

# PROJECTING GLOBAL CLIMATE CHANGE

# 4

## Key points

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

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 mean it is important that current knowledge about such outcomes is incorporated into the decision-making process.

Continued high emissions growth with no mitigation action carries high risks. Strong global mitigation would reduce the risks considerably, 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.

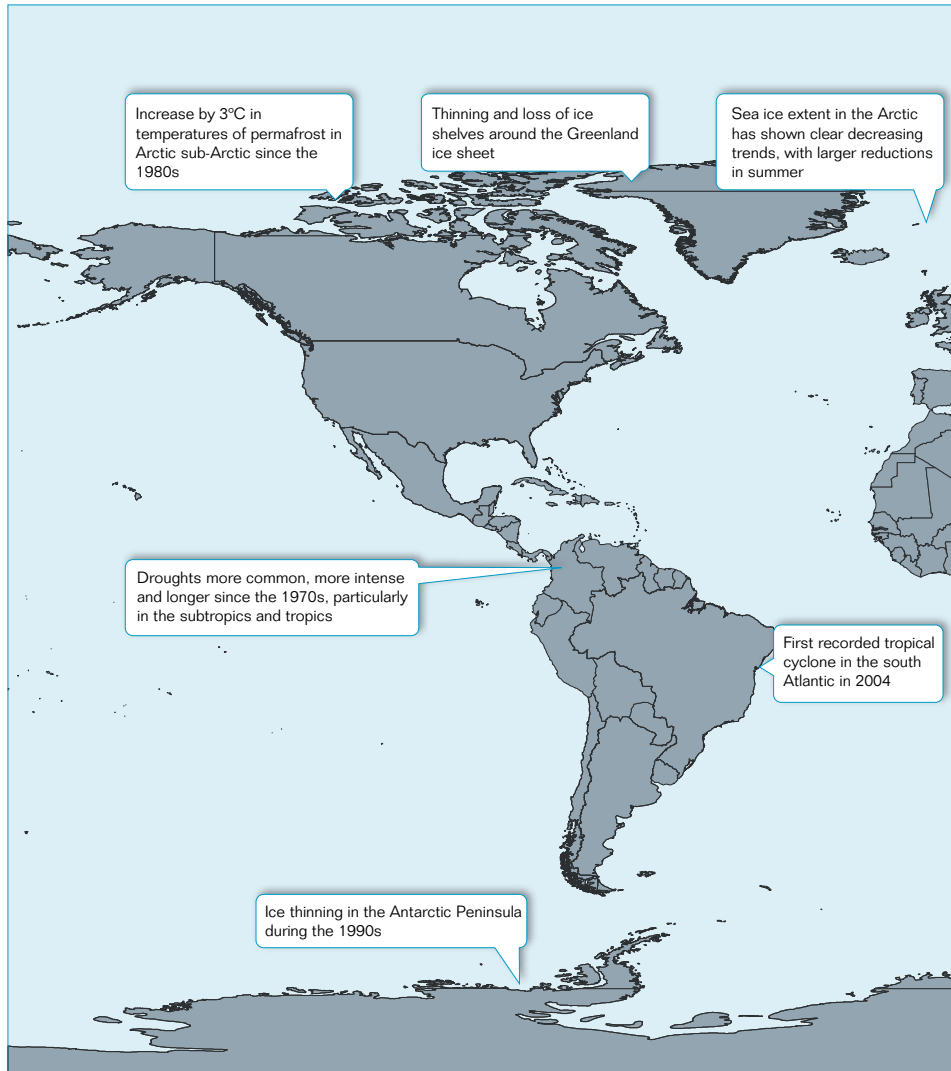
Some climate change has been observed already, and the mainstream science anticipates much more, even with effective global mitigation. The possible outcomes extend into the catastrophic. For any degree of mitigation, or its absence, there are most likely (median) outcomes, and considerable uncertainty around them.

In exploring likely and possible climate change outcomes, the Review has drawn on the IPCC Fourth Assessment Report and, where appropriate, research undertaken since the Fourth Assessment Report was compiled.

## 4.1 How has the climate changed?

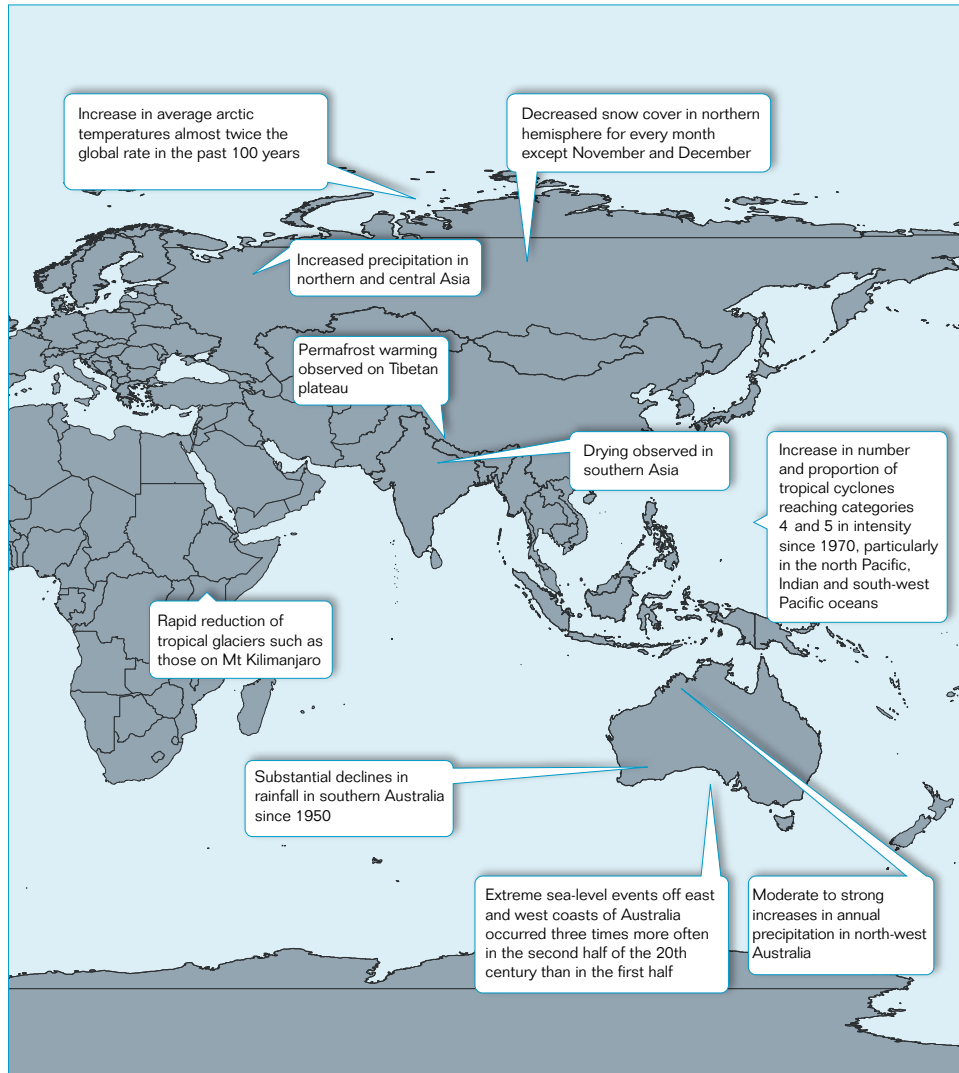
The IPCC states that 'warming of the climate system is unequivocal', and that this is evident in the measured increase in global average air and surface temperatures, and also in the widespread melting of snow and ice and the rising global sea level (IPCC 2007a: 5). The climate system varies considerably on a local and regional basis, so that consideration of global averages can mask large regional variations (see Figure 4.1).

Figure 4.1 Selected regional climate change observations



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

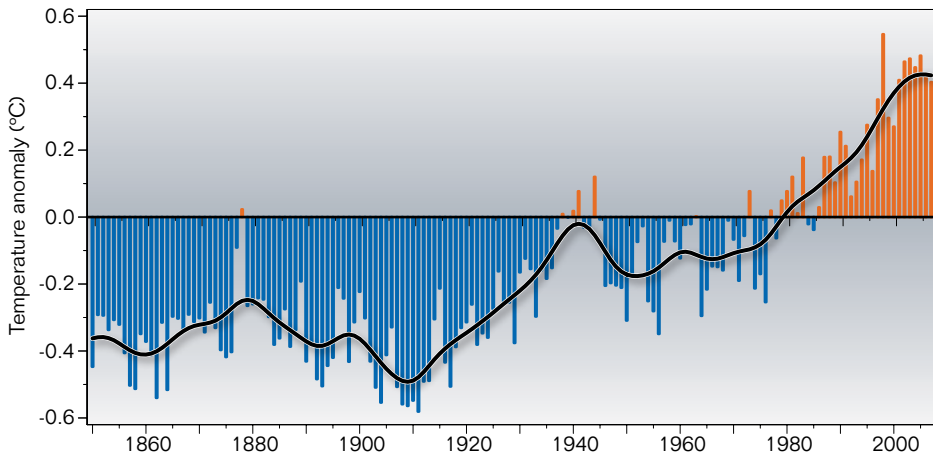
**Figure 4.1** Selected regional climate change observations (*continued*)



#### 4.1.1 Changes in temperatures

Global average temperatures have risen considerably since measurements began in the mid-1800s (Figure 4.2). Since early industrial times (1850–99) the total global surface temperature increase has been estimated at  $0.76^{\circ}\text{C} \pm 0.19^{\circ}\text{C}$ .

**Figure 4.2 Average global air temperature anomalies, 1850–2005**



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

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

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 (IPCC 2007a: 237).

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 2007a: 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 2007a: 10). Both the troposphere and the stratosphere have reacted strongly to events that have suddenly increased the volumes of aerosols in the atmosphere (IPCC 2007a: 270).

### Box 4.1 Is there a warming trend in global temperature data?

Observations show that global temperatures have increased over the last 150 years (Figure 4.2). The data also suggest that the warming has been 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 show 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.<sup>1</sup> 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 mid-2008 in Australia on the interpretation of 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 econometricians from the Australian National University. Trevor Breusch and Farshid Vahid have specific expertise in the statistical analysis of time series—a specialty 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:

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).

### 4.1.2 Changes in the oceans and sea level

The ocean has the 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 the El Niño – Southern Oscillation (IPCC 2007a: 46).

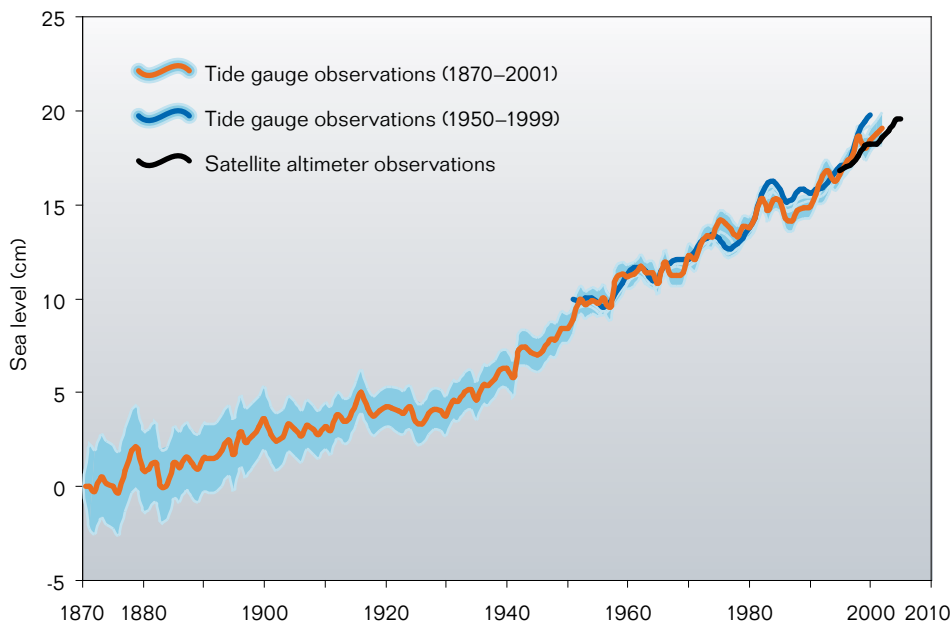
Sea level has varied extensively throughout history during the glacial and interglacial cycles as ice sheets formed and decayed. As oceans warm they expand, causing the volume of the ocean to increase and global mean sea level to rise. Sea level also rises when mass is added through the melting of grounded ice sheets and glaciers.

The total sea-level rise for the 20th century, including contributions from thermal expansion and land ice-melt, was 170 mm (Figure 4.3). The average rate of sea-level rise in the period 1961–2003 was almost  $1.8 \pm 0.5$  mm per year. For 1993–2003 it was  $3.1 \pm 0.7$  mm per year (IPCC 2007a: 387). 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 2007a: 49).

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 temperature and salinity have the potential to modify ocean currents and atmospheric circulation at the global scale. On an interannual 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 exceed the 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 2007a: 405). The oceans are now more acidic than at any time in the last 420 000 years (Hoegh-Guldberg et al. 2007).

**Figure 4.3 Global average sea-level rise, 1870–2005**



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

Sources: Church & White (2006); Holgate & Woodworth (2004); Leuliette et al. (2004).

### 4.1.3 Changes in water and ice

#### Precipitation

Increases in temperature affect the amount of water vapour 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 rather than to warm it. This 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 2007a: 505). These effects can cause an increase in the occurrence and intensity of droughts (IPCC 2007a: 262). Local and regional changes in precipitation are highly dependent on climate phenomena such as the El Niño – Southern Oscillation, changes in atmospheric circulation and other large-scale patterns of variability (IPCC 2007a: 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 2007a: 258). Decreases in annual precipitation have been observed in parts of Africa, southern Asia and southern Australia (IPCC 2007a: 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 2007a: 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 2007a: 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 2007a: 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 September 2007 was 23 per cent lower than the previous record set in 2005 (NSIDC 2007).

Data for the 2008 northern summer show that the rate of daily sea ice loss in August was the fastest that scientists have ever observed during a single August (NSIDC 2008). The rate of ice loss is partly due to a reduction in sea ice thickness over large areas, which means that a small increase in energy can lead to a fast reduction in ice cover (Haas et al. 2008). At the time of printing, sea ice extent in 2008 had not reached the record low set in 2007, but still shows as the second lowest August sea ice extent on record (NSIDC 2008).

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

#### 4.1.4 Changes to severe weather and climate events

Changes in the intensity and frequency of certain severe weather events have been observed throughout the world. 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 heatwaves have been occurring more frequently (IPCC 2007a: 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 2007a: 317). Full assessments of changes in droughts are limited by difficulties in the measurement of rainfall and poor data on soil moisture and streamflow (IPCC 2007a: 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. There is a global trend towards storms of longer duration and greater intensity, factors that are associated with tropical sea surface temperatures (IPCC 2007a: 308).

#### 4.1.5 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. Over the longer term, changes in climate are 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 2007a: 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 are available.

Modelling has been used to attribute a range of observed changes in the climate to human activity, 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 measurements of higher rates of warming over land than over sea, which are not associated with the El Niño – Southern Oscillation, and differential warming in the troposphere and stratosphere, which can be explained by increases in greenhouse gases in the troposphere and the depletion of the ozone layer in the stratosphere (CASPI 2007).

## 4.2 Understanding climate change projections

Future changes in the climate will depend on a range of natural changes—or forcings—as well as human activity, and on the way in which 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 particular elements. 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.

### Box 4.2 What is a climate outcome?

In this report, the term climate *outcome* (or response) is used to refer to a future climate that is one of a range of possible outcomes for a given aspect of the climate, such as rainfall or temperature. The occurrence of a particular climate outcome excludes the occurrence of a different one—it is not possible for more than one estimate of equilibrium climate sensitivity to be correct. There is uncertainty surrounding which outcome will occur, and often about when it will happen and the magnitude of its impact.

Modelling techniques can be used to assess the potential range of climate outcomes based on current understanding. This information can be presented in the form of a probability density function, where the median has the highest probability of occurring, but where there is also a chance of outcomes that are either much more benign or positive, or much more damaging.

A weather or climate *event*—such as a big storm or a drought—can occur repeatedly as a function of climate variability. The occurrence of an event of a given intensity does not exclude the occurrence of a related event at a different intensity. The likelihood of weather and climate events occurring is often referred to in language that reflects the magnitude of the outcome as well as the likelihood—as in the phrase ‘a one-in-a-hundred-year storm’.

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 natural factors as well.

#### 4.2.1 Confidence in the projection of climate change

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 surrounding the 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 depends 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 these have improved considerably in recent years (CSIRO & BoM 2007).

Confidence in models stems 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 the movement of moisture, and are not represented with the same confidence in models.

The likelihood of a particular outcome can be assessed through the use of a range of models. However, outcomes at the high or low end of a range of model results may also be plausible.

There is significant uncertainty around how the atmosphere will respond to a given change in carbon dioxide concentration.

The extent to which the climate warms in response to changes in greenhouse gas concentrations is centrally important to expectations of projected climate change. Many aspects of projected climate change relate closely to global mean temperature (IPCC 2007a: 630). For example, the extent of melting of glaciers and permafrost is related to the magnitude of temperature increase. However, changes in other dimensions of climate, such as regional variation in rainfall, are not so closely correlated with temperature change. Changes in the magnitude, spatial pattern and seasonality of rainfall cannot be directly inferred from temperature change.

### Confidence in other elements of climate change modelling

To assess the risk of climate change it is necessary to understand the different elements that are included in or excluded from the model outcomes. It is also necessary to understand the uncertainty associated with these elements. To gain a comprehensive understanding of potential climate change for a given temperature outcome, the 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 are reliable 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 arises from differences between models. The extent and direction of rainfall change is an example of the latter, although this is becoming more reliable 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 in frequency or intensity, or perhaps decline in influence.

#### 4.2.2 Responding to climate change now

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

An exception is if large changes in emissions of sulphate aerosols occur, where a localised 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 from the present (IPCC 2007a: 68), because there are lags in the climate system. By 2050, however, different trends in emissions have a clear influence on the climate outcomes. 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.

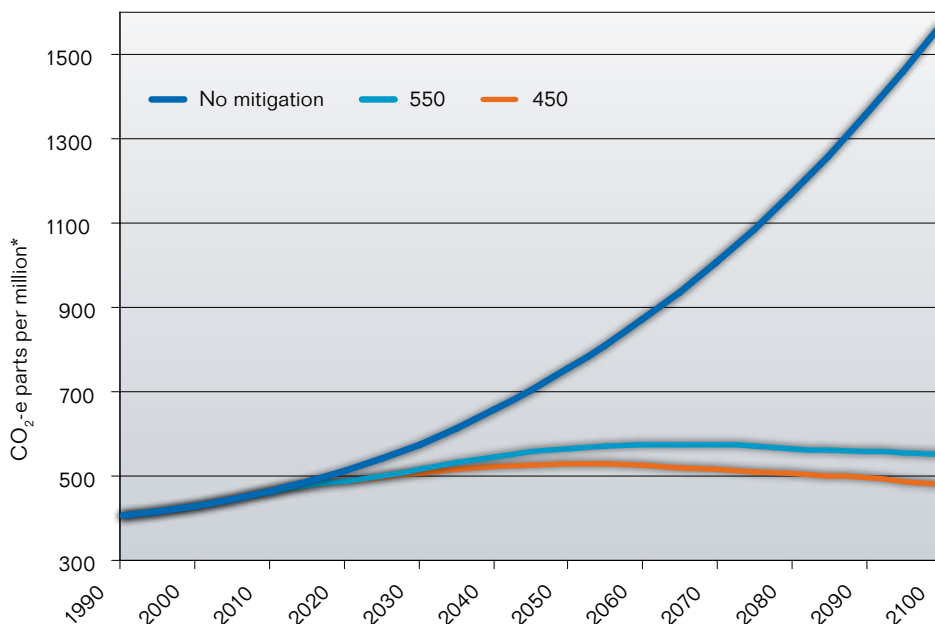
While the SRES scenarios (IPCC 2000) show a range of possible outcomes for a world with no mitigation, the Review looks at three possible futures based on different levels of mitigation.

### The three emissions cases

Figure 4.4 shows the concentration pathways for the three emissions cases considered by the Review:

- **No-mitigation case**—A global emissions case in which there is no action to mitigate climate change—the Garnaut–Treasury reference case—was developed as part of the Review. This emissions case recognises recent high trends in the emissions of carbon dioxide and other greenhouse gases. Emissions continue to increase throughout the 21st century, leading to an accelerating rate of increase in atmospheric concentrations. By the end of the century, the concentration of long-lived greenhouse gases is 1565 ppm CO<sub>2</sub>-e, and carbon dioxide concentrations are over 1000 ppm—more than 3.5 times higher than pre-industrial concentrations.
- **550 mitigation case**—Emissions peak and decline steadily, so that atmospheric concentrations stop rising in 2060 and stabilise at around 550 ppm CO<sub>2</sub>-e—one-third of the level reached under the no-mitigation case.
- **450 mitigation case**—Emissions are reduced immediately and decline more sharply than in the 550 case. Atmospheric concentrations overshoot to 530 ppm CO<sub>2</sub>-e in mid-century and decline towards stabilisation at 450 ppm CO<sub>2</sub>-e early in the 22nd century.

**Figure 4.4 Concentrations of greenhouse gases in the atmosphere for the three emissions cases, 1990–2100**



\* Kyoto gases and CFCs only.

### 4.2.3 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 they have been extensively used to provide a consistent basis for climate change projections. 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 2007a: 754).

The summary of projected climate change for the three emissions cases considered by the Review 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 2007a), based on the SRES scenarios.

## 4.3 Projected climate change for the three emissions 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 an indication of the magnitude and possible range of lower-probability outcomes. Severe weather events and changes in variability are considered at a general level.

### 4.3.1 Aspects of temperature change

Many of the changes to the climate system are related to changes in global average temperature. They tend to increase in magnitude and 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 three emissions cases.

#### Box 4.3 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 by the Review are expressed as the difference from the period 1980–99, usually expressed as '1990 levels' in 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'.

## Committed warming

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

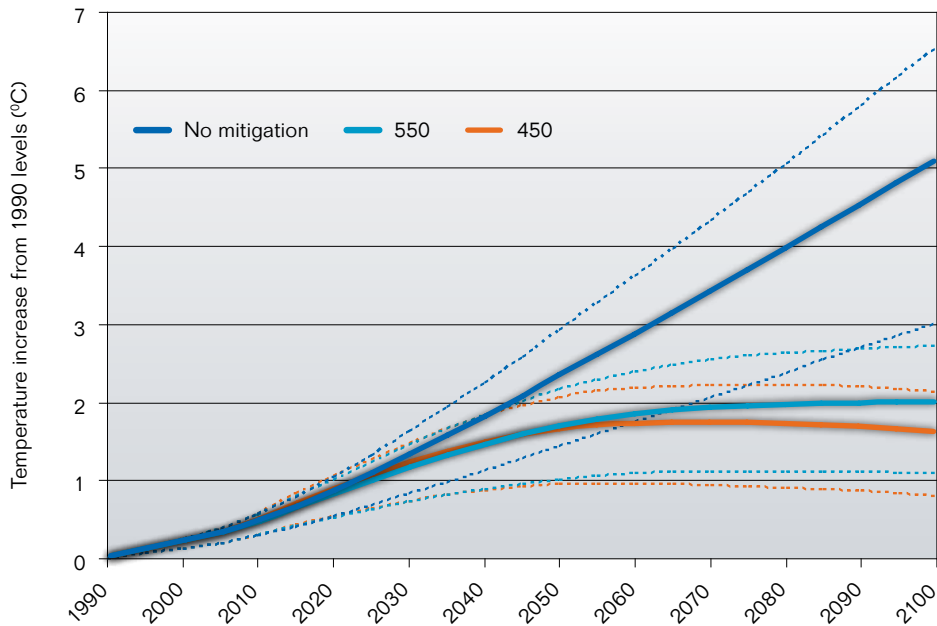
The IPCC estimated that the warming resulting from atmospheric concentrations of greenhouse gases being kept constant at 2000 levels would produce an increase of 0.6°C by 2100. The increase for each of the next two decades would be 0.1°C from past emissions alone (IPCC 2007a: 79).

As a result of committed warming, the temperature outcomes for the next few decades are minimally affected by mitigation in the intervening years. The average warming for the period 2011 to 2030 for the middle to lower SRES scenarios is 0.64–0.69°C above 1990 levels, with high agreement between models (IPCC 2007a: 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 4.5 shows the projected temperature increases for the three emissions cases for the best-estimate climate

**Figure 4.5 Global average temperature outcomes for three emissions cases, 1990–2100**



Note: Temperature increases from 1990 levels are from the MAGICC climate model (Wigley 2003). The solid lines show the temperature outcome for the best-estimate climate sensitivity of 3°C. The dashed lines show the outcomes for climate sensitivities of 1.5°C and 4.5°C for the lower and upper temperatures respectively. The IPCC considers that climate sensitivities under 1.5°C are considered unlikely (less than 33 per cent probability), and that 4.5°C is at the upper end of the range considered likely (greater than 66 per cent probability).

sensitivity of 3°C, with dashed lines indicating outcomes for climate sensitivities of 1.5°C and 4.5°C. Temperatures are projected to be slightly higher between 2020 and 2030 under the 450 case than under the 550 case, as rapid declines in aerosol emissions are associated with reductions in fossil fuel emissions, and the cooling influence decreases.

By the end of the century the global average temperature increase under the no-mitigation case is 5.1°C, and still increasing at a high rate. The 550 and 450 cases reach 2.0°C and 1.6°C respectively, with the temperatures changing only minimally by 2100 in both cases.

### Spatial variation in temperature

Figure 4.6 shows the spatial variation in the simulated temperature changes at the end of the 21st century under the three emissions cases. The greatest warming occurs at the poles and over large land masses, with less 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. This then absorbs a greater fraction of incoming solar radiation, leading to further warming. In the no-mitigation case, by the end of the century temperatures in parts of the Arctic are more than 10°C above 1990 levels. In the 550 and 450 mitigation cases, the feedback effects of melting ice are restricted and the temperature response in the Arctic is more subdued.

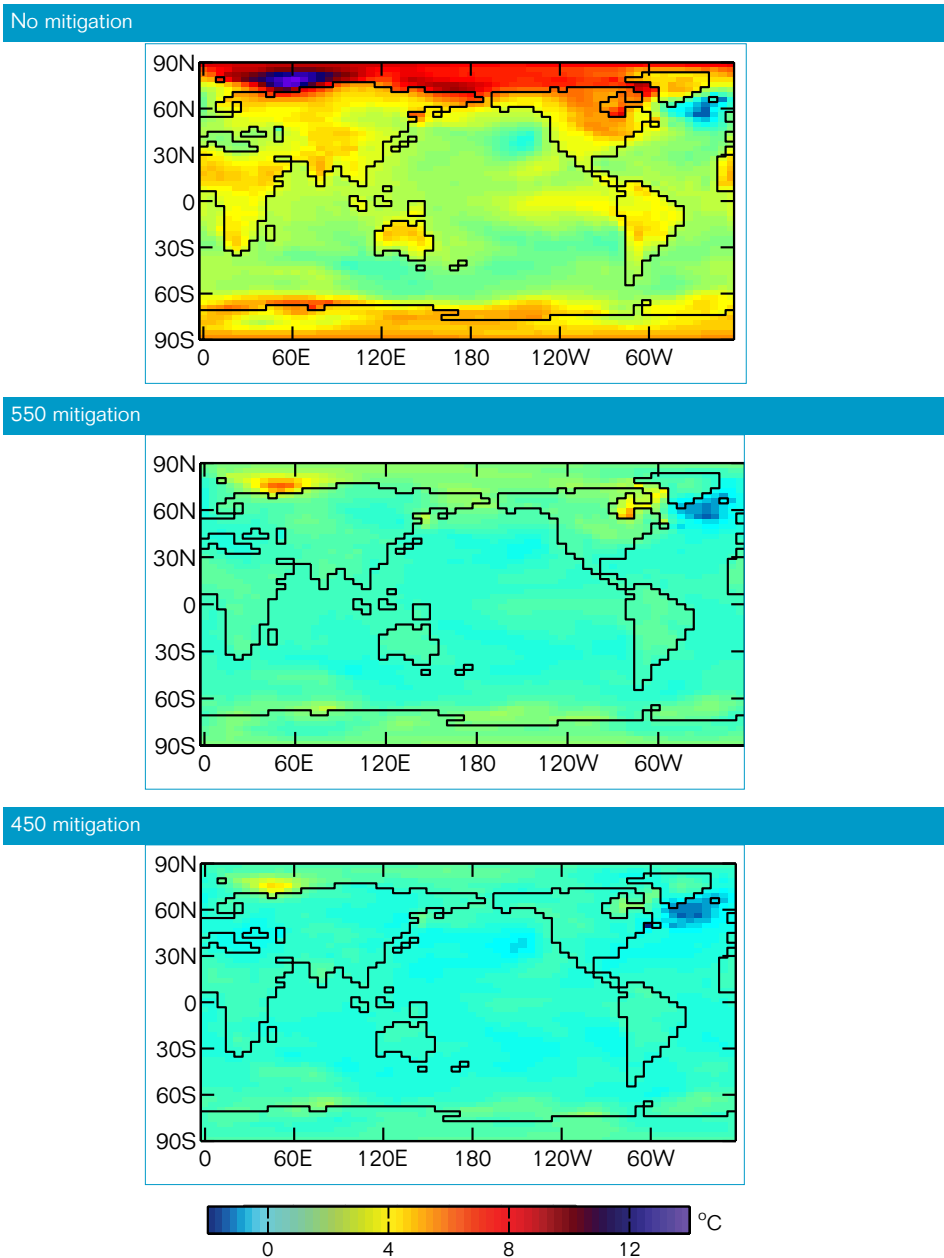
The north Atlantic region is significantly influenced by oceanic circulation. The Gulf Stream transports warm surface waters northward, warming this region relative to others at the same latitude. Climate change is projected to lead to a weakening of the Gulf Stream, resulting in cooler temperatures in the north Atlantic than would otherwise be the case.

### Extremes in global mean temperature response

The discussion of climate sensitivity in Chapter 2 outlined the IPCC assessment of a best-estimate climate sensitivity of 3°C, with a likely (>66 per cent probability) outcome between 2°C and 4.5°C (IPCC 2007a: 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 probability limit of between 1°C and 2.2°C, while the upper 95 per cent probability limit for the same studies ranges from 5°C to greater than 10°C (IPCC 2007a: 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°C above 1990 levels), is virtually zero. A temperature rise of 6.5°C is still within the range considered likely by the end of the century. The chance of avoiding the 2°C threshold by 2100 is around 25 per cent and 50 per cent for the 550 and 450 cases respectively (Jones 2008).

**Figure 4.6 Spatial variation in temperature change in 2100 for the three 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 4.5.



If a higher temperature response were to occur, the large temperature increases 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 550 and 450 global mitigation cases 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.

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. Policy makers considering the impacts of climate change in the future should also 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 affect the short-term temperature response. To achieve some of the lower concentration targets, an overshoot in concentration is required, leading to higher temperature responses for a period.

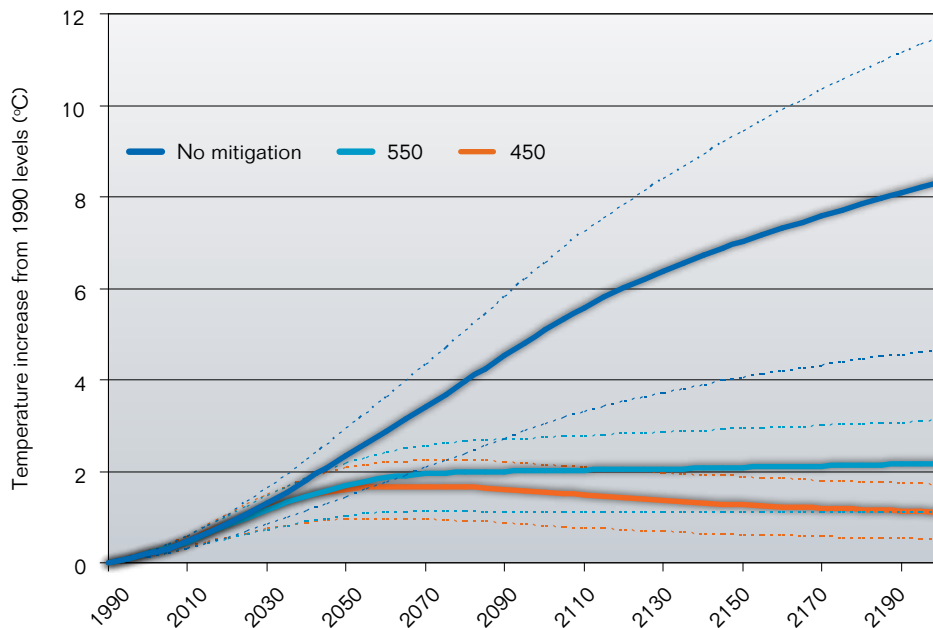
The short-term temperature response can also be influenced by the mix of greenhouse gases emitted. Under an emissions trading scheme, higher reductions in some gases could be traded off against lower reductions in other gases based on what was most economically or technically viable at the time. Methane has a much greater warming effect than carbon dioxide, but this effect will be relatively short-lived due to its shorter residence time in the atmosphere. Reduction of methane emissions could therefore have a proportionally larger effect than reduction of carbon dioxide emissions on global temperature. A focus on methane reduction could potentially offset the warming caused by reductions in aerosol emissions, substitute for reducing other greenhouse gas emissions or be used to avoid key tipping points if a rapid reduction in the rate of temperature increase was required. However, if priority is given to methane reductions in the short term and carbon dioxide concentrations continue to rise, any benefits would be temporary because of the longer residence time of carbon dioxide in the atmosphere. This short-term temperature response could lead to greater impacts and an increased risk of reaching key temperature thresholds.

### Post-2100 temperatures

Climate change comes with long lags. Greenhouse gases emitted today will have warming effects in the atmosphere for decades and centuries, and many of the effects of warming on earth systems, will play themselves out over even longer time frames. The melting of the Greenland ice sheet is an example.

Beyond 2100, modelling of projected climate change becomes even more uncertain; many emissions pathways and scenarios do not extend into the 22nd century. The economic modelling that underpins the three emissions cases

**Figure 4.7 Temperature increases above 1990 levels for the three emissions cases**



Note: Best-estimate figures, shown in solid lines, are calculated with a climate sensitivity of 3°C. The dashed lines show the outcomes for climate sensitivities of 1.5°C and 4.5°C for the lower and upper temperatures respectively. Temperature increases from 1990 levels are derived from the MAGICC climate model (Wigley 2003). Temperature outcomes beyond 2100 are calculated under the simplified assumption that emissions levels reached in each scenario in the year 2100 continue unchanged. They do not reflect an extension of the economic analysis underlying these scenarios out to 2100, and are illustrative only. It is unlikely that emissions in the no-mitigation case will stabilise abruptly in 2101 with no policies in place, and hence the temperatures shown underestimate the likely warming outcomes if continued growth in emissions is assumed.

modelled by the Review only goes to 2100. However, the climate will continue to change beyond 2100, particularly in the no-mitigation case where emissions can be expected to continue at high levels. Figure 4.7 shows the temperature outcomes for an illustrative modelling exercise looking at the temperature in the 22nd century for the three emissions cases, where emissions are held constant at 2100 levels. By 2200, temperatures in the no-mitigation case rise by 8.3°C under the best-estimate climate sensitivity, with a rise of 11.5 °C still within the likely range. Under the other two mitigation scenarios, temperatures are maintained at 2.2°C above 1990 levels for the 550 case, and drop to 1.1°C above 1990 levels in the 450 case due to the low levels of emissions in 2100.

### 4.3.2 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 subtropical and temperate regions (IPCC 2007a: 750).

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 a 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, causing a decrease in rainfall over many of the subtropical and temperate regions. Major regions with substantial decreases in rainfall include Australia, the Mediterranean, Mexico, and north-west and south-west Africa (Watterson 2008). 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.

The interactions among the processes that control rainfall in a particular region are complicated, and rainfall changes can vary considerably at the local level. For example, while most models suggest the likelihood of drying of southern Australia with increases in global average temperature, others suggest some possibility of an increase in rainfall.

Climate change is also likely to affect the seasonal and daily patterns of rainfall intensity, which may not be reflected in annual average data. There is expected to be an increased risk of drought in the mid-latitudes. There is also an increase in the risk of flooding, as precipitation will be concentrated into more intense events (IPCC 2007a: 782).

### 4.3.3 Sea-level rise

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 sea-level rise from thermal expansion and the faster the loss of glacial mass (IPCC 2007a: 830). Current IPCC estimates predict that thermal expansion of the oceans will contribute 70 per cent to 75 per cent of the projected rise to 2100. The level of understanding about the magnitude and timing of contributions to sea-level rise from ice melt is low. Melting of some ice sheets on Greenland and the west Antarctic has accelerated in recent decades (IPCC 2007a: 44), and observed data suggest that sea-level rise has been at the high end of previous IPCC projections (Rahmstorf et al. 2007). The accelerated response in Greenland may be the result of meltwater from the surface lubricating the movement at the base of the ice sheet and increasing the dynamic 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 IPCC estimated sea-level rise in 2100 for a scenario similar to the no-mitigation case (SRES scenario A1FI) at 26–59 cm. This figure does not include the potential for rapid dynamic changes in ice flow, which could add 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 above the upper estimate of 79 cm by 2100 could not be excluded (IPCC 2007a: 14).

A significant change between the IPCC's Third and Fourth Assessment 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 a sufficiently warm climate were sustained, the Greenland and west Antarctic ice sheets would be largely eliminated over a long period. 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 2007a: 752; Oppenheimer & Alley 2005).

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 2007a: 752, 776). Sufficient global temperature rise to initiate ongoing melt of the Greenland ice sheet lies in the range of 1.2–3.9°C relative to 1990 (IPCC 2007a: 752). 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 will be reached during this century.

### **Accelerated sea-level rise**

Some of the recent scientific work suggests that future sea-level rise could be much worse than the sea-level rise outcomes projected in the IPCC's Fourth Assessment Report.

Climate records show that 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).

Estimating the likelihood of rapid disintegration of ice sheets remains very difficult and poorly represented in current models (Oppenheimer & Alley 2005). Recent evidence and comparison with historical rates suggest it is more likely than previously thought (Hansen 2005; Lenton et al. 2008). The IPCC estimates that the complete melting of the Greenland ice sheet would take longer than 1000 years (IPCC 2007a: 794). However, 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 repeated.

It has been suggested that if the relationship between temperature and sea-level rise observed during the 20th century were to continue, under strong warming scenarios a rise of up to 1.4 m by 2100 could occur (Rahmstorf 2007).

#### 4.3.4 Other climate outcomes

Current limitations in scientific understanding and current levels of uncertainty mean that quantifying outcomes under various scenarios is difficult. Box 4.4 summarises trends in projected climate change under the three emissions cases.

Some climate variables are likely to respond to temperature increase in a nearly linear manner. 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 2007a: 70).

#### **Box 4.4 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 2007a: 750).

Future increases in temperature extremes generally follow increases in the mean (IPCC 2007a: 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 2007a: 750).

Snow cover and permafrost area is 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 2007a: 750). Comparisons with observed loss in Arctic sea ice suggest that current models may underestimate the rate of decline.

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 550 and 450 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 2007a: 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 2007a: 750).

#### **Box 4.4 Summary of trends in projected climate change (continued)**

##### **Tropical cyclones and storms**

Tropical cyclones are likely to increase in intensity and to generate greater precipitation in their vicinity. 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 2007a: 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 increase the rate at which carbonate sediments in shallow water dissolve. This 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-and-a-half times pre-industrial concentrations.

## **4.4 Assessing the climate risk**

Understanding the potential risk from climate change requires consideration of both the likelihood and the consequence of an event or outcome occurring. This section identifies climate change outcomes with high consequences due to the extent or speed of the change itself, as well as those with high consequences for human populations.

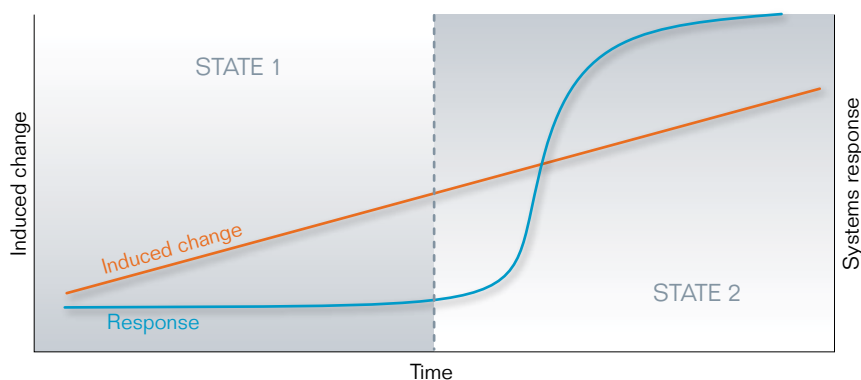
### **4.4.1 Thresholds and tipping points**

Many of the processes within the climate and other earth systems (such as the carbon cycle) are well buffered and appear to be unresponsive to changes until a threshold is crossed. Once the threshold has been crossed, the response can be sudden and severe and lead to a change of state or equilibrium in the system. This is often referred to as rapid or abrupt climate change (see Figure 4.8). Under abrupt climate change, a small change can have large, long-term consequences for a system (Lenton et al. 2008).

The threshold at which a system is pushed into irreversible or abrupt climate change occurs is often referred to as the 'tipping point'.

In other cases, the crossing of a threshold may lead to a gradual response that is difficult or even impossible to reverse. An example is the melting of the Greenland ice sheet, which may occur over a period of hundreds of years, but once started would be difficult to reverse.

**Figure 4.8** Abrupt or rapid climate change showing the lack of response until a threshold is reached



Source: Based on Steffen et al. (2004).

For most elements of the climate system there is considerable uncertainty as to when the tipping point might occur, but with each increment of temperature rise, the likelihood of such an event or outcome increases.

#### 4.4.2 Extreme climate outcomes

Due to the high level of uncertainty and the range of possible climate responses, there is a tendency in the policy community to focus on the median, or best-estimate, outcomes of climate change.

For all climate outcomes, there are levels of change that are at the bounds of the probability distribution—sometimes referred to as the ‘extremes’. While they are by definition less likely to occur based on current knowledge, an understanding of the potential for more damaging climate outcomes is vital to assessing risk.

The potential for high levels of climate sensitivity and abrupt sea level rise are examples of extreme climate outcomes that have already been discussed. This section identifies some other extreme climate outcomes that could have considerable impact at the subcontinental scale.

#### Changes to the El Niño – Southern Oscillation

The El Niño – Southern Oscillation 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 2007a: 945). Its fluctuations involve large changes in the 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 suggest that the nature of the El Niño – Southern Oscillation, and the way it affects the global climate, has changed over time. In the 20th century, El Niño events occurred every three to seven years, but were more intense in the second half of the century (IPCC 2007a: 288).

Based on knowledge of the mechanisms behind the El Niño – Southern Oscillation, 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 – Southern Oscillation (Lenton et al. 2008). Model outcomes suggest that such 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 2007a: 751). 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

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 influence 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. Warming may cause the hydrates to become unstable, leading to the release of methane into the atmosphere.
- **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**—Terrestrial systems could change from a sink to a source of carbon. 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 carbon dioxide by oceans**—The uptake of carbon dioxide by oceans may be reduced due to decreased solubility of carbon dioxide at higher temperatures and changes in ocean circulation.



As the climate warms, the likelihood of the system crossing the thresholds of temperature or emissions that might trigger such outcomes increases (IPCC 2007a: 642).

#### 4.4.3 High-consequence climate outcomes

Some climate outcomes may be highly damaging due to the vulnerability or adaptive capacity of the human or natural systems affected, rather than the severity of the outcome itself.

Severe weather events, or best-estimate climate change outcomes, could be considered of high consequence, or catastrophic, due to a range of factors, including:

- the magnitude, timing, persistence or irreversibility of the changes to the climate system or impacts on natural and human systems
- the importance of the systems at risk
- the potential for adaptation
- the distributional aspects of impacts and vulnerabilities (IPCC 2007b: 781).

#### 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.

These glaciers are receding faster than any other glaciers around the world, and some estimates project that they may disappear altogether by 2035 (WWF Nepal Program 2005).

Rivers fed from glaciers are projected to experience increased streamflows 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 timing or intensity of the monsoon 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 the uncertain response of the El Niño – Southern Oscillation. 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 (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 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. 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 reached (Hoegh-Guldberg et al. 2007).

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 sufficient 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 important 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). Projected climate change under high-emissions scenarios is expected to exacerbate the effects of existing stressors and lead to even further loss of biodiversity (Steffen et al. in press). The projected rate of climate change will be beyond the capability of many organisms to adapt. A further loss of species is likely, particularly among those that are already threatened or endangered (Sheehan et al. 2008). Changes in biodiversity would be an irreversible consequence of projected climate change.

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 (Millennium Ecosystem Assessment 2005).

#### 4.4.4 Evaluating the likelihood of extreme climate outcomes

Table 4.1 summarises the outcomes of a range of studies (Sheehan et al. 2008; Warren 2006; Lenton et al. 2008), considering the potential for a selection of high-consequence and extreme climate outcomes for each of the three emissions cases studied (shown for a range of temperature outcomes). The consideration of higher climate sensitivities in section 4.3.1 suggests that much higher temperature outcomes are possible by the end of the century, even if they have a lower probability of occurring. Under the higher climate sensitivities the likelihood of these outcomes occurring before 2100 becomes much higher.

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

**Table 4.1 Summary of extreme climate responses, high-consequence outcomes and ranges for tipping points for the three emissions cases by 2100**

| Extreme climate response or impact  | 450              | 550            | No mitigation  |
|---|------------------|----------------|----------------|
| Temperature outcomes  | 1.5 (0.8–2.1) °C | 2 (1.1–2.7) °C | 5.1 (3–6.6) °C |
| (a) Species at risk of extinction   | 7 (3–13)%        | 12 (4–25)%     | 88 (33–98)%    |
| (b) Likelihood of initiating large-scale melt of the Greenland ice sheet                | 10 (1–31)%       | 26 (3–59)%     | 100 (71–100)%  |
| (c) Area of reefs above critical limits for coral bleaching                             | 34 (0–68)%       | 65 (0–81)%     | 99 (85–100)%   |
| <b>Estimated lower threshold exceeded by 2100</b>                                       |                  |                |                |
| (d) Threshold for initiating accelerated disintegration of the west Antarctic ice sheet | No               | No             | Yes            |
| (e) Threshold for changes to the variability of the El Niño – Southern Oscillation      | No               | No             | Yes            |
| (f) Threshold where terrestrial sinks could become carbon sources                       | Possibly         | Possibly       | Yes            |

**Notes:**

The temperatures shown are increases from 1990 levels. The central number is based on a best-estimate climate sensitivity of 3°C, while the numbers in brackets relate to the temperature in 2100 for climate sensitivities of 1.5°C and 4.5°C for the lower and upper temperatures respectively. The approach is different to that used in Table 5.1 of the Review's draft report, which showed the range of median outcomes from three separate climate sensitivity studies.

(a) 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 (Sheehan et al. 2008).

(b) Cumulative probability based on four estimates from the literature. The percentage represents the likelihood of triggering the commencement of partial or complete deglaciation. This is considered virtually certain under the best-estimate temperature outcomes in the no-mitigation case (Sheehan et al. 2008).

(c) 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 (Sheehan et al. 2008).

(d) 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).

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

(f) 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), relating to 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.

**Note**

- The three datasets used in this analysis were (1) Hadley Centre HadCRUT3 (Brohan et al. 2006), <[www.cru.uea.ac.uk/cru/data/temperature/hadcrut3gl.txt](http://www.cru.uea.ac.uk/cru/data/temperature/hadcrut3gl.txt)>; (2) the Goddard Institute for Space Studies, NASA, <<http://data.giss.nasa.gov/gistemp/tabledata/GLB.Ts.txt>>; and (3) the National Climatic Data Center, US Department of Commerce, <[ftp://ftp.ncdc.noaa.gov/pub/data/anomalies/annual.land\\_and\\_ocean.90S.90N.df\\_1901-2000mean.dat](ftp://ftp.ncdc.noaa.gov/pub/data/anomalies/annual.land_and_ocean.90S.90N.df_1901-2000mean.dat)>.

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