The Centre for Australian Weather and Climate Research
A partnership between CSIRO and the Bureau of Meteorology

Methods for producing extreme temperature projections for Australia

Kevin Hennessy, John Clarke and Jim Ricketts

CAWCR Technical Report No. 038

July 2011

www.cawcr.gov.au

Methods for producing extreme temperature projections for Australia

Kevin Hennessy, John Clarke and Jim Ricketts

The Centre for Australian Weather and Climate Research
- a partnership between CSIRO and the Bureau of Meteorology

CAWCR Technical Report No. 038

July 2011

ISSN: 1836-019X

National Library of Australia Cataloguing-in-Publication entry

Author: Hennessy, K., Clarke, J. and Ricketts, J.

Title: Methods for producing extreme temperature projections for Australia

ISBN: 978-1-921826-46-7

Series: CAWCR technical report; 38.

Notes: Included bibliography references and index.

Subjects: Environmental monitoring--Australia

Climatic changes--Australia--Measurement.

Climatic changes--Research--Australia.

Dewey Number: 551.5

Enquiries should be addressed to:

Kevin Hennessy
CSIRO Marine and Atmospheric Research
Private bag 1
Aspendale, 3195, Victoria
Australia
Kevin.Hennessy@csiro.au

Reviewers

Tony Rafter (CSIRO)

Sarah Perkins (CSIRO)

Bryson Bates (CSIRO)

Copyright and Disclaimer

CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The world has warmed over the past century. This has been associated with an increase in hot days and warm nights, and a reduction in cool days and cold nights. Climate projections for the 21st century indicate further warming and changes in extreme temperatures. However, there are many ways to estimate these changes in extremes.

This report reviews and assesses a variety of approaches for producing extreme daily temperature projections, particularly in Australia. A preferred method is selected and projections are developed for various years and emission scenarios:

- 2030: scenario A1B
- 2050: scenarios B1, A1B, A1FI
- 2070: scenarios B1, A1B, A1FI

A variety of threshold temperatures is considered at over 100 Australian sites:

- Maximum temperature over 30 to 45^{o}C, in 1^{o}C increments
- Minimum temperatures over 20 to 30^{o}C, in 1^{o}C increments
- Minimum temperatures below 0 to 10^{o}C, in 1^{o}C increments

Projected changes in frequency are calculated for (i) individual days and (ii) 3-5 consecutive days, i.e. hot spells and cold spells. All results are tabulated in Excel spreadsheets (http://www.climatechangeinaustralia.gov.au/resources.php) and sample results are shown in this report.

1 INTRODUCTION

The main purpose of this report is to review and assess the approaches used for producing extreme daily temperature projections, particularly in Australia. This may inform the selection of methods for different purposes.

Section 2 summarises the current evidence for global warming. Section 3 describes the known causes of global warming, both natural and anthropogenic. Section 4 deals with observed trends in extreme temperature. Section 5 looks at annual and seasonal mean temperature projections for Australia. Section 6 describes methods for extreme temperatures projections and examples of where these methods have been used. Section 7 summarises the pros and cons of each method makes some recommendations.

2 EVIDENCE FOR GLOBAL WARMING

There is unequivocal evidence for global warming over the past century. NASA, NOAA and the UK Hadley Centre have each produced global near-surface temperature records from 1880 to present. These all show a warming from 1910 to 1940, followed by a slight cooling in the 1940s, a levelling off in the 1950s and 1960s, then another warming from the 1970s onward. Two of the three temperature records have 2005 as the warmest year, while the third has 1998 slightly warmer than 2005. The period 2000–2009 was the warmest decade in the instrumental record (Arndt et al., 2010). The NASA data are shown in Figure 1. Differences between the data sets reflect slightly different data coverage and underlying variability; the Hadley Centre data shows slightly greater variation associated with El Niño and does not include temperatures from the Arctic.

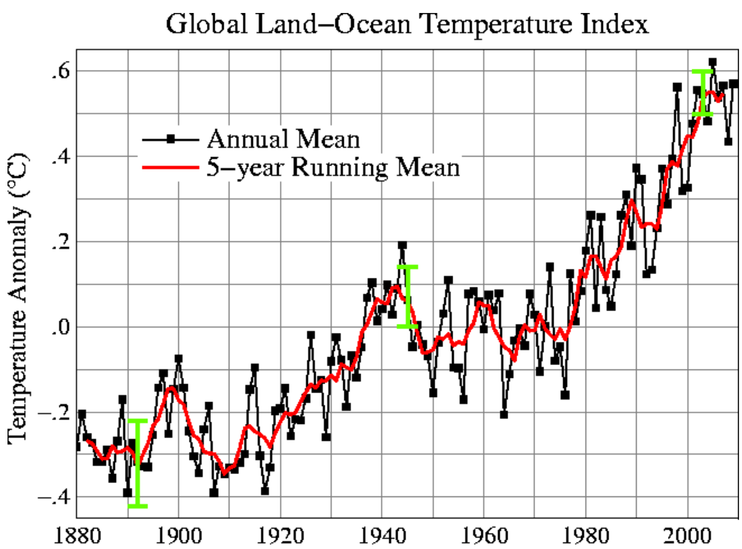


Fig. 1 Global mean land-ocean temperature anomalies, 1880 to present, relative to the base period 1951-1980. The dotted black line is the annual mean and the solid red line is the five-year mean. The green bars show uncertainty estimates. The warmest year is 2005 and the second-warmest is 2009. Source: http://data.giss.nasa.gov/gistemp/graphs.

The surface of the Earth has warmed by 0.74˚C (uncertainty range 0.56 to 0.92˚C) from 1906 to 2005 (IPCC, 2007). When the annual data are adjusted for short-term fluctuations due to El Niño and La Niña, the warming trend is even more obvious (Fawcett, 2008). This is a statistically significant climatic change and it is very unusual in the context of the past 1700 years (IPCC, 2007).

Data over the past decade provide little insight into long-term trends; the period is simply too short, so trend magnitudes are highly sensitive to the choice of start and end years. For example, there has been an insignificant warming trend over the period 1998 to 2008 (due largely to the strong El Niño in 1997 to 1998), but a statistically significant warming from 1999 to 2008 (Easterling and Wehner, 2009). Easterling and Wehner (2009) state:

'Numerous websites, blogs and articles in the media have claimed that the climate is no longer warming, and is now cooling.

Here we show that periods of no trend or even cooling of the globally averaged surface air temperature are found in the last 34 years of the observed record, and in climate model simulations of the 20th and 21st century forced with increasing greenhouse gases.

We show that the climate over the 21st century can and likely will produce periods of a decade or two where the globally averaged surface air temperature shows no trend or even slight cooling in the presence of longer-term warming'.

3 CAUSES OF GLOBAL WARMING

Variations in the Earth's climate over time are caused by natural internal processes, e.g. the El Niño Southern Oscillation (ENSO), as well as changes in external influences. External influences can be natural, such as volcanic activity and variations in solar radiation, or caused by human activity (anthropogenic), such as increases in greenhouse gases and aerosol emissions, ozone depletion and land use change (IPCC, 2007, FAQ 9.2).

The magnitude and pattern of natural internal processes can be estimated by studying observed variations in climate and through the use of climate models. These models are mathematical representations of the Earth's climate system based on well-established laws of physics, such as conservation of mass, energy and momentum.

Scientists have been unable to find any internal processes that explain 20th century global warming (Foster *et al*, 2010). However the effects of natural internal forcing can be seen in the instrumental record. For example, an exceptionally warm year occurred in 1998 as a result of a very strong El Niño event.

According to the IPCC (2007, FAQ 9.2), "Although natural internal climate processes, such as El Niño, can cause variations in global mean temperature for relatively short periods, analysis indicates that a large portion is due to external factors."

External forcing factors affect the radiation-energy balance of the planet. They directly influence the amount of solar radiation (energy) reaching the Earth, the amount of radiation reflected back out to space and the amount of radiation absorbed and re-emitted by the atmosphere and the Earth's surface (IPCC, 2007, FAQ 9.2).

Most volcanic eruptions have little effect on climate, but explosive eruptions can place large amounts of dust and sulphate aerosols into the stratosphere, where they can reflect sunlight back to space. This leads to cooling of the lower atmosphere (troposphere) and warming of the upper atmosphere (stratosphere) that peaks several months after an eruption and lasts a few years (IPCC, 2007). Volcanic eruptions alone would have caused a net cooling over the last 100 years, because there was stronger volcanic activity towards the end of the 20th century (IPCC, 2007, Ch 9).

Solar irradiance is directly affected by sunspot activity. Periods of low sunspot activity correspond with low Earth temperatures, such as the Oort Minimum (1010-1050), Wolf Minimum (1280-1340), Spörer Minimum (1420-1530) and Maunder Minimum (1675-1715) (Bryant, 1997). While the magnitude of solar changes is subject to uncertainty, it has been estimated that solar changes over the 20th century were far too small to explain observed global warming.

Over the period 1750-2005, the increase in radiative forcing from greenhouse gases (carbon dioxide, methane and nitrous oxide) was +2.3 Wm^{-2} (IPCC, 2007, Ch 2), about 20 times greater than that from solar irradiance. Aerosols (fine particles in the atmosphere) contributed a total radiative forcing of -1.2 Wm^{-2} while changes in the amount of sunlight reflected from the surface of the planet (due to changes in land-cover) had a forcing of -0.2 Wm^{-2}.

By studying both the observed climate and output from climate models, scientists have been able to estimate the contribution of different forcing factors to 20th century climate variability. Climate models are based on the fundamental physics and chemistry of the atmosphere, ocean and sea-ice system. Such modelling allows scientists to simulate "control" climates (where external forcing factors are held at fixed levels) as well as many different climate change experiments, such as doubling atmospheric carbon dioxide or changing solar radiation.

In the first half of the 20th century, increasing greenhouse gases, increasing solar radiation and a relative lack of volcanic activity all contributed to a rise in globally averaged temperature. During the 1950s and 1960s, global temperatures levelled off. Climate scientists have shown that this levelling off is most likely explained by an increase in aerosols as a result of increased industrialisation and from the eruption of Mt. Agung in 1963. Since the 1970s, increases in greenhouse gases have dominated over all other factors, and there has been a period of sustained warming (IPCC, 2007).

Greenhouse gas forcing alone during the past half century would likely have resulted in more warming than was physically observed if there had not been an offsetting cooling effect from aerosol and other forcings. The warming took place at a time when natural external forcing factors would likely have produced cooling, e.g. volcanic activity and changes in solar irradiance (IPCC, 2007).

In summary, scientists have looked very closely at all of the natural external forcing factors that have affected climate over the 20th century. Through these studies, they have been able to determine that none of these processes can fully explain the sustained rise in global temperature that has been observed. Rather, changes due to natural forcing have been superimposed on a background warming trend, and it is very likely (at least 90% likelihood) that most of the observed global warming since the mid 20th century is due to anthropogenic increases in greenhouse gases (IPCC, 2007).

4 EXTREME TEMPERATURE TRENDS

The IPCC (2007) states:

Changes in extremes of temperature are also consistent with warming of the climate. A widespread reduction in the number of frost days in mid-latitude regions, an increase in the number of warm extremes and a reduction in the number of daily cold extremes are observed in 70 to 75% of the land regions where data are available. The most marked changes are for cold (lowest 10%, based on 1961–1990) nights, which have become rarer over the 1951 to 2003 period. Warm (highest 10%) nights have become more frequent. Diurnal temperature range (the difference between day and night temperatures) decreased by 0.07°C per decade averaged over 1950 to 2004, but had little change from 1979 to 2004, as both maximum and minimum temperatures rose at similar rates. The record-breaking heat wave over western and central Europe in the summer of 2003 is an example of an exceptional recent extreme. That summer (June to August) was the hottest since comparable instrumental records began around 1780 (1.4°C above the previous warmest in 1807) and is very likely to have been the hottest since at least 1500.

Australian-average annual temperature have increased by 1ºC since 1910, and most of this warming has occurred since 1950 (Figure 2). The warmest year on record is 2005 and 2009 is the 2nd warmest (Australian Bureau of Meteorology, 2010a). From 1957 to 2009, the Australian average shows an increase in hot days (over 35°C) of 2.5 days/decade, an increase in very hot days (over 40°C) of 0.85 days/decade (Figure 3), a decrease in cold days (below 15°C) of 2.5 days/decade and a decrease in cold nights (below 5°C) of 2.4 nights/decade (Australian Bureau of Meteorology, 2010b).

The south-east Australian heatwave from 28 January to 7 February 2009 set many individual-day and multi-day records (Australian Bureau of Meteorology, 2009). This resulted in 374 excess deaths in Victoria over what would be expected (Vic DHS, 2009). The Victorian bushfires in early February 2009 killed 173 people, destroyed 2298 properties and cost $4.4 billion (Victorian Bushfires Royal Commission, 2010).

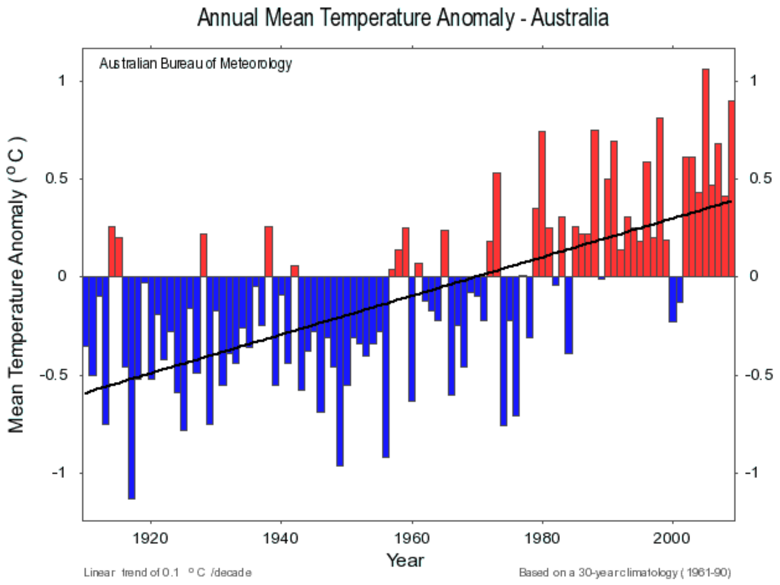


Fig. 2 Australian-average annual temperature anomalies for 1910-2009 relative to the average for the 1961-1990 period. Source: Australian Bureau of Meteorology.

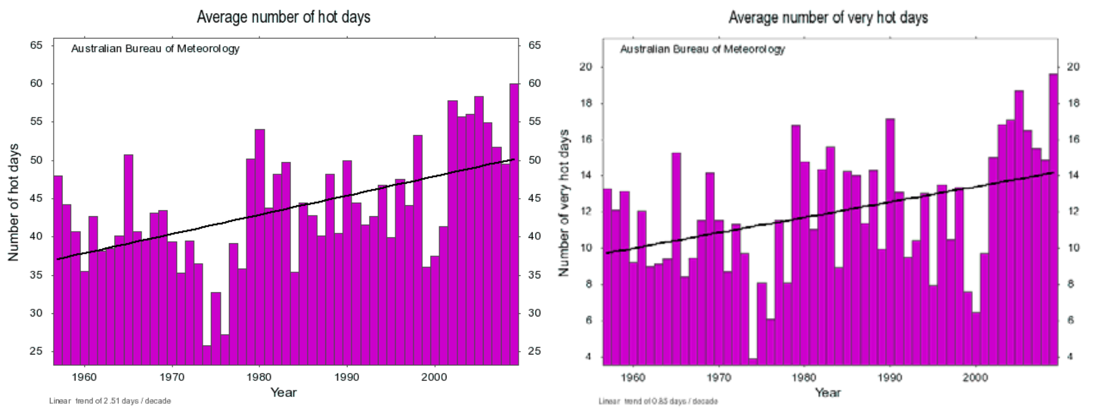


Fig. 3 Australian-average annual temperature number of hot days (over 35oC) and very hot days (over 40oC) from 1957-2009. Source: Australian Bureau of Meteorology.

The IPCC (2007) concluded that discernible human influences extend to continental-average temperatures and temperature extremes (IPCC, 2007). It is more likely than not (a likelihood of at least 50%) that human activities have increased the risk of heat waves (IPCC, 2007). Increases in mean and maximum temperature in Australia since 1950 have been mostly attributed to anthropogenic climate change (Karoly and Braganza, 2005).

Very few studies have focussed on the causes of local extreme weather events. However, the contribution of human influence to the European heatwave during August 2003 has been studied in some detail (Beniston, 2004; Schar *et al.*, 2004; Stott *et al.*, 2004). It is very likely (likelihood of at least 90%) that human influence had at least doubled the risk of exceeding the 2003 heatwave threshold (Stott *et al*., 2004).

While local temperature records continue to be broken every year, this does not mean that anthropogenic climate change is to blame since natural climate fluctuations can also cause weather records to be broken (Allen *et al.*, 2007). However, the weather events may have been made more likely by anthropogenic climate change – in other words the risk or probability of exceeding previous records can be increased by human activities. Matters are complicated by how “the risk of an event” is defined because a number of factors may have contributed to the sequence of events that led up to the event itself (Allen *et al.*, 2007), e.g. an extended drought.

5 ANNUAL AND SEASONAL MEAN TEMPERATURE PROJECTIONS

To provide a basis for exploring future climate change, 40 greenhouse gas and sulphate aerosol emission scenarios were prepared for the 21st century by the IPCC (2000), based on a variety of assumptions about demographic, economic and technological factors. For one of the main greenhouse gases, carbon dioxide (CO_2), emissions have been tracking above the middle of the IPCC range since 2005 (Figure 4).

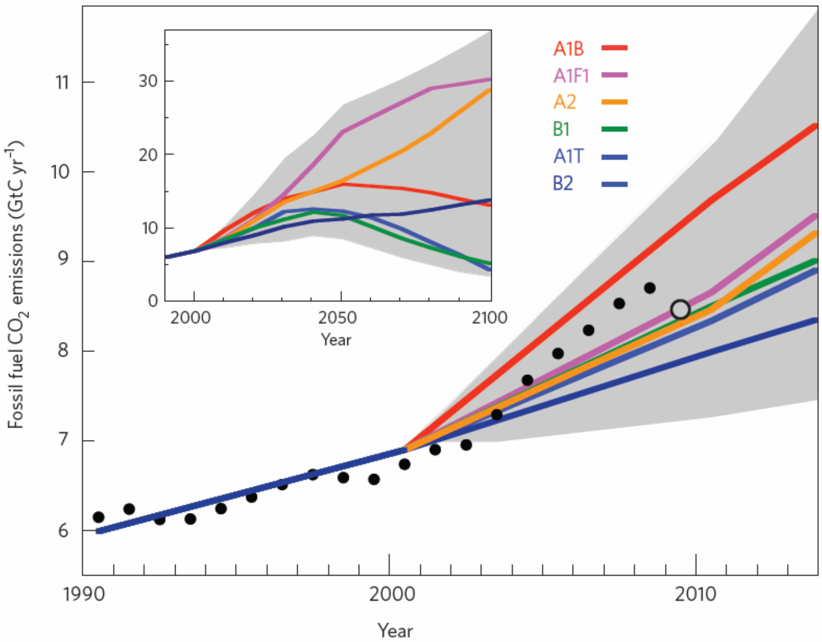


Fig. 4 CO_2 emissions (Gt/year) from 1990-2009 (black dots) compared with IPCC scenarios (grey shading shows the full range, while coloured lines show 6 “marker” scenarios). The open circle shows an estimate for 2009 which includes the effect of the global financial crisis. The inset plot shows IPCC emission scenarios from 1990-2100. Source: Manning *et al* (2010).

The future climate is strongly influenced by inherently uncertain factors, such as the magnitude and timing of El Niño events, so it is not possible to make definitive climate predictions for decades ahead. However, projections that account for uncertainties can be made by analysing the output of climate models and different emission scenarios. Projections of global average warming, relative to 1980-1999, are shown in Figure 5. Within each of the 23 simulations there is substantial variability from year to year, with an underlying trend. Between each simulation, there are differences in the rate of warming which reflect different climate sensitivities. The multi-model-mean warmings are shown in Table 1 for three future time periods.

Table 1 Global mean warming (^{o}C) from 23 climate change simulations for three future time periods, relative to 1980-1999, and three emission scenarios (A2, A1B and B1). Source: IPCC (2007) Table 10.5.

Scenario	2011-2030	2046-2065	2080-2099
A2	0.64	1.65	3.13
A1B	0.69	1.75	2.65
B1	0.66	1.29	1.79

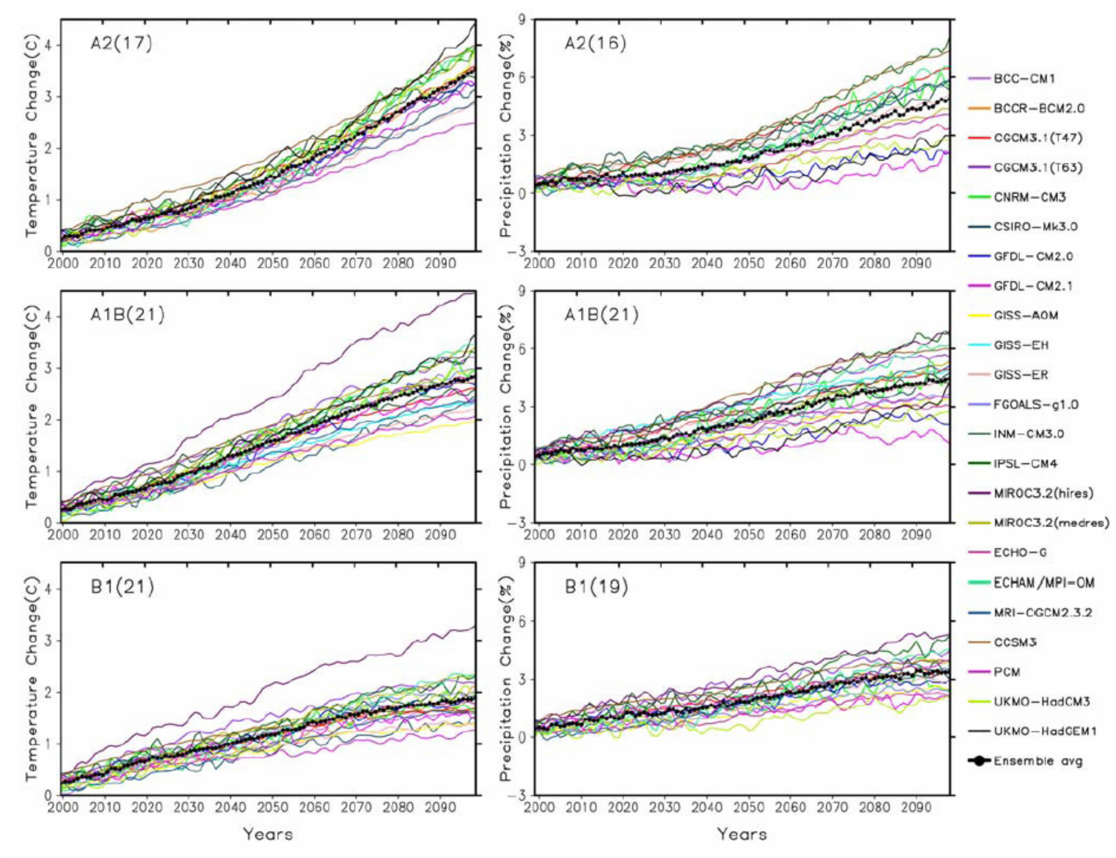
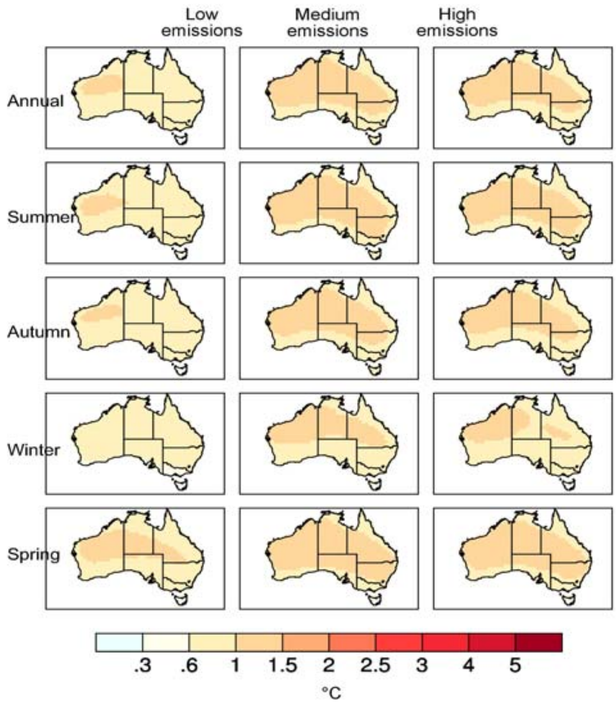


Fig. 5 Global average change in temperature and precipitation from 23 global climate models during the 21st century, relative to 1980-1999, for three emission scenarios (A2, A1B and B1). Source: IPCC (2007) Figure 10.5.

CSIRO has downloaded monthly temperature data from 23 global climate models from 1900-2100 for 3 emission scenarios (A1B, A2 and B2). Using these data, annual and seasonal mean temperature projections were developed for Australia for 2030, 2050 and 2070 (CSIRO and BoM, 2007).

Uncertainties in projected regional climate to 2030 are mostly due to differences between the results of the climate models rather than the different emissions scenarios. In this report, projections for 2030 are given for the IPCC's mid-range A1B emissions scenario while those for 2050 and 2070 are given for the IPCC's low B1 and high A1FI emissions scenarios (IPCC, 2000).

Projected changes in mean temperature for Australia are shown in Figure 6. By 2030, the warming is around 1.0°C (uncertainty range 0.6 to 1.5°C), relative to 1990. In 2070, for a low emission scenario (B1), the warming is around 1.8°C (uncertainty range 1.0 to 2.5°C). In 2070, for a high emission scenario (A1FI), the warming is around 3.4°C (uncertainty range 2.2 to 5°C). Least warming occurs in coastal areas and Tasmania. Maximum temperatures rise faster than minimum temperatures in the south, and converse in the north.



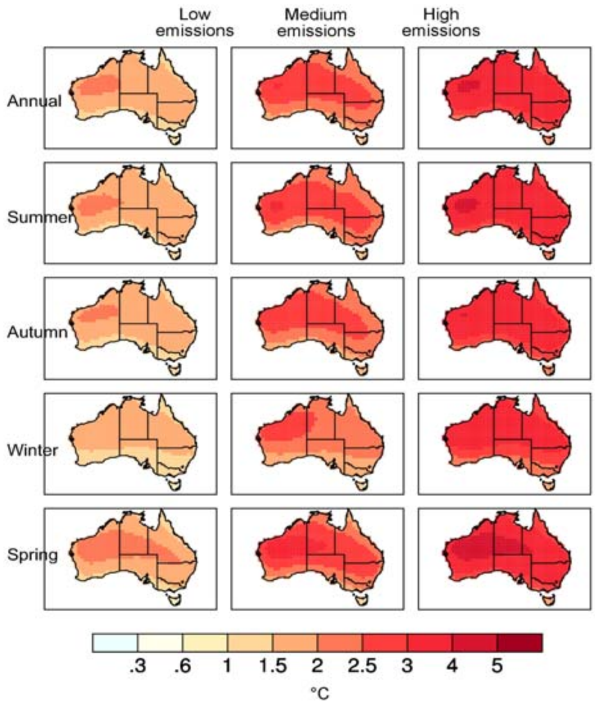


Fig. 6 50th percentile changes in annual and seasonal mean temperature for 2030 (upper panel) and 2070 (lower panel), relative to 1980-1999, for low (B1), medium (A1B) and high (A1FI) emission scenarios. Source: http://www.climatechangeinaustralia.gov.au/

6 REVIEW OF EXTREME DAILY TEMPERATURE PROJECTIONS

Table 2 reviews Australian studies from 1989 to 2010 in which extreme temperature projections have been provided. Most of the projections have come from CSIRO using relatively simple methods. These and other methods outlined in Table 2 are described in more detail below.

Table 2 Studies estimating climate change impacts on extreme temperatures in Australia.

Study	Focus	Method	Scenarios	Main results
Pittock and Hennessy (1989), Pittock and Whetton (1990a), Pittock and Evans (1990), Pittock and Allan (1990)	Climate change impacts on Victoria, NT, NSW, WA	Apply mean warming to observed daily data (no change in variance) and calculate threshold exceedance frequencies	CSIRO (1990) seasonal mean warming projections	More days over 35 C in summer and fewer days below 0 C in winter for mean warmings of 1, 2 and 3 C
Pittock and Whetton (1990b)	Climate change impacts on NSW	Theoretical threshold exceedance frequencies for 3 different mean temperatures and standard deviations, assuming daily temperatures are Normally distributed	Mean warmings of 1-5 C	Changes in frequency can be large for relatively small changes in mean temperature, especially when the variability is small and the average is close to the critical temperature of interest
Whetton et al (1992a, c), Evans et al (1992), Allan et al (1992)	Climate change impacts on Victoria and NSW, NT, WA	Assess projected changes in mean and standard deviation of daily temperature	CSIRO4 GCM 1xCO2 and 2xCO2	Change in mean is much larger than change in standard deviation
Whetton et al (1992b), Fowler et al (1992), Allan et al (1992), Suppiah et al (1992)	Climate change impacts on Victoria and NSW, NT and WA	Assess projected changes in mean and standard deviation of daily temperature	CSIRO9 GCM 1xCO2 and 2xCO2	Standard deviation decreases by about 20% for 2xCO2, but this has little effect on the frequency of extremes for mean warmings of up to 3 C
Mitchell et al (1994a, b, c)	Climate change impact on extreme daily temperatures in NSW, WA and NT	Apply mean warming to observed daily data (no change in variance) and calculate threshold exceedance frequencies	CSIRO (1992) seasonal mean warming projections for 2030	More summer days over 35 and 40 C and fewer winter days below 0 C
Hennessy and	Climate	Apply mean warming	CSIRO (1992)	More extremely hot

Pittock (1995)	change impact on extreme daily temperatures in Victoria	to observed daily data (no change in variance) and calculate threshold exceedance frequencies	seasonal mean warming projections	days and fewer extremely cold days
Whetton et al (1997), Whetton et al (2000a)	Climate change impact on extreme daily temperatures in Victoria and NSW	Assess projected changes in mean and standard deviation of daily temperature, and apply to observed temp data	DARLAM60 nested in CSIRO9 slab ocean GCM 1xCO2 and 2xCO2	Standard deviation of Tmax increases in DJF and JJA while Tmin decreases in DJF and JJA for 2xCO2. Maps show 2xCO2 frequency of days over 35 C and below 0 C, but this has little effect on the frequency of extremes for mean warming of up to 3 C
Hennessy et al (1998), Whetton et al (2000b), Walsh et al (2001)	Climate change impact on extreme daily temperatures in Victoria, NSW, Qld	Assess projected changes in extreme temperatures using raw DARLAM60 data	DARLAM60 nested in CSIRO9 coupled ocean-atmosphere GCM from 1961-2100	Little change in standard deviation of Tmax or Tmin. Maps and time series show changes in the frequency of summer days over 35 C and winter days below 0 C
Suppiah et al (1998)	Climate change impact on extreme daily temperatures in northern WA, Qld and NT	Apply mean warming to observed daily data (no change in variance) and calculate threshold exceedance frequencies.	CSIRO (1996) seasonal mean temperature projections for 2030	Table of projections for 2030 and 2070 for days over 35 and 40 C
Hennessy et al (2004 a, b), McInnes et al (2002)	Climate change impact on extreme daily temperatures in NSW, NT, SA	Apply mean warming to observed daily data (no change in variance) and calculate threshold exceedance frequencies.	CSIRO (2001) seasonal mean temperature projections	Table of projections for 2030 and 2070 for days and 3-5-day spells over 35 and 40 C
CSIRO and BoM (2007)	Climate change impact on extreme temperatures in Australia	Apply mean warming to observed daily data (no change in variance) and calculate threshold exceedance frequencies. For frost days, these results were compared with those using statistical downscaling (which includes changes in daily variability)	CSIRO and BoM (2007) seasonal mean Tmax and Tmin projections for 2030 and 2070	Table of projections for 2030 and 2070 for days over 35 C. Table of projections for days below 0 C in 2050. The mean warming method over-estimates the reduction in frost days because it doesn't account for the increase in variance

Hennessy et al (2008), Alexander and Arblaster (2009)	Projected changes in climate extremes over Australia	Analyse raw GCM data	IPCC AR4 GCMs	More extremely hot years (20-year return period). More warm nights (90^{th} percentile of Tmin), fewer frosts (below 0 C), and longer heatwave duration (period of at least 5 consecutive days with Tmax at least 5 C above the 1961-90 mean Tmax)
Perkins et al (2009)	1-in-20 year daily temperature extremes in Australia	GEV fitted to raw GCM data. GCMs selected based on ability to simulate observed mean climate, daily pdf and tails of distribution	IPCC AR4 GCMs (6 models for Tmax, 9 models for Tmin)	More extremely high temperatures and fewer extremely low temperatures. Results are sensitive to the selection of models, with more-reliable models giving smaller changes

Trend extrapolation

This method is very simple but it assumes that recent trends are likely to continue in future. This may be reasonable for components of the climate system that have high inertia, such as ocean temperatures, but changes may be non-linear, e.g. cyclic (Wilby et al., 2009). Trends are sensitive to the choice and length of record, and may be influenced by non-climatic inhomogeneities such as changes in instrumentation (Wilby et al., 2009). If data quality is good and the trend is based on about 30 years of recent data, it may be valid to extrapolate the trend for up to a decade. However, extrapolation is unreliable beyond a decade into the future due to decadal variability and the possibility of non-linear or abrupt changes.

Analysis of raw GCM or RCM data

If extreme temperatures are defined as upper or lower percentiles of daily temperature (e.g. 1^{st}, 5^{th}, 10^{th}, 90^{th}, 95^{th}, 99^{th} percentiles), then raw GCM or RCM data can be used. The first step is to calculate the percentile thresholds from the model data for some reference period in the 20^{th} century. The next step is to calculate the frequency of events below the lower thresholds or above the upper thresholds for selected periods in the 21^{st} century. This method is simple and works well for percentiles events and multi-year mean return periods (Perkins et al., 2009; Alexander and Arblaster, 2009). However, it is not suitable for actual temperature thresholds such as $0^{o}C$ or $40^{o}C$ due to biases in the raw data. While the availability of daily GCM is reasonably good (20 models with daily maximum and minimum temperature data for A1B and 16 for A2), RCM data are limited. GCM and RCM data have coarse spatial resolution.

Weather generators

Weather generators replicate statistical attributes of weather records, but do not reproduce actual sequences of observed events (Wilby et al., 2007). Most generators use rainfall models based on either Markov chains (Richardson, 1981; Hanson et al., 1994; Nicks and Gander, 1993) or empirical distributions of wet/dry spells (Semenov and Brooks, 1999), or Neyman-Scott rectangular pulses of rainfall (Kilsby et al., 2007). Secondary variables such as temperature, solar radiation and wind-speed are related to daily rainfall through regression equations (Wilby et al., 2009). Long time series can be generated, which is useful for estimating extreme events. These models tend to be complex with many parameters. Correlation coefficients between different climate variables are assumed to be constant over time, which may not be valid for future climate change. Weather generators have difficulty reproducing inter-annual variability (e.g. due to ENSO) and tropical weather phenomena such as monsoons and tropical cyclones.

Bias-corrected GCM or RCM data

While most methods involve adjustment of observed daily temperature data using change parameters from climate models, it is also possible to adjust climate model data using observed temperature parameters. This may be preferred when projected changes in annual and multi-year variability are considered important, e.g. changes in ENSO. Monthly climate model data have been bias-corrected by matching simulated and observed quantiles (Li et al., 2010), but this has not been attempted for daily data yet.

Extreme value theory

Extreme value theory, through the use of the Generalised Extreme Value (GEV) distribution, has been used extensively to examine climatic extremes at the global scale (e.g. Zwiers and Kharin, 1998; Kharin and Zwiers, 2000; Wehner, 2004; Kharin et al., 2005; Kharin et al., 2007) and over some continental regions (e.g. Semmler and Jacob, 2004; Fowler et al., 2007; Schaeffer et al., 2005; Rusticucci and Tencer, 2008; Perkins et al., 2009; Wehner et al., 2010; Fowler et al., 2010). A full description of the statistical model may be found in Coles (2001).

The GEV distribution has three parameters, location (μ), scale (σ), and shape (ξ). The three distributional sub-families are distinguished by ξ. In the limit as $\xi \rightarrow 0$, the GEV reduces to the Gumbel distribution, which exhibits exponential (light) tail decay; $\xi > 0$ leads to the Frechét distribution with polynomial (heavy) tail decay; $\xi < 0$ leads to the Weibull distribution, which has a finite upper endpoint. (Occasionally publications will refer to the shape parameter as being opposite in sign to the above; we have used the nomenclature from Coles (2001)). Two methods that are commonly used to estimate the parameters of the GEV distribution are L-moments (which is also closely related to probability-weighted moments) and maximum likelihood estimation (MLE) (Hosking, 1990, 1992; Zwiers and Kharin, 1998; Semmler and Jacob, 2004; Kharin and Zwiers, 2005; Kharin et al., 2005). The L-moments method assumes stationarity of annual extremes (i.e. a trend), making it inappropriate for extended periods of climatic data where the underlying mean or variability changes with time. Maximum likelihood can incorporate non-stationarity, however is less efficient for short samples (Kharin and Zwiers, 2005; Kharin et al., 2007). Further, Von Storch and Zwiers (1999) state that L-moments is more robust than maximum likelihood, particularly for shorter time series.

Prior to fitting the GEV distribution, maxima or minima (typically annual values) are extracted from the original sample to form an extreme value sample. Once the parameters of the GEV have been estimated, the resulting cumulative density function (F(X)) is inverted to estimate the return value with the given return period (T). For maxima extremes F(X) = 1 - 1/T, for minima extremes F(X) = 1/T. The 20-year return value for Tmax is F(X) = 0.95 and for Tmin is F(X) = 0.05.

Due to biases and poor spatial and temporal resolution in global and regional models, the extreme events simulated may not necessarily be of a realistic magnitude; however we are still able to examine the changes between a "baseline" and a "future" climate. Comparisons are also able to be performed between different observational climates. The outputs of extreme value analysis can be used to compare the changes in intensity of extreme events with a certain return period, or to relate changes in expected return period of a given magnitude.

Statistical downscaling

Mean change method

This is the simplest and most common approach used in Australia over the past 20 years (see Table 2). It requires observed daily temperature data and GCM or RCM seasonal mean changes in temperature. The method involves (1) calculating the present annual or seasonal mean number of days above/below a given threshold temperature using data for a BoM climate station over a specified reference period, (2) producing a time series of future daily temperature data by applying the seasonal mean warming for a future year (from various climate models) to observed daily temperature data, and (3) recalculating the annual or seasonal mean number of days above/below a given threshold temperature. This method assumes no change in daily temperature variability. Since changes in variability are often small, this assumption is fairly robust. However, if changes in variability are large, this assumption could bias the extreme temperature frequencies. Therefore, it is recommended that changes in variability are included in extreme temperature estimates.

Decile scaling method

This is a relatively simple method that includes projected changes in daily variability. It requires observed daily temperature data and model daily temperature data (Hennessy et al., 2005). There are four steps:

1. For each model, the regional warming values for each month are calculated for each decile (10^{th}, 20^{th}, 30^{th}, 40^{th}, 50^{th}, 60^{th}, 70^{th}, 80^{th}, 90^{th}) as well as the mean. These warming values are expressed as the linear regression of the regional temperature with the global annual mean temperature. Since CMIP3 climate models only archived time slices of daily data for 1981-2000, 2046-2065 & 2081-2100, these were used in the regression.

2. The simulated regional warming per degree of global warming for each decile is then scaled by the global warming for selected years and emissions scenarios. The global warming values can be taken from the multi-model ensemble in the IPCC 4^{th} Assessment Report or from individual climate models.

3. For each day in the observed dataset, the temperature values are modified depending on the decile in which each value falls. For example, if the value lies between the minimum and 1st decile value, it has the change for the 1^{st} decile added to its value.

4. An adjustment was applied in order to ensure that the change in the mean for each month was the same in the scaled observed time-series as the model output data. To do this, the change in monthly mean between the original observed data and the decile scaled data was calculated and subtracted from every day of the decile scaled data. The modelled monthly mean change values were then added to each day's data. This results in a monthly change value equal to that of the modelled data while maintaining the different perturbation dependent on the decile value of each daily value.

M-quantile method

This method modifies historical daily climate data based on a combination of median climate information from the models and historical trends in the distribution of climatic quantiles. Hence, daily historical climate data are transformed by both observed climate trends and model-derived projections (Crimp et al., 2002). The method includes temperature and rainfall. Major steps in this process include:

1. Trend detection: changes in the observed distribution of daily weather events (e.g. 10th, 50th and 90th percentile temperature and rainfall events) examined for individual months across the reference period;
2. Extrapolation of statistically significant trends out to the future period: data pre-transformation is used to ensure projections remain within range. Consequently, this method is not recommended for future periods beyond 2040;
3. Projection of changes in the 50th percentile values of temperature and rainfall, derived from the GCM scenarios: one way of doing this is to use a simple scaling approach;
4. Variations in other daily climate variables (e.g. evaporation, vapour pressure deficit and solar radiation) can be derived using a multiple regression approach driven by local historical interactions between temperature, rainfall and other variables.

Analogue method

This is a statistical method of weather classification, in which predictands are chosen by matching previous (i.e. analogous) situations to the current weather state (Crimp et al., 2010). Daily temperature and rainfall data have been generated across Australia through the selection of analogues using monthly or seasonal GCM data as predictors (Timbal et al., 2003; 2009). This approach assumes that there is often a strong statistical relationship between synoptic weather patterns and local climate variables at the surface. This is particularly true at mid-latitudes where the synoptic situation dominates daily values for rainfall and temperature, but the statistical relationships are not as strong in the tropics. This approach is well developed and can be applied to locations across most of Australia. A web-based tool is available at http://gale.ho.bom.gov.au/~elf/sdm_gui.html.

However, it is unclear whether values beyond those in the observed range can be simulated. For example, the method currently does not generate new high temperature extremes because it relies on past analogues. The method assumes that the current relationship between local and synoptic scales stays the same in the future, which may not be valid.

Non-homogeneous Hidden Markov Chain method (NHMM)

The NHMM uses weather classification schemes from large scale atmospheric circulation patterns and simulates the daily rainfall process depending on the circulation patterns (Charles et al., 1999). While many schemes of this type attempt to link the synoptic scale with the point scale, the NHMM determines the most distinct patterns in a multi-site climate rather than patterns in atmospheric circulation (Crimp et al., 2010). These distinct patterns may not represent potential future climates well. It is a very complex method.

State-Space modelling approach

The linear state-space modelling approach represents a generalisation of the multiple linear regression approach. It is similar to the NHMM approach but represents an improvement on this approach by allowing the latent state variables to evolve continuously and non-linearly over time (Crimp et al., 2010). Historical monthly statistics (e.g. median and proportion of zeros of climate variables) are determined from daily climate station data, and their relationship to GCM variables is calculated. The major steps in this process include:

1. Model parameter estimation. An automated procedure that selects statistically significant variables and decides which should be treated as non-linear terms or as fixed terms.
2. Extrapolation of monthly statistics out to a selected future period.

Currently, the method has only been tested using monthly rainfall and temperature data out to 20 years in the future. It is unclear whether practical constraints will impinge on the method when applying it to a broader range of climate variables (Crimp et al., 2010). It requires a large amount of observed data and is computer-intensive.

7 ASSESSMENT OF EXTREME TEMPERATURE PROJECTION METHODS

The pros and cons of the methods are summarised in Table 3. Criteria for selection of methods are shown in Table 4. Crimp et al (2010) proposed nine criteria, some of which are similar to those in Table 4:

1. Ease of implementation;
2. Transparency of method;
3. Degree of acceptance amongst the climate change data user community;
4. Internal consistency in approach when modifying or producing variables;
5. Comprehensive enough to be applied to a range of applications and locations;
6. Demonstrably better than a simple change in the observed monthly mean;
7. Able to produce a spatially coherent set of values;
8. Matches/reproduces features/statistics of the observations; and
9. Able to include transient rather than stepwise emission changes.

The over-riding imperative is that the most appropriate method is matched to the intended application (Wilby et al., 2009), i.e. the method must be fit for purpose. The purpose is taken to be the provision of daily temperature time series for selected sites, for a range of years and emission scenarios in future, for use in risk assessments that require probabilities or frequencies of days over/under specific threshold temperature thresholds. Assuming this does not require preservation of existing relationships between temperature and other climate variables (which may not be valid in future anyway), we have scored each method against the selection criteria in Table 4, using expert judgement (Table 5).

This leads to the conclusion that the *Decile scaling* method is best, followed by the *M-quantile* method and the *Mean change* method. On this basis, an updated set of extreme temperature projections has been produced for Australia using the *Decile scaling* method, and sample projections are presented in Section 8.

Table 3 Advantages and disadvantages of different approaches to construct extreme daily temperature projections

Approach	Advantages	Disadvantages
Trend extrapolation	Easy to apply Reflects local conditions Uses recent patterns of climate variability and change	Assumes linear projection Trends are sensitive to the choice/length of record Needs high quality observations (free of inhomogeneities) Unlikely to be valid beyond one decade in future due to non-linear changes
Analyse raw GCM data	Data can be downloaded without cost from PCMDI Easy to calculate extreme temperature threshold exceedances Produces continuous data from 1900-2100 Includes plausible changes in relationships between climate variables	GCM data are often biased (too hot / cold / wet / dry) compared with observed data, which requires some form of bias-correction Very coarse spatial resolution (100 to 500 km between gridpoints)
Analyse raw RCM data	Easy to calculate extreme temperature threshold exceedances Produces continuous data from 1960-2100. Includes plausible changes in relationships between climate variables	RCM data are often biased (too hot / cold / wet / dry) compared with observed data, which requires some form of bias-correction Moderately coarse spatial resolution (60 km over Australia, 14-20 km in parts of Qld and Tasmania) Daily RCM data availability is limited
Weather generator	Data generated for individual sites Preserves relationships between weather variables Tools freely available and widely used	Complex to implement Modest computational demand Not appropriate for the tropics Scenarios are time-slice rather than transient
Bias-corrected model data	Monthly temperature data look “realistic” (bias-free) Might work for daily data Produces continuous data (see	Complex to implement Not proved for daily data Coarse spatial resolution (see above)

		above)	
Statistical downscaling	Mean change	The monthly or seasonal mean temperature change for a variety of years, emission scenarios and models can be quickly extracted from OzClim Easy to calculate extreme temperature threshold exceedances Commonly used	Requires high quality observed daily temperature data Scenarios are time slice rather than transient Assumes that the current shape of the daily temperature distribution remains the same in future (no change in variance) Assumes the sequence of daily events is unchanged in future (no change in auto-correlation)
	Decile scaling	Relatively simple calculation for individual sites. Includes GCM / RCM changes in daily variability Projected mean warming in GCM / RCM is preserved in adjusted observed data	Assumes the sequence of daily events is unchanged in future (no change in auto-correlation) Scenarios are time slice rather than transient
Statistical downscaling	Extreme Value Analysis (via GEV)	Examines very extreme values (i.e. above 99th percentile) giving indication of quantities only experienced on time scales of multiple years No restriction on type of variable to be examined Performed on outputs at various spatial and temporal scales, including observational or grid-box (modelled) data Can incorporate trends or changes in variables that influence extremes (covariates) Allows for changes in mean, variance and tail behaviour	Results sensitive to length of record Generally conducted on time slices rather than transient data Depending on technique used, calculation can be complex Assumption of stationarity of climate (unless covariates are employed) Longer return period estimates can involve large uncertainties Cannot take into account any biases in model data

Statistical downscaling	M-quantile method	Combines model median changes and observed trends in daily variability (10^{th}, 50^{th}, 90^{th} percentiles) Applied to BoM data at individual sites	Moderately complex calculation Projected mean change in GCM / RCM is not preserved in adjusted observed data Assumes observed trends in 10^{th} and 90^{th} percentiles are more reliable than model trends, even though mode 50^{th} percentile is considered reliable Excludes model-simulated changes in daily variability Assumes that the current relationship between local and synoptic scales stays the same in the future. Not appropriate 20 to 30 years beyond the observational record
	Analogue method	Includes GCM or RCM changes in daily variability BoM website allows relatively simple calculation at individual sites Can be applied to any year in future	Not appropriate for high temperature extremes in summer Assumes that the current relationship between local and synoptic scales stays the same in the future. Limited suitability in tropics
	NHMM	Identifies weather patterns associated with extreme events	Specialized knowledge is required to apply the techniques correctly. Lots of observational data may be required to establish statistical relationships for the current climate. Assumes that the current relationship between local and synoptic scales stays the same in the future.
	State space modelling approach	Similar to NHMM but better Can correct GCM biases at specific locations. Can jointly model several climate variables accounting for the correlation between variables. Can account for serial correlation and seasonality in the time series, and models all months simultaneously.	Complex and computer-intensive Only tested for monthly data to 20 years in the future Not appropriate for daily data at this stage Observed trends tend to over-ride changes projected by climate models

Table 4 Criteria for selecting projection methods. Source: Wilby et al (2009).

Indicator	Preferred attributes
Capacity	Low personnel, technical and infrastructure requirements
Resources	Low data, time and financial costs
Spatial	High resolution (site or region)
Temporal	High resolution (hourly or daily)
Outputs	High realism and links between weather variables
Forcing	High ability to represent different external forcing factors, e.g. greenhouse gases
Uncertainty	High capacity for providing probabilistic information
Pattern	High ability to provide maps
Transient	High ability to provide transient (rather than time slice) scenarios
Tools	High availability of tools, supporting data and guidance

Table 5 Ranking of each method against the criteria in Table 4, with 5 being well aligned with desirable attributes and 1 being poorly aligned. TE = trend extrapolation, GCM = analysis of GCM data, RCM = analysis of RCM data, WG = weather generator, BCM = bias-corrected model data, Mean = mean change, Decile = decile scaling, MQ = M-quantile, AM = Analogue method, NHMM = Non-homogeneous Hidden Markov Chain method, SS = State Space method.

Indicator	TE	GCM	RCM	WG	BCM	Mean	Decile	GEV	MQ	Analog	NHMM	SS
Capacity	5	2	2	2	1	5	4	4	3	3	1	1
Resources	5	2	2	2	1	5	4	4	3	3	1	1
Spatial	5	1	2	5	2	5	5	5	5	5	3	3
Temporal	5	3	3	5	1	5	5	3	5	5	3	1
Outputs	2	4	4	3	4	2	5	4	3	3	2	2
Forcing	1	5	3	3	5	5	5	3	5	3	5	5
Uncertainty	1	5	3	1	5	4	5	5	5	3	5	5
Pattern	2	5	5	1	5	3	5	5	5	3	3	5
Transient	1	5	5	1	5	1	1	1	2	1	1	1
Tools	5	2	2	5	1	1	1	3	1	3	1	1
Total	**32**	**34**	**31**	**28**	**30**	**36**	**40**	**37**	**37**	**32**	**25**	**25**

8 UPDATED EXTREME TEMPERATURE PROJECTIONS FOR AUSTRALIA

The decile scaling method has been applied to observed daily temperature data at 103 Australian climate stations (list of station in Appendix 1). Scaling factors have been calculated from four CGMs: CSIRO Mk3.5, MIROC MEDRES 3.2, CCCMA CGCM3.1 T47 and CNRM CM3. These models have daily data and sample projected changes in seasonal mean temperature that cover most of the range of possibilities from 23 climate models.

For each model and site, the projected changes in daily temperature (per degree of global warming) were classified into 10 deciles for each of the 12 months. These changes were scaled by the IPCC (2007) mid-range global warming values for various years and emission scenarios:

- 2030 A1B
- 2050 B1, A1B, A1FI
- 2070 B1, A1B, A1FI

These projected changes were then added to the observed daily temperatures from 1971-2000 at 103 climate stations, for the corresponding deciles and months. To ensure that the change in the mean was consistent between the model and the downscaled data at each site, a small correction was applied to the downscaled data.

A variety of threshold temperatures was considered.

- Maximum temperature over 30 to 45°C
- Minimum temperatures over 20 to 30°C
- Minimum temperatures below 0 to 10°C

Projected changes in frequency were calculated for (i) individual days and (ii) 3-5 consecutive days, i.e. hot spells and cold spells. All results have been tabulated in an Excel spreadsheet (available from the authors). Sample results for Canberra are given in Tables 6 and 7.

Table 6 Annual mean frequency of days and 3-5-day hot spells with maximum temperatures over 35°C in Canberra for 1971-2000 (present) and 30-year periods centred on 2030 (A1B emissions), 2050 (B1, A1B and A1FI emissions) and 2070 (B1, A1B and A1FI emissions), based on the decile scaling method. Monthly scaling factors were derived from four GCMs that span most of the range of warming from 23 GCMs.

Year	Emission scenario	GCM	Days	Hot spells
Present			5.4	0.7
2030	A1B	cccma_cgcm3_1_t47	9.2	1.2
2030	A1B	cnrm_cm3	8.5	1.2
2030	A1B	csiro_mk3_5	10.5	1.4
2030	A1B	miroc3_2_medres	5.5	0.7
2050	A1B	cccma_cgcm3_1_t47	12.9	2.0
2050	A1B	cnrm_cm3	11.8	1.7
2050	A1B	csiro_mk3_5	15.4	2.5
2050	A1B	miroc3_2_medres	5.8	0.7
2050	A1FI	cccma_cgcm3_1_t47	14.7	2.3
2050	A1FI	cnrm_cm3	13.4	2.1
2050	A1FI	csiro_mk3_5	17.9	2.8
2050	A1FI	miroc3_2_medres	5.9	0.7
2050	B1	cccma_cgcm3_1_t47	10.5	1.4
2050	B1	cnrm_cm3	9.9	1.3
2050	B1	csiro_mk3_5	12.1	1.7
2050	B1	miroc3_2_medres	5.6	0.7
2070	A1B	cccma_cgcm3_1_t47	17.0	2.8
2070	A1B	cnrm_cm3	15.3	2.4
2070	A1B	csiro_mk3_5	20.2	3.2
2070	A1B	miroc3_2_medres	6.0	0.7
2070	A1FI	cccma_cgcm3_1_t47	23.3	4.0
2070	A1FI	cnrm_cm3	19.9	3.3
2070	A1FI	csiro_mk3_5	27.7	4.8
2070	A1FI	miroc3_2_medres	6.3	0.7
2070	B1	cccma_cgcm3_1_t47	12.7	2.0

Table 7 Annual mean frequency of days and 3-5-day cold spells with minimum temperatures below 0°C in Canberra for 1971-2000 (present) and 30-year periods centred on 2030 (A1B emissions), 2050 (B1, A1B and A1FI emissions) and 2070 (B1, A1B and A1FI emissions), based on the decile scaling method. Monthly scaling factors were derived from four GCMs that span most of the range of warming from 23 GCMs.

Year	Emission scenario	GCM	Days	Cold spells
Present			59	11.5
2030	A1B	cccma_cgcm3_1_t47	47.7	8.8
2030	A1B	cnrm_cm3	47.0	8.8
2030	A1B	csiro_mk3_5	46.7	8.7
2030	A1B	miroc3_2_medres	50.1	9.3
2050	A1B	cccma_cgcm3_1_t47	41.2	7.4
2050	A1B	cnrm_cm3	41.3	7.6
2050	A1B	csiro_mk3_5	39.7	7.1
2050	A1B	miroc3_2_medres	43.8	7.9
2050	A1FI	cccma_cgcm3_1_t47	38.1	6.7
2050	A1FI	cnrm_cm3	39.1	7.0
2050	A1FI	csiro_mk3_5	36.1	6.3
2050	A1FI	miroc3_2_medres	42.1	7.5
2050	B1	cccma_cgcm3_1_t47	45.1	8.3
2050	B1	cnrm_cm3	44.6	8.3
2050	B1	csiro_mk3_5	43.2	7.9
2050	B1	miroc3_2_medres	47.6	8.7
2070	A1B	cccma_cgcm3_1_t47	34.7	5.8
2070	A1B	cnrm_cm3	37.5	6.5
2070	A1B	csiro_mk3_5	32.8	5.6
2070	A1B	miroc3_2_medres	39.2	6.7
2070	A1FI	cccma_cgcm3_1_t47	25.9	3.9
2070	A1FI	cnrm_cm3	32.2	5.5
2070	A1FI	csiro_mk3_5	24.2	3.7
2070	A1FI	miroc3_2_medres	32.5	5.2
2070	B1	cccma_cgcm3_1_t47	41.8	7.5

ACKNOWLEDGMENTS

This report was supported by the Australian Climate Change Science Project (ACCSP).

We acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, US Government Department of Energy.

REFERENCES

Allan, R.J., Drury, S., Mitchell, C.D. and Pittock, A.B. (1992). *The enhanced greenhouse effect: regional implications for Western Australia: annual report, 1991-92*. CSIRO report for W.A. Environment Protection Authority, 72 p.

Allan, R.J., Mitchell, C.D. and Pittock, A.B. (1992c). *The greenhouse effect: regional implications for Western Australia, annual report, 1990-91*. CSIRO report for the WA government, 72 p plus appendices.

Allen et al. (2007). Scientific challenges in the attribution of harm to human influence on climate. *University of Pennsylvania Law Review*, **155 (6),** 1353-1400.

Arndt, D.S., Baringer, M.O. and Johnson, M.R. (2010). State of the Climate in 2009. *Bull. Amer. Meteor. Soc*., **91** (6), S1–S224.

Australian Bureau of Meteorology (2010a). Annual Australian Climate Statement. http://www.bom.gov.au/announcements/media_releases/climate/change/20100105.shtml

Australian Bureau of Meteorology (2010b). Australian Climate Extremes - Time series. http://www.bom.gov.au/cgi-bin/climate/change/extremes/timeseries.cgi

Beniston, M. (2004). The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulations. *Geophys. Res. Lett.* **31**, doi: 10.1029/2003GL018857.

Bryant, E. (1997). *Climate process and change*. Cambridge Uni Press, 209 pp.

Charles, S.P., Bates, B.C., Whetton, P.H. and Hughes, J.P. (1999). Validation of downscaling models for changed climate conditions: case study of southwestern Australia. *Climate Research*, **12**, 1-14.

Coles, S.G. (2001). *An Introduction to Statistical Modeling of Extreme Values.* Springer-Verlag, London, pp. 225.

Crimp, S.J., Flood, N.R., Carter, J.O., Conroy, J.P. and McKeon, G.M. (2002). *Evaluation of the Potential Impacts of Climate Change On Native Pasture Production – Implications for livestock carrying capacity.*: Final Report for the Australian Greenhouse Office, 60pp. 2002.

CSIRO and BoM, 2007. *Climate change in Australia*, *Technical Report*, 148pp. http://www.climatechangeinaustralia.com.au/resources.php.

Easterling D.R., and Wehner, M.F. (2009). Is the climate warming or cooling? *Geophys. Res. Lett*. **36**. L08706.

Evans, J.L., Suppiah, R., Mitchell, C.D., and Pittock, A.B., (1992). *Regional impact of the enhanced greenhouse effect on the Northern Territory, annual report, 1990-91*. CSIRO research undertaken for the Northern Territory Environment Protection Unit, 79 p.

Fawcett, R. (2008). Has the world cooled since 1998? *Bulletin of the Australian Meteorological and Oceanographic Society*. **20**: 141-148.

Foster, G., Annan, J. D., Jones, P. D., Mann, M. E., Mullan, B., Renwick, J., Salinger, J. Schmidt, G. A. and Trenberth, K. E. (2010). Comment on “Influence of the Southern Oscillation on tropospheric temperature” by J. D. McLean, C. R. de Freitas, and R. M. Carter. *JGR*, **115**, D09110, doi:10.1029/2009JD012960

Fowler, A.M., Wang, Y-P., Pittock, A.B., and Mitchell, C.D. (1992). *Regional impact of the enhanced greenhouse effect on New South Wales, annual report, 1991-92*. CSIRO research undertaken for the NSW Environment Protection Authority, 64 p.

Fowler, H.J., Cooley, D. Sain, S.R. and Thurston, M. (2010). Detecting change in UK extreme precipitation using results from the climate*prediction*.net BBC climate change experiment. *Extremes,* **13,** 241-267.

Fowler, H.J., Ekström, M., Blenkinsop, S. and Smith, A.P. (2007). Estimating change in extreme European precipitation using a multimodel ensemble. *J. Geophys. Res.*, **112,** doi:10.1029/2007JD008619.

Hanson, C.L., Cumming, K.A., Woolhiser, D.A. and Richardson, C.W. (1994). *Microcomputer program for daily weather simulation*. U.S. Dept. Agric., Agric. Res. Svc. Pub. No. ARS-114, 38 pp.

Hennessy, K. J., Lucas, C., Nicholls, N., Bathols, J. M., Suppiah, R., and Ricketts, J. R. (2005). Climate change impacts on fire-weather in south-east Australia. CSIRO Atmospheric Research Report C/1061, Aspendale, Vic., 88 p.

Hennessy, K. J., McInnes, K. L., Abbs, D. J., Jones, R. N., Bathols, J. M., Suppiah, R., Ricketts, J. R., Rafter, A. S., Collins, D., and Jones, D. (2004). *Climate change in New South Wales. Part 2, Projected changes in climate extremes*. CSIRO Atmospheric Research consultancy report for the New South Wales Greenhouse Office, 79 p.

Hennessy, K. J., Page, C. M., McInnes, K. L., Walsh, K. J. E., Pittock, A. B., Bathols, J. M., and Suppiah, R. (2004). *Climate change in the Northern Territory*. CSIRO Atmospheric Research consultancy report for the Northern Territory Department of Infrastructure, Planning and Environment, 64 p.

Hennessy, K. J., Whetton, P. H., Katzfey, J. J., McGregor, J. L., Jones, R. N., Page, C. M., and Nguyen, K. C. (1998). *Fine resolution climate change scenarios for New South Wales: annual report 1997-1998*. CSIRO research undertaken for the New South Wales Environment Protection Authority, 48 p.

Hennessy, K.J., and Pittock, A.B. (1995). Greenhouse warming and threshold temperature events in Victoria. *International Journal of Climatology*, **15 (6)**, 591-612.

Hennessy, K.J., Holper, P.N., and Pittock, A.B. (1995). *Regional impact of the greenhouse effect on New South Wales: final report.* CSIRO report for N.S.W. Environment Protection Authority, 97 p.

Hosking, J.R.M., 1990: L-moments: Analysis and estimation of distributions using linear combinations of order statistics. *J. Roy. Stat. Soc.*, **B52,** 105–124.

Hosking, J.R.M., 1992: Moments or L-moments? An example comparing the two measures of distributional shape. *Am. Stat.*, **46,** 186-189.

IPCC (2000). *Emissions Scenarios. Special Report of the Intergovernmental Panel on Climate Change*. Nakicenovic, N., and R. Swart, (eds). Cambridge University Press, UK. 570pp.

IPCC (2007). *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B.,Tignor, M., and Miller, H.L. (Eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Karoly, D. and Braganza, K. (2005). Attribution of Recent Temperature Changes in the Australian Region. Journal of Climate, 18(3), 457–464. http://ams.allenpress.com/perlserv/?request=get-abstract&doi=10.1175%2FJCLI-3265.1

Kharin, V. and Zwiers, F. (2000). Changes in the extremes in an ensemble of transient climate simulations with a coupled atmosphere-ocean GCM. *J. Climate*, **13**, 3760- 3788.

Kharin, V.V., Zwiers, F.W., Zhang X. and Hegerl, G.C. (2007). Changes in temperature and Precipitation Extremes in the IPCC Ensemble of Global Coupled Model Simulations. *J. Climate*, **20,** 1419-1444.

Kharin, V., Zwiers F. and Zhang, X. (2005). Intercomparison of near surface temperature and precipitation extremes in AMIP-2 simulations. *J. Climate,* **18,** 5201-5223.

Kilsby, C.G., Jones, P.D., Burton, A., Ford, A.C, Fowler, H.J., Harpman, C., James, P., Smith, A. and Wilby, R.L. (2007). A daily weather generator for use in climate change studies. *Environmental Modelling and Software*, **22**, 1705-1719.

Li, H., Sheffield J. and Wood, E. F. (2010). Bias correction of monthly precipitation and temperature fields from Intergovernmental Panel on Climate Change AR4 models using equidistant quantile matching. *J. Geophys. Res.*, 115, D10101.

Manning, M. *et al* (2010). Misrepresentation of the IPCC CO_2 emission scenarios. *Nature Geoscience*, **3**, 367-377

McInnes, K. L., Suppiah, R., Whetton, P. H., Hennessy, K. J., and Jones, R. N. (2002). *Climate change in South Australia: report on assessment of climate change, impacts and possible adaptation strategies relevant to South Australia*. CSIRO Atmospheric Research report for the SA government, 61 p.

Mitchell, C. D., Hennessy, K. J. and Pittock A. B. (1994a). *Regional impact of the enhanced greenhouse effect on New South Wales: annual report, 1992-93*. CSIRO report for N.S.W. Environment Protection Authority, 83 p.

Mitchell, C. D., Hennessy, K. J. and Pittock A. B. (1994b). *The greenhouse effect: regional implications for Western Australia: final report, 1992-93*. CSIRO report for W.A. Department of Environmental Protection.

Mitchell, C. D., Hennessy, K. J. and Pittock A. B. (1994c). *Regional impact of the enhanced greenhouse effect on the Northern Territory, 1992-93*. CSIRO research undertaken for the Northern Territory Environment Protection Unit.

Nicks, A.D. and Gander, G.A. (1993). *Using CLIGEN to stochastically generate climate data inputs to WEPP and other water resource models*. USGS Water-Resources Investigations Report 93-4018, USGS, Fort Collins, CO.

Perkins, S.E., Pitman, A.J. and Sisson S.A. (2009). Smaller projected increases in 20-year temperature returns over Australia in skill-selected climate models, *Geophys. Res. Lett.*, 36, L06710, doi:10.1029/2009GL037293.

Pittock, A.B. and Evans, J.L. (1990c). *Regional impact of the greenhouse effect on the Northern Territory: Annual report 1989-90*. CSIRO Division of Atmospheric Research report for the Northern Territory Government, 68 pp

Pittock, A.B. and Hennessy, K.J. (1989). *Regional impact of the greenhouse effect on Victoria*. CSIRO Division of Atmospheric Research, report for Victorian Environment Protection Authority, 14 pp

Pittock, A.B. and Whetton, P.H. (1990a). *Regional impact of the greenhouse effect on NSW: Annual report 1989-90*. CSIRO Division of Atmospheric Research report for NSW State Pollution Control Commission, 76 pp

Pittock, A.B. and Whetton, P.H. (1990b). *Regional impact of the greenhouse effect on Victoria*. CSIRO Division of Atmospheric Research, report for Victorian Environment Protection Authority, 70 pp

Richardson, C.W. (1981). Stochastic simulation of daily precipitation, temperatures and solar radiation. *Water Resources Research*, **17**, 182-190.

Rusticucci, M. and Tencer, B. (2008). Observed changes in return values of annual temperature extremes over Argentina. *J. Climate*, **21**, 5455-5467.

Schaeffer, M., Selten F.M. and Opsteegh, J.D. (2005). Shifts in means are not a proxy for changes in extreme winter temperatures in climate projections. *Clim. Dynam.*, **25,** 51-63.

Schar et al., (2004). The role of increasing temperature variability in European summer heatwaves. *Nature*, **427**, 332-336.

Semmler, T. and Jacob, D. (2004). Modeling extreme precipitation events – a climate change simulation for Europe. *Global Planetary Change*, **44**, 119-127.

Stott, P.A., Stone, D.A. and Allen, M.R. (2004). Human contribution to the European heatwave of 2003. *Nature*, **432**, 610-614.

Suppiah, R., Hennessy, K. J., Hirst, A. C., Jones, R. N., Katzfey, J. J., Pittock, A. B., Walsh, K. J. E., Whetton, P. H., and Wilson, S. G. (1998). *Climate change under enhanced greenhouse conditions in northern Australia: final report 1994-1997*. CSIRO Division of Atmospheric Research, 50 p.

Suppiah, R., Hennessy, K. J., Hirst, A. C., Jones, R. N., Katzfey, J. J., Pittock, A. B., Walsh, K. J. E., Whetton, P. H., and Wilson, S. G. (1998). *Climate change under enhanced greenhouse conditions in northern Australia: third annual report 1996-1997*. CSIRO Division of Atmospheric Research, 95 p.

Suppiah, R., Pittock, A. B., Evans, J. L. and Mitchell, C. D. (1992). *Regional impact of the enhanced greenhouse effect on the Northern Territory, annual report, 1990-91*. CSIRO research undertaken for the Northern Territory Government, 71 p.

Timbal, B., Dufour A. and McAvaney, B.J. (2003). An estimate of climate change for Western France using a statistical downscaling technique, *Climate Dynamics*, **17**, 947-963.

Timbal, B., Fernandez, E. and Li, Z. (2009). Generalization of a statistical downscaling model to provide local climate change projections for Australia. *Environmental Modelling and Software*, **24,** 341–358.

Vic DHS (2009). *Heatwave in Victoria: an assessment of health impacts*. http://www.health.vic.gov.au/chiefhealthofficer/downloads/heat_impact_rpt.pdf

Victorian Bushfires Royal Commission (2010). Final Report, Volume 1: The fires and the fire-related deaths. Government Printer for the State of Victoria, Melbourne, 361 pp. http://www.royalcommission.vic.gov.au/getdoc/f91ff31a-f477-4543-85ca-ead47f27c58f/Print-Friendly-Version

Von Storch, H. and Zwiers, F.W. (1999). *Statistical Analysis in Climate Research.* Cambridge University Press, pp. 484.

Wehner, M.F. (2004). Predicted twenty-first-Century changes in Seasonal extreme precipitation events in the parallel climate model. *J. Climate*, **17,** 4281-4290.

Wehner, M.F., Smith, R.L. Bala, G. and Duffy, P. (2010). The effect of horizontal resolution on simulation of very extreme US precipitation events in a global atmosphere model. *Clim. Dyn.*, **34,** 241-247.

Whetton, P. H. (1995). *Climate change under enhanced greenhouse conditions in northern Australia: first annual report 1994-1995*. CSIRO Division of Atmospheric Research, 33 p.

Whetton, P. H., Fowler, A. M., Mitchell, C. D. and Pittock, A. B. (1992a). *Regional impact of the enhanced greenhouse effect on Victoria, annual report, 1990-91*. CSIRO research undertaken for the Victorian Government funded by the Environment Protection Authority, 68 p.

Whetton, P. H., Fowler, A. M., Mitchell, C. D. and Pittock, A. B. (1992c). *Regional impact of the enhanced greenhouse effect on New South Wales, annual report, 1990-91*. CSIRO research undertaken for the NSW State Pollution Control Commission, 68 p.

Whetton, P. H., Hennessy, K. J., Katzfey, J. J., McGregor, J. L., Jones, R. N., and Nguyen, K. C. (2000b). *Fine Resolution Assessment of Enhanced Greenhouse Climate Change in Victoria Annual Report; 1997-98. Climate averages and variability based on a transient CO_2 simulation*. CSIRO research undertaken for the Department of Natural Resources and Environment., 38 p.

Whetton, P. H., Hennessy, K. J., Pittock, A. B., Fowler, A. M., and Mitchell, C. D. (1992b). *Regional impact of the enhanced greenhouse effect on Victoria, annual report, 1991-92*. CSIRO research undertaken for the Victorian Environment Protection Authority, 64 p.

Whetton, P. H., Katzfey, J. J., Nguyen, K. C., McGregor, J. L., Page, C. M., Elliott, T. I., and Hennessy, K. J. (2000a). *Fine Resolution Assessment of Enhanced Greenhouse Climate Change in Victoria Annual Report; 1996-97. Climate averages based on a doubled CO_2 simulation*. CSIRO research undertaken for the Victorian Department of Natural Resources and Environment, 48 p.

Whetton, P. H., Katzfey, J. J., Nguyen, K. C., McGregor, J. L., Page, C. M., Elliott, T. I., and Hennessy, K. J. (1997). *Fine resolution climate change scenarios for New South Wales. Part 2: climatic variability*. CSIRO research undertaken for the New South Wales Environment Protection Authority, 51 p.

Wilby, R.L., Troni, J., Biot, Y., Tedd, L., Hewitson, B.C., Smith, D.M. and Sutton, R.T. (2009). A review of climate risk information for adaptation and development planning. *Int. J. Climatol*., **29**, 1193-1215.

Zwiers, F. and Kharin, V. (1998). Changes in the extremes of climate simulated by CCC GCM2 under CO_2 doubling. *J. Climate*, **11**, 2200-2222.

APPENDIX 1: LIST OF CLIMATE STATIONS

NSW	Vic	Tas	Qld	NT	WA	SA
Bathurst	Cape Otway	Butlers Gorge	Amberley	Alice Springs	Albany	Adelaide
Bourke	Forrest	Cape Bruny	Barcaldine	Darwin	Broome	Cape Borda
Cabramurra	Gabo Island	Hobart	Birdsville	Rabbit Flat	Cape Leeuwin	Ceduna
Cobar	Kerang	Inverell	Boulia	Tennant Creek	Carnarvon	Marree
Coffs Harbour	Laverton	Launceston Airport	Brisbane AP	Victoria River	Cunderdin	Mount Gambier
Deniliquin	Melbourne	Lowhead	Bundaberg		Dalwallinu	Nuriootpa
Dubbo	Mildura		Burketown		Eddystone	Oodnadatta
Jervis Bay	Nhill		Cairns		Esperance	Port Lincoln
Moree	Orbost	**ACT**	Camooweal		Geraldton	Robe
Moruya	Rutherglen	Canberra	Charleville		Giles	Snowtown
Nowra	Sale		Charters Towers		Grove	Tarcoola
Port Macquarie	Wilsons Promontory		Gayndah		Halls Creek	Woomera
Richmond	Cape Otway		Gunnedah		Kalgoorlie	
Scone	Forrest		Longreach		Kalumburu	
Sydney	Gabo Island		Mackay		Learmonth	
Tibooburra	Kerang		Miles		Meekatharra	
Wagga			Palmerville		Perth Ap	
Walgett			Richmond		Port Hedland	
Wilcannia			Rockhampton		Wandering	
Williamtown			St George		Wittenoom	
Wyalong			Tewantin			
Yamba			Thargomindah			
			Thursday Island			
			Townsville			
			Weipa			

The Centre for Australian Weather and Climate Research is a partnership between CSIRO and the Bureau of Meteorology.