

The Science of Climate Change

Questions and Answers



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Foreword

The science of climate is at the intersection of a number of science disciplines and sub-disciplines. At its heart are physics, chemistry, biology and mathematics – each with their sub-disciplines of atmospheric physics and chemistry, oceanography, hydrology, geology etc – and each of which can be considered as mature within the framework required to discuss climate. It is at this intersection of the disciplines where uncertainty can and will arise, both because of the yet poorly understood feedbacks between the different components of the climate system and because of the difficulty of bringing these components together into a single descriptive and predictive model. This would include, for example, the biological consequences of how increasing carbon dioxide (CO₂) feeds back into climate and into the climate model, or how the consequences of atmospheric warming on water vapour, cloud cover, ocean warming and circulation feedback can be described and quantified in a coherent and integrated theory. It is these feedbacks and interactions that make it difficult to realistically quantify the uncertainty in the outputs of climate models at levels that the experimental scientist is usually accustomed to. In a process as intrinsically complex as climate it should not be surprising that the path to understanding is long and arduous.

In many other areas of experimental science the paths to full understanding are equally complex. What makes climate change different is that the consequences are not only potentially global and serious but also that they occur over long time scales (decades to centuries) so that actions need to be contemplated before full understanding is achieved. These actions themselves are built on economic, social and

political models each with their own inherent assumptions and difficulties with data and observations. In the presence of uncertain scientific uncertainty, it should not be surprising that, when it comes to recommendations about how to respond to a threat of climate change, the spectrum of opinions is broad indeed.

The Australian Academy of Science is strongly committed to enhancing public understanding of scientific issues and how these may impact on society and the planet. Through its members and through its National Committees for Science it is able to draw on expertise from across a broad sector of the Australian science community to report on important scientific issues.

This includes climate science. The Academy recognises that decisions on how to respond to climate change will have to be made by our society as a whole. These decisions need to consider the findings of climate change together with many considerations that go beyond the science and must include, amongst others, ethics and equity, economics, risk management and politics. The purpose of this document is to contribute to the public understanding of the state of the science and to attempt to tread a path through the often contradictory public commentary on the science. It is not a formulation of a policy response but an attempt to improve the public understanding of the science upon which any policy response should be constructed.

To this effect the Academy's Council established two committees to address some of the major questions that are frequently asked about climate change science. First, an expert Working Group carefully formulated the questions and answers about the science of climate change. This group consists of internationally recognised scientists who have contributed extensively to the underpinning science, including contribution to the successive IPCC assessments. Seven 'big' questions were identified within each of which 'lower-level' questions have also been addressed. Second, an Oversight Committee comprehensively reviewed the answers provided to ensure that

they are authoritative within the current state of knowledge. This Committee consists of eminent Fellows of the Academy and other experts with both extensive research experience in related fields and in the leadership of climate-related programs and organisations.

While it is important to emphasise that it is not possible to provide definitive answers to many of the questions that are being asked about climate change, it is also important to stress that considerable progress has been made in understanding climate change and why it occurs. The role of greenhouse gases in the atmosphere is qualitatively well understood. It is known that increasing the atmospheric concentration of the principal anthropogenic greenhouse gas, CO₂, leads to higher mean global surface temperatures. It is known that CO₂ has increased very substantially during the last century, to the highest levels seen in the past 800,000 years, and that this increase is primarily of anthropogenic origin. It is also beyond serious question that some CO₂ from human activities remains in the atmosphere for a very long time, as is the message that unless greenhouse gas emissions are reduced, an upward trend in global temperature will continue.

The uncertainties in the science do not affect such major conclusions but they will affect the precise timescales or magnitudes of the change and they will affect the global distribution of its impact. It is important therefore that extensive research and rigorous scientific debate continue within the expert scientific community and that the communication of that research to the broader community be effective. The Academy therefore hopes that this report will provide a firmer basis for understanding the science of climate change and its implications.

The Academy is very appreciative of the contributions made to this report by the members of the Working Group and Oversight Committee to provide authoritative answers to these important questions on the science of climate change. The Academy also thanks the Department of Climate Change and Energy Efficiency for providing financial support to prepare this document.

Summary

The Earth's climate has changed. The global average surface temperature has increased over the last century and many other associated changes have been observed. The available evidence implies that greenhouse gas emissions from human activities are the main cause. It is expected that, if greenhouse gas emissions continue at business-as-usual rates, global temperatures will further increase significantly over the coming century and beyond.

The science behind these statements is supported by extensive studies based on four main lines of evidence:

Physical principles established more than a century ago tell us that greenhouse gases, such as carbon dioxide (CO₂), trap heat and keep the planet warmer than it would otherwise be. Increasing greenhouse gas levels raise the temperature of the Earth's surface.

The record of the distant past (millions of years) tells us that we cannot take a stable climate for granted. Climate has varied greatly through the Earth's history. It has, for example, gone through 10 major ice age cycles over approximately the past million years. The past few thousand years have been unusually stable. Together with our understanding of

physical principles, evidence from the past shows that climate can be sensitive to small external influences.

Measurements from the recent past (the last 100 years) tell us that the Earth's surface is warming along with rising levels of greenhouse gases from human activities, and that this warming is leading to other environmental changes. Although climate varies from year to year and decade to decade, the overall upward trend of average global temperature over the last century is clear.

Climate models, together with physical principles and knowledge of past variations, tell us that, unless greenhouse gas emissions are reduced and greenhouse gas concentrations in the atmosphere are stabilised, global warming will continue.

Climate models estimate that, by 2100, the average global temperature will be between 2°C and 7°C higher than pre-industrial temperatures, depending on future greenhouse gas emissions and on the ways that models represent the sensitivity of climate to small disturbances. Models also estimate that this climate change will continue well after 2100.

A 2°C global warming would lead to a significantly different world from the one we now inhabit. Likely consequences would include more heat waves, fewer cold

spells, changes to rainfall patterns and a higher global average rainfall, higher plant productivity in some places but decreases in others, disturbances to marine and terrestrial ecosystems and biodiversity, disruption to food production in some regions, rising sea levels, and decreases in Arctic ice cover. While aspects of these changes may be beneficial in some regions, the overall impacts are likely to be negative under the present structure of global society.

A warming of 7°C would greatly transform the world from the one we now inhabit, with all of the above impacts being very much larger. Such a large and rapid change in climate would likely be beyond the adaptive capacity of many societies and species.

There are uncertainties in climate science. For example, a precise value cannot be given for the likely range of warming because of uncertainties in climate sensitivity to small disturbances, although climate models and evidence from past climate change provide a plausible range of values. Climate changes over small regions and changes in rainfall patterns are very hard to estimate. Tipping points or rapid climate transitions associated with overall global warming are possible but cannot yet be predicted with confidence. These uncertainties work in both directions: there is a chance that climate change will be less severe than the current estimates of climate science, but there is also a chance that it will be more severe.

This document aims to summarise and clarify the current understanding of the science of climate change for non-specialist readers. The document is structured around seven questions.

1 What is climate change?

Climate is a statistical description of weather conditions and their variations, including both averages and extremes. Climate change is a change in the average pattern of weather over a long period of time. Greenhouse gases play an important role in determining climate and causing climate change.

2 How has Earth's climate changed in the distant past?

Global climate has varied enormously through Earth's history. Evidence from the past shows that global climate can be sensitive to small influences. Past records also show that climates can shift abruptly.

3 How has climate changed during the recent past?

Global average temperature has increased over the past century. Evidence for this comes from instrumental temperature records in the air and the ocean. Temperature observations are not the only evidence of recent climate change: other sources include trends in sea levels, glaciers, ice caps and atmospheric water vapour that are consistent with global warming. Australia's climate has changed along with global climate.

4 Are human activities causing climate change?

Human activities are increasing greenhouse gas levels in the atmosphere. It is very likely that most of the recent observed global warming is caused by this increase in greenhouse gases.

5 How do we expect climate to evolve in the future?

Climate models and studies of past climates indicate that global warming and associated changes will continue if greenhouse gas levels keep rising as they are now. It is very likely there will be significant warming through the 21st century and beyond. Reduction of greenhouse gas emissions could significantly reduce long-term warming.

6 What are the consequences of climate change?

Climate change will have significant impacts on our society and environment, both directly and by altering the impacts of other stresses.

7 How do we deal with the uncertainty in the science?

Although climate forecasts are uncertain and will remain so, the broad conclusions of climate change science as outlined above are based on many lines of evidence which together give a high degree of confidence. Partly because of scientific uncertainty but also because many aspects of human life are involved, decisions about action on climate change will need to involve extensive consideration of issues beyond science, including ethics, economics and risk management.

1

What is climate change?

Climate change is a change in the average pattern of weather over a long period of time

Climate is a statistical description of weather conditions and their variations, including both averages and extremes. Climate change refers to a change in these conditions that persists for an extended period, typically decades or longer.

Weather variables such as temperature and rainfall fluctuate naturally (see Box 1). These

changes in weather from day to day, between seasons, and from one year to the next, do not represent climate changes. The period for estimating climate is usually 30 years or more, long enough to sample a full range of weather.

Climate can be defined for a particular place or region, usually on the basis of local rainfall patterns or seasonal temperature variations. Climate can also be defined for the entire Earth. For global climate, a key variable is the average surface temperature.

BOX 1

Could the 20th century warming be just a part of the natural variability of climate?

Climate varies naturally on many timescales. Much of this variation arises from the exchange of heat and water between the deep oceans and upper ocean layers (typically the top 50 to 100 metres), which in turn has an impact on the atmosphere. A well-known example is the El Niño oscillation in the tropical Pacific Ocean, which influences temperatures and rainfall patterns throughout the tropical Pacific region and far beyond. Other ocean basins have similar oscillations. Such phenomena typically change the global average temperature by no more than a few tenths of a degree, and only for up to a year or two.

In principle, a natural fluctuation could last for a century. However, evidence going back up to 20 centuries does not show changes in global temperature resembling those that have taken place in the last 100 years¹⁻³. Moreover, there is compelling independent evidence (see Question 4) that this warming is being caused largely by the enhanced greenhouse effect due to human activities. The response of the climate system to human causation was foreseen by scientists more than a century ago⁴. If this warming continues as now projected, it will soon dwarf any change in the last 10,000 years.

Sustained and truly global changes in average temperature require some global heating or cooling influence such as variations in heat output by the Sun, changes to the Earth's orbit around the Sun, changes in cloudiness, changes to the extent of ice on Earth's surface, or changes in greenhouse gas concentrations in the atmosphere.

Identifying climate change that is truly global in extent requires simultaneous observations from a network of locations around the world (see Question 3). Such a network of instrumental observations has only been available since the second half of the 19th century. Climate changes that occurred before this time can be identified by reconstructing records from climate-sensitive indicators like ocean sediments, ice-cores, tree rings and coral reefs.

Greenhouse gases play an important role in determining climate and causing climate change

Greenhouse gases include water vapour, carbon dioxide (CO₂), methane, nitrous oxide and some industrial gases such as chlorofluorocarbons (CFCs). These gases act like an insulating blanket, keeping the Earth's surface warmer than it would be if they were not present in the atmosphere. Except for water vapour, the atmospheric concentrations

BOX 2

If water vapour is the most important greenhouse gas, why all the fuss about CO₂?

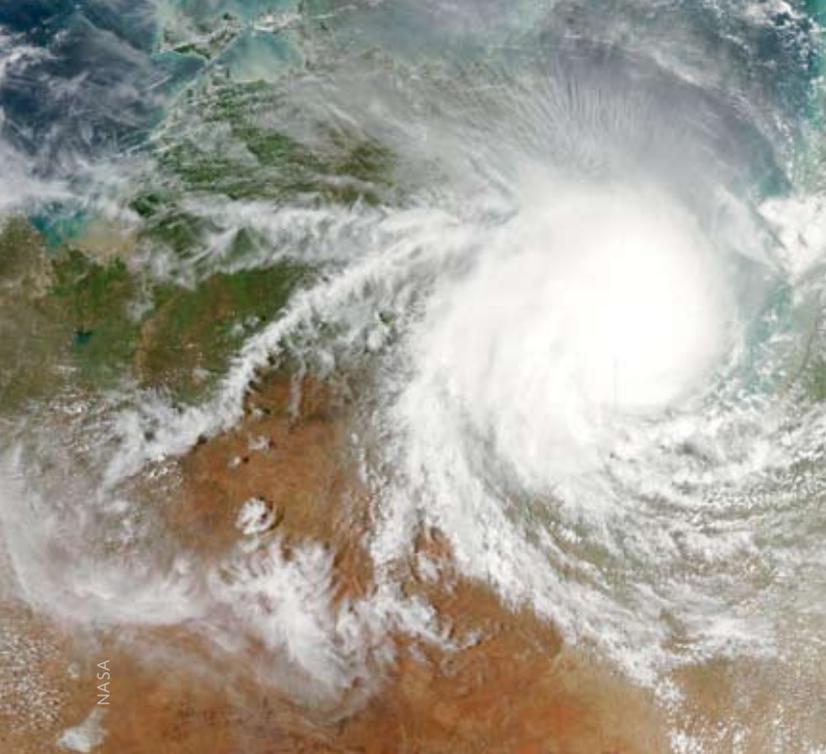
Water vapour accounts for about half the present-day greenhouse effect. Its global average concentration in the troposphere (where most water vapour is found) is controlled mainly by the atmospheric temperature and winds, with warmer temperatures causing higher water vapour concentrations. This is in contrast with other greenhouse gases, for which concentrations are strongly influenced by human-induced inputs to the atmosphere.

If other factors warm the atmosphere, then water vapour concentrations are expected to increase and, because water vapour is a greenhouse gas, the increased concentrations would amplify the initial warming (see Figure 1.1). This is known as a positive feedback.

The water vapour feedback is supported by most evidence and analyses so far⁵⁻¹¹, although some views are different¹².

of all of these gases are being directly influenced by human activities (see Question 4). Once released into the atmosphere, many of these gases remain there for a long time: in particular, a significant fraction of CO₂ emissions remains in the climate system for hundreds to thousands of years.

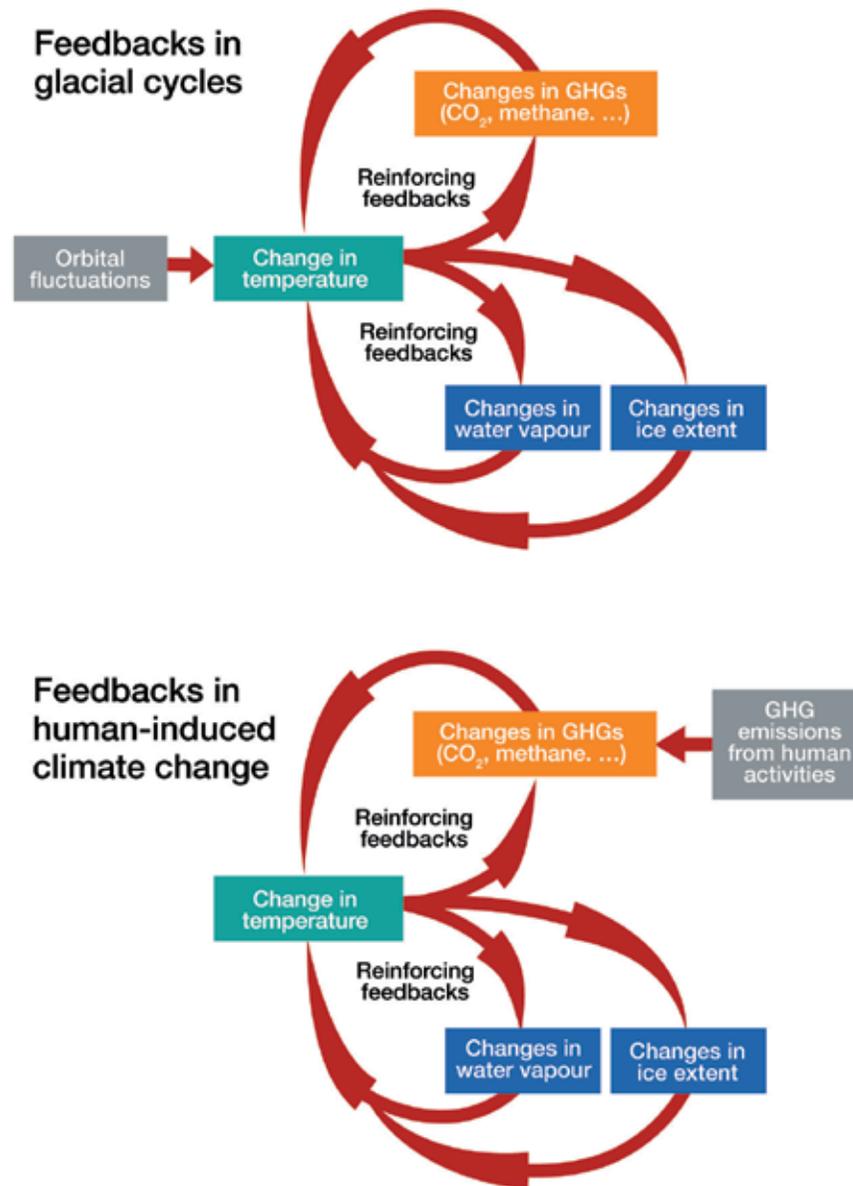
Water vapour is an important greenhouse gas but it is not like the greenhouse gases affected directly by human activities. Its concentration in the atmosphere is controlled by the climate itself, rather than by human activities. Water vapour therefore reacts to,



and amplifies, climate change caused by other factors (see Box 2 and Figure 1.1).

The effects of changing greenhouse gas levels on climate can be distinguished from the effects of other factors such as changes to the Sun's radiation. These different causes lead to different patterns or "fingerprints" in the resulting climate changes, which assist in identifying the cause of observed changes. For example, increases in solar radiation would be expected to warm both the upper and lower parts of the atmosphere and result in days warming more than nights. On the other hand, increases in greenhouse gases would be expected to result in a cooling, not a warming, in the stratosphere (the layer of the atmosphere above 15 km elevation), and cause nights to warm more than days. The observed patterns of change more nearly match those expected from increasing greenhouse gases.

Figure 1.1 Feedbacks in the climate system



There are close connections between global temperature, atmospheric water vapour, the extent of polar ice caps and levels of greenhouse gases (GHGs) in the atmosphere. When one of these is disturbed, the others react through processes that amplify the original disturbance until a new, different climate equilibrium is reached. In the glacial cycles over the past million years, the disturbance came from fluctuations in the Earth's orbit around the Sun (grey box in upper diagram). This caused temperatures to change (green box), in turn inducing rapid changes in water vapour (left blue box), and much slower changes in ice caps (right blue box) and greenhouse gas levels (orange box), which together amplified the temperature change. In modern climate change, the disturbance comes from human-induced changes in atmospheric CO₂ and other greenhouse gas levels (grey box in lower diagram). In both cases, the disturbance is amplified by similar reinforcing processes.



2 How has Earth's climate changed in the *distant* past?

Climate has varied enormously through Earth's history

Since the Earth was formed 4.5 billion years ago, the global climate has changed dramatically many times due to the changing configuration of continents and oceans, natural variations in the levels of greenhouse gases in the atmosphere, the Sun's intensity, and the Earth's orbit around the Sun¹³⁻²⁰.

Evidence from the past shows that global climate is sensitive to small influences

During the past million years, the average temperature of the Earth's surface has risen and fallen by about 5°C, through 10 major ice age cycles. The last 8,000 years have been relatively stable at the warmer end of this temperature range²¹. These cycles were initiated by subtle variations in the Earth's orbit that altered the pattern of absorbed sunlight. Measurements from ice cores and other sources strongly suggest that as temperatures changed, other changes were triggered that had an amplifying effect: during warm periods, CO₂ and methane were released into the atmosphere, and ice sheets receded and so reflected less sunlight to space^{14, 22-24}. This meant that small influences were amplified into larger changes (see Figure 1.1).

An important implication of this finding from past climate changes is that similar processes are likely to amplify current human influences on climate.

Past temperature changes affected the world dramatically. For example, in the coldest period of the last ice age (approximately 20,000 years ago) sea level was at least 120 metres lower²⁵. The atmosphere was also very dusty, probably because of dramatic regional reductions in vegetation cover associated with the colder climate and reduced CO₂²⁶⁻²⁷. In even earlier times, several million years ago, global temperature was several degrees higher than today and warm, tropical oceans may have reached much farther from the equator, causing significant changes to atmospheric flow patterns²⁸.

Past records also show that climates can shift abruptly

The largest global temperature changes evident in the geologic record have typically occurred fairly slowly over tens of thousands or millions of years, much more gradually than the warming over the past century¹⁴. However, some rapid changes have been documented both in very warm past climates and in more recent ice ages.

One of these rapid changes took place 56 million years ago, when the global temperature increased by about 5°C, accompanied by an unexplained release of greenhouse gases into the atmosphere²⁹. This release may have been so rapid as to be comparable to the current human release of fossil fuels^{14, 30, 31}. Other rapid changes during

the last ice age, of 5°C or more over as little as a few decades, were probably mostly regional and due to sudden collapses of ice sheets or changes in ocean currents^{14, 29, 32-34}.

Although the millennium before the industrial revolution was relatively stable, there were variations in climate over that period

The Medieval Warm Period (AD 800-1300) and Little Ice Age (AD 1500-1800) are two well-known climate episodes during the past thousand years. The Northern Hemisphere may have been up to 1°C warmer on average during the former period than during the latter. However, several assessments indicate that Northern Hemisphere average temperatures over the last fifty years have been warmer than during the Medieval Warm Period, and temperatures over the last decade are warmer still. Records are sparse in the Southern Hemisphere, but those available indicate little or no correlation with warming in the Northern Hemisphere during the Medieval Warm Period, unlike the more globally coherent cooling in the Little Ice Age and warming over the past century^{1, 14, 35-40}.

There have also been regional variations in climate, particularly rainfall, that are not associated with global changes. For example, regional droughts appear to have contributed to the collapse of the ancient Akkadian empire in the Middle East and the Mayans in Mexico^{41, 42}.

3 How has climate changed during the *recent past*?

Global average temperatures have increased over the past century

Measurements from many hundreds of thermometers around the globe, on land and over the ocean, show that the average near-surface air temperature increased over the 100 years to 2009 by more than 0.7°C⁴³⁻⁴⁶.

Many of these instrumental records, which began in the second half of the 19th century, were not initially designed to be used for climate monitoring. This means they have to be carefully analysed to deal with changes in instruments, observational practice, location, and the growth of cities (see Box 3). After accounting for these issues, temperature increases are largest in the continental interiors of Asia and north Africa, regions which are distant from major population growth areas (see Figure 3.1 and Figure 3.2)⁴³⁻⁴⁶.

The rates of observed near-surface warming increased in the mid-1970s. Since then, the global land surface has warmed at about double the rate of the ocean surface. Measured warming over the past 50 years was nearly

twice the rate of that for the past 100 years. The last decade has been the warmest yet recorded⁴³⁻⁴⁶ (see Box 4).

The overall warming has led to an increase in the number of record high temperatures, and decrease in frost frequency and the number of record low temperatures over the past century^{46, 47} (see Figure 3.3).

Over the past three decades, satellite observations of temperature at the Earth's surface and in the lower atmosphere have also shown warming^{46, 48, 49} (see Box 5). In contrast to the surface warming, the atmosphere above about 15 km elevation (the stratosphere) has cooled over the past four decades^{46, 50-52}. This provides one clue that the observed warming is due to human activities (see Question 4).

The upper 700 m of the ocean is storing about 90% of the additional heat absorbed by the Earth's whole climate system since 1961⁵³. The surface ocean has warmed by 0.5°C from the 1970s to the early 2000s. Averaged over the upper 700 m of the ocean, the average warming is much

BOX 3

Does warming in cities affect global temperature records?

The temperatures recorded by some weather stations in cities have been affected by non-climate related changes, including warming due to their proximity to buildings and other structures that emit, absorb and radiate heat.

Climate researchers have made extensive efforts to avoid or correct such problems, and several tests show that this has minimised any effects on long-term trends, particularly when averaged over large regions⁵⁹⁻⁶¹. Nonetheless regional and year-to-year variability is not known precisely, especially earlier in the record.

Figure 3.1 Global surface temperature anomalies relative to 1951–1980, from surface air measurements at meteorological stations and ship and satellite sea surface temperature measurements. Differences between the series arise from different ways of deriving a global average surface temperature from measurements at numerous points. Data from: Climate Research Unit, University of East Anglia (www.cru.uea.ac.uk/cru/data/temperature/); Goddard Institute for Space Studies (<http://data.giss.nasa.gov/gistemp/>); National Climate Data Center, NOAA (www.ncdc.noaa.gov/cmb-faq/anomalies.html)

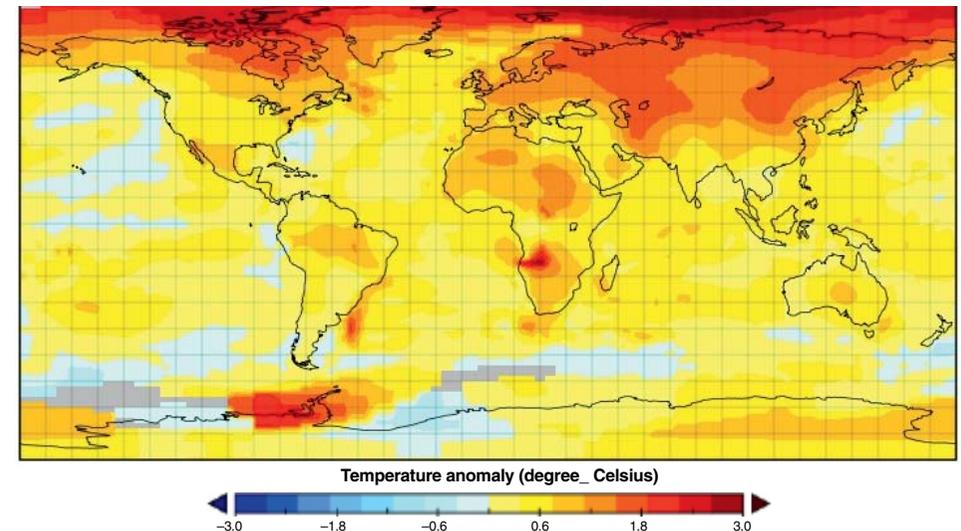
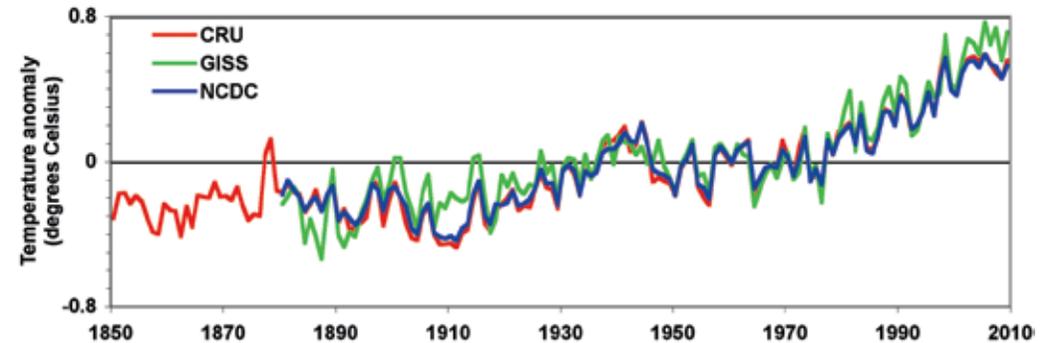


Figure 3.2 Distribution of global surface temperature anomalies for the period 2005–2009, relative to 1951–1980 as a baseline, from surface air measurements at meteorological stations and ship and satellite sea surface temperature measurements. Note that warming is greatest over continental interiors and where there is no urban heat island effect (e.g. Antarctic Peninsula, Siberia). Data: <http://data.giss.nasa.gov/gistemp/maps/>

Has there been a global cooling trend since 1998?

No, 1998 was an extremely warm year but the overall warming trend has continued over the past decade. The temperature trend in any given 10-year interval (such as 1 January 1990 to 31 December 1999, or 1 January 1998 to 31 December 2007) can be determined by a standard statistical process called linear regression. Since the 1970s, decadal global temperature trends have consistently demonstrated warming in almost all such 10-year intervals, although the magnitude of the trend varies because of natural climate variability (see Box 1)⁶². The decadal temperature trends over recent 10-year intervals remain positive.

Submarine observations suggest that the Arctic Ocean sea ice thickness has decreased since 1958, and satellite measurements indicate a thickness decrease of about 0.6 m between 2003 and 2008^{71,72}. However, in the Southern Ocean, total sea ice extent has increased slightly^{70,73}.

■ The average water vapour content in the atmosphere, both at the Earth's surface and higher in the atmosphere, has been increasing at a rate of 1–2% per decade since reliable measurements began in the 1980s^{9,46}. The greater intensity of heavy rains expected from this increasing humidity has been observed in some regions⁷⁴. Observed changes in ocean salinity are consistent with intensification of the water cycle over the oceans⁷⁵.

■ There is evidence of a shift in weather systems toward the Earth's polar regions, and an apparent strengthening in the winds over the Southern Ocean over the last 40 years. This is believed to have contributed to observed warming over the Antarctic Peninsula and Patagonia, to cooling over eastern Antarctica and the Antarctic plateau⁷⁶,

smaller, only about 0.1°C, but very important because of the large amount of stored heat this represents⁵³⁻⁵⁸.

Temperature observations are not the only evidence of recent climate change

Many other changes have been observed that are consistent with the recorded increase in global average temperature, and indicate some of its consequences:

■ There has been widespread melting of mountain glaciers and ice caps. While many of these have been shrinking since about 1850, there has been a significant increase in the rate of average glacier melt since the 1990s⁶³⁻⁶⁶.

■ Satellite instruments show that the Greenland ice sheet is losing more ice than it gains by snowfall, due to increased surface melting and increased flow of ice into the ocean. The rate of loss of ice from Greenland has risen since the mid-1990s. There are strong indications that West Antarctica has also been recently losing ice due to increased ice flow. Most recent estimates show Antarctica as a whole is losing ice^{67,68}.

■ Sea level rise is an inevitable consequence of global warming because ocean water expands as it warms, and because melted ice from the land adds more water to the oceans. The rate of rise increased from the 19th to the 20th centuries, with the result that ocean levels are now more than 20 cm higher than in 1870^{69,70}. Satellite and coastal measurements show that the rate of sea level rise since the early 1990s has been substantially larger than the average rate for the 20th century, and larger than for any similar length period in the historical record⁶⁹ (see Figure 3.4). The observed rise is consistent with increased rates of ice melt and ocean warming⁵⁵.

■ Arctic sea ice extent has decreased significantly in all seasons, but particularly in summer, since satellite records began in 1979.

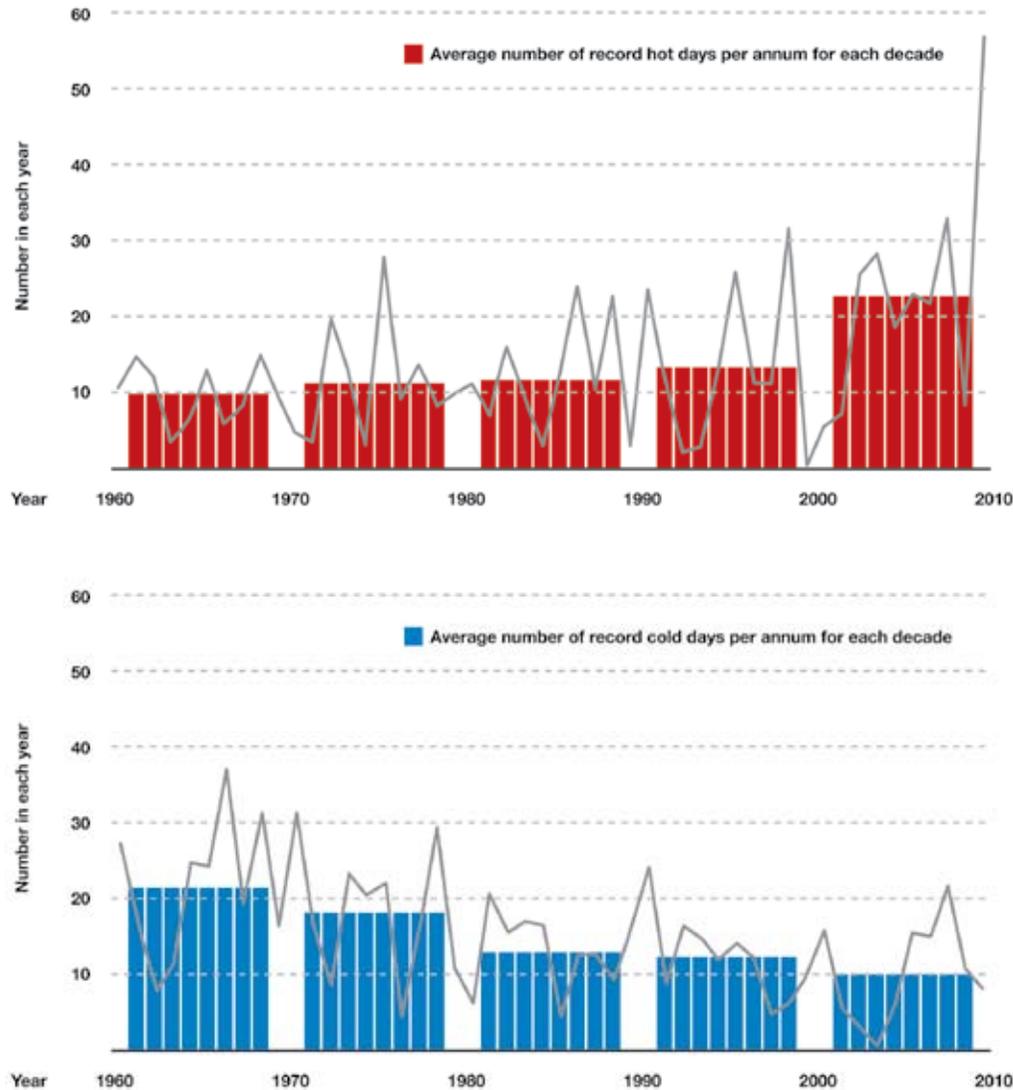


Figure 3.3 Changes in the number of record hot day maxima and record cold day maxima at Australia's climate reference stations. The number of days with record hot temperatures has increased each decade over the past 50 years; there have been fewer record cold days each decade; and 2000 to 2009 was Australia's warmest decade on record. Source: CSIRO, Bureau of Meteorology (2010) "State of the Climate".

to associated changes in sea ice and the ocean^{73,77}, and probably to the decreases in rainfall over south-western Australia^{78,79}.

■ There are indications of recent changes in the temperatures and salinities of deep ocean currents such as those which carry North Atlantic water southward at depth and Antarctic bottom water north⁸⁰.

Australia's climate has changed along with the global climate

In Australia, the average surface temperature has increased by about 0.7°C since 1960, with some areas having warmed faster and some showing relatively little warming (see Figure 3.5)⁸¹. The warming has caused an Australia-wide average increase in the frequency of extremely hot days and a decrease in the frequency of cold days^{81,82} (see Figure 3.3).

While the longer term trends in rainfall are less marked, there have been significant

increases over north-western Australia, and decreases over south-western and south-eastern Australia since 1960 (see Figure 3.6)⁸¹. The warming and decreased rainfall over south-east Australia have exacerbated the background conditions conducive to fire⁸³. In southwest Western Australia and the southeast coast, there is evidence for a systematic decline in rainfall in recent decades⁷⁹, and for declining trends in storminess⁸⁴. It is likely that these trends are related to shifts in pressure patterns over southern Australia, particularly the intensification of the subtropical high pressure belt⁸⁵.

Regional ocean currents have also changed. For example there has been a southward shift of the Antarctic Circumpolar Current⁸⁶ and an increasing southward penetration of the East Australian Current, associated with wind changes in the South Pacific⁸⁷.

Sea level has risen around Australia at a rate of about 1.2 mm per year since 1920, resulting in coastal inundation events becoming more frequent⁸⁸. Since the establishment of the Australian Baseline Sea-level Monitoring Project in the early 1990s, sea level measured relative to the land has risen at about 2 mm per year in the south east, and over 8 mm per year in the north west⁸⁹.

BOX 5

Is there a disagreement between satellite and surface temperature records?

Not any more. While a disagreement did exist in the 1990s, it has largely been resolved by correction of biases in the satellite data, for example to account for drift in satellite orbits over time^{48,49}. Given the remaining uncertainties in satellite-derived trends, there is now acceptable agreement between satellite and ground-based measurements of surface temperature.

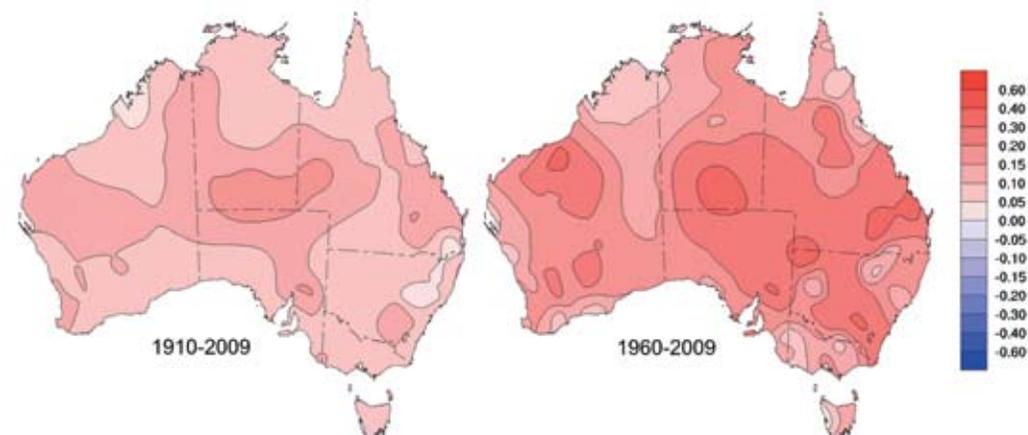
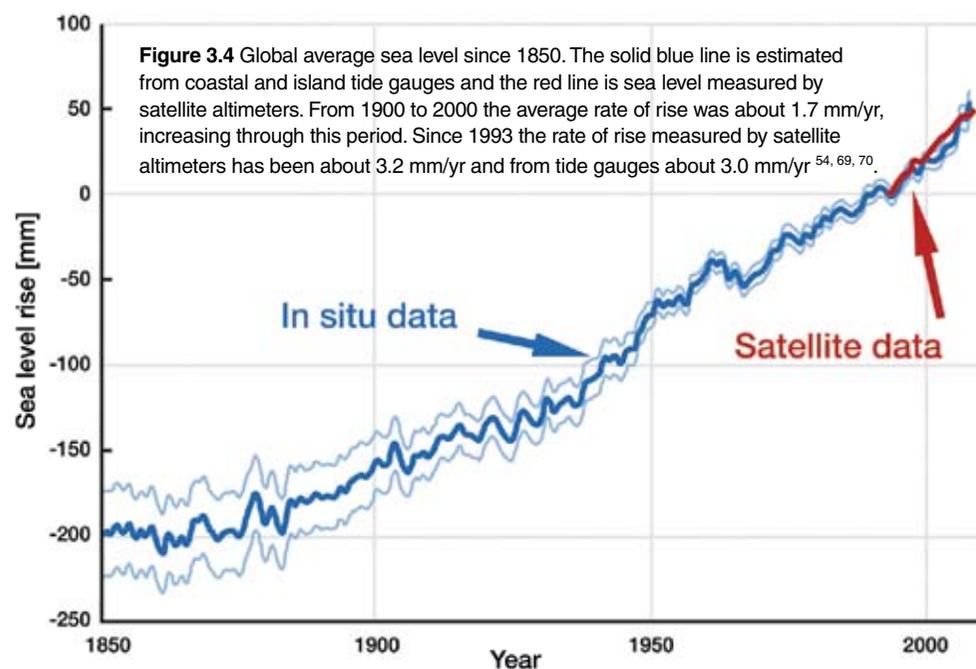


Figure 3.5 Trends in Australian annual temperature (°C/decade) over the periods 1910–2009 (left) and 1960–2009 (right). Source: Australian Bureau of Meteorology (<http://www.bom.gov.au/cgi-bin/climate/change/trendmaps.cgi>)

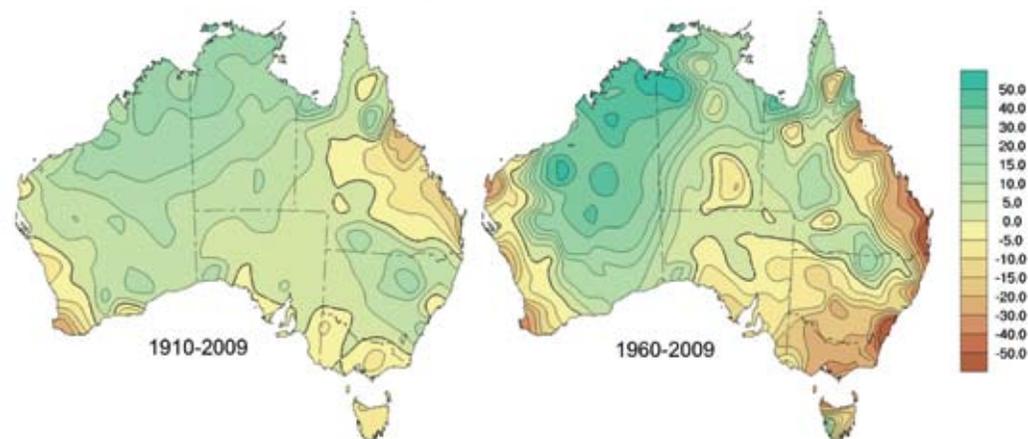


Figure 3.6 Trends in Australian annual rainfall (in mm per decade) over the periods 1910–2009 (left) and 1960–2009 (right). Source as for Figure 3.5.

4 Are human activities causing climate change?

Human activities are increasing greenhouse gas levels in the atmosphere

The concentrations of greenhouse gases in the atmosphere are well known, both from modern measurements⁹⁰⁻⁹⁴ and by analysis of the air from past eras, trapped as bubbles in ice from Antarctica and Greenland^{95, 96} (see Figure 4.1). These observations tell us that atmospheric concentrations of CO₂, methane and nitrous oxide began to rise two to three hundred years ago, after changing relatively little since the end of the last Ice Age thousands of years earlier.

This increase in greenhouse gas concentration happened around the same time as industrialisation, when the global

human population began growing rapidly and farming also increased. The growth in greenhouse gases has accelerated through the 20th century to the present⁹⁰⁻⁹⁶ (see Figure 4.1). Studies of the stores and sources of these gases, both natural and human-induced, show that the main causes of the increasing concentrations are emissions from human activities⁹⁷⁻¹⁰¹ (see Figure 4.2).

Human activities cause CO₂ input to the atmosphere from fossil fuel burning, other industrial sources such as cement production, and deforestation. Measurements over the past 50 years show that only about 45% of the combined CO₂ emissions from these sources remain in the air to cause atmospheric CO₂ to rise^{102, 103}. About 25% of the total CO₂ input is being absorbed by the oceans, making sea water more acidic^{104, 105}, and the remaining 30% is being taken up on land, with the largest probable cause being increased growth of plants⁹⁹ (see Box 6). This is shown by a wide range of measurements and models^{99, 101-103, 106, 107}.

There has been a recent acceleration in the growth rate of CO₂ emissions from fossil fuels and industrial sources. From 2000 to 2007 these emissions grew by 3.5% per year, exceeding almost all assumed scenarios generated in the late 1990s^{99, 108, 109}. This pulse of CO₂ emissions growth coincided with a period of rapid global economic growth. There will be a small, temporary downturn in CO₂ growth, associated with the 2008–09 global financial crisis^{99, 109}.

It is very likely that most of the recent observed global warming is caused by increasing greenhouse gas levels

It was predicted more than a century ago that increases in CO₂ would act like added insulation in the Earth's atmosphere, trapping more heat near the surface⁴. This extra CO₂ was also predicted to make the stratosphere colder¹¹⁰ (see Question 1).

Satellite measurements over recent decades have confirmed the extra insulating effect not only of CO₂, but also of each

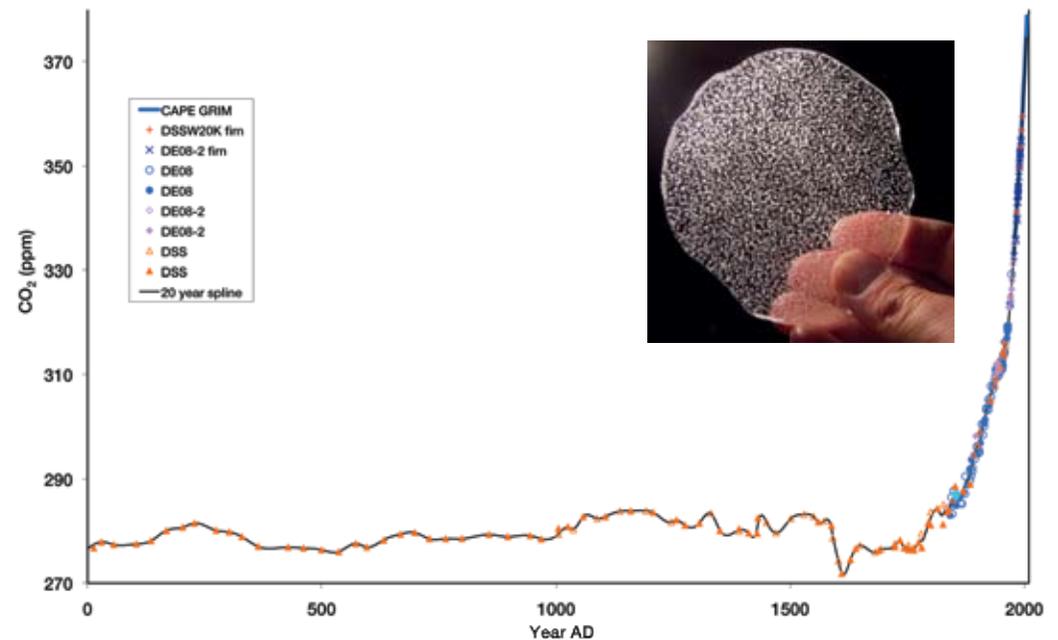
additional greenhouse gas¹¹¹. Moreover, trends over the last 40 years, superimposed on natural year-to-year variations, have been observed which show that the upper atmosphere has cooled and the surface of the Earth and the lower atmosphere have warmed significantly (see Question 3 and Boxes 1, 4 and 5). These are the predicted consequences of the additional levels of greenhouse gases^{46, 48, 50}. In contrast, both the lower and upper atmosphere might have been expected to have warmed if the amount of the

Why are CO₂ emissions from human activities regarded as so significant?

BOX 6

Large amounts of CO₂ are continually transferred to and from the atmosphere, which exchanges carbon with the oceans and vegetation on land. Until around 200 years ago, these natural exchanges were in rough balance, shown by the nearly constant concentrations of atmospheric CO₂ for most of the last two thousand years. The importance of human-caused CO₂ emissions is that they are disturbing this balance, adding carbon to the atmosphere faster than it can be removed by uptake by vegetation, the slow mixing of CO₂ into the deep oceans, or the even slower weathering processes that control the carbon balance on geological timescales.

Figure 4.1 Atmospheric CO₂ over the last 2000 years, based on direct measurements in the atmosphere at Cape Grim, Tasmania, older air extracted from Antarctic snow (firn) and from air bubbles trapped in various ice cores (various symbols). The inset shows the air bubbles in Antarctic ice. Image: Australian Antarctic Division. Data: CSIRO



BOX 7**Could changes in the Sun be causing global warming?**

Not much of it. Most estimates show that solar output has not significantly increased since 1979, when satellites began measuring it accurately^{121, 122}. Indeed, some estimates indicate that the Sun has grown slightly cooler since 1960, a period during which global temperatures have risen. While there have been some suggestions of a significant solar contribution to the observed warming

over the past 20 years, all the trends in the Sun that could have had an influence on the Earth's climate have been in the opposite direction to that required to explain the observed rise in global average temperatures^{123, 124}. Indirect estimates for earlier times suggest that the Sun has contributed only about 10% of the global warming since 1750^{125, 126}.

Sun's energy being received by the Earth had increased (see **Question 1** and **Box 7**).

As well as emitting greenhouse gases, human activities affect climate through the release of small particles in industrial haze, which reflect sunlight. The amount of cooling by this pollution is not known precisely, but is likely to be offsetting some of the warming from the increases in greenhouse gases¹¹²⁻¹¹⁶.

Another way humans change local climates is by changing land use, building cities, or introducing irrigation. These changes can affect the amount of sunlight reflected from the surface, local wind flow and evaporation. The impact of these effects in recent decades has been small on a global scale^{112, 117}.

Natural factors that have changed climate in the distant past, such as the brightness of the Sun or volcanic activity, have made only a small contribution to recent climate change (see **Boxes 7** and **8**).

Putting all these factors together, the observed global warming during the past century has been consistent with that expected^{26, 118, 119} from the combination of increasing greenhouse gases and increasing particulates^{112, 117, 120}, with small contributions from other factors.

Some recent Australian climate changes have been linked to rising greenhouse gases

Modelling studies indicate that rising greenhouse gases have made a clear contribution to the recent observed warming across Australia^{117, 127, 128}.

Decreases in atmospheric ozone over Antarctica and increases in greenhouse gases

are also likely to have contributed significantly to climate trends that have been observed over the Southern Ocean in the past few decades, including stronger westerly winds and the southward shift of weather systems^{76, 129, 130}.

The human contribution to the recent observed rainfall increases in northwest Australia and decreases in southern Australia cannot as yet be clearly separated from natural climate variations^{79, 82}. However, the decreases in rainfall in southern Australia have been linked to stronger high pressure weather systems⁸². The overall pattern of increasing pressure in mid-latitudes over time in the Southern Hemisphere is consistently seen in climate model projections and is therefore likely to be due to human-induced climate change through a combination of increases in greenhouse gases and decreases in stratospheric ozone¹³⁰⁻¹³³.



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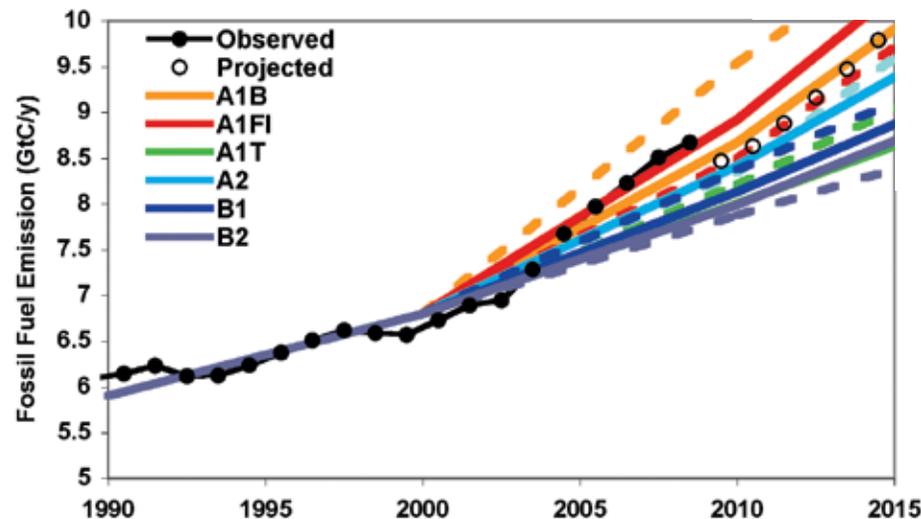


Figure 4.2: Observed past emissions of CO₂ from fossil fuels and other industrial processes (black points) with economics-based projections to 2014 (open circles). Coloured lines represent emissions futures from a range of IPCC scenario families representing combinations of economic (A) versus environmental (B) and globalised (1) versus localised (2) orientations for world development in the 21st century. Solid and dashed coloured lines respectively represent averages of scenarios within families and particular “marker” scenarios used in climate projections. Data: Carbon Dioxide Information and Analysis Center (http://cdiac.esd.ornl.gov/trends/emis/em_cont.htm). Figure adapted from published sources^{99, 108, 109}.

BOX 8**Do volcanoes emit more CO₂ than human activities?**

No. The combined annual emissions from volcanoes on land and under the sea^{117, 127, 128}, averaged over several decades, are less than 1% of CO₂ emissions in 2009 from fossil fuels, industrial processes and deforestation⁹⁹.



5 How do we expect climate to evolve in the future?

Climate models and studies of past climates indicate that global warming and associated changes will continue if greenhouse gas levels keep rising as they are now

Basic physical principles tell us that rising levels of greenhouse gases will warm the Earth's surface. To answer more complex questions, computer simulations, or models, of the Earth's climate are used. These models incorporate the many factors that affect our climate, using mathematical equations based on fundamental laws of nature, together with approximations of some physical processes that cannot be represented exactly (see Box 9).

Models simulate reasonably well the broad features of the present climate and the 20th century warming. This, however, does not guarantee accurate predictions into the future; changes could be more rapid or more gradual than projected. Overall, there is good agreement between models and observations at global and continental scales, but simulations are less reliable at the local scale¹³³. Some properties of climate are better captured by models than others; for example, temperature is generally more accurately simulated than rainfall.

Independent of climate models, another important way to estimate the implications of greenhouse gas increases is to examine how climate has responded to such increases in the past, both over geological time (see Question 2) and in recent centuries (see Question 3)¹⁴.

While these two approaches – modelling and studying the past – rely on markedly different

methodologies, they both yield broadly similar indications of where global climate is headed. For example, both methods project a long-term warming of global air temperature of around 3°C (within an uncertainty range of 2°C to 4.5°C) in response to a doubling of the concentration of CO₂ in the atmosphere¹³⁴. Evidence from Earth's past (see Question 2) indicates that changes of this magnitude can have major long-term ramifications, such as sea level rise of many metres¹³⁵⁻¹³⁷.

Continued increases in greenhouse gas levels are expected to lead to significant warming through the 21st century and beyond

Continued “business as usual” reliance on fossil fuels is expected to lead to a

doubling of pre-industrial CO₂ levels by about 2050, and possibly a tripling by about 2100¹³⁸. This emission pathway for CO₂, coupled with rises in the other greenhouse gases, would be expected to produce a warming of around 4.5°C by 2100, but possibly as low as 3°C or as high as 7°C^{139, 140}.

If society were to shift rapidly away from using fossil fuels, there would be little reduction in the rate of global warming in the first couple of decades, but warming later this century and beyond would be significantly reduced (see Figure 5.1).

Climate models and basic physical principles indicate that global warming will generally be accompanied by increases in global-average humidity; more extreme hot

BOX 9

If we can't forecast the weather 10 days in advance, why should we believe long-term climate forecasts?

Weather and climate are not the same: weather is chaotic and unpredictable over times longer than a week or two (see Box 1), whereas climate is the average of weather over time. Therefore, the challenges of predicting weather and climate are very different. Predicting the weather is akin to predicting how a particular eddy will move in a turbulent river: it is possible over short timescales by extrapolating the previous path of the eddy, but eventually the eddy is influenced by neighbouring eddies and currents to the extent that predicting its exact

path becomes impossible. This is analogous to the predictive limit for individual weather systems in the atmosphere, which is around 10 days. On the other hand, predicting climate is akin to predicting the flow of the whole river, which requires a consideration of the major forces controlling the river, such as valleys and dams. Projections of climate change over decades to centuries are possible because of our progressively improving understanding of the forces affecting climate, including global warming caused by greenhouse gases.

events such as heat waves but fewer cold extremes; further decreases in the extent and thickness of Arctic sea-ice; shifts in rainfall (generally an increase in the tropics and high latitude regions and a decrease in the subtropics); further ocean warming; melting of mountain glaciers and polar ice sheets; and rising sea levels¹¹⁸. Most of these impacts have already been observed (see Question 3).

Warming rates and other climate changes are not expected to be the same everywhere, due to changes in atmospheric circulation or other regional influences. Projections of future climate for individual regions remain much less certain than global-scale projections. Different models often disagree, so definitive localised projections are not yet possible¹¹⁸. This is particularly the case for regional rainfall projections.

Some models also project substantial changes to phenomena such as El Niño or dramatic changes to vegetation¹⁴¹. Many aspects of climate change will likely remain difficult to foresee despite continuing modelling advances, leaving open the possibility of climate change “surprises”¹⁴².

Some climate change will continue for centuries, and some change will be essentially irreversible on a 1,000-year timescale

Stabilisation of climate requires stabilisation of greenhouse gas concentrations. However, the inertia of the climate system, particularly the oceans and the ice sheets, means that climate change will continue for centuries after greenhouse gas concentrations have stabilised.

Even if human societies completely ceased greenhouse gas emissions at some time in the

future, atmospheric temperatures would not be expected to fall significantly for a thousand years, as CO₂ and heat are only gradually absorbed by the deep oceans¹⁴³. Sea level rise is also expected to continue for many centuries due to the ongoing melting of ice sheets and the gradual thermal expansion of the oceans in response to atmospheric warming¹⁴³.

Global warming above some threshold, believed to lie between about 2°C and 4.5°C, would lead to an ongoing melting of the Greenland ice sheet. If sustained for thousands of years, this would virtually eliminate the ice sheet, raising sea level by about seven metres¹⁴⁴. Most of the Antarctic ice sheet, by contrast, is expected to remain too cold for widespread melting. It is possible that increased snowfall over Antarctica may partially offset other contributions to sea level rise¹⁴⁵.

In addition, accelerated outflow of ice has been observed from Greenland and West Antarctica. This is poorly understood, but could make these ice sheets more vulnerable to future warming¹³⁵.

Reduction of greenhouse gas emissions could significantly reduce long-term warming

To have a better than even chance of preventing the global average temperature from eventually rising more than 2°C above pre-industrial temperatures, the world would need to be emitting less than half the amount of CO₂ by 2050 than it did in 2000^{138, 146}. To do this on a smooth pathway, global emissions (which are still rising) would need to peak within the next 10 years and then decline rapidly¹⁴⁷.

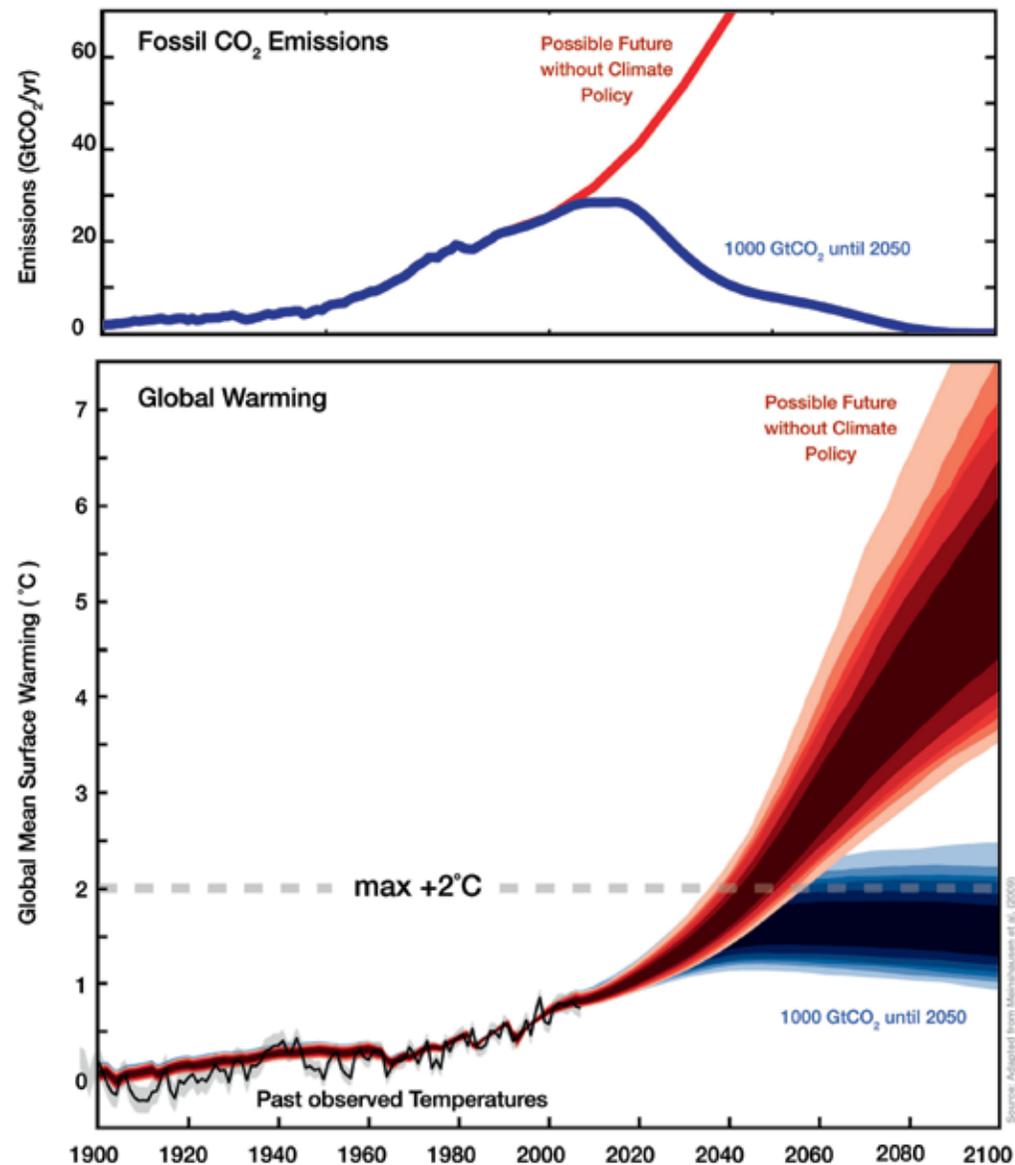


Figure 5.1 Top panel: Fossil-fuel CO₂ emissions for two scenarios: one “business as usual” [red] and the other with net emissions peaking before 2020 and then reducing rapidly to near zero emissions by 2100, with the cumulative emission between 2000 and 2050 capped at 1000 billion tonnes of CO₂ [blue]. Bottom panel: Median projections and uncertainties of global-mean surface air temperature based on these two emissions scenarios out to 2100. The darkest shaded range for each scenario indicates the most likely temperature rise (50% of simulations fall within this range). Adapted from Meinshausen *et al.* (2009)¹³⁸.

6 What are the consequences of climate change?

Climate change will have significant impacts on our society and environment

Historically, the Australian climate has been highly variable. This variability makes it challenging to predict the future consequences of human-induced climate change. However, climate models and past experience provide some guidance.

By around 2030, Australian temperatures are likely to be a half degree or more higher than 1990 and the frequency of hot days and nights will have increased^{148, 149}. Sea level is expected to be about 15 cm higher and there is some evidence to suggest that tropical cyclones will become more severe, but less frequent¹⁵⁰.

It is likely that future rainfall patterns across Australia will be different from today. Changes in rainfall patterns are hard to predict: regional rainfall projections from different climate models (or between different runs of the same model with different starting conditions) are frequently quite different from one another (see Question 7). Nevertheless, some future trends are projected fairly consistently, including increases in rainfall in northern Australia and decreases in Victorian and southwest WA coastal regions^{148, 151, 152}. The projections for rainfall trends across the entire Murray-Darling basin remain uncertain¹⁵³.

It is likely that higher temperatures and changing patterns of wind and rainfall will change the patterns and frequency of extreme fire weather^{149, 154}, and also lead to more heat-related deaths and fewer cold-related deaths^{155, 156}.

Farming in Australia is vulnerable to climate change but skilful management is expected to be able to alleviate some of this vulnerability¹⁵⁷. Higher CO₂ levels, fewer

frosts and changed rainfall patterns may be beneficial to agriculture in some parts of Australia, but decreases in rainfall in other Australian regions are likely to have a detrimental effect on agriculture.

Warmer ocean temperatures will lead to further changes in the distribution of marine animals and plants, with some tropical fish moving progressively southward¹⁵⁸. As a result of increased CO₂ in the atmosphere, oceans will become more acidic and, in combination with the higher temperatures, coral bleaching events are likely to become more frequent and severe around northern Australia^{159, 160}.

Sea level will increase, inundating parts of the Kakadu freshwater wetlands^{160, 161} and causing increased coastal flooding^{88, 162}, with consequent change to sandy coastlines. As sea levels rise, coastal infrastructure around Australia will become more susceptible to damage¹⁶³⁻¹⁶⁵. Tourism may be adversely affected, in part due to the sector's dependence on natural assets and the built environment, both of which are vulnerable to the physical impacts of climate change¹⁶⁶.

The impact of climate change on plants and animals will be variable. Habitat will expand for some species, while for others it will contract¹⁶⁰. However, the inability of many species to migrate as a result of both land use change and habitat fragmentation

means that biodiversity is likely to decline overall¹⁶⁷, in line with observed global trends¹⁶⁸. Higher temperatures on the forested mountaintops of north-east Queensland, for example, may exceed the heat tolerance of some endemic species in the wet tropics, resulting in their extinction¹⁶⁹.

Climate change will exacerbate the impacts of other stresses

The world's population is approaching seven billion people, and is expected to increase to around nine billion by mid-century, with two thirds of the world's population living in the Asia-Pacific region¹⁷⁰. This population growth will place additional stress on the planet and its people. For example, half of all readily available fresh water is already appropriated for human use^{171, 172}.

Without major changes to population growth policies, land use, city development, and economic and social systems, the additional potential burdens of climate change impacts could lead to social unrest across large parts of the world. Further pressures arise because there is now little room for many populations to relocate in response to climate change^{173, 174}. These factors are likely to affect developed as well as developing nations^{173, 175}.

The recent global financial crisis has demonstrated how interconnected the world





has become. It is also dependent on a finite resource base. All of these factors demonstrate the need for an integrated approach to understanding how a sustainable planet can be attained in the presence of population pressures, risks from climate change, and other stresses¹⁷⁶.

Future impacts are expected to be more severe

If emissions continue unabated, current mid-range estimates are for 4.5°C higher global average temperatures by 2100 (see Question 5), which would mean that

the world would be hotter than at any time in the last few million years. Sea level would continue to rise for many centuries. The impacts of such changes are difficult to predict, but are likely to be severe for human populations and for the natural world. The further climate is pushed beyond the envelope of relative stability that has characterised the last several millennia, the greater becomes the risk of passing tipping points that will result in profound changes in climate, vegetation, ocean circulation or ice sheet stability.

Figure 6.1 Climate change may have severe impacts across Australia. Days of extreme fire danger are likely to increase (**top right**).

Rainfall patterns are likely to change, leading to changes in river environments: the **image on the far left** shows stranded reeds and saline mud flats in September 2007, caused by the rapidly retreating waters of Lake Bywater (near Walkers Flat, SA). This lake is fed by the River Murray, which has seen major falls in level since 2000, particularly below Lock 1. The **image on the top left** shows heavy rain in the Northern Territory.

The **centre left image** shows healthy coral and the **centre right image** shows bleached coral near Keppel Island.

Biodiversity is likely to decrease: the **image to the right** shows the endangered lemuroid possum from North Queensland.



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7 How do we deal with the uncertainty in the science?

No scientific conclusion can ever be absolutely certain

However, a balanced assessment of the available evidence and prior knowledge allows us to attach levels of confidence to the findings of climate science.

There is a high degree of confidence in the broad conclusions of climate science

We are very confident of several fundamental conclusions about climate change: that human activities since the industrial revolution have sharply increased greenhouse gas concentrations; that these added gases have a warming effect; and that the Earth's surface has indeed warmed since the Industrial Revolution. Therefore, we are very confident that human-induced global warming is a real phenomenon.

Another important conclusion is supported unambiguously by all the evidence so far: “business as usual” emissions, with continuing high reliance on fossil fuels, will lead to a significantly warmer world.

Some aspects of climate science are still quite uncertain

The exact amount of warming that will result from any particular trajectory for future greenhouse gas emissions cannot be projected precisely, because it depends on details of processes that reinforce or dampen disturbances to the climate system. Important processes involve clouds, water vapour, ocean circulations and natural influences on greenhouse gas levels in the atmosphere. However, future warming can be specified within plausible bounds, not only from climate models but also from interpretations of climate changes in the past.

How climate change will affect individual regions is very hard to project in detail, particularly future changes in rainfall patterns, and such projections are highly uncertain. Neither can “tipping points” or rapid climate transitions be projected with any confidence, although they involve high risks should they occur.

Uncertainty about future climate change works in both directions: there is a chance that climate change will be less severe than current best estimates, but there is also a roughly equal chance that it will be worse.

Despite the uncertainties, climate science has an important role to play in informing public policy on climate change

Decisions on when and how to respond to climate change involve many factors that lie outside the realm of science, including ethical and economic considerations. An appropriate response will depend on value judgements and an assessment of the risks of various courses of action. Just as in any other sphere of human activity, decisions will need to be made before we have absolute certainty about the future. The role of climate science is to inform these decisions by providing the best possible knowledge of climate outcomes and the consequences of alternative courses of action.

References

1. Committee on Surface Temperature Reconstructions for the Last 2,000 Years, Board on Atmospheric Sciences and Climate, and Division on Earth and Life Studies (2006) *Surface temperature reconstructions for the last 2,000 years*, National Academies Press, Washington DC.
2. Kaufman, D. S., Schneider, D. P., McKay, N. P., Ammann, C. M., Bradley, R. S., Briffa, K. R., Miller, G. H., Otto-Bliesner, B. L., Overpeck, J. T., Vinther, B. M., and Arctic Lakes 2k Project Members (2009) Recent warming reverses long-term Arctic cooling, *Science* **325**, 1236–1239.
3. Mann, M. E., Zhang, Z. H., Hughes, M. K., Bradley, R. S., Miller, S. K., Rutherford, S., and Ni, F. B. (2008) Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia, *Proceedings of the National Academy of Sciences of the United States of America* **105**, 13252–13257.
4. Arrhenius, S. (1896) On the influence of carbonic acid in the air upon the temperature of the ground, *Philosophical Magazine* **41**, 237–276.
5. Chen, J. Y., Del Genio, A. D., Carlson, B. E., and Bosilovich, M. G. (2008) The spatiotemporal structure of twentieth-century climate variations in observations and reanalyses. Part I: Long-term trend, *Journal of Climate* **21**, 2611–2633.
6. Dessler, A. E., Zhang, Z., and Yang, P. (2008) Water-vapor climate feedback inferred from climate fluctuations, 2003–2008, *Geophysical Research Letters* **35**, L20704.
7. McCarthy, M. P., Thorne, P. W., and Titchner, H. A. (2009) An analysis of tropospheric humidity trends from Radiosondes, *Journal of Climate* **22**, 5820–5838.
8. Santer, B. D., Mears, C., Wentz, F. J., Taylor, K. E., Gleckler, P. J., Wigley, T. M. L., Barnett, T. P., Boyle, J. S., Bruggemann, W., Gillett, N. P., Klein, S. A., Meehl, G. A., Nozawa, T., Pierce, D. W., Stott, P. A., Washington, W. M., and Wehner, M. F. (2007) Identification of human-induced changes in atmospheric moisture content, *Proceedings of the National Academy of Sciences of the United States of America* **104**, 15248–15253.
9. Sherwood, S. C., Roca, R., Weckwerth, T. M., and Andronova, N. G. (2010) Tropospheric water-vapor, convection, and climate, *Reviews of Geophysics* **48**, RG2001.
10. Soden, B. J., Jackson, D. L., Ramaswamy, V., Schwarzkopf, M. D., and Huang, X. L. (2005) The radiative signature of upper tropospheric moistening, *Science* **310**, 841–844.
11. Willett, K. M., Gillett, N. P., Jones, P. D., and Thorne, P. W. (2007) Attribution of observed surface humidity changes to human influence, *Nature* **449**, 710–716.
12. Paltridge, G., Arking, A., and Pook, M. (2009) Trends in middle- and upper-level tropospheric humidity from NCEP reanalysis data, *Theoretical and Applied Climatology* **98**, 351–359.
13. Hart, M. H. (1978) Evolution of atmosphere of Earth, *Icarus* **33**, 23–39.
14. Jansen, E., Overpeck, J. T., Briffa, K. R., Duplessy, J.-C., Joos, F., Masson-Delmotte, V., Olago, D., Otto-Bliesner, B. L., Peltier, W. R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina, O., Villalba, R., and Zhang, D. (2007) Paleoclimate, *Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Eds.), Cambridge University Press, Cambridge.
15. Kasting, J. F., and Catling, D. (2003) Evolution of a habitable planet, *Annual Review of Astronomy and Astrophysics* **41**, 429–463.
16. Kasting, J. F., Toon, O. B., and Pollack, J. B. (1988) How Climate Evolved on the Terrestrial Planets, *Scientific American* **258**, 90–97.
17. Kennett, J. P. (1977) Cenozoic evolution of Antarctic glaciation, Circum-Antarctic Ocean, and their impact on global paleoceanography, *Journal of Geophysical Research-Oceans and Atmospheres* **82**, 3843–3860.
18. Rind, D. (2002) Climatology – the sun’s role in climate variations, *Science* **296**, 673–677.
19. Ruddiman, W. R. (2001) *Earth’s Climate: Past and Future*, Freeman, New York.
20. Sijp, W. P., England, M. H., and Toggweiler, J. R. (2009) Effect of ocean gateway changes under greenhouse warmth, *Journal of Climate* **22**, 6639–6652.
21. Roberts, N. (1998) *The Holocene*, Blackwell, Oxford.
22. Archer, D., Winguth, A., Lea, D., and Mahowald, N. (2000) What caused the glacial/interglacial atmospheric pCO₂ cycles?, *Reviews of Geophysics* **38**, 159–189.
23. Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J. M., Chappellaz, J., Fischer, H., Gallet, J. C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J. P., Stenni, B., Stocker, T. F., Tison, J. L., Werner, M., and Wolff, E. W. (2007) Orbital and millennial Antarctic climate variability over the past 800,000 years, *Science* **317**, 793–796.
24. Luthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J. M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K., and Stocker, T. F. (2008) High-resolution carbon dioxide concentration record 650,000–800,000 years before present, *Nature* **453**, 379–382.
25. Rohling, E. J., Grant, K., Bolshaw, M., Roberts, A. P., Siddall, M., Hemleben, C., and Kucera, M. (2009) Antarctic temperature and global sea level closely coupled over the past five glacial cycles, *Nature Geoscience* **2**, 500–504.
26. Kohler, P., Bintanja, R., Fischer, H., Joos, F., Knutti, R., Lohmann, G., and Masson-Delmotte, V. (2010) What caused Earth’s temperature variations during the last 800,000 years? Data-based evidence on radiative forcing and constraints on climate sensitivity, *Quaternary Science Reviews* **29**, 129–145.
27. Mahowald, N. M., Muhs, D. R., Levis, S., Rasch, P. J., Yoshioka, M., Zender, C. S., and Luo, C. (2006)

Change in atmospheric mineral aerosols in response to climate: Last glacial period, preindustrial, modern, and doubled carbon dioxide climates, *Journal of Geophysical Research-Atmospheres* **111**, D10202.

28. Brierley, C. M., Fedorov, A. V., Liu, Z. H., Herbert, T. D., Lawrence, K. T., and LaRiviere, J. P. (2009) Greatly expanded tropical warm pool and weakened Hadley circulation in the early Pliocene, *Science* **323**, 1714–1718.

29. Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K. (2001) Trends, rhythms, and aberrations in global climate 65 Ma to present, *Science* **292**, 686–693.

30. Dunkley Jones, T., Ridgwell, A., Lunt, D. J., Maslin, M. A., Schmidt, D. N., and Valdes, P. J. (2010) A Palaeogene perspective on climate sensitivity and methane hydrate instability, *Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences* **368**, 2395–2415.

31. Pagani, M., Caldeira, K., Archer, D., and Zachos, J. C. (2006) An ancient carbon mystery, *Science* **314**, 1556–1557.

32. Clement, A. C., and Peterson, L. C. (2008) Mechanisms of abrupt climate change of the last glacial period, *Reviews of Geophysics* **46**, RG4002.

33. Severinghaus, J. P. (2009) Climate change: Southern see-saw seen, *Nature* **457**, 1093–1094.

34. Siddall, M., Rohling, E. J., Thompson, W. G., and Waelbroeck, C. (2008) Marine isotope stage 3 sea level fluctuations: data synthesis and new outlook, *Reviews of Geophysics* **46**, RG4003.

35. Broecker, W. S. (2001) Paleoclimate – was the medieval warm period global?, *Science* **291**, 1497–1499.

36. Cook, E., Bird, T., Peterson, M., Barbetti, M., Buckley, B., Darrigo, R., Francey, R., and Tans, P. (1991) Climatic-change in Tasmania inferred from a 1089-year tree-ring chronology of Huon Pine, *Science* **253**, 1266–1268.

37. Cook, E. R., Palmer, J. G., and D'Arrigo, R. D. (2002) Evidence for a 'Medieval Warm Period' in a 1,100 year tree-ring reconstruction of past austral summer temperatures in New Zealand, *Geophysical Research Letters* **29**, doi:10.1029/2001GL014580.

38. Mann, M. E., Zhang, Z. H., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F. B. (2009) Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly, *Science* **326**, 1256–1260.

39. Palmer, J. G., and Xiong, L. M. (2004) New Zealand climate over the last 500 years reconstructed from *Libocedrus bidwillii* Hook. f. tree-ring chronologies, *Holocene* **14**, 282–289.

40. Polyak, L., Alley, R. B., Andrews, J. T., Brigham-Grette, J., Cronin, T. M., Darby, D. A., Dyke, A. S., Fitzpatrick, J. J., Funder, S., Holland, M., Jennings, A. E., Miller, G. H., O'Regan, M., Saville, J., Serreze, M., St. John, K., White, J. W. C., and Wolff, E. (2010) History of Sea Ice in the Arctic, *Quaternary Science Reviews* **29**, 1757–1778.

41. Cullen, H. M., deMenocal, P. B., Hemming, S., Hemming, G., Brown, F. H., Guilderson, T., and Sirocko, F. (2000) Climate change and the collapse

of the Akkadian empire: Evidence from the deep sea, *Geology* **28**, 379–382.

42. Hodell, D. A., Brenner, M., and Curtis, J. H. (2005) Terminal Classic drought in the northern Maya lowlands inferred from multiple sediment cores in Lake Chichancanab (Mexico), *Quaternary Science Reviews* **24**, 1413–1427.

43. Brohan, P., Kennedy, J. J., Harris, I., Tett, S. F. B., and Jones, P. D. (2006) Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850, *Journal of Geophysical Research-Atmospheres* **111**, D12106.

44. Hansen, J., Ruedy, R., Sato, M., Imhoff, M., Lawrence, W., Easterling, D., Peterson, T., and Karl, T. (2001) A closer look at United States and global surface temperature change, *Journal of Geophysical Research-Atmospheres* **106**, 23947–23963.

45. Smith, T. M., and Reynolds, R. W. (2005) A global merged land-air-sea surface temperature reconstruction based on historical observations (1880–1997), *Journal of Climate* **18**, 2021–2036.

46. Trenberth, K. E., Jones, P. D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D. E., Rahimzadeh, F., Renwick, J. A., Rusticucci, M., Soden, B. J., and Zhai, P. (2007) Observations: surface and atmospheric climate change, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Avery, K. B., Tignor, M., and Miller, H. L., Eds.), Cambridge University Press, Cambridge.

47. Meehl, G. A., Tebaldi, C., Walton, G., Easterling, D., and McDaniel, L. (2009) Relative increase of record high maximum temperatures compared to record low minimum temperatures in the U. S., *Geophysical Research Letters* **36**, L23701.

48. Karl, T. R., Hassol, S. J., Miller, C. D., and Murray, W. L., (Eds.) (2006) *Temperature trends in the lower atmosphere: steps for understanding and reconciling differences*, NOAA/NCDC, Asheville.

49. Mears, C. A., and Wentz, F. J. (2005) The effect of diurnal correction on satellite-derived lower tropospheric temperature, *Science* **309**, 1548–1551.

50. Ramaswamy, V., Schwarzkopf, M. D., Randel, W. J., Santer, B. D., Soden, B. J., and Stenchikov, G. L. (2006) Anthropogenic and natural influences in the evolution of lower stratospheric cooling, *Science* **311**, 1138–1141.

51. Randel, W. J., Shine, K. P., Austin, J., Barnett, J., Claud, C., Gillett, N. P., Keckhut, P., Langematz, U., Lin, R., Long, C., Mears, C., Miller, A., Nash, J., Seidel, D. J., Thompson, D. W. J., Wu, F., and Yoden, S. (2009) An update of observed stratospheric temperature trends, *Journal of Geophysical Research-Atmospheres* **114**, D02107.

52. Thompson, D. W. J., and Solomon, S. (2009) Understanding Recent Stratospheric Climate Change, *Journal of Climate* **22**, 1934–1943.

53. Bindoff, N. L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J. M., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C. K., Talley, L. D., and Unnikrishnan, A. (2007) Observations: oceanic climate change and sea level, *Climate Change 2007: The Physical Science Basis. Contribution of*

Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Eds.), Cambridge University Press, Cambridge.

54. Murphy, D. M., Solomon, S., Portmann, R. W., Rosenlof, K. H., Forster P. M., Wong, T. (2009) An observationally based energy balance for the Earth since 1950, *Journal of Geophysical Research-Atmospheres* **114**, D17107.

55. Domingues, C. M., Church, J. A., White, N. J., Gleckler, P. J., Wijffels, S. E., Barker, P. M., and Dunn, J. R. (2008) Improved estimates of upper-ocean warming and multi-decadal sea-level rise, *Nature* **453**, 1090–1096.

56. Gille, S. T. (2002) Warming of the Southern Ocean since the 1950s, *Science* **295**, 1275–1277.

57. Ishii, M., and Kimoto, M. (2009) Reevaluation of historical ocean heat content variations with time-varying XBT and MBT depth bias corrections, *Journal of Oceanography* **65**, 287–299.

58. Levitus, S., Antonov, J. I., Boyer, T. P., Locarnini, R. A., Garcia, H. E., and Mishonov, A. V. (2009) Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems, *Geophysical Research Letters* **36**, L07608.

59. Parker, D. E. (2004) Climate: large-scale warming is not urban, *Nature* **432**, 290–290.

60. Parker, D. E. (2006) A demonstration that large-scale warming is not urban, *Journal of Climate* **19**, 2882–2895.

61. Peterson, T. C. (2003) Assessment of urban versus rural in situ surface temperatures in the contiguous United States: no difference found, *Journal of Climate* **16**, 2941–2959.

62. Easterling, D. R., and Wehner, M. F. (2009) Is the climate warming or cooling?, *Geophysical Research Letters* **36**, 8706–8718.

63. Cogley, J. G. (2009) Geodetic and direct mass-balance measurements: comparison and joint analysis, *Annals of Glaciology* **50**, 96–100.

64. Kaser, G., Cogley, J. G., Dyurgerov, M. B., Meier, M. F., and Ohmura, A. (2006) Mass balance of glaciers and ice caps: consensus estimates for 1961–2004, *Geophysical Research Letters* **33**, L19501.

65. Lemke, P., Ren, J., Alley, R. B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R. H., and Zhang, T. (2007) Observations: changes in snow, ice and frozen ground, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Eds.), Cambridge University Press, Cambridge.

66. Meier, M. F., Dyurgerov, M. B., Rick, U. K., O'Neel, S., Pfeffer, W. T., Anderson, R. S., Anderson, S. P., and Glazovsky, A. F. (2007) Glaciers dominate Eustatic sea-level rise in the 21st century, *Science* **317**, 1064–1067.

67. Allison, I., Alley, R. B., Fricker, H. A., Thomas, R. H., and Warner, R. C. (2009) Ice sheet mass balance and sea level, *Antarctic Science* **21**, 413–426.

68. Velicogna, I. (2009) Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, *Geophysical Research Letters* **36**, L19503.

69. Church, J. A., and White, N. J. (2006) A 20th century acceleration in global sea-level rise, *Geophysical Research Letters* **33**, L01602.

70. Cazenave, A. and Llovel, W. (2010) Contemporary Sea Level Rise, *Annual Review of Marine Science* **2**, 145–173.

71. Kwok, R., Cunningham, G. F., Wensnahan, M., Rigor, I., Zwally, H. J., and Yi, D. (2009) Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008, *Journal of Geophysical Research-Oceans* **114**, C07005.

72. Kwok, R., and Rothrock, D. A. (2009) Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008, *Geophysical Research Letters* **36**, L15501.

73. Turner, J., Comiso, J. C., Marshall, G. J., Lachlan-Cope, T. A., Bracegirdle, T., Maksym, T., Meredith, M. P., Wang, Z. M., and Orr, A. (2009) Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent, *Geophysical Research Letters* **36**, L08502.

74. Allan, R. P., and Soden, B. J. (2008) Atmospheric warming and the amplification of precipitation extremes, *Science* **321**, 1481–1484.

75. Durack, P. J., and Wijffels, S. E. (2010) Fifty-year trends in global ocean salinities and their relationship

to broad-scale warming, *Journal of Climate* doi: 10.1175/2010JCLI3377.1.

76. Thompson, D. W. J., and Solomon, S. (2002) Interpretation of recent Southern Hemisphere climate change, *Science* **296**, 895–899.

77. Hall, A., and Visbeck, M. (2002) Synchronous variability in the southern hemisphere atmosphere, sea ice, and ocean resulting from the annular mode, *Journal of Climate* **15**, 3043–3057.

78. Nicholls, N. (2006) Detecting and attributing Australian climate change: A review, *Australian Meteorological Magazine* **55**, 199–211.

79. Timbal, B., Arblaster, J. M., and Power, S. (2006) Attribution of the late-twentieth-century rainfall decline in southwest Australia, *Journal of Climate* **19**, 2046–2062.

80. Rintoul, S. R. (2007) Rapid freshening of Antarctic Bottom Water formed in the Indian and Pacific oceans, *Geophysical Research Letters* **34**, L06606.

81. CSIRO and the Bureau of Meteorology (2010) *State of the Climate*.

82. Alexander, L. V., and Arblaster, J. M. (2009) Assessing trends in observed and modelled climate extremes over Australia in relation to future projections, *International Journal of Climatology* **29**, 417–435.

83. Lucas, C., Hennessy, K., Mills, G., and Bathols, J. (2007) *Bushfire weather in the southeast Australia: Recent trends and project climate change impacts*,

(Consultancy report prepared for Climate Institute of Australia by the Bushfire CRC Australian Bureau of Meteorology and CSIRO, Ed.).

84. Alexander, L. V., and Power, S. (2009) Severe storms inferred from 150 years of sub-daily pressure observations along Victoria's "Shipwreck Coast", *Australian Meteorological and Oceanographic Journal* **58**, 129–133.

85. Larsen, S. H., and Nicholls, N. (2009) Southern Australian rainfall and the subtropical ridge: Variations, interrelationships, and trends, *Geophysical Research Letters* **36**, L08708.

86. Boning, C. W., Dispert, A., Visbeck, M., Rintoul, S. R., and Schwarzkopf, F. U. (2008) The response of the Antarctic Circumpolar Current to recent climate change, *Nature Geoscience* **1**, 864–869.

87. Hill, K. L., Rintoul, S. R., Coleman, R., and Ridgway, K. R. (2008) Wind forced low frequency variability of the East Australia Current, *Geophysical Research Letters* **35**, L08602.

88. Church, J. A., Hunter, J. R., McInnes, K. L., and White, N. J. (2006) Sea-level rise around the Australian coastline and the changing frequency of extreme events, *Australian Meteorological Magazine*, 253–260.

89. National Tidal Centre. (2009) *The Australian baseline sea-level monitoring project, annual sea-level data summary report*, Bureau of Meteorology.

90. Conway, T. J., Lang, P. M., and Masarie, K. A. (2009) Atmospheric carbon dioxide dry air mole fraction from the NOAA ESRL carbon cycle

cooperative global air sampling network, 1968–2008, file:///Volumes/ftp.cmdl.noaa.gov/ccg/co2/flask/event.

91. Dlugokencky, E. J., Bruhwiler, L., White, J. W. C., Emmons, L. K., Novelli, P. C., Montzka, S. A., Masarie, K. A., Lang, P. M., Crotwell, A. M., Miller, J. B., and Gatti, L. V. (2009) Observational constraints on recent increases in the atmospheric CH₄ burden, *Geophysical Research Letters* **36**, L18803.

92. Dlugokencky, E. J., Houweling, S., Bruhwiler, L., Masarie, K. A., Lang, P. M., Miller, J. B., and Tans, P. P. (2003) Atmospheric methane levels off: Temporary pause or a new steady-state?, *Geophysical Research Letters* **30**, doi:10.1029/2003GL018126.

93. Dlugokencky, E. J., Lang, P. M., and Masarie, K. A. (2009) Atmospheric methane dry air sampling network, 1983–2008, file:///Volumes/ftp.cmdl.noaa.gov/ccg/ch4/flask/event/.

94. Prinn, R. G., Weiss, R. F., Fraser, P. J., Simmonds, P. G., Cunnold, D. M., Alyea, F. N., O'Doherty, S., Salameh, P., Miller, B. R., Huang, J., Wang, R. H. J., Hartley, D. E., Harth, C., Steele, L. P., Sturrock, G., Midgley, P. M., and McCulloch, A. (2000) A history of chemically and radiatively important gases in air deduced from ALE/GAGE/AGAGE, *Journal of Geophysical Research-Atmospheres* **105**, 17751–17792.

95. McFarling Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., van Ommen, T., Smith, A., and Elkins, J. (2006) Law Dome CO₂, CH₄ and N₂O ice core records extended to 2000 years BP, *Geophysical Research Letters* **33**, L14810.

96. Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J. M., Basile, I., Bender, M., Chappellaz, J.,

Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M. (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature* **399**, 429–436.

97. Ehhalt, D., Prather, M., Dentener, F., Derwent, R., Dlugokencky, E. J., Holland, E., Isaksen, I., Katima, J., Kirchhoff, V., Matson, P., Midgley, P. M., and Wang, M. (2001) Atmospheric chemistry and greenhouse gases, in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Eds.), Cambridge University Press, Cambridge.

98. Le Quéré, C., and Metzl, P. (2004) Natural process regulating the oceanic uptake of CO₂, in *The Global Carbon Cycle: Integrating Humans, Climate and the Natural World* (Field, C. B., and Raupach, M. R., Eds.), Island Press, Washington D.C.

99. Le Quéré, C., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J. I., Huntingford, C., Levy, P. E., Lomas, M. R., Majkut, J., Metzl, N., Ometto, J. P., Peters, G. P., Prentice, I. C., Randerson, J. T., Running, S. W., Sarmiento, J. L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G. R., and Woodward, F. I. (2009) Trends in the sources and sinks of carbon dioxide, *Nature Geoscience* **2**, 831–836.

100. Prentice, I. C., Farquhar, G. D., Fasham, M.

J. R., Goulden, M. L., Heimann, M., Jaramillo, V. J., Kheshgi, H. S., Le Quéré, C., Scholes, R. J., and Wallace, D. W. R. (2001) The carbon cycle and atmospheric carbon dioxide, *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Eds.), Cambridge University Press, Cambridge.

101. Sabine, C. L., Hiemann, M., Artaxo, P., Bakker, D. C. E., Chen, C.-T. A., Field, C. B., Gruber, N., Le Quéré, C., Prinn, R. G., Richey, J. E., Romero, P., Sathaye, J. A., and Valenti, R. (2004) Current status and past trends of the global carbon cycle, *The Global Carbon Cycle: Integrating Humans, Climate and the Natural World* (Field, C. B., and Raupach, M. R., Eds.), 17–44, Island Press, Washington D.C.

102. Canadell, J. G., Le Quéré, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., Conway, T. J., Gillett, N. P., Houghton, R. A., and Marland, G. (2007) Contributions to accelerating atmospheric CO₂ growth from economic activity, carbon intensity, and efficiency of natural sinks, *Proceedings of the National Academy of Sciences of the United States of America* **104**, 18866–18870.

103. Raupach, M. R., Canadell, J. G., and Le Quéré, C. (2008) Anthropogenic and biophysical contributions to increasing atmospheric CO₂ growth rate and airborne fraction, *Biogeosciences* **5**, 1601–1613.

104. Doney, S. C., Fabry, V. J., Feely, R. A., and Kleypas, J. A. (2009) Ocean Acidification: The Other CO₂ Problem, *Annual Review of Marine Science* **1**, 169–192.

- 105.** Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., Wanninkhof, R., Wong, C. S., Wallace, D. W. R., Tilbrook, B., Millero, F. J., Peng, T. H., Kozyr, A., Ono, T., and Rios, A. F. (2004) The oceanic sink for anthropogenic CO₂, *Science* **305**, 367–371.
- 106.** Broecker, W. S., Peng, T. H., and Engh, R. (1980) Modeling the Carbon System, *Radiocarbon* **22**, 565–598.
- 107.** Manning, A. C., and Keeling, R. F. (2006) Global oceanic and land biotic carbon sinks from the Scripps atmospheric oxygen flask sampling network, *Tellus Series B-Chemical and Physical Meteorology* **58**, 95–116.
- 108.** Raupach, M. R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J. G., Klepper, G., and Field, C. B. (2007) Global and regional drivers of accelerating CO₂ emissions, *Proceedings of the National Academy of Sciences of the United States of America* **104**, 10288–10293.
- 109.** Raupach, M. R., and Canadell, J. G. (2010) Carbon and the anthropocene, *Current Opinion in Environmental Sustainability* **2**, doi:10.1016/j.cosust.2010.04.003.
- 110.** Manabe S. and Wetherald, R. T. (1967) Thermal equilibrium of the atmosphere with a given distribution of relative humidity, *Journal of the Atmospheric Sciences* **24**, 241–259.
- 111.** Harries, J. E., Brindley, H. E., Sago, P. J., and Bantges, R. J. (2001) Increases in greenhouse forcing inferred from the outgoing longwave radiation spectra of the Earth in 1970 and 1997, *Nature* **410**, 355–357.
- 112.** Hegerl, G. C., Zwiers, F., Braconnot, P., Gillett, N., Luo, Y., Marengo Orsini, J. A., Nicholls, N., Penner, J. E., and Stott, P. A. (2007) Understanding and attributing climate change, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Eds.), Cambridge University Press, Cambridge.
- 113.** Penner, J. E., Andreae, M., Annegarn, H., Barrie, L., Feichter, J., Hegg, D., Jayaraman, A., Leaitch, R., Murphy, D., Nganga, J., and Pitari, G. (2001) Aerosols, their direct and indirect effects, *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Eds.), Cambridge University, Cambridge.
- 114.** Quaas, J., Ming, Y., Menon, S., Takemura, T., Wang, M., Penner, J. E., Gettelman, A., Lohmann, U., Bellouin, N., Boucher, O., Sayer, A. M., Thomas, G. E., McComiskey, A., Feingold, G., Hoose, C., Kristjansson, J. E., Liu, X., Balkanski, Y., Donner, L. J., Ginoux, P. A., Stier, P., Grandey, B., Feichter, J., Sednev, I., Bauer, S. E., Koch, D., Grainger, R. G., Kirkevåg, A., Iversen, T., Seland, O., Easter, R., Ghan, S. J., Rasch, P. J., Morrison, H., Lamarque, J. F., Iacono, M. J., Kinne, S., and Schulz, M. (2009) Aerosol indirect effects – general circulation model intercomparison and evaluation with satellite data, *Atmospheric Chemistry and Physics* **9**, 8697–8717.
- 115.** Wild, M. (2009) Global dimming and brightening: A review, *Journal of Geophysical Research-Atmospheres* **114**, D00D13.
- 116.** Yu, H., Kaufman, Y. J., Chin, M., Feingold, G., Remer, L. A., Anderson, T. L., Balkanski, Y., Bellouin, N., Boucher, O., Christopher, S., DeCola, P., Kahn, R., Koch, D., Loeb, N., Reddy, M. S., Schulz, M., Takemura, T., and Zhou, M. (2006) A review of measurement-based assessments of the aerosol direct radiative effect and forcing, *Atmospheric Chemistry and Physics* **6**, 613–666.
- 117.** Stott, P. A., Gillett, N. P., Hegerl, G. C., Karoly, D., Stone, D., Zhang, X., and Zwiers, F. (2010) Detection and attribution of climate change: a regional perspective, *WIREs: Climate Change* **1**, 192–211.
- 118.** Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J., and Zhao, Z.-C. (2007) Global climate projections, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Eds.), Cambridge University Press, Cambridge.
- 119.** Royer, D. L., Berner, R. A., and Park, J. (2007) Climate sensitivity constrained by CO₂ concentrations over the past 420 million years, *Nature* **446**, 530–532.
- 120.** Hegerl, G. C., Karl, T. R., Allen, M., Bindoff, N. L., Gillett, N., Karoly, D., Zhang, X. B., and Zwiers, F. (2006) Climate change detection and attribution: Beyond mean temperature signals, *Journal of Climate* **19**, 5058–5077.
- 121.** Frohlich, C., and Lean, J. (2004) Solar radiative output and its variability: evidence and mechanisms, *Astronomy and Astrophysics Review* **12**, 273–320.
- 122.** Solanki, S. K., Schussler, M., and Fligge, M. (2002) Secular variation of the Sun's magnetic flux, *Astronomy & Astrophysics* **383**, 706–712.
- 123.** Lockwood, M., and Frohlich, C. (2007) Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature, *Proceedings of the Royal Society A: Mathematical Physical and Engineering Sciences* **463**, 2447–2460.
- 124.** Lockwood, M., and Frohlich, C. (2008) Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature. II. Different reconstructions of the total solar irradiance variation and dependence on response time scale, *Proceedings of the Royal Society A: Mathematical Physical and Engineering Sciences* **464**, 1367–1385.
- 125.** Forster, P., Ramaswamy, V., Artaxo, P., Bernsten, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, J. A., Myhre, G., Nganga, J., Prinn, R. G., Raga, G., Schulz, M., and Van Dorland, R. (2007) Changes in atmospheric constituents and in radiative forcing, *Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Eds.), Cambridge University Press, Cambridge.

- 126.** Lean, J. L., Rottman, G. J., Kyle, H. L., Woods, T. N., Hickey, J. R., and Puga, L. C. (1997) Detection and parameterization of variations in solar mid- and near-ultraviolet radiation (200–400 nm), *Journal of Geophysical Research-Atmospheres* **102**, 29939–29956.
- 127.** Karoly, D. J., and Braganza, K. (2005) Attribution of recent temperature changes in the Australian region, *Journal of Climate* **18**, 457–464.
- 128.** Stott, P. A. (2003) Attribution of regional-scale temperature changes to anthropogenic and natural causes, *Geophysical Research Letters* **30**, 1728.
- 129.** Arblaster, J. M., and Meehl, G. A. (2006) Contributions of external forcings to southern annular mode trends, *Journal of Climate* **19**, 2896–2905.
- 130.** Fogt, R. L., Perlwitz, J., Monaghan, A. J., Bromwich, D. H., Jones, J. M., and Marshall, G. J. (2009) Historical SAM Variability. Part II: Twentieth-Century Variability and Trends from Reconstructions, Observations, and the IPCC AR4 Models, *Journal of Climate* **22**, 5346–5365.
- 131.** Gillett, N. P., Allan, R. J., and Ansell, T. J. (2005) Detection of external influence on sea level pressure with a multi-model ensemble, *Geophysical Research Letters* **32**, L19714.
- 132.** Gillett, N. P., Zwiers, F. W., Weaver, A. J., and Stott, P. A. (2003) Detection of human influence on sea-level pressure, *Nature* **422**, 292–294.
- 133.** Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R. J., Sumi, A., and Taylor, K. E. (2007) Climate models and their evaluation, *Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Eds.), Cambridge University Press, Cambridge.
- 134.** Knutti, R., and Hegerl, G. C. (2008) The equilibrium sensitivity of the Earth's temperature to radiation changes, *Nature Geoscience* **1**, 735–743.
- 135.** Alley, R. B., Clark, P. U., Huybrechts, P., and Joughin, I. (2005) Ice-sheet and sea-level changes, *Science* **310**, 456–460.
- 136.** Overpeck, J. T., Otto-Bliesner, B. L., Miller, G. H., Muhs, D. R., Alley, R. B., and Kiehl, J. T. (2006) Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise, *Science* **311**, 1747–1750.
- 137.** Kopp, R. E., Simons, F. J., Mitrovica, J. X., Maloof, A. C., and Oppenheimer, M. (2009) Probabilistic assessment of sea level during the last interglacial stage, *Nature* **462**, 863–867.
- 138.** Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., Frame, D. J., and Allen, M. R. (2009) Greenhouse-gas emission targets for limiting global warming to 2 degrees C, *Nature* **458**, 1158–1162.
- 139.** IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, Geneva.
- 140.** Sokolov, A. P., Stone, P., Forest, C. R., Prinn, M. S., Webster, M., Paltsev, S., Schlosser, C., Kicklighter, D., Dutkiewicz, S., Reilly, J., Wang, C., Felzer, B., Melillo, J., & Jacoby, H. (2009) Probabilistic forecast for 21st century climate based on uncertainties in emissions (without policy) and climate parameters, *Journal of Climate* **22**, 5175–5204.
- 141.** Cook, K. H., and Vizy, E. K. (2008) Effects of twenty-first-century climate change on the Amazon rain forest, *Journal of Climate* **21**, 542–560.
- 142.** Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J. (2008) Tipping elements in the Earth's climate system, *Proceedings of the National Academy of Sciences of the United States of America* **105**, 1786–1793.
- 143.** Solomon, S., Plattner, G. K., Knutti, R., and Friedlingstein, P. (2009) Irreversible climate change due to carbon dioxide emissions, *Proceedings of the National Academy of Sciences of the United States of America* **106**, 1704–1709.
- 144.** Gregory, J. M., and Huybrechts, P. (2006) Ice-sheet contributions to future sea-level change, *Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences* **364**, 1709–1731.
- 145.** Huybrechts, P., and de Wolde, J. (1999) The dynamic response of the Greenland and Antarctic ice sheets to multiple-century climatic warming, *Journal of Climate* **12**, 2169–2188.
- 146.** Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., and Meinshausen, N. (2009) Warming caused by cumulative carbon emissions towards the trillionth tonne, *Nature* **458**, 1163–1166.
- 147.** Anderson, K., and Bows, A. (2008) Reframing the climate change challenge in light of post-2000 emission trends, *Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences* **366**, 3863–3882.
- 148.** Hennessy, K., Fitzharris, B., Bates, B. C., Harvey, N., Howden, S. M., Hughes, L., Salinger, J., and Warrick, R. (2007) Australia and New Zealand, in *Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Eds.), Cambridge University Press, Cambridge.
- 149.** Hennessy, K., Lucas, C., Nicholls, N., Bathols, J., Suppiah, R., and Ricketts, J. (2006) *Climate change impacts on fire-weather in south-east Australia*, CSIRO.
- 150.** Knutson, T. R., McBride, J. L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J. P., Srivastava, A. K., and Sugi, M. (2010) Tropical cyclones and climate change, *Nature Geoscience* **3**, 157–163.
- 151.** Chiew, F. H. S., Kirono, D., Kent, D., and Vaze, J. (2009) Assessment of rainfall simulations from global climate models and implications for climate change impact on runoff studies, *18th World IMACS/ MODSIM Congress*, Cairns, Australia.
- 152.** Hennessy, K., Fawcett, R., Kirono, D., Mpelasoka, F., Jones, D., Bathols, J., Whetton,

P., Stafford Smith, M., Howden, M., Mitchell, C., and Plummer, N. (2008) *An assessment of the impact of climate change on the nature and frequency of exceptional climatic events*, Commonwealth of Australia, Canberra.

153. Lim, W. H., and Roderick, M. (2009) *An atlas of the global water cycle based on the IPCC AR4 climate models*, ANU epress, Canberra.

154. Hasson, A. E. A., Mills, G., Timbal, B., and Walsh, K. J. E. (2008) Assessing the impact of climate change on extreme fire weather in south east Australia, CAWCR.

155. McMichael, A. J., Woodruff, R. E., and Hale, S. (2006) Climate change and human health: present and future risks, *Lancet* **368**, 859–869.

156. Woodruff, D., Hales, S., Butler, C., and McMichael, A. J. (2005) *Climate change health impacts in Australia: effects of dramatic CO₂ emissions reductions*, Australian Conservation Foundation and the Australian Medical Association.

157. Stokes, C. J., and Howden, S. M., (Eds.) (2008) *An overview of climate change adaptation Australian primary industries – impacts, options and priorities*, CSIRO, Canberra.

158. Hobday, A. J., Poloczanska, E. S., and Matear, R. J., (Eds.) (2008) *Implications of climate change for Australian fisheries and aquaculture: a preliminary assessment*, Department of Climate Change, Canberra.

159. Hughes, T. P., Baird, A. H., Bellwood, D. R., Card, M., Connolly, S. R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J. B. C., Kleypas, J.,

Lough, J. M., Marshall, P., Nystrom, M., Palumbi, S. R., Pandolfi, J. M., Rosen, B., and Roughgarden, J. (2003) Climate change, human impacts, and the resilience of coral reefs, *Science* **301**, 929–933.

160. Steffen, W., Burbidge, A. A., Hughes, L., Kitching, R., Lindenmayer, D., Musgrave, W., Stafford Smith, M., and Werner, P. A. (2009) *Australia's biodiversity and climate change: a strategic assessment of the vulnerability of Australia's biodiversity to climate change*, CSIRO Publishing, Canberra.

161. Eliot, I., Finlayson, C. M., and Waterman, P. (1999) Predicted climate change sea-level rise and wetland management in the Australian wet-dry tropics, *Wetlands Ecology and Management* **7**, 63–81.

162. McInnes, K. L., Walsh, K. J. E., Hubbert, G. D., and Beer, T. (2003) Impact of sea-level rise and storm surges on a coastal community, *Natural Hazards* **30**, 187–207.

163. (2008) *Assessment of impacts of climate change on Australia's Physical Infrastructure*, ATSE, Melbourne.

164. Hennecke, W. G., Greve, C. A., Cowell, P. J., and Thom, B. G. (2004) GIS-based coastal behavior modeling and simulation of potential land and property loss: Implications of sea-level rise at Collaroy/Narrabeen Beach, Sydney (Australia), *Coastal Management* **32**, 449–470.

165. House of Representatives Standing Committee on Climate Change, W., Environment and Arts. (2009) *Managing our coastal zone in a changing climate: The time to act is now.*, Commonwealth of Australia, Canberra.

166. Australian Department of Resources Energy and Tourism. (2008) *Tourism and climate change – A framework for action.*

167. Howden, M., Hughes, L., Dunlop, M., Zethoven, I., Hilbert, D., and Chilcott, C. (2003) *Climate change impacts on biodiversity in Australia*, CSIRO Sustainable Ecosystems.

168. Thomas, C. D., Cameron, A., Green, R. E., Bakkenes, M., Beaumont, L. J., Collingham, Y. C., Erasmus, B. F. N., de Siqueira, M. F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A. S., Midgley, G. F., Miles, L., Ortega-Huerta, M. A., Peterson, A. T., Phillips, O. L., and Williams, S. E. (2004) Extinction risk from climate change, *Nature* **427**, 145–148.

169. Williams, S. E., Bolitho, E. E., and Fox, S. (2003) Climate change in Australian tropical rainforests: an impending environmental catastrophe, *Proceedings of the Royal Society of London Series B-Biological Sciences* **270**, 1887–1892.

170. World Population Project. (2007) *2007 Update of probabilistic world population projections.*

171. Vitousek, P. M., Mooney, H. A., Lubchenco, J., and Melillo, J. M. (1997) Human domination of Earth's ecosystems, *Science* **277**, 494–499.

172. Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzer, C., Gingrich, S., Lucht, W., and Fischer-Kowalski, M. (2007) Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems, *Proceedings of the National Academy of Sciences of the United States of America* **104**, 12942–12945.

173. Dupont, A., and Pearman, G. (2006) *Heating up the planet: climate change and security*, Lowy Institute for International Policy.

174. (2007) *World in transition – climate change as a security risk: summary for policy makers*, (German Advisory Council on Climate Change, Ed.), 14.

175. Garnaut, R. (2008) *The Garnaut Climate Change Review*, Cambridge University Press, Port Melbourne.

176. Rockstrom J., Steffen W., Noone K., Persson A., Chapin F. S., Lambin E. F., Lenton T. M., Scheffer M., Folke C., Schellnhuber H. J., Nykvist B., de Wit C. A., Hughes T., van der Leeuw S., Rodhe H., Sorlin S., Snyder P. K., Costanza R., Svedin U., Falkenmark M., Karlberg L., Corell R. W., Fabry V. J., Hansen, J., Walker B., Liverman D., Richardson K., Crutzen P., Foley J. A. (2009) A safe operating space for humanity, *Nature* **461**, 472–475.

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