1 Beyond reasonable doubt

THE INTERNET is a wonderful research tool. With the click of a mouse, you can beam yourself into what seems an infinite number of important lectures by eminent thinkers around the world.

Just such an opportunity awaits if you search for Richard A. Muller, professor of physics at the University of California, Berkeley. The results of such a search include a video of Professor Muller castigating the scientists at the centre of the 2009 Climategate scandal.

'Climategate' is the name given by sections of the American media to the 2009 imbroglio surrounding leaked emails from the Hadley Centre in the United Kingdom. The emails were used to suggest that some scientists had been selective in their use of data to support the idea of global warming. In the video, Professor Muller berates the Hadley Centre scientists for smoothing data to produce alarming graphs that would make global warming 'incontrovertible' to the public. Professor Muller concludes by announcing his own major study into the measurement of global warming, the Berkeley Earth Project, without 'the bias', he says in the video.

Some months later, in March 2011, Professor Muller appeared before a US congressional committee at the invitation of Republican members opposing action on climate change. He was there to present the preliminary results of his bias-free project. To his surprise, he said, and certainly to the surprise of his hosts, the results of the project tallied very closely with those of the Hadley Centre's temperature measurements, as well as those of the US National Aeronautics and Space Administration and the National Oceanic and Atmospheric Administration.

The fact is, that despite human imperfection, modern science on climate change has held up well under withering scrutiny. The vast majority of those who have spent their professional lives seeking to understand climate and the impacts of human activity on it have no doubt that average temperatures on earth are rising and that human-induced increases in greenhouse gases are making major contributions to these rises. They are supported in this by the learned academies of science in all of the countries of scientific accomplishment.

Where dissent is found in the community of scientists with genuine climate credentials, it is among a small number who argue that the effects of increases in greenhouse gases are small compared with other sources of changes in temperature.

But a larger number of alternative views can also be found on the other side of the debate. There are reputable scientists who argue that great changes in climate are triggered by lower greenhouse gas concentrations than the mainstream science suggests.

There are other important debates in the scientific community about the impacts of rising temperatures. For example, scientific climate models reveal wide variations in the regional distribution of projected changes in rainfall.

Another example is the extent of sea-level rise that is likely to be associated with specified degrees of warming. The decisive research relates to the mass of land-based ice in Greenland and Antarctica. This is a large issue, as the complete melting of Greenland ice would raise sea levels by about 7 metres, of west Antarctica by about 6 metres, and of east Antarctica by much larger amounts. The mainstream view from the peer-reviewed literature, brought into the public domain through the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, argued that sea-level rise would result from expansion of the oceans' volume as ocean temperatures rose and from the melting of alpine glaciers. It also included contributions from the surface melting of land-based ice in Greenland and Antarctica but not the potential losses from dynamical processes—the calving of large icebergs from outlet glaciers. This was not because the scientists with relevant expertise didn't think that these processes were important, but because not enough was known about them to include them in models of sea-level rise.

During the early research for this book, it was disconcerting to find that the few deep specialists in land-based ice expressed the view privately that there *would* be a major contribution from dynamical processes in Greenland and west Antarctica to sea-level rise this century. The dimensions of the contribution are uncertain, but they are certainly substantial and possibly greatly disruptive. All declined to put their private views on the public record.

The end point of the four-year research process that produced this book is the conclusion that it is highly probable that the central proposition of the mainstream science is correct. Most of the global warming since the mid-20th century is very likely due to human-caused increases in greenhouse gas concentrations. Furthermore, the range of genuine scientific views from the peer-reviewed mainstream suggests that temperatures and damage from a specified level of emissions over time will be larger than is suggested by the middle ground of the mainstream science.

The carbon cycle

Carbon is transferred, in various forms, through the atmosphere, oceans, plants, animals, soils and sediments as part of the carbon cycle. The term 'carbon budget' is often used to describe the balance of inflows and outflows that lead to the accumulation of carbon dioxide in the earth's atmosphere. These natural inflows and outflows were approximately equal for several thousands of years before the effects of the industrial revolution became apparent around 1800.

Since the early 19th century there has been a large and increasing inflow of carbon dioxide into the atmosphere from human activities. The burning of fossil fuels, cement production and other industrial processes, as well as deforestation or land clearing, are largely the cause.

Emissions from fossil fuels are the largest source of atmospheric carbon dioxide from human activities. Carbon dioxide emissions from fossil fuel combustion increased by about 2 per cent per year in the 1970s and 1980s, and by only around 1 per cent in the 1990s. Between 2000 and 2008, the annual increase in fossil fuel emissions grew to 3.4 per cent.

This trajectory is well above the IPCC scenario with the highest emissions through to 2100, which had been considered to be extreme until the publication in the 2008 Review of more realistic assessments. It is tracking closely the projections presented under business as usual in the 2008 Review. Even with a recent slight drop in the annual rate of increase due to the Great Crash, the average increase in emissions for the last decade was around 3 per cent.

Land-use changes, such as deforestation and conversion to crops, are the second-largest source of carbon dioxide emissions from human activities. In contrast to the 29 per cent increase in fossil fuel emissions between 2000 and 2008, land-use change emissions have been fairly steady and now account for less than 15 per cent of total emissions.

The human-caused increase in carbon dioxide in the atmosphere is partly offset by natural carbon dioxide 'sinks' in both the land and oceans. The efficacy of land-based carbon sinks is determined by the balance between plant growth, respiration from plants and soils, and land-use disturbances, such as fire and forest clearing. The ocean acts as a carbon sink because carbon dioxide dissolves in ocean waters when concentrations in the atmosphere are higher than those at the ocean's surface. This dissolved carbon is moved into the deeper ocean by overturning currents, and also by the sinking of dead organisms.

Over the past 50 years, the uptake by these natural sinks has continued to remove around half of the carbon dioxide put into the atmosphere, despite the increasing human-caused emissions. The carbon is taken up in roughly equal proportions by the land and the oceans. There is considerable variation in the strength of these natural sinks from year to year, largely in response to climate variability.

Some recent studies have indicated that there has been a decline over the last five decades in the percentage of carbon dioxide emissions from human activities that is absorbed by natural carbon sinks. There have been suggestions that this shows that natural carbon sinks are slowly 'losing the race' against the rapidly growing human-caused emissions. But there is controversy in the scientific community over these results.

The magnitude and the rate of the increase in concentrations of carbon dioxide, methane and nitrous oxide in the atmosphere in the last century have increased considerably compared to the past millennium. Between the years 1000 and 1750, carbon dioxide concentrations ranged between 275 and 285 parts per million (ppm). It then took more than 200 years, until the 1970s, for concentrations to increase by 50 ppm, but only another 30 years for a further increase of about 50 ppm to the current levels. Carbon dioxide concentrations have increased from 379 ppm in 2005 to 390 ppm in early 2011.

Concentrations of the two other main greenhouse gases—methane and nitrous oxide—have also increased, and remain well above concentrations of the last 20,000 years. Methane concentrations have more than doubled since the industrial revolution and increased by about 30 per cent in the 25 years up to the IPCC Fourth Assessment Report, although with some recent reductions in the rate of growth. The increase in methane concentrations is probably due to increased methane emissions from high latitudes and tropical wetlands, linked to increases in global temperatures and tropical precipitation. The concentration of nitrous oxide is now about 18 per cent above the 1750 level.

Between 1998 and 2010, the increase in greenhouse gas concentrations in the atmosphere is equivalent to a change in carbon dioxide concentrations from 438 ppm to 465 ppm.

Temperature trends

One of the IPCC's main conclusions in its 2007 report was that the 'warming of the climate system is unequivocal'. Global average temperatures had risen considerably since measurements began in the mid-1800s, and since pre-industrial times (1850–99) the global surface temperature had increased by

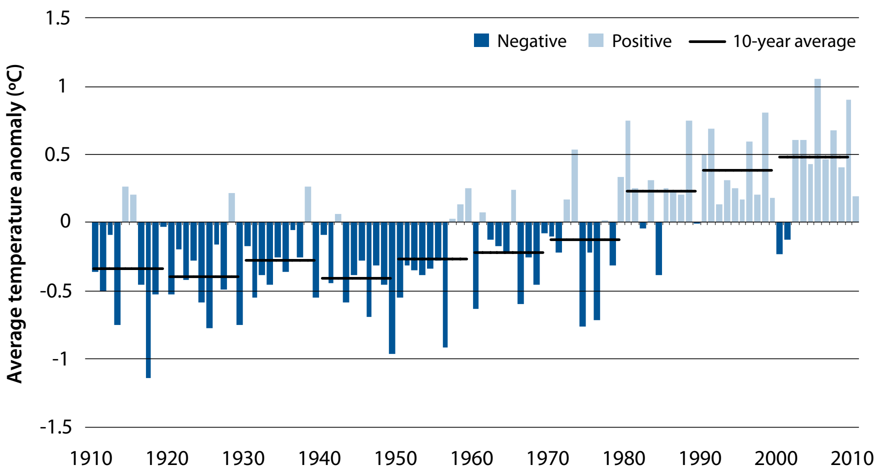
0.76 +/- 0.19°C. The Royal Society recognises that there is wide agreement in the scientific community on this aspect of climate change.

The World Meteorological Organization concluded: 'The year 2010 ranked as the warmest year on record, together with 2005 and 1998. Data received by the WMO show no statistically significant difference between global temperatures in 2010, 2005 and 1998. In 2010, the global average temperature was 0.53°C … above the 1961–90 mean.'

The IPCC's 2007 conclusion about warming trends was not based only on surface temperature data, but also on the changes in other levels in the atmosphere. Trends in other areas of the climate system, such as the uptake of heat by the oceans and the melting of land ice, such as glaciers, are also occurring. Hence, there is wide-ranging evidence of a warming trend in different indicators produced by independent researchers that provides a consistent story of a warming world.

In Australia, annual average temperatures have increased by 0.9°C since 1910. Figure 1.1 shows Australian average temperature anomalies since 1910. While 2005 is still the hottest year on record based on the mean annual temperature across Australia, 2009 was the second-warmest year.

Figure 1.1: Australian annual average temperature anomalies, 1910–2010



Note: The data show temperature difference from the 1961–90 average.

Source: Bureau of Meteorology time series data, retrieved 10 February 2011.

The decade ending in 2010 has easily been Australia's warmest since record keeping began. It continues a trend of each decade being warmer than the previous that extends back to the 1940s. The milder year in 2010 demonstrates that individual years can still be relatively cool even as the warming of Australia's climate continues.

New climate observations

When reporting on newly observed changes in the climate that have accompanied increases in temperature, we must remember that we are looking at a relatively short period (the research for this book was conducted over four years from 2007). There is inevitably a focus on recent weather and extreme events. Any set of observations over a short period will reflect the dynamic nature of the climate. Apparently random fluctuations from the norm create 'noise' that can make longer-term patterns and trends difficult to identify over a short period. Rather than being viewed as indicative of a change in climate or otherwise, single events or annual data must be considered within the context of the growing dataset of climate information.

So, in the future, it is quite consistent with the strictures of scientific observation of climate change to expect the climate system to respond in variable ways to an increased concentration of greenhouse gases.

Years like 2010 will continue to occur, where temperatures were high globally but some countries (in this case Australia) were relatively cool.

The regional variability of climate change will also manifest in severe weather events of an intensity that is rare at a particular place and time of year. 'Severe weather events' include (among others) heatwaves, heavy rainfall and floods, droughts, tropical cyclones and bushfires.

While it is difficult to attribute specific causes to individual severe weather events, climate change is expected to increase the risk of extreme events. The changes include greater frequency (heatwaves, bushfire conditions, floods, droughts), greater intensity (all of these plus cyclones) and changes in distribution (average rainfall).

The potential impact of climate change on severe weather events has been brought to the fore recently due to a series of major climate events globally and in Australia. Individual events may be assessed for their consistency with expectations in a warmer world and compared with the equivalent expectations if the underlying climate conditions had not been changing. For example, the conditions of the 2009 Black Saturday fires in Victoria were consistent with expectations for a warming world. There will be an increase in the frequency of such conditions as the world continues to warm.

However, such comparisons generally do not allow us to state categorically that such an event could only have occurred with climate change. We can say that the extreme conditions that were the backdrop to the Victorian bushfires or the 2011 Queensland cyclones and floods will be more likely to occur and will occur more often in a warmer world.

In making assessments about the effects of warming on extreme events, we should keep in mind that we are only in the early stages of global warming. Land temperatures have increased by less than half of the level that would be expected even with effective, strong mitigation to hold greenhouse gas concentrations to 450 ppm carbon dioxide equivalent. They have increased only one-quarter of the rise expected in the event of partially successful mitigation to 650 ppm carbon dioxide equivalent. And the increase to date is only a small fraction of ultimate temperature rises in the event of no mitigation at all.

The strength of some severe weather events is likely to rise more than proportionately with the increase in average global temperature. It is therefore to be expected that the reflection of global warming in severe weather events is in an early and weak stage.

Some recent work looking at events in the northern hemisphere has advanced understanding of the probability of a link between extreme events and climate change. A recent study looked at the probability of human-induced climate change increasing the risk of an extreme autumn flood event that occurred in the United Kingdom in 2000.

To analyse this single flood event, thousands of simulations of the weather experienced at the time were generated under realistic conditions, and also under conditions where the warming influence from greenhouse gas emissions had been removed. In nine out of ten cases, the results showed that human-induced greenhouse gas emissions in the 20th century increased the risk of the flood event by more than 20 per cent, and in two out of three cases by more than 90 per cent.

Another study used a similar approach to severe rainfall and heavy snowfall in the northern hemisphere. It found these events could not be explained without factoring in the increases in greenhouse gases from human activity.

A recent study on Australian temperature and rainfall records between 1911 and 2008 investigated changes in the percentage area of the continent experiencing extreme cold, hot, dry or wet conditions. It showed that for Australia as a whole—not at all locations—there has been an increase in the extent of wet extremes and a decrease in the extent of dry extremes, both annually and during all seasons.

Historically, co-variations in Australian extremes have been either hot and dry, or cold and wet. The same study detected a long-term shift towards wet extremes and hot extremes occurring at the same time, which is not consistent with processes causing variability between years and decades.

This suggests that the long-term trends are influenced by a separate process. The increase in both hot and wet extremes is consistent with changes as a result of increased concentrations of greenhouse gases.

One of the more obvious severe weather events on the wet side of the climate ledger is tropical cyclones. With more heat energy in the atmosphere and oceans, there will be fewer cyclones overall but more cyclones with extreme force. Tropical cyclones occur when warm, moist air rises and then condenses, leading to the release of energy and the formation of wind. Tropical cyclones do not form unless the sea surface temperature is above 26.5°C. Theory and modelling suggest that, as oceans warm, there will be more energy for conversion into tropical cyclone wind, leading to increased wind speeds and more intense cyclones.

Analysis has shown that rainfall associated with tropical cyclones (within 300 kilometres) is likely to increase by 17 per cent on average by 2070 compared to 1980. The same study showed that a larger percentage of tropical cyclones will produce higher wind speeds in 2070 than in either 1980 or 2030. These regional findings are consistent with recently published international studies.

The El Niño – Southern Oscillation will have a significant effect on future cyclones and storms in Australia, so it is difficult to project changes in the frequency and intensity of cyclones without a better understanding of this phenomenon.

Conversely, a considerable body of Australian research suggests that the persistent dry conditions in parts of the south-west and south-east of Australia are at least in part due to climate change. In the south-west, the movement of autumn and winter rain-bearing weather fronts to the south is associated with a southward shift of a large-scale atmospheric circulation system that has been linked to climate change. In the south-east, decreasing rainfall is strongly associated with strengthening over the region of high surface pressure that causes much of the seasonal variation in weather in the south of the continent. This increasing pressure is consistent with the rise in global mean temperature, and expectations from the physics of the climate system.

Climate models indicate that as temperatures rise further, rainfall will increase close to the poles and in equatorial regions, and decrease in subtropical and some temperate regions. Climate change will also influence the seasonal and daily patterns of rainfall intensity. The risk of drought is expected to increase in the mid-latitudes (southern Australia). Increased flood risk is also expected as rainfall is concentrated into more intense events.

Unlike future temperature, which is always simulated to increase throughout Australia, the results from some climate models show that many locations could be drier, while others suggest those locations could be wetter. However, the majority of climate models project a drier future for southern Australia than was experienced last century.

The 2008 Review noted research showing that up to 50 per cent of the decline in south-west Western Australia's rainfall was due to human-induced climate change. A reduction in rainfall results in a proportionately larger fall in stream flows. Annual inflows to Perth's water storages have declined markedly since the 1970s, and since 2006 have been only 17 per cent of the long-term average before this observed decline. Inflows reached a record low in 2010, which was the driest year on record for south-west Western Australia. Climate change is likely to contribute to further reductions in surface water availability in southern Australia.

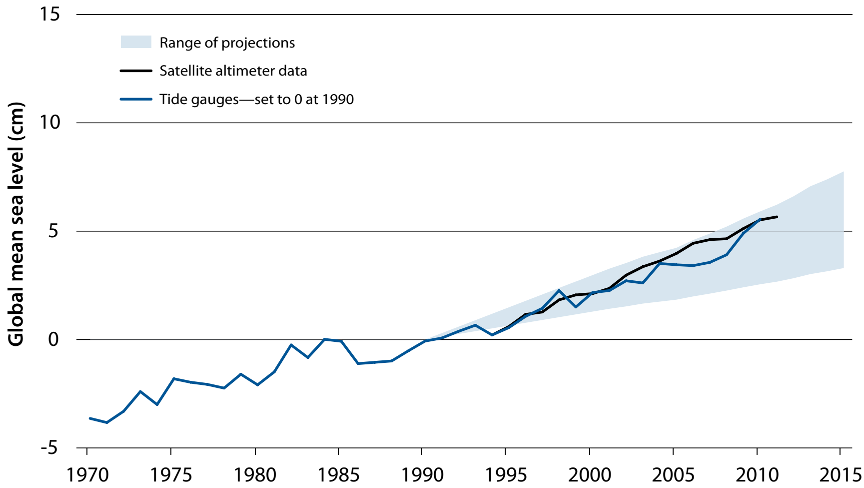
Changes to oceans and sea levels

The world's oceans store the majority of heat within the climate system. As a result, changes in the heat content of the oceans are a critical element in climate change, leading to increased sea surface temperatures and contributing to changes in sea level. Analysis of historical observations confirms that the oceans have warmed since 1950 and that they have stored more than 90 per cent of the increase in heat associated with global warming. This warming has continued over the last 15 years.

As any high school student should be able to tell you, as water warms it also expands in volume. When applied to the oceans, this process—called thermal expansion—results in rising sea levels. The total observed sea-level rise during the 20th century was about 160 millimetres, averaged over the global oceans. More recent observations indicate that sea level has been rising more rapidly over the past two decades, with the average rates since 1993 about 3.2 millimetres a year.

The sea-level rises from 1990 were anticipated in the two most recent IPCC reports. Observed sea level is tracking near the upper limit of the IPCC's 2007 projections for sea-level rise, as shown in Figure 1.2.

Figure 1.2: Changes in observed global sea level since 1970, compared with the IPCC Fourth Assessment Report sea-level rise projections



Note: Observational estimates of global averaged sea level estimated from tide gauges and the satellite altimeter data are shown in blue and black respectively. The shaded area shows the full range of global averaged projections of sea-level rise based on the scenarios used in the 2007 IPCC Fourth Assessment Report up to 2015. These projections do not include an additional allowance for a potential rapid loss of the Greenland and west Antarctic icesheets, which only becomes significant in the IPCC projections after about 2020. The tide gauge data is set to zero at the start of the IPCC projections in 1990 and the altimeter data is set equal to the tide gauge data at the start of the record in 1993.

Source: J.A. Church, J.M. Gregory, N.J. White, S. Platten and J.X. Mitrovica 2011, 'Understanding and projecting sea-level change', *Oceanography* 24(2): 84–97, updated from S. Rahmstorf, A. Cazenave et al. 2007, 'Recent climate observations compared to projections', *Science* 316(5825): 709.

The IPCC's Fourth Assessment Report in 2007 estimated that in a scenario similar to the 2008 Review's no-mitigation scenario, sea levels would rise in the range of 26 to 59 centimetres by 2100, with a lower limit for all IPCC scenarios of 18 centimetres. This figure did not include the potential dynamic losses from the Greenland and west Antarctic icesheets (increased calving), which could increase the upper end by about 10 to 20 centimetres by the end of this century. The IPCC also concluded that larger values above this upper estimate could not be excluded.

Quantitative estimates and upper limits for the contribution of the potentially rapid response of icesheets were not included because no consensus could be reached on the potential magnitude of these contributions by 2100.

The large land-based icesheets are currently losing mass to the ocean through both melting (Greenland) and dynamical flow (Greenland and Antarctica). The recent acceleration in the dynamical flow of both icesheets is thought to have been the result of incursion of relatively warmer ocean water underneath iceshelves. The warming leads to basal melting and thinning of the iceshelf, reducing the buttressing effect of the iceshelf on the icesheet, and the ice flow on land consequently accelerates towards the ocean, as observed in the Antarctic Peninsula.

There is considerable uncertainty whether this dynamical flow will continue as observed, or accelerate or decline in the future. The trends are based on shorter-term observation records and therefore are more difficult to distinguish from natural variability. However, a review of all observations shows that there is a net loss of mass from the Greenland and Antarctic icesheets. The uncertainty is about the rate at which this ice loss is occurring, not whether it is occurring at all. This uncertainty about the dynamics of the icesheets means that there could be a larger sea-level rise than current projections but not a significantly smaller rise.

There has been a significant focus on rates of sea-level rise and the future of the icesheets since the IPCC Fourth Assessment Report. The fact that observed sea-level rise is tracking near the upper limit of IPCC estimates has raised concerns that the IPCC projections may be underestimates. This is particularly so in the context of the current inability to adequately model the response of icesheets to global warming. These concerns have led to the development of several models of sea-level rise that use 20th century sea level and temperature records.

These 'semi-empirical' models all indicate larger rates of rise during the 21st century than the IPCC Fourth Assessment Report projections, with upper values as high as 1.9 metres by 2100. However, significant concerns have been raised about whether these projections are robust.

Other work suggests that a sea-level rise of more than two metres by 2100 is not physically possible, and that a more plausible rise—including icesheet contributions—is 80 centimetres, near the upper end of the IPCC estimates. The upper limit of sea-level rise in the 21st century is a matter for continuing research. There has been no credible publication of views that sea-level rise could be less than that suggested by the IPCC.

Changes to ecosystems

Another clear signal that warming is well under way can be found in the changing behaviours of various ecosystems. Research is showing that a warming signal is now evident in an increasing number of Australian and global observations of species. These include the southward expansion of the breeding range of black flying foxes and shifts in the timing of plant flowering. In some cases, such as the early emergence of butterflies in Melbourne, these changes have been attributed to climate change.

Responses to warming have also been observed in marine ecosystems, including the southward shift or extension of sea urchins and intertidal species. An important example is the increase in bleaching events on the Great Barrier Reef. There have been eight mass bleaching events on the Great Barrier Reef since 1979, with no known widespread bleaching events prior to that date.

Future climate change in Australia is likely to have impacts on ecosystems through increases in land temperatures and an increase in the variability, along with an overall decline, in rainfall in southern Australia. Major threats to ecosystems include extended drought periods, invasion of weeds and pests encouraged by the change in climate, altered fire regimes, land-use changes, direct temperature effects, increases in salinity and other water quality issues and changes in water availability.

Australia's biodiversity is not distributed evenly over the continent but is clustered in a small number of 'hotspots' with exceptionally rich biodiversity. Most of these areas, as well as many of Australia's most valued and iconic natural areas, are among the most vulnerable to future climate change. They include the Great Barrier and Ningaloo Reefs, south-west Western Australia, the Australian Alps, the Wet Tropics of Queensland and the Kakadu wetlands.

Predicting the future effects of climate change on Australia's biodiversity in these iconic areas and elsewhere is challenging for a variety of reasons. The effects of climate change will interact with other effects of human activities on biodiversity. Properties of ecological systems—communities of interacting species and their environment—are often complex, and can be difficult to understand and predict. A change in the average value of a variable, such as temperature, may not be as important ecologically as a change in the variability or extremes of that variable. Also, basic knowledge is generally lacking about limiting factors, genetics, dispersal rates and interactions among species that comprise Australian ecosystems.

Furthermore, many of the most important impacts of climate change on biodiversity will be the indirect ones, acting together with other factors. For example, for the Kakadu wetlands, the major threats of climate change are not the direct impacts on vulnerable species but rather an intersection of effects due to changing fire regimes, rising sea level and the resulting saltwater intrusion into freshwater wetlands, as well as the consequences of climate change for a suite of invasive weed and feral animal species.

Tipping points

Some climate change outcomes can be projected in a linear form based on current tendencies. There are also risks of abrupt, non-linear and irreversible changes in the climate system. These outcomes may have high consequences due to the extent or speed of the change. Other climate outcomes may have high consequences due to the numbers of people affected, including through the loss of ecosystem services such as pollination.

Some elements of the climate appear to be unresponsive to changes until a threshold is crossed, after which the response can be sudden, severe or irreversible. This threshold is referred to as a 'tipping point'. There is considerable uncertainty regarding the temperature at which this point may occur, as well as the likelihood of a given degree of human-driven climate change triggering any of these events.

One phenomenon that is irreversible is the acidification of oceans, which is caused by carbon dioxide dissolving in seawater. This has the potential to significantly affect marine organisms and ecosystems, including those that sustain important fisheries.

Measurements indicate that the average seawater acidity has increased by 30 per cent since pre-industrial times. Ocean acidification directly follows the accelerating trend in world carbon dioxide emissions, and the magnitude of ocean acidification can be determined with a high level of certainty based on the predictable marine carbonate chemistry reactions and cycles within the ocean. It is predicted that by 2050 ocean acidity could increase by 150 per cent. This is an added stressor for coral reefs because more acidic oceans lead to reduced calcification in corals.

There are a number of outcomes that could be considered extreme or high-consequence climate outcomes. They include changes to the El Niño – Southern Oscillation, the melting of the Himalayan glaciers, failure of the Indian Monsoon, the destruction of coral reefs and species extinction.

New research has focused on the tipping elements in the climate system. Progress has been made in identifying and testing potential early warning indicators of an approaching tipping point.

Attempts have also been made to better understand the probabilities of various tipping points by obtaining expert opinions from scientists. In a 2009 survey of 43 experts, each was asked about their views on the probability that certain major climate outcomes would occur. The results indicated that, while there is a range of views among experts about the prospect of major changes in the climate system being triggered, this does not necessarily imply that the probability of such outcomes occurring is considered to be low.

In fact, significant probability was allocated to some events, such as the dieback of the Amazon rainforest and melting of the Greenland icesheet.

The Amazon rainforest is the most widely cited example of a major plant and animal ecosystem at risk of abrupt change from a warming climate. Temperature increase, changes to the length of the dry season and the drought intensity anticipated under climate change will all influence the viability of the rainforest.

Simulations that incorporate the complex ecological processes in the rainforest system suggest that there is a threshold around a 2°C temperature increase above pre-industrial levels. Beyond that increase, the area of the Amazon forests subject to dieback rises rapidly, from 20 per cent to more than 60 per cent.

Severe droughts were recorded in the Amazon Basin in 2005 and 2010. The 2005 event was associated with the release of 5 billion tonnes of carbon dioxide due to the death and subsequent rotting of trees. Even larger emissions are expected as a result of the 2010 drought. Each time, the ability of the rainforest to absorb additional carbon dioxide is reduced.

Along with the observation that such droughts occur at the same time as peaks of fire activity, these recent events support the assessment that this ecosystem will be affected at relatively small temperature increases.

Such a dieback is an example of a carbon–climate feedback. These occur when changes in the climate affect the rate of absorption or release of carbon dioxide and other greenhouse gases from land and ocean sinks. Other examples of carbon–climate feedbacks include a reduction in the ability of the oceans to remove carbon dioxide from the atmosphere as water temperature increases, and the weakening of uptake by vegetation due to increased temperatures and reduced water availability.

There is also the risk of release of methane from permafrost and methane hydrate in the oceans as the world warms. This could lead to a positive feedback effect, where the increased temperatures cause a further release of these gases.

A recent study suggested that there are more than 1,700 billion tonnes of carbon stored in permafrost, which is about twice the amount stored in the atmosphere at present. It is unknown at what temperature this stored carbon might become unstable, or whether it would be released to the atmosphere over a short or long period of time. However, only about 100 of the 1,700 billion tonnes are considered to be vulnerable to thawing this century. Research on past and present emissions from these sources shows that current rates of emissions are low relative to overall global emissions, but it is not known whether these are new sources or just newly observed.

While the existence of tipping points can be anticipated with high confidence, specific thresholds at which they will occur cannot yet be predicted. Actively managing ecosystems to improve their resilience is important to ensure that the services that economies depend on—including pollination of crops and native vegetation, shade and shelter, maintenance of fertile soil and productive oceans, clean water and climate regulation—are available over the longer term.

Widespread ecological restoration could play an important role in ensuring the provision of ecosystem services and the maintenance of biodiversity. By addressing the range of pressures caused by human activities that, in combination, may push an ecosystem past a tipping point, we can help avoid or at least reduce the possibility of crossing a critical threshold. While climate change is a common driver of tipping point scenarios, in addition to reducing greenhouse gas emissions, investing in actions to improve ecosystem management will be needed to strengthen the ability of ecosystems to absorb and recover from shocks and reduce the risk of reaching irreversible tipping points.

Correlation is not causation

The dynamic and unpredictable nature of the earth's climate can make the detection of a climate change trend difficult. Even if observations are showing that trends are occurring in a range of climate variables, detection of a climate change trend is not the same as determining the cause. We need further evidence to establish a link between the observations and the cause.

The temperature of the earth and its atmosphere is determined by the balance of the incoming solar radiation and the heat that is radiated by the earth back into space. Temperature changes can occur as a result of more or less radiation coming in, or a change in the amount of outgoing radiation that is trapped by the atmosphere.

This balance can be influenced by a range of disturbances, including the sun's output, volcanic eruptions and, over hundreds of thousands of years, changes in the earth's orbit. To establish whether humans are responsible for the warming trend over the last 50 years, scientists need to establish that the changes are not explained by these natural factors.

Changes in the amount of solar radiation reaching the earth have been implicated in temperature fluctuations of the last 10,000 years. For the last 150 years, and especially since 1970, changes in solar output have been tracked with greater accuracy. Recent research suggests that solar output could have contributed at most 10 per cent to the observed warming trend in the 20th century, so other warming influences need to be considered.

Other important influences on the weather are shorter-term modes of natural variability, such as the El Niño – Southern Oscillation and the North Atlantic Oscillation. These phenomena may cause significant climatic variations on a year-to-year basis, but they cannot explain globally synchronous trends in temperature that occur from decade to decade.

To distinguish the contribution of greenhouse gases to observed trends from other potential influences, scientists have identified 'fingerprints of forcing'. These 'fingerprints' show patterns of change that are consistent with warming caused by greenhouse gases, rather than other sources, such as solar radiation.

One 'fingerprint' is the pattern of warming in the layers of the atmosphere. Models predict—and observations have confirmed—that the lowest layer of the atmosphere (the troposphere) is warming, while the next layer up (the stratosphere) is cooling. Increased output from the sun would be expected to warm both layers. This pattern can be explained by increases in greenhouse gases and the depletion of the ozone layer.

Scientists have also been able to use improved observational data to resolve what were viewed as inconsistencies between observations and expectations. Greenhouse theory and modelling anticipated that a hotspot should occur in the atmosphere about 10 to 15 kilometres above the earth's surface at the tropics, but this was not previously supported by observations. More accurate temperature observations are now available and greater warming has been detected in that area, which has provided another 'fingerprint' of changes caused by greenhouse gases.

Since the IPCC Fourth Assessment Report in 2007, climate model simulations have been run that reinforce earlier conclusions that both natural drivers (volcanic aerosols, solar variations and orbital variations) and human drivers (greenhouse gases and aerosols) are required to explain the observed recent hemispheric and global temperature variations. But greenhouse gas increases are the main cause of the warming over the past century.

Conclusion

In order to understand the mechanisms and implications of climate change, an interested non-scientist must draw on the publications of experts in the field. In this sense, the challenge facing each of us can be compared to that facing a judge in a court of law, who must make a decision on a balance of probabilities. How often does a case come before one of Australia's superior courts where the defence is so weak that it cannot find a so-called expert to blow a fog through the proceedings? The judge's job is to avoid wrong steps through the fog—to assess the chances that the opinion of just one so-called expert is more likely to be right than the established opinion.

The evidence for the prosecution in this case is considerable. The most important and straightforward of the quantitatively testable propositions from the mainstream science—upward trends in average temperatures and increases in sea levels—have been either confirmed or shown to be understated by the passing of time.

Some important parameters have been subject to better testing as measurement techniques have improved and numbers of observations increased. On these, too, the mainstream science's hypotheses have been confirmed. They include the warming of the troposphere relative to the stratosphere, and the long-term shift towards wet extremes and hot extremes.

The science's forecast of greater frequency of some extreme events and greater intensity of a wider range of extreme events is looking uncomfortably robust.

A number of measureable changes are pointing to more rapid movement towards climate tipping points than previously suggested by the mainstream science. The rates of reduction in Arctic sea ice and the accumulation of methane in the atmosphere are examples.

Indeed, scientific developments since 2008 have introduced additional caution about whether 'overshooting' emissions scenarios—where greenhouse gas concentrations peak above a goal before declining—will lead to temperature increases that are not quickly reversible.

Regrettably, there are no major propositions of the mainstream science from 2008 that have been weakened by the observational evidence or the improved understanding of climate processes over the past three years.

The politicisation of the science as many countries have moved towards stronger action to reduce greenhouse gas emissions has placed institutions conducting the science under great scrutiny. Exhaustive reviews have revealed some weaknesses in execution of the scientific mandate, but none that is material to the reliability of the main propositions of the mainstream science.

There is still a high degree of uncertainty about myriad important details of the impact of increased concentrations of greenhouse gases. But the uncertainty in the science is generally associated with the rate and magnitude, rather than the direction, of the conclusions.

Indeed, the consistency of the understatement since climate change became a large policy issue in the early 1990s is a cause for concern. It would be much more of a surprise if the next large assessment of the IPCC in 2014 led to a downward rather than upward revision of expectations of damage from unmitigated climate change.

This raises a question whether scientific research on climate change has a systematic tendency to understatement. It may be tempting to correct for this by giving more weight to the more concerned end of published research. This would be a mistake. In a highly contested and complex scientific matter with immense implications for public policy it is important to base policy on the established propositions of the science.

In drawing our judgment on the science, the evidence is now so strong that it is appropriate that we move beyond the civil court parameters of 'balance of probabilities' that I applied in 2008 towards the more rigorous criminal court conclusion of 'beyond reasonable doubt'.