Living in a variable climate

Author:

Dr Greg McKeon, CRC for Greenhouse Accounting
Queensland Department of Natural Resources and Water
80 Meiers Road, Indooroopilly, Queensland, 4068.

Peer reviewers:
Dr David Jones, Australian Bureau of Meteorology
Dr Michael Roderick, CRC for Greenhouse Accounting
Dr Roger Stone, Queensland Department of Primary Industries and Fisheries

Citation:

McKeon, G 2006, 'Living in a variable climate', article prepared for the 2006 Australia State of the Environment Committee, Department of Environment and Heritage, Canberra, <http://www.deh.gov.au/soe/2006/integrative/climate/index.html>.

Introduction

Australia has a wide range of climate types, including equatorial, tropical, subtropical desert grassland and temperate (Lindesay 2003). The regions in which agricultural and urban developments have occurred have high year-to-year variability in rainfall. During the last 200 years of agricultural and urban settlement, there has been considerable adaptation in terms of land use and infrastructure development in response to increasing awareness of rainfall variability and the demands of an increasing population. Since settlement, the success of agriculture, despite a highly variable climate, has contributed greatly to the development of Australia's economy (Pestana 1993). This success has also highlighted the potential economic sensitivity to climate variability and resource degradation.

Water availability has been a major limitation to agricultural development during the last 200 years. Periods of drought have placed great stress on human and animal welfare, economic production and resource sustainability. The scarcity of water supply in all aspects of Australian agriculture (such as cropping and grazing) has been the driving force behind the development of on-farm water infrastructure to 'drought-proof' properties, as well as the development of large irrigation schemes (such as the Murray and Murrumbidgee regions), earthen tank technologies, and use of the underground water resources of the Great Artesian Basin.

To continue to successfully adapt to climate variability and climate change, the community will need to increase its 'climate literacy' (Botterill 2003, p 197) so that political, social, economic and environmental decisions are better informed. As explored in this commentary, a major difficulty in achieving this goal of improved climate literacy is that climate science is continuing to discover new knowledge about the global climate system, and Australia's regional climates. Future climate changes are expected, not only due to long-term natural variability of the global climate system, but also due to human-induced influences through increasing greenhouse gas concentration, stratospheric ozone depletion, aerosol emissions and land use change (Burroughs 2003, pp 92–102).

In assessing how the challenge of 'living in a variable climate' has been, and is being addressed, the commentary presents: an example from the history of Australia's rangelands (Box 1); current case studies of adaptation to anticipated climate change (Box 2); and an assessment of responses to the current drought (Box 3). These case studies provide examples of how the community may continue to plan for, and adapt to, a changing climate.

Australia's variable climate

The imagery of Australia as a 'wide brown land' with stoic Australian farmers and graziers battling drought is rooted deep in the national ethos of an increasingly urban Australia. 'Australia's climate' and its year-to-year variability in rainfall could well claim to be a major determining factor in the development of this national identity and the attitude to the future. As strong as such general national images are, Australia nevertheless has a very wide variety of 'climates' including tropical, monsoonal, temperate, sub-humid, semi-arid, alpine and desert climates, with different patterns of historical rainfall variability. The seasonal distribution of rainfall, which is so important in determining vegetation and land use, varies from summer-dominant rainfall in the northern regions of the continent to winter-dominant rainfall in the southern regions. Despite this large variation in climate types, and associated differences in land use, Australia is overall the driest inhabited continent from the viewpoint of continental rainfall and streamflow (McTainsh and Boughton 1993). Importantly this widespread aridity, in combination with extensive marine sedimentary rock deposits and internally draining river basins, is associated with Australian soils having high proportions of salts (McTainsh 1993) with potential problems for agricultural production.

This 'average' view of a dry continent, however, obscures the fact that reasonable rainfall occurs on coastal fringe of eastern and south-west Australia and across inland south-eastern Australia. This rainfall has supported large urban populations, profitable dryland and irrigated agriculture, and pastoralism. Furthermore, this 'average' view has also contributed to three great myths (Williams 2003, p40): '(1) water allowed to run to the sea is wasted; (2) we must make the desert bloom; and (3) we must drought-proof Australia.' Williams (2003, p40) stated that 'each of these persistent ideas holds great danger, both for our landscape and for our sustainable future within it. We need to rid ourselves of them if we are to live like true Australians, in harmony with our land.'

Australia's climates are highly variable as a result of its small landmass in relation to the expanse of ocean that surrounds it and its location across tropical, subtropical and temperate climate zones. Furthermore, year-to-year variations in sea surface temperatures in both the Indian and Pacific Oceans and variations in atmospheric circulation—such as the latitude of the sub-tropical high-pressure belt—exert a significant influence on Australia's rainfall (Drosdowsky 2002, 2005).

Several studies have also noted the larger annual variability of rainfall and streamflow in regions of Australia when compared with other comparable locations in the world (see, for example, McMahon et al 1992, Nicholls et al 1997). In most Australian catchments, average annual streamflow is a small proportion of the overall water balance. Small changes in average rainfall due to natural climate variability at longer time scales, or due to climate change, can result in large changes in streamflow. For example, for a catchment in south-west Western Australia, Sadler et al (1988) estimated that a decrease of 20 per cent in rainfall would result in a 45 per cent decline in streamflow.

The high variability in Australian rainfall is in part the result of the strong control of meteorological mechanisms associated with the phases of the El Niño-Southern Oscillation (ENSO). ENSO is a global phenomenon that involves coupling of anomalies in sea surface temperature and atmospheric pressure (Burroughs 2003, p 72). The climate science community has several formal definitions of these phases of ENSO. In general terms, El Niño refers to warm sea surface temperature anomalies in the central equatorial and eastern regions of the Pacific Ocean, and it is associated with higher atmospheric pressure over Australia and cold water anomalies in the Coral Sea. As a consequence, in El Niño years, lower rainfall often occurs over much of eastern Australia and some regions of Western Australia (Lindesay 2003). Opposite anomalies of sea surface temperature and pressure occur during La Niña conditions. In La Niña years, high rainfall has occurred over most of Australia and there has been an increased frequency of tropical cyclones, particularly in the number crossing the coast of Queensland (Partridge 1994). Thus, over much of Australia, the phases of the Southern Oscillation (El Niño, La Niña or 'neutral') may be regarded as a second dimension to the traditional seasons.

El Niño and La Niña events generally commence in autumn (March–May) and last for approximately 12 months. About 40 to 50 per cent of years may be classified into these ENSO phases (depending on the definition) and the remainder as 'neutral' ENSO years. Regrettably, the perceived need to simplify the communication of climate science has led to the simplistic association of the words 'drought' with 'El Niño', and 'floods' with 'La Niña' when, in fact, in some years the opposite has occurred. Extremes of rainfall (wet and dry) have also occurred in 'neutral' years, with severe multi-year drought periods occurring during sequences of 'neutral' ENSO years (McKeon et al 2004).

The understanding of ENSO as a major driver of Australia's climate variability is relatively new. It was not until the late 1970s and early 1980s that the impact of ENSO on Australian rainfall was confidently understood by scientists (Pittock 1975, McBride and Nicholls 1983, Allan 1985, Stone et al 1996, Nicholls 2005) and communicated to the wider community (see, for example, Coughlan 1988, Clewett et al 1988, 1991, Coughlan et al 2003). At the same time, analysis by ecologists and climatologists revealed that ENSO has been a driving force, shaping the ecology of Australia (Nicholls 1991). For example, in northern Australia, ENSO events accounted for half of the major ecologically significant extremes of climate, driving biological processes such as population recruitment, distribution and survival (Taylor and Tulloch 1985). ENSO is not the only contributor to temporal climate variability and recent studies have indicated the impact of other components of the climate system (Meinke and Stone, 2005).

The risk of drought has been a major control on agricultural land use and, simply put, 'Drought is a normal feature of the Australian farmer's operating environment' (Botterill and Fisher 2003, p 1). Yet, despite the physical hardship, social heartbreak, animal suffering, financial and economic consequences—and the environmental damage that is expected to occur—both urban and rural communities appear to be surprised by the next drought. The range of attitudes that Australians have with regard to climate variability (and in particular drought) has recently been reviewed by many leading scientists and commentators (Botterill and Fisher 2003). Botterill (2003, p 197) concluded the review with a plea for a deeper understanding of the reality of climate variability and recognition that:

> The concept of 'average' rainfall is essentially a statistical construct that bears little resemblance to most seasons. This approach suggests that the notion of 'drought' may be meaningless in an environment in which extremes are the norm, particularly as the term is so value laden and evocative of unexpected disaster.

This insight could have been written during the widespread Federation drought (1895–1902) and the extended regional droughts of the 1920s, 1930s, and 1940s, and, in fact it has been stated previously in general terms (for example, Anon 1901, Ratcliffe 1938, 1970). As such, Botterill's conclusion is more of a rebuke to an Australian community that is still failing to acknowledge the variable nature of its climate, and to plan and respond accordingly. The expectation of future climate change (but of somewhat uncertain direction in terms of regional rainfall) highlights the need for the development of improved climate literacy and hence is the theme of this commentary.

Current debate on climate variability and appropriate land use

At the time of writing (October 2005), the impact of the drought that commenced in 2001 is now stimulating much public debate on climate variability, climate change and appropriate land and water use. This so-called 'millennium' drought (Whitaker 2005, p220) is now being compared to the historic Federation drought that started in the mid-1890s and caused so much hardship and resource damage (Anon 1901, Gibbs and Maher 1967, Condon 2002, McKeon et al 2004).

Adding to this very public debate on what to do in response to current and projected rainfall deficits are global images of the damaging impact of climate variability on human survival, global economies, and the infrastructure of civilisation (for example, drought and famine in Niger, extreme rainfall in India, increased frequency of hurricanes in the Gulf of Mexico). The combination of these local and global images, and the immediate experience of limited water availability in rural and urban communities, raises two major public issues.

- How much of the current variability is due to human-induced effects (global warming, stratospheric ozone depletion, aerosol concentrations, and land use change) in contrast to expected variability resulting from natural fluctuations of the global climate system?
- What planning and infrastructure investment should occur to manage for both a possible repetition of historical climate variability and future projected climate changes?

In the case of global warming, the debate extends to global initiatives recognising the importance of reducing greenhouse gas emissions, and the political, social and technical difficulties of achieving these emission targets. Politically, the two issues are inter-related. The relative attribution of current climate trends and extremes (such as Karoly and Braganza 2005) to ‘natural’ or ‘human-induced’ causes should influence the urgency for planning, and community support for mitigation of greenhouse gas emissions.

Even more explicit climate-related questions for public administration of government funding are being posed: how often should ‘drought’ be declared; how to define ‘Exceptional Circumstances’; what is the appropriate level of government financial support to the agricultural community; when should local government impose restrictions on urban water use; and what government support should there be for investment in infrastructure to deal with rural, industrial and urban water needs? Although the answers to these explicit questions are outside this commentary, these issues provide examples of the application of climate science to support improved adaptation to climate variability and climate change. Fundamental to answering these questions is the development of climate literacy that is based on: (1) the emerging understanding how the climate systems work; (2) knowledge of historical climate variability; and (3) plausible projections of future climate variation. To this end, climate science is playing a major role in informing the public and decision makers (see, for example, Power et al 2005 and Box 2).

Various responses to climate variability (mainly rainfall deficits) have been supported at different times over the last two hundred years of settlement in terms of land use policy, choice of agricultural enterprise and infrastructure investment. The public and government responses—of (1) ‘defending’ current land use and communities against the extremes of climate (drought, flood, cyclone damage, heat waves), and (2) ‘investing’ in new enterprises and closer land settlement—have developed and supported the nation. The alternative responses of ‘doing nothing’ or ‘retreating’ have, in the past, been unacceptable to community expectations and a national ethos of expansion and development. For example, the option of pastoralists ‘retreating’ from western New South Wales following the drought episode of the early 1940s (Beadle 1948) was, in the words of the time (post-war), regarded as ‘defeatist’. Similarly recent public suggestions that unspecified areas should be withdrawn from current land use (Cullen 2005) have provoked widespread debate. Despite the emotion and pain involved, history indicates that ‘retreat’ will be inevitable where rainfall deficits continue, and that the continued support for inappropriate land use will result only in further land degradation (e.g. Condon 2002, McKeon et al 2004).

Climate variability and change are not the only drivers affecting the viability and performance of agricultural enterprises. The review of historical degradation and recovery episodes in Australia’s rangelands (McKeon et al 2004) highlighted how the coincidence of declining commodity prices with high variability in rainfall (at decadal time scales) damaged grazing enterprises and their natural resource base. Nelson et al (2005, p 171) developed an index to assess ‘the vulnerability of Australian farm households to structural adjustment’ defined ‘as their relative exposure to external events, and their internal capability to cope with external events as they occur’. Examples of external trends include declining terms of trade and climate variability. Using ABARE farm survey data, they assessed the multiple dimensions of a ‘vulnerability’ index, namely human, social, natural, physical and financial. They found that ‘farming in a harsh environment’ does not necessarily lead to a high score on the vulnerability index, indicating that ‘appropriate farming systems can effectively manage the risks associated with a highly variable, low rainfall climate so long as they have adequate scale’ (Nelson et al 2005, p 178).

Understanding and forecasting the behaviour of the climate system

Agricultural land uses can be ranked in terms of water requirements that range from extensive grazing in arid environments to irrigated pastures, sugar cane and horticulture in coastal high rainfall locations. Year-to-year variability in rainfall places a potential stress on the viability and vulnerability of particular land uses. For example, dryland cropping has had fluctuating fortunes at its margins in western New South Wales (Condon 2002, p 189). Not surprisingly, the ‘forecasting’ of rainfall at annual to generational time scales has been seen as a way of improving land and water use planning, and has been the ‘holy grail’ of Australian climate science.

During the last 100 years there has been increased understanding of the components of the climate system. Some of the year-to-year variability is the result of the ‘chaotic’ nature of the climate system (Burroughs 2003, p 53). Major fluctuations have also occurred in the ‘forces’ that drive the climate system. These include natural forces, such as solar variability and volcanic eruptions (Burroughs 2003, p 88), and the human-induced impacts listed previously (Burroughs 2003, p 92-100). Variation in these natural and human-induced ‘forcings’, in combination with chaotic climatic processes, results in a complex global climate system in which ‘cause and effect’ are not easily identified.

As well as variability in sea surface temperatures, atmospheric pressures and rainfall at ENSO time scales (three to seven years), there have also been consistent patterns of variability in global sea surface temperatures and pressures at longer time scales (for example, decadal and multi-decadal, Allan 2000). Of particular importance for Australian rainfall, are the longer-term (15–20 years) fluctuations in basin-wide Pacific Ocean sea surface temperatures (Mantua et al 1997, Power et al 1999, Lindesay 2003). The newness of this scientific understanding is reflected in: (1) the various names for this multi-decadal feature of the Pacific Ocean referred to as the Pacific Decadal Oscillation (PDO), or Inter-decadal Pacific Oscillation (IPO); (2) the difficulty of explicitly separating possible long-term (about 20 years) sea surface temperature fluctuations from the chaotic clustering of El Niño and La Niña events; and (3) assessing the impact of human-induced term climate change.

The interaction of the La Niña phase of ENSO and the ‘cool’ phase of the PDO/IPO (Mantua and Hare 2002) has been associated with above-average annual rainfall, particularly in eastern Australia (for example, early 1890s, 1916–18, mid-1950s, early 1970s and perhaps the late 1990s). The understanding of the behaviour of the PDO/IPO is still the subject of scientific debate and, as yet, no climate forecasting capability exists at decadal or multi-decadal time scales (Power et al 2003). Currently, available climate forecasts are at seasonal and annual time scales with probabilistic forecasts reflecting the uncertain non-deterministic behaviour of the climate system.

Climate change projections over the next 100 years are derived from simulations using a number of global climate models, each with different mathematical representations of the climate system and different capabilities in terms of available computing resources. More importantly, the simulations also necessarily include a range of predictions or scenarios of future global economic development, population growth and technological advances. Hence, there can be a wide range of plausible outcomes in terms of regional changes in rainfall and temperature. In addition to these uncertainties, regional climates are also subject to uncertain biophysical feedbacks from the impact of climate changes on vegetation and landscape hydrology. Thus, decision makers now face the problem of integrating knowledge of historical variability, seasonal and annual outlooks, and a range of long-term climate change projections.

The major gap in climate forecasting capability is at the decadal and multi-decadal scale. Recent studies have emphasised the importance of climate variability at decadal and multi-decadal time scales that affect important regional climate elements such as seasonal rainfall and severe storm frequency (such as cyclones and hurricanes). Furthermore, reconstructions of regional rainfall records for north-east Queensland for a few hundred years before the instrumental record (Lough 2003), indicate that major decadal and multi-decadal periods have occurred that may have been drier than have been experienced in the last 100 years (the main period of agricultural and urban development). Thus, climate science, through the study of historical records and future projections, is providing evidence to support the changing perceptions of Australia’s rainfall variability. Instead of a ‘random and unpredictable’ climate that varies about a constant long-term (stationary) average, land managers should now expect rainfall (and other climate elements) to vary on time scales that may require changes in existing land use and business practices (choice of crops, livestock carrying capacity, water allocation and insurance risk assessment). The alternative of allowing or supporting inappropriate land and water use, or livestock carrying capacity, has in the past led to resource degradation (Condon 2002, McKeon et al 2004) and impeded structural adjustment (McColl and Young 2005) by maintaining enterprises not suited for surviving climatic and economic variability.

The history of government policy on land use in Australia provides examples of successes and failures in managing for climate uncertainty. In some cases, the lack of understanding of rainfall variability at decadal and multi-decadal time scales has led to false expectations and inadequate planning. The uncertainty resulting from such variability has been compounded in Australia by the fact that agricultural and urban settlements were occurring before or at the same time that meteorologists, farmers and graziers were collecting the necessary data to measure climate variability. These data were necessary to formulate appropriate land use recommendations (such as extensive grazing in contrast to dryland cropping) and to indicate what government support was likely to be required through drought and flood events. Despite a lack of knowledge of the forces driving climatic variability, the substantial economic contribution that agriculture (including pastoralism) has made to the development of the national economy is testament to the successful adaptation that has occurred over the last 200 years (Burroughs 2003, p 152). Ironically, with current and expected changes in climate, resource-use planners may now be in a similar position of climatic uncertainty as those who were developing land and water-use policy one hundred years ago. Thus the current challenge for decision-making is to integrate the emerging capability from climate science, with all its transparent uncertainty, to make better decisions at both individual time scales (individual farmers' and graziers' lifetimes or business life cycles) and at societal (multigenerational) time scales. Examples of current approaches to meet this challenge are presented later in this paper (Box 2).

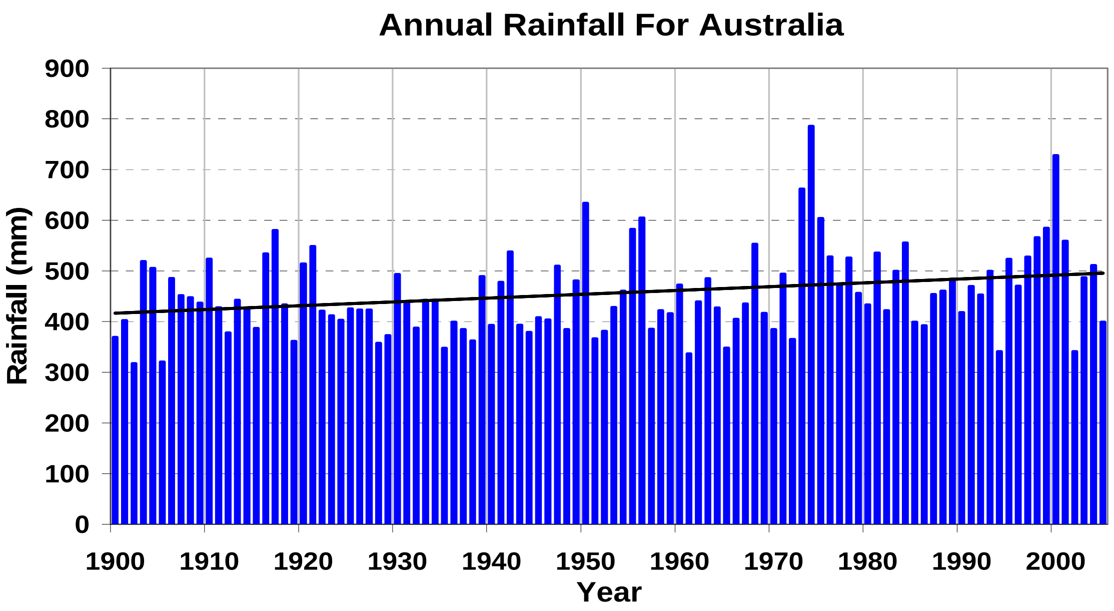
Historical variability in rainfall

As described above, in eastern Australia, the interaction of the La Niña phase of ENSO and the 'cool' phase of the Pacific Decadal Oscillation or Inter-decadal Pacific Oscillation (Power et al 1999, Mantua and Hare 2002) has resulted in sequences of wet years (early 1890s, 1916–18, early 1920s, mid-1950s, early 1970s and late 1990s). These wet periods were likely to have led to biased expectations of livestock carrying capacity, agricultural production and water availability, leading to government and community support for inappropriate land use (such as cropping of marginal areas and small grazing property sizes; Heathcote 1965, Russell 1988, Condon 2002). Dry conditions in various rural regions followed these wet sequences (drought periods 1896–1902, 1919–20, 1926–31, mid-1960s, early 1980s, 2001–present). The rapidity of decline in rainfall, and the large contrast between the drier and wetter rainfall periods, demonstrated the high variability of the climate. In several of these drought episodes, there have been major re-examinations of appropriate land use as well as the public call for major infrastructure development to ‘drought-proof’ regions.

From the viewpoint of understanding longer term climate change or ‘regime shifts’ in the natural climate system, the instrumental record for most locations in Australia is relatively short (about 100 years). Importantly, where historical records commenced after the Federation drought (ending after 1902), they do not include the extreme variations of the wet, early 1890s and the later severe drought (Gibbs and Maher 1967). For some locations, such as north-east Queensland, proxy climatic information can be reconstructed from coral records (Lough 2003). The reconstructed rainfall record suggests that the driest and wettest years in the past 230 years (1754 to 1985) have occurred in the twentieth century (1902 and 1974, respectively). However, the driest ten- and 30-year periods occurred at the end of the eighteenth century (1766–75 and 1770–99 respectively) prior to the period of northern settlement and instrumental record (post-1870). The wettest ten- and 30-year periods occurred in the last 50 years (1972–81 and 1950–79, respectively). Thus climatic extremes of rainfall deficit that may be outside the community’s experience would appear to have occurred in the natural climate system. These extremes will undoubtedly challenge the capacity for managing climate risk should they occur again.

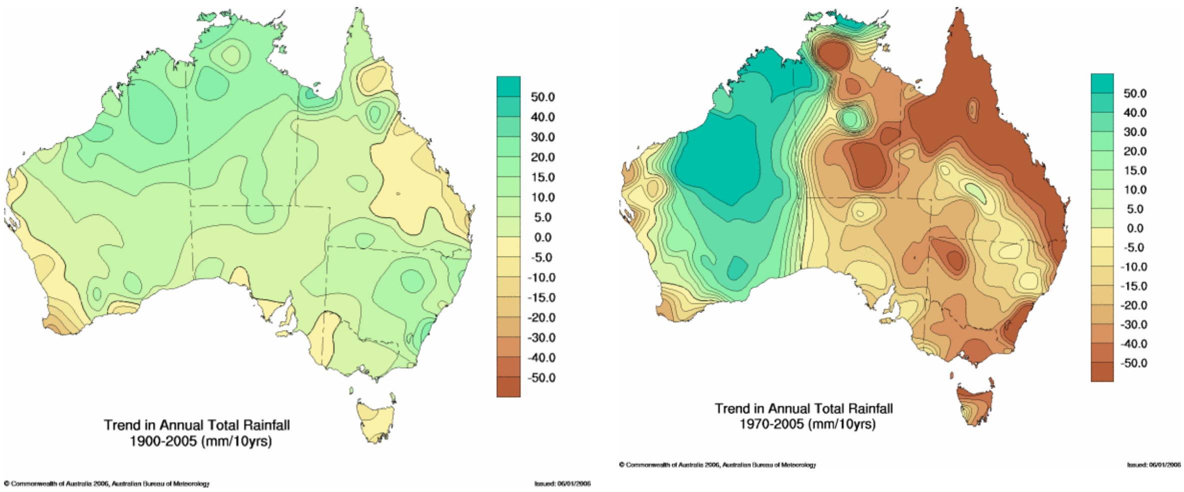
The direction and magnitude of rainfall changes or trends for the last one hundred years over the continent vary regionally, with increases in north-western Australia and decreases in south-western Australia and coastal Queensland. Given the influence of decadal and multi-decadal variability in the climate system on Australian rainfall, the start and finish year of analysis also affect the reported magnitude and direction of the trends (1900–2005 compared with 1970 to 2005 in eastern Australia; see Figure 1 and Figure 2). The choice of period for analysis has been determined by either scientific need (accuracy of records, behaviour of climate system) or practical application (recent resource management issues).

Figure 1: Annual rainfall for Australia, 1900–2005



Source: Bureau of Meteorology, January 2006.

Figure 2: Trends in Annual Rainfall 1900-2005 and 1970-2005.



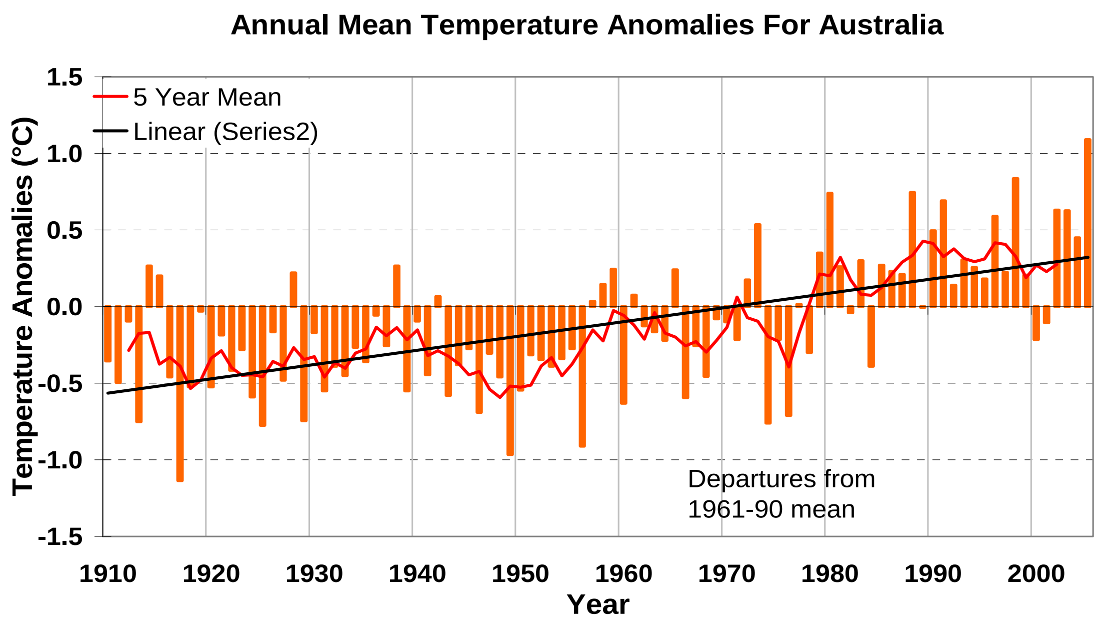
Source: Bureau of Meteorology, June 2006.

The community, through its funding of research, expects (or hopes) that climate science will become more confident in the future projections of climate, integrating: (1) multi-decadal variability; (2) human-induced climate ‘forcings’; and (3) associated predictions of future development (such as energy use) and mitigation responses. The current emphasis on the use of historical rainfall variability for planning could then evolve to include the comparison of current climate trends (last 30 years) with the expected trajectory for the future (typically 30 to 70 years). Management and infrastructure changes can then be made in terms of considering not only necessary responses to current trends and conditions (for example, multi-year drought) but also future expectations of climate change (for example, lower or higher average rainfall).

Historical variability in temperature and potential evaporation

The human-induced climate forcings listed above are expected to influence, and are already affecting components of Australia's climate (see, for example, Cai 2003, Nicholls 2003, Whetton and Suppiah 2003, Karoly and Braganza 2005, Syktus 2005, Watkins 2005, Cai 2006). Night-time minimum temperatures have increased by 1.08^{o}C since 1910, with most of the increase since 1950. The increase in daytime maximum temperatures averaged across Australia (0.58^{o}C) has not been as great, which has resulted in a reduction in diurnal temperature range. The average temperature (that is, average of maximum and minimum) across Australia (Figure 3) has risen by 0.82^{o}C between 1910 and 2004, with much of the warming occurring in the second half of the twentieth century.The warmest year on record is now 2005, which highlights the current nature of climate change. Up to 2004, the warmest year had been 1998 with all of the ten warmest years since 1910 occurring in the last 32 years (1973–2004). Important regional differences in a warming trend of maximum and minimum temperature are described in Beer (2006).

Figure 3: Annual mean temperature anomalies for Australia, 1910–2005



Source: Bureau of Meteorology, January 2006.

Rainfall is not the sole climatic determinant of land use and water availability. Potential evaporation, the rate of evaporation from a wet surface, such as an irrigated crop or open water surface, affects water availability. It also determines the water use efficiency of photosynthesis (how much photosynthesis is completed for a given amount of water). The term ‘potential’ is used because it is an upper limit on the actual evaporation rate, which is negligible when there is little water available in the soil (as in drought). Potential evaporation depends on several climatic factors—humidity, wind, air temperature and (mostly solar) radiation. With the increasing daytime temperatures that are projected as part of global warming, there has long been an expectation that potential evaporation will increase, effectively reducing water availability. However, as evident from the above list of climate factors, this is not necessarily the case, as potential evaporation depends on more than just air temperature.

Although temperatures averaged across Australia have increased, the average continental trends in potential evaporation over the last 30 years surprisingly indicate a decline, albeit small—for example, about three millimetres per year for each year at 30 measuring sites from 1970 to 2002 (Roderick and Farquhar 2004). This represents a decline of approximately five per cent over about 30 years. A similar pattern of declining potential evaporation has been reported in many regions of the world (the United States of America, China, the former Soviet Union, Turkey, India, Thailand and New Zealand). In Australia, there are large regional differences in the trends: south-eastern and western Australia show a decrease in potential evaporation; and some sites in north-eastern Australia show an increase or little change, depending on the starting year (Roderick and Farquhar 2004). The observed decline in potential evaporation across important agricultural regions of south-eastern Australia may have enhanced plant growth and plant water use efficiency. These trends have occurred while average air temperature has increased. It can be concluded that something else must have changed, such as a decline in wind speed or solar radiation, or an increase in relative humidity, or some combination of these variables. The continued monitoring of trends in potential evaporation, and understanding of the contributing factors, will be important in estimating future water availability and demand for rural and urban use.

Projected climate change

Simulations by global climate models – of future temperature changes due to increasing greenhouse gas concentrations—suggest a rise of 0.4 to 2.0^{o}C by 2030 across much of Australia (CSIRO 2001, Lindesay 2003). By 2070, temperatures are expected to be between 1.0 and 6.0^{o}C higher than in 1990 (Figure 4). The largest increases are projected to occur in summer. Projected changes in regional rainfall are spatially and seasonally variable. Under enhanced greenhouse conditions, most of the climate models that have been used so far have simulated decreased rainfall in southern and eastern Australia in winter and spring (CSIRO 2001, Whetton and Suppiah 2003). Increased carbon dioxide concentrations in the atmosphere, and any further declines in potential evaporation, would tend to reduce the impact of any reduction in rainfall on plant growth (Howden 2002).

Figure 4: Ranges of average annual warming for 2030 and 2070 relative to 1990

Figure 1: Ranges of average annual warming (°C) for around 2030 and 2070 relative to 1990. Coloured bars show changes for areas with corresponding colours in the map.

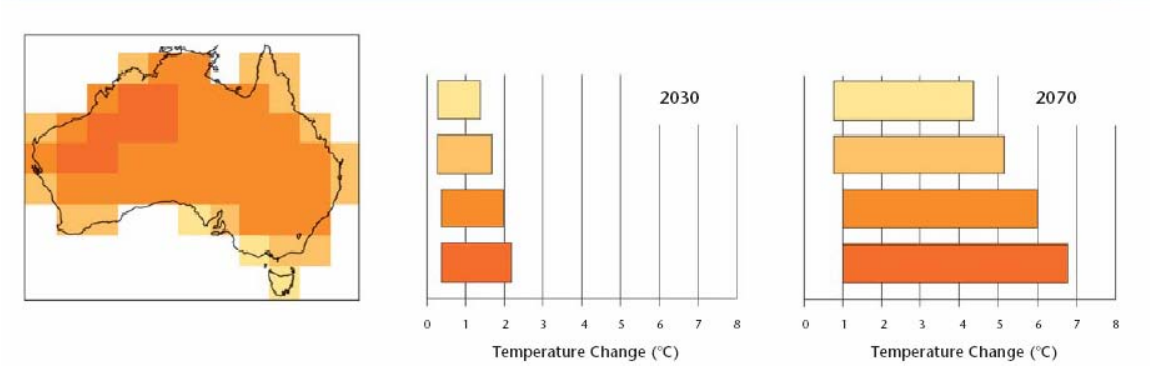
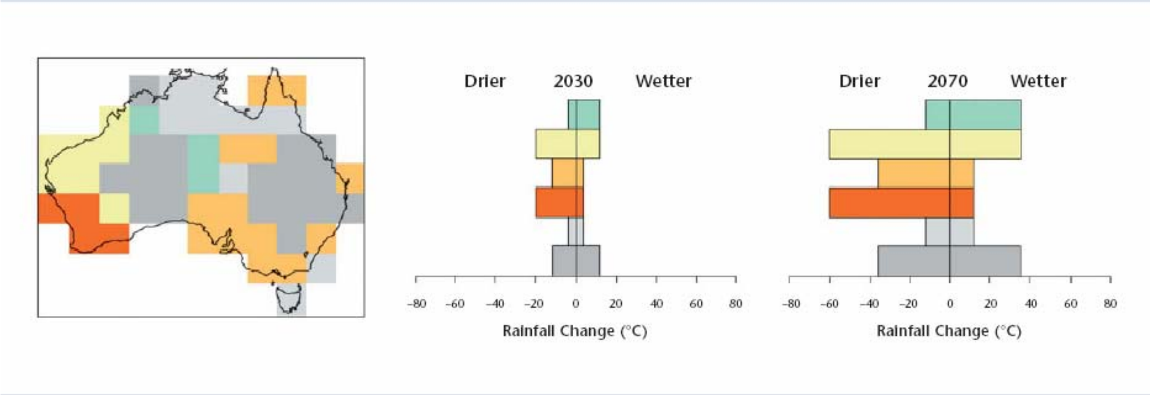


Figure 2: Ranges of annual average rainfall change (%) for around 2030 and 2070 relative to 1990. Coloured bars show changes for areas with corresponding colours in the map.



Source: CSIRO (2001)

Even though some of the projected changes in rainfall ranges appear small (plus or minus ten per cent), it is important to recognise that these changes are of the same magnitude as those that have occurred over historical 30-year periods. For example, in the Murray Darling Basin averaged 30-year rainfall was eight per cent lower for 1917 to 1946, but was ten per cent higher for the subsequent period 1947 to 1976. Given the difficulties that agricultural land use experienced in this region during the drier 30-year period and the beneficial impact of the subsequent wetter period (Condon 2002, McKeon et al 2004), small projected changes of ten per cent in average rainfall in some regions should not be dismissed as unimportant for land use or biodiversity.

A major uncertainty in projections of future climate change for Australia has been the direction of future rainfall trends. This uncertainty relates in part to the uncertainty in the response of ENSO to global warming. Whetton and Suppiah (2003, p 134) commented on likely future changes in ENSO as a result of the enhanced greenhouse effect, based on the review of the Intergovernmental Panel on Climate Change (IPCC 2001). Whetton and Suppiah (2003, p 134) noted a ‘tendency for most models to show a pattern of change in the average sea surface temperature in the Pacific that was ‘El Niño-like’ (meaning a greater warming of the central and eastern Pacific Ocean). They also found that simulated pressure anomalies near Australia did not follow those that are usually associated with El Niño events (higher pressures over eastern Australia). They concluded, ‘this result strongly suggests that caution should be applied when translating apparent model simulated changes in ENSO to rainfall changes in the Australian region’ (p 136). Thus simplistic statements that ‘more El Niños under climate change will mean more droughts’ may correctly alert the public to future risks associated with climate change, but may not necessarily be scientifically sound.

More recent examination of the simulation of ENSO by 20 atmosphere-ocean global climate models has indicated ‘that those models that have the largest ENSO-like climate change also have the poorest simulation of ENSO variability’ (Collins 2005, p 89). They concluded that ‘the most likely scenario … is for no trend towards either mean El Niño-like or La Niña-like conditions’. They estimated a small chance (16 per cent) of a change to El Niño-like conditions under a climate change regime that resulted from a one per cent increase per year in carbon dioxide. The apparent variation between global climate models in forecasting ENSO behaviour under climate change, and the rapidity of improving understanding that is occurring in climate science, highlights the real difficulty that science and the community are having in understanding the likely mechanisms of future climate change impacts.

Another major uncertainty in future rainfall projections is the role of human-induced forcings other than increasing greenhouse gas concentrations (such as, stratospheric ozone depletion and aerosols). The Intergovernmental Panel on Climate Change in 1990 (Houghton et al 1990, p 7) indicated that scientific understanding of the climate system was still at an early stage and that ‘the complexity of the [climate] system means that we cannot rule out surprises’. One such ‘surprise’ has been the emerging hypothesis that Antarctic stratospheric ozone depletion has been affecting atmospheric circulation in the Southern Hemisphere and rainfall over Australia (Pittock 2003, pp 43, 51, Watkins 2005, Cai 2006). A current challenge for climate science in constructing climate change scenarios (such as for 2030 and 2070) is, therefore, how to include the interactive effects of stratospheric ozone depletion, anthropogenic aerosols and increasing greenhouse gas concentrations on atmospheric circulation, especially in the Southern Hemisphere, and on Australia’s climate. As indicated in Beer (2006), the decline in stratospheric ozone has stabilised, although the time required for recovery is uncertain.

Scientific understanding and model representations of important physical, chemical and biological processes in global climate models have greatly advanced over the last 30 years. For example, global climate models have been extensively used for climate change projections for more than 30 years (for example, Manabe and Wetherald 1975) and have proven accurate in their general predictions of the late twentieth-century temperature rise.

Uncertainty remains at regional scales, and particularly for variables such as rainfall. Despite this achievement of climate science, currently some regional climate changes would appear to be occurring faster than climate science can understand and predict them. The public can therefore be forgiven for being confused about the cause of current regional rainfall deficits, which have been variously ascribed by scientists in the media to a range of natural and human-induced effects. Nevertheless, global climate models continue to be perceived as the best hope to address this uncertainty. The projections of future rainfall and temperature are derived from simulations conducted with global climate models that are also currently being used in seasonal climate forecasting (for example, Alves et al 2003, Syktus et al 2003). The continuing assessment of the accuracy of global climate models, and their operational use in seasonal and annual decision-making, will help the community develop confidence in climate change predictions that are derived from these global climate models.

Conclusion

This commentary concludes that the future success of 'living in a variable climate' will depend on developing an understanding of Australia's changing climate. This commentary has reviewed some of the uncertainties associated with climate change science. Scientific uncertainty is not particularly useful for decision makers who cannot (should not) delay their long-term planning or their responses to immediate and emerging climate impacts. To some extent, the formulation of risk management strategies in response to uncertain (probabilistic) climate change information could draw on the experience gained in the current use of probabilistic climate forecasts based on ENSO development. Successful management strategies such as the 'precautionary principle' or 'just in time' have been developed. The state of environment reporting process, in monitoring climate variability and trends, provides a powerful objective and scientific base to support decision-making in an uncertain climate future. The three boxes provide examples of past and current responses to climate variability and expected climate change.

The history of agriculture and pastoralism in Australia provides a successful case study in terms of adapting agricultural practices and technologies to better manage for a variable and dry climate in a semi-arid land (Pestana 1993, Burroughs 2003, p 152). Evolving agricultural technologies have contributed to national wealth. Crop production has been improved through plant breeding, and better crop and water management. Livestock enterprises have developed better-adapted animal breeds, improved pasture species and animal husbandry, and improved drought management. However, the use of these technologies has in some cases also resulted in resource damage, as documented in previous state of the environment reports (for example, increased rate of soil erosion with loss of soil protection, increased salinity risk with loss of perennial plants). The knowledge gained from the successes and failures of the last 200 years, in combination with agricultural and climate sciences, is now being used to underpin government initiatives for better climate risk management, drought preparedness and adaptation to the future impact of climate change.

Urban Australia is similarly being challenged to conserve its limited water resources and invest in alternative water sources, especially where increasing demand is outstripping supply. Thus both rural and urban communities are responding to an increased sensitivity to, and awareness of, climate variability and change.

Examples (Boxes 1, 2 and 3) of current policy and science responses to climate variability provide some practical guidance for how the challenge of uncertain climate change may continue to be addressed in the future. The key components are: (1) the informed debate on community expectations of natural resource use and an improving ‘climate literacy’; (2) improved understanding of the behaviour of the complex global and regional climate systems; and (3) the monitoring of climate variability and trends with management responses guided by objective, if uncertain, climate change projections. With this approach, the community may build upon the success of past generations, avoid their mistakes, and safeguard the nation’s natural resources for future generations.

Box 1: Rangelands as a case study in adapting to climate variability and climate change

The history of Australia’s rangelands provides a case study in how the lack of understanding of Australia’s climate has led to decisions that have resulted in economic and social ‘misfortune’, and resource damage in Australia’s rangelands. Thus the history of grazing in Australia’s rangelands (the main land use on more than 40 per cent of the continent) provides an important case study in terms of the impacts of climate variability and climate change on livestock and economic production, animal welfare, human stresses, resource degradation and government policy. The lessons learnt from how these issues have been addressed in the extensive grazing lands may help the wider community and other industries adapt to future climate variability and change.

History of climate variability impacts in Australia’s rangelands

Australia’s rangelands are characterised by a high temporal variability in rainfall. Fluctuations in Pacific Ocean sea surface temperatures at inter-annual and multi-decadal time scales have been identified as major contributors to year-to-year variability in rainfall across rangelands in eastern Australia and the more general ‘drought–flood’ perception of Australia’s climate. Whilst individual El Niño years have been associated with widespread drought, important sequences of drought years have also occurred during periods of ‘neutral’ ENSO years, contributing to losses of agricultural production, economic and social stresses, and resource damage (McKeon et al 2004).

A recent report on degradation and recovery in the rangelands describes in detail eight major drought and degradation episodes that have occurred in Australia's grazing lands since the expansion of cattle and sheep numbers in the 1870s (McKeon et al 2004). These episodes involved not only extended drought periods that lasted from four to eight years, but also considerable resource damage in terms of wind and water erosion and infestation by woody and other weeds.

The episodes comprised a general sequence of degradation and partial recovery in which: (1) the population of livestock and other herbivores (rabbits, goats and macropods) built up during sequences of years with above-average rainfall; (2) resource damage occurred due to the high herbivore numbers and intermittent drought; (3) rapid decline in commodity prices for beef and wool occurred devaluing herds and flocks and delaying destocking; (4) severe and extended drought led to heavy utilisation of pasture and further resource damage; and (5) partial resource recovery did not occur until a sequence of above-average rainfall years, which was sometimes decades after the degradation episode.

Despite these painful drought episodes, many graziers have learnt, and documented, how to successfully manage livestock numbers under highly variable climatic and economic conditions. The successful strategies include: (1) maintaining relatively low numbers of livestock (and other herbivores); (2) frequently adjusting livestock and other herbivore numbers to match changing feed availability and responding quickly at the first sign of drought (either as indicated by rainfall deficits or by climate forecasts); and (3) delayed restocking of the resource after drought to allow for recovery of the desired pasture species. Combinations of these strategies have been successful in the highly variable climates (and economies) of Australia's rangelands by conserving pasture and fodder shrubs: thus reducing the impact of rainfall deficits on animal nutrition; minimising the loss of soil carbon and decline in infiltration capacity; and reducing soil erosion. These historical episodes of drought and recovery show that any particular period of drought or dry conditions can be followed by favourable rainfall providing the opportunities to manage for recovery of resource condition and finances. In particular, for eastern Australian rangelands, resource recovery occurred in sequences of wet years that were associated with the interaction of fluctuations in Pacific Ocean sea surface temperatures at different time scales (La Niña years in the cool phase of PDO).

A major development resulting from the drought–degradation episodes was a procedure for objectively estimating the 'safe' grazing capacity of individual properties using historical climate information (Johnston et al 2000). This calculation procedure successfully combined two types of knowledge in the community: (1) the experience and knowledge of successful graziers who have maintained their grazing enterprises through long periods of climate and economic variability; and (2) the capacity to use computer simulation models that were based on scientific grazing trials to calculate pasture growth using historical climate data. This procedure represents a major 'learning from history' experience and provides a potential adaptation response to climate change.

The historical review indicated the information needs (Stone et al 2003) that could have 'softened' the impact of climate variability during these previous degradation episodes. These important information needs may also be appropriate to other enterprises operating in variable climates, and are:

- objective and reproducible monitoring of resource condition and grazing pressure in near 'real-time'
- objective estimates of property 'safe carrying capacity' based on historical rainfall and an ability to extrapolate management practices of long-term successful managers
- knowledge and monitoring of the forces driving climate variability
- climate forecasting or climate risk-assessment systems
- projections of degradation risk combining resource condition, grazing pressure and climate and economic forces
- understanding that the perceived resource resilience partly comes from the climate system and that conservative grazing management can enhance the rate of recovery from inevitable drought periods.

Box 2: Case studies of current climate impacts for urban and rural Australia

There are currently major management issues resulting from climate impacts that provide useful examples of how governments and communities are dealing with current climate variability and expected climate change. The following examples, water availability in south-west Western Australia and heat wave preparedness in Queensland, indicate that adaptation planning and responses to observed climate changes and projections are beginning to occur. Other expected climatic extremes pose major risks to human welfare, infrastructure, and conservation of natural heritage. Such examples include: increased flooding resulting from greater rainfall intensities; higher coastal storm surges associated with more intense tropical cyclones and sea level rise; and greater bushfire intensities caused by increased temperatures and lower humidity. A major concern resulting from decadal and multi-decadal variability in the climate system is that the perception of the actual risk of these extremes is reduced, or even lost from the community's memory. Preparing for future climate extremes remains a challenge for communities and governments alike.

South-western Australian rainfall (Indian Ocean Climate Initiative)

The decline of winter rainfall in south-west Western Australia provides one of the best examples of the application of emerging climate literacy. Since the mid 1970s, winter rainfall has decreased 'sharply and suddenly' in the region of south-western Australia (IOCI 2002, Abstract). By the mid-1980s, water managers were concerned, and subsequently downgraded expected long-term average inflow (called ‘derating’). Water managers also developed water sources more quickly than originally planned, and stepped up efforts to conserve water (Power et al 2005). A five-year (1998 to 2002) programme of strategic research known as the Indian Ocean Climate Initiative (IOCI) was conducted to evaluate the likely causes of this climate shift. It indicated that both natural variability and the enhanced greenhouse effect were likely to have contributed to the rainfall decrease, and that the determination of the relative influences of natural multi-decadal variability and the enhanced greenhouse effect was a major scientific challenge (IOCI 2002, Abstract). The report recommended that ‘decision-makers need to alter their decision base-lines to reflect observed and projected changes but also to include increased levels of uncertainty’ (IOCI 2002, Abstract).

With other regions in Australia also experiencing rainfall declines and water restrictions over the last decade, there has been a greater need to link climate science with water planning and community education so as to correctly support changes in community attitudes to water use. Power et al (2005) reviewed the role that climate science played in influencing the successful changes in water management from the mid-1980s onwards, at a time of growing awareness of the likely impacts of global warming (Pearman 1988). The scenarios developed at the time (late 1980s) were based on the likely global warming effects on atmospheric circulation, and ‘included a 20 per cent decline in rainfall by 2040 over southern Australia’ (Power et al 2005, p 840). Power et al (2005, p 840) recognised that some ‘derating’ would have occurred in response to the observed drying without information from climate science. Further ‘derating’ occurred in 1998 under the assumption that rainfall in the region had changed more as a result of a ‘regime shift’ than a downward trend. The useful interaction of water managers and climate scientists appears to have resulted in a continuing adaptation to the uncertain combination of climate variability and change and community support for such adaptation and investment in new infrastructure.

Heatwave precautions for south-east Queensland

Heatwaves have impacts on human health, energy and water consumption, and agricultural and horticultural production. The number of hot days is expected to increase as a result of global warming. For example, in Brisbane, the current long-term annual average number of days above 35ºC is three. By 2030, Brisbane could experience an average of up to six days above 35ºC and by 2070, up to 35 days (NR&M 2004, p 12). This likelihood of increasing summer daytime maximum temperatures followed by warm nights offering little relief, poses a potential threat to urban communities where housing design and services may not be appropriate.

Emergency Management Australia (2004) stated, ‘In Australia during the 20th century, heatwaves have caused more deaths than any other natural hazard (except disease), yet they remain one of the least-studied and most-underrated.’ Woodruff et al (2005, pp 20–21), using the death records from Australian cities over the period 1997–99 for the age group over 65 years of age, estimated that around 1100 people died each year due to high temperatures.

More recent heatwave examples in south-east Queensland include: (1) January 2000, 22 recorded deaths and 350 injuries costing an estimated $2 million; and (2) in February 2004, 12 recorded deaths and 221 heat related hospitalisations (preliminary data) (Queensland Health 2004, p 4).

As part of the Queensland Heatwave Response Plan, the Bureau of Meteorology now issues advice to Queensland Health when the ‘heat index’ is forecasted to exceed 36ºC in Brisbane for at least two consecutive days. Queensland Health, in turn, forwards this advice to hospitals and other agencies, and provides public advice on managing heat stress.

Box 3: The current drought 2001 to 2005

In the past, the extent of the impacts of each drought period has usually not been documented until after the event, when sufficient information becomes available. Not surprisingly then, there appears to be a need during each drought event to describe it as the worst in ‘a very long time’ (a decade, generation, lifetime, century, since records began), perhaps to jolt the wider community into action and support. The 2001–05 drought has also been shaping the debate in the wider community in terms of expectations on appropriate drought management practices, land and water use, and government support (Botterill 2003, McColl and Young 2005). In the following section the current drought (2001–05) is reviewed from the perspectives of historical droughts and future climate change. The following review was prepared in October 2005. Important updates of the impacts of continuing drought conditions can be found in Watkins (2005) and Bureau of Meteorology (2006).

The so-called ‘millennium’ drought (Whitaker 2005, p 220) commenced in 2000 in regions across Australia (Figure 5) and has been a major cause of hardship for rural and urban communities   It should be noted that the term ‘millennium drought’ reflects its timing in terms of dates not its implied frequency. The assessment of the drought’s severity in relation to historical variability is important in the context of monitoring the emerging impact of climate change. The drought period commenced after a sequence of above-average years of rainfall (1998–99 to 2000–01). The effect of the drought occurred earlier (2000) in the south-west of Western Australia impacting on water inflow into dams and grain production (Stephens et al 2003). In 2001–02 there were high commodity prices, and incomes for many farms were at record levels (Martin et al 2005, p 23). Important exceptions during this period, as discussed above, are south-eastern and coastal Queensland and south-western Australia, which have experienced drier conditions for at least the last 15 years. In 2001–02, drought began in areas of south-western Queensland, western New South Wales, eastern South Australia, north-western Victoria and the Gascoyne region of Western Australia. In eastern Australian rangelands, the previous sequence of favourable years had led to a build up in kangaroo numbers (Stone et al 2003) and, with emerging drought conditions, high grazing pressure in rangeland areas became apparent. In 2002–03, an El Niño year, extreme drought occurred across much of eastern Australia and areas of Western Australia, further exacerbating drought conditions in those areas where the drought had already commenced

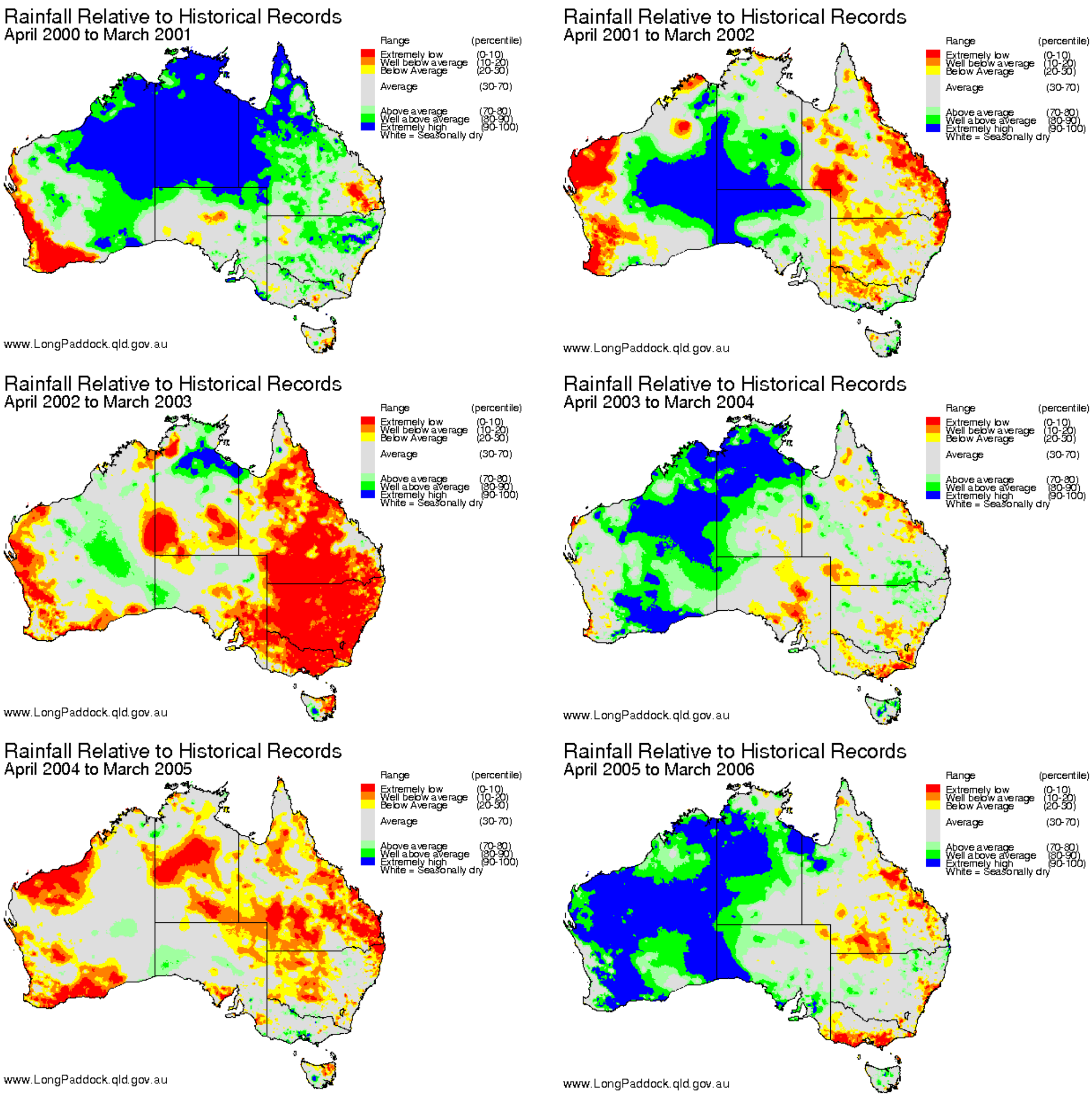
(McKeon et al 2004). The year 2002 had the highest daytime average temperature aggregated across Australia. ‘The impact of the rainfall deficiencies was exacerbated by high [potential] evaporation rates in response to the very high daytime temperatures’ (Bureau of Meteorology, 2002, p 10).

A substantial number of regional submissions for declaration of Exceptional Circumstances commenced towards the end of 2002. By August 2003, more than 80 per cent of New South Wales was declared to be under Exceptional Circumstances. In October 2002, the Farmhand Foundation organised financial support from the wider community and started a public debate on issues such as ‘drought-proofing’ Australia (Hayman 2003, p 16; the debate regarding drought-proofing is further discussed below). The statewide retention rate of livestock in New South Wales, a major livestock producing state, was ‘surprisingly high’ (71 per cent of sheep and 75 per cent of cattle, Hayman 2003, p 15) placing a potentially high feeding cost on livestock producers. In contrast, there were substantial reductions in livestock numbers in several rangeland regions across Australia. For example, sheep numbers in the western districts (i.e. rangelands) of New South Wales had been reduced to 30-40 per cent of pre-drought numbers and were lower than reported in 1902, at the end of the extended Federation drought. Whilst indicating the severity of the ‘millennium’ drought, this response also suggests an improvement in the management for drought compared to previous historical drought and degradation episodes in the rangelands, when stock were retained too long (McKeon et al 2004).

The millennium drought also had important impacts on urban water availability and property damage (Watkins 2005). For example, associated with the extreme dry conditions, there were very destructive bushfires. In Canberra in January 2003, fires resulted in the loss of lives and property as described in Beer (2006).

With the general warming trend of the Australian continent since 1910, a major concern for agriculture and biodiversity is the possibility that the impact of drought will be amplified by higher temperatures and potential evaporation rates. Nicholls (2003) evaluated the 2002 drought in terms of its historical climate context, asking whether the 2002 drought was the worst. He found that the severe 1940 drought in the Murray Darling Basin was 0.6^{o}C cooler than 2002 and was also restricted to the southern half of the country. Nicholls (2003, p 3) concluded, ‘on these broader comparisons, the combination of extreme temperatures with low rainfall during 2002 does seem unique even if, on shorter averaging periods and smaller scales, similar high temperature – low rainfall combinations have occurred in the past.’ Nicholls (2003) examined possible causes of high temperatures in 2002 by comparing maximum temperatures with rainfall (from 1952 to 2002). He showed that droughts were in fact becoming warmer and that the nature of droughts in eastern Australia was changing over the last 50 years. ‘The apparently inexorable warming from the mid-20th century has meant that each drought was warmer than the previous drought, both during the daytime and at night’ (p 5). He noted that the warming over Australia over the past century matched global warming and stated carefully that ‘the possibility that the warming observed over Australia, with its consequent effects on the 2002 drought, is also likely due to the enhanced greenhouse effect warrants consideration' (p 5).

Figure 5: Rainfall percentiles for each twelve month period April to March for 2001/01 to 2005/06.



Source: From poster 'Australia's Variable Rainfall' www.LongPaddock.qld.gov.au.Queensland Department of Natural Resources, Mines and Water using rainfall data from Australian Bureau of Meteorology.

Assessment of the drought in terms of the other factors that affect potential evaporation (solar radiation, vapour pressure deficit and wind) are yet to be completed, but it is necessary to determine to what extent the observed warming reduced soil moisture availability and hence amplified the damaging effects of low rainfall on agricultural production. Nevertheless, should the 'warming' of droughts continue, then 2002 could well be seen, with the benefit of hindsight, as the forerunner of things to come.

Further record high temperatures occurred in January to April 2005, exacerbating dry conditions across much of Australia (Bureau of Meteorology 2005). April 2005 was, in terms of maximum temperature anomaly, the "hottest April on record by a considerable margin for Australia and also across, NSW, Victoria, SA and the NT" (Bureau of Meteorology 2005). Similarly, the average Australian April minimum temperature was also the highest on record. The occurrence of these types of extremes, coupled with an expectation of global warming trends, provides powerful examples supporting the urgency for developing future adaptation strategies.

Following average conditions in 2003–04, severe drought returned in many regions of Australia in 2004–05 (a year with marginal El Niño conditions). For many regions, the overall five-year period from 1 April 2000 to 31 March 2005 had extremely low rainfall compared with historical records of 115 years commencing in 1890.The severity and duration of the millennium drought invites comparisons with the seven year Federation drought (mid/late 1890s, early 1900s). The Federation drought was particularly severe and protracted across eastern Australia. Extremely low rainfall (less than Decile 1) was also recorded in many regions across the continent during this period. For the 5-year periods ending in March 2005 and March 2006, some stations have recorded lower rainfall than in the Federation drought, for example, in 2005 south-west Western Australia and south-eastern Queensland; and in 2006 south-west Queensland, central coastal Queensland and areas of south-eastern Australia. However, it should be noted that the Federation drought in eastern Australia spanned seven years with severe rainfall deficits in many regions across Australia. As a result this difficult period in our history remains a benchmark for planning and climate risk management.

It is difficult to compare how well droughts have been managed over the last hundred years, given the many changes that have occurred in: drought management practices; infrastructure developments such as dams and transport; rural populations; commodity prices; property size and land use; the contribution of agriculture to the national economy; and government provision of financial support. Responses to, and features of, the current drought that have probably reduced its impact on resource condition and farm financial performance include: awareness of seasonal climate forecasts based on El Niño development in 2002 (Stephens et al 2003), and to a lesser extent in 2004; early reductions in stock numbers reducing resource damage in rangeland regions; use of farm management deposits 'to manage exposure to adverse economic events and seasonal fluctuations' (Martin et al 2005, p 23); substantial government support 'targeting farm business and welfare needs of farming families' (Martin et al 2005, p 20); and relatively high prices in historical terms for livestock and grains 'assisting farmers to manage cash-flow at a time of reduced production' (Martin et al 2005, p 1).

To better monitor and document the impact of drought and streamline Exceptional Circumstances application and assessment processes, a National Agricultural Monitoring Systems (NAMS) has been developed (www.nams.gov.au). NAMS contains current and historical climate data, model output and remotely sensed information to indicate the agricultural and financial impact of current seasonal conditions and to place these in an historical context.

A feature of the current drought has been a renewal of the debate on 'drought proofing' agriculture and rural Australia. 'Drought proofing' describes the concept of changing management practices and infrastructure to reduce the impact of drought on production and communities. At the core of the debate is the clash between two opposing approaches to managing for drought. On one hand, it is argued that technical advances (drought-adapted crop varieties, water storage for irrigation) and financial support are needed to maintain a high level of agricultural production and to protect the stability of rural communities in periods of rainfall deficit. On the other hand, there is a call for the recognition that Australia has a relatively high frequency of drought occurrence in many regions and that agricultural enterprises and practices, financial management options, and structural adjustment support should reflect a more conservative expectation of resource use. This latter view argues that better individual climate risk management and more appropriate land use would be less environmentally damaging and require less financial support.

This commentary does not seek to resolve this hundred-year-old debate. Nevertheless, the transparent debate is, in itself, a feature of successful adaptation to 'living in a variable climate' in that the ideological views on land and water use that dominated agricultural development since settlement can at least now be evaluated from scientific and economic perspectives (for example, McColl and Young 2005). To this end, the continued monitoring of environmental indicators and the separation of climate and management effects represent the next major challenges for environmental science.

Acknowledgements

The critical review and insights of the peer reviewers (Drs David Jones, Michael Roderick and Roger Stone), colleagues in Climate Impacts and Natural Resource Systems (QNRW) and Dr Mark Howden are gratefully acknowledged. The support of Alan Peacock, Neil Flood, Tracy van Bruggen and Jackie Wakefield in preparing the document and maps is also gratefully acknowledged.

References

Allan RJ 1985, ‘The Australasian summer monsoon, teleconnections, and flooding in the Lake Eyre Basin’, *South Australian Geographical Papers,* no. 2, 1985, Royal Geographical Society of Australasia (S.A Branch).

Allan RJ 2000, ‘ENSO and climatic variability in the last 150 years’, in HF Diaz and V. Markgraf (eds.) *El Niño and the Southern Oscillation: Multiscale Variability, Global and Regional Impacts,* Cambridge University Press, Cambridge, pp 3–55.

Alves O, Wang G, Zhong A, Smith N, Tzeitkin F, Warren G, Schiller A, Godfrey S and Meyers G 2003, ‘POAMA: Bureau of Meteorology operational coupled model seasonal forecast system’, in R Stone and I Partridge (eds.) *Science for Drought, Proceedings of the National Drought Forum, Brisbane, April 2003*, Queensland Department of Primary Industries, pp 49–56.

Anon 1901, *Royal Commission to Inquire into the Condition of the Crown Tenants, Western Division of New South Wales,* Government Printer, Sydney.

Beadle NCW 1948, *The Vegetation and Pastures of Western New South Wales with Special Reference to Soil Erosion*, Government Printer, Sydney.

Beer,T 2006, ‘Atmosphere’, theme commentary prepared for the 2006 Australia State of the Environment Committee, Department of Environment and Heritage, Canberra, <http://www.deh.gov.au/ soe/2006/commentaries/atmosphere/index.html >.

Botterill LC 2003, ‘Beyond drought in Australia: the way forward’, in LC Botterill and M Fisher (eds.) *Beyond Drought: People, Policy and Perspectives*, CSIRO Publishing, Collingwood, Victoria, pp 197–207.

Botterill LC and Fisher M 2003, Introduction. in LC Botterill and M Fisher (eds.) *Beyond Drought: People, Policy and Perspectives,* CSIRO Publishing, Collingwood, Victoria, pp 1–7.

Bureau of Meteorology 2002, *Annual Climate Summary 2002,* prepared by the Climate Analysis Section, National Climate Centre, Commonwealth Bureau of Meteorology. Melbourne, <http://www.bom.gov.au/announcements/ media_releases/climate/change/20030106.shtml>.

Bureau of Meteorology 2005, *More than 150 high temperature records set in January and April,* media release 2 May 2005, Australian Bureau of Meteorology, Melbourne.

Bureau of Meteorology 2006, *Special Climate Statement 9: An exceptionally dry decade in parts of southern and eastern Australia*: *October 1996-September 2006*. Issued 10 October 2006, National Climate Centre, Australian Bureau of Meteorology, Melbourne.

Burroughs W 2003, *Climate into the 21st Century*, Cambridge University Press, Cambridge.

Cai W 2006, 'Antarctic ozone depletion causes an intensification of the Southern Ocean super-gyre circulation' *Geophysical Research Letters*, 33, L03712, doi:10.1029/2005GL024911.

Cai W 2003, 'Australian droughts, climate variability and climate change: insights from CSIRO's climate models', in R Stone and I Partridge (eds.) *Science for Drought, Proceedings of the National Drought Forum, Brisbane, April 2003*, Queensland Department of Primary Industries, pp 12–20

Clewett JF, Young PD and Willcocks JR 1988, 'Effect of climate change on agriculture in Central Queensland: rainfall variability analysis', in ER Anderson (ed.) *The Changing Climate and Central Queensland Agriculture*, Australian Institute of Agricultural Science, Rockhampton, Queensland, pp 43–52.

Clewett JF, Howden SM, McKeon GM and Rose CW 1991, 'Use of systems analysis and the Southern Oscillation Index to optimise management of grain sorghum production from a farm dam irrigation system', in *Climate risk in Crop Production Models and Management for the Semi-arid Tropics and Subtropics*, International Symposium and Workshop, Brisbane, Australia, July 1990, CSIRO, pp 307–28.

Collins M 2005, El Niño or La Niña-like climate change? *Climate Dynamics* 24: 89–104.

Condon RW 2002, *Out of the West: Historical Perspectives on the Western Division of New South Wales*. Lower Murray Darling and Western Catchment Management Committees, Rangeland Management Action Plan.

Coughlan M 1988, 'Seasonal climate outlooks', in ER Anderson (ed.) *The Changing Climate and Central Queensland Agriculture*, Australian Institute of Agricultural Science, Rockhampton, Queensland, pp 17–26.

Coughlan M, Jones D, Plummer N, Watkins A, Trewin B and Dawkins S 2003, 'Impacts of 2002–03 El Niño on Australian climate', in: N Plummer, M Flannery, C Mullen, B Trewin, A Watkins, W Wright, T Powell, S Power (eds) *DroughtCom Workshop: Improving the Communication of Climate Information*, Melbourne, July 2003. volume 2, Extended abstracts, pp 7–12.

CSIRO 2001, *Climate Change Projections for Australia*, CSIRO Atmospheric Research, Melbourne, viewed 1 February 2005, <http://www.dar.csiro.au/publications/projections2pppdf>.

Cullen P 2005, ‘Farmers lose in the dust-up’, *The Australian,* 30 May 2005, p 9.

Drosdowsky W 2002, ‘SST phases and Australian rainfall’, *Australian Meteorological Magazine* 51:1–12.

Drosdowsky W 2005, ‘The latitude of the sub-tropical ridge over eastern Australia: The L index revisited’, *International Journal of Climatology* 25:1291–99.

Emergency Management Australia 2004, *Emergency Management for Schools: Categories; Heatwaves*, <http://www.ema.gov.au/agd/ema/emaschools.nsf>, last modified 2 August 2004.

Gibbs WJ and Maher JV, 1967, *Rainfall Deciles as Drought Indicators*, Bureau of Meteorology Bulletin No. 48, Bureau of Meteorology, Melbourne.

Hayman P 2003, ‘Climate information to manage drought risk in NSW’, in: N Plummer, M Flannery, C Mullen, B Trewin, A Watkins, W Wright, T Powell, S Power (eds) *DroughtCom Workshop: Improving the Communication of Climate Information*, Melbourne, July 2003. volume 2, Extended abstracts, pp 15–19.

Heathcote RL 1965, *Back of Bourke: A Study of Land Appraisal and Settlement in Semi–Arid Australia*, Melbourne University Press, Melbourne.

Houghton JT, Jenkins GJ and Ephraums JJ 1990, *Executive Summary. Climate Change the IPCC Scientific Assessment*, Intergovernmental Panel on Climate Change, Report prepared for IPCC by Working Group 1, Cambridge University Press, Cambridge.

Howden SM 2002, ‘Potential global change impacts on Australia’s wheat cropping systems’, in OC Doering, JC Randolph, J Southworth and RA Pfeifer (eds) *Effects of Climate Change and Variability on Agricultural Production Systems*, Kluwer Academic Publications, pp 219–247.

Indian Ocean Climate Initiative (IOCI) 2002, *Climate Variability and Change in Southwest Western Australia*, September 2002, http://www.ioci.org.au/publications/pdf/IOCI_TechnicalReport02.pdf (Accessed 8 August 2005)

IPCC 2001, *Climate Change 2001: The Scientific Basis,* Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change (eds. JT Houghton, Y. Ding, DJ Griggs, M. Noguer, PJ van der Linden, X. Dai, K. Maskell and CA Johnson), Cambridge University Press, Cambridge, UK, and New York, NY.

Jeffrey SJ, Carter JO, Moodie KB and Beswick AR, 2001, Using spatial interpolation to construct a comprehensive archive of Australian climate data, *Environmental Modelling and Software* 16(4):309–330.

Johnston PW, McKeon GM, Buxton R, Cobon DH, Day KA, Hall WB and Scanlan JC 2000, ‘Managing climatic variability in Queensland’s grazing lands – new approaches’, in G

Hammer, N Nicholls and C Mitchell (eds.) *Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems – the Australian Experience*, Kluwer Academic Press, Netherlands, pp 197–226.

Karoly DJ and Braganza K 2005, Attribution of recent temperature changes in the Australian region, *Journal of Climate* 18(3):457–464.

Lindesay JA 2003, 'Climate and drought in Australia', in LC Botterill and M Fisher (eds.) *Beyond Drought: People, Policy and Perspectives*, CSIRO Publishing, Collingwood, Victoria, pp 21–47.

Lough JM 2003, 'Lessons from the past: climate from corals', in R Stone and I Partridge (eds.) *Science for Drought, Proceedings of the National Drought Forum*, Brisbane, April 2003, Queensland Department of Primary Industries, pp 28–34.

Manabe S and Wetherald RT 1975, 'The effects of doubling the CO_2 concentration on the climate of a general circulation model', *Journal of the Atmospheric Sciences* 32:3–15.

Mantua NJ and Hare SR 2002, 'The Pacific Decadal Oscillation', *Journal of Oceanography* 58:35–44.

Mantua NJ, Hare SR, Zhang Y, Wallace JM and Francis RC 1997, 'A Pacific inter-decadal climate oscillation with impacts on salmon production', *Bulletin of the American Meteorological Society* 78:1069–79.

Martin P, King J, Puangsumalee P, Tulloh C and Treadwell R 2005, *Australian Farm Survey Results 2002–03 to 2004–05*, Australian Bureau of Agricultural and Resource Economics, Canberra, Australian Farm Survey Results, March, 2005. pp1-26.

McBride JL and Nicholls N 1983, Seasonal relationships between Australian rainfall and the Southern Oscillation. *Monthly Weather Review* 111: 1998–2004.

McKeon GM, Hall WB, Henry BK, Stone GS and Watson IW 2004, *Pasture Degradation and Recovery in Australia's Rangelands: Learning from History*, Queensland Department of Natural Resources, Mines and Energy.

McMahon TA, Finlayson BL, Haines AT and Srikanthan R 1992, *Global Runoff - Continental Comparisons of Annual Flows and Peak Discharges*, Catena Paperback, Cremlingen-Destedt.

McColl JC and Young MD 2005, *Managing Change: Australian Structural Adjustment Lessons for Water*, CSIRO report no 16/05, September 2005.

McTainsh G 1993, 'Soils', in G McTainsh and WC Boughton (eds.) *Land Degradation Processes in Australia*, Longman, Melbourne, pp 52–89.

McTainsh GH and Boughton WC 1993, Land degradation in Australia – an introduction', in G McTainsh and WC Boughton (eds.) *Land Degradation Processes in Australia*, Longman, Melbourne, pp 1–16.

Meinke H. and Stone RC 2005, 'Seasonal and inter-annual climate forecasting: the new tool for increasing preparedness to climate variability and change in agricultural planning and operations', *Climatic Change* 70(1–2):221–53.

Nelson R, Kokic P, Elliston L and King J 2005, 'Structural adjustment. A vulnerability index for Australian broadacre agriculture', *Australian Commodities* 12(1), March.

Nicholls N 1991, The El Niño – Southern Oscillation and Australian vegetation, *Vegetatio* 91:23–36.

Nicholls N 2003, 'Climate change: are droughts becoming drier and more frequent?', in R Stone and I Partridge (eds.) *Science for Drought, Proceedings of the National Drought Forum*, Brisbane, April 2003, Queensland Department of Primary Industries, pp 1–7.

Nicholls N 2005, 'Climatic outlooks: from revolutionary science to orthodoxy', chapter 2 in T Sherratt, T Griffiths and L Robin (eds.) *A Change in the Weather: Climate and Culture in Australia*, National Museum of Australia, Canberra.

Nicholls N, Drosdowsky W and Lavery G 1997, 'Australian rainfall variability and change'. *Weather,* 52(3), 66-71.

NR&M, 2004, 'Climate change – the challenge for natural resource management'. The State of Queensland (Department of Natural Resources and Mines), Brisbane.

Partridge IJ 1994, *Will it Rain? The Effects of the Southern Oscillation and El Niño on Australia*, Information Series QI94015, Queensland Department of Primary Industries, Brisbane.

McColl JC and Young MD 2005, *Managing Change: Australian Structural Adjustment Lessons for Water,* CSIRO report no. 16/05 September 2005, Canberra, ACT, 37p

Pearman GI 1988, 'Greenhouse gases: evidence for atmospheric changes and anthropogenic causes', in GI Pearman (ed.) *Greenhouse: Planning for Climate Change,* CSIRO Melbourne pp 3–21.

Pestana B 1993, *Australian Agriculture. The complete reference on rural industry,* A publication of the National Farmers Federation, Camberwell, Vic.

Pittock AB 2003, *Climate Change: An Australian Guide to the Science and Potential Impacts*, Australian Greenhouse Office, Department of Environment and Heritage, Canberra.

Pittock AB 1975, 'Climatic change and the patterns of variation in Australian rainfall', *Search* 6:498–504.

Power S, Casey T, Folland C, Colman A, Mehta V, 1999, 'Inter–decadal modulation of the impact of ENSO on Australia', *Climate Dynamics* 15:319–24.

Power S, Colman R and Wang X 2003, 'Can we predict decadal changes in Australia's climate?' in R Stone and I Partridge (eds.) *Science for Drought, Proceedings of the National Drought Forum*, Brisbane, April 2003, Queensland Department of Primary Industries, pp 21–23.

Power S, Sadler B, and Nicholls N 2005, 'The influence of climate science on water management in Western Australia: lessons for climate scientists', *Bulletin of the American Meteorological Society*, 86: 839–844.

Queensland Health 2004, *Queensland Heatwave Response Plan*, Queensland Health Emergency Preparedness and Continuity Management Project.

Ratcliffe FN 1970, *Flying Fox and Drifting Sand: The Adventures of a Biologist in Australia*, Pacific Books, Sydney, first published in 1938 by Chatto and Windus, London in Great Britain.

Roderick ML and Farquhar GD 2004, 'Changes in Australian pan evaporation from 1970 to 2002', *International Journal of Climatology* 24:1077–90.

Russell JS 1988, 'The effects of climatic change on the productivity of Australian agroecosystems', in GI Pearman (ed.) *Greenhouse: Planning for Climate Change*, CSIRO, Melbourne, pp 491–505.

Sadler BS, Mauger GW and Stokes RA 1988, 'The water resource implications of a drying climate in south-west Western Australia', in GI Pearman (ed.) *Greenhouse: Planning for Climate Change*, CSIRO, Melbourne, pp 296–311.

Stephens D, Foster I, Fletcher W, Hamersley J, Herbert A and Dracup M 2003, 'Experiences in the use of climate information, and its communication in 2002/03, from the perspective of the Department of Agriculture WA.', in: N Plummer, M Flannery, C Mullen, B Trewin, A Watkins, W Wright, T Powell, S Power (eds) *DroughtCom Workshop: Improving the Communication of Climate Information*, Melbourne, July 2003. volume 2, Extended abstracts, pp 42-45.

Stone RC, Hammer GL and Marcussen T, 1996, 'Prediction of global rainfall probabilities using phases of the Southern Oscillation Index', *Nature* 384:252–56.

Stone G, Crimp S, Day K, Hall W, Henry B, McKeon G, Owens J, Power S, Syktus J and Watson I, 2003, 'Preventing the 9th degradation episode in Australia's grazing lands', in R

Stone and I Partridge (eds.) *Science for Drought, Proceedings of the National Drought Forum*, Brisbane, April 2003, Queensland Department of Primary Industries, pp 62–73.

Syktus J 2005, ‘Reasons for decline in eastern Australia’s rainfall’, *Bulletin of American Meteorological Society* 86:624.

Syktus J, McKeon G, Flood N, Smith I and Goddard L 2003, ‘Evaluation of a dynamical seasonal climate forecast system for Queensland’, in R Stone and I Partridge (eds.) *Science for Drought, Proceedings of the National Drought Forum*, Brisbane, April 2003, Queensland Department of Primary Industries, pp 160–173.

Taylor JA and Tulloch D 1985, ‘Rainfall in the wet–dry tropics: extreme events at Darwin and similarities between years during the period 1870–1983 inclusive’, *Australian Journal of Ecology* 10:281–95.

Watkins AB 2005, *‘The Australian Drought of 2005’*, Bulletin of the World Meteorological Organisation 54:156-162.

Whetton P and Suppiah R 2003, ‘Climate change projections and drought’, in R Stone and I Partridge (eds.) *Science for Drought, Proceedings of the National Drought Forum*, Brisbane, April 2003, Queensland Department of Primary Industries, pp 130–136.

Whitaker R 2005, *Australia's Natural Disasters*, New Holland Publishers, Australia.

Williams J 2003, ‘Can We Myth-Proof Australia?’, *Australasian Science*, January-February 2003, 24(11):40-42.

Woodruff R, Hales S, Butler C and McMichael A, 2005, *Climate Change Health Impacts in Australia: Effects of Dramatic CO_2 Emission Reductions*, a report for the Australian Conservation Foundation and the Australian Medical Association.