

# Detecting and attributing Australian climate change: a review

Neville Nicholls

School of Geography and Environmental Science, Monash University, Australia

(Manuscript received May 2006)

In climate change science, detection is the demonstration that climate has changed in some defined statistical sense. A change is detected in observations if its likelihood of occurrence by random chance due to internal, natural climate variability is small. Attribution is the process of establishing the most likely causes for the detected change with some defined level of confidence. Evidence of a human influence on the global climate has accumulated steadily during the past two decades, based on such detection and attribution studies. This paper is a review of detection and attribution studies of Australian climate trends. The major Australian climate trends observed over the past 50 years or so are:

- Mean maximum (daytime) temperature has increased over most of Australia, with cooling in the northwest (very strong in summer) and along the south coast of Western Australia (in most seasons).
- Mean minimum (night-time) temperature has increased over nearly all of the country except for cooling in some parts in the inland northwest (in all seasons except spring, although the location of the cooling varies between seasons).
- Annual rainfall has increased in the northwest (a summer phenomenon), decreased in the southwest (a winter phenomenon) and along and inland from the east coast (Queensland in summer; New South Wales in winter).
- Pan evaporation has declined about three per cent since the mid-1970s.

Detection and attribution studies of Australian climate indicate that:

- The widespread warming is very likely to be due to increased greenhouse gas concentrations.
- The rainfall decrease in southwest Western Australia is likely due to a combination of increased greenhouse gas concentrations, natural climate variability and land-use change.
- The increased summer rainfall in northwest Australia may be due to increased aerosols resulting from human activity, especially in Asia.
- The apparent decline in pan evaporation is mainly due to changes in instrumental exposure.
- No study has attributed a cause to the rainfall decrease along the east coast.

The highest priority for new detection and attribution studies would appear to be the decline in east coast rainfall, because of the large population and high economic value of this region, the dearth of relevant studies, and the magnitude of the apparent change. A more comprehensive, Australia-wide, formal detection and attribution study to determine how firmly we can conclude that human activity has affected Australian rainfall in general, is also a high priority.

## Introduction: what is climate change detection and attribution?

Climate has always varied. In Australia, the impact of the El Niño – Southern Oscillation on variations in rainfall over centuries has been documented (e.g.

Nicholls 1988, 1989). Other natural, internal processes also affect climate on different time-scales. As well, volcanic activity is known to cause cooling of the surface temperature, and variations in solar activity and orbital changes that affect the interception of sunlight by the earth also have a clear effect. Such impacts on the climate, i.e. those due to natural internal climate processes, and those resulting from natural external forcings (such as orbital variations), will continue to

---

*Corresponding author address:* Dr N. Nicholls, School of Geography and Environmental Science, Building 11, Monash University, Vic. 3800, Australia.  
Email: Neville.Nicholls@arts.monash.edu.au

affect the climate in the future, and there is little that can be done to mitigate such changes. However, climate changes and variations resulting from human activity such as changes in atmospheric composition and land use changes could, feasibly, be somewhat mitigated. As well, knowing that such human activities are resulting in climate change can allow us to better prepare for continued climate change due to these human activities, over and above the natural climate variations. A first step to undertaking activity to either mitigate or adapt to expected climate change is to determine whether we are already changing the climate, and in what ways. This is the process labelled 'climate change detection and attribution'.

The concepts of climate change detection and attribution were defined in the IPCC Third Assessment Report (TAR IPCC 2001). Detection 'is the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change'. A change is detected in observations if its likelihood of occurrence by random chance from internal variability alone is small. A failure to statistically detect a change might occur for a number of reasons, including the possibility that the change is small relative to internal variability, or that the metric used to measure change is insensitive to the expected change. For example, the annual global mean precipitation may not be a sensitive indicator of anthropogenic influence because it is expected that anthropogenic forcing would result in increased rainfall in some latitudes and drying elsewhere.

Detection does not imply attribution of the detected change to the assumed cause. Attribution is the process of establishing the most likely causes for the detected change with some defined level of confidence. Unequivocal attribution would require controlled experimentation with our climate system. That, of course, is not possible, and thus from a practical perspective, attribution of anthropogenic climate change requires:

- detection of a change;
- demonstration that the detected change is 'consistent with the estimated responses to the given combination of anthropogenic and natural forcing'; and
- demonstration that the detected change is 'not consistent with alternative, physically-plausible explanations of recent climate change that exclude important elements of the given combination of forcings' (IPCC 2001).

The second of these requirements, the assessment of the consistency between an observed change and the estimated response to a hypothesised forcing, is often achieved by determining whether the amplitude of the pattern of observed change estimated is statistically consistent with that expected. However, this statistical

consistency forms only a part of the evidence that is used in attribution studies. Another key element is the consideration of the physical consistency of multiple lines of evidence.

Many studies use climate models to predict the expected responses to external forcing, and these predictions are usually represented as patterns of variation in space, time, or both. Such patterns, or fingerprints, are usually derived from a climate model in response to forcing (such as changes in greenhouse gases). Physical understanding can also be used to develop conceptual models of the anticipated pattern of response to external forcing and the consistency between responses in different variables and different parts of the climate system. For example, in many regions precipitation and temperature are ordinarily inversely correlated, with increases in temperature corresponding to drying conditions. Thus a warming trend in a given region that is not associated with rainfall change may indicate an external influence on the climate of that region (Nicholls et al. 2004).

The third requirement for attribution listed above is to estimate the chance that the observed change may be consistent with alternative explanations. Physical understanding plays an important role in such an evaluation, but statistical analysis that identifies the separate influences of the individual forcing agents in observations is also important. For example, the attribution of recent warming to greenhouse gas forcing is more credible if the influences of other external forcings, for example solar forcing, are explicitly considered in the analysis.

All three aspects of attribution require knowledge of the internal climate variability. This can be estimated from the residual variability that remains in instrumental observations after the estimated effects of external forcing are removed. Internal climate variability can also be estimated from long control simulations from coupled climate models (i.e. simulations without external forcings). Confidence in these estimates is increased by comparison between climate reconstructions from paleoclimatic data and climate simulations of the last millennium.

Formal statistical approaches have been used in many detection and attribution studies in recent years, especially on global scales (see IAHDAG 2005). Most such studies rely on the optimal fingerprinting technique. Optimal fingerprinting is generalised multivariate regression adapted to the detection of climate change and the attribution of change to externally forced climate change signals. The regression model has the form  $y = Xa + u$ , where vector  $y$  is a filtered version of the observed record, matrix  $X$  contains the estimated response patterns to the external forcings (signals) that are under investigation,  $a$  is a vector of

scaling factors that adjusts the amplitudes of those patterns, and  $u$  represents internal climate variability.

The matrix  $X$  typically contains signals that are estimated with a climate model. Because models simulate natural internal variability as well as the response to specified anomalous external forcing, the simulated climate signals are typically estimated by averaging across an ensemble of simulations. The vector  $a$  accounts for possible errors in the amplitude of the external forcing and the amplitude of the climate model's response by scaling the signal patterns to best match the observations.

Detection and attribution questions are assessed through a combination of physical reasoning and by evaluating specific hypotheses on the scaling factors  $a$ . Detection of a postulated climate change signal occurs when its amplitude in observations is shown to be significantly different from zero. Subsequently, the second attribution requirement (consistency with a combination of external forcings and natural internal variability) is assessed with an attribution consistency test (i.e. is the vector  $a$  compatible to that expected from the model estimates?).

Such formal detection and attribution studies are not yet feasible for all variables, and few such formal studies have been applied to climate change in Australia. This is particularly the case for variables such as rainfall that are less reliably modelled or observed, or are expected to respond less strongly to external forcing. This is even more pertinent when regional changes, e.g. southwest Western Australia, are considered. But these regional changes need to be considered in the context of the global results of detection and attribution, and it is these global studies, in particular of temperature, that we discuss in the next section.

While the approach used in most detection studies is to determine whether observations exhibit the expected response to external forcing, for many decision-makers a question posed in a different way may be more pertinent. For instance, they may ask, 'Are the continuing drier-than-normal conditions in the southwest of Western Australia due to human causes?'. Such *post hoc* questions are difficult to answer conclusively because of a statistical phenomenon known as 'selection bias'. The fact that the questions are 'self selected' from the observations (only large observed climate anomalies in a historical context, such as the decline in rainfall in the southwest, would likely be the subject of such a question) makes it difficult to assess their statistical significance simply with a statistical test on the observations (see for example von Storch and Zwiers (1999)). Nevertheless, there is a need for answers for such questions, and studies that adopt this approach are also considered when we turn to Australian climate change detection and attribution studies.

## Global detection and attribution – current status

Evidence of a human influence on the recent evolution of the climate has accumulated steadily during the past two decades. The first IPCC Assessment Report (IPCC 1990) contained little observational evidence of a detectable anthropogenic influence on climate. Six years later the IPCC WG1 Second Assessment Report (SAR IPCC 1996) concluded that 'the balance of evidence' suggested there had been a 'discernible' human influence on the climate of the 20th century. Considerably more evidence accumulated during the subsequent five years, and the TAR (IPCC 2001) was able to reach a much stronger conclusion, not just on the detectability of a human influence, but on its contribution to climate change during the 20th century. More detection and attribution studies have been carried out since the TAR, and IAHDAG (2005), after reviewing these studies, concluded that 'Externally driven climate change has been detected by a number of investigators in independent data covering many parts of the climate system, including surface temperature on global and large regional scales, ocean heat content, atmospheric circulation, and variables of the free atmosphere, such as atmospheric temperature and tropopause height.'

Even at the time of the TAR the available evidence was considerable. Based on a range of detection studies of the instrumental record, output from several climate models for fingerprints, and estimates of internal climate variability, the TAR concluded that the warming over the 20th century was 'very unlikely to be due to internal variability alone as estimated by current models'. Simulations of global mean 20th century temperature change that took into account the changes in anthropogenic greenhouse gases and sulphate aerosols as well as natural influences, specifically solar and volcanic forcing, were found to be consistent with observed variations in temperature. Simulations of the response to known natural forcings without the inclusion of human forcings indicated that these natural influences may have contributed to the observed warming in the first half of the 20th century, but could not provide an adequate explanation of the warming in the second half of the 20th century. The estimated rate and magnitude of warming over the second half of the 20th century due to increasing greenhouse gas concentrations alone was comparable with, or larger than, the observed warming. The TAR also reported qualitative consistencies between observed climate changes and model responses to anthropogenic forcing, including global warming, increasing land-ocean temperature contrast, diminishing Arctic sea-ice extent, glacial retreat and increases

in precipitation at high northern latitudes. The TAR concluded 'in the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations'.

Since the TAR, many new studies have confirmed and extended these conclusions. Every year since the publication of the TAR has been in the top ten warmest years in the instrumental global record of near-surface temperatures (available since the mid-19th century). Many climate models simulate the global mean temperature changes over the last century but only when they include the most important forcings (both natural and anthropogenic) of the climate system. These studies lead to the conclusion that greenhouse gas forcing has very likely been the dominant cause of the observed global warming over the last 50 years. Cooling by aerosols and natural forcings has likely offset some of the warming due to increased greenhouse gas concentrations.

An important development since the TAR has been the identification of an anthropogenic signal in surface temperature changes on continental and sub-continental-scale land areas (e.g. Stott 2003; Karoly et al. 2003; Zwiers and Zhang 2003; Karoly and Braganza 2005). The ability of models to simulate many aspects of the temperature evolution on these scales and the detection of significant anthropogenic effects on individual continents provides even more compelling evidence for human influence on climate. The chance that all the regional results in different parts of the globe are spurious is very small, considering that different regions are affected by different uncertainties in observations, external forcings and internal variability.

Evidence for changes in extreme temperatures is beginning to emerge. There has been a substantial decrease in the frequency of frost days and an increase in the incidence of warm nights. A recent analysis has shown a significant human influence on patterns of changes in extremely warm nights and evidence for a human-induced warming of the coldest nights and days of the year (Christidis et al. 2005). Human influence appears to have more than doubled the risk of European mean summer temperatures as high as those recorded in the very warm summer of 2003 (Stott et al. 2004).

Other climate variables show some evidence of a human influence. Trends in the atmospheric circulation in the high latitudes of the southern hemisphere over recent decades (with sea-level pressure declining over the pole) have been simulated by models that include greenhouse gas and stratospheric ozone changes, suggesting a human influence on global atmospheric pressure. Large-scale changes in land

precipitation over the 20th century are qualitatively consistent with simulations, suggesting a possible human influence, although no formal detection study has confirmed this. Declines in alpine snow depth, glacier reductions, and reduction in Arctic sea-ice extent, are all consistent with warming.

A further development of detection and attribution studies in recent times has been the concept of 'joint attribution' whereby human activities can be attributed to changing surface air temperatures at a local or regional scale and then biological responses can be attributed to this human-induced temperature increase. Root et al. (2005) used modelled temperature changes and observed species data relating to various phenological traits (e.g. timing of blooming or migration) over the northern hemisphere, and found that the climate model temperatures when forced with anthropogenic influences were more closely associated with the observed species changes than was the case for the model when forced only with natural influence such as volcanoes and solar variations. The species phenological data provide an independent proxy of change over time of surface temperature.

Thus there is an accumulation of evidence, on a global scale, of a human influence on climate. Next we consider the Australian climate record, to document the trends in climate since the mid-20th century, as a prelude to discussing detection and attribution studies of some of these trends. Note that we omit extensive consideration of changes in extremes from this discussion, and from the remainder of this report, focussing instead on changes in means or totals of climate variables.

## Australian climate trends since the mid-20th century

The Australian Bureau of Meteorology has developed a number of datasets for use in climate change monitoring. These datasets typically include 50 to 200 stations distributed as evenly as possible over the Australian continent, and have been subject to detailed quality control and homogenisation (Trewin et al. 2006; Trewin and Collins 2006). This involves identifying and correcting data problems using statistical techniques, visual checks and station history information (Lavery et al. 1992, 1997; Torok and Nicholls 1996; Trewin 2001; Jones and Trewin 2002; Della-Marta et al. 2004; Lucas et al. 2004; Jovanovic and Collins 2006).

Whilst nearly all Australian monthly and daily precipitation data have been digitised, a significant quantity of pre-1957 data (for temperature and evapora-

tion) or pre-1987 data (for some other elements) are yet to be digitised, and so are not yet available for climate change monitoring. In the case of temperature and evaporation, the start date of the datasets is also determined by major changes in instruments or observing practices for which no adjustment is feasible at the present time.

The datasets currently available are:

- monthly and daily precipitation (most stations commence 1915 or earlier, with many extending back to the late 19th century, and a few to the mid-19th century);
- annual temperature (commences 1910);
- daily temperature (commences 1910, with limited station coverage pre-1957);
- dew-point/relative humidity (commences 1957);
- monthly and daily evaporation (commences 1970).

Trends calculated from some of these datasets, and reported below, can be found at [http://www.bom.gov.au/cgi-bin/silo/reg/cli\\_chg/trendmaps.cgi](http://www.bom.gov.au/cgi-bin/silo/reg/cli_chg/trendmaps.cgi). This site uses gridded analyses based on the datasets, and also provides more information about the datasets. Nicholls and Collins (2006) also provide more information about trends in Australian climate over the 20th century.

Care does need to be taken with using Australian climate datasets. For instance, some earlier work reported a substantial decline in precipitation in the Snowy Mountains, but this was an artificial decline resulting from changes in stations used to calculate District Average Rainfall (Nicholls 2000).

**Temperature**

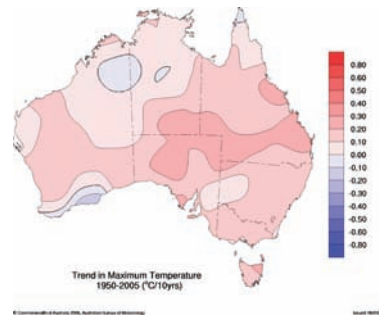
Mean maximum temperature has increased over most of Australia since 1950 (Fig. 1). There has been cooling in the northwest (strong in summer) and along the south coast of Western Australia (in most seasons).

Mean minimum temperature has increased over nearly all of the country (Fig. 2) except for cooling in some parts in the inland northwest. The cooling in the northwest is evident in all seasons except spring, but the exact location of the area exhibiting a cooling trend varies somewhat between seasons.

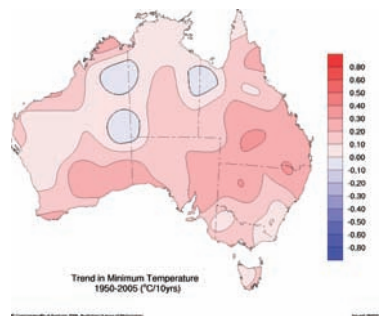
**Rainfall**

The pattern of trends over the second half of the 20th century in Australian annual rainfall total (Fig. 3) is dominated by the increase in rainfall in the northwest (a summer phenomenon – Döerte Jakob, personal communication). Decreases are evident in the southwest (a winter phenomenon) and the east coast (and stretching inland somewhat from the coast). IOCI (2002) reported that winter rainfall in the southwest of Western Australia has decreased substantially since the mid-20th century. The rainfall decrease was only observed in early winter (May-July) rainfall; late winter

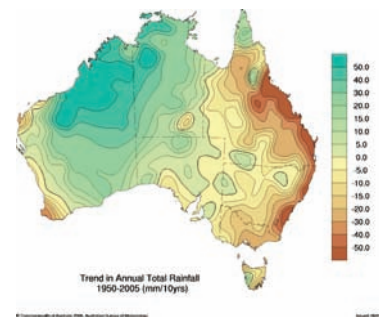
**Fig. 1** Trend in annual mean maximum temperature, 1950-2005.



**Fig. 2** Trend in annual mean minimum temperature, 1950-2005.



**Fig. 3** Trend in annual rainfall total, 1950-2005.



(August-October) rainfall has actually increased, although by a smaller amount. The winter rainfall sharply and suddenly decreased in the mid-1970s by about 15-20 per cent. It was not a gradual decline but more of a switching into an alternative rainfall regime.

The coastal decrease in Queensland is mainly a summer phenomenon, while it has occurred in winter along coastal New South Wales. The east coast trend is weaker (but still evident) if the trends are calculated beginning from either 1940 or 1960, because heavy rains in the 1950s contribute strongly to this trend. Smith (2004) noted most of these trends.

### Drought

Outside the regions with pronounced decreases in total rainfall (especially southwest Western Australia) recent Australian droughts (2002, 1994), in general, were no worse, in terms of total precipitation, than were earlier droughts (Nicholls 2004). The driest extended period, averaged across Australia, since the start of the 20th century was, in fact, the 1930s and early 1940s. However, temperatures have been higher in the more recent droughts. Thus mean maximum temperatures were very high during the 2002 drought, as was evaporation. This would suggest that drought conditions (precipitation minus evaporation) were worse than in previous droughts with similarly low rainfall (1982, 1994). Mean minimum temperatures were also much higher during the 2002 drought than in the 1982 and 1994 droughts. The relatively warm temperatures in 2002 were partly the result of a continued warming evident in Australia since the middle of the 20th century.

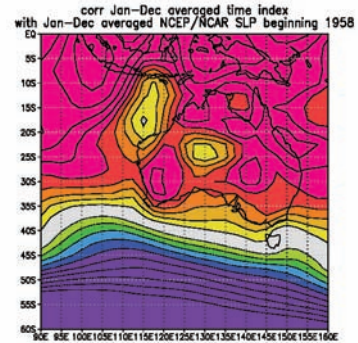
### Atmospheric circulation and pressure

The correlation with year (calculated at the KNMI Climate Explorer site, <http://climexp.knmi.nl/>) of the annual mean sea-level pressure (from NCEP/NCAR Reanalyses), shown in Fig. 4, indicates that pressures have increased over the Australian region, and decreased further polewards (Smith and Hope 2005). This should have led to increased westerlies over and south of Australia. There are concerns with the quality of reanalyses for investigating trends, but their quality over Australia should be sufficient for describing trends in atmospheric pressure (Hope 2005).

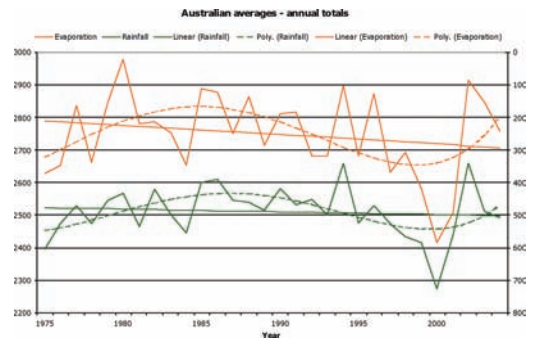
### Other variables

The annual rate of evaporation from open pans ('pan evaporation') averaged over Australia between 1970 and 2004 shows variability around a long-term downward trend (Fig. 5). The variability around the downward trend involves a decrease in the early 1970s, followed by increase up to the early 1980s, then decrease over the next two decades before increasing from 2001. The overall downward trend averaged 2.8 mm per year for the 30 years from 1975, when widespread reliable data became available, to 2004. Overall, there has been a three per cent decrease of the annual pan evaporation rate over 30 years (Roderick and

**Fig. 4** Correlation of annual sea-level pressure with year 1958 to date (from NCEP/NCAR reanalyses).



**Fig. 5** Australian average annual total pan evaporation (orange line) and rainfall (green). Broken lines are polynomial fits to the data. Thin full lines are linear least squares trends.



Farquhar 2004; B. Jovanovic, personal communication 2005; Gifford et al. 2005).

Maximum winter snow depth (Nicholls 2005) at Spencers Creek in the Snowy Mountains of southeastern Australia has decreased slightly since 1962, but the snow depth in spring has declined strongly (by about 40 per cent).

## What is known about the possible causes of these trends?

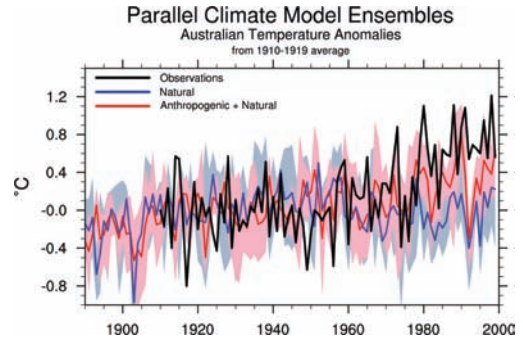
Considerable research has been carried out to determine the causes of interannual and interdecadal variations in the Australian climate (e.g. Meinke et al. 2005). Many of these studies have focussed on the

effects of the El Niño – Southern Oscillation on Australian rainfall and temperature. Some more recent studies have investigated the impact of variations in the Indian Ocean on interannual variations of the Australian climate. However, the studies documented in this section largely focus on studies that have attempted to attribute trends in Australian climate, rather than variations from year to year, or even somewhat longer quasi-oscillatory modes and time-scales (e.g. the Inter-decadal Pacific Oscillation or IPO, Power et al. (1999)). It is presumed that such variations are most likely the result of internal, natural variability of the climate system, and so are somewhat outside the scope of this document. Model studies such as those of Watterson (2001) found internally generated patterns of variability of Australian climate. The extent to which long-term variations in these natural mechanisms (e.g. Nicholls et al. 1996; Power et al. 1998), possibly due to external forcings, are leading to changes in the Australian climate is within the scope of this document, but little work has been done on this topic.

### Widespread warming

Figure 6 (courtesy of Julie Arblaster) shows observed mean Australian temperature, along with ensembles of computer model simulations forced by only natural forcings and by both natural and anthropogenic forcings. There is a clear separation between the ‘natural only’ and ‘all forcings’ ensembles, and the latter more closely reproduces the observed warming, indicating that human activities have likely contributed to the observed Australian warming in recent decades. However, Stott (2003), in his detection and attribution study on sub-continental scales, concluded that ‘it is not possible to reliably attribute Australian temperature changes’ because the ‘level of agreement between observed Australian temperature changes and anthropogenic forced model simulations was not as good as for other regions’. Karoly and Braganza (2005), however, using a variety of simple temperature indices (mean maximum and mean minimum temperatures, mean temperature, and mean diurnal temperature range), different climate models, and a slightly different temperature dataset to Stott, concluded that Australian temperature changes over the 20th century were ‘very unlikely’ to be due to natural climate variations alone, and that it was ‘likely that there has been a significant contribution to the observed warming during the second half of the century from increasing atmospheric greenhouse gases and sulphate aerosols’. Nicholls et al. (1996) and Nicholls (2003) examined the relationship between observed Australian-average maximum temperature and rainfall variations, demonstrated that the recent

**Fig. 6** Ensembles of climate model forced with natural forcings only (blue), natural and anthropogenic forcings (pink) and observed Australian mean annual temperature (black line), courtesy Julie Arblaster.



increase in temperatures was unconnected with changes in rainfall (unlike previous long-term changes and interannual-scale variations), and concluded that the recent warming was therefore, unlikely to be due to natural climate trends.

Hendon et al. (2006) examined the contribution of trends in the Southern Annular Mode (SAM) to trends in summer mean maximum temperature. Over the period (1979–2005) considered by Hendon et al., the long-term warming in the southeast has been weaker than elsewhere. This region of weaker warming in the south and east coincides with the area where the expected SAM contribution to the temperature trend (1979–2005) is a cooling of up to 0.5°C. Thus it is tempting to suggest that the recent upward trend in the SAM during summer has acted to offset some of the longer term warming across central-east Australia.

### Drought

White et al. (2003) reported that in Australia extended periods of drought resulted from the constructive interference of quasi-decadal and interdecadal global modes/waves in sea-surface temperature (SST) and atmospheric pressure, accompanied by a weakening of year-to-year variability associated with either weak quasi-biennial and interannual modes/waves or their destructive interference, i.e. that extended droughts (measured as rainfall deficiencies) were associated with natural variations in the atmospheric and oceanic circulation. The rainfall variations were associated with the result of variations in the troposphere moisture flux converging onto the grazing districts from regional tropical and extratropical oceanic source regions.

Nicholls (2004) demonstrated that recent Australian droughts (1994, 2002) were being accompanied by increasing temperatures, even though in terms of precipitation they were not obviously more severe than droughts earlier in the instrumental record. Since, in turn, the warming is attributable to anthropogenic actions, the increased warmth accompanying recent droughts could also be attributed to human activity.

#### **Rainfall decline in southwest Western Australia**

The rainfall decrease in the southwest accompanied, and was apparently associated with, a well-documented change in the large-scale global atmospheric circulation at this time (e.g. Li et al. 2005). Rainfall variations from year to year are closely related to variations in atmospheric pressure in the surrounding region, including over the Indian Ocean (Allan and Haylock 1993; Smith et al. 2000; IOCI 2002), as is the decline in rainfall (IOCI 2002). Locally, average June and July atmospheric pressure shows a strong upward trend (Hope et al. 2006) – this trend is significantly correlated with the rainfall changes, with a correlation of -0.81 (significant at the 99 per cent level); removing the trend by correlating first differences produces an even stronger correlation of -0.84. Thus, an important feature associated with the rainfall changes in the southwest is the change in the pressure. The number of low-pressure systems in the decades 1959-1968 and 1969-1978 were calculated by Smith et al. (2000) who found a reduction in the number of low-pressure systems in the latter period across the southwest region, with an increase to the south and north. Simmonds and Keay (2000) also found a negative trend from 1958 to 1997 in the number of low-pressure systems affecting the southwest region.

Hope et al. (2006) found that the frequency of the troughs associated with wet conditions across the southwest has declined markedly since 1975 while the frequency of the synoptic types with high pressure over the continent, associated with dry conditions in the southwest, has increased. Combining the frequency of the synoptic systems with the amount of observed rainfall allowed a quantitative analysis of the rainfall decline. The decreased frequency of the troughs associated with very wet conditions accounted for half of the observed rainfall decline. Reductions in the amount of rainfall precipitating from each system also contributed to the decline. Large-scale circulation changes, including increases in the mean sea-level pressure and a decrease in the general baroclinicity of the region, were associated with the rainfall decline.

Frederiksen and Frederiksen (2006) examined the proximate causes of the rainfall decline by using an

instability model and found that the rainfall reduction during the early to mid-1970s was associated with a reduction in the vertical mean meridional temperature gradient and in upper tropospheric jet-stream zonal winds near 30° south. As a consequence of these changes, the atmosphere has been more stable since the mid-1970s around 30° south but also more unstable further south over the Southern Ocean. These changes are reflected in the properties of the leading southern hemisphere cyclogenesis modes: the fastest growing mode for 1975-1994 has a growth rate which is around 30 per cent smaller than for 1949-1968 and on average the 10 leading southern hemisphere cyclogenesis modes for 1975-1994 have growth rates that are 32 per cent smaller than for the corresponding modes for 1949-1968. These results suggest that an immediate cause of the rainfall reduction over the southwest is the reduction of the intensity of cyclogenesis (as observed by Hope et al. 2006) and the southward deflection of some storms, and that these changes in the transient instabilities are in turn attributable to the changes in the large-scale southern hemisphere circulation. Frederiksen and Frederiksen (2006) did not determine the ultimate cause of this change in the large-scale circulation.

The decrease in rainfall, and the associated circulation and synoptic changes, bears some resemblance to changes most climate models project for an enhanced greenhouse effect (IOCI 2002; Hope 2006). However, the changes have not been sufficiently similar to conclude that the enhanced greenhouse effect is responsible, beyond reasonable doubt, for the rainfall decrease. As well, model simulations can, occasionally, produce a decline as substantial as that observed in the southwest, without changes in external forcings (Cai et al. 2005). That is, it is possible that the rainfall decline (or some part of it) could simply reflect natural internal climate variations. Because of such considerations IOCI (2002) concluded that both natural variability and anthropogenic factors, notably the enhanced greenhouse effect, most likely had contributed to the rainfall decrease. Other local factors, such as land-use changes in the southwest, or increased local air pollution, seemed unlikely to be major factors in the rainfall decrease, but were thought (by IOCI 2002) to be possible secondary contributors. However, Narisma and Pitman (2003) found that southwestern Australia winter rainfall decreased in their climate model if they replaced original (1788) vegetation over Australia with modern vegetation type and cover, suggesting a larger possible role for land use change. But the decline in their model was much weaker than had been observed, suggesting that the local land use change was at best a secondary cause of the rainfall decrease. One argument against a

major role of local land-use changes is that there are strong rainfall decreases towards the coast and even off the coast at Rottnest Island, where land-use changes have been smaller than further inland. It is difficult to see how changes in land use further inland could lead to these rainfall decreases. Another argument is that the observed rainfall decrease has been associated with the change in the large-scale pattern of climate variability (e.g. surface atmospheric pressure). The chances of a local factor such as land-use changes or local air pollution sources (another factor sometimes suggested as contributing to the decline) causing a change of this scale are low.

Subsequently, Timbal (2004) and Timbal et al. (2006) used relationships between patterns of various atmospheric fields with station records of rainfall ('downscaling') to improve simulations of southwest rainfall variability. The technique was applied to two four-member ensembles of simulations of the climate from 1870 to 1999 performed with the Parallel Climate Model (PCM). The first ensemble was forced only with natural variations (volcanic activity and solar forcing). The second ensemble also included human-induced forcing from changes in greenhouse gases, ozone and aerosols. The downscaling approach provided a more accurate reproduction of the variability of rainfall in the southwest than did the rainfall simulated directly by the model. The downscaled ensemble mean rainfall in the 'Full Forcing' ensemble exhibited a rainfall decrease with a spatial pattern of change similar to that observed. On the other hand, rainfall increased in the downscaled ensemble simulations without anthropogenic forcings. These results strongly suggest that anthropogenic forcing has played a role in the drying of the southwest, although the ensemble mean rainfall decline was only about half that observed, and drying did not occur in all the four 'Full Forced' ensemble members. Furthermore, while the observed rainfall decline was a sharp reduction in the 1960s, followed by a near-constant rainfall regime, the downscaled model ensemble suggests a more gradual rainfall decline over 40 years from 1960.

The possibility that large-scale land clearance was contributing to the rainfall decline (IOCI 2002; Narisma and Pitman 2003) was further tested by Pitman et al. (2004) following observational studies of the impact of land cover in the southwest (Lyons 2002). The clearance of the land due to European settlement started in the early 19th century. Much of the land clearance occurred by and large during the middle of the 20th century (1920 to 1980). Pitman et al. (2004) were able to simulate a rainfall decline to that observed by reducing forest cover in perpetual July simulations, using regional climate models. The mechanism suggested by Pitman et al. (2004) is that the

land clearance reduces the roughness length, which then increases the low level wind, decreases the moisture convergence, and thus affects the rainfall.

The role of land-use change was again examined in Timbal and Arblaster (2006) who, using a fully coupled climate model forced with natural and anthropogenic atmospheric forcings, found that vegetation cover changes enhanced the model response to anthropogenic atmospheric forcings (including greenhouse gases, ozone and sulphate aerosols). This result was observed directly in model rainfall and in downscaled rainfall. While the rainfall response to anthropogenic forcings was driven mostly by the changes in pressure, the land cover influenced the modelled rainfall (large-scale and total) and thus indirectly the downscaled rainfall. These results, when considered with earlier results (Narisma and Pitman 2003; Pitman et al. 2004), suggest that changes in greenhouse gases and land-use changes both contributed to the observed decline in rainfall in the southwest. However, Timbal and Arblaster (2006) ran only one simulation (rather than an ensemble) with land cover change, their land cover change was about four times larger than has actually occurred, and the uncertainty in the ensemble simulations without land cover changes is such that it is feasible that land cover change is not needed to account for the decline. This is especially the case if the possibility that natural internal climate variability is considered as a possible contributor to the decline (Cai et al. 2005). Finally, none of the experiments thus far conducted would suggest that land cover change might affect large-scale atmospheric pressure, yet the observed decline is closely related to changes in atmospheric pressure (Fig. 8 in IOCI 2002), and with a change in the synoptic patterns affecting the southwest (Hope et al. 2006). Further work is needed to separate the factors responsible for the decline in southwest rainfall.

Further complicating the picture is the possibility that changes in the Southern Annular Mode or SAM (measured by the pressure gradient across mid-latitudes of the southern hemisphere), perhaps due to changes in stratospheric ozone and other factors (Marshall et al. 2004), might be contributing to the rainfall decrease in the southwest. Modelling (Cai and Watterson 2002) and observational (Ansell et al. 2000; Cai et al. 2003; Meneghini et al. 2006; Hendon et al. 2006) studies have shown the positive phase of the SAM (a poleward contraction of the mid-latitude westerlies) to be associated with below average rainfall in the southwest, due to fewer extratropical cyclones and cold fronts passing through the region during winter. During summer, a contrasting pattern of increased rainfall on the southern east coast of Australia and decreased rainfall in western Tasmania

(with little correlation in the southwest) accompanies the positive phase of the SAM (Hendon et al. 2006). However, Meneghini et al. (2006) point out that the correlations with rainfall are generally modest. Therefore, the SAM can only partly explain variability and trends in seasonal Australian rainfall. In particular, they conclude that the trend in SAM cannot explain the decline in rainfall in the southwest. Hendon et al. (2006) concur, pointing out that SAM has exhibited a trend towards its positive phase over the period 1979-2005, but the trend is restricted primarily to the summer and, to a lesser extent, autumn months. As there has been no significant trend in the SAM during winter for this period, it is difficult to ascribe any observed wintertime rainfall or temperature trends to a trend in the SAM. However, southwest rainfall decreased prior to 1979, so it may still be possible that the decline is at least partly related to a trend in SAM prior to the period examined by Hendon et al. (2006).

#### **Increased rainfall in northwest Australia**

Wardle and Smith (2004) altered the albedo over Australia, in a model experiment, and found increased rainfall over the entire continent, although most strongly over the north. Their experiment also resulted in decreased temperatures over the north (and increases over the south), similar to those observed (see Figs 1 and 2). They concluded that the temperature changes were possibly leading to a strengthening of the monsoon and that this was the cause of the increased rainfall. However, their model simulation produced decreased sea-level pressures over most of Australia, while in fact pressures have increased (Fig. 5 – although this figure shows trends in annual mean pressure, there is also no evidence of a decrease in summer pressure over Australia). Note, though, that the albedo change they imposed was not intended to represent a land cover change, but simply used to force a change in land temperature and to investigate the influence of this change on the monsoon.

An alternative explanation for the increased northwest rainfall was provided by Rotstayn (personal communications) who demonstrated that including anthropogenic aerosol changes in 20th century simulations of a global climate model gives increasing rainfall and cloudiness over Australia during 1951-1996, whereas omitting this forcing gives decreasing rainfall and cloudiness. Transient climate model simulations forced only by increased greenhouse gases have generally not reproduced the observed rainfall increase over northwestern and central Australia. The pattern of increasing rainfall when aerosols are included is strongest over northwestern Australia, in agreement with the observed trends. The strong

impact of aerosols is predominantly due to the massive Asian aerosol haze, as confirmed by a sensitivity test in which only Asian anthropogenic aerosols are included. The Asian haze alters the north-south temperature and pressure gradients over the tropical Indian Ocean in the model, thereby increasing the tendency of monsoonal winds to flow towards Australia.

#### **Decline in pan evaporation**

Gifford et al. (2005) concluded that year-to-year (and also decade-to-decade) variability in Australian pan evaporation correlates closely with variation in rainfall (Fig. 5). When rainfall is high, pan evaporation is low, and vice versa (presumably at least partly due to decreased solar insolation due to increased cloudiness in rainy periods). However, not all the 30-year trend in Australian pan evaporation can be attributed to the increase in rainfall over that period, and other factors are needed to explain the decline. Well-understood physical theory (Roderick and Farquhar 2005) indicates that there can be only three causes of declining pan evaporation, decreased net radiation impinging on the pan of water (i.e. less heat input), decreased vapour pressure deficit (VPD) of the air passing over the pan, or decreased wind speed (i.e. less ventilation). Previous investigators have found no evidence of a decline in solar radiation in Australia, although the data are scarce and, because of changes in instrumentation, difficult to compare over decades. Roderick and Farquhar (2005) concluded 'the pan evaporation trends were generally consistent with the trends in the underlying meteorological variables (sunlight, VPD, wind speed) at the five sites examined' and that 'a change in rainfall is not by itself sufficient to explain the long term declines in pan evaporation'. Rayner (2006) demonstrated that, apart from the northwest of the country (where increased cloudiness associated with the rainfall increase may play a role), the observed decline in pan evaporation was clearly related to declines in wind speed. He further demonstrated that these wind speed declines were, in general, likely to be artificial and represent changes in instrumentation or exposure of the instruments, i.e. that the wind speed decline is not representative of widespread wind speed decline. Rayner's results suggest that the decline in pan evaporation is artificial, and results from local changes around the pans.

#### **Decline in snow depth in spring**

Nicholls (2005) showed that the snow season in the Australian Alps was shortening, with less snow remaining early in spring, but that this was due to warming rather than any substantial decline in precipitation. Some earlier speculation that precipitation

was declining very substantially in the Snowy Mountains (and speculation that this was due to urban pollution) was due to problems with District Average Rainfall data and changes in the mix of stations used to calculate these averages (Nicholls 2000).

## Concluding remarks

In recent years, as discussed above, there have been numerous studies addressing the possible causes of various observed climate changes in Australia. However, some areas and variables have been studied more comprehensively than others. Thus, the rainfall decline in the southwest has been examined through the Indian Ocean Climate Initiative and in other studies (and these studies have led to the conclusion that the enhanced greenhouse effect and land-use changes, and possibly natural internal variability, have likely contributed to the decline). The widespread increase in temperature across the continent has been demonstrated to be due to human influences. The pan evaporation decline appears to be due to changes in the exposure of the pans, rather than a widespread change in climate. Some other apparent changes have received less attention, especially the increased rainfall in the northwest and the apparent rainfall decline along the east coast.

An immediate priority for future detection and attribution studies would seem, therefore, to be the decline in rainfall along the east coast and stretching inland from the coast. The rainfall decline in this region of large population and high economic value has not been studied as intensely as has been the decline in rainfall in the southwest, or even the increased rainfall in the northwest. It may well be that the rainfall decline simply reflects natural, internal climate variability. Evidence supporting this supposition includes the fact that the post-1950 decline is weaker if the start date is shifted forwards or backwards a decade. The 1950s were very wet over much of the eastern half of the continent, so the decline since then may represent a 'return to normal'. As well, dry conditions have been evident in this region in earlier decades. It might, therefore, be sufficient to examine the statistics of the rainfall along the coast to determine that the decline is not unusual in a statistical sense (a 'detection' study), rather than also undertaking an attribution study. If this turned out to be the case, then the study would still be useful, in concluding that the decline in rainfall was not unusual and could well be attributable to natural variability.

A second priority is for a comprehensive, formal, Australia-wide detection and attribution study for

rainfall. Thus far, nearly all the attribution studies in Australia have been informal, rather than the formal, statistical studies based on model-based 'fingerprints' of climate change (Karoly and Branganza 2005, is an exception). Although, as discussed earlier, such informal approaches are sometimes needed, and can provide useful information, a formal study of whether we can attribute, in some sense, the post-1950 pattern of Australian rainfall change to human activity, would be more useful, especially since such a formal study would also provide an estimate of the confidence in such a conclusion. The advantage of an Australia-wide study is that the pattern of rainfall change (strong declines in some areas and increases elsewhere) should be harder to reproduce by random variations than would a simple trend (decline or increase) in a specific, smaller area. Thus if it was found that the specific pattern was similar to that expected from a combination of forcings, it would be easier to conclude with confidence that these forcings were responsible for the rainfall pattern change. Such conclusions are unlikely to be reached with similar confidence through continuation of the current 'piecemeal' approach to Australian detection and attribution studies (despite the utility of such studies).

A third priority is to account for the change in surface atmospheric pressure in the Australian region, with decreases in pressure at mid-high latitudes and increases in the subtropics and tropics (Fig. 5), and to account for how these changes relate to the changes in Australian temperature and rainfall. Which of the rainfall trends could be understood, if the change in the pressure pattern could be explained? And which changes in rainfall and temperature may have taken place, despite the changes in circulation?

This review has, generally, focused on possible changes in means or totals, rather than extreme events such as frosts, heat waves, or tropical cyclones. Only a handful of formal detection and attribution studies have been completed for extreme events, thus far. Christidis et al. (2005), mentioned earlier, is a rare exception and demonstrated a human influence on some temperature extremes. Clearly, a greater focus on extremes and the attribution of any changes in their frequency or intensity is required, both globally and for Australia.

## Acknowledgments

The Australian Greenhouse Office provided some support for the preparation of this review. Julie Arblaster kindly provided Fig. 6. The Bureau of Meteorology provided Figs 1-3.

## References

- Allan, R.J. and Haylock, M. R. 1993. Circulation features associated with the winter rainfall decrease in southwestern Australia. *Jnl climate*, 6, 1356-67.
- Ansell, T.J., Reason, C.J.C., Smith, I.N. and Keay, K. 2000. Evidence for decadal variability in southern Australian rainfall and relationships with regional pressure and sea surface temperature. *Int. J. Climatol.*, 20, 1113-29.
- Cai, W. and Watterson, I.G. 2002. Modes of interannual variability of the Southern Hemisphere circulation simulated by the CSIRO climate model. *Jnl climate*, 15, 1159-74.
- Cai, W., Whetton, P. and Karoly, D.J. 2003. The response of the Antarctic Oscillation to increasing and stabilized atmospheric CO<sub>2</sub>. *Jnl climate*, 16, 1525-38.
- Cai, W., Shi, G. and Li, Y. 2005. Multidecadal fluctuations of winter rainfall over southwest Western Australia simulated in the CSIRO Mark 3 coupled model. *Geophys. Res. Lett.*, 32, L12701, doi:10.1029/2005GL022712.
- Christidis, N., Stott, P.A., Brown, S., Hegerl, G. and Caesar, J. 2005. Detection of changes in temperature extremes during the second half of the 20th century. *Geophys. Res. Lett.*, 32, L20716.
- Della-Marta, P.M., Collins, D.A. and Braganza, K. 2004. Updating Australia's high-quality annual temperature dataset. *Aust. Met. Mag.*, 53, 75-93.
- Frederiksen, J.S. and Frederiksen, C. 2006. Inter-decadal Changes in Southern Hemisphere Winter Storm Track Modes. *Tellus* (in press).
- Gifford, R.M., Farquhar, G.D., Nicholls, N. and Roderick, M.L. 2005. Workshop summary. In: Gifford, R.M. (ed), *Pan evaporation: An example of the detection and attribution of trends in climate variables*. Proceedings of a workshop held at the Shine Dome, Australian Academy of Science, Canberra 22-23 November 2004. Australian Academy of Science National Committee for Earth System Science, <http://www.science.org.au/natcoms/pan-evap.pdf>.
- Hendon, H.H., Thompson, D.W.J. and Wheeler, M.C. 2006. Australian rainfall and surface temperature variations associated with the Southern Hemisphere Annular Mode. *Jnl climate* (in press).
- Hope, P. 2005. Reanalysis datasets and potential problems. In: *Indian Ocean Climate Initiative Stage 2: Unabridged Reports of Phase 1 Activity*, [http://www.ioci.org.au/publications/pdf/IOCI\\_Stage2\\_UnabridgedReports\\_Phase1Theme1.pdf](http://www.ioci.org.au/publications/pdf/IOCI_Stage2_UnabridgedReports_Phase1Theme1.pdf).
- Hope, P. 2006. Projected future changes in synoptic systems influencing south west Western Australia. *Climate Dynamics*, doi:10.1007/S00382-006-0116-x.
- Hope, P., Drosowsky, W. and Nicholls, N. 2006. Shifts in the synoptic systems influencing southwest Western Australia, *Climate Dynamics*, doi:10.1007/s00382-006-0115-y.
- IAHDAG, International Ad Hoc Detection and Attribution Group, 2005. Detecting and attributing external influences on the climate system: a review of recent advances. *Jnl climate*, 18, 1291-314.
- IOCI 2002. *Climate variability and change in south west Western Australia*. Indian Ocean Climate Initiative Panel, Perth, 34 pp.
- IPCC 1990. *Scientific assessment of climate change – Report of Working Group I*. Cambridge University Press, Cambridge, 365 pp.
- IPCC 1996. *Climate change 1995: The science of climate change*. Cambridge University Press, Cambridge, 572 pp.
- IPCC 2001. *Climate change 2001: The scientific basis*. Cambridge University Press, Cambridge, 944 pp.
- Jones, D.A. and Trewin, B.C. 2002. On the adequacy of digitised historical Australian daily temperature data for climate monitoring. *Aust. Met. Mag.*, 51, 237-50.
- Karoly, D.J., Braganza, K., Stott, P.A., Arblaster, J. M., Meehl, G.A., Broccoli, A.J. and Dixon, K.W. 2003. Detection of a human influence on North American climate. *Science*, 302, 1200-3.
- Karoly, D.J. and Braganza, K. 2005. Attribution of recent temperature changes in the Australian region. *Jnl climate*, 18, 457-64.
- Lavery, B., Kariko, A. and Nicholls, N. 1992. A historical rainfall data set for Australia. *Aust. Met. Mag.*, 40, 33-9.
- Lavery, B., Joung, G. and Nicholls, N. 1997. An extended high-quality historical rainfall dataset for Australia. *Aust. Met. Mag.*, 46, 27-38.
- Li, F., Chambers, L. and Nicholls, N. 2005. Relationships between rainfall in the southwest of Western Australia and near-global patterns of sea surface temperature and mean sea level pressure variability. *Aust. Met. Mag.*, 54, 23-33.
- Lucas, C., Trewin, B. and Nicholls, N. 2004. Development of an historical humidity database for Australia. *Abstracts for 16th Australia New Zealand Climate Forum*, Lorne, 8-10 November 2004, 59 p.
- Lyons, T.J. 2002. Clouds prefer native vegetation. *Met. Atmos. Phys.*, 80, 131-40. doi:10.1007/s007030200020.
- Marshall, G.J., Stott, P.A., Turner, J., Connolley, W.M., King, J.C. and Lachlan-Cope, T.A. 2004. Causes of exceptional atmospheric circulation changes in the Southern Hemisphere. *Geophys. Res. Lett.*, 31, DOI:10.1029/2004GL019952.
- Meinke, H., deVoil, P., Hammer, G.L., Power, S., Allan, R., Stone, R.C., Folland, C. and Potgieter, A. 2005. Rainfall variability at decadal and longer time scales: Signal or noise? *Jnl climate*, 18, 89-96.
- Meneghini, B., Simmonds, I. and Smith, I.N. 2006. Association between Australian rainfall and the Southern Annular Mode. *Int. J. Climatol.* (in press).
- Narisma, G.T. and Pitman, A.J. 2003. The impact of 200 years of land cover change on the Australian near-surface climate. *J. Hydrometeorol.*, 4, 424-36.
- Nicholls, N. 1988. More on early ENSOs: Evidence from Australian documentary sources. *Bull. Am. Met. Soc.*, 69, 4-6.
- Nicholls, N. 1989. How old is ENSO? *Climatic Change*, 14, 111-15.
- Nicholls, N. 2000. An artificial trend in District Average Rainfall in the Snowy Mountains. *Aust. Met. Mag.*, 49, 255-8.
- Nicholls, N. 2003. Continued anomalous warming in Australia. *Geophys. Res. Lett.*, 30, 1370.
- Nicholls, N. 2004. The changing nature of Australian droughts. *Climatic Change*, 63, 323-36.
- Nicholls, N. 2005. Climate variability, climate change, and the Australian snow season. *Aust. Met. Mag.*, 54, 177-85.
- Nicholls, N., Lavery, B., Frederiksen, C., Drosowsky, W. and Torok, S. 1996. Recent apparent changes in relationships between the El Niño - Southern Oscillation and Australian rainfall and temperature. *Geophys. Res. Lett.*, 23, 3357-60.
- Nicholls, N., Della-Marta, P. and Collins, D. 2004. 20th century changes in temperature and rainfall in New South Wales. *Aust. Met. Mag.*, 53, 263-8.
- Nicholls, N. and Collins, D. 2006. Observed climate change in Australia over the past century. *Energy & Environment*, 17, 1-12.
- Pitman, A.J., Narisma, G.T., Pielke, R.A. and Holbrook, N.J. 2004. The impact of land cover change on the climate of south west Western Australia. *J. Geophys. Res.*, 109, D18,109.
- Power, S., Tseitkin, F., Torok, S., Lavery, B., Dahni, R. and McAvaney, B. 1998. Australian temperature, Australian rainfall and the Southern Oscillation, 1910-1992: coherent variability and recent changes. *Aust. Met. Mag.*, 47, 85-101.
- Power, S., Casey, T., Folland, C., Colman, A. and Mehta, V. 1999. Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics*, 15, 319-24.
- Rayner, D.P. 2006. Wind run changes are the dominant factor affecting pan evaporation trends in Australia. *Jnl climate* (in press).
- Roderick, M. and Farquhar, G.D. 2004. Changes in Australian pan evaporation from 1970 to 2002. *Int. J. Climatol.*, 24, 1077-90.
- Roderick, M. and Farquhar, G.D. 2005. An analysis of pan evaporation changes in relation to possible explanatory factors. In:

- Gifford, R.M. (ed), *Pan evaporation: An example of the detection and attribution of trends in climate variables*. Proceedings of a workshop held at the Shine Dome, Australian Academy of Science, Canberra 22-23 November 2004. Australian Academy of Science National Committee for Earth System Science, <http://www.science.org.au/natcoms/pan-evap.pdf>.
- Root, T.L., MacMynowski, D.P., Mastrandrea, M.D. and Schneider, S.H. 2005. Human-modified temperatures induce species changes: Joint attribution. *Proc. Nat. Acad. Sciences*, *102*, 7465-9.
- Simmonds I. and Keay, K. 2000. Variability of Southern Hemisphere extratropical cyclone behavior, 1958-97. *Jnl climate*, *13*, 550-61.
- Smith, I.N. 2004. Trends in Australian rainfall - are they unusual? *Aust. Met. Mag.*, *53*, 163-73.
- Smith, I.N., McIntosh, P., Ansell, T.J., Reason, C.J.C. and McInnes, K. 2000. Southwest Western Australian winter rainfall and its association with Indian Ocean climate variability. *Int. J. Climatol.*, *20*, 1913-30.
- Smith, I. and Hope, P. 2005. How our winter atmospheric circulation has changed, [http://www.ioci.org.au/publications/pdf/IOCIclimatenotes\\_4.pdf](http://www.ioci.org.au/publications/pdf/IOCIclimatenotes_4.pdf)
- Stott, P.A. 2003. Attribution of regional-scale temperature changes to anthropogenic and natural causes. *Geophys. Res. Lett.*, *30*, 1728, doi:10.1029/2003GL017324.
- Stott, P.A., Stone, D.A. and Allen, M.R. 2004. Human contribution to the European heatwave of 2003. *Nature*, *432*, 610-14.
- Timbal B. 2004. Southwest Australia past and future rainfall trends. *Clim. Res.*, *26*, 233-49
- Timbal, B. and Arblaster, J.M. 2005. Land cover change as an additional forcing to explain the rainfall decline in the southwest of Australia. *Geophys. Res. Lett.*, *33*, LO7717, doi:10.1029/2005GL025361.
- Timbal, B., Arblaster, J.M., and Power, S.P. 2006. Attribution of the late 20th century rainfall decline in Southwest Australia. *Jnl climate*, *19*, 2046-62.
- Torok, S.J. and Nicholls, N. 1996. A historical annual temperature dataset for Australia. *Aust. Met. Mag.*, *45*, 251-60.
- Trewin, B.C. 2001. Extreme temperature events in Australia. PhD Thesis, School of Earth Sciences, University of Melbourne, Australia.
- Trewin, B., Jones, D., Collins, D., Jovanovic, B., Lucas, C. and Jakob, D. 2006. Homogenised Australian climate data sets used for climate change monitoring. *Workshop on Climate Variability and Extremes During the Past 100 Years*, Gwatt, Switzerland, 24-26 July 2006.
- Trewin, B. and Collins, D. 2006. Century-scale temperature data sets for Australia. *Workshop on Climate Variability and Extremes During the Past 100 Years*, Gwatt, Switzerland, 24-26 July 2006.
- von Storch, H. and Zwiers, F.W. 1999. *Statistical Analysis in Climate Research*. Cambridge University Press, Cambridge CB2 2RU, UK, 484 pp.
- Wardle, R. and Smith, I. 2004. Modelled response of the Australian monsoon to changes in land surface temperatures, *Geophys. Res. Lett.*, *31*, L16205, doi:10.1029/2004GL020157.
- Watterson, I.G. 2001. Wind-induced rainfall and surface temperature anomalies in the Australian region. *Jnl climate*, *14*, 1901-22.
- White, W.B., McKeon, G. and Syktus, J. 2003. Australian drought: The interference of multi-spectral global standing modes and travelling waves. *Int. J. Climatol.*, *23*, 631-62.
- Zwiers, F.W. and Zhang, X. 2003. Toward regional-scale climate change detection. *Jnl climate*, *16*, 793-7.