecosystems that currently do not exist. The projected rate of climate change will be beyond the capability of many organisms to adapt. A further loss of species is likely, particularly if they are already threatened or endangered (Jones & Preston 2006).

Changes in biodiversity resulting from projected climate change would be an irreversible consequence. Recently there has been increased recognition of the so-called ecosystem services that biodiversity provides.

Industries such as forestry, agriculture and tourism that rely directly on ecosystem services are most exposed to risks linked to declines in biodiversity as a result of climate change (UNEP FI 2008). Ultimately all human beings, even those in highly urbanised areas, are completely dependent on a wide range of ecosystem services for their well-being and even their existence (MEA 2005).

5.4.3 Assessing the likelihood of extreme climate responses

For many extreme climate responses and high-consequence outcomes there is considerable uncertainty around the threshold or tipping point at which an abrupt or ongoing change will occur. With each increment of temperature rise, the likelihood of such an event or outcome increases.

Decision making is aided by the best possible understanding of potential impacts and consequences, and in the case of climate change this is most appropriately provided by the experts in those fields. Where there is insufficient data or an inability to model these processes, it is becoming increasingly recognised that expert judgment—unverified by data—can play a valuable role in informing climate policy decisions (2008).

Table 5.1 and Figure 5.8 summarise the outcomes of a range of studies (Jones & Preston 2006; Warren 2006; Lenton et al. 2008). For the percentage of species at risk of extinction, mortality in coral reefs and irreversible melt of the Greenland ice sheet, the assessment involved the translation of a wide range of results from the literature into a ‘damage function’, which relates the magnitude of loss, or the likelihood of occurrence to global average temperature (Jones & Preston 2006). For the accelerated melt of the west Antarctic ice sheet, changes to the variability of the El Niño – Southern Oscillation and impacts on terrestrial sinks, an approach is taken that identifies a range of temperatures that are likely to include the tipping point or threshold at which these events would occur under the current understanding, based on a critical review of the literature and a survey of experts (Lenton et al. 2008; Warren 2006).

Assessment of these outcomes is complicated by the uncertainty in the temperature response. Table 5.1 shows the potential impacts for the range of best-estimate temperature outcomes for each of the four emissions cases studied. The climate sensitivity studies also suggest that much higher outcomes are possible by the end of the century, even if they have a much lower probability of occurring. Figure 5.8 shows the likelihood of given temperatures being exceeded by 2100 for the four emissions cases, alongside the likelihood of outcomes and potential threshold ranges for some high-consequence and extreme climate responses. It shows that for the higher sensitivity outcomes the damage is considerable and the likelihood almost certain for the climate responses considered.

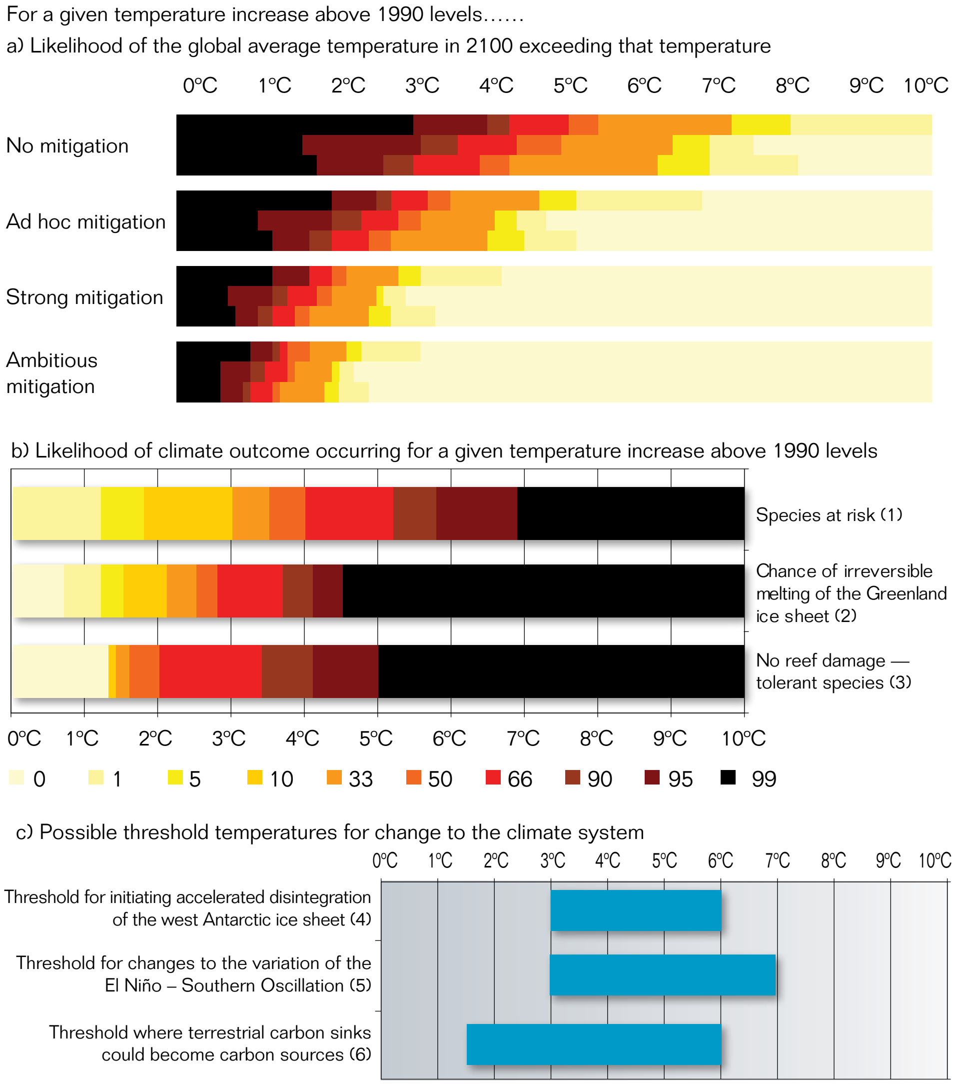
The climate outcomes discussed in this section are sometimes referred to in the literature as 'high-consequence, low-probability events' under human-induced climate change. This assessment shows that these events are of high consequence, but not always of low probability.

Table 5.1 Summary of a selection of extreme climate responses, high-consequence outcomes and ranges in which tipping points may occur under median temperature outcomes for the four emissions cases by 2100

Extreme climate response or impact	Ambitious mitigation	Strong mitigation	Ad hoc mitigation	No mitigation
Range of best-estimate outcomes	**1.3–1.8°C**	**1.8–2.3°C**	**2.9–3.7°C**	**4.5–5.7°C**
a) Percentage of species at risk of extinction	5–10%	10–17%	30–55%	77–94%
b) Likelihood of initiating irreversible melt of the Greenland ice sheet	6–19%	19–40%	67–89%	98–100%
c) Percentage of mortality in tolerant coral species	0–56%	56–73%	84–92%	97–100%
Estimated lower threshold exceeded?				
d) Threshold for initiating accelerated disintegration of the West Antarctic ice sheet	No	No	Possibly	Yes
e) Threshold for changes to the variation of El Niño system	No	No	Possibly	Yes
f) Threshold where terrestrial sinks could become carbon sources	Yes	Yes	Yes	Yes

Note: The probabilities given for the events above are based on a combination of data available in the literature and expert judgment. For a) – c) a 'best fit' damage function has been developed that links the outcomes to global temperature rise (Jones & Preston 2006). The definition of lower thresholds is based on values from the literature and expert elicitation (Lenton et al. 2008 Warren 2006). Further detail is provided in the notes to Figure 5.8.

Figure 5.8 Likelihoods and temperature thresholds for extreme climate outcomes



Notes:

(1) The percentage of all species 'committed to extinction' due to shifts in habitat caused by temperature and climate changes, from sample regions covering 20 per cent of the earth's land surface. The upper limit (>3.5°C) is based on less comprehensive datasets and is therefore more uncertain (Jones & Preston 2006).

(2) Cumulative probability based on four estimates on the threshold for collapse of the Greenland ice sheet from the literature (Jones & Preston 2006).

(3) Percentage of reef area in which there is widespread mortality in slow-growing, tolerant reef species on a frequency of less than 25 years, based on a range of studies from the literature (Jones & Preston 2006).

(4) A range in which the threshold for initiating accelerated disintegration of the West Antarctic ice sheet is expected to occur. The outcomes combine a literature review and expert judgment (Lenton et al. 2008).

(5) A range in which the threshold for changes to the variation of El Niño system is expected to occur. The outcomes combine a literature review and expert judgment (Lenton et al. (2008).

(6) A range in which the threshold where terrestrial sinks could be damaged to the extent that they become carbon sources is expected to occur. This includes a combination of outcomes from Lenton et al. (2008) considering the threshold for extensive damage to the Amazon rainforest boreal forest systems, and Warren (2006) relating to desertification leading to widespread loss of forests and grasslands.

References

Breusch, T. & Vahid, F. 2008, *Global Temperature Trends*, report prepared for the Garnaut Climate Change Review, Australian National University.

Brohan, P., Kennedy, J.J., Harris, I., Tett, S.F.B. & Jones, P.D. 2006, 'Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850', *Journal Geophysical Research*, 111, D12106, updated from <www.cru.uea.ac.uk/cru/info/warming/>, accessed 10 June 2008.

CASPI (Climate Adaptation – Science and Policy Initiative) 2007, *The Global Science of Climate Change*, report prepared for the Garnaut Climate Change Review, University of Melbourne.

Cazenave, A. & Nerem, R.S. 2004, 'Present-day sea level change: observations and causes', *Reviews of Geophysics* 42, RG3001, doi:10.1029/2003RG000139.

Challinor, A., Slingo, J., Turner, A. & Wheeler, T. 2006, *Indian Monsoon: Contribution to the Stern Review*, University of Reading, UK, available at <www.hm-treasury.gov.uk/media/3/4/Challinor_et_al.pdf>.

Church, J. & White, N.J. 2006, 'A 20th century acceleration in global sea-level rise', *Geophysical Research Letters*, 33, L01602, doi:10.1029/2005GL024826.

Church, J., White, N., Aarup, T., Stanley Wilson, W., Woodworth, P., Domingues, C., Hunter, J. & Lambeck, K. 2008, 'Understanding global sea levels: past, present and future', *Sustainability Science*, 3(1): 1862–4065.

CSIRO (Commonwealth Scientific and Industrial Research Organisation) & BoM (Bureau of Meteorology) 2007, *Climate Change in Australia: Technical report 2007*, CSIRO, Melbourne.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H.D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.-G., Schnur, R., Strassmann, K., Weaver, A.J., Yoshikawa, C. & Zeng, N. 2006, 'Climate-carbon cycle feedback analysis: results from the C4MIP model intercomparison', *Journal of Climate* 19(14): 3337–53.

Hansen, J. 2005. 'A slippery slope: how much global warming constitutes "dangerous anthropogenic interference"?' *Climatic Change* 68: 269–79.

Hoegh-Guldberg, O., Mumby, P., Hooten, A., Steneck, R., Greenfield, P., Gomez, E., Harvell, C., Sale, P., Edwards, A., Caldeira, K., Knowlton, N., Eakin, C., Iglesias-Prieto, R., Muthiga, N., Bradbury, R., Dubi, A. & Hatziolos, M. 2007, 'Coral reefs under rapid climate change and ocean acidification', *Science* 318(5857): 1737–42.

Holgate, S. & Woodworth, P.L. 2004, 'Evidence for enhanced coastal sea level rise during the 1990s', *Geophysical Research Letters* 31, L07305, doi:10.1029/2004GL019626.

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*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller (eds), Cambridge University Press, Cambridge and New York.

Jones, R. & Preston, B. 2006, *Climate Change Impacts, Risk and the Benefits of Mitigation: A report for the Energy Futures Forum*, CSIRO, Aspendale, Victoria.

Jones, R. 2008, *Warming Probabilities for the Garnaut Review Emissions Cases*, data prepared for the Garnaut Review, CSIRO, Aspendale, Victoria.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S. & Schellnhuber, H.J. 2008, 'Tipping elements in the Earth's climate system', *Proceedings of the National Academy of Sciences of the USA*, 105(6): 1786–93.

Leuliette, E.W., Nerem, R.S. & Mitchum, G.T. 2004, 'Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change', *Marine Geodesy* 27(1–2): 79–94.

Lindenmayer, D. 2007, *On Borrowed Time*, CSIRO Publishing/Penguin.

MEA (Millennium Ecosystem Assessment) 2005, *Synthesis Report*, Island Press.

Meinshausen, M., Hare, B., Wigley, T.M.L, van Vuuren, D., den Elzen, M. & Swart, R. 2006, 'Multi-gas emissions pathways to meet climate targets', *Climatic Change* 75: 151–94.

NSIDC (National Snow and Ice Data Centre) 2008, 'Arctic sea ice shatters all previous record lows', press release, 1 October, <http://nsidc.org/news/press/2007_seaiceminimum/20071001_pressrelease.html>.

Oppenheimer, M. & Alley, R. 2005, 'Ice sheets, global warming, and Article 2 of the UNFCCC', *Climatic Change* 68: 257–67.

Pew Centre on Global Climate Change 2007, 'Sea level rise: the state of the science', February 2, <http://www.pewclimate.org/global-warming-basics/slr.cfm>.

Phipps, S.J. 2006, *The CSIRO Mk3L Climate System Model, Technical Report 3*, Antarctic Climate & Ecosystems Cooperative Research Centre, Hobart.

Rahmstorf, S. 2007, 'A semi-empirical approach to projecting future sea-level rise', *Science* 315, <www.sciencemag.org/cgi/content/full/1135456/DC1>.

Rahmstorf, S., Cazenave, A., Church, J., Hansen, J., Keeling, R., Parker, D. & Somerville, R. 2007, 'Recent climate observations compared to projections' *Science* 316(5825): 709.

Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q., Casassa, G., Menzel, A., Root, T.L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C., Rawlins, S. & Imeson, A. 2008, 'Attributing physical and biological impacts to anthropogenic climate change', *Nature*, 453: 353–57.

Ruddiman, W.F. 2008, *Earth's Climate: Past and future*, 2nd edition, W.H. Freeman and Company, New York.

Steffen, W., Burbidge, A., Hughes, L., Kitching, R., Lindenmayer, D., Mummery, J., Musgrove, W., Stafford Smith, M. & Werner, P. in press, *Conserving Our Biotic Heritage in a Rapidly Changing World*, CSIRO Publishing.

Steffen. W., Sanderson, A., Tyson, P., Jäger, J., Matson, P., Moore, B. III, Oldfield, F., Richardson, K., Schellnhuber, H.-J., Turner, B.L. II & Wasson, R. 2004, *Global Change and the Earth System: A planet under pressure*, IGBP Global Change Series, Springer-Verlag, Berlin.

Stroeve, J., Holland, M., Serreze, M. & Scambos, T. 2007, 'Arctic sea ice decline: faster than forecast?' *Geophysical Research Abstracts* 9: 01362.

UNEP FI (United Nations Environment Programme Finance Initiative) 2008, *Biodiversity and Ecosystem Services: Bloom or Bust? A Document of the UNEP FI Biodiversity & Ecosystem Services Work Stream (BESW)*, Genève, Switzerland.

Warren, R. 2006, 'Impacts of global climate change at different annual mean global temperature increases', in *Avoiding Dangerous Climate Change*, H.J. Schellnhuber, C. Cramer, N. Nakicenovic, T. Wigley & G. Yohe (eds), Cambridge University Press, Cambridge, pp. 94–131

Watterson, I. 2008, *Global Climate Change Projections Results of Interest to the Garnaut Review*, paper prepared for the Garnaut Review, CSIRO, Aspendale, Victoria.

Wigley, T.M.L. 2003, *MAGICC/SCENGEN 4.1: Technical Manual*, National Center for Atmospheric Research, Colorado.

WWF Nepal Program, 2005, *An Overview of Glaciers, Glacier Retreat, and Subsequent Impacts in Nepal, India and China: WWF Nepal Program March, 2005*, S. Chamling Rai (ed), available at <assets.panda.org/downloads/himalayaglaciersreport2005.pdf>.