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Department of the Environment and Water Resources
Australian Greenhouse Office

DETECTING, UNDERSTANDING & ATTRIBUTING CLIMATE CHANGE

A background report on research priorities prepared for the Australian Greenhouse Office

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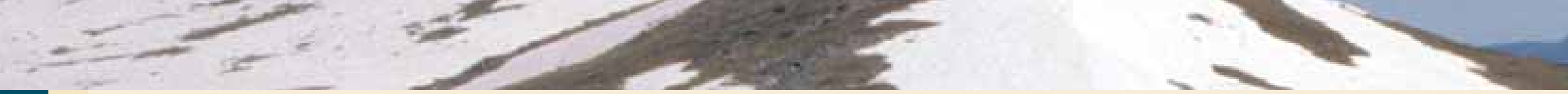


EXECUTIVE SUMMARY

Climate has always varied, since well before humans evolved. Now, however, we are changing the climate. *Climate change* is defined as a change that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of one or more climate variables (e.g. rainfall, temperature) that persists for, typically, decades or longer.

Societal responses to climate change can be improved if we can determine the cause of the change. This requires 'climate change detection and attribution' studies. *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 due to internal, natural climate variability alone is small. *Attribution* is the process of establishing the most likely causes for the detected change with some defined level of confidence.

Evidence of human influence on the global climate has accumulated steadily during the past two decades. A recent review of such global 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."

The major Australian climate trends observed over the past 50 years or so are:

- Mean maximum (day time) temperature has increased over most of Australia, with cooling in the north-west (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 north-west (in all seasons except spring, but the location of the cooling varies somewhat between seasons).
- Annual rainfall has increased in the north-west (in summer), and decreased in the south-west (in winter) and along and inland from the east coast (Queensland in summer; New South Wales and Victoria in autumn and winter).

Detection and attribution studies of Australian climate indicate that:

- The widespread warming is very likely to be due to increased greenhouse gas concentrations in the atmosphere.
- The rainfall decrease in south-west 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 north-west Australia may be due to increased aerosol particles in the atmosphere resulting from human activity, especially in Asia.

The *highest priorities* for new detection and attribution studies are, in order:

- The decline in east coast and south-east rainfall.
- Changes in atmospheric circulation across the Australian region.
- Possible changes in drought frequency and/or intensity.
- Possible changes in tropical cyclone frequency and/or intensity.
- Changes in extreme temperatures.
- Ocean changes around Australia (temperature, sea level, circulation, chemistry).

WHY IS UNDERSTANDING THE CAUSES OF CLIMATE CHANGE IMPORTANT?

Climate has always varied. In Australia, the impact of the El Niño-Southern Oscillation (ENSO) 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*[1] (such as orbital variations), will continue to affect the climate in the future, and are beyond human influence.

However, climate changes resulting from human activity such as alterations 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 mitigate and/or adapt to expected climate change is to determine whether we are already changing the climate, and in what ways. This is the process of ‘climate change detection and attribution’.

WHAT IS CLIMATE CHANGE DETECTION AND ATTRIBUTION?

The concepts of climate change *detection and attribution* were defined in the Intergovernmental Panel on Climate Change’s 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 regions with drying elsewhere.

Because detection studies are necessarily statistical in nature, the inferences that can be made about whether an external influence has been detected can never be absolutely certain. It is always possible that a statistically significant result at, say, the 5% level, could simply reflect a rare event (e.g. a trend) that would have occurred in any case with less than one chance in 20 in an unchanged climate. Corroborating lines of evidence providing a physically consistent view of the likely cause for the changes may reduce the risk of such spurious detection.

Detection does not, by itself, establish the cause of the climate change. *Attribution* is the process of establishing the most likely causes of the detected change with some defined level of confidence. Unequivocal attribution would require controlled experimentation with our climate system. That is not generally 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” (IPCC 2001).

BOX 1:

Climate change – two definitions

Climate change, for the purposes of this report, is defined as a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability, and that persists for an extended period, typically decades or longer. This definition corresponds with that adopted by the Intergovernmental Panel on Climate Change (IPCC).

With this definition, *climate change* may result from internal processes of the climate system and/or external forcings. Some external influences, such as changes in solar radiation and volcanism, occur naturally and contribute to the total natural variability of the climate system. Other external changes, such as the change in the composition of the atmosphere that began with the industrial revolution, are the result of human activity.

This IPCC definition differs from that adopted by the United Nations Framework Convention on Climate Change (UNFCCC) where *climate change* refers to a change in the climate that is attributable directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods.

Under the UNFCCC definition, natural processes (either internal to the climate system or external, such as volcanic activity) do not result in *climate change*, nor does other human activity such as land use change.

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

[1] Some definitions are included in the Glossary at the end of this report.

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 external 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, or is associated with a rainfall increase, may indicate an external influence on the climate of that region (e.g. Nicholls *et al*. 2004).

The third requirement for attribution in the above list 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 is also 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 palaeo-climatic data and climate simulations of the last millennium.

BOX 2:

Other uses of detection and attribution studies

The focus of this report is on the use of detection and attribution studies to determine the likely causes of recent changes in climate variables. However, there are other uses of detection and attribution studies. These include:

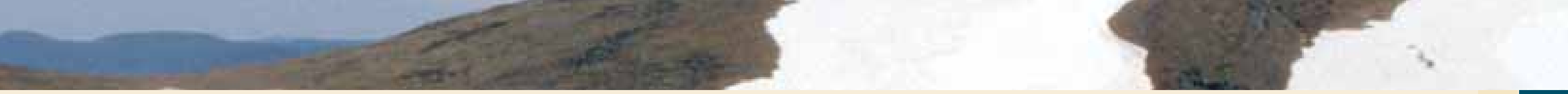
- assessing the credibility of climate models (by examining how well model simulations reproduce observed changes in climate variables when all important forcings are included), and
- constraining climate projections (by using detection and attribution studies to determine which models are most credible, for instance).

Stott *et al*. (2006) provide an example of how detection and attribution studies can constrain projections of climate change. More tightly constrained predictions of temperature change were obtained by using the errors in global mean temperature change to scale the regional projections. Probabilistic forecasts of future warming rates in continental-scale regions were produced by assuming that a model that under- or over-estimates the climate response will under- or over-estimate the climate response in the future.

Karoly and Braganza (2005b) illustrate the value of detection and attribution studies in model validation in their study of Australian temperature variability. They found that model-simulated temperature variations were closer to the variations observed if the rainfall-related part of the temperature variations were first removed, suggesting that problems with simulation of rainfall, cloudiness, soil moisture or surface energy balance were degrading the performance of the models.

Detection and attribution studies can also focus on past climate changes inferred from palaeo-climatic data. Such climate changes are the result of natural processes, rather than human causes, so they can inform studies of modern climate change by determining how strongly and rapidly climate can change without human interference. In this report, however, the focus is on the causes of modern, especially post-1950, climate change.

Model and forcing uncertainties are important considerations in attribution studies. Model uncertainty includes uncertainties in model parameters and in the representation of physical processes in models (the latter is called *structural uncertainty*). The effects of uncertainties in the history of changes in some forcing agents such as solar and aerosol forcing are difficult to evaluate. Detection and attribution studies that use several models or several forcing histories provide information on the effects of model and forcing uncertainty. Such considerations suggest that while model uncertainty is important, key results such as the attribution of a human influence on global temperature change during the latter half of the 20th century are robust.



The usual, formal approach to detection and attribution is described briefly in the Appendix. Such complete detection and attribution studies are not yet feasible for all climate variables (e.g. no formal studies have been undertaken of ocean wave height) and few formal studies have been applied to climate change in Australia (and only for temperature, as yet). This lack of formal studies is particularly true for variables such as rainfall that are less reliably modelled, or are expected to respond less strongly to external forcing. This is even more pertinent when regional changes, e.g. south-west Western Australia, are considered – considerable uncertainty exists in model simulations of such regional rainfall changes. But these regional Australian 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 global attribution 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, a decision-maker may ask, "Are the continuing drier-than-normal conditions in the south-west 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 south-west, 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 (e.g. von Storch and Zwiers 1999). Nevertheless, there is a need for answers for such questions, and studies that adopt this approach are also considered in this report, when we review 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. However, 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, leading the TAR (IPCC, 2001) 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. Even more detection and attribution studies were carried out subsequent to the TAR, and the IAHDAG (2005), after reviewing recent detection and attribution 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 (solar and volcanic forcing) were 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 explain the warming in the second half of the 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. Climate models are only able to reproduce observed temperature changes over the 20th century when they include anthropogenic forcings and their failure to do so when they exclude anthropogenic forcings is strong evidence of the influence of humans on global climate. 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. Analyses of 20th century spatial and temporal changes in temperature indicate that there has likely been a cooling influence from aerosols and natural forcings counteracting some of the warming influence of the increasing concentrations of 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 2005a, 2005b). 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, particularly 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).

Some climate variables other than temperature also show 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 'sequential 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 evidence of change over time of surface temperature.

The Summary for Policymakers of the contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (approved Paris, February 2007) concluded that:

- Most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* (> 90% likelihood) due to the observed increase in anthropogenic greenhouse gas concentrations.
- It is *likely* (> 66% likelihood) that increases in greenhouse gas concentrations alone would have caused more warming than observed because volcanic and anthropogenic aerosols have offset some warming that would otherwise have taken place.
- The observed widespread warming of the atmosphere and ocean, together with ice mass loss, support the conclusion that it is *extremely unlikely* (> 95% likelihood) that global climate change of the past fifty years can be explained without external forcing, and *very likely* (> 90% likelihood) that it is not due to known natural causes alone.
- It is *likely* (> 66% likelihood) that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica.
- Anthropogenic forcing is *likely* (> 66% likelihood) to have contributed to changes in wind patterns13, affecting extra-tropical storm tracks and temperature patterns in both hemispheres.
- Temperatures of the most extreme hot nights, cold nights and cold days are *likely* (> 66% likelihood) to have increased due to anthropogenic forcing. It is *more likely than not* (> 50% likelihood) that anthropogenic forcing has increased the risk of heat waves.

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.

AUSTRALIAN CLIMATE TRENDS SINCE THE MID-20TH CENTURY

Temperature

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

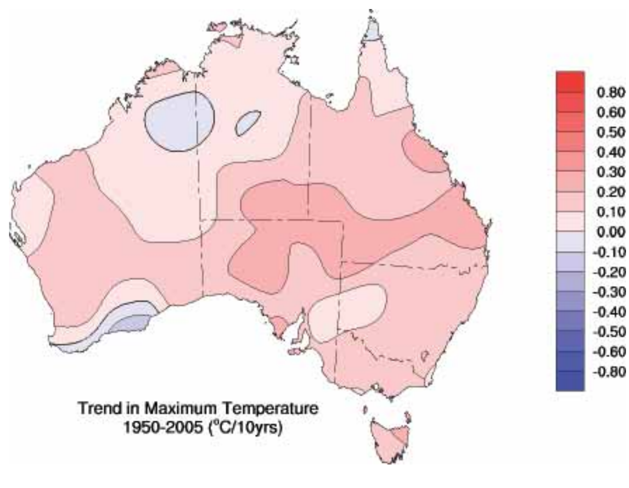
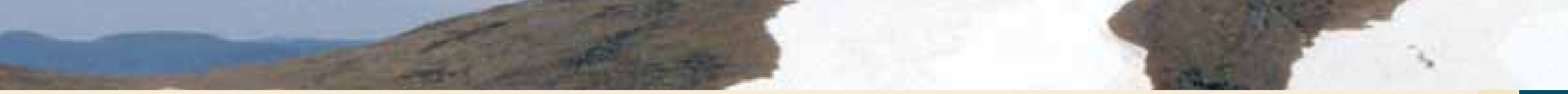


Figure 1

Trend in annual mean maximum temperature 1950-2005.



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.

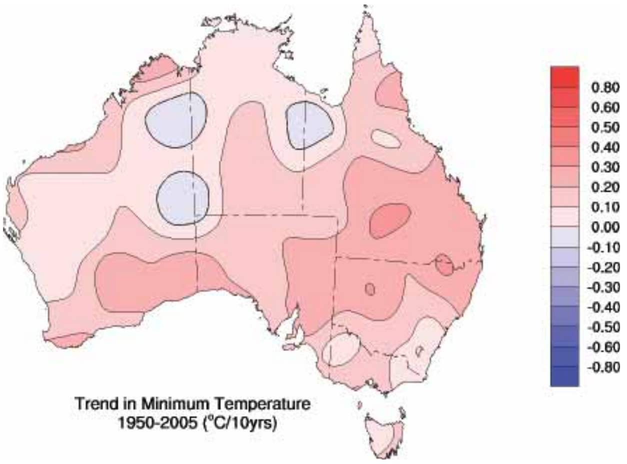


Figure 2

Trend in annual mean minimum temperature 1950-2005.

BOX 3

Australian climate data – quality and availability

The Australian Bureau of Meteorology has developed a number of data sets for use in climate change monitoring. These data sets typically include 50-200 stations distributed as evenly as possible over the Australian continent, and have been subject to detailed quality control and adjustments for changes in instrumentation or instrumental exposure (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 *et al*. 2006).

The period for which data are available for each climate variable is largely determined by the availability of data in digital form. Whilst nearly all Australian monthly and daily precipitation data have been digitised, a significant quantity of pre-1957 data (for temperature and evaporation) or pre-1987 data (for some other elements) is yet to be digitised, and so is not currently available for use in the climate change monitoring. In the case of temperature and evaporation, the start date of the data sets is also determined by major changes in instruments or observing practices for which no adjustment is feasible at the present time.

The data sets currently available cover:

- 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);
- Dewpoint/relative humidity (commences 1957); and
- Monthly and daily evaporation (commences 1970).

Data sets covering cloud amount, wind speed and mean sea level pressure are under development. The development of a homogenised wind speed data set is expected to be particularly challenging because of the great sensitivity of measured wind speed to changes in instruments or the local site environment, and a lack of field comparison studies between different types of instruments used over the period of record.

The trends based on these data sets, as they become available, can be found at http://www.bom.gov.au/cgi-bin/silo/reg/cli_chg/trendmaps.cgi. This site uses gridded analyses based on the data sets, and also provides more information about the data sets.

Care does need to be taken with using Australian climate data sets. 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).

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 north-west (mainly in summer). Decreases are evident in the south-west (in winter) and the east coast and south-east. 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. Gallant and Hennessy (2006) provide more detail on these trends.

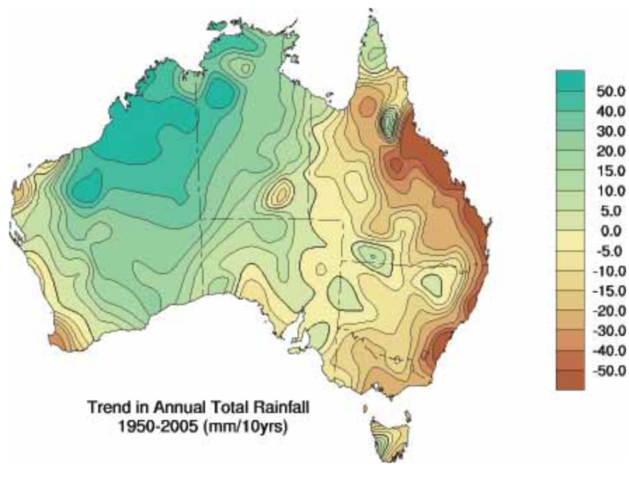


Figure 3

Trend in annual rainfall total 1950-2005

Drought

Outside the regions with pronounced decreases in total rainfall (especially south-west Western Australia) recent Australian droughts (1994, 2002), 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 – see Fig. 4).

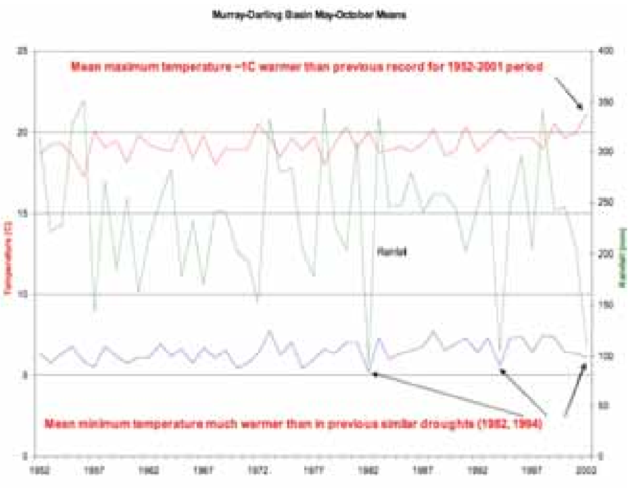


Figure 4

Time-series of May-October total rainfall, and mean maximum and minimum temperatures across the Murray Darling Basin (Nicholls 2004).

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. Dai *et al*. (2004) produced time-series of the Palmer Drought Severity Index (PDSI) and demonstrated that many regions (including eastern and south-west Australia) exhibited a trend towards 'droughtier' behaviour, as measured by the PDSI. Although Dai *et al*. demonstrated that the PDSI is related to soil moisture and runoff, a more physically based drought index may be more appropriate. Day *et al*. (2003) discuss the problems and possibilities of using rainfall alone as a drought indicator.

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 Figure 5, 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).

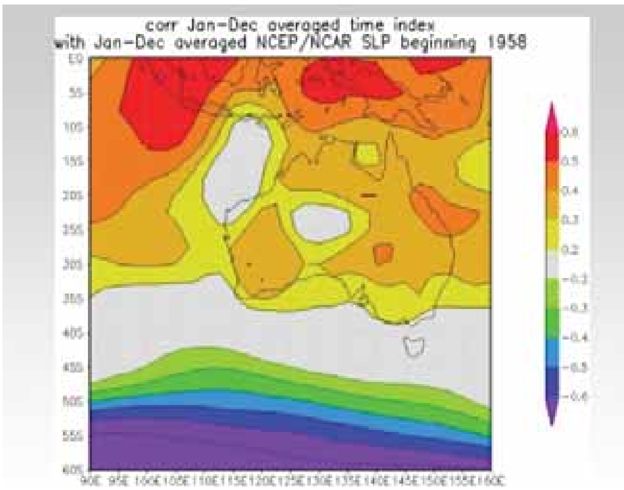


Figure 5

Correlation of annual sea level pressure with year 1958-date (from NCEP/NCAR Reanalyses)

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. 6).

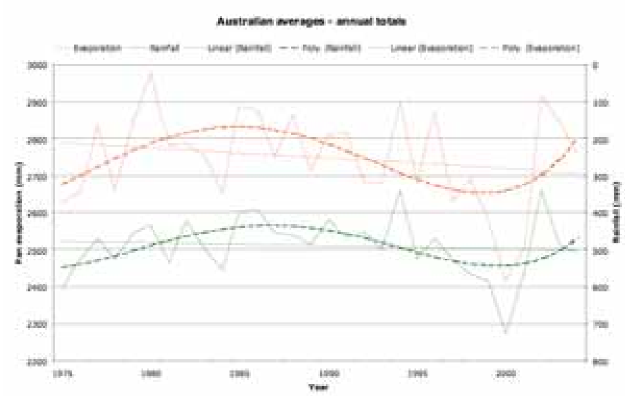
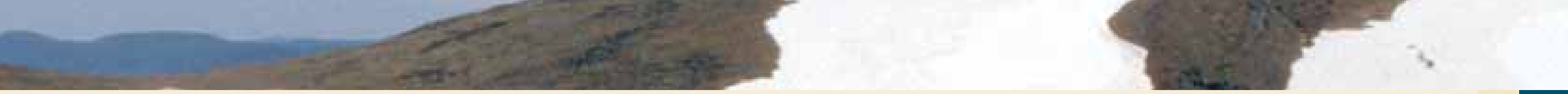


Figure 6

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

The variability around the downward trend involves a decrease in the early 1970s, followed by an increase up to the early 1980s, then a decrease over the next two decades before increasing from 2001. The overall downward trend averaged 2.8 mm per year per year for the 30 years since 1975 (when widespread reliable data became available). Overall, there has been a 3% decrease of the annual pan evaporation rate over 30 years (Roderick and Farquhar 2004, Jovanovic *et al*. 2006, Gifford *et al*.



2005) although this is probably not statistically significant, given the year-to-year variability evident in Figure 6.

Ocean temperatures around Australia have generally warmed, but there are geographical variations in the amount of this warming (Fig. 7).

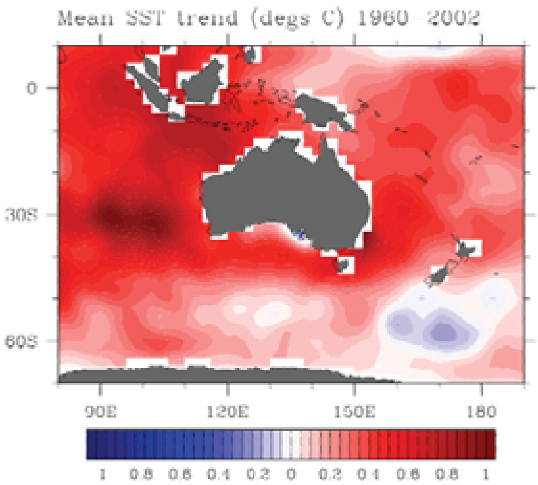


Figure 7

Linear trend in sea surface temperature 1960-2002 (ºC) (Courtesy of Caroline Ummenhofer)

Maximum winter snow depth (Nicholls 2005) at Spencers Creek in the Snowy Mountains of south-eastern Australia has decreased slightly since 1962, but the snow depth in spring has declined strongly (by about 40%, Fig. 8).

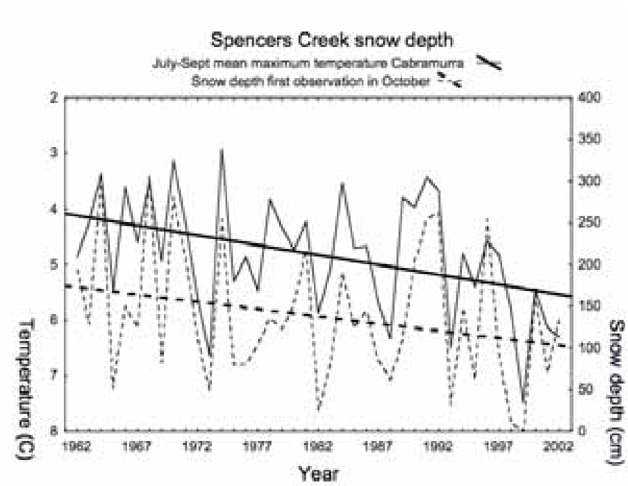


Figure 8

Snow depth at Spencers Creek in first observation in October (broken lines) and July-September mean maximum temperature at Cabramurra (full lines – note reversed scale). Trends shown as thick lines. (Nicholls, 2005).

Investigation of trends in other variables (especially surface humidity, cloudiness and wind speed) awaits the development of high-quality historical data sets of these variables. A complete understanding of how and why Australia's climate has been changing will not be possible until these data sets are completed and have been studied.

WHAT IS KNOWN ABOUT THE POSSIBLE CAUSES OF THESE TRENDS?

Considerable research has been carried out to determine the causes of inter-annual and inter-decadal variations in the Australian climate (e.g. Power *et al*. 1999, Meinke *et al*. 2005, Power *et al*. 2006). Many of these studies have focussed on the effects of the El Niño-Southern Oscillation on Australian rainfall and temperature. Some studies also investigated the impact of variations in the Indian Ocean on inter-annual variations of the Australian climate.

However, the focus of this section is 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 seasonal to inter-annual 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, although rather little work has been done on this topic.

Widespread warming

Figure 9 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 contributed to the observed Australian warming in recent decades.

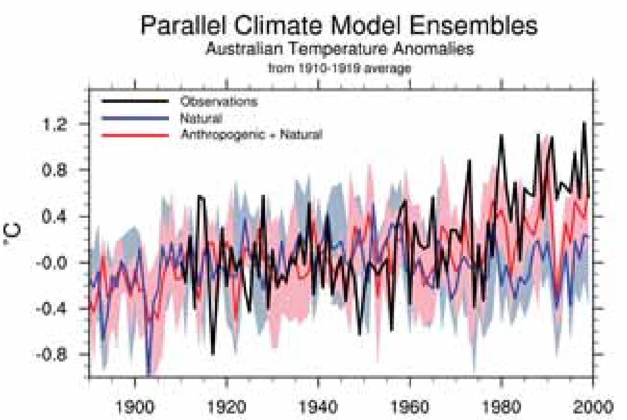


Figure 9

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

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 (2005a) however, using a variety of simple temperature indices (mean maximum and mean minimum temperatures, mean temperature, and mean diurnal temperature range), and different climate models, and a slightly different temperature data set[2] 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”.

Karoly and Wu (2005) examined even smaller regions for evidence of an anthropogenic influence on temperature. They compared observed trends in surface temperature over the last 100, 50, and 30 years at individual grid boxes in a 5° latitude–longitude grid with model estimates of the natural internal variability of these trends and with a model response to increasing greenhouse gases and sulphate aerosols. Significant warming trends were observed at a large fraction of the individual grid boxes over the globe, a much larger fraction than could be explained by internal climate variations. The observed warming trends over the last 50 and 30 years were consistent with the modelled response to increasing greenhouse gases and sulphate aerosols in the models leading Karoly and Wu to conclude that they had detected warming trends consistent with the response to anthropogenic forcing at scales on the order of 500 km in many regions of the globe (including the Australian region).

A different approach was adopted by Nicholls *et al*. (1996) and Nicholls (2003) who examined the relationship between observed Australian-average maximum temperature and rainfall variations, demonstrated that the recent increase in temperatures was unconnected with changes in rainfall (unlike previous long-term changes and inter-annual scale variations), and concluded that the recent warming was therefore unlikely to be due to natural climate trends.

Karoly and Braganza (2005b) extended this concept by removing the rainfall-related component of the temperature variations using linear regression. Trends in the residual variations of maximum, mean and minimum temperature over the last 50 years could not be explained by natural climate variations and were consistent with the response to increasing greenhouse gases and sulphate aerosols in the climate models. This new approach was able to enhance the signal-to-noise ratio for anthropogenic temperature change signals in the Australian region and to show that there is a clear anthropogenic warming signal in observed regional temperature trends, even for regions as small as the south-east of Australia.

BOX 4:

Climate models – credibility for attribution studies

Model and forcing uncertainties are important considerations in attribution research. Ideally, the assessment of model uncertainty should include uncertainties in model parameters, and in the representation of physical processes in models (structural uncertainty). Such an assessment is not yet available, although research with that goal in mind is underway and model intercomparison studies continue to improve our appreciation of these uncertainties.

The effects of forcing uncertainties, which can be considerable for some forcing agents (such as solar and aerosol forcing) also remain difficult to evaluate, despite advances in research. Detection and attribution results that are based on several models or several forcing histories do provide information on the effects of model and forcing uncertainty that leads towards a more reliable attribution of climate change to a cause. Such considerations suggest that while model uncertainty is important, key results, such as attribution of a human influence on global temperature change during the latter half of the 20th century, are robust.

The frequency of extreme temperatures has changed in Australia, with a tendency for increased numbers of warm days/nights and fewer cool days/nights (Nicholls and Collins 2006) similar to what has been observed throughout east Asia and west Pacific (Griffiths *et al*. 2005). Griffiths *et al*. (2005) also showed that the frequency of extremes was largely determined by changes in mean temperatures. So, to the extent that regional-scale mean temperatures have changed as a result of human interference with the atmosphere (e.g. Stott 2003, Karoly and Braganza 2005a, 2005b) it is reasonable to conclude that the changes in frequency of extremes in Australia (e.g. heat waves) can also be attributed to human factors.

Are changes in atmospheric circulation contributing to these warming trends? Not a great deal of work has been done on this aspect of the problem. 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 considered by Hendon *et al*. (1979-2005), the long-term warming in the south-east has been weaker than elsewhere. This region of mitigated 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 0.5ºC. 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.

[2] Karoly and Braganza (2005) use the Australian high quality annual temperature data set updated by Della-Marta et al. (2004) based on Torok and Nicholls (1996).

Drought

White *et al*. (2003) reported that in Australia extended periods of drought resulted from the constructive interference of quasi-decadal and inter-decadal global sea surface temperature/sea level pressure (SST/SLP) modes/waves, accompanied by a weakening of year-to-year variability associated with either weak quasi-biennial and inter-annual 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 extra-tropical 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.

As yet, no study has credibly attributed a change in the duration or frequency of Australian droughts to anthropogenic factors, although there is evidence (see below) that rainfall changes in some parts of Australia have been at least partly the result of human influences. Such changes would also, most likely, have resulted in changes in drought frequency and/or duration. Dai *et al*. (2004) found trends in drought in Australia, as measured by the Palmer Drought Severity Index (PDSI), although there are concerns about the validity of the PDSI in monitoring drought.

Rainfall decline in south-west Western Australia

IOCI (2002) reported that winter rainfall in the south-west of Western Australia has decreased substantially since the mid-20th century. The rainfall decrease was observed in autumn and early winter (March-July) rainfall; late winter (August-October) rainfall has actually increased by a small amount. The winter rainfall sharply and suddenly decreased in the mid-1970s by about 15-20%. It was not a gradual decline but more of a switching into an alternative rainfall regime. The rainfall decrease 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% 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 south-west is the change in atmospheric pressure. Smith *et al*. (2000) found a reduction in the number of low-pressure systems in the period 1969-1978 compared with 1959-1968 across the south-west 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 cyclones in the south-west region. Charles *et al*. (2004) used downscaling techniques to reproduce the change in synoptic conditions affecting the south-west.

Hope *et al*. (2006) reported that the frequency of the troughs associated with wet conditions across the south-west has declined markedly since 1975 while the frequency of the synoptic types with high pressure over the continent (usually associated with dry conditions in the south-west) 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. Hope *et al*. (2006) also found that the amount of rainfall from less intense systems had decreased. This decrease is most likely linked to a shift in the location of the storms, but may be linked to local causes.

There have been some suggestions that changes in circulation associated with 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 south-west. 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 south-west, due to fewer extra-tropical 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 south-west) 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 the SAM cannot explain the decline in rainfall in the south-west. Hendon *et al*. (2006) concur, pointing out that the SAM has exhibited a trend towards its positive phase over the period 1979-2005, but the trend is restricted primarily to the summer 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, south-west rainfall decreased prior to 1979, and has seen little change since, so it may still be possible that the decline is at least partly related to a trend in the SAM prior to the period examined by Hendon *et al*. (2006). Cai and Cowan (2006) also found, using a variety of climate model simulations, that the changes in the SAM (which they confirmed were likely due to stratospheric ozone depletion) did not contribute much to the observed decline in winter rainfall in the south-west.

Frederiksen and Frederiksen (2006) examined the 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 north-south temperature gradient and in upper tropospheric jet-stream zonal winds near 30ºS. As a consequence of these changes, the atmosphere has been more stable during the later period 1975-94 for latitudes around 30ºS but also less stable 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 1975-94 has a growth rate which is around 30% smaller than for 1949-68 and on average the 10 leading Southern Hemisphere cyclogenesis modes for 1975-94 have growth rates that are 32% smaller than for the corresponding modes for 1949-68. These results suggest that a primary cause of the rainfall reduction over the south-west 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 are in turn attributable to the changes in the large-scale Southern Hemisphere circulation.

The above studies discuss the proximate causes of the rainfall decline, but other studies are required to attribute the ultimate cause of the decline. 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, IOCI (2002) concluded that the changes are not sufficiently similar to indicate 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 south-west, without changes in external forcings (Cai *et al*. 2005). 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 south-west, or increased local air pollution, seemed unlikely to be major factors in the rainfall decrease, but were thought to be possible secondary contributors.

Subsequently, Narisma and Pitman (2003) found that south-western Australia winter rainfall decreased in their climate model if they replaced original (1788) vegetation over Australia with modern vegetation type and cover. 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 seems unlikely that changes in land use further inland could be the principal cause of these substantial rainfall decreases, although any circulation or wind speed changes induced over the continent may have an ‘upstream’ effect.

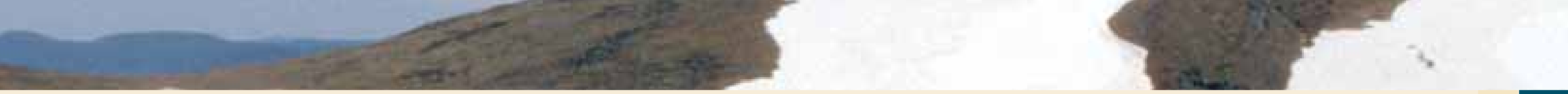
Another argument against the possibility that land use changes might be the primary factor in the rainfall decline is that the observed rainfall decrease has been associated with a change in the large-scale pattern of climate variability (e.g. surface atmospheric pressure – see earlier comments), so any local changes are likely only to be a secondary, contributing factor, rather than being the principal cause of the decline in rainfall.

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 south-west rainfall variability. The technique was applied to two four-member ensembles of simulations of the climate from 1870 to 1999 performed with the NCAR Parallel Climate Model. The first ensemble (‘Natural’) was forced with natural variations in both volcanic activity and solar forcing. The second ensemble (‘Full Forcing’) also included human-induced forcing from changes in greenhouse gases, ozone and aerosols.

The ‘Full Forcing’ runs provided a better match to observational changes in sea surface temperature in the vicinity of the south-west. The observed rainfall decline was not well captured by rainfall changes simulated directly by the model in either ensemble. The downscaling approach provided a more accurate reproduction of the variability of rainfall in the south-west than did the rainfall simulated directly by the model. The downscaled ensemble mean rainfall in the ‘Full Forcing’ ensemble declined with a spatial pattern of change similar to that observed. On the other hand, rainfall increased in the downscaled ‘Natural’ ensemble simulations.

These results provide a clearer indication that anthropogenic forcing may have played a role in the drying of the south-west. However, although the observed decline fits within the range of downscaled model simulations, the ensemble mean rainfall decline is only about half the strength of the observed decline, 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 or 1970s, followed by a near constant rainfall regime, the ‘Full Forcing’ ensemble suggested a more gradual rainfall decline over 40 years from 1960. The model also simulated a decline in spring rainfall, which has not been observed.

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 apparent impact of land cover in the south-west (Lyons 2002). Pitman *et al*. (2004) were able to simulate a rainfall



decline similar 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. This mechanism could conceivably explain why rainfall declined ‘upstream’ of the continent (e.g. Rottnest Island).

The possibility that land use change was contributing to the rainfall decline was further developed 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, suggest that changes in greenhouse gases and land use changes contributed to the observed decline in rainfall in the south-west.

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 local land cover change might affect large-scale atmospheric pressure, yet the rainfall decline is clearly being driven by this large-scale circulation change (Figure 8 in IOCI 2002), and by changes in the synoptic patterns affecting the south-west (Hope *et al*. 2006). Further work is clearly needed to separate the responsibility for the decline in south-west rainfall. But, although work since IOCI (2002) has strengthened the possibility that land cover change is contributing to the rainfall decline, there still seem to be strong arguments that the principal driver of the decline is a much larger scale factor (most likely anthropogenic change to atmospheric greenhouse gases).

A different approach has recently been taken by Smith (2006) who reports that the rainfall decline in the south-west is correlated with global surface temperature variations. This association, while not proving a causal relationship, does suggest that the enhanced greenhouse effect may be implicated in the rainfall decline, thereby providing support for the model-based studies noted above.

Increased rainfall in north-west 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 Fig. 1 and Fig. 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 (whatever might be the cause of such continental warming) on the monsoon.

An alternative explanation for the increased north-west rainfall was proposed by Rotstayn *et al*. (2006) 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 north-western and central Australia. The pattern of increasing rainfall when aerosols are included is strongest over north-western 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. The results from Rotstayn *et al*. (2006) suggest that a possible reason for this failure may be the omission of forcing by Asian aerosols. However, their simulations do not reproduce the Australia-wide pattern of rainfall trends shown in Figure 3.

Smith (2006) reported a significant correlation between the increase in summer rainfall in the north-west and global surface temperature variations. This association implies a relationship between the rainfall increase and the factors leading to the increase in global temperature, most likely the enhanced greenhouse effect.

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. 6). When rainfall is high, pan evaporation is low, and vice versa (presumably at least partly due to decreased 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 windspeed (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."

The underlying causes of the changes in sunlight, vapour pressure deficit and wind speed, remain to be explained. Rayner (2006) demonstrated that at least some of the apparent decline in pan evaporation was associated with apparently artificial declines in wind speed at the observing site (resulting presumably from site or exposure changes). The detailed explanation of why pan evaporation has not increased as temperatures have increased remains to be documented.

Atmospheric circulation and pressure

As noted above, the Southern Annular Mode (SAM) has exhibited a trend towards its high index polarity over the period 1979-2005, but the trend is restricted primarily to the summer and, to a lesser extent, autumn months (Thompson and Solomon 2002, Marshall 2003). As there has been no significant trend in the SAM during winter for this period, it is difficult to ascribe any observed Australian wintertime rainfall or temperature trends to a trend in the SAM (see above). This does not preclude, however, the possible contribution of the SAM to the wintertime rainfall decline in the south-west prior to 1979 (e.g. Smith 2004), however reliable estimates of daily variations in the SAM in global reanalyses are not available prior to the satellite era (~1970s; e.g. Marshall 2003) to enable this possibility to be checked.

What has caused the changes in the SAM? Although the annular modes are naturally occurring patterns of variability in the climate system, they are sensitive to increasing greenhouse gases and ozone depletion in model simulations (e.g. Shindell *et al*. 1999, Fyfe *et al*. 1999, Kushner *et al*. 2001, Cai *et al*. 2003, Gillett and Thompson 2003, Miller *et al*. 2006, Arblaster and Meehl 2006). Over the past few decades, the SAM has exhibited a positive trend during austral summer that is consistent with forcing by the Antarctic ozone hole (Thompson and Solomon 2002, Gillett and Thompson 2003). Detection of an upward trend in the SAM during winter post-1979 (the satellite era) has not been substantiated. However, model simulations suggest that increased greenhouse gases should also act to drive the SAM into its high polarity phase during winter. A reliable estimate of the SAM is required in the pre-satellite era in order to substantiate the possible upward trend in the SAM during winter and to possibly attribute it to enhanced greenhouse gases.

There have also been changes in Southern Hemisphere synoptic activity. Simmonds and Keay (2000) analysed the variability and trends associated with Southern Hemisphere cyclones as represented in the NCEP/NCAR reanalyses. Over the last four decades, sea level pressures have decreased south of 40ºS and increased north of this latitude, a result confirmed by independent analysis of the ERA-40 dataset and an ensemble of IPCC scenarios by Lynch *et al*. (2006), and consistent with the findings of Cai *et al*. (2003). Several authors have documented this 'seesaw' in pressure between middle and high southern latitudes, which shows considerable zonal symmetry. The average annual cyclone intensity and size have increased throughout the record, but annual cyclone number has decreased by up to 10% since the early 1970s. Fyfe (2003) found similar changes to Simmonds and Keay and showed that these changes were associated with the change in the SAM, and that similar changes can be simulated in anthropogenically forced model simulations of the 20th century.

Consistent with Simmonds and Keay (2000), 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 Figure 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).

One specific circulation change that has been studied is an apparent poleward shift of the position of the sub-tropical ridge over eastern Australia. However, Drosdowsky (2005) found no evidence of such a shift and concluded that previous reports of this shift were flawed because they had combined various historical analyses of the latitude of the sub-tropical ridge that were not known to be comparable.

BOX 5:

Trends in extremes and their causes

The major focus in this report is on changes in averages of climate variables. A comprehensive assessment of changes in Australian climate and weather extremes will be produced as a separate study. However, some extremes warrant detection and attribution studies, and are included in this report for completeness. Thus some temperature extremes (especially the frequency of very low temperatures) have changed substantially in recent decades. Some other extremes (e.g. the frequency of tropical cyclones around Australia) have not changed substantially despite changes in variables known to affect cyclone behaviour.

Recent work has suggested that there are large trends in existing tropical cyclone data in some regions of the globe (Emanuel 2005, Webster *et al*. 2005), but theoretical arguments and model results suggest that the warming to date should not have caused detectable effects on tropical cyclones, partly due to the high inter-annual variability of cyclone numbers (Walsh 2004, Kepert 2006). There are concerns about the long-term homogeneity of existing tropical cyclone data, which has likely been affected by changes in observing practices. Work is needed to improve our confidence in the existing tropical cyclone record.

In the Australian region (Nicholls *et al*. 1998) there appears to have been a slight increase in the number of intense tropical cyclones since 1969, while the number of weak and moderate tropical cyclones observed decreased consistent with changes in ENSO, although possibly partly caused by changes in the observational network.

Nicholls *et al*. (2000) examined Australian trends in a wide variety of climate extremes and concluded that:

- There has been a strong decrease, since 1910, in the intensity of rain falling on very wet days, and in the number of very wet days, in the south-west of the continent;
- There has been a strong increase in the proportion of annual rainfall falling on very wet days in the north-east;
- No clear trend has emerged in the percentage of the country in extreme rainfall (drought or wet) conditions, since 1910;
- There is a downward trend in frequency of cool nights, with some evidence of an upward shift in frequency of warm nights (since 1957);
- There is some suggestion of an increase in frequency of warm days since the mid-1970s; and
- No clear trend exists in the frequency of cool days.

No regional attribution studies have been completed on these trends in extremes, although more recent studies have confirmed many of these trends, and Christidis *et al*. (2005) did attribute some global changes in temperature extremes to human factors.

Ocean changes

Although warming of the regional seas is similar to that observed over land, a separate study of the oceans would help provide convincing evidence of the cause of the Australian-region warming. Recent studies have attributed the observed ocean warming in individual basins, including the South Pacific and South Indian Oceans, to human factors (Pierce *et al*. 2006), but there are also variations in the warming rate around Australia (Fig. 7).

For example, there is a region of enhanced warming off the north-west shelf that has the capacity to affect the behavior of the Indian Ocean Dipole, as well as providing increased SST in a region of tropical cyclone formation. There is also an area of enhanced warming in the Tasman Sea (long-term observations at Maria Island near Tasmania reveal a warming trend that is more than three times as fast as the global average sea surface temperature) likely due to strengthened flow in the East Australian Current forced by gyre-scale adjustment to the recent southward trend in the sub-polar westerly winds (Oke and England 2005, Cai 2006). Applying summer surface wind changes associated with the upward trend of the summer SAM, principally induced by ozone depletion, to an ocean circulation model Cai (2006) showed the wind changes should have generated an intensifying flow of the East Australian Current passing the Tasman Sea. This would advect more warm water southwards thereby contributing to the large warming rate.

There are other regional ocean changes, other than warming, that have yet to be fully documented and attributed including changes in sea level, ocean circulation, and ocean chemistry. Little is known of how ocean circulation has changed around Australia over the past half century. While there is anecdotal evidence that some change has occurred (e.g. an increase in the East Australian Current as suggested by Tasman Sea warming) historical records of transport rates are very sparse. Decadal records are available across some sections (e.g. the Indonesian throughflow), although generally the measured inter-annual transport variability is much larger than any trend. Apart from the few direct historical measurements, ocean re analysis products are available, although these are relatively poorly constrained by observations before around 1980.

It is important that regular occupation of key oceanic sections continues as a means of detecting change in regional Australian ocean circulation. These include sections such as those south from Tasmania to Antarctica, the Indian Ocean lines used to estimate Indonesian throughflow rates, and transects in the Tasman Sea and off the coast of Western Australia.

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 (Fig. 8). Some earlier speculation that precipitation was declining very substantially in the Alps (and speculation that this was due to urban pollution) reflected problems with District Average Rainfall data and changes in the mix of stations used to calculate these averages (Nicholls 2000).

Changes in seasonal cycle

Many farmers are concerned about the timing of the 'break' of the season, either the winter break or the start of the wet season. Little work has been done to investigate trends in such indicators of seasonality. One exception is Alexander *et al*. (2005) who found that the warmest time of the year in south-east Australia was occurring about a week later now than at the start of the 20th century. They did not identify the cause of this delay. Precipitation-based indicators of seasonality have not been examined for trends even though some of these (e.g. the onset of the northern wet season) have long been known to be related to large-scale climate indicators such as the El Niño-Southern Oscillation (Nicholls 1984).

PRIORITISING STUDIES OF DETECTION, ATTRIBUTION AND UNDERSTANDING

A checklist for prioritising

The main large-scale climate trends observed over Australia are listed in Appendix 2, along with suggestions that have been made to account for these changes. Some variables where there appears not to have been a strong trend are also included because of stakeholder or scientific interest in the specific variable (or because the absence of a trend is intriguing).

The selection of which regions and variables should be examined with the highest priority, given limited available funding for detection and attribution studies, requires the establishment of criteria against which the region and/or variable can be assessed. The following are the proposed criteria for determining such priorities:

1. The observed trend should be strong, relative to inter-annual variability.
2. The observed trend should have continued over a considerable period.
3. The region affected should be socially, environmentally, or economically important.
4. The region or variable should be amenable to simulation in available climate models.
5. High-quality historical observed data should be available.
6. The cause should not be obvious.
7. Only a few (or no) studies of the variable/region have been completed or are underway.
8. Extent to which stakeholders assume a trend exists and is understood.
9. Strong trend in 21st century projections of the variable in the region considered.

These criteria have been applied to the various trends listed in Appendix 2 and the conclusions from this exercise are listed in the table and in the following section.

Note that contrary to the first criterion in this list, the non-existence of a trend can, in some cases, be sufficient reason for a detection and attribution study. For instance, it appears that there is no evidence of a trend in the frequency or intensity of tropical cyclones in the Australian region, despite the well-documented increase in sea surface temperatures. It would seem useful, therefore, to establish the credibility of any trend in tropical cyclones, as well as the factors affecting tropical cyclone frequency and intensity, to account for the absence of a trend.

What needs to be done?

As can be seen from the above discussion of the various detection and attribution studies that have been undertaken in the Australian region, there are some regions (e.g. south-west Australia) and some variables (temperature, pan evaporation) that have received considerable attention. There are also regions (e.g. the east coast) and variables (e.g. ocean circulation) where little work has been concentrated. As well, several research programs do include ongoing detection and attribution studies (IOCI, SEACI).

A major focus of this report was to identify the regions and variables that should be investigated in the near future, to complement the ongoing studies. The following are the regions/variables identified as being of highest priority. It should be noted, however, that there are some other variables that would be a high priority, if high quality data sets were currently available. As such data sets are prepared, the list of high priority variables could evolve.

Rainfall decline along the east coast and in the south-east of Australia

A high priority for detection and attribution studies is the decline in rainfall along the east coast and in the south-east of the country. 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 south-west, or even the increased rainfall in the north-west.

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. Studies similar to that carried out by Cai *et al*. (2005) would assist in determining how likely it is that natural variability alone can explain the apparent rainfall trends. Smith (2006) does not report strong correlations between the east coast rainfall decline and global air temperature, suggesting that the decline may not be attributable to human factors.

On the other hand preliminary studies (Syktus, pers. comm.) suggest that an atmospheric model forced with observed sea surface temperatures and anthropogenic external factors including ozone decreases and greenhouse gas increases, simulates the decline in east coast rainfall. Given the economic importance of this region, the amount of attention the apparent decline in rainfall is receiving seems inappropriately low. The newly established South-East Australian Climate Initiative (SEACI) may undertake relevant research.

Changes in Australian region atmospheric circulation

A second priority is to account for the changes in Australian region atmospheric circulation, exemplified by the increase in surface atmospheric pressure across the Australian region, with decreases in pressure at mid-high latitudes and increases in the sub-tropics 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?

Investigation of the links between the Australian region circulation changes and hemispheric (or global) changes is also important – do the local changes simply reflect the global scale changes? Because circulation changes are linked to changes in other climate variables, attribution of the cause of the apparent change in the Australian region atmospheric circulation could simplify other attribution studies, justifying a high priority for this topic. Studies of the type described by Frederiksen and Frederiksen (2006), Charles *et al*. (2004), Hope *et al*. (2006), and Lynch *et al*. (2006) can help in determining what is driving the changes in circulation and synoptic systems, and the impact of these changes on regional climate variables.

Drought

There is a widespread belief that droughts are becoming more severe, especially over the mid-latitude continents. In Australia, if droughts are judged solely on the basis of rainfall, it appears that there is no trend towards more frequent or intense droughts, although recent droughts have been warmer than in the past. However, the severity of a drought may not be simply judged by the extent of rainfall deficiencies and temperature. A detection and attribution study of droughts, using an appropriate drought index, should be a *priority* in a drought-prone country such as Australia.

Tropical cyclones

Similarly, the public, political and media interest in possible changes in tropical cyclone frequency or intensity justifies a *priority* examination of how Australian regional tropical cyclones are changing, and what may be the cause of any observed changes. It may well be that the important question regarding tropical cyclones is why they are *not* changing.

BOX 6:

Prerequisites for detection and attribution studies

Although data and models have improved considerably in recent years, further improvement in both is required if the credibility of detection and attribution studies is to continue to improve. Programs addressing all these prerequisites are underway in Australia and require continued support if we are to produce more credible detection and attribution studies of climate change.

Data. Although Australian historical climate data are generally good (see Box 3), continued efforts to develop accessible, high-quality data sets is needed. For some variables (wind, cloud) the development of high-quality databases is still in its infancy. Yet these data sets are essential if we are to determine the causes of trends in other climate variables such as evaporation.

Models. Climate models have improved in resolution in recent years. Uncertainties remain in the parameterization of some processes important to detection and attribution studies (e.g. clouds). Continued work to develop a state-of-the-art Australian climate model is essential for Australian climate change detection and attribution studies.

Forcing factors. Our knowledge of the time evolution of some external factors required to force climate models (e.g. aerosols, land surface changes) is still less than complete. The development of databases of the historical evolution of these factors is critical to improved detection and attribution studies.

Availability of model simulations. Once models and forcing factors have been improved, it is important to ensure that model simulations are available to those undertaking detection and attribution studies. This requires multiple model runs (i.e. ensembles) forced by various combinations of natural and anthropogenic forcing factors. The requirement for ensembles is especially important for regional scale studies, where variability will be relatively large. Storage and transfer of the large model-generated data sets appropriate for attribution studies is also an issue.

Palaeo-data. Palaeo-climatic studies can provide important information about natural climate variations. This information can be useful in understanding whether a specific climate change could be due to natural climate variability without the influence of anthropogenic factors such as the enhanced greenhouse effect.

Extreme temperatures

A further *priority* is for a detection and attribution study of extreme temperatures. Some Australian temperature extremes, especially very cool nights, have changed substantially in frequency, but no detection and attribution study has yet been undertaken. It may well be that the observed changes in extreme temperature simply reflect the changes in mean temperature that have already been attributed to human factors. If so, attribution of the changes in extremes should be a relatively simple task, but the importance of extremes to decision-makers justifies this being a priority nevertheless. Schaeffer *et al*. (2005) have proposed a technique to determine whether changes in circulation are leading to changes in extreme temperatures somewhat different from those expected from simple shifts in the mean temperature, and their approach could be usefully employed in Australia.

Regional ocean changes

Regional ocean changes, especially sea surface temperature trends, in the Australian region are also a *priority*. Although warming of the regional seas is similar to that observed over land, a separate study of the oceans would help provide convincing evidence of the cause of the Australian region warming. The causes of observed changes in sea level around the Australian coast also need to be addressed, along with circulation changes (e.g. changes in East Australian Current) and ocean chemistry.

GLOSSARY

(mainly following IPCC 2001)

Attribution	Process of establishing the most likely cause for a detected change with some defined level of confidence.
Climate change	A statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer).
Detection	Process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change.
Downscaling	Using statistical relationships between patterns of various atmospheric fields with station climate records to improve the simulation of the local climate variability.
External variability	Climate variability caused by either natural external forcings (such as volcanoes) or human-induced forcings (such as land use change).
Fingerprint	Patterns of variation of climate in space, time, or both expected from a particular forcing.
Forcings	External factors (either natural such as volcanoes or solar variability, or human-induced such as changes in atmospheric composition or land use change) that may lead to climate changes.
Internal variability	Climate variability induced by processes within the climate system, e.g. the El Niño-Southern Oscillation.
Natural climate variability	Climate variability due to natural (i.e. not induced directly or indirectly by human action) processes.
Structural uncertainty	Uncertainties in the representation of physical processes in models, over and above the uncertainties in the parameters governing the model representation of these physical processes.

APPENDIX 1: FORMAL DETECTION AND ATTRIBUTION APPROACHES

This is a brief outline of the formal statistical methods that have been used in much recent detection and attribution work, especially on global scales (largely following 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.

Fitting the regression model requires an estimate of the covariance matrix **C** (i.e. the internal variability) which is usually obtained from long control simulations because the instrumental record is too short to provide a reliable estimate and is also affected by external forcing. Models may not simulate natural internal climate variability accurately, particularly on small spatial scales, and thus a test is typically applied to assess the model-simulated variability on the scales that are retained in the analysis.

Detection and attribution questions are assessed through a combination of physical reasoning (to determine, for example, by assessing consistency of possible responses, whether other mechanisms of change not included in the climate model could plausibly explain the observed change) and by evaluating specific hypotheses on the scaling factors **a**. Most studies evaluate these hypotheses using standard frequentist methods. Several recent studies use a Bayesian approach.

In the standard approach, 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?).

Bayesian approaches can integrate information from multiple lines of evidence, and can incorporate independent prior information into the analysis. Inferences are based on a posterior distribution that blends evidence from the observations with the independent prior information, which may include information on the uncertainty of external forcing estimates, climate models, and their responses to forcing. In this way, all information that enters into the analysis is declared explicitly.

APPENDIX 2: CLIMATE VARIABLES AND TRENDS IMPORTANT IN THE AUSTRALIAN CONTEXT, THE LIKELY CAUSES OF ANY MAJOR TRENDS, AND PRIORITIES FOR NEW STUDIES.

Relative priorities for new or expanded studies for the near-term are colour coded (dark yellow = high priority; light yellow = medium priority; blue = low priority).

Region	Variable & change (where known)	Proposed cause(s)	References	Study continuing?	Tractability	Priority (for new and increased studies)
Australia	Widespread warming	Enhanced greenhouse effect	Stott (2003), Karoly and Braganza (2005)	Karoly	High. Data and models good.	Low. Simple, well understood and easily predicted cause.
Australia	Pan evaporation decrease	Increased cloud (north-west); decreased wind (south-east)	Gifford (2005), Roderick and Farquhar (2005), Rayner (2006)	Roderick, Rayner	Medium. Data quality improving. Physics well studied.	Low. Considerable study already.
South-west Western Australia	Winter rainfall decrease since ~1970	Enhanced greenhouse effect plus land use change	Lyons (2002), Timbal (2004), Pitman *et al.* (2004), Timbal *et al*. (2006)	IOCI[3]	Medium. Well-established trend. Some models appear able to simulate decline	Low. Considerable study already completed, and ongoing studies.
North-west Australia	Increased summer rainfall	Aerosols	Wardle and Smith (2004), Rotstayn *et al*. (2006)	IOCI, ACCSP[4]	Medium. Well-established trend. Some models appear able to simulate increase.	Medium. New study suggests cause, but requires confirmation. Low population.
East coast & south-east Australia	Decreased summer rainfall (Queensland) and autumn-winter rainfall (New South Wales, Victoria)	Stratospheric ozone, greenhouse gases	Syktus (2005)	Syktus	Medium. Well-established trend. Some models appear able to simulate decline	High. Large population, poorly understood mechanism. No published studies.
Alpine region	40% decline in spring snow depth	Warming, due to enhanced greenhouse effect	Nicholls (2005)	No	High. Good data and no requirement for models.	Low. Simple, well understood and easily predicted cause.
Australia	Droughts - warmer. Evaporation effect uncertain.	Enhanced greenhouse effect	Nicholls (2004), Dai *et al.* (2004)	Hobbins and Farquhar; Pitman	Medium. Better index of drought is required.	High. No studies of trends in droughts other than with rainfall deficit or PDSI as drought index.
Australian region	Circulation changes (e.g. ENSO, SAM, latitude of subtropical ridge)	Ozone (SAM); greenhouse	Drosdowsky (2005), Hendon *et al.* (2006), Meneghini *et al*. (2006), Frederiksen and Frederiksen (2006)	Lynch; Simmonds & Keay; IOCI, SEACI[5]	High. Some data inhomogeneity problems before satellites. Models should simulate changes.	High. Circulation changes impact on other variables such as rainfall.

Continued overpage

Region	Variable & change (where known)	Proposed cause(s)	References	Study continuing?	Tractability	Priority (for new and increased studies)
Australian region seas	Sea surface temperature, sea level, ocean chemistry, circulation	Greenhouse	Cai (2006)	England; Church	Data OK, regional modelling possibly difficult?	High. Economic impacts. Independent evidence of human impact on temperature.
Australia	Seasonal cycle changes, (e.g. monsoon onset, autumn 'break')	Greenhouse (?), aerosols (?)	Alexander *et al.* (2005)	No	High. Good data. Models should simulate seasonal cycles.	Medium. Data quality good; models should simulate changes well.
Australia	Cloud cover	Greenhouse (?), aerosols (?)		Jakob, Lynch, Alexander	Low. Data inhomogeneities and difficulties in model simulations.	Low. Limited stakeholder interest, but important physical links with other variables.
Australia	Wind speed – apparent decline in southeast	Ozone & greenhouse (via SAM?)	Rayner (2006)	See "circulation changes" above	Major data inhomogeneities. Model simulations should be feasible.	Low. Major data problems; limited impact and stakeholder interest
Australia	Atmospheric moisture	Changes in SSTs?	Lucas *et al.* (2004)	No	Medium. Data, models OK	Medium. Low stakeholder interest, but data good.
Australian tropics	Tropical cyclone intensity & frequency – no evidence of clear trends in region	Lack of trend is not understood	Nicholls et al. (1998); McBride *et al.* (2006)	McBride; Walsh	Low. Problems with credible model simulations. Suspected data inhomogeneities	High. High impact and stakeholder interest. Few studies
Australia	Extreme temperatures: cold temperatures decreasing, warm temperatures increasing	Greenhouse effect	Alexander *et al.* (2006)	Karoly, Nicholls	Medium. Good data; simulations problematic.	High. Good data. Few studies. High impact.
Australia	Heavy rainfall events – geographically varying trends	Greenhouse effect, natural variability	Alexander *et al.* (2006)	Alexander	Low. Problems with model simulations.	Medium. High stakeholder interest, but difficult to simulate.
Australia	Greening, NDVI	Direct CO_2 effect		No	Problems with data homogeneity	Low. Well-understood cause, but data problems

[3] Indian Ocean Climate Initiative (assuming continuation past current phase)

[4] Australian Climate Change Science Program

[5] Southeast Australian Climate Initiative

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