

# Climate Change Science: Status, and Next Steps in the Projection of Future Changes

Andrew J. Pitman and Sarah Perkins

**Climate Change Research Centre, University of New South Wales**

*The status of the science underpinning global warming is reviewed briefly using the recently released Intergovernmental Panel on Climate Change's assessment. The latest science clearly reinforces the conclusion of global warming and associated changes in rainfall, sea level rise and other phenomenon. It is noted that climate models are now impressively skilful at large spatial scales, but that these are rarely the resolution useful to impacts modellers. The methods for downscaling climate model results are reviewed. We then show results from new analyses of the likely impact of global warming on the Australian temperature and rainfall patterns. We show not the changes in the mean, but rather we focus on changes in extremes to highlight emerging capacity in climate science. Results show that under a low emission future the scale of projected changes are possibly able to be adaptable to, at least through to 2050, but further into the future and under higher emissions, the projected changes in temperature and rainfall are confronting. We show a new result that highlights the change in the frequency of very hot days over a selected region of Australia, noting that the increase in frequency appears very concerning, but also that the climate models have much less agreement on these projected changes than on the commonly reported means. We propose some guidelines for researchers wanting to incorporate climate model data in their work.*

**Key words:** Global Warming; Climate Change; Australia; Climate Models; Climate Projection; Extremes

Weather and climate have an impact on human health (McMichael et al. 2006; Patz, Engelberg & Last 2000). The primary effect of global warming on human health is via changes in temperature. Periods of extreme hot or cold temperatures increase mortality (Curriero et al. 2002; Keatinge et al. 2000). It is estimated, for instance, that the 2003 heatwave, probably Europe's hottest summer on record (Trigo et al. 2005), caused nearly 15,000 excess deaths during the period of August 4-18 in France alone (Vandentorren et al. 2004). Indirect effects of warming include changes in drought that might be associated with mental illness, increased risk of flooding that might increase water borne disease and increased risk of cyclones that might directly impact on communities through wind damage and flooding (Haines et al. 2006). Other indirect effects of climate change include increased risk of bush fires (Pitman, Narisma

& McAneney 2007) which can directly kill, but also impact on human health through air pollution (Coghlan 2004) during the actual fires, from burns and smoke inhalation and from post-fire psychological trauma (Sim 2002). An emerging concern is the capacity of our health infrastructure to accommodate changes in patient load associated with extreme climate changes (McCarthy et al. 2001). Other potential impacts include asthma (Beggs & Bambrick 2005) and the vulnerability of some medications to higher ambient temperatures (Beggs 2000).

There is also a likely link between global warming and increased risk of high air pollution events. Global warming is likely to enhance air pollution in many cities by enhancing photochemical smog formation. Possible interactions between temperature and air pollution can have serious effects on health outcomes (Ren & Tong 2006; Ren, Williams

& Tong 2006). Other serious health-related impacts could include infectious diseases, especially those transmitted by water or by insect or rodent vectors; and refugee health issues linked to mass migrations and wars, as people fight each other for water, food, land and energy. It is estimated that the climatic changes that have occurred since the mid-1970s could already be causing over 150,000 deaths annually and five million disability-adjusted life-years, mainly in developing countries (Patz et al. 2005).

It is, therefore, important in health planning, which in the case of infrastructure might have commitments of many decades, for example, the location of hospitals, that there is a strong infusion of knowledge from the climate sciences into the human health sciences. It is challenging to keep up to date with the rapidly evolving knowledge in other disciplines and climate science is evolving particularly rapidly as acknowledgement of the challenges that confront us in respect of climate change become clearer. This paper will provide an up to date guide to the current status of the science underpinning 20th and 21st century climate change and then provide guidance to the latest projections of how climate is likely to change in the next 50 to 100 years. Our aim is to inform the health sciences of advances in climate science and climate modelling post about 2000.

We begin by providing a brief overview of the current state of the science. We then outline briefly how projections of future climate at regional scales are achieved; identifying where confidence is high and low. Alternative approaches are identified - not to identify the 'best way' for the health community to obtain projections of the future climate, but rather to inform this community that there are a variety of approaches with relative strengths and weaknesses, and to explain why obtaining detailed regional-scale projections of how climate might change, remains extremely challenging.

## **The State of the Science**

In 2007, the Intergovernmental Panel on Climate Change (IPCC) released its 4th Assessment Report (AR4). The IPCC reports are critical assessments of what is, or is not, known reliably in terms of the science of global warming. The full report, a technical summary and a summary for policy makers are all available on-line ([www.ipcc.ch](http://www.ipcc.ch)). The AR4 effectively supersedes all previous assessments by the IPCC and makes work based on the 1990, 1995 and 2001 reports outdated. In work utilising climate change projections for the possible impacts, it is very important to understand that any projections that were used in the 2001 (or earlier) reports are now seriously out of date. It is also important to realise that the 2007 IPCC report is already becoming dated (much of the material is 12-24 months old) and that it is a consensus assessment of the science. It might therefore under-emphasise some very recent findings, or apparently anomalous findings, that might turn out to be correct. The AR4 remains, however, the best, most rigorous and most robust assessment of the science of global warming.

The AR4 notes that it is now virtually certain (99% probability) that humans are warming the planet and will continue to do so. It is now extremely likely (> 95% probability) that this warming is causing changes in climate such as climate extremes, and will continue to do so in the future. We are committed to at least several more decades of warming and associated changes in temperature, in sea levels and other impacts due to inertia in the climate system and the time it takes for the oceans to equilibrate to atmospheric greenhouse gas induced warming. Overall, our confidence in these statements has increased since the 3rd Assessment Report released in 2001.

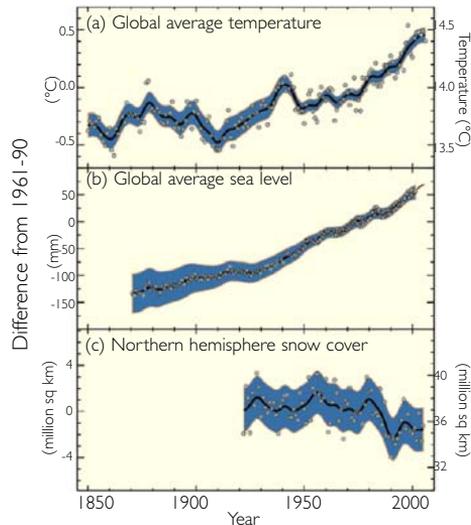
The Earth is warming due to the release of greenhouse gases into the atmosphere. Concentrations of carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) far exceed anything that has

occurred over the previous 650,000 years. This is due to fossil fuel use, to agriculture, and to land-use changes. In 2005, CO<sub>2</sub> was at 379 ppm (up from 280 ppm pre-industrial). Emissions have increased from near zero to 6.4 GtC y<sup>-1</sup> in the 1990s, to 7.2 Gt C y<sup>-1</sup> in 2000-2005. The rate of increase of greenhouse gases is *very likely* (> 90% probability) to be unprecedented in more than 10,000 years. It is worth reflecting that it is less the amount of increase in CO<sub>2</sub> and associated warming projected for the future that concerns climate scientists; rather it is the *rate* and *accelerating rate* of change that concerns us.

The IPCC AR4 notes that warming of the climate system seen in observations is unequivocal. Over time, through previous IPCC assessments, our knowledge of the science underpinning global warming, and an improved understanding of natural variability, has gradually increased our confidence about the causes of observed warming. Warming is now evident in global average air and ocean temperatures, melting of snow and ice, and rising sea levels. Ocean warming now extends to at least 3000 m. While popular fiction might attempt to explain these changes by solar or volcanic activity, urbanisation, or natural processes, it is unfortunately the case that these remain fictions. Indeed, changes in solar output since 1750 are now believed to be less than half the previous estimates and simply do not explain 20th century warming. Warming has now reached the level that 11 of the last 12 years rank among the 12 warmest years in the instrumental record of global surface temperature since 1850. The 100-year trend is now 0.74°C (up from an earlier estimate of 0.6°C. This increase in the amount of warming over the previous century is due to the acceleration of warming towards the end of the 20th century. Figure 1 shows the latest estimate of global average temperature change (IPCC 2007).

In the IPCC's first report in 1990, projections suggested globally-averaged temperature increases should have been between about 0.15 and 0.3°C per decade for 1990 to 2005.

**Figure 1: Observed changes in (a) global average surface temperature; (b) global average sea level rise from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April.**



All changes are relative to corresponding averages for the period 1961-1990. Smoothed curves and shaded areas represent decadal averaged values and their assessed uncertainty intervals, while circles show yearly values.

Source: Taken from the Summary for Policy Makers - [www.ipcc.ch](http://www.ipcc.ch).

This can now be compared with observed values of about 0.2°C per decade. Thus, the 1990 projections by the IPCC were proven true by observations. There is an argument that if the IPCC successfully predicted the high degree of warming towards the end of the 20th Century, then they are likely to be able to simulate the amount of warming over the next 10-20 years with a high degree of confidence. The continued emission of greenhouse gases at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century. These changes would *very likely* (> 90% probability) be larger than those observed during the 20th century. Projected globally-averaged surface warming for the end of the 21st Century (2090-2099) depends greatly on which emissions path we take, but ranges at present between 1.7 to 4.0°C. A 'best estimate' of global warming

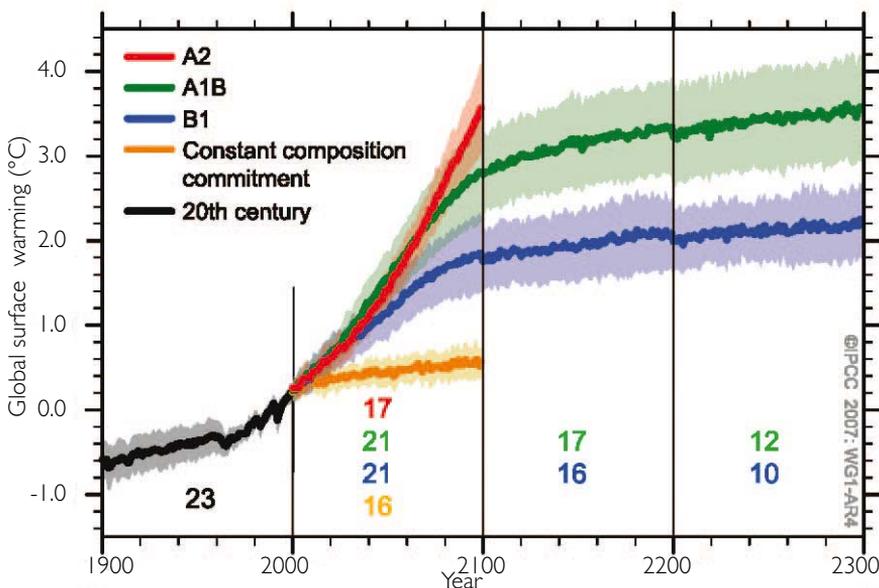
by the end of the century suggests a global mean warming of about 3.25°C (Murphy et al. 2004) but this hides substantial regional variability and does not account for some possible acceleration of warming due to loss of terrestrial carbon (Cox et al. 2000).

Figure 2 shows the projection of warming from the AR4 report. Three features are particularly apparent. First, there is no conceivable future that does not include substantial further additional warming; second, the amount of warming depends critically on the level of greenhouse gas emissions; third, warming continues long into the future - in all projections shown below greenhouse gases cease to increase at 2100. Additionally, due to inertia in the system, the Earth continues to warm for several centuries.

It is worth reflecting on these projected temperature changes in some detail. First, the amount of global warming projected for a given increase in greenhouse gases has not changed

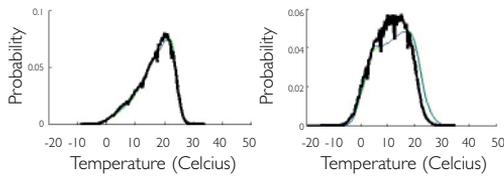
significantly since early projections with much simpler climate models (e.g. Manabe & Stouffer 1980). In simple terms, increases in greenhouse gases leads to increases in the absorption of infrared radiation emitted by the Earth's surface and this in turn leads to more energy being retained within the atmosphere leading to higher temperatures. The transfer of energy within the atmosphere, the absorption and re-emission of this energy and its impacts on temperature are all described by fundamental physics equations (the laws of thermodynamics, the conservation of energy and so on). While there are complications to this simple picture (the role of water vapour, or clouds) the foundation of temperature projections within well known physics equations provides a very high level of confidence in climate model capacity to simulate temperature, and most likely rises in temperatures projected into the future. An objective analysis of the skill of climate

**Figure 2: Multi-model means of surface warming (relative to 1980-1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulation.**



Values beyond 2100 are for the stabilisation scenarios. Lines show the multi model means, shading denotes the plus minus one standard deviation range of individual model annual means

**Figure 3: Simulation of the observed minimum daily temperature for two 10° x 10° regions of Australia (solid line). The thin line shows the simulation by a set of the AR4 climate models.**



models in simulating daily temperature over the 20th century, region-by-region over Australia demonstrated that many climate models have surprisingly impressive capacity in simulating temperature (Perkins et al. 2007). Figure 3, for example, shows how well some AR4 models can capture the observed probability density function (PDF) of daily minimum temperature for two 10°x10° regions of Australia. Note that the models capture the different shapes of the PDFs and their position on the horizontal axis. A similar result can be obtained for daily maximum temperature.

In terms of sea level, warming the oceans directly causes sea level rise via thermal expansion, and indirectly causes them to warm through melting of ground-based glaciers. Global sea levels rose at an average rate of 1.8 mm y<sup>-1</sup> over 1961 to 2003. The rate was faster over 1993 to 2003, about 3.1 mm y<sup>-1</sup> (Figure 1b). There is high confidence that the rate of observed sea level rise increased from the 19th to the 20th century, and the total 20th century rise is estimated to be

0.17m (see the Summary for Policy Makers of Working Group 1 at [www.ipcc.ch](http://www.ipcc.ch)).

The projected globally-averaged sea level rise at the end of the 21st century is between 0.28 m and 0.43 m. However, if increases in ice melt from Greenland and the Antarctic continue, these projections might increase by a further 10 to 25%. It is worth noting two issues here that have been misrepresented in the media. First, if the Earth warms by 1.9 to 4.6°C, the Greenland ice cap would completely melt and contribute about a 7m rise in sea level. However, this is extremely unlikely to occur unless the warming was sustained for millennia. Ice sheet melt and thermal expansion will lead to sea level rise, and this will dramatically affect vulnerable coastal communities. In particular, coastal settlements built close to mean sea level are already highly vulnerable to storm surge irrespective of additional sea level rise. Building settlements close to sea level, or on flood plains, does not require sea level rise to be flooded, and examples of coastal flooding need not be caused by global warming. Settlements in coastal Queensland and the Gold Coast will be inundated due to cyclonic activity and storm surges this century irrespective of how rapidly mean sea level increases.

Many other changes resulting from global warming are anticipated. For example, more intense and longer droughts have been observed over wide areas since the 1970s, particularly in the tropics and subtropics. Zhang et al. (2007) attribute for the first

**Figure 4: Simulation of the observed rainfall in two 10°x10° region of Australia (solid line).**



The thin lines show the simulation by a set of the AR4 climate models. The three model averages (shown by the thin lines) reflect increasing skill achieved via omitting models using an objective skill score

Source: (Perkins et al. 2007).

time some of the decline in rainfall to human influences. The frequency of heavy precipitation events has increased, consistent with warming and observed increases of atmospheric water vapour. It is expected that this trend will continue. However, changes observed over most of Australia cannot be attributed to human activity within the region at this time because no statistically robust long term trend over Australia has been identified. It is considerably more likely that this is because the studies have not been conducted, rather than that no trend due to warming exists.

Simulating rainfall in climate models is well known to be challenging and there are limits to the capacity of models (Sun et al. 2006). Over Australia, Perkins et al. (2007) showed that some of the AR4 models could demonstrate significant skill in the simulation of the observed probability density function of daily rainfall. Figure 4 shows that there are substantial differences between the observed PDF of rainfall (solid black line) and the all AR4 model rainfall PDF (highest line on each panel), particularly for smaller magnitude events. Perkins et al. (2007) suggested a means of omitting specific climate models from this overall PDF based on an assessment of each model's skill in simulating rainfall over the 20th Century. However, Figure 4 shows that even if only the very best climate models are included, there is still a residual error. The line closest to the observed reflects the skill of the best models and at low rainfall rates there remains a systematic error of excess simulation of low rainfall intensities and an underestimation of intensity at high rainfall intensities.

Rainfall is not understood to the same degree as temperature - there are not equivalent laws for rainfall as there are for temperature. Rainfall occurs through a suite of processes, commonly occurring at relatively small spatial scales (e.g. convection, which undermines the development of thunderstorms). In climate models, these processes must be

parameterised using a combination of theory, experimentation and observations. This inevitably introduces uncertainties in the simulation of both rainfall, and how rainfall might change in the future. Ultimately, this makes the projection of how rainfall patterns and rainfall amounts will change in the future very difficult. The recent attribution of changes in observed rainfall to human influence by Zhang et al. (2007) is an important step forwards in building confidence of how rainfall might change in the future. There are also major studies that explore how rainfall extremes might change in the future (Kharin et al. 2007). There are clearly increases in the amount of rainfall that is likely to occur in an event of a given size. The suggestion, combining Zhang et al. (2007) with Kharin et al. (2007) is a clear re-enforcement of a future where rainfall is likely to be more extreme, but more spread out in terms of the frequency of a given event so that there are longer dry spells.

In terms of other climate changes, the AR4 notes that there is no clear trend in the annual number of tropical cyclones. However, there is a suggestion of a trend towards more intense tropical cyclones since about 1970. The number of cyclones per year is projected to decrease but their intensity is expected to increase, with larger peak wind speeds and more intense precipitation. There is simply insufficient evidence to determine whether trends exist in tornadoes, hail, lightning and dust-storms on small scales. There is a high likelihood that there will continue to be a decreasing trend in snow cover (Figure 1). Finally, it is very likely (> 90% probability) that the Atlantic meridional overturning circulation will slow down during the 21st century but it is very unlikely (< 10% probability) that it will undergo a large abrupt transition during the 21st century. The Atlantic meridional overturning circulation is part of the Gulf Stream that keeps Western Europe substantially warmer than the equivalent latitude on the western side of the

north Atlantic. Any change that this might undergo a collapse (even if this is less than a 10% chance) deserves to be taken seriously.

In summary, observed changes at the large scale in warming (Hegerl et al. 1997), observed changes in rainfall (Zhang et al. 2007), sea level rise (Rhamsdorf et al. 2007), ocean temperatures (Barnett et al. 2005) and even sea level pressure (Gillett et al. 2003) have all been detected and attributed to human activity through the enhanced greenhouse effect. This is no longer in debate since there is strong scientific evidence to support the role of human activity on climate (see for example Solomon et al. 2007; www.ipcc.ch) and there are no credible counter arguments that offer alternative explanations of why the changes that have been observed are occurring. A debate might develop in the future if a credible alternative hypothesis is developed to explain the observed changes, but until this occurs, it is reasonable to accept the global warming hypothesis and to explore what might happen in the future at time and space scales of relevance to Australian communities. Unfortunately, this is not in any sense straightforward.

### Regional Projections of Future Climate

At the heart of climate projections are coupled climate models; the tool that underpins the AR4 assessment by the IPCC. Climate models are based on well established physical principles and have been demonstrated to reproduce most significant features of the observed climate (Randall et al. 2007). Indeed, Randall et al. (2007) conclude that there is now considerable confidence that coupled climate models provide credible quantitative estimates of future climate change particularly at continental scales and above. They note that confidence in these estimates is higher for some climate variables (e.g. temperature) than for others (e.g. precipitation).

To assess the impact of climate change on human health, for example, continental-

scale projections are not particularly practical. While climate models were developed to simulate large spatial scales on longer (monthly, seasonal, annual) time scales, the impact of global warming is likely to be realised at finer spatial and temporal scales. In the AR4 assessment of warming on the Australian climate, Christensen et al. (2007) state:

*All of Australia [is] very likely to warm during this century ... comparable overall to the global mean warming. The warming is smaller in the south, especially in winter ... Increased frequency of extreme high daily temperatures [will occur] in Australia ... and [a] decrease in the frequency of cold extremes is very likely.*

*Precipitation is likely to decrease in Southern Australia in winter and spring. Precipitation is very likely to decrease in Southwestern Australia in winter ... Changes in rainfall in Northern and Central Australia is uncertain. Extremes of daily precipitation will very likely increase. The effect may be offset or reversed in areas of significant decrease in mean rainfall (southern Australian in winter and spring).*

These statements by Christensen et al. (2007) are based on the ensemble mean model performance of all AR4 models. They noted a small cold bias over land, particularly in winter in the southeast and southwest of the continent. Large-scale precipitation was shown to have systematic biases averaged across Northern Australia (the median model error was 20% more precipitation than observed, but the range of biases in individual models ranged from -71% to +131%). The median annual bias in the southern Australian region was -6%, and the range of biases -59% to +36%. In most models the northwest was too wet and the northeast and east coast too dry, and the central arid zone was insufficiently arid.

Several important questions come from this large scale analysis. First, how do we get projections at a higher spatial resolution? Second, how do we obtain more confident projections? Third, what about extremes (heat, rainfall, drought, flood and so on) that are more likely to directly affect human health?

### **i. How do we get projections at a higher spatial resolution?**

Climate models are mathematical formulae that are integrated on very large computers. Each simulation takes many months to complete and each experiment needs to be run at least four or five times to obtain rigorous statistics (these are known as 'realisations'). Thus, it can be 1-2 years from when one presses 'enter' on the computer to when the several terabytes of data are potentially available, describing the evolution of the climate from say 2000 to 2100, for analysis. Climate models divide space into latitude and longitude elements and divide the vertical dimension into layers. The latest climate models use a spatial resolution of about  $3^\circ \times 3^\circ$  (approximately 300 x 300 km) meaning that at about 300 km intervals the equations used to predict temperature, cloud cover, rainfall, humidity, wind, soil moisture and so on are solved to produce a single value for each  $3^\circ \times 3^\circ$  area. Climate models use about 15 levels in the atmosphere - so there are roughly 100,000 grid elements for the atmosphere and about 750,000 grid elements for the ocean (which uses a higher spatial resolution).

Each equation is updated in time using a discrete 'time step'. The length of this time step is proportional to the size of each grid element such that as you increase the spatial resolution (make the grid elements smaller) you have to make the time step shorter. At a  $3^\circ \times 3^\circ$  resolution, the time step is about 15 minutes. To double the spatial resolution of a climate model from (say)  $3^\circ \times 3^\circ$  to  $1.5^\circ \times 1.5^\circ$ , therefore, involves substantially more grid points *and* a reduction (but is this an increase? For example, 15min to one hour = increasing waiting time between time steps?) in the time step. This effectively results in a factor of eight increase in computation time for a given simulation. A 1-2 year simulation then becomes an 8-16 year simulation and the results are *still* roughly 150 x 150 km pixels. To obtain results, using a coupled climate model, at a resolution of direct value

to impacts researchers (say to the level of a suburb or postcode - perhaps 5 x 5 km) at present computational capacity requires simulations that take several hundred years.

It is, therefore, simply impossible with current computational capacity to imagine coupled climate models running at spatial resolutions of direct value to impacts modellers and, with computing developments, it will be decades before this is achievable. There are, therefore, four approaches used to 'down-scale' simulations to resolutions of immediate value (regression methods, weather pattern-based approaches, stochastic weather generators and limited-area modeling, see Wilby and Wigley 1997). Statistical (regression-based) downscaling (e.g. Timbal 2004) links large-scale atmospheric variables to local climate variables and are combinations of the weather pattern-based and regression based approaches. In effect, a series of large-scale predictors (pressure, winds, specific humidity, for example) are used and statistically linked to observed patterns of a climate variable using observations. These relationships are then used with the climate model large scale predictors to produce a higher resolution projection. Statistical downscaling requires a good understanding of the climate processes that exist within a region. The strength of this approach is that it is computationally cheap and relatively simple to implement. Questions over whether the regression-based relationships are reliable under future climates remain unanswered.

A major alternative is to use limited area modelling (also known as dynamical downscaling). This is very common - in effect a model mathematically similar to the fully coupled climate model is used at very high spatial resolution but only over a limited region of the Earth. Outside of this region, data from a coupled climate model are commonly used to provide the large-scale meteorology. This approach was developed by Giorgi, Shields-Brodeur and Bates (1994;

Giorgi et al. 1998) and was very effectively implemented by Whetton et al. (2001) over Australia. A review of some issues that relate to this approach is provided by Giorgi and Mearns (1999). One key issue is that errors in the large-scale forcing of the regional models (originating in the coupled climate models) are known to propagate into the limited area models. A second problem is that these models are very expensive computationally and there tends to be only a small number of experiments conducted which might bias the scenarios developed. Ultimately, simulations to a resolution of 1km are currently possible (Gero & Pitman 2006) but how reliable these approaches might be in future climate projection are not known.

## **ii. How do we obtain more confident projections?**

In the past, the convention was to reduce uncertainty in climate projection by using as many climate models as possible (Cubash et al. 2001). In part this was an attempt to maximise the chances that model uncertainty was sampled, and in part it was due to there being no agreed way objectively to omit a specific climate model. Attempts to provide metrics that quantify climate model skill have been developed. Johns et al. (2006), for example, used a simple weighted non-dimensional index of root-mean-square errors compared to present-day climatological means (based on Murphy et al. 2004). Monthly, seasonal and annual data were used for a range of simulated quantities, and a skill metric, the 'Climate Prediction Index' was presented. Other measures of skill have been suggested by Watterson (1996), Taylor (2001), Knutti et al. (2006), Piani et al. (2005) and Shukla et al. (2006) but tend, when implemented, to use monthly to annual timescale data; sometimes over ensemble means of climate models with several realisations.

Perkins et al. (2007) introduced one metric that assessed climate models by comparing

the observed and modeled distribution of a variable using daily data. Probability density functions (PDFs) were calculated for each observed and modeled dataset to calculate the probability of each event in the distribution occurring, not just at a priori points, such as the mean. The metric then compares the observed and simulated probabilities at each magnitude to give an overall performance score for each climate model. This procedure was performed using daily data, region-by-region for precipitation, minimum temperature and maximum temperature. Perkins et al. (2007) ranked the AR4 models using the PDF-weighted skill score demonstrating considerable variation among the AR4 models over regional Australia with MIROC-M, CSIRO and MRI overall performing best. Table 1 shows the top eight performing models over Australia based on their simulation of daily rainfall, maximum and minimum temperature.

There are other approaches to selecting climate models for regional projections. A method developed in Australia by Whetton et al. (1996) and used by CSIRO (1992, 1996, 2005) selects climate models based on their capacity to capture the observed patterns of temperature, mean sea level pressure and rainfall via root mean squared error and pattern correlation statistics. Models were omitted based on demerit points exceeding a pre-defined threshold. This approach is probably reliable if the changes in mean climate are required. This is sufficient for most purposes but as daily data become available (e.g. Perkins et al. 2007) and as the focus moves increasingly to how extremes on daily timescales might change, other approaches that evaluate the capacity of models beyond their simulation of the mean are required.

## **(iii) What about extremes?**

While climate models were developed to simulate large spatial scales on longer (monthly, seasonal, annual) time scales, the impact of global warming is likely to be

**Table 1: Ranking of climate models for  $P$ ,  $T_{MAX}$  and  $T_{MIN}$  over Australia.**

	P	Rank	$T_{MAX}$	Rank	$T_{MIN}$	Rank	Overall	Rank
MIROC-m	0.77	5	0.87	3	0.84	5	0.83	1
CSIRO	0.73	7	0.80	6	0.88	2	0.80	2
ECHO-G	0.83	3	0.87	2	0.69	12	0.80	3
IPSL	0.65	12	0.85	4	0.83	7	0.78	4
MRI	0.65	11	0.78	8	0.86	4	0.76	5
GISS AOM	0.64	13	0.78	7	0.83	8	0.75	6
FGOALS	0.70	9	0.81	5	0.69	13	0.73	7
CGCM-I	0.60	14	0.68	10	0.86	3	0.71	8

*MIROC-m: Centre for Climate System Research, University of Tokyo; National Institute for Environmental Studies; Frontier Research Centre for Global Change; CSIRO: Australian Commonwealth Scientific and Research Organization; ECHO-G: Max Planck Institut für Meteorologie; IPSL: Institut Pierre Simon Laplace; MRI: Japan Meteorological Agency; GISS-AOM: Goddard Institute of Space Studies (NASA); FGOALS: Institute of Atmospheric Physics, Chinese Academy of Sciences; CGCM-I: Canadian Centre for Climate Modeling and Analysis.*

realised at finer spatial and temporal scales. Climate on timescales of days has a direct impact on human health (Trigo et al. 2005) and human activities (e.g. agriculture, Luo et al. 2005) and changes in parts of a modeled distribution other than the mean (e.g. the tails) are likely to affect humans, natural ecosystems, agricultural crops and so on, more than changes in the mean (Colombo et al. 1999; Easterling et al. 2000; Katz & Brown 1992). There are mixed views as to the relation between projected changes in mean and the change in extremes. Mearns et al. (1984), Mearns et al. (1990), Katz and Brown (1992), Hennessy and Pittock (1995), Colombo et al. (1999) and Meehl et al. (2000) suggest that extremes might change more than indicated by a change in the mean. Some studies have looked at a sequence of extreme events, rather than a single threshold. For example, Hennessy and Pittock (1995) noted that if mean temperature increased by 3°C, the probability of 5 consecutive days above 35°C increased five-fold. Important advances have been achieved recently by, for example, Alexander et al. (2006) using the statistics proposed by Frich et al. (2002) that explore changes in the probability of specific climate events. In contrast, Kharin and Zwiers (2005) found that warm extremes change at a similar rate as mean temperature

while cool extremes change at a faster rate in a warming world. In all studies, PDFs shift towards the right, that is, the probability of warmer events increased and cooler events decreased. Disagreement stems from whether the shape of the PDF changes. There is also disagreement about the effect of a change in mean precipitation on extreme precipitation. Yonetani and Gordon (2001) conclude that increases (decreases) in mean precipitation occur in the same regions where there are extremes of large (small) annual precipitation. However, Kharin and Zwiers (2005) conclude that changes in extreme precipitation are substantially larger than the mean, and increase by a factor of two by the end of the 21st Century.

There are, therefore, a variety of ways to downscale, and a variety of ways to select climate models in order to provide regional scale projections of climate into the future. We provide one set of projections below as an indication of what is now achievable. This is not intended as the projections to use, rather this is intended to illustrate results from the best climate models of what we might expect over Australia.

### Recent projections

The approach by Perkins et al. (2007) provides an objective basis to determine those AR4 models that have clear skill in

simulating the PDFs of temperature and rainfall over all regions of Australia. Using this approach, allows us to omit inferior models from any multi-model ensemble and therefore explore how the better models project changes in climate over Australia. Fundamental to this approach, is an assertion that a model that is able to simulate the PDF of a variable well for the 20th century is more likely to be able to simulate a future PDF. Clearly, we cannot prove this assertion because we cannot know the future perfectly. However, consider a model that has a high level of skill in simulating the current PDF of daily maximum temperature. This model must be able to simulate the drivers and associated feedbacks for the current climate well. To simulate the observed PDF, the model must capture, at a daily timescale, the interactions between the surface, boundary layer, clouds and radiation well, else the PDF would be biased towards high values (too little soil moisture, too little evaporation, or too little cloud) or low values (too much surface moisture, high evaporation and associated cloud leading to too little radiation). It is difficult to imagine a model capturing the observed PDF of maximum daily temperature with a high degree of skill fortuitously. Now, imagine the PDF for maximum temperature for 2050. There will be a considerable overlap between this future PDF and the current PDF. Within this region where the two PDFs overlap is a region of physical and biophysical climate-space where the model has already demonstrated that it can capture the processes and feedbacks. The demonstration that a model has skill in this overlap region gives us confidence that it can capture these processes and feedbacks in the future. As the change in the PDF increases such that the overlap is reduced, our confidence might decline, but Earth would be uninhabitable well before this overlap becomes negligible. In the following scenarios, daily climate model data over

Australia for  $P$ ,  $T_{\text{MIN}}$  and  $T_{\text{MAX}}$  were taken from the IPCC AR4 data archive ([http://www.pcmdi.llnl.gov/ipcc/about\\_ipcc.php](http://www.pcmdi.llnl.gov/ipcc/about_ipcc.php)). Data from 1981-2000 from the Climate of the Twentieth Century simulations were used as the control (these are fully discussed in Perkins et al. 2007). In this paper, we also use results from the B1 (relatively low emissions) and A2 (relatively high emissions) scenarios for two time periods: a 20-year time period from 2046-2065 (here after 2050) and a 20-year period from 2081-2100 (hereafter 2100). These time periods were chosen as they were common among all AR4 models. By using daily data we retain the maximum time resolution possible and necessary for studying the effects of extremes, and minimise the hiding of biases through averaging. Daily observed  $P$ ,  $T_{\text{MIN}}$  and  $T_{\text{MAX}}$  were obtained from the Australian Bureau of Meteorology (BOM) for the period 1981-2000. The use of observed data is fully discussed in Perkins et al. (2007).

In this paper, we use the skill scores obtained by Perkins et al. (2007) as the basis for omitting models from an assessment of the impact of increasing greenhouse gases over Australia. We omit models based on a threshold of 0.8. The choice of these was subjective, balancing the desire to only include those climate models with demonstrated skill, while recognising that the sample size of models needs to be kept reasonable. Had we chosen a skill score of 0.6 virtually no models would be excluded while 0.9 would mean virtually no models were included.

## Simulation of Mean Changes over Australia

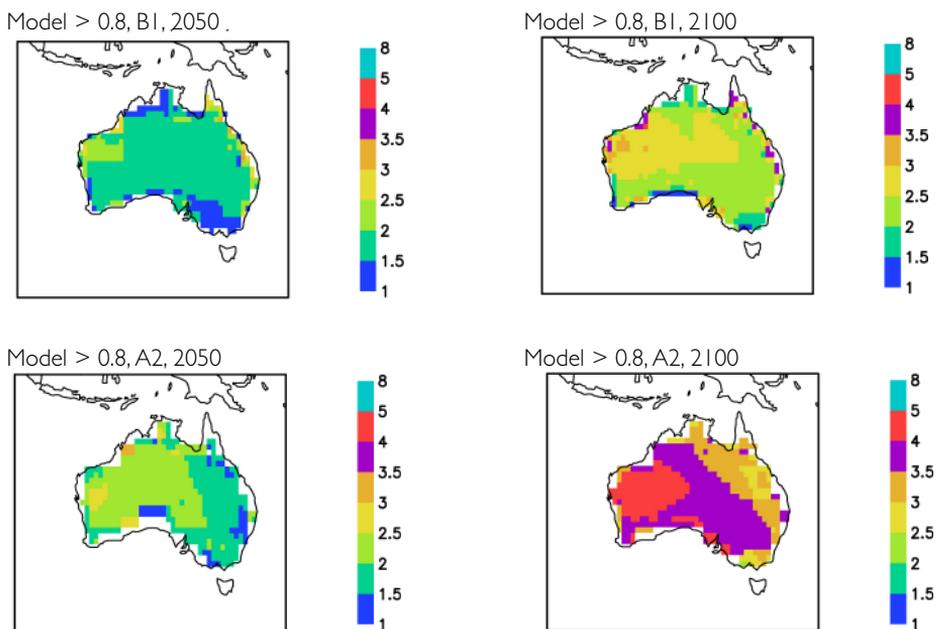
### Maximum temperature

Figure 5 shows the simulations by the AR4 climate models of the mean change in  $T_{\text{MAX}}$  over Australia for the B1 and A2 emission scenarios for 2050 and 2100 (only models with skill-scores > 0.8 are included).

Figure 5 shows that the amount of warming in  $T_{MAX}$  is quite consistent between the B1 (low) and A2 (high) emission scenarios by 2050. Warming is mainly constrained to less than  $2^{\circ}\text{C}$  under the B1 scenario and less than  $2.5^{\circ}\text{C}$  in the A2 scenario. This might sound quite small, but this is the warming in the daily maximum temperature

2050 might be worrisome but these have to be combined with increasing urban heat island effects and interactions between this, global warming and urban air quality. Specifically, estimates of the vulnerability of human populations to environmental change cannot be treated in isolation of the interactions between forcing factors.

**Figure 5: Change in the annually averaged daily maximum temperature ( $^{\circ}\text{C}$ ) simulated by AR4 models with skill scores  $> 0.8$  for (top left) the B1 emission scenarios in 2050, (top right) the B1 emission scenarios in 2100; (bottom left) the A2 emission scenarios in 2050, (bottom right) the A2 emission scenarios in 2100.**



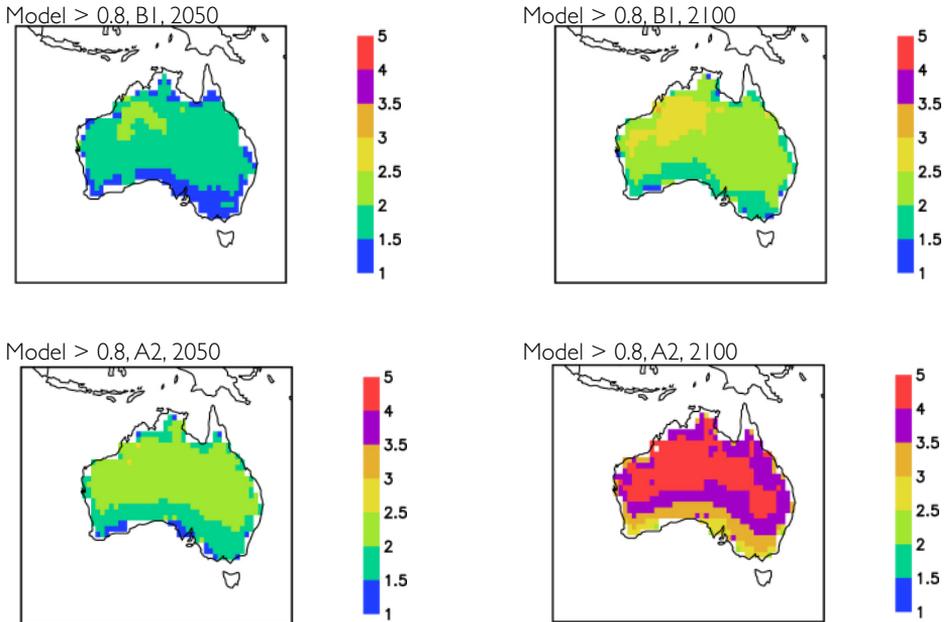
rather than the mean. By 2100, warming under the B1 scenario is generally less than  $3^{\circ}\text{C}$  and is mainly less than  $2.5^{\circ}\text{C}$  over the main population centres. The warming under the high emissions scenario is clearly more dramatic with much of Australia warming by more than  $3.5^{\circ}\text{C}$  and most population centres warming by about  $3^{\circ}\text{C}$ . A very similar set of results can be obtained for  $T_{MIN}$  (Figure 6). Recognising that increases in  $T_{MIN}$  appears to affect human mortality, increases of  $\sim 2^{\circ}\text{C}$  by

### Precipitation (P)

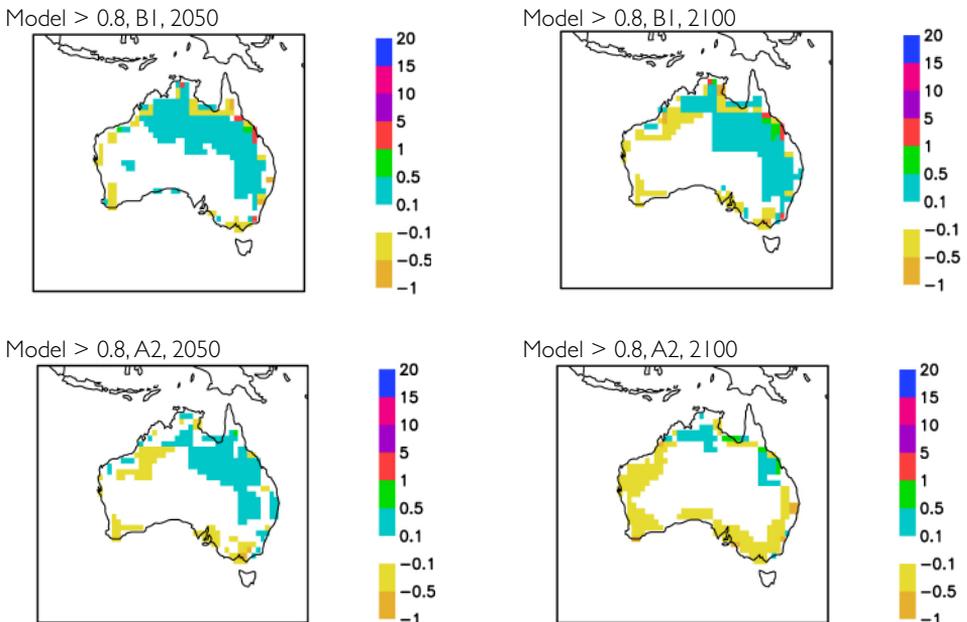
Figure 7 shows the projected changes in rainfall from those AR4 models with regional skill exceeding 0.8 over Australia (Perkins et al. 2007).

There are two common results to all scenarios and all time periods. First, the models simulate increasing rainfall over the tropics and eastern region of Australia until emissions become very high around 2100. This increase in rainfall is not very large - ranging from 0.1-0.5 mm d<sup>-1</sup>. Second, there is an emerging result of reduced coastal rainfall. Under low emissions (2050), this reduced

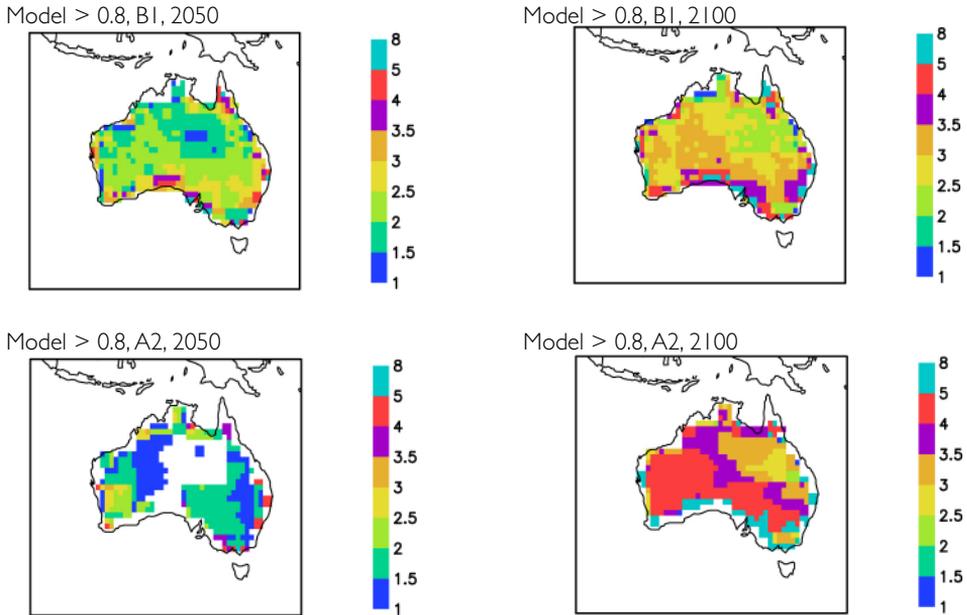
**Figure 6:** Change in the annually averaged daily minimum temperature (°C) simulated by AR4 models with skill scores > 0.8 for (top left) the B1 emission scenarios in 2050, (top right) the B1 emission scenarios in 2100; (bottom left) the A2 emission scenarios in 2050, (bottom right) the A2 emission scenarios in 2100.



**Figure 7:** change in the annually averaged precipitation (mml/d) simulated AR4 models with skill scores > 0.8 for (top left) the B1 emission scenarios in 2050, (top right) the B1 emission scenarios in 2100; (bottom left) the A2 emission scenarios in 2050, (bottom right) the A2 emission scenarios in 2100.



**Figure 8: change at the 99.7th percentile for the daily maximum temperature (°C) simulated by AR4 models with skill scores > 0.8 for (top left) the B1 emission scenarios for 2050, (top right) the B1 emission scenarios in 2100; (bottom left) the A2 emission scenarios in 2050, (bottom right) the A2 emission scenarios in 2100.**



coastal rainfall is relatively heterogeneous, but intensified through to 2100. Under the high emissions, it is quite common in 2050, but intensifies strongly through to 2100. The 2100 (high emissions) future is confronting with small areas of rainfall increase over the tropics and large coastal areas of declining rainfall. Again, it is noteworthy that the actual amount of rainfall is not enormous (0.1-0.5 mm d<sup>-1</sup>, for each rain day), but increased drying of the surface due to evaporative demand coupled with reduced coastal rainfall is not an ideal scenario of an already water-limited continent with high coastal population densities.

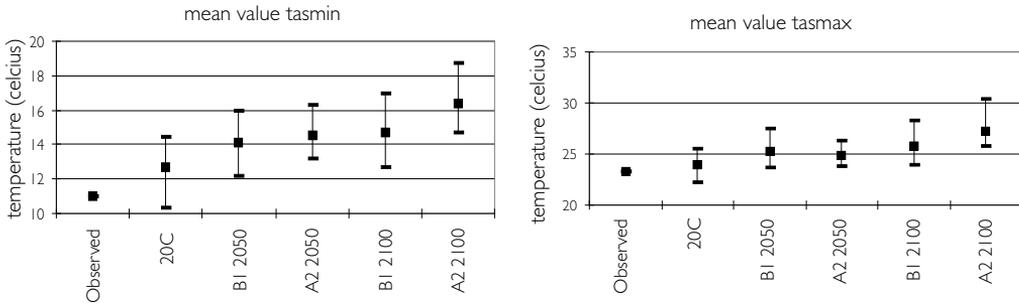
### Simulation of Changes in The Annual Event over Australia

Since these projections are based on daily climate model data, we can also explore the future behavior of extremes compared to the mean by analysing the change at the 99.7th percentile for T<sub>MAX</sub> from the AR4 models

(approximately the annual event). We can, for example, explore whether the changes in the annual return for T<sub>MAX</sub> is larger than the change in the mean amongst those climate models with strong 20th century skill scores.

Figure 8 shows the change at the 99.7th percentile for T<sub>MAX</sub> for the B1 emission scenario (this can be compared with Figure 2 for the mean). While the mean warmed mostly by 2050 by 1.5-2°C, the 99.7th percentile warms mostly by 2.0-2.5°C. This 0.5°C difference between the mean and the 99.7th percentile warming also occurs in the all-model ensemble by 2100. Figure 8 shows the difference between the all-model ensemble, and the average from just the models with skill scores exceeding 0.8. In contrast to the mean (Figure 2) where the better models projected more warming, the 99.7th percentile generally increases, but over Western Australia the best models simulate a smaller increase at the 99.7th percentile. Under the A2 scenario (Figure 9) an extra 0.5°C-1.0°C of warming occurs at the 99.7th

**Figure 9:** The observed and simulated mean  $T_{MIN}$  and  $T_{MAX}$  ( $^{\circ}C$ ) for a  $10^{\circ} \times 10^{\circ}$  region including Sydney. The black square represents the ensemble mean of all AR4 models with a skill score  $> 0.8$ . The first point is the current observed, followed by the simulation by the models of the 20th Century climate. Then, results for BI 2050, A2 2050, BI 2100 and A2 2100 are shown.

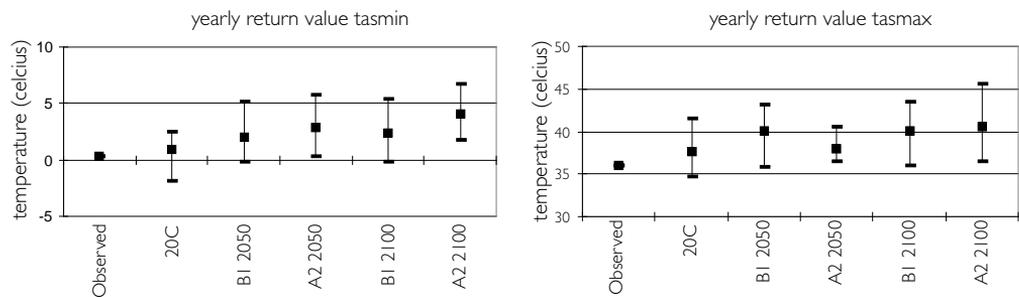


percentile compared to the mean. However, the ensemble of better models (Figure 9) generally shows considerably less warming than the all-model ensemble. The main exception to this is over Victoria in 2100 where the better models project a larger change in  $T_{MAX}$  than the all-model average. Note the projected warming in Figure 9 that exceeds  $5.0^{\circ}C$  over Western Australia is due entirely to weak models and is absent in Figure 9.

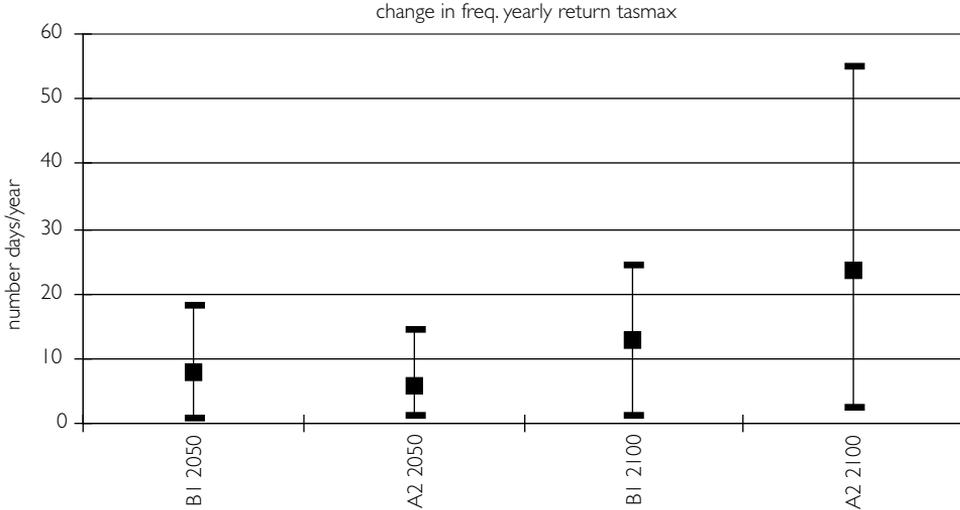
Figure 8 highlights a significant result that while the warming at the 99.7th percentile is higher than the mean (Figure 5) it is not generally substantially warmer. Over most of the continent, an extra  $\sim 1^{\circ}C$  is simulated, although there appears to be substantially more warming simulated along the southern coast of Australia at the 99.7th percentile.

This result is probably affected by the drying shown earlier, in that drying tends to reduce evaporation. Around the coastline, and associated with the population centers, Figure 8 points to  $3-5^{\circ}C$  of warming by 2100 under low emissions and  $5-8^{\circ}C$  by 2100 under high emissions. There are regions of  $3-5^{\circ}C$  warming by 2050 around the coasts in both the low and high emission scenarios. To reiterate, this is on the average hottest day of the year and represents a confronting scenario for heat susceptible systems. Given we are, in the best case, largely committed to warming at the low end of emissions through to 2050, Figure 8 (low emissions, 2050) represents the kind of future that we have to strive very hard to achieve through emission reductions and is probably unattainable.

**Figure 10:** The observed and simulated 99.7th percentile for  $T_{MIN}$  and  $T_{MAX}$  ( $^{\circ}C$ ) for a  $10^{\circ} \times 10^{\circ}$  region including Sydney. The black square represents the ensemble mean of all AR4 models with a skill score higher than 0.8. The first point is the current observed, followed by the simulation by the models of the 20th Century climate. Then, results for BI 2050, A2 2050, BI 2100 and A2 2100 are shown.



**Figure 11: The frequency of the currently observed 99.7th percentile of  $T_{MAX}$  ( $^{\circ}C$ ) in the future. The black square represents the ensemble mean and the thin bars show the range of temperatures simulated within an ensemble for each of 2050 B1, 2050 A2, 2100 B1, 2100 A2. Only models with skill scores > 0.8 are included.**



Our projections approach, using daily data and a probabilistic framework allows us to isolate key regions and explore these results in more detail. Figure 9 shows, for a  $10^{\circ}x10^{\circ}$  region encompassing Sydney, the mean and range of projections for  $T_{MAX}$ .

Figure 9 shows, for  $T_{MIN}$  and  $T_{MAX}$ , the annual mean result while Figure 10 shows the annual return value. First, in the case of the results for the 20th century climate, the mean of the ensemble for both the mean and the annual return value are close to the observed, supporting Cubasch et al.'s (2001) recommendation to use multi-model ensembles where possible. In terms of the mean,  $T_{MAX}$  is simulated better by the best models than  $T_{MIN}$  where there remains a systematic bias of  $\sim 2^{\circ}C$ . The thin bars on each figure represent the range of the results from the members of each ensemble. First, as the levels of greenhouse gases are increased, the amount of warming increased, thus there is a gradient from B1 to A2 and from 2050 to 2100. Second, the range of projections highlighted by the error bars is similar across the range of simulations and is similar for  $T_{MIN}$  and  $T_{MAX}$ . The bars provide an estimate of the range of projections simulated by these

well-performing models. The amount of warming in the mean is confronting by 2100 under high emissions but may be adaptable to under low emissions through to 2100.

The change at the 99.7th percentile shows similar results, over this region, to the change in the mean. The models capture the observed  $T_{MIN}$  and  $T_{MAX}$  well and simulate warming in both variables. The actual increase at the 99.7th percentile is similar, in this region to a change in the mean. This brings us to a confronting question. If the increase in the mean is 'merely' a few degrees, and the increase at the 99.7th percentile in  $T_{MIN}$  and  $T_{MAX}$  is only a few degrees, why are we worried about climate change and human-health? There are several answers to this question. First, a small increase in temperature need not generate a small change in terms of human health (that is, this relationship is non-linear). Second, a 'few degrees' is a lot on the daily maximum or minimum values. Third, Figure 11 shows the change in the frequency of the current 99.7th percentile value. If you imagine the average hottest day of the year (about  $36^{\circ}C$  in this region), Figure 10 suggests this might increase to  $39^{\circ}C$  by 2100. It follows therefore that more rare temperature extremes will

occur more frequently as the distribution of temperatures is shifted towards higher values. It also follows that the frequency of the current 99.7th percentile will occur more frequently in the future, that is, more than once per year. Figure 11 supports this by showing the change in the frequency of the temperature that currently occurs once per year. Taking the average over those models with demonstrated skill, this 'once per year' even becomes 8-9 times per year by 2050, 12 times per year by 2100 under low emissions and 23 times per year under high emissions. This is quite a confronting result with major implications for health, power consumption and indeed water use, biodiversity and fire risk. However, Figure 11 is undermined by very considerable uncertainty within the climate models. Some of those models demonstrated as skilful for the 20th century simulate very different changes in the frequency of the annual extreme than others. The range of the error bars highlights this with one skilful climate model simulating no change in the frequency of the 99.7th percentile from the present day, until the high emissions scenario for 2100. Other models, with comparable skill over the 20th century simulate 15-25 days of this extreme. Under the high emission scenario (2100) the results from these models ranges from 3-55 days per year experiencing the current annual extreme.

The challenge, for climate modellers, is no longer to be able to simulate the basic climate of large regions; this is already possible (Randall et al. 2007). The challenge is how to reduce the uncertainty in model projections of quantities such as temperature extremes, which are by definition rare and yet have a disproportional impact on humans, flora and fauna. Reducing the projected range in Figure 11 is clearly important, but no strategy to achieve this is presently available bar the on-going incremental improvements in climate models.

## Discussion and Summary

The science that underpins the theory of global warming is convincing and robust. The Earth is warming due primarily to the release of greenhouse gases through industrial activity and land use change. While alternative explanations have been proposed, these only survive in the popular press and not in the scientific literature. The issue is no longer whether global warming is 'true' or whether the greenhouse effect is 'real' and acerbated by human activity, rather the issue is how much the Earth will warm in the future, what other changes might take place and how quickly will these changes occur. These issues need to be considered in the context of what to then do about global warming. This is, of course, a substantially more challenging issue than the science.

There are close to 20 climate models available through the IPCC. These have each conducted several experiments to consider various emission scenarios and have conducted each experiment several times. The multiple Terabyte data store that comprise these model data is somewhat confronting to an impacts modeller wanting to know what is going to happen in the future to a few variables that affect their system. Our recommendations, to potential users of climate models, are therefore as follows:

1. select a sample of the climate models objectively. If your system is sensitive to temperature and rainfall, Table 1 would give you a reasonable guide to those models to use *over Australia*. Table 1 tells you nothing of value for other regions. Most probably, other variables or other regions will be needed and our strong advice is to determine those variables that most strongly affect your system and evaluate the available climate models against those explicit variables. We strongly

advise that this should be done, if possible, on daily time scales. This is not always possible of course, but using something like the Perkins et al. (2007) approach provides a strong sense of those models with genuine skill. If your interests are in data that are sequential (number of days in a row with rain, number of days in a row above a specific temperature and so on) we recommend the work of Alexander et al. (2006) to you. If you do not like the Perkins et al. (2007) or Alexander et al. (2006) approaches then think through a suitable means of systematically and objectively choosing those climate models to use. We strongly advise against simply choosing models on the basis of easy availability.

2. Downscale the data from the climate model intelligently. This can be statistical or dynamical downscaling. If you do not know how to do this collaborate with groups that do (CSIRO, Bureau of Meteorology and several Australian university groups have this capacity).
3. Use more than one climate model and more than one realisation from each climate model to sample uncertainty. Ideally, use enough models and enough realisations to express the results from your work in terms of probabilities. It might be appropriate to calculate ensemble means from a large sample of climate models if an objective selection of those models has been made, but (for example) Figures 10 and 11 show that an ensemble mean might not be a good reflection of the future.
4. Global warming is by no means the only changing environmental

variable (Vörösmarty et al. 2000). Using a vulnerability approach to exploring the sensitivity of a system to external forcing is probably sensible. For example, Tuvalu is very worried about sea level rise due to global warming. However, it is also vulnerable to storm surges associated with cyclones. The perfect plan to protect Tuvalu from sea level rise, implemented on timescales associated with global warming, could make the island more vulnerable to storm surges than necessary as smaller adaptations might be easy and quick to put in place. It is, in summary, foolish to keep your eye on just one emerging threat, however serious, at the expense of a total-system approach (Bravo de Guenni et al. 2004).

In summary, there are now climate models with significant and useful skill for impacts assessment. They require careful choosing and validation and then skilful downscaling to be directly useful to most impacts researchers. These models can now be used to provide a suite of information that allows impacts modellers access to data that is probably more useful than the traditional means of temperature, or rainfall, that have been used in the past. However, the science of climate change and climate modelling is developing very quickly, which makes keeping up with this area challenging. The building of bridges between the climate science community and the impacts community is a clear national priority. The Australian Research Council's Research Network for Earth System Science has a suite of initiatives to try to bridge the chasm between communities and we welcome suggestions on how to further these objectives (see [www.arcness.mq.edu.au](http://www.arcness.mq.edu.au)).

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Correspondence to:

A.J. Pitman  
Climate Change Research Centre  
Red Centre Building  
The University of New South Wales  
Sydney, NSW, 2052  
AUSTRALIA  
Email: a.pitman@unsw.edu.au

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