



Garnaut
CLIMATE CHANGE
REVIEW UPDATE 2011

5

The science of climate change

Update Paper **5**



Garnaut

CLIMATE CHANGE REVIEW UPDATE 2011

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Garnaut Climate Change Review – Update 2011

Update Paper five:

The science of climate change

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THE SCIENCE OF CLIMATE CHANGE

Key points

- Observations and research outcomes since 2008 have confirmed and strengthened the position that the mainstream science then held with a high level of certainty, that the Earth is warming and that human emissions of greenhouse gases are the primary cause.
 - By mainstream science I mean the overwhelming weight of authoritative opinion in the relevant disciplines, as expressed in peer reviewed publications.
- The statistically significant warming trend has been confirmed by observations over recent years:
 - global temperatures continue to rise around the midpoints of the range of the projections of the Intergovernmental Panel on Climate Change (IPCC) and the presence of a warming trend has been confirmed;
 - the rate of sea level rise has accelerated and is tracking above the range suggested by the IPCC; and
 - rates of change in most observable responses of the physical and biological environment to global warming lie at or above expectations from the mainstream science.
- It is an awful reality that no major developments in the science hold out realistic hope that the judgements of the 2008 Review erred in the direction of overestimating the risks of climate change.
 - The judgement of the Review—that the greater risks of severe consequences under a scenario of 550 ppm concentrations of greenhouse gases make the extra mitigation cost to achieve a 450 ppm outcome worthwhile—has been confirmed.
- There is increasing discussion in the legitimate scientific literature of the possibility that large damage will occur at smaller increases in global average temperature than the IPCC focus and United Nations (Copenhagen and Cancun) agreement on holding temperature increase to 2°C or less above pre-industrial level.
 - There is a case in managing the risks of climate change for seeking to reduce emissions concentrations below 450 ppm carbon dioxide equivalent, but that would first require a credible programme to get to 450 ppm.
- Despite the increased scientific understanding of climate change, and confidence in the science's conclusions about climate change, public confidence in the science seems to have weakened somewhat in Australia and some other countries since 2008.
- The scientific community has given greater attention to the 'emissions budget' approach that was introduced in the 2008 Review to the global and national task of reducing emissions. This approach warns us that we are rapidly utilising the atmosphere's remaining capacity to absorb greenhouse gases without generating high risks of dangerous climate change—and now face the challenge of absorbing more carbon dioxide from the atmosphere than we are adding from human activity.
 - The immediate implication is that avoiding high risks will require large changes in trajectories at an early date.

Table of contents

1. How do we know if the science is right?	6
1.1. The starting point of the 2008 Garnaut Climate Change Review	8
1.1.1. Three possible futures	8
1.2. Objectives and scope of the Update Paper	9
2. Climate change observations and projections	10
2.1. The complexity of the climate system	11
2.2. The process for updating projections of climate change	12
2.3. Greenhouse gases and the carbon cycle	14
2.3.1. Changes in the composition of the atmosphere	14
2.3.2. Carbon dioxide and the carbon cycle	16
2.4. A warming world	17
2.4.1. Observed temperature trends	17
2.4.2. Temperatures in the future	18
2.5. Changes in oceans and sea level	20
2.5.1. Observed changes to oceans	20
2.5.2. Sea level rise in the future	22
2.5.3. Sea-level rise and Australia	24
2.6. Changes in water and ice	26
2.6.1. Observed changes in precipitation	26
2.6.2. Precipitation in the future	28
2.6.3. Ice caps, Ice sheets and frozen ground	29
2.7. Severe weather events	29
2.7.1. Rainfall extremes	30
2.7.2. Tropical cyclones	30
2.7.3. Droughts and heat waves	31
2.7.4. Insurance markets and severe weather	32
2.8. Changes to ecosystems	33
2.9. Tipping points, extreme and high consequence climate outcomes	33
2.10. Why the climate system is changing	34
3. The science of global mitigation	36
3.1. Defining 'dangerous climate change'	36
3.1.1. Is the 2°C target right?	38
3.2. Global mitigation goals	39
3.2.1. Cumulative emissions targets	39
3.2.2. Is overshooting feasible?	40
3.2.3. Options for a rapid response	41
3.3. Beyond 2 degrees	42
3.3.1. A four degree world	43

4. Developments in the debate about the science	44
4.1. How science advances through questioning and review	44
4.2. Assessing the majority opinion.....	45
4.2.1. The Intergovernmental Panel on Climate Change (IPCC).....	45
4.2.2. National academies of science	47
4.2.3. Other assessments of consensus and disagreement on climate science	48
5. Public perceptions of climate change	49
5.1. The Australian public's perceptions on climate change	49
5.2. Factors contributing to public perceptions	51
6. Conclusion	52
6.1. Reflections on scholarly reticence.....	53

List of Figures

Figure 1: Global emissions and atmospheric concentration pathways for the Garnaut non-mitigation, 550 and 450 cases out to 2100	9
Figure 2: A comparison of the four Representative Concentration Pathways with the 2008 Garnaut no-mitigation and mitigation scenarios (long-lived greenhouse gases only)	14
Figure 3: Changes in observed annual global temperature since 1970, compared with the SRES scenarios of the IPCC.....	18
Figure 4: Australian annual average temperature anomalies, 1910 - 2010.....	19
Figure 5: Annual sea surface temperature anomalies in the Australian region relative to the 1961-1990 average of 21.9°C.	20
Figure 6: Changes in observed global sea level since 1970, compared with the IPCC Third Assessment Report sea-level rise projections	21
Figure 7: Sea level rise: estimates for twenty-first century sea level rise from semi-empirical models as compared to the IPCC Fourth Assessment Report.....	23
Figure 8: Extreme sea-level event multipliers for a 0.5m sea level rise.....	25
Figure 9: Changes in global temperature over the last 400,000 years	35
Figure 10: Risks of climate change by reasons for concern – 2001 compared with 2009 update	37

List of Boxes

Box 1: Additional resources	10
Box 2: Definition of climate change	11
Box 3: How climate models work	12
Box 4: Updated scenarios for global climate modelling	13
Box 5: Is there a warming trend in global temperature data?	17
Box 6: Ocean acidification and the Great Barrier Reef	22
Box 7: Sea level rise and planning decisions	26
Box 8: Was climate change responsible for the weather conditions of Black Saturday?	31
Box 9: The health impacts of the 2009 south-eastern Australian heatwave	32
Box 10: Climate in the period of human civilisation	35
Box 11: Update of the IPCC's 'reasons for concern'	37
Box 12: The health co-benefits of mitigation	41
Box 13: Climate change statements from national academies of science	48

Commonly used terms and abbreviations

- **IPCC** – Intergovernmental Panel on Climate Change
- **CO₂-e** – Carbon dioxide equivalent
- **BoM** – Australian Bureau of Meteorology
- **CSIRO** – Commonwealth Scientific and Industrial Research Organisation
- **UNFCCC** – United Nations Framework Convention on Climate Change

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1. How do we know if the science is right?

I have been deeply immersed in many dimensions of the climate change question for almost four years, since I was commissioned in April 2007 by all of the State and Territory Governments and then by the Commonwealth Government as well to undertake the 2008 Garnaut Climate Change Review (the Review).

At the commencement of the Review, I faced the question that confronts all who are not climate scientists and who are required for one reason or another to take a position on the climate science: how do we know if propositions put forward by some climate scientists are right? I began with some general awareness of the issues (derived in part from my association with the International Food Policy Research Institute in Washington, which was undertaking research on the effects of climate change and its mitigation on global food security), but with no strong views and no more than a common knowledge of climate change science. I did not know how strongly the main propositions of climate change science were held in the mainstream science community. I was aware of sceptical views and set out to understand them. By “sceptics” I mean those with genuine scientific credentials.

By the time I concluded the Review in September 2008, I had read a fair bit of climate science, published by people, including some “sceptics”, with genuine credentials and records of publication in professionally reputed scientific journals. Few who contributed to this climate science doubted that the average temperatures on earth were rising, and that this reflected the increase in concentrations of greenhouse gases in the atmosphere as a result of human activity. I was exposed to more of the literature through the work of a conscientious team in the Review’s secretariat, and of scientists advising me in various ways.

As I noted in the Review, there is no genuinely scientific dissent from the main propositions of the physics of climate change—that increased concentrations of greenhouse gases raise the earth’s temperature by calculable amounts. A small number of scientists with relevant credentials held the view that increases in emissions concentrations as a result of human activity caused warming, but thought that these effects were small compared with other sources of changes in temperature, including feedbacks from greenhouse gas warming that counteract rather than extend the effects. There were other reputed scientific views, larger in number than the sceptics within the genuine scientific community, who thought that the effects of increased greenhouse gases on the world’s climate would be much larger than suggested by the mainstream science and would be triggered by lower greenhouse gas concentrations and at lower temperatures. Examination of the credentials and numbers of climate scientists who expressed both the mainstream and sceptical views led me to the premise upon which the Review was built, that the central conclusions of the mainstream science were right “on a balance of probabilities” (pxvii). Some in the community of Australian climate scientists told me that I had offered unwarranted respect and credence to dissenting views.

To say that there is overwhelming support within the mainstream scientific community for the central propositions about climate change is not to say that there is no debate about myriad and important detail. For example, while there is little dissent about the association of increased greenhouse gas concentrations with warming, the scientific climate models reveal wide variations in expectation of the regional distribution of changes in precipitation, and in some regions about the direction of change.

I ran into one example of this in the Review, when converting the information from the climate models into likely impacts on Australia that would affect economic activity. I applied the insights from the excellent Australian climate projection work of the CSIRO, which embodied expectations of greater drying in southern Australia than is suggested by some other legitimate approaches. The Review had modelled “wet” and “dry” as well as “most likely” futures for the Murray Darling under the warming associated with unmitigated, moderately mitigated and strongly mitigated climate change. Recognition of this uncertainty was not enough for some participants in the scientific exchange. The Australian Academy of Sciences’ 2009 report on priorities for climate change science research noted that some other models gave different results (Australian Academy of Science 2009). I was grateful for the careful attention to the Review’s work.

Another example of an issue that is strongly contested in detail amongst scientists with relevant expertise who hold to the general mainstream propositions about climate change 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. There are few deep specialists in this area. The mainstream view from the peer-reviewed literature, brought into the public domain mainly through the 2007 IPCC Report, embodied sea level rise for thermal expansion of the oceans as temperature rose, and some contribution from melting of alpine glaciers, but did not take into account the potential for accelerated losses from land-based ice in Greenland and Antarctica (IPCC, 2007). It was disconcerting to find the specialists in both hemispheres to whom I spoke personally expressing private opinions that there would be a contribution from Greenland and west Antarctica to sea level rise this century of uncertain, but substantial and possibly greatly disruptive, dimension. All declined to put private views on the public record, because the views were not yet reflected in the peer-reviewed scientific literature.

My early exposure to sceptical and dissenting views identified a number of propositions that seemed to be worthy of exploration. It also identified some that discredited themselves with internal inconsistencies or contradiction of well-established facts.

The propositions that were discredited by contradiction of well-established facts included one that was common in 2008 as I was preparing the Final Report of the Review. This proposition was pervasive amongst the many dissenters who were prominent in the Australian public discussion, and about whom I said in 2008 that “sceptic is a misnomer for their position because (they) hold strongly to the belief that the mainstream science is wrong”. (Garnaut, 2008, pxvii). The proposition, or belief, was that the earth was cooling. The question “is there a warming trend?” can be answered by statistical analysis of time series data, of a kind that is familiar to economists. I asked two leading econometricians (Trevor Breusch¹ and Farshid Vahid²) respected authorities on the analysis of time series, to examine the temperature record from the three authoritative global sources. They concluded that “the temperatures recorded in most of the past decade lie above the confidence level that is produced by any model that does not allow for a warming trend” (Garnaut, 2008, ppxvii-xviii and Box 4.1). I asked them to repeat for the Garnaut Climate Change Review Update – 2011 (the Update) the analysis for a period that included data since the Review up to the present, and they have confirmed the earlier conclusion (Breusch and Vahid, 2011 – see also Box 5). The statistical evidence did not stop assertions in the public debate that the earth was cooling, but it does seem to have discouraged at least the numerate and rational from repetition of errors into which they had carelessly fallen.

As I absorbed more of the complexity of the science—both mainstream and sceptical—I began to recognise a number of recurring criticisms of the mainstream for which there were rounded and effective responses in the science.

The end point was an increase in personal confidence in the mainstream science. “On a balance of probabilities” would understate my current view of the likelihood that the mainstream science is correct. I would now say that it is highly probable that the central proposition of the mainstream science—that most of the global warming since the mid 20th century is very likely due to anthropogenic increases in greenhouse gas concentrations—is correct. Of the range of genuine scientific views around the mainstream—defining the centre of peer-reviewed literature as the mainstream—I would now be tempted to say that views that temperatures and damage from a specified level of emissions over time will be larger than is suggested by the mainstream science are much more likely to be proven correct than those that embody the opposite expectations.

But I won’t say that, at least not in the main body of this paper. Later sections of this paper present evidence from the peer-reviewed literature as if it were all that we know. To allow all people of intellectual integrity to remain in touch with each other on this critical subject, it is important that our dialogue remains grounded in the mainstream scientific literature, whatever our personal views about whether the received wisdom understates or overstates the reality. I will, however, return to these issues in a few final reflections on publications lags and scholarly reticence.

¹ Australian National University

² Monash University

1.1. The starting point of the 2008 Garnaut Climate Change Review

The Review took as its starting point:

... on the balance of probabilities and not as a matter of belief, the majority opinion of the Australian and international scientific communities that human activities resulted in substantial global warming from the mid-20th century (Garnaut 2008).

Also underpinning the Review was the knowledge from the majority science, that continued growth in greenhouse gas concentrations caused by human-induced emissions would generate high risks of dangerous climate change.

Chapters two, four, five and six of the Review outlined the fundamentals of climate science, presented observations on anticipated global and Australian changes in elements of the climate, considered the case for human attribution of climate change and explored the potential outcomes, impacts and uncertainties for projected climate change in a set of possible futures.

The Review drew extensively on the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) published in 2007. The IPCC Assessment Reports are a consolidation of all the peer-reviewed science on climate change, its impacts, and mitigation. They represent the research and input of thousands of scientists and are the authoritative point of reference on climate change. However, due to the time taken to pull the reports together, there is a lag between the cut-off for research to be included and the release of the final document. In recognition of this lag, the Review drew from more recent research as well as the IPCC Fourth Assessment Report.

1.1.1. Three possible futures

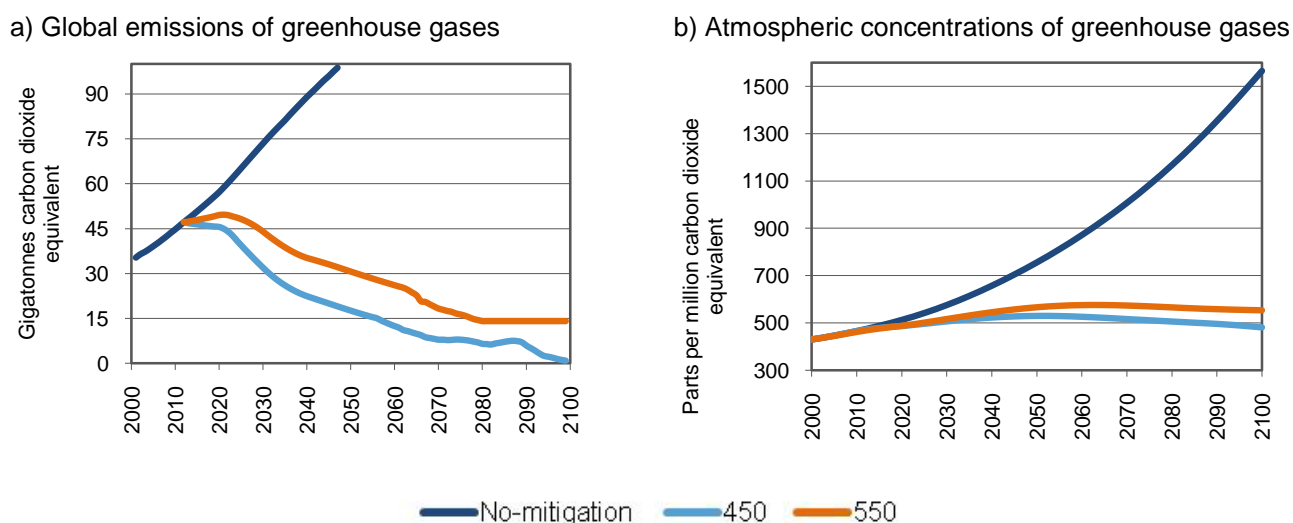
The primary question that the Review sought to answer in 2008 was: What extent of global mitigation, with Australia playing its proportionate part, provides the greatest excess of gains from reduced risks of climate change over costs of mitigation?

To answer this question, the Review developed a framework to consider whether the costs of policies designed to mitigate the effects of climate change—to reduce greenhouse gas emissions—exceeded the benefits of mitigation. This framework is described in detail in Update Paper one (*Weighing the costs and benefits of climate change action*). Within the framework, detailed economic modelling of costs and benefits of the kinds that are valued through markets was undertaken, as well as a qualitative assessment of those impacts that could not be modelled due to inherent uncertainty or limitations in the modelling framework or in the subjective nature of the values affected.

To estimate the possible magnitude of climate change in the future, the potential costs of those changes and the benefits of avoiding them, it is necessary to make an assessment of the potential future level of global emissions of greenhouse gases and other relevant substances such as aerosols, and how these might change as a result of mitigation. In its assessment of the potential changes to the global and Australian climate, and the impacts of those changes, the Review explored three possible futures based on different levels of mitigation:

- **No-mitigation case** – based on no action undertaken to mitigate climate change, and used as a ‘reference’ to assess the benefits of climate change action that accrue from the climate change impacts that are avoided. By the end of the century the concentration of long-lived greenhouse gases in the atmosphere is 1565 ppm carbon dioxide equivalent.
- **550 mitigation case** – the less ambitious mitigation scenario of the two investigated by the Review. Emissions peak and then decline steadily to stabilise at 550 ppm carbon dioxide equivalent.
- **450 mitigation case** – the more ambitious mitigation scenario of the two investigated by the Review, involving an earlier peak in emissions and a sharper decline. Atmospheric concentrations overshoot to 530 ppm carbon dioxide equivalent and decline towards 450 ppm carbon dioxide equivalent early in the 22nd century.

Figure 1: Global emissions and atmospheric concentration pathways for the Garnaut no-mitigation, 550 and 450 cases out to 2100



Source: Garnaut 2008, Figures 9.3 and 4.4. Note: Concentrations in (b) include Kyoto gases and CFCs only.

The Review used these three emissions cases as the basis of its summary of projected climate change. To inform this summary, the Review drew from a range of sources, including direct modelling of the Garnaut scenarios and interpretation of the model results from the IPCC. In recognition of the varying levels of uncertainty associated with the response of different elements of the climate, a mixture of quantitative and qualitative description was provided.

The Review considered the relative benefits and costs of the 450 and 550 mitigation cases, and compared them both with no mitigation. The largest differential between the two mitigation cases in terms of the avoided impacts of climate change was the 'insurance value' provided by a lower probability of exceeding threshold temperature values for key 'tipping elements' in the climate system. As a result of this assessment, the Review judged it was in Australia's national interest to play its proportionate part in a global agreement directed at securing concentrations at 450 ppm carbon dioxide equivalent or lower.

1.2. Objectives and scope of the Update Paper

The Review aimed to provide a non-scientist's perspective on how decision-makers could consider and view scientific evidence.

In 2008, the Review integrated complex economic modelling of the costs of mitigation jointly with the Australian Treasury, with its own modelling of the benefits of avoided climate change impacts. This involved over a year of intense work involving scientists and economists from around the country. This collective exercise was the most detailed, comprehensive and long-dated modelling exercises ever undertaken on the Australian economy. The output of the modelling exercise fed into the Review's central analysis, and also formed the basis of the Review's discussion of climate change impacts on Australia.

It is not possible to repeat with updated data the modelling exercise in the limited time that is available. This Update Paper examines developments in the science upon which the Review was based and qualitatively assesses whether changes would affect the overall conclusions of the Review.

This paper provides an update and synthesis of the discussion of climate change science and impacts in the Review. It does not aim to provide a comprehensive analysis of the science, but instead focuses on areas of new knowledge of particular importance to Australia and the policy debate.

The references to the science in this Update Paper – not the commentary on the debate – draw heavily on summary documents prepared for the Update by the Centre for Australian Weather and Climate Research (CAWCR) (Keenan and Cleugh 2011) and work by Professor Will Steffen in his role as an

independent expert adviser to the Government's Multi Party Climate Change Committee. These authorities draw on and refer to recent peer reviewed scientific publications. For a more detailed consideration of the science, the Update by the Centre for Australian Weather and Climate Research is available at www.garnautreview.org.au. Other sources on recent developments in climate change science are provided in Box 1.

Section 2 identifies and discusses the implications of science developments since the IPCC Fourth Assessment Report and the Review and what this means for climate change policy. It explores the changes in different climate elements that would be expected from an increase in greenhouse gases. It shows how observational evidence of changes in the climate is supporting these expectations, and how new observations since 2008 reinforce these trends. While it is not possible to discuss all areas of advancement in the climate science, there is further information available in the technical report prepared for the Update by Centre for Australian Weather and Climate Research (Keenan and Cleugh 2011) and from the other sources listed in Box 1. Section 2 also provides an update on the implications of the new observations for Australia.

Section 3 of the paper revisits the Review's discussion on dangerous climate change, considers cumulative emissions budgets, options for a rapid response, and the risks that climate change might pose if the world is less ambitious in its mitigation efforts.

Section 4 and 5 look at the status of the scientific debate and public perceptions of climate change in Australia.

Box 1: Additional resources

In addition to the documents developed for the Update mentioned above, there is an abundance of clear and accessible information on the climate change science and impacts available from scientific institutions and government departments around the world. The following are useful for those seeking additional information on the science and impacts of climate change:

- Intergovernmental Panel on Climate Change - <http://www.ipcc.ch/>
- Commonwealth Department of Climate Change and Energy Efficiency – www.climatechange.gov.au
- Commonwealth Scientific and Industrial Research Organisation (CSIRO) - <http://www.csiro.au/>
- Australian Bureau of Meteorology (BoM) – www.bom.gov.au
- National Climate Change Adaptation Research Facility (NCCARF) - <http://www.nccarf.edu.au/>
- Garnaut Climate Change Review 2008 – www.garnautreview.org.au
- Australian Academy of Science “The Science of Climate Change – Questions and Answers, 2010” - <http://www.science.org.au/reports/climatechange2010.pdf>
- Royal Society “Climate change: A Summary of the Science 2010” - http://royalsociety.org/Report_WF.aspx?pageid=4294972964&terms=climate+change&fragment=&SearchType=&terms=climate+change

2. Climate change observations and projections

When reporting on new observational data over a relatively short period (in this case, since 2008), there is inevitably a focus on recent weather and extreme events. It is important to recognise that any set of observations over a short period will be reflective of the dynamic nature of our 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.

There is new evidence on both the '*detection*' of climate change, which is focused on demonstrating that a climate or a system affected by climate has changed in a statistically significant way, and the '*attribution*' of climate change, which is the process of evaluating the relative contributions of multiple causal factors to a change or event (IPCC 2009).

Box 2: Definition of climate change

This Update Paper continues to use the IPCC definition of climate change that was adopted in the Review:

“a change in the state of the climate that can be identified (for example, by using statistical tests) by changes in the mean and/or variability of its properties, and that persists for an extended period, typically decades or longer” (IPCC 2007).

This definition is not limited to changes contributed directly or indirectly to human activity. It therefore includes changes to the climate caused by natural phenomena such as volcanic eruptions. While humans are unable to influence the effects of such natural phenomena on the climate, such events will interact with the influences of human activities. Human influences will be superimposed on natural variability.

2.1. The complexity of the climate system

The climate system will respond in complex ways to an increased concentration of greenhouse gases in the future.

The climate processes that determine variability in the present day climate will continue to operate in the future, although they may be affected in different ways by global warming. For example, the land will warm faster than the oceans and the greatest warming will be over the poles. Years like 2010 will continue to occur, where temperatures are high globally but some countries (in this case Australia) were relatively cool, and some regions (Europe and parts of North America) experienced periods of unusually heavy snowfalls and cold weather. Global climate models show that global warming due to higher concentrations of greenhouse gases is consistent with both an increased risk of drying in the mid-latitudes, associated with an increased risk of drought, and an increase in the chance of intense precipitation and flooding. This may be somewhat counter-intuitive. This outcome occurs because rainfall and snowfall is projected to be concentrated into more intense events, with longer periods of lower precipitation in between. Particularly in the sub-tropics, this means that there will be more intense and heavy episodic rainfall events with high runoff interspersed with longer relatively dry periods with increased evapo-transpiration³ (IPCC 2007).

The complexity of the Earth's systems that lead to this natural variation in space and time makes it challenging to project the likely outcomes of climate change in particular regions. However, reliable projections are valuable for adaptation planning.

This section explores how our understanding and modelling of the climate system, and analysis of observational data, can help us to understand how the climate might change in the future.

³ IPCC Fourth Assessment Working Group I, Section 10.3.6.1, available online: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch10s10-3-6-1.html.

Box 3: How climate models work

Climate models are designed to help us to understand the complex response of the Earth's systems to human influences. A number of climate models have been developed in institutions for climate research throughout the world, including Australia. They have been gradually improved since early versions were developed in the 1970s.

Climate models are mathematical representations of the climate system that aim to simulate the complex interactions of physical, chemical and biological processes. Models divide the world into grid cells, which makes the calculations computationally tractable. However, the method means that small scale influences on the climate, such as clouds and vegetation changes, cannot be explicitly 'resolved' (represented). Physical representations of these and other small scale processes are included in models in approximate form, and are developed from theoretical understanding, empirical evidence and extensive observational data. Models are tested by their ability to represent observed features of current climate and past climate changes.

Different approaches can be taken to the way processes are represented in the model, particularly for processes where there is less understanding or detailed observational data. The difference in these approaches makes the main contribution to the range of model outcomes (often referred to as 'uncertainty'). To reduce the influence of particular model assumptions on its assessments, the IPCC uses an "ensemble" approach where it draws from a range of climate models (IPCC 2007).

Climate models also vary in complexity. 'Simple climate models' tend to aggregate processes to much larger scales, and often deal only with the global average. This allows for much faster analysis of policy questions, but limits understanding of geographical variation. The outcomes of the simple climate models are generally 'tuned' to reproduce the global temperature results of more complex models, or 'general circulation models'. General circulation models represent many more of the complex climate interactions at a finer scale, but the trade-off is that a simulation of long term climate change can take several months to complete (Lowe, Huntingford et al. 2009).

Improvements in understanding and computing power have allowed new versions of general circulation models to factor in additional processes and increase their spatial resolution. These more sophisticated model outcomes will feed into the analysis and assessment undertaken as part of the IPCC's Fifth Assessment Report, due in 2014.

As discussed in Box 4, issues beyond the physical climate and weather system also need to be explained. Integrated Assessment Models are often used to assess human influences by considering demographic, political and economic variables. Integrated Assessment Models generally use the simpler climate models, but the framework enables the integrated assessment of human and climate systems to inform policy and decision makers (Keenan and Cleugh 2011).

Source: Drawn from Ananthaswamy, 2011 'Behind the predictions', New Scientist, and other references as indicated.

2.2. The process for updating projections of climate change

Currently, global climate change modelling groups around the world are working on a new set of climate model experiments that will be examined as part of the IPCC Fifth Assessment Report to be released in 2014 (Taylor, Stouffer et al. 2011). Improved versions of many of the global climate models will be used to run these experiments. The new modelling will be based on a set of Representative Concentration Pathways that have replaced the scenarios from the 'Special Report on Emissions Scenarios' (SRES) used for previous IPCC reports (see Box 4).

The simulations being undertaken for the Fifth Assessment Report represent an important new resource for the task of assessing regional climate change and will be the basis for updated national projections to be delivered for Australia in 2013. At present, there are no more recent national climate change projections than those released by CSIRO and the Bureau of Meteorology in 2007 that were used in the Review. These projections were primarily based upon global climate modelling experiments prepared for the Fourth Assessment Report of the IPCC (CSIRO & BoM 2007).

While there has not been a major update to the set of climate modelling experiments used in the regional projection work upon which the Review's modelling was based, there have been significant developments in our understanding of how the climate is likely to change regionally in Australia. Recent work has provided more detail on projected climate change through the application of high resolution downscaling techniques⁴. It has also provided further insight into changes to climatic extremes (Hennessy, Fawcett et al. 2008). There have also been some significant developments in methods used for regional projections in Australia and in our understanding of the processes that drive the regional climate changes simulated by the models.

Box 4: Updated scenarios for global climate modelling

Scenarios are used by the scientific community to illuminate the complex interactions between human activities, changes in land use, ecosystems and natural cycles, atmospheric composition and the climate. They are not designed to be forecasts or projections, but are developed on the basis of expert judgements to provide plausible descriptions of how the future might unfold (Moss, Edmonds et al. 2010).

The Review developed its own emissions scenarios for the analysis of costs and benefits of climate change mitigation, but drew extensively on scenarios in the literature, including the IPCC's 'Special Report on Emissions Scenarios' (SRES), for the assessment of climate change impacts and to inform discussions on uncertainty and the range of possible futures.

The SRES scenarios were developed in the late 1990s and are not reflective of current economic and emissions growth rates. The strength of the SRES scenarios was that the datasets have been used extensively as a basis for climate change projections, so the 'ensemble' approach could be used for assessment of impacts and uncertainty (see Box 3). The Review's influential upward revision of global emissions growth in the absence of effective mitigation led it to use the SRES scenario with the highest levels of emissions this century, "A1FI", as a basis for its modelling of impacts.

In the past, the IPCC has approved and coordinated emissions scenario development. In 2006 the IPCC decided to shift its focus to encouraging the development of new scenarios by others. The new scenarios would update assumptions with a decade of new economic and emissions data and include input from experts in developing and transitional economies (IPCC 2006).

Scenarios are needed that explore a range of different approaches to mitigation to allow in-depth analysis of a range of plausible mitigation scenarios, such as a trajectory defined to meet the target to hold global average temperature increase to 2°C above pre-industrial levels (refer to section 3), and allow both near-term (20 to 30 years) and long-term assessments (greater than 100 years). More detailed scenarios are also required to reflect improvements in model capability (Moss, Edmonds et al. 2010).

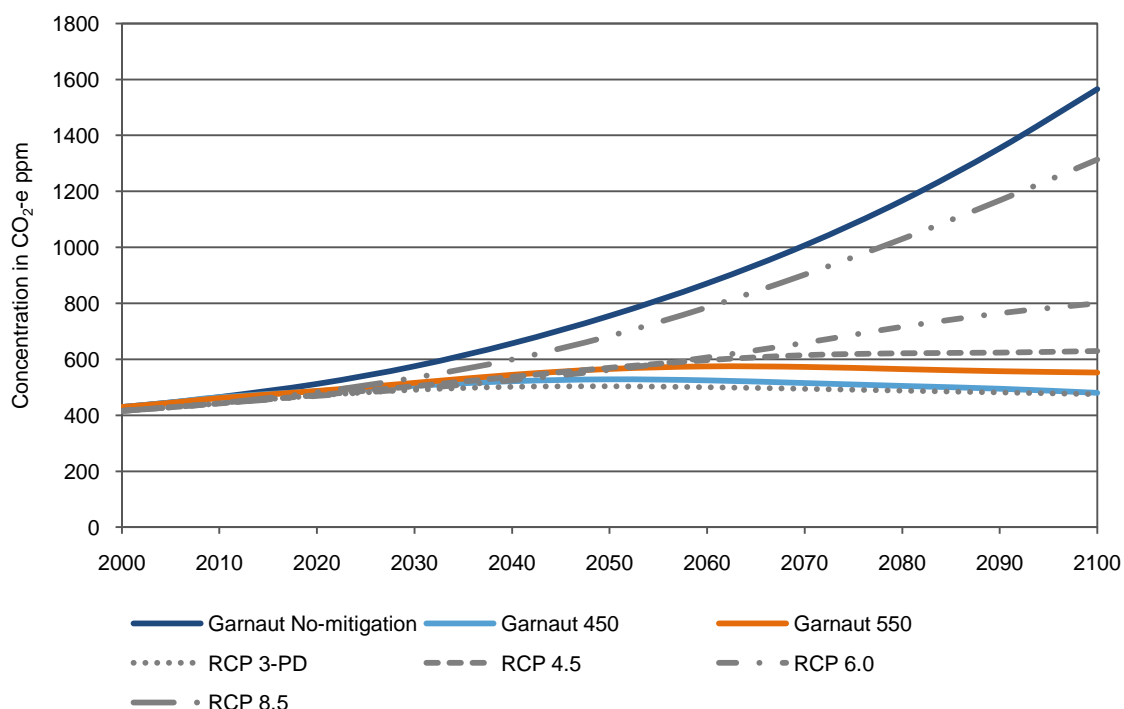
The scientific community has taken a new approach to scenario development. Rather than the previous time-consuming approach of 'bottom-up development' of scenarios starting with detailed socio-economic storylines, four plausible 'Representative Concentration Pathways' ('the Pathways') were selected to reflect the full range of concentration outcomes discussed in the literature (Moss, Edmonds et al. 2010).

The climate outcomes and socio-economic storylines and assumptions related to each of the Pathways can be assessed at the same time, shortening the process and allowing more detailed analysis of uncertainties and policy responses (Moss, Edmonds et al. 2010). This will enable coordination between researchers in different fields and reveal new insights into the potential costs and benefits of different mixes of adaptation and mitigation policy (Moss, Edmonds et al. 2010). The Pathways and underlying assumptions have been made publicly available as the starting point for new research that will feed into

⁴ For example, Grose M.R, I. Barnes-Keoghan, et al. (2010). Climate futures for Tasmania: general climate impacts technical report. Antarctic Climate & Ecosystems Cooperative Research Centre. Hobart, Tasmania.

the IPCC's Fifth Assessment Report.

Figure 2: A comparison of the four Representative Concentration Pathways with the 2008 Garnaut no-mitigation and mitigation cases



Note: Includes long-lived greenhouse gases only. Source: RCP Database (Version 2.0.5) and Garnaut 2008.

The four concentration Pathways out to 2100 are shown in Figure 2, alongside the scenarios used for the Review (RCP Database 2009). The Pathways do not represent a fundamental shift in the range of potential emissions and concentrations from those represented in the SRES scenarios, except at the lower end where a relatively ambitious mitigation pathway is included. The lowest Pathway tracks very closely to the 450 case assessed by the Review. The highest Pathway represents a continued increase in emissions over time, but concentrations of long-lived greenhouse gases are still well below the 2008 Garnaut 'no-mitigation' scenario (RCP Database 2009). With the current policies in place in the largest emitting countries, and a commitment to achieving the Cancun commitments, it will hopefully be unnecessary to know the consequences of concentrations of greenhouse gases above 1300 ppm carbon dioxide equivalent.

2.3. Greenhouse gases and the carbon cycle

2.3.1. Changes in the composition of the atmosphere

Greenhouse gases

In 2008, the Review presented data demonstrating that the magnitude and the rate of the increase in concentration of carbon dioxide, methane and nitrous oxide was unusual in the context of the past millennium. Updated measurements⁵ show that carbon dioxide concentrations have increased from 379 parts per million (ppm) in 2005 to 386 ppm in 2009.

⁵ The 2009 figures are based on CSIRO analysis. CSIRO have used measurements from air samples taken from Cape Grim, Tasmania, and from the CSIRO global network of observing stations to update the IPCC's 2005 data on global atmospheric concentrations. See Keenan, T. and H. Cleugh (2011). *Climate Science Update for the Garnaut Review*, CAWCR Technical Report No. 036, 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 (IPCC 2007: Figure 6.4). The increase in methane concentrations is likely to be due to increased methane emissions from high latitudes and tropical wetlands, linked to increases in global temperatures and tropical precipitation (Bousquet, Ringeval et al. 2010).

Between 2005 and 2010 the increase in greenhouse gas concentrations in the atmosphere is equivalent to a change in carbon dioxide concentrations from 455 ppm to 465 ppm⁶.

Atmospheric aerosols

Some of the warming effects of greenhouse gases are masked temporarily by the emission of aerosols with the combustion of fossil fuels.

Atmospheric aerosols are solid or liquid particles that are suspended in the air and are often visible as dust, smoke, and haze. Aerosols can affect the Earth's energy budget by scattering and absorbing heat and sunlight (known as "direct effects") and by modifying the properties of clouds (known as "indirect effects") (Chin, Kahn et al. 2009). These influences can lead to both warming and cooling.

The impact of aerosols on atmospheric temperatures is characterised by large variation over time and space due to many different types and varied sources of aerosols, their short atmospheric lifetime and the way they react with other components of the atmosphere. The complexity in these interactions, particularly the indirect effects on clouds, is the dominant uncertainty in understanding changes to the energy balance of the atmosphere and is a major obstacle in developing reliable projections of future change (Chin, Kahn et al. 2009).

Aerosol concentrations are driven by both human and natural sources. Aerosols in the lower atmosphere are removed largely through precipitation. They may stay in the lower atmosphere for as little as one week. If aerosols reach the upper atmosphere, perhaps through volcanic eruptions, they are above most clouds and can persist in the atmosphere for several years (Chin, Kahn et al. 2009).

While some aerosols (such as black carbon) can have a warming influence, at the global average level the overall effect of aerosols is a cooling influence. This has 'masked' some of the warming resulting from long-lived greenhouse gases. In 2007 the IPCC indicated that the consideration of aerosols (and other non-greenhouse gas factors such as land use change, which are less significant⁷) would reduce the carbon dioxide equivalent concentration to a range of 311 to 435 ppm carbon dioxide equivalent, with a central estimate of about 375 ppm⁸. The masking effect is temporary.

Black carbon, a major component of soot, is an aerosol that has a warming effect on the atmosphere by absorbing sunlight, influencing cloud formation and darkening snow and ice on the ground. Black carbon particles are produced by incomplete combustion in cars and trucks, and by forest fires and some industrial facilities, and are known to have a negative effect on human health (UNEP and WMO 2011). A recent assessment estimated that the warming contribution of 1 gram of black carbon could be anything from 100 to 2000 times that of the same amount of carbon dioxide⁹ (UNEP and WMO 2011).

Globally, levels of aerosol emissions from human activities are expected to decrease in coming decades in response to action on concerns about the adverse health effects of aerosols and associated

⁶ CSIRO calculated the total radiative forcing in 2009 from the long-lived greenhouse gases as 2.78 W/m², up from the IPCC's 2007 estimation of 2.63 W/m² in 2005 (Keenan and Cleugh 2011). In terms of carbon dioxide equivalence, this equates to a concentration of around 465 ppm, compared to IPCC's 2007 figure of 455 ppm CO₂-e (range: 433–477 ppm CO₂-e) (IPCC (2007). Climate Change 2007: Working Group III: Mitigation, Intergovernmental Panel on Climate Change

).

⁷ These include the cooling effect of changes to land use, and the warming effect of black carbon (e.g. soot) on snow, and cloud formation from aviation (linear contrails). For further information see Garnaut 2008 (Figure 2.3) and IPCC 2007, Figure TS5 (http://www.ipcc.ch/publications_and_data/ar4/wg1/en/tssts-2-5.html)

⁸ See page 102, IPCC (2007). Climate Change 2007: Working Group III: Mitigation, Intergovernmental Panel on Climate Change

⁹ Warming as seen over a period of 100 years.

efforts to reduce air pollution. This will lead to a reduction in the ‘masking’ of human-induced greenhouse warming by aerosols globally and regionally, which will amplify the warming effect of increasing greenhouse gases alone (Kloster, Dentener et al. 2010). Due to the expected decline in aerosol emissions and the fact that the cooling effect can be reversed relatively quickly, the influence of aerosols is not included in the carbon dioxide equivalent concentrations referred to in discussions of long-term mitigation targets in this paper¹⁰.

Levels of aerosol emissions from human activities are expected to decrease in coming decades, leading to a reduction in the ‘masking’ of human-induced greenhouse warming by aerosols.

A reduction in the masking effect of aerosols is likely to cause an acceleration of global warming by 2030.

2.3.2. Carbon dioxide and 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 (Raupach and Fraser 2011).

Since the early nineteenth century there has been a large and increasing added inflow of carbon dioxide into the atmosphere from human activities such as the burning of fossil fuels, cement production and other industrial processes, and deforestation or land clearing. Emissions from fossil fuels are the largest source of atmospheric carbon dioxide from human activities. Between 2000 and 2008, fossil fuel emissions increased at a rate of 3.4 per cent per year, compared to 1 per cent in the 1990s (Le Quere, Raupach et al. 2009), and have continued to track well above the IPCC scenario (“A1FI”) with the highest emissions through to 2100.

Land use changes, such as deforestation and conversion to crops, are the second largest source of carbon dioxide emissions from human activities. Emissions from these sources can be offset to some extent by biosequestration. In contrast to the 29 per cent increase in fossil fuel emissions over 2000-2008, land use emissions have been fairly steady (Le Quere, Raupach et al. 2009).

The human-caused inflow into the carbon cycle is partly offset by natural carbon dioxide ‘sinks’ in both the land and oceans. Changes in the carbon dioxide sink on land are determined by the balance between plant growth and land use disturbances such as fire and clearing. The ocean acts as a carbon sink because carbon dioxide dissolves in ocean waters when carbon dioxide concentrations in the atmosphere are higher than those at the ocean’s surface. This dissolved carbon is moved into the deeper ocean by overturning circulations, and also by the sinking of dead organisms (Raupach and Fraser 2011).

Over the past half-century the uptake by these natural sinks has continued to remove around half of the carbon dioxide put into the atmosphere, despite the increasing human emissions. The carbon is taken up in roughly equal proportions by the land and the ocean. There is considerable variation in the strength of these natural sinks from year to year, largely in response to climate variability (Raupach and Canadell 2010; Raupach, Canadell et al. 2011). Some recent studies have indicated that there has been a decline over the last 5 decades in the fraction of carbon dioxide emissions from human activities that is absorbed by natural carbon sinks (Canadell, Le Quéré et al. 2007; Raupach and Canadell 2008; Le Quéré, Raupach et al. 2009), but there is controversy in the science community over these results and uncertainty remains as to the magnitude of the decline. There have been suggestions that this shows that natural carbon sinks are slowly ‘losing the race’ against the rapidly growing human emissions (Keenan and Cleugh 2011).

¹⁰ While aerosols are excluded from long-term concentration targets, their influence on the climate is factored into future temperatures projections.

The ongoing strength of the natural carbon sinks is crucially important for an assessment of the level of mitigation effort that will be required to achieve a desired concentration of carbon dioxide in the atmosphere (see Section 3).

2.4. A warming world

2.4.1. Observed temperature trends

Global average temperature

The IPCC's Fourth Assessment Report concluded that the '*warming of the climate system is unequivocal*'. Global average temperatures had risen considerably since measurements began in the mid-1800s, and that since pre-industrial times (1850-99) global surface temperature had increased by 0.76 +/- 0.19°C (IPCC 2007).

The IPCC's 2007 conclusion was based on temperature information available up to 2005 and part way through 2006 only, and global average temperature data is now available up to the end of 2010. These observed data led the World Meteorological Organization to conclude that "*the year 2010 ranked as the warmest year on record, together with 1998 and 2005. Data received by the WMO show no statistically significant difference between global temperatures in 2010, 2005 and 1998*". In 2010, global average temperature was 0.53°C above the 1961-90 mean, and the decade ending in 2010 was the warmest on record (WMO 2011). Figure 3 shows how observed global average temperatures are tracking against the IPCC projections.

The IPCC used the term "*unequivocal*" to describe the level of confidence in observations of global temperature trends, and the Royal Society recognises that there is wide agreement in the scientific community on this aspect of climate change (Royal Society 2010).

Box 5: Is there a warming trend in global temperature data?

Trevor Breusch and Farshid Vahid have updated their paper "Global Temperature Trends", originally prepared for the Review in 2008 (see Box 4.1, Garnaut 2008), for the three more years of data. Again they examine the three long time series of recorded data, one from the Hadley Centre and the Climatic Research Unit in the UK starting in 1850, one from the USA National Climatic Data Centre starting in 1880, and one from the Goddard Institute for Space Studies of NASA in the USA also starting in 1880.

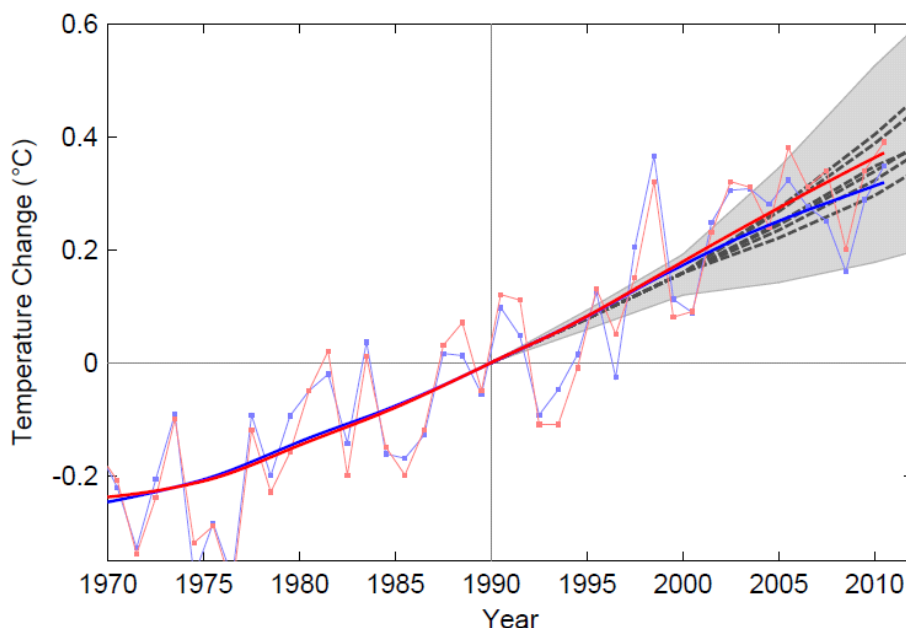
Taking a broad view across all three data series and across time, Breusch and Vahid ask the question "Is there clear evidence of a trend?". It may seem obvious from simple plots that global temperatures are on an upward or warming trend, but temperatures like many natural phenomena are variable and serially correlated. The question then is whether the apparent upward movement is more persistent than can be attributed to variability and serial correlation, and thus might properly be called a "trend".

Their findings indicate that, even when the model allows for extreme serial correlation of a unit root, the upward persistence or trend remains statistically significant. When the question is asked whether the trend has changed over the 130-160 years of available data, the most prominent feature is found to be an increased steepness in the upward trend since the mid-1970s. There is no evidence of a weakening or reversing trend in more recent years, as suggested by some commentators.

An innovative way to answer the question about trend is to imagine an analyst 30 or 50 years ago making predictions about future temperatures, who makes extreme assumptions about the variability and high serial correlation observed to date, but who assumes there is no trend otherwise. Such an exercise is subject to considerable uncertainty, which would be shown by ever widening error bands as the predictions are made further into the future. As Breusch and Vahid show, the actual temperatures over most of the recent decade 2001-2010 were above even this wide range of uncertainty. They conclude that there is sufficient evidence in the long run of temperature records to support the existence of a warming trend. The additional three years for which temperature data are now available were among the warmest on record.

Source: Breusch and Vahid, 2011, available at www.garnautreview.gov.au.

Figure 3: Changes in observed annual global temperature since 1970, compared with the SRES scenarios of the IPCC.



IPCC scenarios are shown as dashed lines and grey ranges. GISS data is in red, Hadley centre in blue.

Source: Rahmstorf 2011, updated from (Rahmstorf, Cazenave et al. 2007).

The IPCC's 2007 conclusion regarding warming trends was not based only on land surface temperature data, but also the changes in other levels of the atmosphere (Arndt, Baringer et al. 2010; Kennedy, Thorne et al. 2010). 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 and are discussed below. 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 (Kennedy, Thorne et al. 2010).

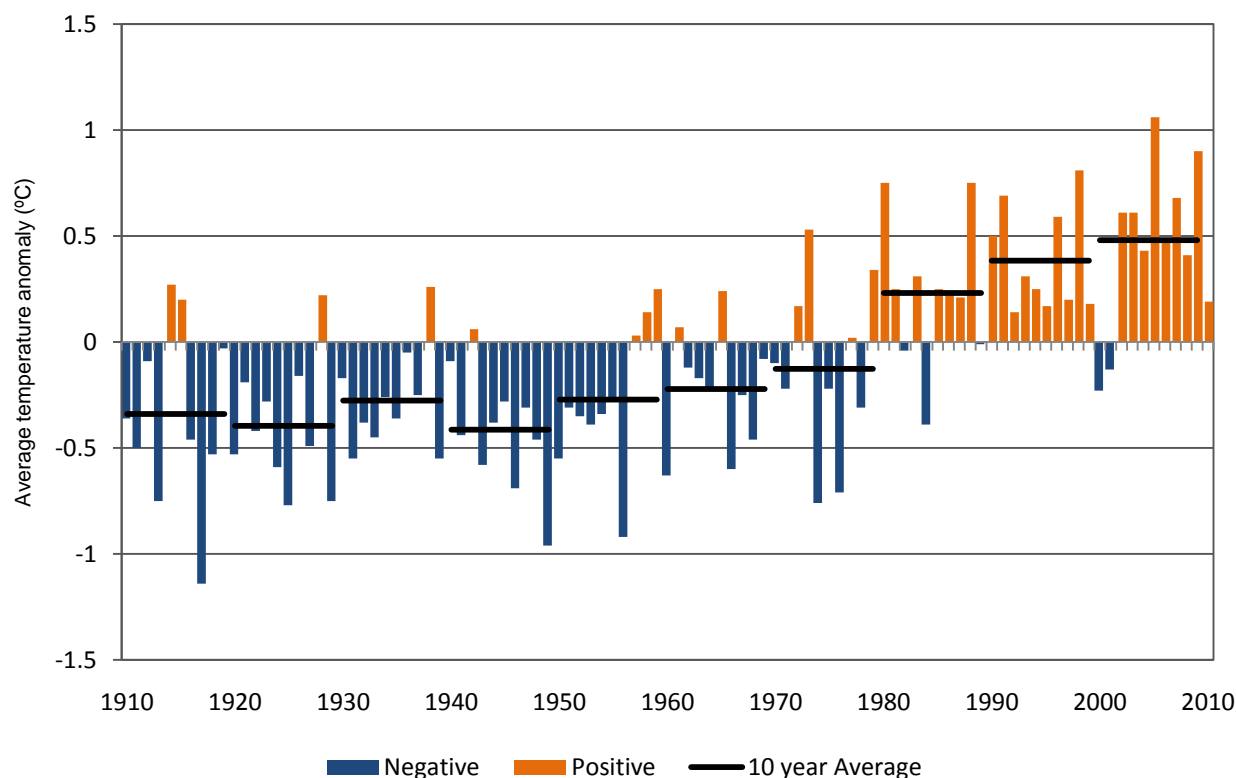
Australian temperature trends

Since 1910, annual average temperatures in Australia have increased by 0.9°C (CSIRO & BoM 2007). Figure 4 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.

The decade ending in 2010 has easily been Australia's warmest decade since record keeping began and 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 (Keenan and Cleugh 2011).

2.4.2. Temperatures in the future

Projections of future changes in temperature are heavily dependent on how sensitive the climate is to sustained changes to the energy balance of the atmosphere (referred to as 'radiative forcing' – see Garnaut 2008). A number of 'feedbacks' in the climate system affect how global temperatures respond to changes in the atmosphere's energy balance, and hence the 'climate sensitivity'. These include water vapour changes, the response of clouds, and changes in snow and ice that modify how the surface reflects or absorbs sunlight (IPCC 2007). Uncertainty about how the global climate system responds to a given increase in concentrations of greenhouse gases is one of the largest sources of uncertainty affecting the assessment of warming.

Figure 4: Australian annual average temperature anomalies, 1910 - 2010

Note: the data show temperature difference from the 1961 – 1990 average.

Source: Bureau of Meteorology, retrieved 10 February 2011,
http://www.bom.gov.au/web01/ncc/www/cli_chg/timeseries/tmean/0112/aus/latest.txt.

Some recent research supports a climate sensitivity at or above the IPCCs 'best estimate' of 3°C in 2007. Such a 'climate sensitivity' would mean a 3°C change in average global surface temperature would follow when the climate reaches equilibrium following a doubling of atmospheric equivalent carbon dioxide concentrations (IPCC 2007). The observed change in temperature resulting from changes to the atmosphere's energy balance during the transition of the Earth from the last ice age to the current interglacial period also indicates a value of about 3°C (Hansen, Sato et al. 2008). Recent analyses of observed humidity variability and trends have provided new evidence supporting a strong positive water vapour feedback, similar to that found in models (Dessler, Zhang et al. 2008; Gettelman and Fu 2008; Dessler and Wong 2009; McCarthy, Thorne et al. 2009; Sherwood, Roca et al. 2010), although some alternative results have also been recorded (Paltridge, Arking et al. 2009). Recent observational evidence and modelling studies also suggest that cloud feedbacks reinforce the warming, consistent with the way models currently simulate cloud feedbacks and the general scale of overall warming (Clement, Burgman et al. 2009; Dessler 2010).

The IPCC used the term “*unequivocal*” to describe the level of confidence in observations of temperature trends. Global average temperature data shows that since the IPCC drew its conclusion in 2007, global average temperatures have continued to be on a rising trend within the range of IPCC scenarios.

There is wide agreement in the scientific community on this aspect of climate change, but research is continuing into the magnitude of future temperature changes that will be associated with various increases in concentrations of greenhouse gases.

2.5. Changes in oceans and sea level

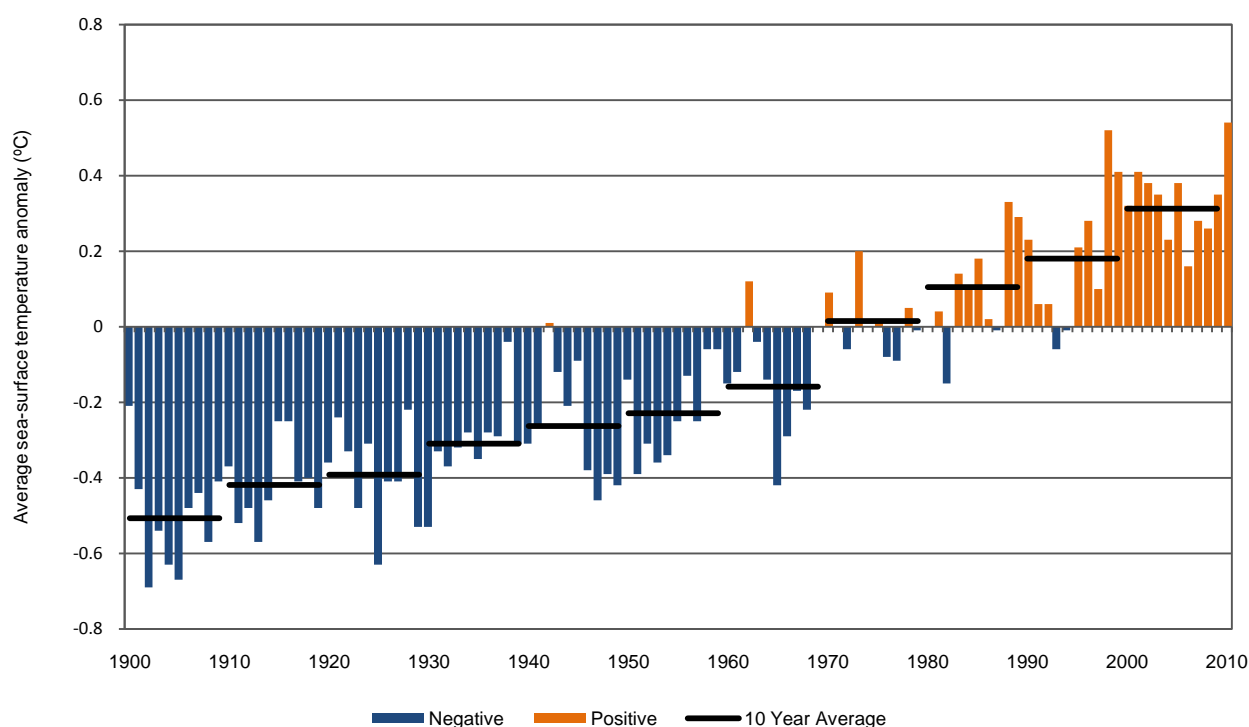
2.5.1. Observed changes to oceans

Temperature

The world's oceans store the majority of heat within the climate system. As a result changes in heat content of the oceans are a critical element in climate change as they reflect the sum of the competing effects of greenhouse warming and aerosol cooling. Analysis of historical observations by many groups 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 (Domingues, Church et al. 2008; Ishii and Kimoto 2009; Levitus, Antonov et al. 2009). This warming has continued over the last 15 years (Lyman, Good et al. 2010). Since the Review, the identification and removal of biases in some historical ocean temperature data has increased the level of certainty associated with the warming of the ocean and removed spurious decadal warming evident in the older data (Domingues, Church et al. 2008).

The temperature of the sea surface has a considerable influence on local weather patterns. Sea surface temperatures in the Australian region were the highest on record during 2010, at 0.54 °C above the 1961 to 1990 average. The decade ending 2010 was also the warmest decade on record for sea surface temperatures near Australia, consistent with the temperature pattern observed over land (BoM 2011)¹¹.

Figure 5: Annual sea surface temperature anomalies in the Australian region relative to the 1961-1990 average of 21.9 °C.



Source: Bureau of Meteorology, retrieved 10 February 2011, http://www.bom.gov.au/web01/ncc/www/cli_chg/timeseries/sst/0112/aus/latest.txt

Rainfall in northern and eastern Australia is strongly influenced by sea surface temperatures in the tropics around northern Australia, and the unprecedented (in the era of observation) warm sea surface temperatures in 2010 contributed to the record rainfall and high humidity across eastern Australia during winter and spring (see Section 2.6).

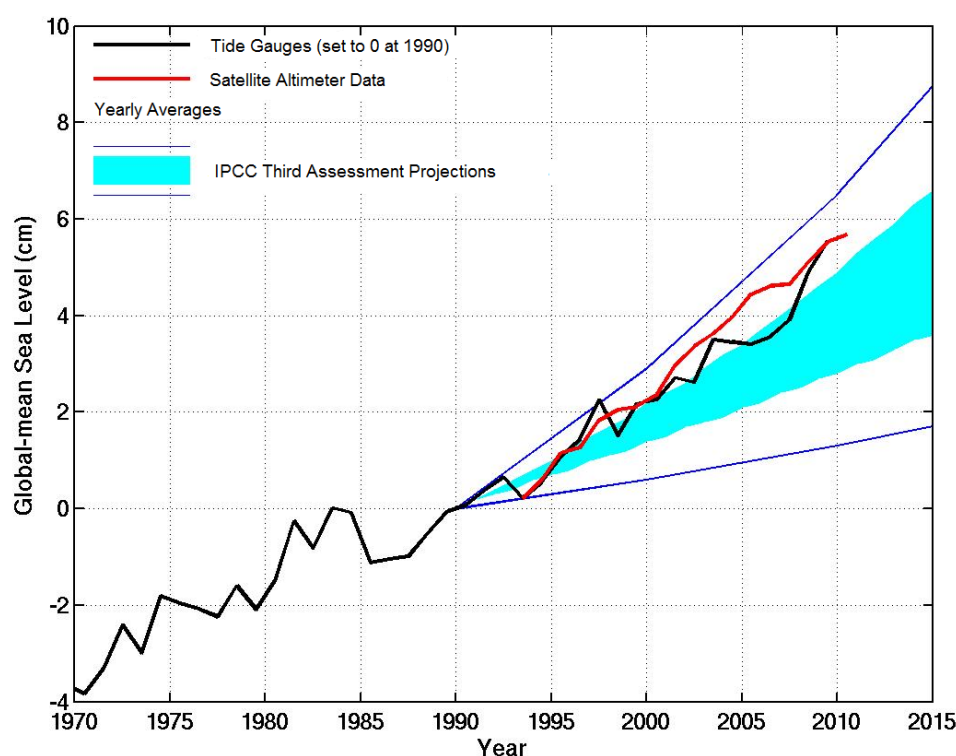
¹¹ Note that there are gaps in sea surface temperature data prior to the satellite era (post 1978) that lower the confidence in these historic records compared to land-based data shown in Figure 4, as discussed in: Keenan, T. and H. Cleugh (2011). *Climate Science Update for the Garnaut Review*, CAWCR Technical Report No. 036, 2011.

Observed sea level rise

The Review noted that the total sea level rise during the 20th century was 170mm. More recent observations indicate that sea level has been rising more rapidly over the past one and two decades, with the average rates since 1993 about 3.2 ± 0.4 mm/yr (Church and White submitted 2011). When observed sea-level rise is compared to projections of modelled sea level rise for the period from 1990 in the two most recent IPCC reports, it shows that observed sea level is tracking near the upper limit of the model projections (see Figure 6:). The data indicate that over recent decades there has been an increased contribution to sea level rise from grounded glaciers and ice caps, and since the 1990s from the Greenland and West Antarctic ice sheets (Cogley 2009; Velicogna 2009). Studies show that the area and mass of melt from the Greenland Ice Sheet are continuing to increase (Mote 2007; Hanna, Huybrechts et al. 2008).

Rising sea levels will continue to increase the frequency and intensity of coastal flooding events during the 21st century. Observations indicate that there has been a significant increase in the frequency of extreme high sea levels within Australia (Church, Hunter et al. 2006; Church, White et al. 2008) and globally (Menéndez and Woodworth 2010). Methods for assessing the risk of these extreme events on coastal infrastructure have recently been developed (Hunter 2009).

Figure 6: Changes in observed global sea level since 1970, compared with the IPCC Third Assessment Report sea-level rise projections



The black curve is the CSIRO reconstruction of global averaged sea level from tide-gauges, red curve is the altimeter data starting in 1993. The solid blue lines indicate the upper and lower limits of sea-level projections from the IPCC Third Assessment Report including uncertainty in land-ice changes, permafrost changes and sediment deposition. The turquoise shading represents the range of all Atmospheric-Ocean General Circulation Models for all 35 IPCC scenarios. The Third Assessment Report is used because IPCC AR4 did not include upper and lower bounds by decades (as in the Third Assessment Report and required here). There are uncertainties of about 0.6 to 0.7 cm in gauge data but these are not plotted in this figure.

Source: CSIRO update of Figure 1 in (Rahmstorf, Cazenave et al. 2007).

Ocean acidification

Carbon dioxide dissolves in the ocean and some is returned to the atmosphere through dissolution in a continuous exchange. The uptake of carbon dioxide by the ocean causes seawater to become more acidic, which can then affect marine organisms, ecosystems and ocean biogeochemistry. Measurements indicate that the average seawater acidity has increased by 30 per cent since pre-industrial times (Pelejero, Calvo et al. 2010). Ocean acidification directly follows the accelerating trend in world carbon dioxide emissions, and the magnitude of ocean acidification can be ascertained with a

high level of certainty based on the predictable marine carbonate chemistry reactions and cycles within the ocean (SCBD 2009). It is predicted that by 2050 ocean acidity could increase by 150 per cent (Steinacher et al, 2009).

Box 6: Ocean acidification and the Great Barrier Reef

The Great Barrier Reef is one of the most vulnerable of the iconic Australian ecosystems. A temperature increase of around 3°C would lead to 65 per cent of corals being above the critical limit for bleaching (GBRMPA 2009).

Another risk to the Great Barrier Reef is an increase in ocean acidity, which lowers the concentration of carbonate ions, limiting the ability of calcifying organisms, such as corals, to form their skeletons. The level of ocean acidity today is as high as it was 25 million years ago, the previous most acidic state in the record. The rapid increase in acidity levels over the last 200 years is unprecedented in the last 25 million years (SCBD 2009). The impacts of increasing ocean acidity are already evident in some marine species with calcification rates having dropped by about 14 per cent over the past two decades (De'ath, Lough et al. 2009). Studies suggest that there is a critical level of 450 ppm of atmospheric carbon dioxide and that beyond this coral reef structures may suffer declining growth rates and erosion (Kleypas and Langdon 2006; Hoegh-Guldberg, Mumby et al. 2007; Silverman, Lazar et al. 2009). Rising ocean acidification, combined with thermal stress has already affected growth and skeletal strength of corals in the Great Barrier Reef (De'ath, Lough et al. 2009).

Climate change projections also indicate an increase in the more intense tropical cyclones. The severity and scale of reef damage from two recent category five cyclones (Tropical Cyclone Hamish in 2009 and Tropical Cyclone Yasi in 2011) demonstrate the potential for cumulative and far-reaching impacts to the reef ecosystem if cyclone risks increase in the future. Both of these cyclones caused patchy but severe damage to reefs spanning hundreds of kilometres. While coral reefs have evolved to cope with cyclones, an increase in the more intense tropical cyclones, combined with the multiple other stressors, pose significant challenges for the reef's resilience (Hoegh-Guldberg, Mumby et al. 2007).

The Great Barrier Reef is recognised as the best managed reef ecosystem in the world (Wilkinson 2008), yet it is still subject to increased levels of sediments, nutrients and pesticides. These stressors also act to undermine the long-term resilience of this sensitive ecosystem (Johnson and Marshall 2007).

There is a high risk that a temperature increase above 2°C and carbon dioxide concentrations above 500 ppm will lead to large portions of the Great Barrier Reef being converted to an algae-dominated ecosystem (Hoegh-Guldberg, Mumby et al. 2007). The Great Barrier Reef Outlook Report 2009 indicates that at carbon dioxide equivalent concentrations above 450 ppm, most of the Reef's ecosystem components will be severely threatened (GBRMPA 2009).

2.5.2. Sea level rise in the future¹²

The physics behind sea level rise from the thermal expansion of the oceans is well understood, and this mechanism contributes most of the IPCC projected rise out to 2100. The melting of glaciers is understood and also contributes significantly to the 21st century sea level rise. However, the level of understanding about the magnitude and timing of ice sheet contributions from Greenland and West Antarctica is low, due to the potential acceleration of the 'dynamic response' of these ice sheets.

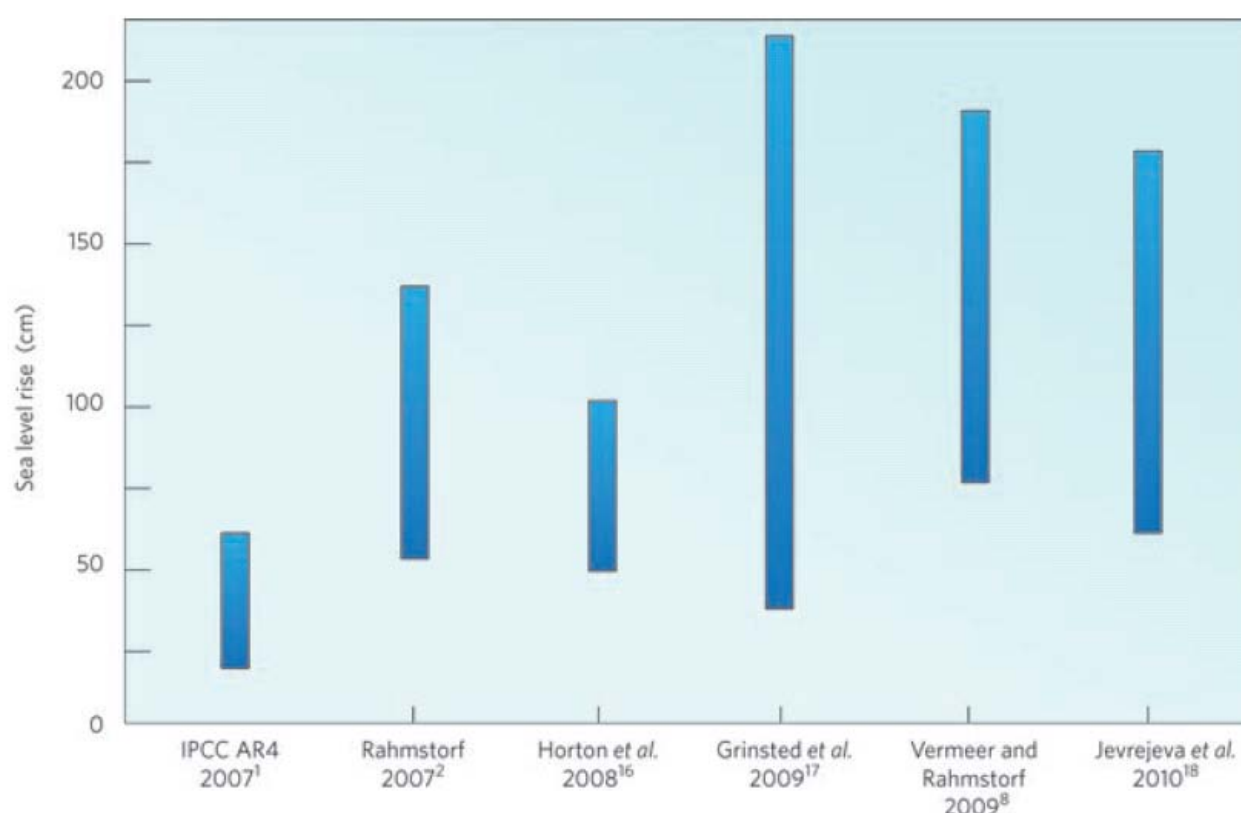
In 2007, the IPCC estimated that the sea level rise for a scenario similar to the no-mitigation case (A1FI) would be 26-59 cm by 2100, with a lower limit for all scenarios of 18cm. This figure did not include the potential dynamic losses (calving) from ice sheets, which could increase the upper end to

¹² For more detail on the studies referred to in this section, please refer to the following report available at www.garnautreview.org.au - *ibid*.

76 cm by 2095. Note that the IPCC concluded 'that larger values above this upper estimate could not be excluded' (Rahmstorf 2010). The reason quantitative estimates for the contribution to sea-level rise of the potentially rapid response of ice sheets were not included was that no consensus could be reached on the potential magnitude of these contributions by 2100 (Hulme and Mahony 2010).

The large land-based ice sheets on Greenland and Antarctica are currently losing mass to the ocean through both melting and 'dynamical flow'. Dynamical flow occurs when some of the water melting on the surface of the ice caps seeps through to the base and acts as a lubricant, speeding the movement of the ice towards the sea. There is considerable uncertainty about the rate at which this dynamical flow is occurring or whether it will continue into the future, as the trends are based on shorter-term observation records and therefore are more difficult to distinguish from natural variability¹³. However, a review of all observations shows that there is a net loss of mass from the Greenland (and Antarctic) ice sheets. The uncertainty is around the rate at which this ice loss is occurring, not whether it is occurring at all.

Figure 7: Sea level rise: estimates for twenty-first century sea level rise from semi-empirical models as compared to the IPCC Fourth Assessment Report



Source: (Rahmstorf 2010). For exact definitions of the time periods and emissions scenarios considered, see the original references quoted in Rahmstorf, 2010.

Note: The IPCC AR4 (Fourth Assessment Report) bar shows the range of sea level rise for the full set of IPCC scenarios.

Significant concerns have been raised about the robustness of the range of alternative projections on several grounds (Holgate, Jevrejeva et al. 2007; Schmith, Johansen et al. 2007; Von-Storch, Zorita et al. 2008; Abbs and Rafter 2009; Lowe and Gregory 2010) and they should be used with caution. See Keenan and Cleugh (2011) for additional discussion.

There has been a significant focus on rates of sea level rise and the future of the ice sheets since the 2007 IPCC Fourth Assessment Report and the Review. The fact that observed sea-level rise is tracking near the upper limit of IPCC estimates (Figure 6:) has raised concerns that the IPCC projections may be underestimates, particularly in the context of the current inability to adequately model the response

¹³ For example, Rignot, E., J. Bamber, et al. (2008). "Recent mass loss of the Antarctic Ice Sheet from dynamic thinning." *Nature Geoscience* 1.

of ice sheets to global warming. These concerns have led to the development of several “semi-empirical” models of sea-level rise, the parameters of which are determined from 20th century sea level and temperature records (Rahmstorf 2010).

These semi-empirical models all give larger rates of rise during the 21st century than the IPCC Fourth Assessment Report projections, with upper values as high as 1.9 m by 2100. A selection of these estimates is shown in Figure 7: compared to the IPCC’s estimates. However, significant concerns have been raised about whether these projections are robust. They should be used with caution (Holgate, Jevrejeva et al. 2007; Schmith, Johansen et al. 2007; Von-Storch, Zorita et al. 2008; Abbs and Rafter 2009; Lowe and Gregory 2010). Other work not included in the above diagram suggested that a sea level rise more than 2m by 2100 was not physically possible, and that a more plausible rise – including ice-sheet contributions - was near the upper end of the IPCC estimates (Pfeffer, Harper et al. 2008). The upper limit of sea level rise in the 21st century is a matter for continued research; there has been no credible publication of views that sea level rise could be less than suggested by the IPCC (2007).

Both the oceans and ice sheets will take many centuries to respond to the changes. The biggest concern in terms of long term sea level rise is the ongoing melt – well beyond 2100 - of the West Antarctic and Greenland Ice Sheets, which collectively contain enough water to raise global sea levels by 13m (IPCC 2007). Recent model simulations are consistent with concerns in the IPCC’s Fourth Assessment Report that melting of the Greenland Ice Sheet, once it commences, may be irreversible (Ridley, Gregory et al. 2010).

The oceans are warming: more than 90 per cent of the extra heat stored by the earth system in the last 50 years is found in the ocean.

Sea levels are continuing to rise at a rate considerably higher than the average rate over the 20th century.

The acidity of sea water has increased by 30 per cent since pre-industrial times.

The area and mass of melt from the Greenland Ice Sheet is continuing to increase, but experts disagree over how much ice sheet melt will contribute to sea level rise by 2100.

2.5.3. Sea-level rise and Australia

Infrastructure impacts and mapping

The impact of sea-level rise and other effects of climate change on buildings in coastal settlements was the subject of detailed work commissioned by the Review. The outcomes of this work were incorporated into the modelling exercise. This work was based on the IPCC (2007) projections. The potential impacts on the coast include: sea-level rise; cyclones; severe storms; and riverine flooding.

The Review found that the increased magnitude of storm events and sea-level rise (70cm by 2100) under a no mitigation case is likely to exert significant pressure on coastal infrastructure through storm damage and localised flash flooding. This would cause immediate damage to assets, particularly building contents, and accelerate the degradation of buildings. In the medium term (2030 to 2070) the cost of climate change for coastal settlements would mainly arise from repair and increased maintenance, clean-up and emergency response. Later in the century, costs for preventive activity are likely to be higher. There will be large costs associated with altered building design, sea-wall protection and higher capital expenditure for improved drainage. The overall impacts to buildings in coastal settlements were found to be substantially lower under the global mitigation cases (Maunsell Australia 2008).

The impact of sea level rise on Australia’s coastlines has been a focus of research and policy development since the Review. The lack of regional detail limited the Review’s modelling exercise. The Department of Climate Change and Energy Efficiency (DCCEE - formerly Department of Climate Change) undertook a ‘first pass’ national assessment of the extent and magnitude of climate change risks to Australia’s coastal zone, released in 2009. This included the development of a detailed national coastal geomorphology map that used a consistent methodology for the entire Australian coastline (DCC 2009). The work on geomorphology mapping has assisted in understanding the vulnerability of

different sections of the coastline due to differences in topography and geology. Beaches that have been relatively stable for many decades may start to recede, putting properties at risk from erosion.

Based on recent science that suggested the IPCC may have underestimated 2100 sea level rise (see Section 2.5.2), the Department of Climate Change and Energy Efficiency chose to model a sea level rise by 2100 of 1.1 metres, higher than that modelled by the Review in 2008. This was chosen for the purposes of assessing risk, and was different to the values chosen by jurisdictions in Australia as benchmarks for land use planning (DCC 2009).

The Department of Climate Change and Energy Efficiency identified between 157,000 and 247,600 existing residential buildings were at risk of inundation from a sea level rise of 1.1 metres at a current value of between \$41 billion - \$63 billion (DCC 2009). Coastal climate change impacts also pose significant risk for essential services and infrastructure on the coastline, including water treatment plants, landfill sites, hospitals and power stations. Ports and coastal areas are also at risk (DCC 2009).

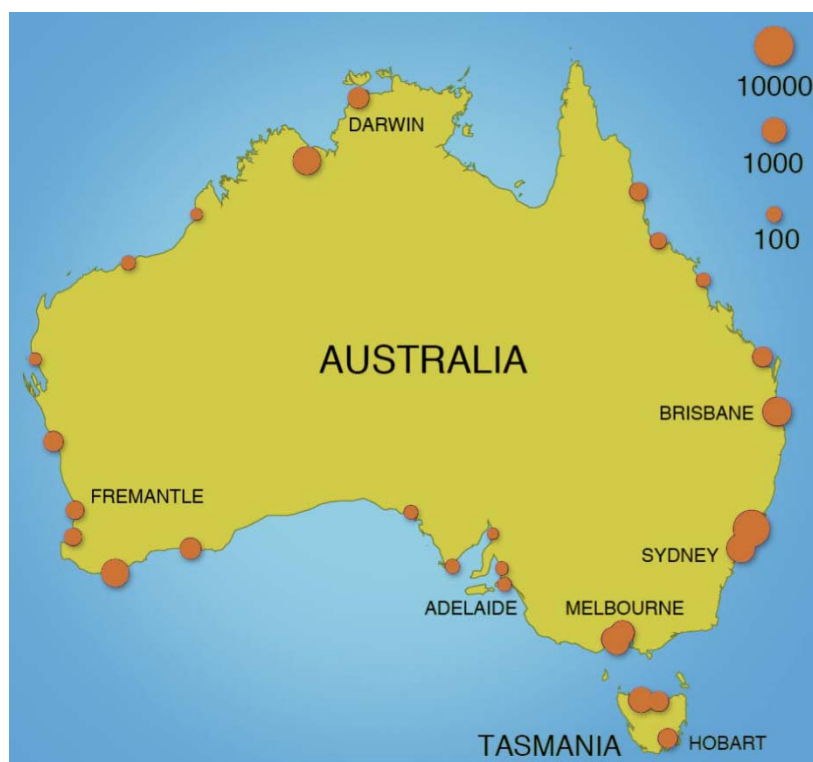
The Commonwealth and many state governments have invested in high resolution elevation data (10-15 cm) in order to produce detailed maps. These maps will allow governments and local communities to better understand the impacts of coastal climate change and to help incorporate this understanding into how coastal areas are managed (DCCEE 2011; Victorian Government 2011). Further modelling at the national level is intended to improve the sophistication of the risk analysis. This will incorporate the higher resolution elevation data and incorporation of more detailed assessment of sensitivity to erosion.

Extreme events in the coastal zones

In addition to increases in average sea level, impacts on coastlines will be magnified by storm surges caused by falling atmospheric pressure and increased wind speeds during severe storms. The geomorphology of the coastline will also have an impact on the magnitude of storm surges. The outcomes of an analysis of the impacts of sea level rise for extreme sea level events around the Australian coastline are shown in Figure 8.

Figure 8: Extreme sea-level event multipliers for a 0.5m sea level rise

Estimated multiplying factor for the increase in the frequency of occurrence of high sea-level events with a sea-level rise of 0.5 metre.



Source: (Church, White et al. 2008) and Hunter (pers. comm.).

Even for a sea level rise that is at the low end of post-IPCC estimates, the implications for extreme sea level events are significant. The increase in incidence of extreme sea level events for some of Australia's largest cities is a factor of 1000, and for Sydney it is 10,000. For a multiplying factor of 100, events with a current occurrence of once every hundred years would occur every year (ACECRC 2008). This analysis is supported by observational data from places such as Fremantle and Fort Denison in Sydney Harbour, where very long records are available. In these locations there has been a 3-fold increase in inundation events (Church, White et al. 2008)

Since 2008, a series of decisions have been made to prevent development on low-lying areas vulnerable to sea-level rise, with a well known example being the Gippsland Coastal Board case (see Box 7).

Box 7: Sea level rise and planning decisions

In 2008 the Gippsland Coastal Board appealed to the Victorian Civil and Administrative Tribunal (VCAT) to review a decision made by the South Gippsland Council to approve the construction of six residential developments in a low-lying coastal region on the Victorian coastline. One of the main objections raised by the Gippsland Coastal Board in their appeal was that the residential developments were not appropriate when sea level rise projections were considered.

While VCAT overturned the approval on the basis of inconsistency with zoning and planning controls, it also determined that the application should be refused on the basis that relevant scientific evidence suggested that there was a 'reasonable and foreseeable risk of inundation' of the land and proposed residences due to sea level rise.

The relevant planning laws did not contain specific provisions that required such considerations, but VCAT determined that the potential threat was sufficient to invoke the precautionary principle. Based on their understanding of the science and the uncertainty involved, VCAT also noted that for effective risk assessment relying upon historic data was not sufficient.

VCAT's decision in the Gippsland Coastal Board case is considered to be a turning point in the approach to coastal development in the context of climate change.

Drawn from: (Peel and Godden 2009)

The impacts of sea level rise on our coastal communities are already being felt.

More than 85 per cent of Australia's population lives in coastal regions so the impacts of sea level rise could be significant.

Improved data, modelling and planning strategies will assist in the effective assessment of future risk.

2.6. Changes in water and ice

2.6.1. Observed changes in precipitation

The temperature of air affects the amount of moisture it can hold and higher temperatures can lead to increased evaporation of water from the surface. The water-holding capacity of the atmosphere is expected to increase roughly exponentially with temperature rises (Stott, Gillett et al. 2010). This will alter the water cycle and influence the amount, frequency, intensity, duration and type of precipitation.

The relationship between rainfall and atmospheric temperature at the local and regional scale is much more complex. Regional precipitation can be sensitive to small differences in topography, circulation and other processes – this is evident in the large natural variability of observed precipitation over Australia (CSIRO & BoM 2007). Regional rainfall patterns are also influenced by large-scale patterns of variability such as the El Niño – Southern Oscillation and Southern Annular Mode (Hendon, Thompson et al. 2007).

Despite the inherent variability in rainfall, the IPCC (2007) identified some observed long-term trends in regional precipitation, including increases in Europe and North America and decreases in southern Asia and southern Australia.

There has been recent work on the detection and attribution of precipitation change, but there are difficulties in applying it at the regional level because of the high level of 'noise' and limited observations (Stott, Gillett et al. 2010). Some comparisons of observed trends with model simulations suggest that human-induced warming has had a detectable influence on observed changes in average precipitation (Zhang, Zwiers et al. 2007). Observed changes in global average land precipitation also appear to be consistent with the expected effects of both natural and human influences (Lambert, Stott et al. 2004; Lambert and Allen 2009). However, other studies looking at modelled versus observed rainfall, suggest it may be 20 years or more before it can be determined whether observations and models agree on the effect of global warming on precipitation due to observational limitations (Liepert and Previdi 2009).

Australian rainfall observations

There has been a major change in Australian rainfall patterns since the 1950s, with large geographic variation. Over this period, rainfall in the north-west of Australia has increased, and eastern and south-western Australia have become drier (CSIRO & BoM 2007). Rainfall in Australia is strongly influenced by El Niño and La Niña events, which are the extreme parts of the Southern Oscillation. El Niños tend to bring dry conditions, while La Niñas tend to bring wet conditions.

The long-term drying trends in the southern part of the continent are related to a systematic and continuing reduction in the strength of the sub-tropical jet stream, the weaker growth of mid-latitude storms and a southward deflection of some storms (Frederiksen and Frederiksen 2007; Frederiksen, Frederiksen et al. 2011). A considerable body of research undertaken within Australia suggests that the persistent dry conditions in parts of the southwest and southeast of Australia are at least in part due to climate change (Cai and Cowan. T. 2006; Bates, Hope et al. 2008; Cai, Sullivan et al. 2009; CSIRO 2010; Hope, Timbal et al. 2010; IOCI 2010; SEACI 2010).

A series of major rain events affected large parts of eastern Australia in late 2010 and early 2011 (Keenan and Cleugh 2011), resulting in widespread flooding on many rivers. The rains in 2010 are consistent with long-term trends and the strong La Niña event in the Pacific Ocean. Previous strong La Niña events, such as those of 1955 and 1974, were also associated with widespread and severe flooding in eastern Australia (Keenan and Cleugh 2011). While warming of the atmosphere and record high sea temperatures across northern Australia can be expected to have increased the intensity of rainfall events, the degree to which global warming may have enhanced heavy rainfall in some parts of eastern Australia cannot be precisely determined from current observations.

High rainfall in 2010 ended a decade-long dry spell in the southern Murray-Darling Basin, Victoria, and south-west Australia that was unprecedented over the 110 years of reliable Australian rainfall records (Timbal 2009). However, despite the high average rainfall for the continent in 2010, not all areas of Australia were wet.

For example, the south-west of Western Australia had its driest year on record in 2010, which resulted in record low inflows to Perth region water storages. Dry conditions also occurred in central and eastern Gippsland during 2010, particularly during autumn and winter, continuing the dry pattern observed in this region since 1997 (Keenan and Cleugh 2011)

Studies have shown that the observed drying over south-west Western Australia is likely to be linked to anthropogenic climate change (Power, Sadler et al. 2005; Timbal, Arblaster et al. 2006; Bates, Hope et al. 2008) and might also be linked to anthropogenic changes in the land surface (Timbal and Arblaster. J. 2006).

Significant progress has been made in understanding the causes of the recent changes in rainfall in south-eastern Australia through the work of the South East Australia Climate Initiative (SEACI). There has been an increase in surface pressure over much of Australia and an observed strengthening of the 'subtropical ridge', which causes much of the seasonal variation in weather in the south of the continent. The strengthening of the subtropical ridge is consistent with the rise in global mean temperature, and expectations from the physics of the climate system (CSIRO 2010).

2.6.2. Precipitation in the future

Climate models indicate that as temperatures rise, rainfall will increase at high latitudes and equatorial regions, and decrease in the subtropical and some temperate regions. This occurs in large part due to an intensification of existing patterns, and changes in circulation pushing rain towards the poles (Held and Soden 2006), although other important shifts and changes may also occur. Climate change will also influence the seasonal and daily patterns of rainfall intensity. There is expected to be an increased risk of drought in the mid-latitudes (southern Australia), and an increase in the risk of flooding as rainfall is concentrated into more intense events (Abbs, McInnes et al. 2007; IPCC 2007; Abbs 2009; Abbs and Rafter 2009).

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. Two thirds of the 23 climate models used to inform Australian projections agree that rainfall will decrease in southern areas (for both the annual average and in winter), in southern and eastern areas in spring, and along the west coast in autumn (CSIRO and BoM 2007). In other regions and seasons less than two thirds of models agree on the direction of change, but in almost no region or season do more than two-thirds of models suggest an increase in rainfall (CSIRO and BoM 2007). There is a high level of consistency in models showing a total precipitation decline in the area between the coast and the wheat-belt in south-western Australia (CSIRO & BoM 2007).

Efforts have been made recently to reduce the uncertainty in regional rainfall projections and to understand the impact of excluding global models that poorly simulate Australia's current climate from the 'ensemble' approach (see Box 3)¹⁴. There is some evidence that this approach can narrow the range of uncertainty in projection results, provides an example. The work on the Murray-Darling Basin that indicates a tendency for a drier outcome (Smith and Chandler 2010).

Analysis of observed rainfall trends has identified associations between dry conditions over parts of Australia, with changes to Pacific and Indian Ocean circulation and atmospheric pressure systems (Nicholls 2009). Climate models indicate that such changes to circulation are likely to intensify and become more persistent in future as climate continues to change. As a result, the majority of climate models project a drier future for southern Australia than was experienced last century (Keenan and Cleugh 2011).

Surface water availability is likely to be reduced across the entire Murray-Darling Basin, but more particularly in south-eastern Australia, where the median decline in runoff from 2008 levels may be as high as 13 per cent by 2030. Recent modelling has shown that the change in average stream flow under a median 2030 climate is a decline from 2008 levels of 10 per cent in Melbourne catchments, and 25 per cent in south-western Australia (CSIRO 2009; Post, Chiew et al. 2010). The warmer climate and increased evapo-transpiration will also increase demand for water in irrigated agriculture, cities and by water-dependent ecosystems, such as wetlands (Keenan and Cleugh 2011).

A considerable body of research undertaken within Australia suggests that the persistent dry conditions in parts of the southwest and southeast of Australia are, at least in part, due to climate change.

In a warmer climate there is expected to be an increased risk of drought in southern Australia and an increase in the risk of flooding as rainfall is concentrated into more intense events.

Unlike future temperature, which is always simulated to increase throughout Australia, the results for rainfall change from different climate models show potential decreases and increases for many locations. Understanding future rainfall in Australia is an area of active research.

¹⁴ For examples of recent research please refer to the Centre for Australian Weather and Climate Research Technical Report No. 036, 'Climate Science Update for the Garnaut Review', available at www.garnautreview.org.au.

2.6.3. Ice caps, Ice sheets and frozen ground

As the climate warms, snow cover and ice extent will decrease. Extensive changes to ice and frozen ground have been observed in the last 50 years, consistent with the warming of the surface of the Earth (IPCC 2007). Records from the National Snow and Ice Data Centre show that January 2011 had the lowest Arctic sea ice extent for that month since the beginning of satellite records (in 1979), continuing a long-term trend of decline in January ice-cover of 3.3 per cent per decade (NSIDC 2011). The large land-based ice sheets on Greenland and Antarctica are currently losing mass to the ocean through both melting and 'dynamical flow', as discussed in Section 2.5.1

A global retreat of mountain glaciers is one of the clearest signals of ongoing climate change (Haeberli and Hoelzel 1995 in (Arndt, Baringer et al. 2010)). The World Glacier Monitoring Service (WGMS) records annual changes in the behaviour of 30 reference alpine glaciers. Changes are recorded in the mass balance, which is the difference between accumulation and melt, and behaviour at the end of the glacier (whether they are advancing or retreating). The recorded mass balance for the reference glaciers was negative in 2008 for the 18th year in a row, and preliminary results from parts of the northern hemisphere indicate that it is likely that this trend continued for 2009 (Arndt, Baringer et al. 2010). Strong reductions in mass balance along with recent rapid retreat has led to some glaciers disappearing (Pelto 2010 in Arndt, Baringer et al. 2010). The mean annual mass balance was a loss of 198 mm in the decade of the 1980s, a loss of 382 mm in the decade of the 1990s, and a loss of 624 mm for 2000–08. The declining trend is consistent from region to region (Arndt, Baringer et al. 2010). Recent research looking at 2000–2008 changes in glaciers in the Himalaya region shows that there is strong spatial variation in glacier behaviour linked to topography and climate. Almost two-thirds of the monsoon-influenced glaciers that were monitored were retreating, but other glaciers with a high amount of debris cover and shallower slopes were stable (Scherler, Bookhagen et al. 2011).

2.7. Severe weather events

'Severe weather events' are of an intensity that is rare at a particular place and time of year. Severe weather events include (among others) heat waves, heavy rainfall and floods, droughts, tropical cyclones and bushfires.

While it is difficult to attribute specific causes to individual extreme weather events (Allen, Pall et al. 2007), climate change is expected to increase the risk of extreme events occurring and lead to changes to the frequency, intensity and distribution of weather events that are considered 'severe' in the current climate.

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. As noted in the 2008 Review, the natural variability in extreme events such as cyclones, and the varying quality of historical records, makes it difficult to detect trends in some extreme events. In addition, the evidence for a human contribution to existing extreme weather and climate events through increases in greenhouse gases varies regionally and for different climate variables.

It is possible to look at the probability of such an event, or of the physical components of such an event, and ask: "How likely was this event of this severity with warming, and how likely would this event have been if no global warming had taken place?".

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 recent Black Saturday Fires in Victoria were consistent with expectations for a warming world. It would be expected that there will be an increase in the frequency of such conditions as the world continues to warm (Lucas, Hennessy et al. 2007).

However, such comparisons generally do not allow us to state categorically that "such an event could only have occurred with climate change" (Keenan and Cleugh 2011).

In making assessments about the effects of warming on extreme events, we should keep in mind that we are in the early stages of warming. Land temperatures have increased less than half as much as they would do even with effective strong mitigation to hold temperatures to 450 ppm carbon dioxide

equivalent; only one quarter of the temperature increase with partially successful mitigation to 650 ppm carbon dioxide equivalent; and a small fraction of temperature increase with no mitigation at all. Some severe weather events are likely to increase in severity much more than proportionately with the increase in temperature (Church, White et al. 2008). It is therefore to be expected that the reflection of global warming in severe weather events is in an early and weak stage.

Since 2008 there have been some important developments in the understanding of severe weather events, the detection of trends and the attribution of events to climate change. Some of these are discussed below.

2.7.1. Rainfall extremes

Some recent work looking at events in the ‘data rich’ 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. 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 9 out of 10 cases, the results showed that anthropogenic 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 (Pall, Aina et al. 2011). Another study used a similar approach to severe rainfall and heavy snowfalls in the Northern Hemisphere, and found they could not be explained without factoring in the increases in greenhouse gases from human activity (Min, Zhang et al. 2011).

New research on Australian temperature and rainfall records between 1911 and 2008 has investigated changes in the percentage area of the continent experiencing extreme cold, hot, dry or wet conditions. It has shown 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 (Gallant and Karoly 2010).

Historically, co-variations in Australian extremes have been either hot and dry, or cold and wet. The Gallant and Karoly (2010) study detected a long-term shift towards wet extremes and hot extremes occurring at the same time, which is not consistent with processes causing inter-annual and decadal variability. 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 in greenhouse gases.

2.7.2. Tropical cyclones

The 2008 Review noted that studies suggest the frequency of east coast cyclones may decrease, but that category 3-5 storms will increase in intensity (Garnaut 2008 p117, see also IPCC 2007: Section 10.3.6.3).

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, and theory and modelling suggest that as oceans warm, there is more energy for conversion into tropical cyclone wind, leading to increased wind speeds and more intense cyclones (Elsner, Kossin et al. 2008)

According to the Bureau of Meteorology, the recent Cyclone Yasi was one of the most powerful cyclones to have affected Queensland since records commenced. Previous cyclones of a comparable measured intensity include the 1899 cyclone Mahina in Princess Charlotte Bay, and the two cyclones of 1918 at Mackay (January) and Innisfail (March) (BoM 2011).

Research since the 2008 Review supports the judgement of the science that climate change may lead to more intense but potentially less frequent tropical cyclones. Investigations into simulations from regional climate models have shown, on average, about a 50 per cent decrease in occurrence of tropical cyclones for the Australian region for the period 2051-2090 relative to 1971-2000 (Abbs 2009). Separate analysis has shown that rainfall associated with tropical cyclones (within 300 km) would increase by 17 per cent on average, and that there was a larger percentage of tropical cyclones

producing higher wind speeds in the 2070 climate than either the 1980 or 2030 climates. These regional findings are consistent with recently published international studies (Bender, Knutson et al. 2010; Knutson, McBride et al. 2010). 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 frequency and intensity of cyclones without a better understanding of this phenomenon.

Box 8: Was climate change responsible for the weather conditions of Black Saturday?

On the 7th February 2009, there were a number of devastating fires to the north and north-east of Melbourne. An area of over 350,000 hectares was burnt (Cameron, Mitra et al. 2009), 2,133 houses were destroyed and 173 people were killed (Victorian Bushfire Royal Commission 2010).

On the days of the fires parts of south-eastern Victoria experienced a Macarthur Forest Fire Danger Index estimated to be as high as 200 (Sullivan and McCaw 2009). The Fire Danger Index was originally calculated on a scale of 0 to 100 (with the destructive Black Friday Victorian fires of 1939 receiving a rating of 100), and hence the scale is effectively 'capped' at 100, though higher values are possible (VBRC 2009). A review of the conditions on Black Saturday suggest that it ranks as one of the worst, if not the worst, fire weather day in Australia's recorded history, in terms of drought conditions in the lead-up and the combination of heat, wind and dryness (Parkyn, Yeo et al. 2010).

While it is very difficult to attribute single weather events to climate change, the conditions of Black Saturday were consistent with expectations for a warming world. It would be expected that there will be an increase in the frequency of such conditions as the world continues to warm (Lucas, Hennessy et al. 2007).

Multiple aspects of the extreme weather conditions associated with Black Saturday were consistent with our understanding of conditions that are more likely under global warming and human-induced climate change than without those effects.

These include:

1. Prolonged drought: Some aspects of the prolonged drought in the south-east of Australia are consistent with our understanding of changes likely to occur with human-induced climate change. In particular, increases in atmospheric pressure and the strength of the subtropical ridge across southern Australia have been linked with global warming, and are probably the strongest influence on systematic rainfall declines in the region. Prolonged drought greatly increases fire potential, and hence fire danger.
2. Longer-term higher temperatures: Higher maximum and minimum temperatures, have been observed across south-eastern Australia over recent decades and have been attributed to the effects of increasing greenhouse gases in the atmosphere, driven largely by emissions from human activities. Higher temperatures lead to a greater frequency of extreme heat and hotter extreme heat days. Record high temperatures have outnumbered record low temperatures in Australia by a ratio of 2-3 to 1 since 1997 (Trewin and Vermont 2010). In general, higher temperatures exacerbate drought conditions in Victoria. Sequences of very hot days, with increased frequency, also act to dry fuel loads.

Source: Drawn from (Keenan and Cleugh 2011)

2.7.3. Droughts and heat waves

Considerable uncertainty remains regarding projection of future drought. To support government drought policy formation, further work has sought to better understand how climate change may affect the occurrence of a one in 20 year exceptional hot or dry year (Hennessy, Fawcett et al. 2008). The analysis found that regions experiencing exceptionally hot years had a long term average of 5 per cent of their area (1900 - 2007), which increased to 10-12 per cent in recent decades (1968 – 2007). By 2010 – 2040, areas experiencing exceptionally hot years are likely to increase to a mean area of 60-80 per cent of each region for a mid-range IPCC emission scenario (A1B). Exceptionally dry years are likely to occur more often and over larger areas in the south and southwest with little detectable change in other regions for 2010-2040. Years with exceptionally low soil moisture are likely to occur more often,

particularly in the south and southwest (Hennessy, Fawcett et al. 2008). The severity of Australian droughts may also increase due to higher temperatures leading to increasing evaporative demand (Nicholls 2008). The expectation that droughts will become more frequent and more intense in southern Australia may increase the significant social and economic impacts of drought that have already been experienced in recent years (Drought Policy Review Expert Social Panel 2008; Productivity Commission 2009).

As the world warms, heatwaves will become more intense and last longer and cold episodes and frost days will decrease. Recent analyses have found that more warm nights, extremely high temperatures and longer heatwave duration are likely throughout Australia (Alexander and Arblaster 2009; Keenan and Cleugh 2011). Heatwave events can have serious consequences for human health and well-being (see Box 9:). Low moisture availability and high temperatures will also influence fire weather (see Box 8:).

Box 9: The health impacts of the 2009 south-eastern Australian heatwave

The early 2009 severe heatwave in south-eastern Australia provides another example. During the 2009 heatwave, Adelaide and Melbourne both experienced the highest number of consecutive days above 43°C in recorded history (National Climate Centre 2009). The heatwave led to direct and indirect impacts to human health. Vulnerable groups were mostly affected, due to lack of their ability to avoid exposure to the high heat levels and due to the extended period of heat exposure (Victorian Government Department of Human Services 2009). Power failures and transport disruptions were also experienced (Queensland University of Technology 2010).

An increase in heat-related illness and deaths was recorded over that period. Compared to expected outcomes, some 374 additional deaths were recorded in Melbourne and an estimate of up to 150 in Adelaide (Queensland University of Technology 2010). In total for Victoria, there were more than 3000 reports of heat-related illnesses (such as heat stress and dehydration) including: 46 per cent increase emergency cases over the three hottest days; a 34 fold increase in cases with direct heat-related conditions; and a 2.8 fold increase in cardiac arrest cases (Victorian Government Department of Human Services 2009). In addition to direct impacts on human health, the heatwave placed significant indirect pressure on the health and emergency service sector and associated infrastructure.

2.7.4. Insurance markets and severe weather

More frequent or more intense severe weather events pose new challenges for insurance markets by widening the probability distribution of possible losses and increasing the scale of large losses. In work commissioned for this Update Paper, the Institute of Actuaries of Australia (the Institute) estimates that premiums for insurance against weather events amount to around \$5 billion each year in Australia (IAA 2011).

The risks that are covered by private insurance markets are likely to rise with climate change, given expectations of more frequent and/or intense weather events. This would lead to an increase in both the size and number of insurance claims, and higher premiums for many types of insurance. The Institute analysed a scenario in which insurance claims were to double as a result of more frequent and/or severe weather events. An increase in the level of claims of \$3 billion could be expected to yield an even higher increase in insurance premiums of around \$4.5 billion. This does not consider any increase in the volatility of events, which can be expected to result from climate change. This would increase insurance costs even further. For further information on the Institute's submission please refer to the Garnaut Review website: www.garnautreview.org.au.

Theory and modelling suggest that as the world warms, the frequency, intensity and location of severe weather events will change.

Heatwaves will become more intense and last longer; tropical cyclones will decrease in overall frequency but increase in intensity; more areas will experience exceptionally hot years; and the frequency of conditions like those that led to the Black Saturday fires is likely to increase.

2.8. Changes to ecosystems

The observed long-term increase in temperature should be evident in species and ecosystems as they respond to the changes in the physical environment.

Research is showing that a warming signal is now evident in an increasing number of Australian and global observations of species and ecosystem responses. These include: the southward expansion of the breeding range of black flying foxes (J. A. Welbergen, Klose et al. 2007), and shifts in the timing of plant flowering (Gallagher, Hughes et al. 2009; Rumpff, Coates et al. 2010). In some cases, such as the early emergence of butterflies in Melbourne, these changes have been attributed to climate change (Kearney, Briscoe et al. 2010).

Responses to warming have also been observed in marine ecosystems, including the southward-shift or extension of sea-urchins and intertidal species (Poloczanska, Hobday et al. 2009). 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 wide-spread bleaching events prior to that date (Done, P. Whetton et al. 2003).

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. 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 including carbon forestry and water storages, direct temperature effects, increases in salinity and other water quality issues and changes in water availability (Steffen, Burbidge et al. 2009).

2.9. Tipping points, extreme and high consequence climate outcomes

In addition to the more linear projected climate change outcomes that depend on the projection of current tendencies, there is also the risk 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 extent of the human population affected.

The Review noted that in some cases, elements of the climate may 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', but there is considerable uncertainty regarding the temperature at which this point may occur, or the likelihood, or not, of a given degree of human-driven climate change triggering any of these events.

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

New research has remained focussed on the tipping elements in the climate system identified by Lenton et al. in 2008 and discussed in the Review (Garnaut 2008: Section 4.4.1 and 271-272). Some progress has been made in identifying and testing potential early warning indicators of an approaching tipping point, such as a flickering between the states of a system, or a slower than expected response to a disturbance (Allison, Bindoff et al. 2009). Attempts have also been made to better understand the probabilities of various tipping points occurring by eliciting expert opinions from scientists (Kriegler, Hall et al. 2009). In a survey of 43 experts, Kriegler et al (2009) aimed to characterise each expert's belief of the probability of occurrence of certain major climate outcomes. The results indicated that while there is large uncertainty among experts about the prospect of triggering major changes in the climate system, it does not necessarily imply that the probability of such outcomes occurring is considered to be low (Kriegler, Hall et al. 2009). In fact significant probability was allocated to some events, such as the dieback of the Amazon rainforest and melt of the Greenland ice sheet.

Die-back of the Amazon Rainforest

The Amazon rainforest is the most widely quoted example of a large biome at risk of abrupt change from a warming climate. Temperature increase, changes to the length of the dry season and 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. Beyond that increase, the area of the Amazon forests subject to dieback rises rapidly from 20 to over 60 per cent (Jones and Lowe 2011).

Severe droughts have been 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, and the ability of the rainforest to absorb additional carbon dioxide is also reduced. Along with the observation that such droughts co-occur with peaks of fire activity, the recent events support the assessment that this ecosystem will be affected at relatively low temperatures (Lewis, Brando et al. 2011).

Carbon-climate feedbacks

Carbon-climate feedbacks occur when changes in the climate affect the rate of absorption or release of carbon dioxide from land and ocean sinks. 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 (IPCC 2007). Other carbon-climate feedbacks discussed in the 2008 Review in terms of potential ‘tipping points’ in the climate system were the release of methane from permafrost and methane hydrate in the ocean as the world warms. This could lead to a positive feedback effect, where the increased temperatures lead to a further release.

A recent study suggested that there are over 1,700 billion tonnes of carbon stored in permafrost, which is about twice the amount stored in the atmosphere at present (Tarnocai, Canadell et al. 2009). 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 (Schuur, Vogel et al. 2009). Research on past and present emissions from these sources (Shakhova, Semiletov et al. 2010) 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 (Petrenko, Etheridge et al. 2010).

Observations suggest that climate change will not occur smoothly, but may occur in more abrupt shifts such as that experienced in rainfall in southwest Western Australia.

Other changes to the climate, such as the loss in mass from the Greenland ice sheet, may be irreversible in a time period relevant to human planning.

2.10. Why the climate system is changing

The dynamic and unpredictable nature of our climate can make the detection of a climate change trend difficult, but observations are showing that trends are occurring in a range of climate variables. However, detection of a climate change trend is not the same as determining the cause. The process of attributing a change to a given forcing requires further evidence to establish a link between the cause and the observations (Royal Society 2010).

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 in the last 10,000 years. For the last 150 years, and especially since 1970, changes in solar output have been known with greater accuracy. Recent research suggests that solar output could have

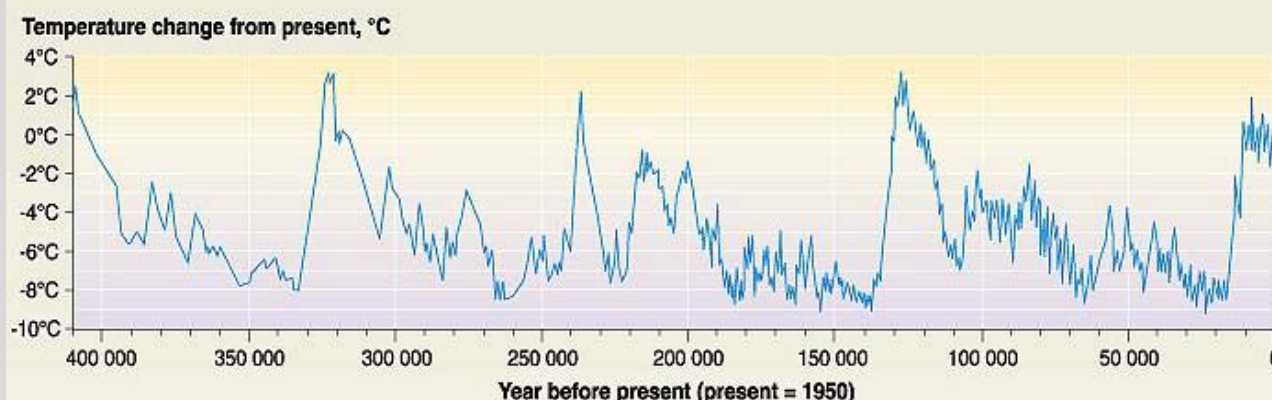
contributed at most 10 per cent to the observed warming trend in the 20th century, so other warming influences need to be considered (Lean and Rind 2008).

Other important influences on the weather that people experience 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 multi-decadal, globally synchronous trends in temperature.

Box 10: Climate in the period of human civilisation

Long-term records show that over the past several million years the temperature of the Earth has been much colder and much warmer than the present day. However, the period in which human civilisation has developed, has been the last 10,000 years. This period is referred to as the Holocene.

Figure 9: Changes in global temperature over the last 400,000 years



Source: J.R Petit, J Jouzel., et al. Climate and atmospheric history of the past 420,000 years from the Vostok ice core in Antarctica, Nature 399, pg 429-436, 1999. Available online at <http://www.grida.no/publications/vg/climate/page/3057.aspx>

Compared to the pattern of ice-ages and interglacial periods over the previous 400,000 years (Figure 9), the Holocene has been a period of an unusually long and stable warm period. This stability supported the establishment of complex agriculture and urban systems. It is the conditions during this period of human advancement and civilisation that provide the most relevant baseline for consideration of the impacts of climate change.

Source: (Rockstrom, Steffen et al. 2009)

To distinguish the contribution of greenhouse gases to observed trends from other potential influences scientists have been able to identify ‘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 (Kennedy, Thorne et al. 2010). 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 (IPCC 2007).

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 ‘hot-spot’ should occur in the tropical atmosphere about 10-15 km above the Earth’s surface, but this expectation was not previously supported by observations. More accurate temperature observations are now available and greater warming has been detected in the region, which has provided another ‘fingerprint’ of changes caused by greenhouse gases (Allen and Sherwood 2008; Kennedy, Thorne et al. 2010).

The IPCC outlined a technique for testing attribution where models were found to be unable to simulate the recent observed global or continental scale temperature trends without including the influence of human activity (IPCC 2007). Since the IPCC Fourth Assessment Report, additional simulations have

been run that reinforce earlier conclusions that both natural drivers (volcanic aerosols, solar variations, orbital variations) and human drivers (greenhouse gases and aerosols) are required to explain the observed recent hemispheric and global temperature variations and that the greenhouse gas increases are the main cause of the warming over the past century (Hegerl, Karl et al. 2006; Tett, Betts et al. 2007; Wanner, Beer et al. 2008). Temperature changes due to human activities have now been detected on each of the seven continents (Stott, Gillett et al. 2010). Recent research has also extended this conclusion to smaller regions and seasonal scales (Min and Hense 2007; Bhend and von Storch 2008; Bonfils, Pierce et al. 2008; Jones, Stott et al. 2008).

The IPCC stated in 2007 that there is a greater than 90 per cent chance that ‘the global average net effect of human activities since 1750 is one of warming’ (IPCC 2007). It also found:

- Most of the global warming since the mid 20th century is very likely due to anthropogenic increases in greenhouse gas concentrations (IPCC 2007).
- Discernible human influences extend to other aspects of climate including ocean warming, continental-average temperatures, temperature extremes and wind patterns (IPCC 2007).

Research over the past few years has further strengthened confidence in the IPCC’s assessment of attribution (Stott, Gillett et al. 2010). However, the Royal Society notes that while human attribution of climate change is widely accepted, there is continuing debate and discussion on this aspect of the climate change science (Royal Society 2010).

Research in recent years has strengthened the IPCC’s assessment that human activities have influenced global temperatures since 1750. This includes more observations of trends and patterns in climatic change that are characteristic of the expected influences from increased concentrations of greenhouse gases.

3. The science of global mitigation

In 2008, the Review explored how global mitigation targets have been framed, and discussed the need to go beyond the science and consider ethical, economic and political complexities in defining appropriate national and international goals and responsibilities. Update Paper two (*Progress towards effective global action on climate change*) discussed advances in international action. This section of the Update Paper will revisit the science behind global mitigation, and the impact of new knowledge on the overall task and the implications for international progress.

3.1. Defining ‘dangerous climate change’

The goal for global mitigation was set out in Article 2 of the United Nations Framework Convention on Climate Change (UN Framework Convention) as “*stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*” (UN (United Nations) 1992). The United Nations Framework Convention does not define the point at which ‘dangerous anthropogenic interference with the climate system’ or ‘dangerous climate change’ might occur, and the interpretation of the phrase has been the subject of intense debate (Jaeger and Jaeger 2010). At the time of the Review in 2008, the goal of limiting warming to 2°C above pre-industrial levels had been endorsed by the European Union, but there was minimal reference to a specific goal in other international documents, and none in official United Nations Framework Convention texts.

References to 2°C emerged in the late 1970’s. The unofficial adoption of the target by the Council of the European Union in 1996 that gave it more prominence, following advice in a number of reports by scientists that risks of non-linear responses and serious damage could occur at higher temperatures (Rijsberman and Swart 1990; WBGU 1995). Further assessments following the EU’s decision, such as the ‘tipping points’ discussion in the 2008 Review (Lenton, Held et al. 2008), have reinforced support for such a target (Jaeger and Jaeger 2010).

Since 2008 there has been international acceptance of 2°C as a global mitigation objective. The 2°C goal appeared in the Declaration of Leaders of the Major Economies Forum on Energy and Climate in July 2009 (MEF 2009). The Copenhagen Accord agreed that deep cuts in global emissions were

required “to reduce global emissions so as to hold the increase in global temperature below 2 degrees Celsius” (UNFCCC 2010). As part of the Cancun Agreement in 2010, the 2°C target was incorporated into the official United Nations Framework Convention negotiation process for the first time.

Box 11: Update of the IPCC’s ‘reasons for concern’

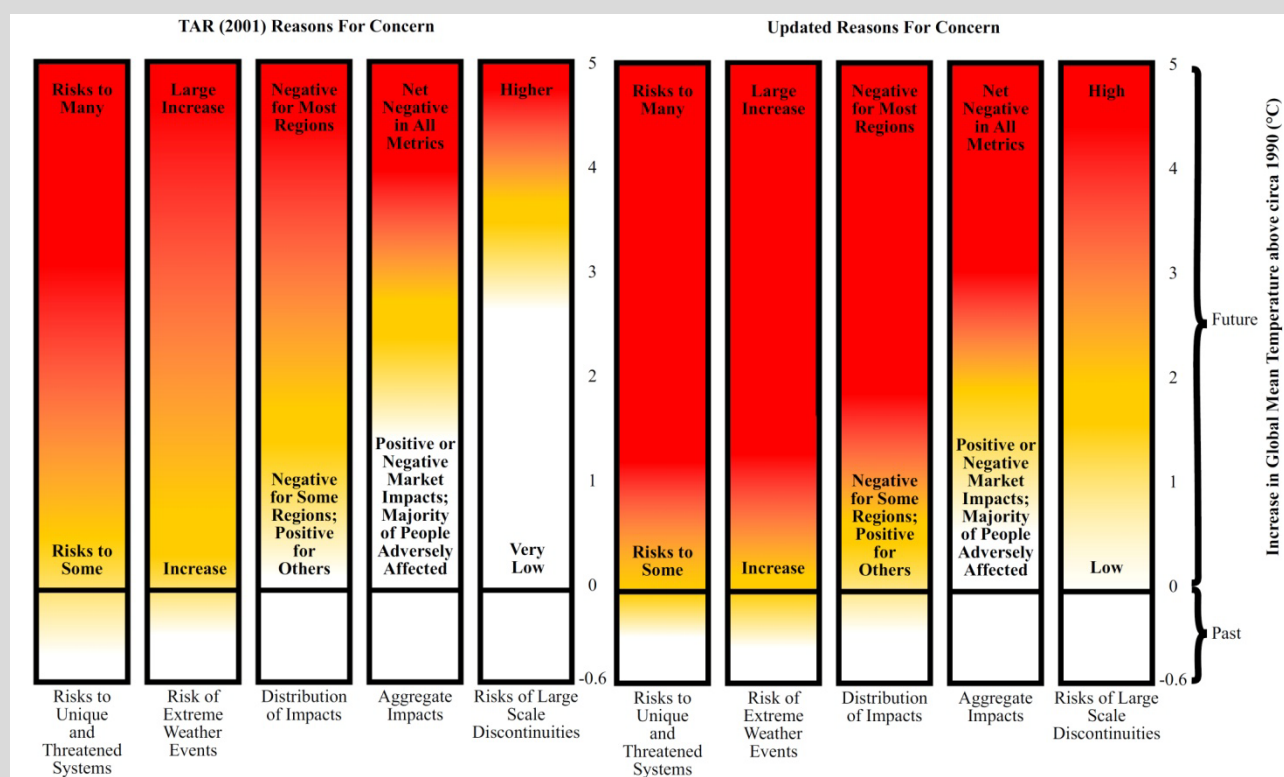
The original ‘burning embers diagram’ was prepared by authors of the IPCC’s Third Assessment Report (2001) to provide some insight into the United Nations Framework Convention’s reference to avoiding ‘dangerous anthropogenic interference’. The diagram (Figure 10) identified five ‘reasons for concern’ and showed the sensitivity of these different potential impacts to increases in global temperature based on expert assessment of the available scientific literature.

The white regions suggest low or neutral impacts, the yellow areas negative impacts or more significant risks, and the red areas substantial negative impacts or risks that are more widespread or severe. The ‘fuzzy’ transition represents the uncertainty regarding the point at which impacts will occur, but also the uncertainty in the aggregation of risks into the five categories. The width of the transition is an indication of the speed at which impacts may occur (Smith, Schneider et al. 2009).

In 2009, the diagram was updated on the basis of scientific progress on observations of warming, better understanding and confidence in the likelihood of events and impacts, and better identification of the areas and populations affected.

The new research showed that significant consequences to human-wellbeing and ecosystems were projected to occur at smaller increases in global average temperature. Temperature levels associated with substantial negative impacts and severe risks from extreme weather events (associated with the red shading) start at temperatures less than 1°C above 1990 levels.

Figure 10: Risks of climate change by reasons for concern – 2001 compared with 2009 update



Source: (Smith, Schneider et al. 2009)

3.1.1. Is the 2°C target right?

As a result of the emphasis on the 2°C goal in the international debate as an interpretation of ‘dangerous climate change’, 2°C has become a benchmark for the consideration of emissions scenarios and concentration pathways in the scientific community (Anderson and Bows 2008; Johansson 2010).

But is 2°C an appropriate threshold between acceptable and ‘dangerous’ climate change?

In truth, there is no ‘scientific’ way of drawing a boundary between acceptable and unacceptable damage from global warming. Some people may think it unacceptable that species extinction due to warming should proceed at the current rate. Some may think that the loss of the current splendour of the Great Barrier Reef would be unacceptable whatever the cost of preserving it; others may judge that the loss of the Great Barrier Reef would be bad, but not as bad as the sacrifice in living standards that would be required to preserve it against human-induced warming. In the end, the constituent entities of the international community must form a judgement about the right balance between the costs of mitigation and the benefits of avoiding dangerous climate change. That takes us back to the framework of decision-making in Update Paper one (*Weighing the costs and benefits of climate change action*). We can take the international community’s contemporary focus on 2°C as reflecting the current balance. That could change with new knowledge of impacts of climate change or of the costs of mitigation.

While no unique scientific status can be claimed for the 2°C target, it provides an important focus for action by organisations and governments that can motivate and provide structure for practical steps. It also represents a strong call for action, and no other target has achieved a similar status in the international debate (Jaeger and Jaeger 2010).

Since the Review, there has been more comment in the mainstream science that a 2°C target may be insufficient to avoid ‘dangerous climate change’. Anderson and Bows (2011) suggest that based on updates to the science, 2°C could now be considered as a threshold between ‘dangerous climate change’ and ‘extremely dangerous climate change’ (Anderson and Bows 2011). Hansen et al’s proposed target of 350 ppm carbon dioxide (Hansen, Sato et al. 2008) was supported by Rockstrom et al (2009) in their assessment of the boundaries for a ‘safe operating space for humanity’ (Rockstrom, Steffen et al. 2009).

In March 2009, ahead of the Copenhagen discussions later that year, around 2500 researchers attended a climate change congress in Copenhagen to bring together new knowledge that had emerged since the IPCC’s Fourth Assessment Report. The synthesis report prepared following this congress found that the latest science indicated that “*recent observations show that societies and ecosystems are highly vulnerable to even modest levels of climate change, with poor nations and communities, ecosystem services and biodiversity particularly at risk. Temperature rises above 2°C will be difficult for contemporary societies to cope with, and are likely to cause major societal and environmental disruptions through the rest of the century and beyond*” (Richardson, Steffen et al. 2009). As we have discussed in Section 2, there is growing evidence that the current temperature increase on pre-industrial levels (~0.8°C) is already increasing the likelihood of severe and damaging events occurring (Min, Zhang et al. 2011; Pall, Aina et al. 2011).

The UK Committee on Climate Change, which provides advice to the UK Government on setting mitigation targets and the impacts of climate change, also reviewed the science of climate change since the IPCC’s Fourth Assessment Report in the preparation of its ‘Fourth Carbon Budget’ report in December 2010. They found that while the evidence suggested that the risks to human welfare and ecosystems had worsened since their 2008 report, it did not warrant a change in the target they advised in 2008 – to limit global average temperature change to as little over 2°C as possible (CCC 2010).

In addition to recognising that global warming should be limited to no more than 2°C, the Cancun Agreement also recognises “the need to consider, in the context of the first review..... strengthening the long-term global goal on the basis of the best available scientific knowledge, including in relation to a global average temperature rise of 1.5°C”.

The Review made the case that it was in Australia's interests to seek a goal of 450 ppm carbon dioxide equivalent or lower. The fact that concentrations now exceed that level indicates that 450 ppm carbon dioxide equivalent is possible only with some degree of overshooting, a major elevation of the priority of climate change in the priorities of the world's nation states, and major new developments in technology. From the perspective of early 2011, for the world to hold emissions concentrations to 550 ppm carbon dioxide equivalent would be an achievement of international cooperation and national economic policy innovation of large dimension. To achieve 450 ppm carbon dioxide equivalent with only the degree of overshooting envisaged in the Review would be an international relations and national public policy achievement of historic dimension. The path to anything lower than 450 ppm carbon dioxide equivalent now has to be back through 450 ppm carbon dioxide equivalent.

This is the awful arithmetic of strong mitigation of climate change. To have any chance of achieving a goal tighter than 450 ppm carbon dioxide equivalent requires the international community (with Australia playing its proportionate part) soon to define a credible path to that goal. The discussion in the science of 350 ppm sits there as a warning of danger, but with no prospect of serious adoption as a goal of concerted international policy action.

3.2. Global mitigation goals

3.2.1. Cumulative emissions targets

Chapter nine of the Review explored the positives and negatives of a range of approaches to setting global goals for climate change mitigation, including 'impact goals', 'concentration goals' and 'emissions goals'.

The most important development in scientific discussion of mitigation goals since 2008 is an increasing focus on a cumulative emissions budget. This budget approach was favoured conceptually by the Review, which formulated the global mitigation problem as one of optimal depletion of a finite resource—the resource in this case being the atmosphere's capacity to absorb greenhouse gases without triggering dangerous climate change. To make this operational, an initial allocation of the whole budget would need to be made across countries. This was not considered to be practical at this time: the only basis that held any prospect of securing widespread international support would be equal per capita allocations, which would impose massive immediate costs on the three high-emitting countries in particular, which includes the United States. The Review therefore focussed on interim and long-term national emissions targets within a framework of convergence towards equal per capita entitlements over a period extending to 2050, that defined a curve of annual national entitlements which 'added up' to the global accumulated emissions budget.

The benefit of a 'budget' approach at the global and domestic level is its flexibility: it allows inter-temporal tradeoffs and smoothing, so the 'economically optimal path can be chosen (Garnaut 2008; Zickfeld, Eby et al. 2009).

Cumulative carbon dioxide emissions can be determined so that a 'budget' can be defined that is essentially independent of timescale and trajectory. However, it is not possible to achieve this for the full set of greenhouse gases, as for gases with a lifetime shorter than a few decades the rate of emissions has a strong influence on concentrations at that time, and hence impacts¹⁵ (Allen, Frame et al. 2009; Bowerman, Frame et al. 2011). The short term or transient temperature is also more significantly influenced by the mix of greenhouse gases emitted, while over the long term carbon dioxide has the largest influence (see Section 4.3.1, Garnaut 2008, pg 91).

The main value of the cumulative or budget approach is to focus attention on the limited volume of greenhouse gases that can be released into the atmosphere over long periods without creating large risks of dangerous climate change. The basic arithmetic within this approach is sobering. At current rates of emissions, the global budget for an objective of 2°C will have been exhausted within a couple of decades.

¹⁵ An exception to this rule may be nitrous oxide, which has an atmospheric lifetime of greater than 100 years, which is longer than the timeframes for response for some elements of the climate system (Bowerman, Frame et al 2011).

Meinshausen et al (2009) analysed the allowable global cumulative carbon dioxide emissions between 2000 and 2050 in terms of a number of different probabilities of exceeding the 2°C target by 2100. Around 350 gigatonnes of carbon dioxide were emitted globally between 2000 and 2009, which represents between around 24 and 35 per cent of the total budget¹⁶ (Meinshausen, Meinshausen et al. 2009; WBGU 2009).

Another study looked at carbon dioxide budgets over a longer period out to 2500 compatible with a long-term global temperature stabilisation at less than 2°C above pre-industrial (Zickfeld, Eby et al. 2009). For a chance greater than two-thirds of achieving this target, this study proposed that accumulated net carbon dioxide emissions should not exceed 2165 gigatonnes. Between 2000 and 2010 around a sixth of this budget has already been utilised. If an even greater chance of achieving the 2°C target (greater than 90 per cent) is sought, the smaller budget to achieve this outcome would be emitted by as early as 2017, if emissions continue unabated over the next few years. (England, Gupta et al. 2009).

The German Advisory Council on Global Change (WBGU) propose a global budget of 750 gigatonnes of carbon dioxide from fossil fuel emissions for the period 2010-2050, based on a two-thirds probability of achieving the 2°C target (based on the Meinshausen et al 2009 work). At 2008 levels of emissions, this global budget would have a lifetime of 25 years. The WBGU suggests that equal per-capita emissions should be the basis for the allocation of national budgets (WBGU 2009).

3.2.2. Is overshooting feasible?

In an overshooting profile, concentrations go above a goal (such as 450 ppm carbon dioxide equivalent) for a period before being brought back to the desired level. The 450 mitigation case investigated by the Review was an overshooting scenario, which reflected the costs and practical barriers to the extremely rapid short-term emissions reductions that would be needed to achieve 450 ppm carbon dioxide equivalent without overshooting.

Overshooting scenarios were first considered around 2004 when it was recognised that such an approach would be necessary if a decision were made to aim for stabilisation of greenhouse gas concentrations at, or close to, current levels (IPCC 2007). Overshooting scenarios are attractive as they allow a slower initial reduction in emissions. Some models have shown that the slow response of the climate system can allow a small, short overshoot in concentration without a corresponding overshoot in temperature (den Elzen, Meinshausen et al. 2007). However, for a given concentration stabilisation target, any amount of overshoot enhances the risk of reaching a level of climate change that could be considered 'dangerous' (Johansson 2010).

To achieve reductions in atmospheric concentration and eventual stabilisation, emissions must fall below the natural level of removal from the atmosphere by the oceans and biosphere. The rate of removal can be affected by climate change itself, an outcome referred to as a 'climate-carbon feedback'. Research suggests that the rate of uptake by ocean and land sinks decreases as higher temperatures and greenhouse gas concentrations are reached (England, Gupta et al. 2009; Lowe, Huntingford et al. 2009).

The major risk and uncertainty associated with overshooting scenarios is the level of climate change reversibility (Nusbaumer and Matsumoto 2008). Some models suggest that it may be possible to reduce atmospheric concentrations of greenhouse gases significantly over one or two centuries, other models indicate that the rate of reduction in concentrations and temperature may be considerably slower, and there is also the chance that aspects of the climate may enter a state from which it cannot return (Nusbaumer and Matsumoto 2008; Lowe, Huntingford et al. 2009; Monastersky 2009; Solomon, Plattner et al. 2009). While the timing of the climate response is still uncertain, an overshoot scenario is more likely to lead to reductions in temperature than a scenario where concentrations are stabilised and held at the 'peak' level (Allen, Frame et al. 2009).

¹⁶ The percentages are for probabilities of exceeding 2°C by 2100 of 50 and 25 per cent respectively

It is becoming more difficult for a concentration overshoot to be ‘small and short’ with an objective of 450 ppm carbon dioxide equivalent or 2°C, and therefore to minimise the transient temperature response as outlined in the Review (Section 2.4.1, Garnaut 2008). While ambitious greenhouse gas concentration objectives are becoming increasingly reliant on an overshooting or peaking scenario, new science suggests that it may be more difficult to avoid long-term temperature change than had been expected at the time of the Review.

3.2.3. Options for a rapid response

Dramatic changes in emissions trajectories are required in the next few decades to achieve the long-term goals outlined in the Cancun Agreements, the more so if there is less reliance on overshooting scenarios

It may be that much deeper emissions cuts in many countries will become possible following a large global political response to the reality of worsening impacts of global climate change, within an “emergency” (Royal Society 2009; Swart and Marinova 2010). However, at that point, the lags between emissions and warming would have ‘locked in’ a good deal of additional warming.

The difficulty of the task of attaining the 2°C goal has increased as the scientific constraints tighten, the opportunity for overshooting weakens, the momentum of emissions increases with the expansion of modern economic growth in the Platinum Age (see Update Paper three: *Global emissions trends*), and the developed countries are slow to start in major mitigation efforts. A delay in the peaking of emissions means that there will need to be extensive commercialisation of new sequestration technologies (akin to the ‘backstop technology’ considered in the Review) to make a goal limiting global temperatures to 2°C viable. This has increased the attraction of approaches to mitigation that may delay for a while the full impact of warming from greenhouse gases, or which have the capacity to remove emissions from the atmosphere.

Solar radiation management has come into closer focus as a temporary buffer to the immediate consequences of global warming while other, more comprehensive solutions such as emissions reductions are implemented (Barrett 2006; Royal Society 2009). Geoengineering has moved from science fiction into the realm of responses that are being subject to analysis (Barrett 2006; Royal Society 2009; Swart and Marinova 2010).

Box 12: The health co-benefits of mitigation

The case for reducing emissions of both greenhouse gases and black carbon is strengthened by the likely health co-benefits. Improvements in air quality, through a reduction in transport-related air pollution, ground-level ozone and fossil-fuel based energy production, will have a positive influence on respiratory and cardiovascular health (AIHW 2010; Dennekamp and Carey 2010; InterAcademy Council 2010).

While there is growing evidence to suggest that part of the costs associated with climate change mitigation efforts are likely to be offset by health benefits and health cost savings (Costello, Abbas et al. 2009; Friel, Dangour et al. 2009; Haines, McMichael et al. 2009; InterAcademy Council 2010), it is difficult to quantify the health co-benefits. This type of modelling suffers from many of the same gaps in health research and historical monitoring of relevant phenomena in Australia, such as the links between air pollution and health (AIHW 2010). The likely implementation rate and effectiveness of mitigation efforts across geographic areas and sub-populations is also unknown but likely to be influential in determining the scale of the health co-benefits.

A recent report looking at black carbon and tropospheric ozone noted that reducing these pollutants and their ‘precursors’¹⁷, which have a relatively short life time in the atmosphere¹⁸, would slow the rate of climate change within the first half of this century (UNEP and WMO 2011). The reductions in near-term warming could be achieved through the recovery of methane from fossil fuel extraction and transport, methane capture in waste management, use of clean-burning stoves for residential cooking, diesel particulate filters for vehicles and the banning of field burning of agricultural waste. If these measures were implemented globally by 2030, they could halve the potential increase in global temperature projected for 2050 compared to the reference scenario used in the study¹⁹ (UNEP and WMO 2011). There would also be health benefits associated with reductions in black carbon, as discussed in Box 12.

Actions to reduce black carbon and solar radiation management would complement, but not replace reductions in long-lived greenhouse gas emissions, which would still be required to protect the climate in the long term, and resolve issues such as increased ocean acidification (UNEP and WMO 2011); (Royal Society 2009).

Activities and technologies that remove carbon dioxide from the atmosphere will also need to be developed and implemented effectively to achieve the 450 ppm carbon dioxide equivalent or below. These include: the up-scaling of reforestation, afforestation and forest conservation projects; sequestration by algae; fertilisation of the ocean with nitrogen, phosphorus or iron to encourage increased carbon uptake; the direct addition of limestone to the deep ocean to raise the alkalinity of the ocean water (Harvey 2008); the use of saturated limestone solutions to scrub carbon dioxide from power-plant emissions (Rau and Caldeira 1999; Caldeira and Rau 2000); the addition of biochar to soils; carbon capture and storage (CCS) at the point of emission from fossil-fuel fired power stations in which renewable bio-fuels are the energy source; and direct capture of carbon dioxide from ambient air (Keith 2009; Ranjan and Herzog 2011). Carbon dioxide removal projects, particularly reforestation and algal sequestration, are generally more mature technologies than solar radiation management, with fewer uncertainties that are currently being incorporated into modelling exercises.

3.3. Beyond 2 degrees

As discussed in Update Paper two (*Progress towards effective global action on climate change*), the pledges at Copenhagen and Cancun, particularly by the developing and newly industrialised countries, have substantially shifted global emissions away from the ‘business as usual trajectory’. China’s Copenhagen mitigation commitments to 2020 are stronger than anticipated by the Review. While understanding the potential climate outcomes from the Copenhagen Accord pledges can not be definitive because they say little about likely emissions after 2020 (Rogelj and et al. 2010), some studies have assessed the likely outcomes if the Copenhagen Accord 2020 goals on various assumptions about mitigation after that date.

Some studies suggest that stabilisation of concentrations at 650 ppm carbon dioxide equivalent is a potential outcome if reductions post-2020 are relatively modest. This is roughly equivalent to a 4°C increase on pre-industrial levels (Anderson and Bows 2008; IEA (International Energy Agency) 2010). Stabilisation at 650 ppm carbon dioxide equivalent represents a considerable reduction from the concentrations reached under the no-mitigation case considered in the Review or suggested by Update paper three (*Global Emissions Trends*). It therefore becomes necessary to explore the implications of a global temperature rise of 4°C.

¹⁷ In the troposphere, ozone (O₃) is formed by the action of sunlight on O₃ precursors including methane and nitrogen oxides.

¹⁸ The UNEP and WMO (2011) report refers to methane as a as ‘short-lived climate forcer’, along with black carbon. This Update Paper includes methane in its assessment of ‘long-lived greenhouse gases’, as it survives in the atmosphere for years (~12) rather than days or weeks, as is the case with tropospheric aerosols.

¹⁹ The reference scenario was based on current policies and energy and fuel projections UNEP and WMO (2011). Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers.

3.3.1. A four degree world

In 2008, the chief scientific adviser to the Department for the Environment, Food and Rural Affairs in the UK, Professor Bob Watson, advised that while *“there is no doubt that we should aim to limit changes in the global mean surface temperature to 2°C above pre-industrial.....but given this is an ambitious target, and we don't know in detail how to limit greenhouse gas emissions to realise a 2 degree target, we should be prepared to adapt to 4°C”* (Randerson 7 August 2008).

A 4°C world was the focus of the ‘4 degrees and beyond’ conference in the UK in September 2009, and will be the focus of a July 2011 conference at the University of Melbourne. The emphasis on a temperature rise of 4°C is to assist decision-makers in understanding global and local implications of 4°C and higher temperatures, which is crucial if the international community is to make informed choices about the balance between the ‘extreme’ rates of emissions reductions required to have a chance of avoiding dangerous climate change, and the ‘extreme’ impacts and adaptation costs that are the alternative (Environmental Change Institute 2009).

Research suggests that current global temperatures are near the highest levels reached in the Holocene (Hansen, Sato et al. 2006). A global average temperature rise of 4°C from pre-industrial levels (3.5°C above 1990 levels) is well outside the relatively stable temperatures of the last 10,000 years that have provided the environmental context for the development of human civilisation (see Box 10:) (Rockstrom, Steffen et al. 2009). We would be in unknown territory for humanity.

The risks would be considerable.

Due to the regional variation in temperature change, under a global average of 4°C warming parts of the Arctic could warm by 15°C under ‘high-end’ simulations (Betts, Sanderson et al. 2009), (Betts, Sanderson et al. 2009), with large implications for sea levels and a range of bio-physical systems. The Review noted that a target of 550 ppm carbon dioxide equivalent rather than 450 ppm carbon dioxide equivalent would leave the world open to larger risks of exceeding threshold temperatures. Every degree of temperature increase raises the risks of exceeding tipping points. In 2008, the Review considered the likelihood of the three emissions cases triggering a number of ‘high-consequence outcomes. Using this same assessment, a temperature of 4°C above pre-industrial would give an 85 per cent probability of initiating large-scale melt of the Greenland ice sheet, put 48 per cent of species at risk of extinction, and put 90 per cent of coral reefs above critical limits for bleaching. It would trigger the lower threshold for initiating accelerated disintegration of the west Antarctic ice sheet and changes to the variability of the El Niño – Southern Oscillation, and the upper threshold for terrestrial sinks such as the Amazon Rainforest, becoming sources of carbon rather than sinks (Warren 2006; Lenton, Held et al. 2008; Sheehan, Jones et al. 2008)²⁰. While these probabilities are lower than those under the no-mitigation scenario, it is unlikely that they would be considered acceptable by many members of the community, when, as in the 2008 Review, they are assessed against the likely costs of reducing them. Severe weather events would intensify. Immense changes in the attractiveness of parts of the earth’s surface to support substantial populations would place great strain on national and global political systems. As we have discussed, recent science suggests that severe and catastrophic climate change outcomes may be triggered at lower temperatures than previously thought, further increasing the risks of catastrophic outcomes in a 4°C world. Arnell (2009) discusses effects on displacement of people and changes in suitability of land for farming (Arnell 2009).

The modelling undertaken by the Review in 2008 demonstrated that the benefits of avoided climate change between the 450 mitigation case with considerable overshooting the 550 mitigation case are substantial. The significant body of science looking at the probable climate impacts of climate change, and the risks that more dangerous outcomes will occur, suggests that the risks will increase immensely between 2°C and 3°C; even more for the difference between 3°C and 4°C, and further still for 4°C and 5°C, and again for 5°C and 6°C.

There is no point in time at which it is wise to conclude that the damage already caused from climate change is so large that any subsequent damage is of minor importance. Moreover, beyond two or three degrees the challenges and costs of climate change associated with an additional degree of warming,

²⁰ For more information on this assessment, see notes to Table 4.1, Garnaut 2008.

regardless of the warming the planet has already experienced, are likely to overwhelm any attempts at adaptation to reduce the costs.

4. Developments in the debate about the science

Section 2 of this Update Paper explored new observations of changes in the climate system, improvements in understanding of how the climate system may change in the future, some of the risks to Australia, and advancements in the certainty and confidence in the causes of those changes.

Despite the continued strengthening of scientific knowledge of climate change and increasing confidence that its main propositions are sound, there has been a fierce public debate about whether human actions are causing the climate to change. This section explores the state of the climate change debate in Australia. It discusses the reliance of science on the continued challenging of ideas and how this can be misinterpreted the institutional basis of scientific authority; and how we can judge which amongst several competing views on scientific matters has the strongest support amongst qualified scientists.

4.1. How science advances through questioning and review

Scepticism is an essential part of the scientific process and serves to move the science towards greater understanding and agreement. Once a theory is put forward by a researcher, it is discussed, analysed and criticised by the wider scientific community. Further tests, modelling and research then respond to that questioning. The consequent exchanges determine whether the initial conclusions hold, need refining or are rejected. There is much competition in the science world. The debate is often intense and can be unfriendly. However, the process leads to greater confidence in the eventual conclusions and can inspire new areas of exploration and scientific discovery (Doherty 2009).

The mainstream science has not always been as confident as it is now of humanity's influence on climate change. The Second Assessment Report of the IPCC in 1995 noted that *"the balance of evidence suggests a discernible human influence on global climate"*. In 2001, the Third Assessment Report concluded that *"there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities"* (IPCC 2001). By 2007, the conclusion of the Fourth Assessment Report was that there was *"very high confidence that the global average net effect of human activities since 1750 has been one of warming"* (IPCC 2007). The gradual increase in the confidence of the influence of human activities on climate change is the result of many millions of hours of research and active questioning and exploration by the international science community.

The scientific process generally consists of systematic observation, measurement and experiments and the formulation, testing, and modification of hypotheses. The scientific community as a whole queries and retests a hypothesis using a number of different techniques, or compare observations from a range of different sources to validate other results. There is no 'second earth' on which to experiment, so scientists have created complex models to simulate the effects of changes in the energy balance of the atmosphere (see Box 3:).

Peer review is an important part of the scientific process. It is part of the process that tests the suitability of a paper for publication in scholarly journals, and makes them part of the body of knowledge of the discipline. The review process for scientific journals helps to ensure that published scientific findings are objective and clear, and that the analysis is rigorous. No human quality control process is flawless, but the processes of testing proposals for changing the body of received wisdom make error less likely and have underpinned the extension of valuable knowledge in many areas of science.

Research findings published in scientific journals are open for challenge or endorsement from other scientists, and conclusions are taken seriously. In contrast, articles that appear in newspapers and on websites are often left uncontested by authorities in the field (DCC 2009).

Debate about scientific matters that occur in the public domain (such as in newspapers and on blog sites) can come to be divorced from scientific quality, rigour and authority. One opinion and one blog and one book is as good as another. This is the antithesis to science. Open-minded scepticism and critical review is a vital part of good scientific process. However, many of the vocal participants in the

climate change debate have never been part of the rigorous scientific discourse, or have cut themselves off from it.

4.2. Assessing the majority opinion

In this section we review how science has reached a majority opinion on climate change. The complexity of the climate change issue, the potentially catastrophic consequences of the absence of effective mitigation and the scale of the implications of mitigation for certain sectors of the economy have made the science as contested. As a result, the efforts of the international science community to synthesise the science and communicate the level of consensus and confidence have been unique in the history of science.

4.2.1. The Intergovernmental Panel on Climate Change (IPCC)

The Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988. Its mandate, as defined in the 'Principles for IPCC Work', is *"to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation"* (IPCC 2006). The Principles also state that IPCC reports should be *"neutral with respect to policy"*. Since it was established there has been ongoing debate of the IPCC model in relation to the openness of participation (both geographical and disciplinary), the preservation of trust and the influence of political negotiations (Hulme and Mahony 2010).

The IPCC approach and structure is a unique model in the world of science. Rather than undertaking new research or monitoring, the IPCC reviews and assesses the considerable body of relevant scientific, technical and socio-economic information produced internationally. The IPCC itself only has 10 core staff, so the reports and papers generated by the IPCC are supported and driven by voluntary contributions from thousands of scientists from around the world. To date, the IPCC has produced four assessment reports, the first in 1990 and the most recent in 2007, along with numerous special reports and technical papers. A Fifth Assessment report is due to be released in 2014.

Review is a vital part of the process involved in the preparation of the IPCC's assessment reports. Nominated lead authors prepare the drafts, which are then circulated widely amongst hundreds of scientists to ensure that the assessment is objective, accurate and comprehensive. The IPCC is an intergovernmental body, so member governments are also invited to comment as part of the second round of review and endorse the final reports. During the review process of the Fourth Assessment Report more than 90,000 comments were received (InterAcademy Council 2010). A drawback of this comprehensive review process is that the period between assessments is around 6 years, and by the time the reports are published they do not necessarily reflect the most recent science. There is increasing pressure on the IPCC to provide shorter, more rapidly produced policy updates for policy-makers, particularly in the context of the rate of change in the relevant science (Stocker 2010).

The main assessments of the IPCC are divided into three Working Groups (WG's) which look separately at the underlying climate science (WGI), impacts and adaptation (WGII) and mitigation strategies (WGIII). In addition to three detailed Working Group reports, the IPCC produces a shorter Technical Summary and a Summary for Policymakers for each report. While scientists determine the content of the Summary for Policymakers, the final wording is the result of line-by-line negotiations with government representatives, with the aim of improving the clarity of message and the relevance to decision-makers. The involvement of governments in this process had lead to concerns about the politicisation of the key conclusions and messages (InterAcademy Council 2010).

A stated goal of the IPCC process is that when taking decisions and finalising reports, various groups within the IPCC *"shall use all best endeavours to reach consensus"* (IPCC 2006). The consensus goal in the IPCC principles is underpinned largely by an ambition to communicate the complex science of climate change coherently to a broad policy audience, and has been both a strength and a weakness of the IPCC process. The consensus process allows collective expert judgements to be made about areas of uncertainty, but claims have been made that efforts to achieve consensus marginalise dissenting voices and may also lead to over-conservative estimates of change (Hulme and Mahony 2010).

The communication of the certainty and confidence of the science in the trends, causes and projections of climate change is an important part of the IPCC assessment process, and requires choices on how to simplify and bring together this information for a wide audience. Some researchers and commentators believe that the IPCC has missed the mark in this respect by being inconsistent in its approach to uncertainty and by a lack of effective communication of the differences between uncertainty that is the result of imperfect knowledge, disagreement between experts, or inherent variability in the climate system. Research suggests that the way uncertainty is framed influences the perceptions of likelihood and motivation to respond in individuals, communities and businesses (Dessai, O'Brien et al. 2007; Patt 2007).

As the climate change debate has heightened internationally, the IPCC has been subject to increased scrutiny of its processes, accuracy and objectivity. In November 2009, there was criticism of the inaccuracy of the IPCC's statements in the 2007 Working Group II report (Impacts, Adaptation and Vulnerability) on the rate of Himalayan glacier melt in the fourth assessment report, leading to even greater public scrutiny. The IPCC responded in January 2010 that while the statement was "*entirely consistent with the underlying science and the broader IPCC assessment*", it also contained "*poorly substantiated estimates*" and that "*the clear and well-established standards of evidence, required by the IPCC procedures, were not applied properly*" (IPCC 2010).

In the context of the scrutiny and evidence of a decrease in public confidence in the climate science, the Secretary-General of the United Nations and the Chairman of the IPCC requested that independent review of IPCC processes, administrative structure and strategies for communication by the InterAcademy Council, with a Board composed of the presidents of fifteen academies of science and equivalent organizations²¹ (InterAcademy Council 2010). The final report of the Council, published in October 2010, concluded that the IPCC approach had been successful on the whole, but that the IPCC needed to adapt to the rate of change and complexity in the science, the increased level of debate, and the heightened focus of governments on the potential impacts and policy solutions. Recommendations included changes to the governance structure, a more targeted and effective review process, improvements in characterising and communicating uncertainty, and the development of a communications strategy to allow rapid and relevant responses to stakeholders (InterAcademy Council 2010).

The official review requested by the UN focused on the IPCC process rather than the science in the Fourth Assessment Report. The Netherlands Environment Assessment Agency assessed the reliability of the information in the regional chapters of the 2007 Working Group II (Impacts, Adaptation and Vulnerability) report to evaluate whether any errors had an effect on the conclusions drawn by the IPCC, or on the summary for policymakers (Netherlands Environmental Assessment Agency 2010). The Netherlands Environment Assessment Agency found that the summary conclusions in the Working Group II (Impacts, Adaptation and Vulnerability) report were well founded and free of significant errors, but the origin of those statements could have been more transparent. The report found one significant error in the chapter detail and noted that negative examples of the impacts of climate change tended to be dominant in the document summaries. However, the overall conclusion of the Netherlands Environment Assessment Agency was that the main conclusions of the IPCC on impacts, adaptation and vulnerability were sound. No errors were found in the separate Working Group I (The Physical Science Basis) report on the underlying climate science and the overall conclusions reached by the IPCC in its Fourth Assessment Report (including three separate working groups) have since been reiterated by the United States National Research Council in a comprehensive study of climate change released in 2010 (National Research Council 2010).

The IPCC model and process has been the subject of extensive investigation over the 20 years of its existence. There is considerable divergence in opinions on the success of the model and how it could be improved in the future. While the IPCC attracted some negative publicity, reviews and subsequent reports indicate that the science remains unchallenged.

²¹ Board members include representatives from the African Academy of Sciences and the Academy of Sciences for the Developing World, as well as representatives from the science academies of: the Netherlands, China, Argentina, United States, South Africa, Brazil, Germany, Japan, Turkey, Australia, Indonesia, United Kingdom, France, India (<http://www.interacademycouncil.net/CMS/3239/5933.aspx>)

The IPCC's Fourth Assessment Report had input from more than 450 lead authors, 800 contributing authors and was reviewed by over 2,500 expert reviewers. Many of the lead authors are considered the world's top experts in their field (Anderegg and Harold 2009). The objectives, process and personnel involved in the development of the IPCC Assessment Reports suggests that the reports' conclusions could be reasonably interpreted as representing the majority opinion of the world's scientists. Let us now consider some alternative ways of assessing what is the majority opinion.

4.2.2. National academies of science

In the 17th Century a group of natural philosophers began meeting in London to discuss a new philosophy of promoting improved knowledge of the natural world via observation and experiment, a discipline we now refer to as science. This group became the Royal Society, the oldest scientific academy in continuous existence. The Royal Society's aim is *"to expand the frontiers of knowledge by championing the development and use of science, mathematics, engineering and medicine for the benefit of humanity and the good of the planet"* (Royal Society 2011).

All major countries, and a large number of smaller ones, now have an equivalent body to the Royal Society. In Australia it is the Australian Academy of Science, and in the United States it is the National Academies of Sciences. While each national body differs slightly in the way it operates, membership is determined by election by peers, judged on the basis of excellence in science and achievements in original research. National academies of science represent all scientific disciplines and are regarded as a repository of the highest scientific talent in each country. Governments and citizens often turn to these organisations for advice on the scientific and technological issues that frequently underpin policy decisions. The mission of the National Research Council in the United States, one of the four organisations set up by Abraham Lincoln that are collectively referred to as the 'National Academies', is to *"improve government decision making and public policy, increase public education and understanding, and promote the acquisition and dissemination of knowledge in matters involving science, engineering, technology, and health"* (NRC 2011). The National Research Council recently undertook assessment of the current state of knowledge about global climate change, and concluded that *"climate change is occurring, is caused largely by human activities, and poses significant risks for—and in many cases is already affecting—a broad range of human and natural systems"* (National Research Council 2010: pg 27).

All of the major national academies in the world have issued either a joint or separate a statement on climate change, and some—including the US National Academy of Sciences—have undertaken their own independent review. Prior to the 2009 Copenhagen negotiations the Academies of the G8+5 (Brazil, China, India, Russia, South Africa, Canada, Italy, United Kingdom, Japan, United States of America, France, Mexico and Germany) released a joint statement on "Climate change and the transformation of energy technologies for a low carbon future" that repeated the conclusion of the IPCC's Fourth Assessment Report. The Australian Academy of Science put out its own supporting statement in 2010 (Australian Academy of Science 2010).

Individual academies have applied thorough process to the production of these documents with close peer review by academy members, comments from external reviewers and extensive cross-checking during multi-staged processes. Box 13: includes a selection of these statements.

The statements of these respected and authoritative organisations validate the IPCC's conclusions and add credence to statements on the level of scientific agreement.

Box 13: Climate change statements from national academies of science

As discussed in Section 4.2.2, most national academies of science or equivalent bodies have released joint or individual position statements affirming their views regarding global climate change. None of these statements disagrees with the IPCC's views on human contribution to global warming. A selection of these are included below:

The Australian Academy of Science (August 2010):

"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" (Australian Academy of Science 2010)

The United Kingdom Royal Society (September 2010):

"There is strong evidence that the warming of the Earth over the last half-century has been caused largely by human activity, such as the burning of fossil fuels and changes in land use, including agriculture and deforestation. The size of future temperature increases and other aspects of climate change, especially at the regional scale, are still subject to uncertainty. Nevertheless, the risks associated with some of these changes are substantial." (Royal Society 2010)

G8+5 Academies' joint statement (2009):

Building on a joint statement released in 2005 stating "It is likely that most of the warming in recent decades can be attributed to human activities", the joint academies (including national academies from Brazil, China, India, Russia, South Africa, Canada, Italy, United Kingdom, Japan, United States of America, France, Mexico and Germany) conclude:

"Climate change is happening even faster than previously estimated. The need for urgent action to address climate change is now indisputable. For example, limiting global warming to 2°C would require a very rapid worldwide implementation of all currently available low carbon technologies. The G8+5 should lead the transition to an energy efficient and low carbon world economy, and foster innovation and research and development for both mitigation and adaptation technologies." (G8+5 2009)

Other discipline specific scientific societies and associations have also released statements on climate, and in some cases these reflect a lack of complete consensus:

American Association of Petroleum Geologists:

"Although the AAPG membership is divided on the degree of influence that anthropogenic carbon dioxide has on recent and potential global temperature increases, the AAPG believes that expansion of scientific climate research into the basic controls on climate is important." (AAPG 2011)

Geological Society of Australia (2009):

"Human activities have increasing impact on Earth's environments. Of particular concern are the well-documented loading of carbon dioxide to the atmosphere, which has been linked unequivocally to burning of fossil fuels, and the corresponding increase in average global temperature." (GSA 2011)

4.2.3. Other assessments of consensus and disagreement on climate science

In response to ongoing debate and confusion on the level of agreement amongst climate change scientists on the human attribution of climate change, and frustration amongst scientists at the efforts of non-experts to down-play the level of agreement, a number of researchers have attempted to assess the level of consensus in other ways. These have included assessments of peer reviewed articles, investigation into the 'credibility' of scientists taking different views on climate change, and direct surveys of scientists on their attitude to climate change. These approaches often focus on different or multiple elements of consensus – those being the *manifestation* of climate change (temperature is

increasing), the *attribution* of climate change (humans are the cause) and the *legitimacy* of scientific claims (Bray 2010). Here we present data from literature reviews.

Oreskes (2004) chose to review the level of consensus on human attribution of climate change by analysing the position taken in peer reviewed papers written between 1993 and 2003 that referred to 'global climate change'. Of 968 papers analysed qualitatively, 75 per cent 'explicitly or implicitly' accepted the consensus view. The remaining 25 per cent focused on palaeoclimate (climate before the emergence of modern humans) and did not take a position on human-induced changes to the climate. None of the papers provided scientific data to refute the consensus position (Oreskes 2004). The Oreskes (2004) approach has been criticised due to the subjectivity in determining 'implicit' acceptance and the lack of complete coverage of relevant articles and diversity of scientific opinion (Doran and Zimmerman 2009).

To explore the question of the credibility of scientists taking different position on climate change, Anderegg et al (2010) compared the credentials of scientists who were 'convinced' and 'unconvinced' by the evidence of human-induced climate change. Scientists were selected from lists on public statements either endorsing or criticising the conclusions of the IPCC. 'Credibility' was determined by tallying the number of relevant publications from each researcher (as a determinant of *expertise*), and then counting the number of citations for the four highest papers (as a determinant of *prominence*) (Anderegg, Prall et al. 2010). The results showed that the 'unconvinced' group comprised only 2.5 per cent of the top 200 climate researchers ranked by the study. The average expertise of the 'unconvinced' group was around half that of the 'convinced' group. Anderegg et al (2010) concluded that 'not all experts are equal', and that those with stronger expertise in climate science are generally those that are convinced by the evidence on human-induced climate change.

While these studies can be a useful supplement to other assessments of majority views, there is a feeling within the science community that 'science by opinion poll' is not an appropriate approach, as it over-simplifies the nature of the discussions and the subtleties in the reasoning and positions of individual scientists (O'Neill and Boykoff 2010).

5. Public perceptions of climate change

Despite the high level of confidence within the mainstream Australian and international science communities, there has been recent discussion of whether there has been a decline in public confidence that human activities are contributing to climate change.

5.1. The Australian public's perceptions on climate change

The prominence of climate change in public policy discussions in recent years has caused a rise in the number of polls and surveys of opinion. To determine the state of current knowledge about the Australian public's views on climate change, the Social and Economic Sciences Program group at the CSIRO was commissioned by the Garnaut Climate Change Review Update Secretariat to undertake a brief review of recent studies examining Australians' views of climate change, the role of human activities in producing climate change, and support for various policy responses to climate change²². The review also considered whether, and to what extent, public views had changed in recent years, and how Australian outcomes compared with those in other countries (Leviston, Greenhill M. et al. 2011). The surveys included in the review were drawn from those undertaken by polling agencies, research bodies, interest groups and think tanks²³.

This research found that from the wide range of surveys identified, a large majority of Australians believe the climate is changing. The size of the majority depends on how the question is posed, but ranges from 63 per cent to 83 per cent. Those agreeing with the suggestion that 'climate change is not really happening' represent only 2 to 9 per cent of respondents (Leviston, Greenhill M. et al. 2011).

²² Public views on climate change policy action will be discussed in Update Paper six (Carbon pricing and reducing Australia's emissions).

²³ For full details on the surveys reviewed, please refer to the CSIRO 2011 report 'Australians' views on climate change', available at www.garnautreview.org.au.

Across the surveys, fewer Australians believe that climate change is attributable to human activity with considerable variation across the surveys. In the surveys considered, when those that answered agreed that climate change was happening, around 50 per cent agreed that human activity was driving climate change. The proportion of respondents who believed that climate change was the result of natural influences ranged between 5 and 40 per cent across the surveys, but in every survey the proportion in the affirmative was higher (see Leviston et al. 2011).

Each survey posed the question of human influence in a different way, which influenced the number of affirmative responses and makes simple comparisons more difficult. The surveys that asked questions that gave the option of humans being 'partly' responsible for climate change had a proportion of respondents giving an affirmative response to a human influence on climate change higher than 90 per cent (Ipsos-Eureka 2010; Reser, Pidgeon et al. in Draft).

Some survey responses suggest a level of confusion around the causes of climate change and the appropriate response (Leviston and Walker 2010). One survey undertaken in 2010 found that even amongst the group that considered climate change to be caused by natural processes, there was still a belief that countries, governments and global organisations were partially responsibly for causing climate change (Leviston and Walker 2010). In another survey, 52 per cent of respondents indicated they were 'confused as to what to believe because of conflicting messages' (Cormick 2010).

Questions on how serious the threat of climate change was or how worried they were about climate change were included in some of the surveys. Across the four studies that asked about the seriousness of climate change, respondents who perceived the threat of climate change to be serious or very serious ranged from 46 per cent to 75 per cent, with the proportion believing it was not serious or no threat at all ranging from 13 to 20 per cent. In the six studies that asked questions about the level of concern or worry regarding climate change, those that were somewhat worried or very worried were between 45 and 66 per cent, with those not at all or not very worried representing 31 to 45 per cent, with the remainder neutral or unsure (Leviston, Greenhill M. et al. 2011).

The review of surveys found that demographic factors such as age, income, gender and place have some influence over beliefs and concern about climate change in some surveys. Some evidence of differences was found between those living in urban areas and those in rural areas—this may have been related to differences in voting intention. The division on climate change beliefs by voting intention was a consistent and clear result in Australia, and also in the surveys reviewed in the US and Western European countries (Leviston, Greenhill M. et al. 2011).

A small number of surveys had asked the same questions repeatedly in a number of years in order to assess trends. Those surveys indicated that the proportion of Australians who state that they believe that climate change is happening as a result of human activity has declined over the past three years, as has concern and priority given to climate change. However, the number of surveys that report results over time is small (four), and the time-frames are narrow. Gallup polling (2010) undertaken in Australia indicated that the percentage of respondents who believe human activities contributed to climate change decreased from 72 per cent in 2008 to 65 per cent in 2010, with those indicating it was a result of natural causes increasing from 21 to 31 per cent, and the rest unsure. This decline is significantly higher than the usual variance in Gallup Polling. While some other surveys suggested a decline it could not be considered significant, while others suggested no change. Clear declines are evident in Gallup Polling in the US, where those answering yes to questions on human influence on climate change have dropped from 61 to 50 per cent since 2003 (Gallup 2011).

A 2011 global attitude survey by the Pew Research Centre shows a high proportion of respondents in South America and the Middle East who think that climate change is a 'very serious problem', with Brazil with the highest at 85 per cent. The proportion in India is 62 per cent, China is at 41, and the United Kingdom and United States are at 40 and 37 per cent respectively. Australia is not included in the survey. When changes over time are considered, the Pew Research Centre survey shows a marked reduction in concern and priority across a number of developed countries (United States, Germany, Spain and France), and increased levels of concern in countries including Lebanon, Jordan and Egypt. Trends over time in major emitting countries such as India and China are less clear (Pew Research Center 2010).

5.2. Factors contributing to public perceptions

Many factors have contributed to public attitudes to climate change and how they may have changed over time. As far as the Review Update is aware, no study has been undertaken to investigate the reasons behind the moderate decline in belief of human-induced climate change evident in Australia and other Western countries (Leviston, Greenhill M. et al. 2011).

From a general perspective, views on climate change may depend on direct experience, or a lack of it. The insidious and distant nature of potential climate change impacts makes it hard to detect and track using our established tools of personal observation and inference (Weber 2010). Studies undertaken in the United States suggest that what Americans believe about global warming depends on recent weather events (Anderegg 2010). This represents a common failure to distinguish between long term climate and short term weather events, or where people may incorrectly assign a unique event to climate change (Weber 2010). People living in rural areas who deal constantly with natural climate variation tend to dismiss the argument that climate change is the reason for the current climatic events. This is perhaps an example of where familiarity with a risk gained through exposure and response can lower perceptions of the riskiness of future similar events (Weber 2010). Additionally, by rejecting climate change, farmers are more able to avoid the sense of powerlessness associated with accepting the implications of the negative impact that climate change could have on their livelihood (Donnelly, Mercer et al. 2009).

These factors may contribute to a lack of engagement on climate change. The risks to most of the community are 'virtual' rather than real, which means that people are free to interpret information and act on it or ignore it on the basis of their existing beliefs and attitudes. This turns climate change from a problem based purely in the science to one that is deeply influenced by our society's culture and values (Nerlich, Koteyko et al. 2010; Weber 2010). The division in relation to climate change beliefs by voting intention found in surveys from Australia and other countries is consistent with outcomes from behavioural science studies which show that the experts that people perceive as most credible are the ones who appear to share their values. This is a key factor in the polarisation of the climate change debate, and it has some strong implications for the approach to climate change communication (Kahan 2010).

A nationally representative survey conducted in the United States in 2008 and late 2009/early 2010 found declines in climate change beliefs (consistent with the US Gallup Poll discussed above), risk perceptions, and trust in scientists amongst respondents (Leiserowitz, Maibach et al. 2010). A range of potential explanations were explored, including unusually cold weather at the time the later survey was undertaken, and the poor state of the economy. The analysis also specifically examined the impact of the unauthorised release of more than a thousand emails from the University of East Anglia in the United Kingdom, which was dubbed 'Climategate' by the media. A few of these emails were subsequently cited by climate change sceptics as evidence of misleading conduct by a group of scientists supporting the mainstream view on climate change. The survey in late 2009/early 2010 found a quarter of respondents had heard of or followed the 'Climategate' story. Of those who had heard of the story, 47 per cent said the stories had made them somewhat or much more certain that global warming is *not* happening, while 41 per cent said the stories had no influence on their level of certainty, and 11 per cent said the story had actually made them more certain global warming is happening. More than half said that the controversy had reduced their trust in scientists, with the loss of trust linked to voting intention (Leiserowitz, Maibach et al. 2010). A series of investigations during 2010 of the emails concluded that no scientific misconduct had occurred and nothing in the emails should give cause to doubt the facts which show that global warming is occurring (Russell 2010). Despite this, the authors suggest that the survey demonstrates that Climategate deepened the previously observed declines in public beliefs that global warming is happening and influenced by human activities, and eroded trust in scientists (Leiserowitz, Maibach et al. 2010).

Even amongst people who believe climate change is occurring, there is usually limited understanding of the causes and likely effects. Public concern on the importance and potential severity of climate change impacts seems to be less than warranted by scientific evidence (Weber 2010). The emotions associated with an individual's response to climate change are complex. Perception of risk is influenced by people's assessment of their ability to take corrective action, how they discount future and distant impacts, or how threatened their lifestyle is by the potential change (Kahan 2010; Weber 2010). If the message being conveyed puts pressure on an element of a person's lifestyle that they perceive as

important, it can solidify their resistance to that message and encourage support for alternative proposals (Kahan 2010). A feeling of fear and powerlessness can also act to disable those who believe in, and are alarmed by, human induced climate change (Leviston and Walker 2010).

6. Conclusion

In a speech to the annual conference of Australia's Supreme and Federal Court Judges in early 2010, I compared the challenge facing a judge with that of the lay person assessing the science on climate change:

"A judge in a civil court must make a decision on a balance of probabilities. Rarely in a case that comes before one of Australia's superior courts is the defence so weak that it can find no 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 one so-called expert is more likely to be right than the established opinion." (Garnaut 2010)

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. The Review's acceptance in 2008 "on the balance of probabilities" of the overwhelming majority of opinion of the Australian and international science communities has not been challenged by developments in the genuine science over the past three years.

The most important and straightforward of the quantitatively testable propositions from the mainstream science have been confirmed or shown to be understated by the passing of time: the upward trend in average temperatures; the rate of increase in sea level. 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: the warming of the troposphere and the cooling of the stratosphere (Thorne, Lanzante et al. 2011), and the long-term shift towards wet extremes and hot extremes found by Gallant and Karoly (2010).

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.

There are a number of matters on which measureable changes are pointing to more rapid movement towards climate "tipping points" than suggested by the mid-points of the mainstream science; the rate of reduction in Arctic sea ice; and the emergence of accumulations of methane in the atmosphere at a rate in excess of expectations.

Scientific developments since 2008 have introduced some additional caution about whether "overshooting" emissions scenarios will lead to temperature increases that are not quickly reversed.

Regrettably, there are no major propositions of the mainstream science from 2008 that have been weakened by the observational evidence of these past two 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 are material to the reliability of the main propositions of the mainstream science.

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 led to a downward rather than upward revision of expectations of damage from unmitigated climate change.

This raises a question about whether something in the environment for scientific research on climate change introduces 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—for the allocation of resources and the distribution of income—it is important to base policy on the established propositions of the science.

My personal intellectual journey over these past four years has moved me from acceptance of the mainstream science's main propositions with the degree of certainty required by the civil law—"a balance of probabilities"—closer to the criminal law requirements of "beyond reasonable doubt".

"A balance of probabilities" was enough to draw the conclusions of the Review: that it was in Australia's national interest to do its proportionate part in an effective international effort to hold emissions concentrations to 450 ppm carbon dioxide equivalent. The new scientific knowledge and the realisation of slow progress on mitigation in the developed countries that has come with the passing of time has made 450 ppm a more difficult objective. It would be wise for Australians through their domestic actions and international interactions to work towards achieving that much. Along the way, we can assess whether developments in knowledge have made the case that our national interest requires higher ambition.

"Beyond reasonable doubt" is not the absence of all doubt. If it were, there would be few criminal convictions. On climate change, a small number of scientists who hold climate science qualifications and who continue to publish in credible outlets maintain the view that human activity is small amongst the factors driving global warming. Their views can be respected, and are a reason to continue to interrogate the overwhelming majority of reputed and relevant scientific opinion.

There is still a high degree of uncertainty about myriad important details of the impact of increased concentrations of greenhouse gases.

The uncertainty in the science is generally associated with the rate and magnitude, rather than the direction of the science's conclusions.

There is no question that the presence of uncertainty complicates policy responses. As the Royal Society said in its statement about uncertainty and climate science:

"Like many important decisions, policy choices about climate change have to be made in the absence of perfect knowledge. Even if the remaining uncertainties were substantially resolved, the wide variety of interests, cultures and beliefs in society would make consensus about such choices difficult to achieve. However, the potential impacts of climate change are sufficiently serious that important decisions will need to be made." (Royal Society 2010)

The new scientific evidence has tended towards confirmation of the central points of the old understandings about "climate sensitivity"—that a doubling of concentrations would raise temperature by about 3 degrees. Here the uncertainty has become more narrow, but still covers a range that matters a great deal to human society.

There is little doubt that a warmer climate will mean higher rainfall on average around the earth. However, changes in wind patterns and other aspects of the wider climate system will make some regions drier, and there is uncertainty about the boundaries of those regions. This is of immense practical significance for Australia. The bigger and better climate models being developed in the joint project between the Bureau of Meteorology and the CSIRO are important to our understanding of future Australian reality.

The Review said that to ignore the wisdom of the mainstream science and to instead hold on to the hopes held out by the small minority of genuine sceptics in the relevant scientific communities, let alone to give credence to the wild claims of climate change dissenters, would be to hide from reality. It would be imprudent beyond the normal limits of human irrationality. That is no less true today, when there is higher confidence in the main propositions of the science.

6.1. Reflections on scholarly reticence

Let me use some final reflections to expand upon a question that I raised earlier in the conclusions. It is remarkable that the review of developments in the science—new observations and results of new research—have all either confirmed established scientific wisdom, or shifted the established wisdom in

the direction of greater concern. This continues a pattern that has been present for some time. As noted earlier in this paper, the fourth assessment by the IPCC embodied more concern than the third, the third than the second and the second than the first. The scientific literature that we have discussed in this Update Paper indicates that there is likely to be another disappointing change in the fifth assessment.

In an area of uncertainty, this is not what one would expect. One would expect some new knowledge to surprise by being more worrying than the central points in the mainstream science, and some new knowledge to surprise because it is less worrying. When all the new knowledge that challenges the old is on the more worrying side, one worries about whether the asymmetry reflects some systematic bias.

The publications lags are long. New science undertaken in the middle of the last decade may not have been published in time for incorporation into the 2007 report of the IPCC. The next IPCC report will not be available for another few years. A decade may have passed between the discovery of relevant new knowledge and its incorporation into a report of the IPCC.

Publications lags introduce unfortunate delays between discovery and influence in the policy discussion, but there is no reason to expect them to cause systematic bias in the direction in which new knowledge changes the established wisdom.

I have come to wonder whether the reason why most of the new knowledge confirms the established science or changes it for the worse is scholarly reticence.

I wonder whether we are seeing the effects of a professional reticence about stepping too far in front of received wisdom in one stride. This phenomenon has been described by eminent and now famous climate scientist James Hansen, long time Director of the National Aeronautical and Space Administration (NASA) Goddard Institute for Space Studies:

“Scientific reticence, in some cases may hinder communication with the public. Reticence may be a consequence of the scientific method—success in science depends on continual objective scepticism.One factor in reticence may be “behavioural discounting”—concern about the danger of being accused of “crying wolf”....This history suggested a reticence of scientists to report a result that differed too much from the one established by the (work of one great scientist in the field)—at least not in a single step—until other scientists gave them more courage”. (Hansen 2009) pg 87- 89

I can recognise professional reticence from my own fields of academic research. I was the first economist to work through the implications of China's reforms and opening to the outside world for global trade and development, including for the trade opportunities and growth prospects of the Australian economy. The reforms were initiated in December 1978 at a meeting of the Central Committee of the Chinese Communist Party. I presented my conclusions in public lectures, academic papers and speeches at various times through the 1980s. Some of this thinking was brought together in my 1989 report to the Australian Prime Minister, “Australia and the Northeast Asian Ascendancy”. What was noticeable at the time, around a quarter of a century ago, is that my views on the extent of change were thought to be optimistic about China's prospects and influence in global trade and development.

What is noticeable now, reading back over that work, is that the changes that I foreshadowed in my public lectures and publications were close in shape and direction to what eventually transpired, but understated in scale. The numbers that I used were nevertheless far beyond the conventional wisdom—so far as to seem implausible to some people. They were a long way beyond the published expectations of other analysts contributing to discussion of these issues. And yet they invariably fell short of the realities that have now emerged as history.

From time to time through that decade, and through much of the nineties until the rest of the world began to catch up with the Chinese reality, I worried a little about whether I had been influenced into understatement by repeated criticisms of optimism.

Be that as it may, I responded with personal recognition to Edwin Reischauer's description in his autobiography of the American professional and public response in the early 1950s to his successive publications on postwar Japan. Reischauer was longstanding Professor of Japanese History at Harvard

University and President Kennedy's Ambassador to Japan. This is how he explained his academic reticence in his work in Japan:

"My most substantial work in the early postwar years was "The United States and Japan", published in 1950...In (subsequent editions)...I was much more optimistic about Japan's political future than were almost all the other contemporary scholars and popular writers...and while I viewed Japan's economic future with deep concern, I was less pessimistic than most. Almost all of the criticism of my writing singled out what was considered my excessive optimism, but each time I came to revise my books, I found that I had to make my predictions much more optimistic than before. One can guess how wrong my critics were, but I have discovered that pessimism somehow is regarded as being more scholarly than optimism". (Reischauer 1986)

My own experience and observations of related phenomena suggest that the source of bias is scholarly reticence. It is not optimism that is unscholarly, but being too far away from the mainstream. That could potentially cut either way on climate change. However, in circumstances in which the mainstream has been moving steadily towards more certain views that human-induced climate change is substantial and potentially damaging, and towards expectations of more severe damage, not being too far away from the mainstream has been associated with understatement of the risks.

Four years of reading into and interrogation of the climate science has led me to be uneasy about the interacting roles of publishing lags and scientific reticence in public (and my own) understanding of the risks of climate change.

Is there such understatement amongst the scientific sceptics and the dissenters? For the dissenters, there is no reason for any understatement: the positions that they articulate are not based in science. There are no intellectual constraints on wild assertion.

But the genuine sceptics in the science? Here the direction of change in knowledge is relevant. The genuine scientific sceptics have tended to make fewer and weaker claims as the published science moves away from them. The main response to the change in the position of mainstream science is for the genuine sceptic to be less active in publication in the mainstream journals. That is tacit recognition of changes in the received body of scientific knowledge.

At the other end of the spectrum, the scholars who were as far away from the mainstream in the other direction have found the mainstream science moving towards them. They have tended to remain more active in genuine scientific research and publication. In many cases, they have moved in the same direction as the mainstream views, into positions that remain on the "more concerned" side of the mainstream.

There must be a possibility that scholarly reticence, extended by publications lags, has led to understatement of the risks.

That is not a reason to clutch for knowledge outside the mainstream wisdom: if our discussion ceases to be grounded in the established science, we have no firm, common ground from which to work on the most difficult policy problem of our times.

We should, however, be alert to the possibility that the reputable science in future will suggest that it is in Australians' and humanity's interests to take much stronger and much more urgent action on climate change than might seem warranted from today's peer-reviewed published literature. We have to be ready to adjust expectations and policy in response to changes in the wisdom from the mainstream science.

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