PALAEOCLIMATE STUDIES RELEVANT TO NATURAL RESOURCE MANAGEMENT IN THE MURRAY-DARLING BASIN

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A report for the Murray-Darling Basin Authority

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EXECUTIVE SUMMARY

1. Australian palaeoclimate researchers have generated much data and published many studies relating to climate change and variability across south-eastern Australia and how such changes have affected landscapes, vegetation cover and waterways. These studies have used records of change from a range of resources including speleothems, tree rings, river channels and terraces, dune systems and lake sediments. A suite of biological, geological and chemical indicators have been used to infer system responses to past climate changes.

2. To date, many of these studies have focussed on the understanding of local climate change and system responses, or how local records relate to regional, global or orbital drivers of change. The purpose of these studies has been to examine change *per se*. These studies have rarely therefore, been tailored with the intention of generating data to inform policies aimed at improving natural resource management and developing an interactive dialogue with natural resource managers to explore the benefits of palaeoclimatic data in informing natural resource management.

3. Available scientific evidence reveals that the Murray-Darling Basin has experienced considerable climate change at a range of timescales. Over the last few hundred years (and during the time of European settlement) the MDB has been subjected to extended inter-decadal variability, known as flood and drought dominated phases, and year-to-year ENSO variability. Whilst natural systems have been resilient to historical changes, a recent, statistically significant step change toward regionally drier conditions comes at a time when the system is severely stressed by anthropocentric activities, especially from agriculture, water regulation and decisions regarding landscape restoration or revegetation.

4. Future climate change scenarios suggest a high likelihood of increased temperatures and less effective rainfall across much of the MDB. If the duration of the recent step change extends as long as those past, future climate

will be the critical factor influencing natural resource management and policy considerations within the MDB.

5. A clear opportunity exists to consolidate a network of policy-relevant palaeoclimate researchers and a portfolio of research tailored at informing natural resource managers of the MDB.

6. Improved estimates of past climate variability will provide an opportunity to:

    - test and validate regional climate models;
    - statistically distinguish the relative contribution of intrinsic natural climate variability from anthropogenic climate change;
    - map the record of climate change and resource development to contextualise future climate scenarios and resource availability; and
    - provide a scientific basis for appropriate natural resource management options such as the allocation of water resources.

INTRODUCTION

1.1. The Murray-Darling Basin

The Murray-Darling Basin (MDB) extends over 1.06 million square kilometres, and supports a population of over 2 million people within the Basin and many more outside (Craik, 2005). The geographical orientation of the MDB means the climate varies from cool, humid, eastern uplands, temperate southern mallee, inland, subtropical northern areas to hot, dry, arid and semi-arid country in the west (Craik, 2005). The rainfall (averaging 2 cm yr^{-1}) is highly variable, leaving the basin prone to extreme floods and drought events. The average annual runoff is c. 24,000 GL yr^{-1} (Figure 1). Under natural conditions, c. 11,000 GL yr^{-1} is taken up by wetlands and floodplains, and c. 13,000 GL yr^{-1} flows to the sea. Climate models suggest that potential evaporation across the MDB is four times that of rainfall, and observational data (1998-2002) record a loss of c. 1400 GL yr^{-1} through evaporation from reservoirs (MDBC, 2003). However, given the highly regulated nature of the MDB and surface water extraction, current mean flows are only c. 3000 GL yr^{-1}. The MDB is economically, socially and environmentally important, being the major water supply area for agriculture and contained communities (including the city of Adelaide). The major commercial activity in the MDB is agriculture, which produces c. 40% of Australia's gross value production and 70% gross value of irrigated agricultural production.

1.2. Future climate variability

Following the projected increase in global mean surface air temperatures (1.1-6.4°C) through the 21st Century, exacerbated by increases in anthropogenic greenhouse gas concentrations, the Intergovernmental Panel on Climate Change (IPCC) has predicted a similar temperature increase for Australia (Meehl *et al*., 2007; Hennessy *et al*, 2007). Similarly, evaporation is modelled to increase by almost 8%, though predictions for rainfall are uncertain (Meehl *et al*., 2007). Relative to 1990, different regions of Australia will experience warming of between 0.1°C and 1.5°C by 2020 (Hennessy *et al*., 2007), with more days per year with temperatures over 35°C. The IPCC suggest a tendency towards decreased rainfall over most of southern and sub-tropical Australia and increases in northern territory and northern NSW. A decline in runoff in southern and eastern Australia is also expected. Drought simulations suggest

a 20% increase over much of Australia by 2030, with increases in the Palmer Drought Severity Index (PDSI) over much of eastern Australia (Burke *et al*. 2006; Cai and Cowan, 2008)

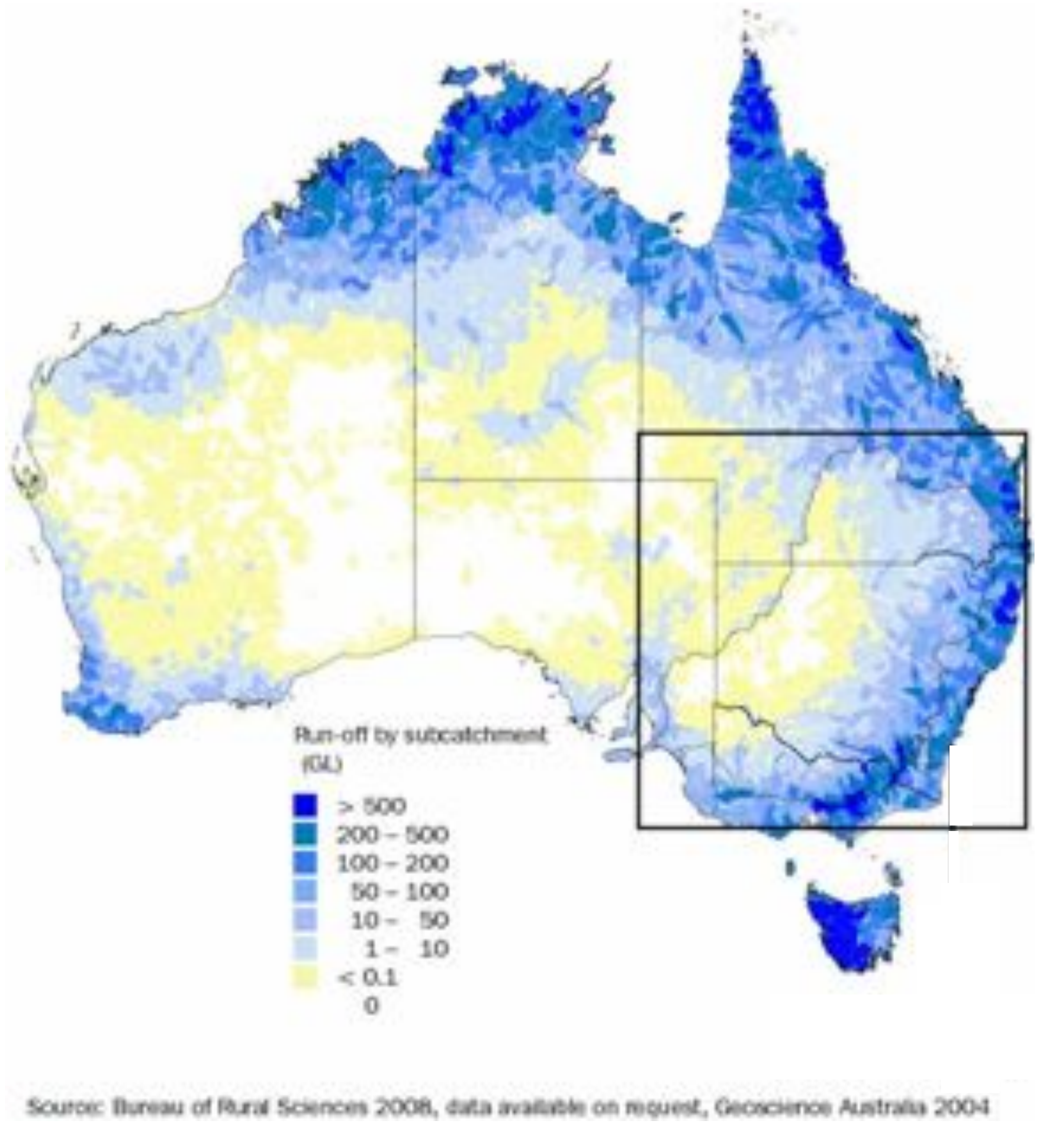

Figure 1. Map of runoff by sub-catchment, box highlights the MDB.

Pittock (2003) demonstrated that mean minimum and mean maximum temperature anomalies over the Murray-Darling Basin have followed an increasing linear trend from 1952 to 2002. Since 1952, mean maximum and minimum temperatures in the region have been increasing at rates of 1.75 ºC and 1.74 ºC per century, respectively. This has led to the increasing severity of drought, for a given rainfall deficiency,

through further or more rapid reduction in soil moisture and greater water demand (Karoly *et al*., 2003; Pittock, 2003; Nicholls, 2004).

Arnell (1999) suggests that the MDB will experience a 12-35% decrease in mean flow by 2050, whilst recent modelling suggests stream flow to Burrendong Dam will decrease by 0-15% by 2030 and 0-35% by 2070 (Jones *et al*., 2002; Hughes, 2003). Annual streamflow in the basin is likely to fall 10-25% by 2050, and there is a 50% chance that the average salinity of the Lower Murray River will exceed the desirable 800 EC threshold (MDBC, 1999) by 2020 (Hennessey *et al*., 2007). In effect, scenarios of drying suggest all freshwater dependent systems will be impacted by changes to patterns of droughts, floods and water quality.

Inter-annual variability of ENSO is the cause of both major flood and drought events in Australia. These variations are expected to continue under climate models and enhanced greenhouse conditions, with greater hydrological extremes as a result of more intense rainfall in La Niña years, and more intense drought resulting from higher rates of evaporation during El Niño years (Walsh *et al.*, 1999; McCarthy *et al.*, 2001). A more El Niño-like mean state of the tropical Pacific Ocean, which is projected by some climate models (Cai and Whetton, 2000) would imply greater drought frequency (Kothavala, 1999; Walsh *et al.*, 2000), as does the drying trend found over the Murray-Darling Basin in model simulations (Arnell, 1999).

1.3. Pressures on natural resource management in the MDB

The environment of the MDB is closely linked to both climate and anthropogenic activity within the catchment and the reliance of humans on a diminishing water resource. The MDB is a particularly vulnerable system when accounting for projected changes in climate coupled with the increasing dependence on the river for irrigation, livestock, recreation and a potable water supply. More than 40% of the MDB mean annual flow is utilised by humans, principally through irrigation. Due to prolonged below-average inflows in recent years, the major water storages in the catchment are currently at 18% capacity (June 2009; MDBC, 2009).

Recent surveys of the health of the Murray-Darling River Basin found that the overall biological and environmental condition of the River Murray and Lower Darling River are considered degraded with increasing degradation toward the mouth (Norris *et al.*,

2001; Pittock, 2003). Under projected climate scenarios irrigation demand will increase in many areas. Wetlands continue to be under threat (*see section 2.1.1*) and large numbers are already degraded (State of the Environment Report, 1996). River Red Gum forests along the Murray River are in a degraded state, and in increasingly poor condition downstream (Cunningham *et al.*, 2009). In the MDB, the quality of wetlands has been significantly reduced, particularly between the Hume Dam and Mildura (Norris *et al.*, 2001). Hydrological condition in the river channel is poor for all reaches, with the extent, timing and duration of floodplain inundation all significantly affected. Damage to aquatic ecosystems has occurred due to decreased streamflow and increased salinity. The irrigation dominated MDB suffers from decreased water inflows to wetlands and high salinity due to irrigation water use (Goss, 2003). With continuing drought, a consequence of flow variability is the increased demands on diminishing water resources (Walker, 2006).

There are a number of emerging management issues across the Murray-Darling Basin, particularly where control of land degradation through farm and plantation forestry is being considered. This option is being pursued partly for its benefits in controlling salinisation and waterlogging, and possibly as a new economic option with the advent of incentives for carbon storage as a greenhouse mitigation measure. The control of issues such as salinisation is especially important given the high total gross agricultural production contributed by the Murray-Darling Basin (*see section 1.1*; Bryan and Marvanek, 2004).

The predominance of irrigation across the MDB has, for much of the region, inextricably linked water security to the rainy season. Effective responses in terms of natural resource management to changing climate can only come from understanding the drivers of changes. Effective prediction of future climate scenarios across the MDB is needed, especially when modelling at a basin, rather than continental scale and at inter- and intra-annual timescales. The short instrumental record (dating only to the 19th Century; Harle *et al.*, 2007) does not capture a time series of sufficient duration to understand the amplitude and frequency of natural climatic events, or the long-term complexities and interactions of the climate system (Harle *et al.*, 2007).

1.4. The need for palaeo-research in the Murray-Darling Basin

Future climate variability will drive many environmental changes, especially in terms of the availability and quality of freshwater resources, land cover, and ecosystem diversity, stability and resilience; many examples of which exist in the palaeo-record. Understanding responses to past change will provide insights for long-term sustainable development and management.

Palaeoenvironmental and palaeoclimatic research within the Murray-Daring Basin is of great importance as it has the potential to provide an important historical perspective on past natural climate variability, and derived information can be used as a baseline for efficient long-term management of natural resources (cf. Olago and Odada, 2004). Data on longer-term cyclical fluctuations are limited, with instrumental meteorological records in Australia confined to the recent past (c. 100 years). Knowledge of long-term climatic change is essential for understanding the significance of historically documented and present day climatic conditions (such as the recent drought). Palaeo-research also enables the estimation of the range of natural climate variability under boundary conditions similar to today. Similarly, palaeo-data can be used to: (a) understand the relationships between forcing mechanisms and feedbacks which in turn may amplify/reduce the direct effects of forcing; (b) identify local and regionally significant human impacts; and (c) validate climate models that are used for future climatic predictions (cf. Olago and Odada, 2004).

Past climate changes have resulted in non-linear system responses in the palaeo-record as critical thresholds within these systems are exceeded. However, our understanding of threshold changes for many global systems is limited, and Australia is no exception. Coupled with natural climate variability, the anthropogenic modification of both the climate and environment (reducing the resilience of many ecosystems) may cause further thresholds to be crossed, beyond which lie alternative system states (Figure 2). Only through the careful analyses of similar changes in the past can scientists, natural resource managers and policy makers understand the potential challenges posed by future changes.

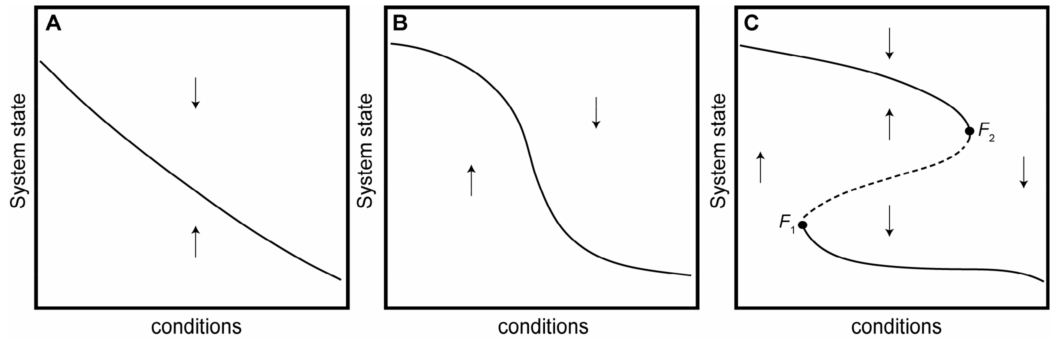

Figure 2. Schematic representation of ways in which the equilibrium state of a system can vary with changing environmental conditions, such as nutrient loading, exploitation, or a rise in temperature. Some systems may respond to environmental changes smoothly (A), they can respond to some threshold condition (B). In some instances when thresholds are crossed the system can have two alternative equilibria (C), separated by an unstable equilibrium (dashed line), which separates the two alternative stable states. *Redrawn from Scheffer and Westley (2007).*

Currently, predictions concerning the trends, significance and consequences of natural climate changes, and the modulation of the climate and environment by anthropogenic forcing, rely on the functioning of earth-climate system models (Jones *et al*., 2000). However, those models applied to the southern hemisphere have not been well validated due to the lack of sufficient palaeo-data, and those for the northern hemisphere tend to misrepresent changes in the southern hemisphere (Harle *et al*., 2007). Reliable, well-dated, high-resolution palaeo-data can provide a critical test of global circulation models. If these models can accurately simulate climatic conditions that are known to have existed, confidence in their future predictive ability will be increased (e.g. Seager *et al*., 2005).

Palaeo-data can be used to infer how biological and environmental systems have responded to past climatic perturbations (e.g. in terms of water quality and freshness and seasonality of rainfall). Climate changes between the glacial-interglacial cycles have been shown to impact on ecosystems however, following these rapid changes, systems had the chance to recover during periods of stability (Jones *et al*., 2000). Processes associated with land degradation (e.g. salinity and erosion) have also occurred as a result of climate change. For example, following a relatively wet phase from 34-26 kyr, salinity affected large parts of the MDB as aridity accompanied the onset of the glacial maximum some 20 kyr ago (Bowler and Wasson, 1984). High

evaporation, combined with a high water table and reduced vegetation cover, led to concentration of salt in the water table. Over large parts of the MDB, saline groundwater is actively discharged into a number of lake basins as shown by relict hypersaline groundwater and sub-surface gypsum deposits. These early periods of erosion and salinity were caused by natural processes and took hundreds or thousands of years to recover. Today similar problems exist, caused by land-use change in a little over 100 years, resulting in the loss of productivity in natural and human systems and compounding problems associated with climate change. Understanding the impacts of past climate changes on vegetation and salinity will contribute to our knowledge and ability to manage these sensitive systems, particularly under a changing climate (Jones *et al*., 2001).

Under future climate scenarios, the IPCC suggest that major water quality problems, as a result of eutrophication, will increase with toxic algal blooms becoming more frequent and longer-lasting (Hennessy *et al*., 2007). These algal blooms pose threats to human health, fisheries and livestock as a result of water quality changes (Falconer, 1997). Furthermore, future climate change will undoubtedly affect land-use in southern Australia, with cropping becoming non-viable at the dry margins if rainfall is reduced substantially. This may generate problems with land degradation through the exacerbation of soil acidification and dryland salinity (Hennessy *et al*., 2007).

Globally, palaeoclimatic research has revealed major changes in the earth's climate system over the last 2.6 million years (Quaternary; *see section 3*). To fully understand the variability of the climate system, a comprehensive network of well-dated, quantitative palaeoclimate data are required. Where high-resolution records have been recovered (e.g. from speleothems and dendrochronology; *see section 4*), they have significantly advanced our understanding of the climate system (Bradley *et al*., 2003). In particular, past rapid changes will provide critical insights into how system responses and interactions can be expected to occur under natural and anthropogenically forced climate scenarios in the future (Bradley *et al*., 2003).

The recent focus of research on continuous palaeoenvironmental records with annual to decadal time resolution over the last few millennia, and decadal to century scale resolution spanning the last several hundred thousand years, is crucial to document lower frequency variability and the full range of short-lived, extreme events that

Australia has experienced in the past (Oldfield and Alverson, 2003). There are, potentially, several climate and environmental proxy records available within the Murray-Darling Basin, most notably: tree rings, terrestrial wetland sediment archives and terrestrial morphology (*sections 3 and 4*). However, many key, high-resolution sites for understanding climate changes within the MDB lie on the margins of the MDB catchment (e.g. speleothems and lake sediment archives). These sites are well placed to understand the various external climatic regimes that influence precipitation and temperature over the MDB. Improving the spatial coverage of palaeo-data will ultimately enhance our knowledge of the effects of 'high impact events' such as fire, drought, storms and floods (Harle *et al*., 2007; Battarbee and Binney, 2008).

1.5. Scope

This report provides an incisive review of palaeo-climate science and its relevance to natural resource management within the Murray-Darling Basin. The aim is to provide up-to-date information on the suite of palaeo-data available within eastern Australia which is directly relevant to the understanding of climate change and variability across the MDB through time. With the current drought focussing scientific, public and media attention on intrinsic climate variability, and the confounding effect of human activity within sensitive catchment systems, a review of this kind is pertinent in understanding how land managers and policy holders can move forward under the current climate stress, especially in terms of water resource management. Many policy and research reviews make statements about future planning with little consideration of climate change and without useful actionable knowledge. To understand future climate changes, modellers need, and demand, better palaeo-data to constrain their model projections. By understanding how natural systems have varied in the past, within an appreciation of the increasing pressure from human activity within catchments and anthropogenically enhanced climate change, we can work towards a scientific framework on which sound decision making can be based. The use of palaeo-science as a tool for understanding potential future climate changes and managing natural resources is not a new concept (Turney *et al*. 2006; Harle *et al*., 2007); however, past reviews are generic and lack the focus and detail required for the information to be successfully applied to natural resource management in individual catchments such as the MDB.

2. CONTEMPORARY SETTING

The increase in scientific and public interest into the effects of human-driven climate change has focused attention on the implications of warming climates for the Murray-Darling Basin. The prevailing drought conditions, which has brought below average rainfall across most of southern Australia since 1998 (State of the Environment, 2006), has raised questions as to how unusual the current dry phase is, and whether it is part of a natural cycle of variability, or whether it is an early warning of different climate states Australia will experience in the future.

2.1. Climate step changes, system states and NRM

Vivés and Jones (2005) identified and analysed evidence for step changes in historical Australian rainfall records. Testing of Australian rainfall series >60 years in length, from 1890–1989 against an independent, random reference series, showed three abrupt shifts over that period.

The first shift occurred in the early 1890s and affected both summer and winter rainfall across much of Australia, especially eastern Australia. Although this shift took place when fewer records are available, extensive evidence from river flows, both in Australia and overseas (Nile, Yangtze), lake sediment records (e.g. Naivasha, Victoria in East Africa) and records of the Indian monsoon (Pant *et al*., 1988) indicate that a large-scale climate shift occurred at this time (Whetton *et al*., 1990). Supporting evidence, in the form of good rains in the 1880s followed by drought in the 1890s, influenced grazing success and stock numbers in Western New South Wales (Williams and Oxley, 1979).

The next major shift occurred in the late 1940s, and was concentrated over eastern Australia, marking the end of a 50-year dry period. Pittock (1975) suggested that shifts in rainfall may be related to the movement of mid-latitude and sub-tropical weather systems; however, subsequent work has not confirmed this link, suggesting that internal feedbacks may be the driving force behind the changes. Later analyses have tended to concentrate on post-1950 climate data for reasons of quality. Analyses using these data identify ENSO as the largest contributor to inter-annual variability and Pacific and Indian decadal oscillations (that modulate inter-annual variability) as the second most important driver (see Smith *et al*., 2000). However, long-term

decreases in sea-level pressure, consistent with the latitudinal movement of weather systems, have occurred simultaneously resulting in decreases in rainfall in SW WA (Smith *et al*., 2000). The third shift occurred between 1967-72, manifesting as a decrease in rainfall in SW WA in the late 1960s and an increase in eastern Australia in the early 1970s.

Several studies have indicated changes in rainfall regimes through observations of streamflow and/or riverine morphology. Based on long-term flood stage records, Warner (1987; 1995) nominated periods of drought dominated regime (DDR) and flood dominated regime (FDR) for the Nepean–Hawkesbury catchment west of Sydney. The periods 1799-1819, 1857-1899 and 1949-1988 are noted as flood dominated and 1820-1856 and 1900-1948 as drought dominated. The 1899 and 1948 dates broadly agree with those determined from the rainfall instrumental records (1988 marks the end of the data then available to Warner rather than a regime change).

In a study of rainfall and river flow variability linked with El Niño, Whetton *et al*. (1990) illustrated seven time series of streamflow from major rivers in Africa, China, India and Australia, including the Darling River. Major variations in the total annual flow for the Darling River are similar to those of the other main rivers of inland eastern and north-east Australia over the period 1884-1984. Flohn (1986) noted a 25% fall in streamflow in the Nile River after 1898-99 referenced to the period 1871-1926. This suggests that the change in regime in eastern Australia at the end of the 19th Century may have been part of a global or hemispheric phenomenon (Figure 3).

2.2. Hydrological impacts of shifts in decadal rainfall regimes

Warner (1987; 1995) suggested that large floods in the second half of the 20th Century initiated significant changes in the coastal rivers of NSW, including rivers where anthropogenic impacts had been relatively low. For example, the mean annual flood stage at Windsor in the Hawkesbury-Nepean River was 9 m during a flood-dominated regime but only about 6 m during a drought-dominated regime (Warner, 1995). The morphological impacts were largest in unconsolidated and/or narrow floodplains with limited flood storage. A change from a DDR to an FDR resulted in substantial changes to banks and floodplains that may not be complete before the next regime change. Impacts are less on large floodplains with adequate flood storage, but these

are now limited due to the narrowing of floodplains for human activities. During a DDR, a narrow floodplain may be set inside the main floodplain which may then be removed in the next FDR. Where human-induced changes have affected catchments, ongoing degradation processes may be accelerated during an FDR. Floodplain management is likely to be problematic in an FDR, compared to a DDR, even where anthropogenic effects are severe. This situation would be exacerbated under climate change (Warner, 1995).

Jones and Pittock (2002) analysed the impacts of decadal rainfall regimes on flows in the Macquarie River, in the eastern MDB. The baseline analysis used inputs of historical daily rainfall and potential evaporation from 1890–1996 applied to 1996 infrastructure and supply management rules (i.e. simulated how today's river would behave under historical conditions). The results show a 20th century of two halves. Between 1895–1946 simulation irrigation allocations were below 50%, 38% of the time, flows into the Macquarie Marshes were below 300,000 Gl (preventing good bird breeding) 48% of the time, and storage in the largest dam was below 500,000 Gl 38% of the time. From 1947–1995, these occurrences fell to 8%, 16% and 16%, respectively. Under the National Land and Water Resources Audit in 2001, the Macquarie catchment was classified as over allocated – this in a flood-dominated climate. It can be assumed that if a DDR similar to the early 20th Century returned, hardship would increase markedly.

Under climate change, simulated critical thresholds for irrigation and bird breeding were exceeded when long-term mean annual flow changes by -10% due to climate change during a DDR; -20% due to climate change during a 'normal' regime, and -30% due to climate change during an FDR (Jones and Pittock, 2002). This indicates that decadal rainfall regime is equally as important as climate change.

Jones and Pittock (2002) and Warner (1995) have identified different risks associated with a decadal rainfall regime interacting with climate change. It now appears as if the current rainfall regime in the eastern states has returned to drought-dominated conditions. Testing of area-averaged rainfall time series over the upper catchments of the Murray River shows a downward step change beginning in 1997. As to whether this is anthropogenic climate change, natural climate variability, or some combination of the two, remains to be determined.

With historical rainfall records indicating step changes in mean decadal rainfall, that can last for two to more than five decades, current management practices within the MDB are based on extrapolated data derived from what is now known to have been a largely wet phase (Vivés and Jones, 2005; Murphy and Timbal, 2008). The post WWII scaling up of the system's regulation and water volume diversion (SoE, 1996) occurred during a period of water surplus, which has led to allocation of water resources that can be considered to be excessive given the longer-term view. In the current dry phase irrigators in NSW and Victoria are experiencing seasonal allocations lower than in any previous season. South Australia, in particular, is experiencing the longest period of limited 'Entitlement Flow', which is creating difficulties with low flow levels and high salinities in the lower lakes (MDBC, 2003). Water resource management must now consider, and adapt to, limits in water availability caused by a switch to a dry state in a naturally oscillating system, as well as the potential of additional desiccation from human driven changes to the natural climate system (Connell, 2007).

Changes in rainfall regime raise key questions for management, especially in terms of natural resources (e.g. availability of freshwater), including whether the current drought phase is likely to persist, and, more critically, will it remain in place for several decades (as did the extended period of rainfall deficit from 1895-1946/8; Jones *et al*., 2001; Vivés and Jones, 2005). Also critical is whether this dry phase is a repeat of the step changes observed in the past, or whether it is a response to anthropogenic climate forcing. The confounding impacts of human climate forcing, coupled with natural inter-decadal variability, leads to an increased risk of extreme, or unusual, climate events within the MDB (Figure 4).

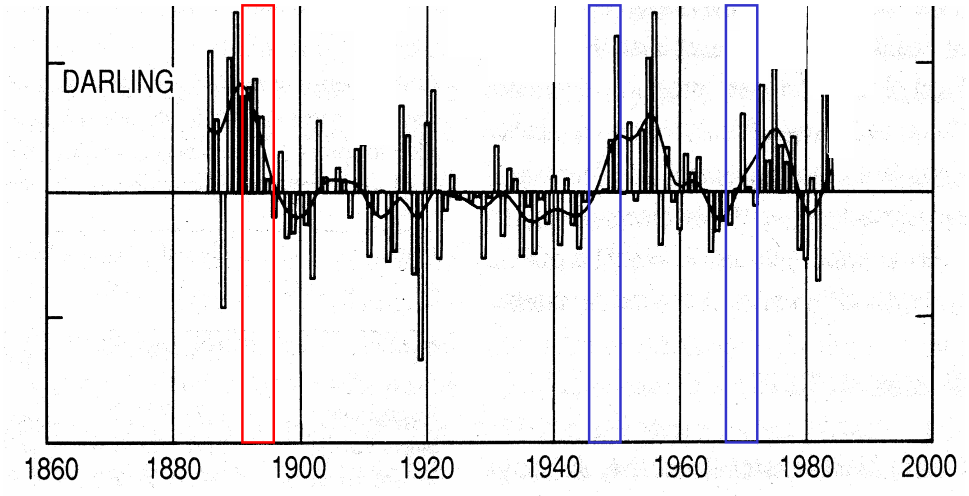

Figure 3. Time series representation of the Darling River stream flow at Wilcannia (32º S, 143º E; Whetton *et al*., 1990). Red shows the 1890-95 decrease and blue shows the 1945-50 and 1967-72 increases.

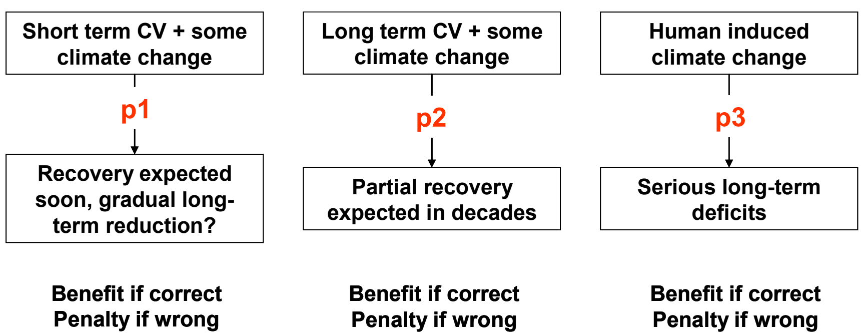

Figure 4. Alternative explanations, expected outcomes and benefit/penalty alternatives for three plausible climate diagnoses affecting water resources futures in south-eastern Australia. If the first alternative is assumed as true, then a return to long-term conditions of relative supply abundance could be expected. However, if wrong, resulting shortages and lack of preparedness will extract a significant penalty. The second alternative would see a response for decade-long drought conditions with partial recovery down the track. The third alternative would see a response to long-term drought with potentially drier conditions occurring over time. For planning horizons covering the next few decades, alternatives two and three would generate a similar response. Over-estimating drought conditions in encountering conditions wetter than anticipated would attract a lesser penalty, than under-estimating drought then encountering it, particularly if more intense rainfall events (a symptom of warming) were also planned for.

The development and management of the MDB waterways would benefit from the identification and understanding of the cyclicity of inter-decadal variations in drought and flood events. With this knowledge, previous plans to develop and allocate waters yielded by the MDB may have been more conservative, rather than the current challenge of trying to retrofit the system commensurate with a drier climate. Looking to the future, plans for allocation, agricultural intensity, and ecosystem restoration can draw on the longer record of change, both from direct catchment modification as well as natural and anthropogenic climatic variability and change.

Natural variability of the climate system has brought about changes in river flow regime, which has driven responses observed in the wetlands, landscape and the biota (Gell *et al*., 2005a, 2005b; Reid *et al*., 2007; Gell *et al*., 2009). Prior to the human settlement of the catchment, this natural variability operated within thresholds; only when climatic events pushed the system to exceed these thresholds were changes in river channel avulsion and drying of wetlands observed and the system forced to enter a new stable state (cf. Reid and Ogden, 2008).

With added pressures of catchment clearance and agricultural development, water regulation and diversion, the likelihood of system thresholds being exceeded is increasing. Such state shifts may closely follow the changes caused by human activities, or there may be lags which cause the system to respond years or decades after the initial perturbation. In many instances, once a state shift has occurred, the possibility of restoration or a return to prior states diminishes, as newly established feedback mechanisms create resistance, even if the original driver of change ceases to exist (‘resilience thinking’, Walker and Salt, 2007).

2.3. The palaeo-record and natural resource management

In order to manage natural systems, under a changing climate, evidence is required to place the contemporary condition in the context of its response to its climate and catchment history. The palaeo-record provides evidence of past responses to changing hydrological regimes and can be used to: (a) understand if a shift in regime has occurred; (b) assess whether the system is operating within its historical range of variability; and (c) ascertain which systems are at risk of regime change.

Evidence of long-term changes to over 40 wetlands across the MDB illustrate the impact of catchment modification and river regulation on waterways, and how anthropogenic changes overwhelm the measurable impact of recent climate change and variability. For example, sedimentation rates and changes in water quality exceed those which could be attributable to climate change and variability (*see section 2.1.1*). Contemporary restoration measures include environmental watering, or lake level drawdown to re-establish variability in a regulated system (Alexander *et al*., 2008; *see section 2.1.2*).

2.3.1. Wetlands of the Murray-Darling Basin

Palaeolimnological evidence from selected wetlands across the Murray-Darling Basin show considerable stability in condition in the centuries leading to first European settlement (Ogden, 2000; Reid *et al*., 2002; Gell *et al*., 2005a, 2005b; Fluin e*t al*., 2007). These sites show abrupt changes in condition soon after settlement. Changes inferred from microfossil remains include increasing salinity, as early as the 1880s, and sustained increases in pH, from an extended baseline of slightly acid conditions to alkaline. Increased sediment flux, which has occurred due to increased catchment flux or increased net accumulation, is a feature of many systems.

From the late 1880s the liberation of fine sediments has impacted on the light balance in several wetlands leading to state shifts from clear water, aquatic macrophyte dominated systems to turbid, phytoplankton dominated systems evident today (Ogden, 2000; Reid *et al*., 2007; Reid, 2008). The regulation of the catchment through the construction of weirs established this switch in most river-linked wetlands driving an almost universal dominance of phytoplankton (Gell *et al*., 2005a, 2005b; Gell and Little, 2006; Gell *et al*., 2007; Reid *et al*., 2007; Reid, 2008). Several, seemingly un-impacted, sites have increased in salinity (Gell *et al*., 2007). Wetlands have suffered from multiple stressors of salinisation, sedimentation and eutrophication due to surface processes simultaneously releasing increased fluxes of sediments, salts and sediment-bound nutrients from catchments.

Regulation of flow and pool level has increased sedimentation rates and led to the reduction of accumulating sulphate salts. These changes, through direct catchment modification, have been exacerbated by the recent extended drought that has seen unprecedented falls in river and wetland level, widespread wetland drying and

exposure of sediment to oxygenation leading to acid sulphate risk. The direct impact of catchment management seems to have overwhelmed evidence for responses to climate variability and change evident elsewhere.

2.3.2. The response of wetlands to wetting and drying

There is an array of plants on wetlands across the Murray-Darling Basin, including species that are adapted to dry almost terrestrial conditions, aquatic conditions, and to the various intermediate conditions. They may be short- or long-lived perennials, biennials or short-lived annuals, or large woody trees. It is also important to realise that at times terrestrial plants may dominate these 'wetlands'.

Drought and flood cycles can be natural, but others have been brought about by anthropogenic activity, and this is when sustained changes to the vegetation are likely to occur. When water levels drop, or the wetland dries, plants can persist in several ways: (a) as growing plants that are drought tolerant; (b) as drought resistant tubers or fragments in the soil; or (c) as seeds in a soil seed bank. If, and when, a wetland floods again the drought-resistant species are refreshed and the tubers and seeds are stimulated to grow.

Changes in the River Red Gums (*Eucalyptus camaldulensis*) in the Booligal wetlands on the Lachlan River are signifying the decline in the ecological health of rivers and their floodplains (Armstrong *et al*., 2009). This species can live for hundreds of years and has survived long periods of drought in the past, but the impacts of river regulation/diversion, and the current drought, have caused high tree mortality along the rivers and in some swamps and marshes.

In the Booligal wetlands the range of flows has halved with river regulation - low flows have increased and the number of periods with zero flow has decreased. With increased water extraction following regulation the frequency of large floods to the wetlands has decreased by 50%. The number and duration of key flood forming flows has decreased by 40%, and the seasonality of flows has changed. As a consequence the estimated tree canopy cover had decreased by 85% from 1993 to 2008, a decline that has accelerated in the last three years. In contrast, 'control' red gums, although affected by the drought with a recent loss of canopy cover, remain mostly alive. Flood events are needed every three years to sustain healthy River Red Gum trees. They are

also needed for germination and to ensure successful seedling survival and recruitment. Whilst seeds are held in the aerial seed bank for a minimum of two years, the volumes of seeds in stressed trees are much reduced.

The response, to inundation, of other wetland plants has been investigated in the Central Murray region (Alexander *et al*., 2008). Here many temporary wetlands, would have received water every 1 in 5 years under natural conditions, with large floods 1 in 10 years. As many of the wetlands in the Central Murray region have not received water for 30 years, their seed bank composition may have changed drastically due to the lack of seed input, with the potential loss of diversity revealed once these wetlands are re-flooded. The response of plants was tested at 21 wetlands that had not been inundated for 10 years by monitoring response after inundation for 3 months. Reduced flow variability and resultant loss of flood events had affected the flora in many ways with the dominance of largely terrestrial species that, before these changes, may not have been common in individual wetlands. While 20% of taxa surveyed were only recorded from one wetland, the majority (70%) were recorded from five or fewer wetlands, with only 30% of all taxa recorded from all. Individual wetlands have a suite of specific plants, although individual taxa may only be present in low numbers.

The majority of wetlands showed an increase native aquatic plant cover, no increase in introduced aquatic plant cover, and a decrease in the cover of non-aquatic plants. Overall, nine wetlands registered increases in native aquatic species cover after flooding. This highlights that the natural recovery potential remained, at least partially, intact despite prolonged periods without flooding. However, some sites did not show increases in the cover of native aquatic plants. Many wetland plants have a persistent, long-lived seed bank. After prolonged drying, germination failed in more than 50% of pre-existing wetland species, even after a period of inundation, suggesting a decline in the seed bank. Watering of long-dry, temporary wetlands that were dominated by terrestrial species can result in increased cover of aquatic species, with wetlands showing a high degree of compositional individuality. Although some wetlands may have reduced biodiversity due to extended drought, it is suggested that environmental flows could be used to promote and maintain biodiversity.

2.3.3. Fire

The record of fire, detected by quantifying sedimentary accumulations of charcoal, provides evidence for the controlling influence of glacial-interglacial cycles (Lynch *et al*., 2007), the initial impact of indigenous people on the landscape and the use and frequency of fire by post-European communities. Prior to the arrival of people fire was influenced by the availability of fuel and the dryness of vegetation to enable ignition. In wet forests, charcoal increased in concert with drier, glacial phases (Kershaw, 1986) that enable drying of fuels to permit and sustain burning. In drier biomes increased rainfall permitted expansion of wooded vegetation providing fuel to sustain fire, and so high charcoal fluxes have been associated with warmer interglacial periods.

Several records show increased charcoal with the impact of indigenous people, at levels that appear to override the influence of climate, or occurred simultaneously with ENSO variability to affect vegetation change. The causative relations are however, unclear as in some instances charcoal peaks lag vegetation change, and in others they precede it (Kershaw *et al*., 2006). Holocene charcoal records show variability, in accord with temperature variations (e.g. Bickford and Gell, 2005), attesting to the continued control of climate on fire regime. High effective rainfall through the mid-Holocene appeared sufficient to suppress much fire activity across south-eastern Australia despite little change in vegetation (Lynch *et al*., 2007). Evidence exists for increased burning associated with the Late Holocene intensification of human activity although this may be attributable to a return to increased climatic variability. Despite this there is no demonstrable link between human occupation of the Sydney Basin and charcoal deposition. Here there has been an historic control of climate on fire, mediated by the regional climate-vegetation relations, with additional fire linked to transitional phases of climate and vegetation change (Black and Mooney, 2006). In particular, there was a steady decline in burning to a recent minimum during the Little Ice Age with widespread increase with post-industrial warming.

Early European settlement saw widespread increase in the use of fire in forests attributable to the management regime of squatters (Banks, 1988; Gell *et al*., 1993; Bickford *et al.*, 2008). Through the 20th Century there was a global reduction of charcoal accumulation (Marlon *et al*., 2008) and this has been attributed to the

increased proportion of land opened up for agriculture. Whilst widespread forest clearance occurred in Australia, the reduction of charcoal in the south-east can be attributed to measures implemented after the Royal Commission into the 1939 wildfires.

The control of climate on past fire regimes raises the prospect of more frequent, more widespread and more intense fires under a warming climate. The 2009 wildfires of Victoria attest to greatly increased fire danger ratings as forecast by Williams *et al*. (2001). How this transpires, in terms of fire frequency and intensity, is mediated by a vastly more complex landscape in terms of potential ignition sources, fuel control technologies and vegetation cover more recently, and into the future. While few of these records are from within the Murray-Darling Basin, the record of past fire-climate-vegetation relations suggest that warmer, drier climates will encourage fire in forested landscapes but that drier biomes may experience less burning where drying, or humans, lead to reduced fuel.

Recent work has also begun linking fire activity with climate teleconnections. The palaeo-record should be able to show a greater range of durations and frequencies of these signals affecting the MDB regions. The most recent step change to a drier climate since 1997, now registers as statistically significant. It has been linked with both anthropogenic and natural change factors. A longer-term view will help show this recent change within a broader context.

3. BACKGROUND TO THE MODERN CLIMATE AND LANDSCAPE: GLACIAL CYCLES AND LONG-TERM CLIMATE TRENDS IN THE MDB

3.1. Climate forcing influences

A context for understanding recent climate variation in the MDB, and how the pattern of climate may vary in the future, can be provided by knowledge of longer-term past climate change and its forcing effects. Due to limitations of the MDB for reconstruction of long, continuous records, and likely movements and reorganisation of the atmospheric circulation system through time, this knowledge needs to derive from a much larger, almost continental scale, examination.

The location of the MDB and selected long continuous records, in relation to the present Australian synoptic situation, is shown on Figure 5. The MDB extends from the westerly wind belt dominated by winter rainfall in the south through the zone of uniformly distributed seasonal rainfall to summer dominated monsoon rainfall in the north (Gentilli, 1986). Monsoon influences are derived from the equatorially dominated, north-west monsoon and, particularly, the quasi-monsoon where moisture is derived from the Pacific Ocean. Rainfall totals are highest along the eastern and south-eastern highlands and decrease substantially to the west and, like much of eastern Australia, are affected by Pacific-generated El Niño variability.

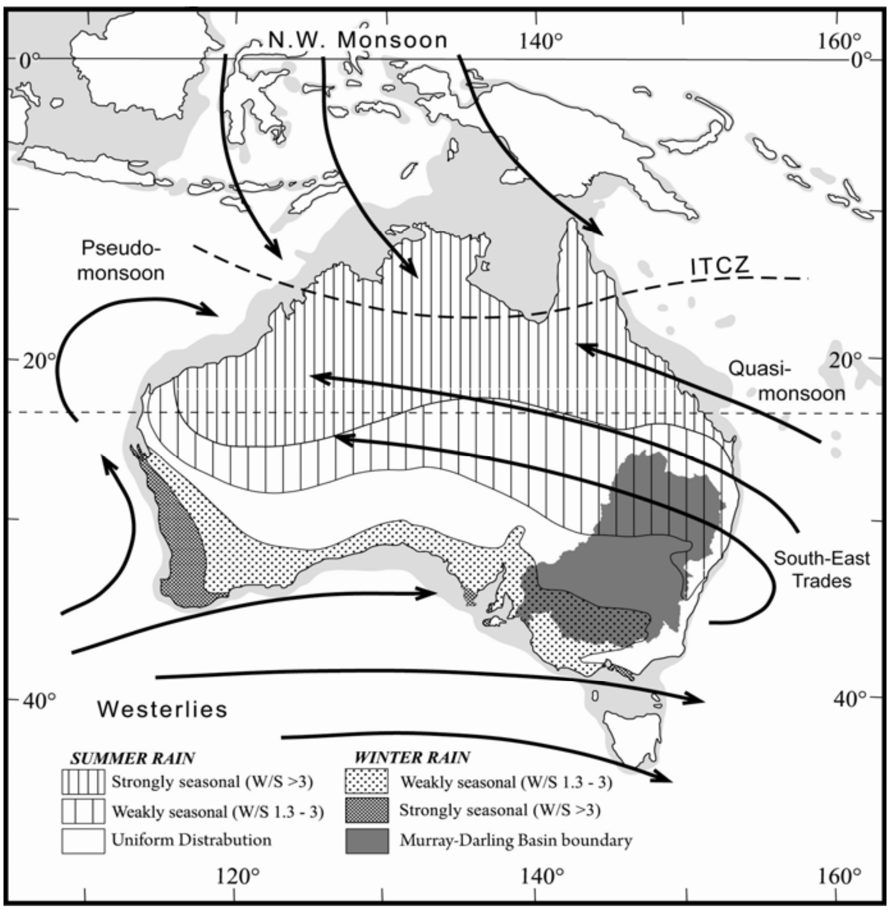

Figure 5. Major climate features and location of selected long proxy climate records in Australia in relation to the MDB. *Adapted from*: Kershaw and van der Kaars (in press).

Over long time-scales, of tens to hundreds of thousands of years, glacial-interglacial cycles dominate climate change (Figure 6). These cycles are the result of variations in solar insolation. Superimposed on these changes are complex feedbacks, between the high-latitude sectors of the North Atlantic and Southern Oceans and the adjacent land masses, and the tropics and involves expansion and contraction of ice sheets and sea ice. These signals are transmitted globally via the atmosphere and oceans, including the westerlies and monsoon systems, overriding regional patterns of insolation (Kershaw and Nanson, 1993). A marked exception to this pattern is Core MD98-2167 off north-west Australia whose pollen record of changing savannah vegetation is dominated by regional insolation variation. This is probably due the pseudo-monsoon that supplies moisture to NW Australia being disconnected from the global circulation system. Although this signal is unlikely to dominate within the MDB, southern insolation can have some influence on records, especially those divorced from coastal areas where changing sea levels, closely related to ice volume variation, have little climatic influence.

The fossil and sediment record preserves both direct evidence of climate change (temperature, wind, precipitation) and the environmental impacts associated with climate change, sometimes through complex interactions. Within the MDB there is evidence that global climate changes have had a strong impact on ecology, hydrology and erosion. Superimposed on the climate forcing is the impact of human (both aboriginal and European) activities. Palaeoenvironmental records provide information about changes in the environment and how climate has forced those changes. For some types of records the complexity of interactions in the natural systems can render the climate link quite obscure.

3.2. Palaeoclimate Records within the MDB

3.2.1. Temperature and glaciation

Through the Quaternary Period (last 2.6 million years), glaciation was restricted to a very small area of the Snowy Mountains on the eastern margin of the MDB, and for short periods at the extremes of the global glacial intervals (Barrows *et al*., 2001). Periglacial (frozen soil) processes, however, would have acted over a broader area down to altitudes of 600-800 m (Galloway, 1965; Barrows *et al*., 2002). This affected many of the headwaters of the major rivers of the MDB and, perhaps, enhanced

seasonal runoff (see below). Modelling of glacier growth and ablation has consistently led to the conclusion that large decreases in temperature were required to form the small ice caps and that moisture supply must have been lower than today (Galloway, 1965; Barrows *et al*., 2001). The degree of temperature change inferred (6-10°C) has been controversial because ocean temperatures in the region declined by only 3-4°C (Barrows and Juggins, 2005), implying either an error or a substantial increase in the adiabatic lapse rate. Data from the western MDB and Lake Eyre Basin has only compounded this dilemma by providing evidence for a substantial temperature decrease (up to 9°C) at sea level from 45-16 kyr (Miller *et al*., 1997). More recently, the work of Calvo *et* al. (2007) lends support to the work of Barrows (2001). Core MD03-2611, offshore of South Australia represents the first continuous, high-resolution temperature record for the Australian region. Alkenone-inferred SST suggest a significantly colder LGM, with temperatures ~8°C cooler. Research into the dust flux and river loads on the same core by Gingele et al (2007) suggest a record dominated by alluvial sediments. Such a substantial, relative cooling of the continent implies a much drier, colder atmosphere during the glacial period. The timing and amount of temperature change is consistent with the more complete record of temperature changes determined from Antarctic ice cores (Figure 6b; Petit *et al*., 1999).

3.2.2. Hydrological records - Rivers and floodplains.

The metamorphosis of the large rivers of the Murray-Murrumbidgee Riverine Plain became obvious with the availability of aerial photographs (Butler, 1950). The modern rivers were shown to be small compared to the traces of older channels still visible on the surface of the plain. These obvious changes in the riverine hydrology (Schumm, 1968) were speculatively linked to glacial cycles through stratigraphic analysis and correlations with other landforms such as sand dunes and dust (parna) layers. Whilst the study of the past hydrology of the MDB extends back to early geological mapping, combined with CSIRO soil and land system mapping (Butler *et al*., 1942), the true timing of events emerged with the use of radiocarbon dating in the 1960s (Bowler, 1967). Problems with the radiocarbon chronology, extending back to only 40 kyr, were overcome in the 1980s with the advent of thermo- and optical-luminescence dating (Page *et al*., 1996). The hydrological record has a reasonably reliable framework of events, dating back to c. 100 kyr, however there are two main

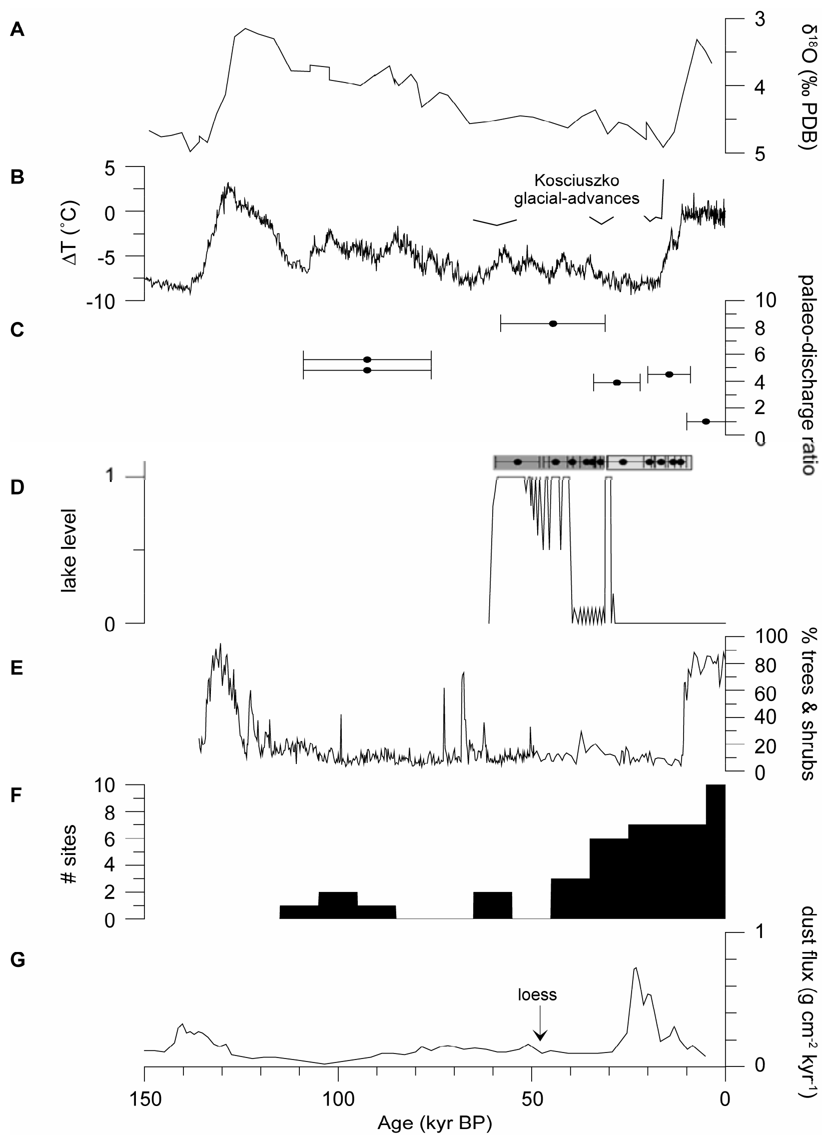

Figure 6. The last glacial cycle in the Murray-Darling Basin. A) Marine Isotope Stages (MIS) 1 to 6 in the oxygen isotope record from ODP Site 677 covering the last glacial cycle (Mix *et al.*, 1995). B) Vostok temperatures derived from deuterium ratios (Petit *et al.*, 1999), expressed as change in temperature from present values. Kosciuszko glacial advances also shown as discontinuous lines (Barrows *et al.*, 2001). C) Palaeo-discharge ratio of the Murrumbidgee River palaeochannels, expressed as multiples of the modern bankfull discharge (Page and Nanson, 1996). D) Lake level history (0=dry, 1=overflowing) of Lake Mungo (Bowler *et al.*, 2003) based on OSL supported chronology. Upper shaded bars and dates are periods of high water level at Lake Urana in the eastern Murray Basin (Page *et al.*, 1994). E) Proportion of tree and shrub pollen at Caledonia Fen, Victorian highlands (Kershaw *et al.*, 2007). F) Number of investigated sites with luminescence dated longitudinal sand dunes in the Murray-Darling Basin (Hesse *et al.*, 2004; Twidale *et al.* 2007; all bins = 10 ka, except 0-5 ka where the # sites has been doubled). G) Dust flux to the Tasman Sea (core E26.1; Hesse, 1994), partly derived from the MDB and the start of accumulation of dust in the loess deposits of the Central Tablelands near Orange (Hesse *et al.*, 2003).

issues: (a) of those examined in detail widely dispersed, studies exist , and (b) these are of low-resolution compared to more recent work. In addition, there remain major uncertainties in our understanding of catchment hydrological change in the Late Pleistocene and the Holocene.

With the exception of early radiocarbon dating of palaeochannels of the Goulburn River (Bowler, 1967; Bowler, 1976), the current framework for understanding climate-driven, fluvial evolution is largely based on the work of Page and Nanson on the Murrumbidgee River (Page *et al*., 1996; Page and Nanson 1996; Page *et al*., 1991) that used thermoluminescence (TL) dating to extend the chronology back to 100 kyr. This work (later supplemented by optically stimulated luminescence (OSL) ages for confirmation [Banerjee *et al*., 2002]) allowed an understanding of the morphology of large palaeochannels of high bankfull discharge through a range of climatic contexts including late Marine Isotope Stage (MIS) 5, MIS3 and MIS2 (arguably with a brief gap at 20 kyr), shrinking to much smaller channels in the Holocene (Figure 6c). These results, at face value, allow for a hydrological interpretation (wet glacial, dry Holocene) contrary to that provided by the pollen record (dry glacial, wet Holocene; Hesse *et al*., 2004). Unfortunately, this work has not been attempted in detail in other MDB river systems to ascertain whether the responses in these channel systems were replicated throughout the MDB (dating by Pietsch (2005) on the Gwydir, unpublished). A few details have emerged from other rivers within the MDB. Whilst they are only partially, or poorly, dated, they appear fit the same general pattern (Darling River, Bowler *et al*., 1978; Nyngan-Waglett area, Watkins, 1993; Namoi alluvial plain, Young *et al*., 2002; Lachlan Valley, Kemp and Spooner, 2007; Lower Macquarie River, Yonge and Hesse, 2009).

Of critical importance to natural resource management is an understanding of the sensitivity of rivers to hydrological change of the kind that has been experienced in the Holocene, as it relates to the range of responses that may be expected under future climate change scenarios. Unfortunately, the transitions to the modern river systems, and changes within the Holocene, have largely been overlooked. The transformation of all the large rivers, around the time of the last glacial termination (15-13 kyr), is well known but, with studies based on few dates, it is difficult to conclude if the changes were synchronous or lagged (Bowler *et al*., 1978; Page *et al*., 1996; Ogden *et al*., 2001; Young *et al.* 2002; Kemp and Spooner, 2007; Yonge and Hesse, 2009). In

many systems this transition remains undated. Likewise, some river systems have multiple channel transformations within the Holocene but there is little geomorphic or chronological detail. Kemp found significantly larger, mid-Holocene palaeochannels on the Lachlan (Kemp and Spooner, 2007) but mapped channels on other river systems have not been studied in such detail (Yonge and Hesse, 2009). Since the transformations involved include discharge of water, sediment load, channel behaviour and channel avulsion, there is much value in the generation of better understanding the response of the rivers to Holocene climate change.

The nature of climate changes that have caused these dramatic changes in river channels remain unclear. Bankfull discharge can be reconstructed from the channel dimensions (Page and Nanson, 1996; Young *et al*., 2002; Wray, 2009) but bankfull discharge may not be the best measure of total annual discharge or precipitation over the headwaters. For example, greater seasonality in flows related to seasonal snow melt in the ice age has been postulated as has the notion that channels may have been dry or low for many months, allowing deflation of sand from the river beds to form source-bordering, sand dunes. The northern rivers of the MDB clearly have very large (undated) palaeochannels which contain evidence to test of the snow-melt hypothesis. Other factors which may have a large impact on runoff are vegetation cover, soil thickness and temperature. The complexity of elements that control catchment hydrology means that there is not a linear relationship between precipitation and runoff or channel size. The sudden and dramatic changes in river courses and channel types are of fundamental environmental importance. To understand the drivers of these changes, palaeo-records with more direct links to precipitation are required.

A record of past, effective rainfall (rainfall minus evaporation) was determined at Naracoorte Caves, South Australia, by Ayliffe *et al*. (1998), using a stacked record of uranium-series ages spanning the last 500 kyr. They found that speleothem growth, a reflection of effective precipitation, was largely absent from both peak interglacial and glacials and, instead, was most prominent during interstadial intervals (brief warm intervals between extreme warm and cold stages of the glacial cycles). Although Naracoorte lies outside the MDB margin, its location is highly relevant because it represents the entry point, to south-eastern Australia, of westerly air masses. This study suggested that effective moisture was greater during the periods when the Riverina palaeochannels were at their largest. However, the large, late-

glacial rivers of the Riverina cannot be explained by this model and may well represent 'flashier' seasonal discharge in an overall drier landscape. Desmarchelier *et al*. (2000) suggested that mean annual temperatures during MIS 6.5 (~185–157 kyr), inferred from speleothem $\delta^{18}O$ values, reached similar levels to those of the present, and that vegetation at Naracoorte shifted from C4 to C3 dominated flora, and back to C4, during this interval. However, interpretation of $\delta^{18}O$ and $\delta^{13}C$ values, in terms of temperature and vegetation structure, is perhaps simplistic (Baker *et al*., 1997; McDermott, 2004), and it seems likely that changes in rainfall were also involved in driving both isotopic signals.

At Cleifden Caves in the Lachlan catchment (Figure 7), McDonald (2000) examined trace element and geochemical variations in speleothems from Murder Cave, spanning the intervals 1-3 kyr, 55-65 kyr and 88-105 kyr. The low resolution sampling methods prevented a reliable interpretation of the Late Holocene record, although growth cessation at ~1 kyr could be indicative of reduced effective moisture. Geochemical variations displayed in the older speleothems show major, coupled shifts in $\delta^{13}C$, Sr and Ba. These are thought to be indicative of changes in effective moisture related to phase-lagged, millennial-scale, and climate changes affecting both hemispheres. However, the timing of these changes was poorly constrained.

3.2.3. Hydrological Records - Lakes and lunettes

Some of the most intensively studied landscapes of the Murray-Darling Basin are the lakes and lunette dunes of the Willandra and Darling Rivers. The place of Lake Mungo in the Quaternary story of Australia is hard to over-estimate as it was one of the first to be elucidated with intensive radiocarbon dating, contained revolutionary evidence of the antiquity of people in Australia and had a coherent environmental history (Bowler *et al*., 1972; Bowler, 1976). Similar sequences from the Menindee Lakes and Lake Victoria (Hope *et al*., 1983; Chen, 1995) reinforced the interpretation from the Mungo system although there has been continuing evolution of the chronology of both burials and palaeohydrological history (Thorne *et al*., 1999; Bowler *et al*., 2003). An important insight from these studies was the realisation that, deflation at the LGM or before, removed sediment records from the lake floors. Instead, the hydrological history is preserved in the lunette dunes surrounding the

lakes. In most cases, lakes with lunettes preserve a Holocene record in lake-floor sediments at best, accumulated since the last deflationary event.

The history of Lake Mungo is intimately tied to the fluvial history of the Lachlan River anabranch/former course of Willandra Creek. Variations in the lake hydrology reflected both variations in the discharge of the trunk stream (in response to upper catchment hydrology and climate) and the tenuous conveyance of water down a long and shrinking channel. The lake was deep and fresh for a long period around 60-40 kyr (Figure 6d; Bowler *et al*., 2003). Final desiccation around the LGM was most likely the result of channel avulsion (described above). A similar history applies to lakes and their lunettes on the Darling, Murray and other river systems where post-glacial river avulsion isolated the lakes and fundamentally changed their hydrology. Similar lakes however, have not formed along the new river courses, since post-glacial climatic amelioration. Lake Tyrrell, on the other hand, has not suffered avulsion of its feeder channel and is still the site of seasonal lake-bed deflation today. Its lunette record shows a deep lake from at least 131±10 kyr to 77±4 kyr followed by stable dry conditions and, then, lake-bed deflation around 27±2 kyr (Stone, 2006). In the Holocene, there has been some renewed lake-bed deposition as well as contemporary deflation (Luly, 1993). In contrast, Lake Urana, on the eastern edge of the Murray Basin, has a high water level phase dated to the LGM (30-12 kyr; Figure 6d) which was produced by evaporation suppression under low temperatures, rather than higher precipitation (Page *et al*., 1994). There are numerous studies of lunettes and lakes across the MDB which have some limited chronology and, therefore, uncertain palaeohydrological history (Ward, 1992). Older compilations of lake levels, including some from the MDB, draw on uncalibrated, sparse or unreliable radiocarbon chronologies and require updating (Wasson and Donnelly, 1991; Harrison, 1993). Ongoing research at Lake Mungo, and other sites, has the potential to reveal high(er) resolution palaeohydrological records for parts of the late Pleistocene.

Bowler early recognised a related, but lagged, influence of groundwater on the hydrology of these lakes which was important in determining the growth of the lunette dunes by lake bed deflation (Bowler, 1973; Bowler, 1986). In addition, the ever-deepening closed lake basins acted as evaporation pans and have become windows to large groundwater brine pools which persist to the present day

(Macumber, 1991). The lakes, and their neighbouring fluvial or aeolian sediments, have a strong impact on the passage and distribution of salt in the landscape today (Macumber, 1969).

Outside of the MDB, understanding of long term water balance has relied on the records of change archived in the large crater lakes of the western Victorian volcanic plains. Sedimentary and microfossil analyses, mostly of ostracods, diatoms and pollen, have revealed lake level changes since the LGM. The deeper sites, such as Lake Bullenmerri, retained water through the dry glacial and reveal low effective rainfall and higher salinity from 15-10 kyr BP (Dodson, 1979). This is supported by the record from Tower Hill (D'Costa *et al*., 1989) that showed shallow lake conditions through the LGM, but maximum aridity from 15-10 kyr BP arising from increasing temperatures. From the commencement of the Holocene effective rainfall was sufficient to generate surface water in most depressions, and this increased through to 7 kyr BP where several large crater lakes are known to have overflowed (Bowler, 1981; Gell *et al*., 1994). Lake levels fell across the region from 5.5-6 kyr BP reaching minima between 2.5-2.5 ka BP (Dodson, 1974). Trees colonising the crater slopes then were drowned when levels rose again after 2.2 kyr BP; and are being now exposed with 19th and 20th century drying (section 3.3).

3.2.4. Pollen records of vegetation and fire

Lakes suitable for palaeoecological study are largely restricted to the humid highland margins of the MDB. Lake George, near Canberra, was investigated during the 1970's and 1980's and still provides the longest pollen and charcoal record in Australia, extending back to beyond 700,000 years ago (Singh *et al*., 1981; Singh and Geissler 1985). It was also the first record to demonstrate a major shift in vegetation associated with increased burning in the late Quaternary. Through much of the recorded period it was considered that interglacial periods were warm and wet, supporting a Casuarinaceae forest or woodland, while intervening glacial periods were cool and dry, with extensive herbaceous vegetation, although patches of cool temperate rainforest did exist. Fire, as indicated by charcoal particles, was largely restricted to the interglacial phases due to a limited cover of vegetation to carry fire during the glacials. This whole pattern changed from the beginning of the last interglacial period.

The general replacement of Casuarinaceae by *Eucalyptus,* the persistence of charcoal through the last glacial period and a demise of rainforest elements were all considered to have resulted from a sustained increase in burning as a result of Aboriginal activity. Debate still continues over interpretation of the record, particularly its dating and degree of continuity, because of the suggestion that people may have arrived some 100,000 years before the first archaeological evidence, However, the mounting evidence for a long term drying trend in climate, with increased variability, may provide the basis for a more palatable explanation for the record (see section 3.3). A more recently produced long pollen record from Caledonia Fen, in the south-eastern highlands of Victoria, with more robust dating by OSL, does not display the same degree of sustained change (Figure 6e), although there is evidence for the extirpation or extinction of cool temperate rainforest elements between 40,000 and 30,000 years ago (Kershaw *et al*., 2007). At this altitude (1300 m), rainfall variation was not as important as that of temperature, and human activity could be expected to have been low. The last glacial period, extending from MIS 5b to MIS2, was dominated by alpine steppe vegetation existing under temperatures at least 5°C lower than today. The last interglacial (MIS 5e) and Holocene (MIS1) together with a short interstadial, dated by OSL to around 68 kyr, are clearly marked by forest expansion to present day levels.

A number of shorter records have been produced from ephemeral lakes on the semi-arid margin, including Lake Tyrrell (Luly, 1993), and sites in the Little Desert (Thomas *et al*., 2001), in the Darling Anabranch region (Cupper *et al*., 2000; Cupper, 2005), and in north-western NSW, for example Cuddie Springs (Field *et al*., 2002). Two relatively continuous sites from the Darling Anabranch region, with generally good dating control from AMS radiocarbon and OSL, provide the clearest picture of change, within a drier part of the MDB, since the mid Late Pleistocene, about 70,000 years ago (Cupper, 2005). In common with the remainder of south-eastern Australia, the predominance of herbaceous vegetation, with a substantial component of chenopodiaceous shrublands, indicates that the last glacial period was much drier and cooler than today. Temperatures began to increase from the end of the LGM, with an increase in vegetation structural complexity and floristic diversity, but trees did not become abundant until the Holocene. This history is common to the headwater site of Ulungra Springs (Castlereagh catchment) where trees in MIS3 gave way to treeless

Chenopodiaceae/Asteraceae-dominated vegetation during the LGM that only returned in the glacial termination (Dodson and Wright, 1989). As with the region generally, the late Glacial period was variable (Turney *et al*., 2006) and probably witnessed the driest conditions of the last glacial cycle (Kershaw and Nanson, 1993).

The early-mid Holocene experienced maximum development of a tree canopy under highest temperature and rainfall conditions - the so-called climatic optimum - before drier and probably more variable conditions, probably related to the latest period of high ENSO activity, reduced their importance. Burning levels appeared to relate positively with precipitation and, hence, fuel availability, with charcoal values being lowest during the Last glacial period and highest during the early-mid Holocene. Although a common pattern within the southeast Australian region, there is variation in relation to the rainfall gradient, with wetter areas often being able to carry fire during dry conditions and exclude fire when rainfall is high (Kershaw *et al*., 2002). After the initial impact of Aboriginal people, it appears that a new vegetation-fire relationship was established with temporal burning patterns largely controlled by climate. However, this pattern was altered with the arrival of Europeans. In some areas, generally in drier areas like the Mallee, charcoal levels indicate that fire activity was reduced while, in wetter areas like Lake George, fire became a major management tool and charcoal values became very high until the recent trend to fire exclusion.

3.2.5. Dunes and dust

Sand dunes of the western Murray Basin are well described and, while there is some growing evidence of their chronology, there remains a lack of detailed OSL studies (Gardner *et al*., 1987; Readhead, 1988; Chen, 1995). The dunefields and marginal sand plains are extensive in the lowlands of the Murray Basin, Darling River corridor, Paroo and Warrego fans (Hesse, *submitted*). A general picture of LGM activity of the longitudinal dunefield has become accepted but suffers from too few dates with large uncertainties and poor stratigraphical control (Hesse *et al*., 2004). Overall, the available luminescence dates point to a dramatic increase in dune activity after around 50 kyr (Figure 6f). There was some dune activity prior to 50 kyr but the ages are few, their uncertainties large and there is no clear pattern of activity. The increase of dune activity after 50 kyr agrees with the available pollen evidence of sparse vegetation leading into the LGM. The persistence of dune activity in the Holocene is not only

due to sampling bias, based on results from the Strzelecki Desert (Fitzsimmons *et al.*, 2007), and continues to the present day with major instability brought about by agricultural practices. Better dated are the source-bordering, sand dunes associated with palaeochannels of the Murray and Murrumbidgee Rivers (Page *et al.*, 1991; Page *et al.*, 1996; Page *et al.*, 2001; Spooner *et al.*, 2001) and one or two other localities (Wasson, 1976; Watkins, 1993; Kemp and Spooner, 2007). These demonstrate that, throughout the last glacial cycle (except for the Holocene), dunes were formed whenever broad, sandy channels were exposed. They therefore record fluvial activity rather than either 'aridity' or wind strength (Hesse *et al.*, 2004).

The first deposits of dust identified in Australia, given the name 'parna' (Butler, 1956), were in the Riverine Plain. None of these has since been studied in any detail (Hesse and McTainsh, 2003), and even in contemporaneous work (Butler and Hutton, 1956) and work of Butler's co-author (Hutton, 1980), there was some ambiguity about these deposits (Ryan and Cattle 2006). However, dust is an important component of many soils in the region, especially in the cropping belt (Cattle *et al.*, 2009). Recently identified dust mantles in the highlands are well established (Dickson and Scott, 1998; Gatehouse *et al.*, 2001; Hesse *et al.*, 2003) and give some sedimentological, chronological and provenance information. Dust began accumulating on the highlands near Blayney around 50 kyr (Figure 6g), contemporaneously with other indicators of increased aridity (Hesse *et al.*, 2003), and reached a maximum flux around the LGM. However, the dust deposited shows wind strength was unchanged throughout the record. There has been much research on historical wind erosion and dust raising (Shao and Leslie, 1997) but the best record of wind erosion from the MDB (and other arid areas of SE Australia) is found in Tasman Sea sediments (Figure 6g; Hesse, 1994; Kawahata, 2002). From these it is clear that dust export was greatest in glacial stages of the last 3-4 glacial cycles. Dust flux was around three times greater than the modern day and the increase was driven by changes in aridity in the source areas (south of around 30° S) rather than wind strength (Hesse and McTainsh, 1999). Dust derived in part from the MDB was deposited over southeast Queensland during the LGM (McGowan *et al.*, 2008; Petherick *et al.*, 2008; Petherick *et al.*, 2009). Dust and parna often appear to be invoked in studies of phenomena within the MDB where there is little compelling

evidence. The relationship to dryland salinity, for example, rests on spurious and misinterpreted evidence (Hesse and McTainsh, 2003).

3.2.6. Wetlands

Ecologically important wetlands dot the MDB and form some of the largest and best-protected (Ramsar) waterbird breeding habitats in Australia. Surprisingly, little direct attention has been paid to these by Quaternary studies, which have typically addressed palaeoclimates or archaeology. Nevertheless, by their very nature wetlands are often part of the fluvial, lacustrine or aeolian landscapes addressed by Quaternary studies. There has been some work on defining types of wetlands in the MDB by hydrological, geomorphological and ecological properties (e.g. Kingsford and Porter, 1999), Timms (1999) on the Paroo; Goodrick (1984) in Western NSW). Many can be categorised according to their geomorphology and something of their history and behaviour inferred from our knowledge of those systems.

There are thousands of ephemeral pans, fed by local runoff, within the MDB dunefields. They post-date dune formation and are often formed by deflation within interdune corridors, in areas where there is groundwater interaction or simply standing water for long periods. There are also many hundreds or thousands of larger lakes in the western MDB. Many are basins formed by deflation (after Bowler's ([1986] model) with downwind lunette dunes. Their hydrology today depends on their connection (or lack of) to the river or groundwater system such that they range from floodbasins of the modern rivers, isolated basins with only local runoff or saline groundwater windows. In all cases they have a history as wetlands which are intimately linked to the Holocene hydrology of the catchment and region.

A third category of wetlands is the fluvial wetlands of the modern drainage system. Even here, ephemeral, floodplain wetlands dependent on episodic, overbank flooding can be differentiated from more frequently inundated palaeochannels (including billabongs, cowals and warrambools) and the nearly perennial 'floodout marshes' of some of the main rivers. In this last category are some of the largest wetlands such as the Macquarie Marshes (Yonge and Hesse, 2009), Gwydir Wetlands, mid-Lachlan and Booligal wetlands, Lowbidgee and similar features on the Loddon, Bogan, Narran, Namoi and other rivers.

The Macquarie Marshes, like the others, are a response of the river systems to Holocene hydrology which results in channel breakdown and dispersal of perennial flows across the floodplain (Yonge and Hesse, 2009; Ralph and Hesse, *submitted*). The extensive wetlands formed after 8-6 kyr and are extremely liable to channel (and wetland) avulsion (Yonge and Hesse, 2009). These systems point to the possible evolution of larger rivers (e.g. Murray, Murrumbidgee, and Darling) under scenarios of low and declining discharges. However, the future evolution of the existing floodout marshes is uncertain: gradual decline is possible as is catastrophic collapse following river avulsion.

3.3. Circulation patterns and drivers

High temperatures, during periods of low global ice volume, are generally associated with denser vegetation and more extensive woodlands through lowland areas of the MDB than during the glacial intervals. However, while vegetation records and aeolian activity suggest more available moisture in the Holocene compared with the LGM, hydrological indicators point in the other direction (Figure 6). Runoff (as measured by lakes and river channels) has a more complex relationship to global climate change because of the added feedbacks of vegetation (transpiration) and temperature (evaporation) on precipitation, amongst other factors. From the known records we can see that, to some extent, the southern winter rainfall and northern summer rainfall behave independently, although both probably respond to global temperature change. Synoptic scale circulation and teleconnections have important regional impacts and local variations in distance from the ocean (as sea-level goes up and down) also have regional impacts on climate.

It is clear from a number of the Australian hydrological records featured in Figure 6 that the present interglacial (the Holocene) appears more arid than the last interglacial (MIS 5e). Records covering a much longer period suggest that this may be part of a trend, particularly in northern and eastern Australia, that has been operating over the last few glacial cycles. Examples come from dust deposited in the Tasman Sea (Core E39.75; Hesse, 1994), the decline of rivers in the Lake Eyre Basin (Maroulis *et al*., 2007) and sea-surface temperature and vegetation changes in tropical north Queensland (especially ODP Site 820; Moss and Kershaw, 2007). These changes in sea surface temperatures can be interpreted as an expansion of the Indo-Pacific Warm

Pool, an important prerequisite for Pacific ENSO activity. The Warm Pool may have expanded as a result of the achievement of a critical threshold in the contraction of the Indonesian Gateway, whereby warm water is transferred from the Pacific to the Indian Ocean, with the continued movement of the Australasian tectonic plate into that of SE Asia. The mechanism of vegetation change is considered to have been through increased fire activity, evident from charcoal concentrations within the pollen records, promoted by increasingly variable climatic conditions, and augmented by human activity, from around 40,000 years ago. This evidence for anthropogenic burning, and associated vegetation change, has formed a basis for explanation of continental megafaunal extinction and, controversially, a sustained reduction in monsoon activity within central Australia (Miller *et al*., 2005; Pitman and Hesse, 2007). While the debate continues, changes of this dimension highlight the capacity for change under the influence of climate change and variability over the longer time frame.

4. HIGH RESOLUTION CLIMATE RECORDS

4.1. Introduction

Climate variability is a major driver of environmental change in the Murray-Darling Basin. Effective natural resource management depends on obtaining high quality and long duration, baseline, climate information to enable planning and decision making that is sufficiently robust and resilient to cope with natural variability, as well as climate change, into the future.

In Australia the observational meteorological record is relatively short (typically 100 years or less). This is insufficient to capture the full range of multi-decadal to centennial scale climate variability. However, these data can be extended by using three sources: (a) historical observations made by early settlers and sailors to Australia; (b) palaeoclimate proxies; and (c) climate model simulations. In this section we consider (i) high resolution palaeoclimate proxies derived from archives such as tree-rings, speleothems (cave deposits), pollen, corals and lake sediments; and (ii) climate, spatial field reconstructions of meteorological observations using multiple palaeoclimate records.

In the Murray-Darling Basin, lake sediments, speleothems, and tree-rings are the most suitable proxies for understanding fine-scale climate variability on annual to decadal timescales. These archives preserve proxy climate records that vary in length, resolution and spatial distribution. Consequently, they also vary in the contribution they make to our understanding of past climates. Each provides multi-centennial records of near-annual, temporal resolution and their records are representative of past climate at a variety of spatial scales within, or on the margins of, the MDB.

4.2. Fine resolution lake sediments

Lakes accumulate sediment from externally derived, (e.g. dust, pollen) and authigenic material (e.g. micro-organisms and carbonate precipitates). The quantity of internal and external inputs into lakes varies seasonally and annually. Consequently, lake sediment records can provide a highly detailed, palaeoclimatic record of historical changes in the condition of a lake and its catchment vegetation at decadal and centennial scales. Ideal sites for fine-resolution lake records maintain those with a continuous sedimentary history (i.e. are permanent water bodies) that have multiple proxies preserved in the sediment column that provide high sedimentation rate and have a small catchment area.

The requirement of a small catchment area excludes many MDB lakes, which are intermittently connected to the Murray River, and therefore may be displaying climate signals transported from distant regions and contrasting climatic influences. A suitable alternative exists in the numerous crater lakes that lie within the volcanic plains of Western Victoria. Climate histories from lakes in the Western Plains region have been correlated with palaeo-flow regimes of the River Murray (Cann *et al*., 2000; Gingele *et al*., 2007). Fine-resolution, palaeoclimate reconstructions based on lake sediments from this region have used proxies such as pollen (Mooney, 1997), ostracods (Radke, 2000) and diatoms. Due to a combination of their short life spans and rapid response to fluctuations in water chemistry, diatoms are particularly suited to sediment-based fine-resolution studies. Quantitative relationships between diatom species and water chemistry parameters such as pH (Tibby *et al.*, 2003), total phosphorus (Tibby, 2004) and salinity (Gell, 1997) have also been developed.

Where a relationship between these variables and climate is demonstrable, climate can then be reconstructed (Gell, 1997; 1998). Calibration between reconstructed

variables and instrumental data validates the model and strengthens confidence in the interpretation (Fritz, 1990). Using these methods, recent results (Barr, unpublished data) indicate greater amplitude wetting and drying phases in the past, than in the historical period, overlaying periods of both extended aridity and humidity.

4.3. Speleothems

Speleothems (cave stalagmites, stalactites) develop from the accumulation of calcite precipitated from water that drips through the ceilings of caves. Because direct hydrological connections between surface water supply and the resultant growth, and geochemical composition, of speleothems exist, they represent excellent terrestrial archives of high-resolution palaeoclimate information (Treble *et al*., 2003; 2005).

Speleothems have the capacity to preserve precisely dated records of rainfall variability extending from modern times back tens of thousands of years. Rainfall isotopes (linked to rainfall characteristics, including amount, season and air-mass trajectory) are preserved in the speleothem calcite, as are trace elements reflecting water residence times, the amount of vegetation/soil microbial activity and weathering, all of which are influenced by local hydrology.

Previous reconstructions of palaeo-rainfall (Ayliffe *et al*., 1998; Desmarchelier *et al*., 2000; McDonald, 2000) are limited by their growth interval and coarse resolution. However, more recent research in southwest Western Australia, using young stalagmites continuously sampled at high-resolution, has demonstrated the utility of the oxygen isotope and trace element signals to record the multi-decadal rainfall decrease that has affected this region since 1970 (Treble *et al*., 2003; 2005).

A further discovery stemming from this work was the sensitivity of the speleothem oxygen isotope signal to switches in the source of oceanic moisture, as modulated by climate mode zonal wave 1 (Fischer and Treble, 2008). This discovery will enable the reconstruction of long-term, large-scale, atmospheric circulation patterns for southern Australia, which is the focus of ongoing work. This approach is now being used at sites directly relevant to the MDB. Other emergent research includes a forward model that simulates the response of speleothem proxies to the instrumental climate record. This model is being used as an investigative tool to understand the sensitivity of particular sites and methods to reconstruct climate modes (Fischer and Treble, 2009).

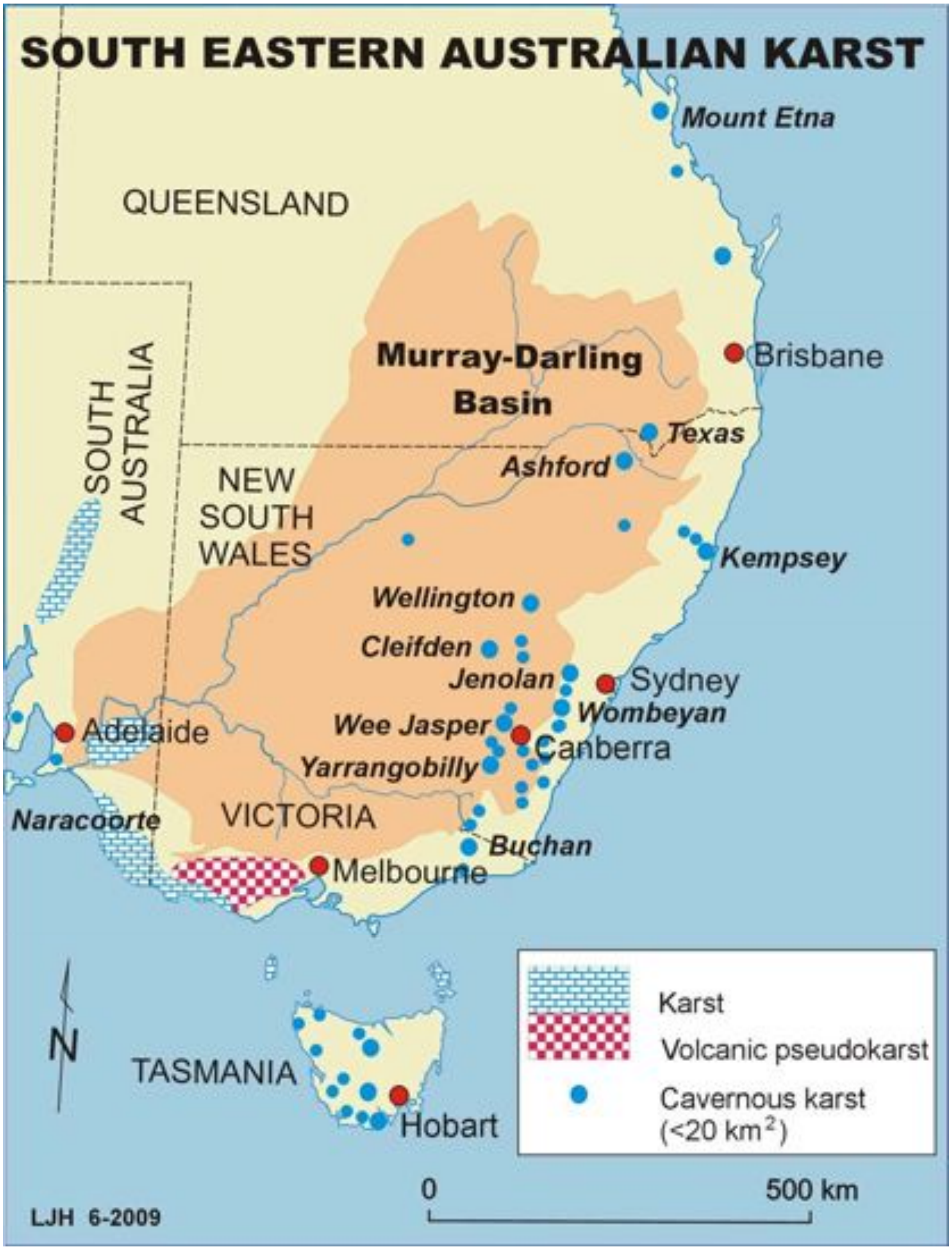

Figure 7. Eastern Australia cavernous karst areas relevant to palaeoclimate research. Blue dots indicate active speleothem studies in progress (e.g. Wombeyan, Yarrangobilly, Cleifden) and potential future study sites relevant to the Murray-Darling Basin.

Present collaborative research (team comprises ANSTO, the Sydney Catchment Authority, ANU, the University of Newcastle and the University of Melbourne) is being undertaken to construct multi-centennial to multi-millennial records of past rainfall from speleothems for two key, water resource regions in southeast Australia: Wombeyan Karst Conservation Reserve (eastern margin of the Basin) and Yarrangobilly Caves (headwaters of the Murray River). Such information will provide critical baseline climatic data to better quantify, and provide new insights into, south-east Australia's historic climate variability. Specifically, rainfall variability records are currently being reconstructed at decadal to sub-decadal, or better, resolution extending back for several centuries.

To date, the main outcomes of this speleothem research include:

- verification that drip water discharge and trace element geochemistry respond to episodes of drought at Wombeyan Caves (Figure 8; McDonald *et al*., 2004; 2007).
- a robust relationship exists between multi-decadal changes in instrumental rainfall data and stable isotope and trace element variations in Wombeyan Caves stalagmites, demonstrating that these stalagmites reliably record site hydrology (Figure 9).
- results are similar in the Yarrangobilly Caves, where research is focusing on a comparison between the instrumental record and two 20th-century stalagmites. An ongoing cave monitoring program at Yarrangobilly Caves is also underway to investigate the links between hydrology/drip water chemistry and surface climate (Treble *et al*., unpublished data).
- multi-decadal, palaeo-rainfall proxy records, extending at least the past 1000 years, are being assembled from Wombeyan Caves, utilising proven geochemical signatures of wet/dry intervals from 20th century stalagmites.

Given the sensitivity of the Basin to changes in Inter-decadal Pacific Oscillation–El Niño Southern Oscillation, and the wide distribution of karst areas along the eastern margin of the Basin, enormous potential exists for the generation of high-resolution multi-proxy records of palaeohydrology. Ayliffe *et al*. (1998) showed how major warm intervals of the past were also periods of reduced moisture.

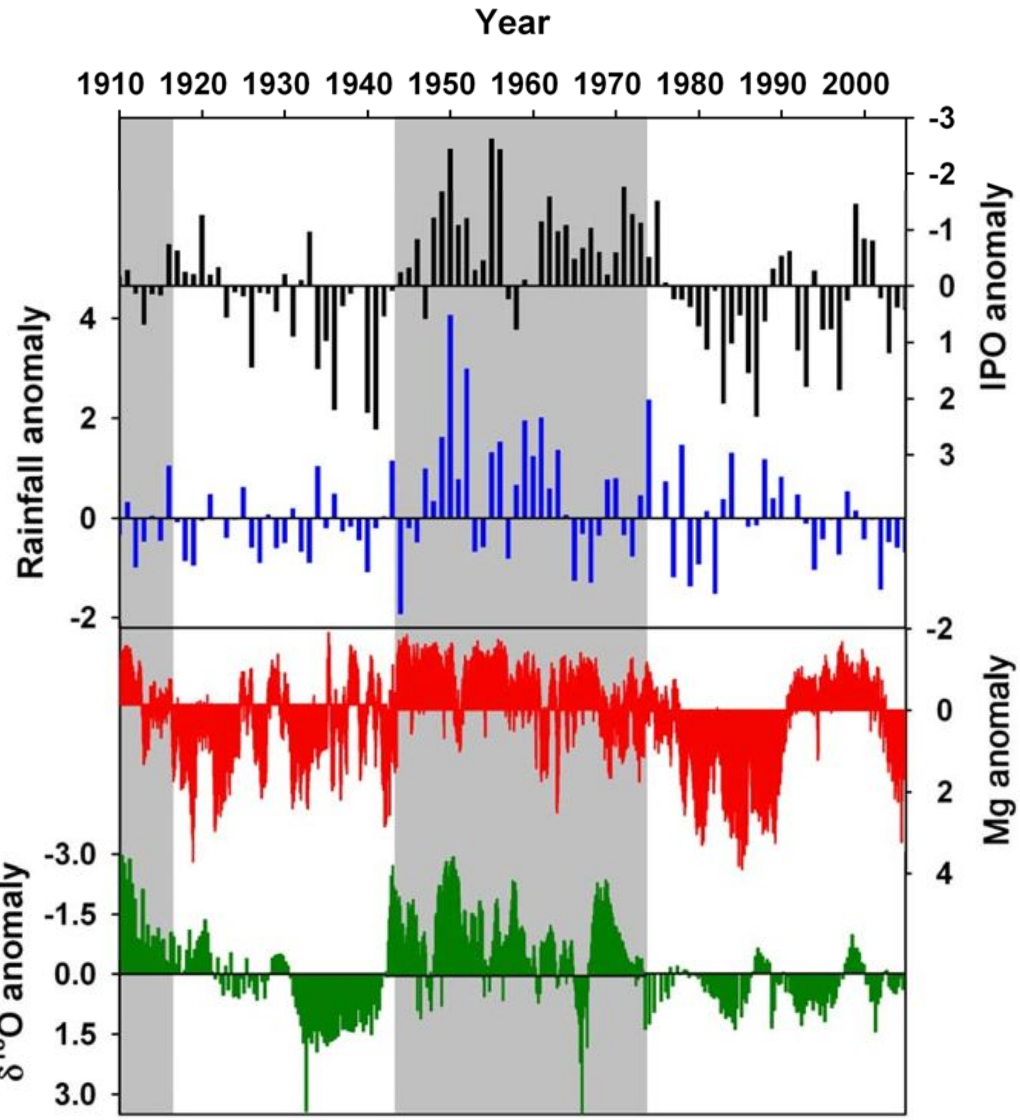

Figure 8. Speleothem oxygen isotope ($\delta^{18}O$) and magnesium (Mg) anomalies (lower two panels) since 1910 compared with the local rainfall and Interdecadal Pacific Oscillation (IPO) anomaly (upper two panels). Except for rainfall, all axes are inverted to show 'wet' at the top and 'dry' at the bottom. The speleothem (stalagmite WM4) is from Wombeyan Caves (100 km SW of Sydney), and was active at the time of collection (June 2005). The site lies adjacent to the eastern margin the MDB. The speleothem $\delta^{18}O$ is sensitive cool-season rainfall amounts, with lower $\delta^{18}O$ anomalies generally corresponding to higher rainfall. The Mg is primarily responsive to the amount of water passing through the limestone bedrock above the cave, with higher values corresponding to drier intervals. The grey vertical bands are IPO negative phases, during which time stronger La Niñas are experienced (more intensive floods). The white bands are IPO positive phases, when El Niños are generally stronger (more intensive droughts). *Source:* McDonald *et al*. (unpublished data).

Future speleothem work focusing on the most recent warm analogues of the past (early to mid Holocene and the Last Interglacial) could provide essential information for evaluating the hydrological vulnerability of the Basin under future greenhouse conditions. Karst sites such as Mt Etna, Kempsey, Wombeyan/Jenolan/Cleifden, Yarrangobilly and Buchan karst areas (Figure 7) are well situated to provide speleothems for reconstructing palaeohydrology in the far northern, central northern, central and southern headwater margins along the eastern sector of the Murray-Darling Basin.

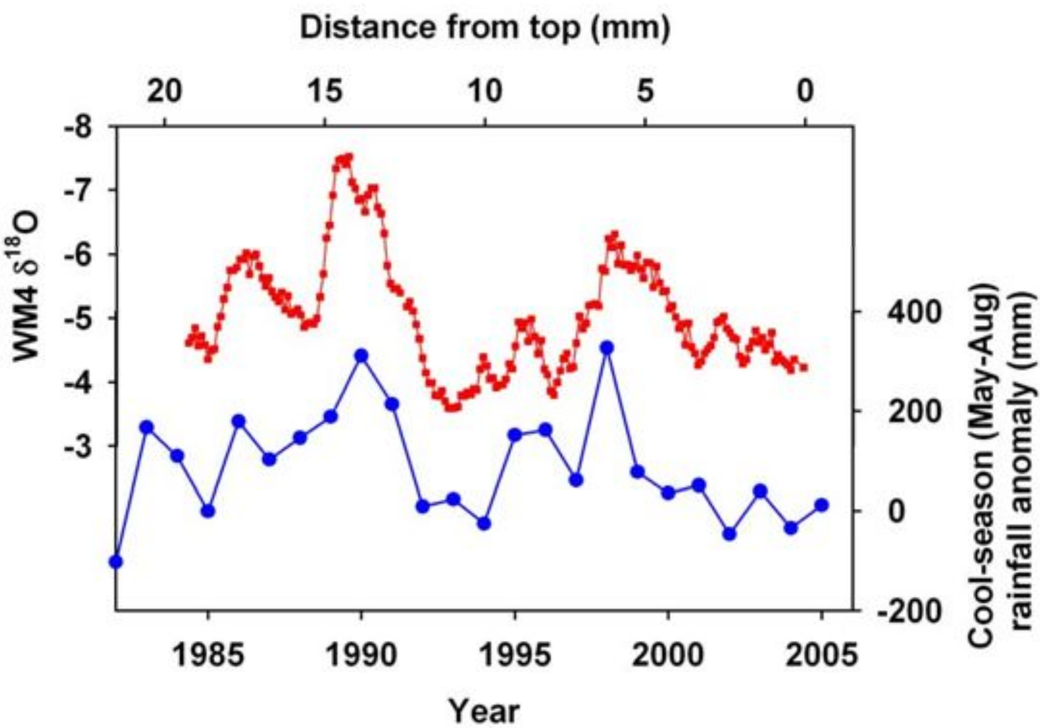

Figure 9. High-resolution oxygen isotope ($\delta^{18}O$) record from the top section of stalagmite WM4 collected from Wombeyan Caves (red, on a depth scale) and the cool-season rainfall anomaly (blue) for the Wombeyan area. Close association between speleothem properties and instrumental rainfall measurements enable cautious extrapolation back beyond the commencement of weather data collection. Stalagmites can thus act as weather gauges for the past. Extrapolation using this technique is currently underway for the past ~1000 years using older Wombeyan stalagmites. *Source*: McDonald *et al*. (unpublished data)

4.4. Dendrology

Dendrochronology, the study of tree-rings, has been widely used to reconstruct historical variation in environmental conditions. Because trees are widely distributed, long-lived, and often form annual growth rings, they can provide unique insights into inter-annual variation in growth, mortality and recruitment of native forests.

Where tree growth is limited by climate (e.g. temperature, rainfall), variation in the width, density and/or chemical composition of the annual growth rings can provide insights into climate variability for decades or centuries into the past. Dendrochronology in Australia has lagged far behind that on other continents due to the preponderance of *Eucalyptus* and *Acacia* species (Brookhouse, 2006), which often do not form discernible annual growth rings, and a highly variable climate, characterised by persistent droughts and infrequent, but severe, flooding.

Most dendrochronological research in Australia has focused on using the long-lived conifers of Tasmania (e.g. *Lagarostrobos franklinii*, Huon Pine; Cook *et al*., 1991), *Phyllocladus aspleniifolius* (Celery-top Pine; Allen *et al*., 2001), and *Athrotaxis* spp (King Billy Pine and Pencil Pine; Allen *et al*., in prep.) to reconstruct climate. Recently, however, several tree-ring reconstructions of climate have been published for other areas, including southwest Western Australia (Cullen and Grierson, 2008), the Northern Territory (Baker *et al*., 2008, D'Arrigo *et al*., 2008) and Queensland (Heinrich *et al*., 2006; 2009).

Few tree-ring studies have been conducted directly within the MDB due to the predominance of *Eucalyptus* spp. in the area. Whilst the assumed longevity of River Red Gum (*E. camaldulensis*) suggests that it may hold dendrochronological potential (Argent *et al*., 2004), recent radiocarbon dating has demonstrated severe difficulties in achieving accurate dating of red gum tree-rings.

One of the more promising species is Snow Gum (*E. pauciflora*). In the Australian Alps, snow gum holds genuine potential for reconstructing climate and river-flow variability in the catchments of the MDB and its surrounds (Brookhouse *et al*., 2008, Brookhouse and Bi, *in press*). In addition, spatially gridded drought data for eastern Australia may enable reconstruction of Murray-Darling Basin hydroclimatic

conditions from tree-ring chronologies located within the Australian region, but not inside the MDB (e.g. D'Arrigo *et al*., 2008).

Tree-rings can also be used to reconstruct historical disturbance regimes and stand- and landscape-scale responses to disturbances. Research on the Australian Alps (Banks, 1988), the Central Highlands of Victoria (Simkin and Baker, 2008) and western New South Wales (Davies and Baker, *in prep*) has shown the potential for using dendrochronology to reconstruct fire histories and fire impacts on complex forested landscapes. These ecological reconstructions have a unique potential to use past forest dynamics to inform future natural resource management, particularly under uncertain future climatic conditions and fire regimes.

4.5. Climate spatial field reconstructions

A suite of global and Northern Hemispheric multi-proxy reconstructions of climate variations over the past 1,000 years has emerged during the last decade. However, global reconstructions suffer from inadequate estimates of Southern Hemisphere variability (Jansen *et al.*, 2007; Jones *et al.*, 2009), let alone regional climate variability.

Multi-proxy reconstructions of Southern Hemisphere climate variability are limited by a relative lack of data and research effort in comparison with the Northern Hemisphere. Given the importance of the 'Water Hemisphere', in driving and moderating many aspects of the global climate system, there is a clear need to generate and synthesise palaeoclimate data in the Australian region (Harle *et al.*, 2007). Although efforts have been initiated to reconstruct Australia-wide, mean annual temperatures, this has only been achieved for the last glacial termination and with limited success (Turney *et al.*, 2006; Turney *et al.*, 2008). The Past Global Changes (PAGES) Aus2K, working group formed to investigate climate variability of the past 2,000 years (http://www.pages.unibe.ch/science/2k/aus2k/index.html), is yet to published any results .

Recently, D'Arrigo *et al*. (2008) showed that experimental, spatial field reconstructions of drought variability for the Australasian region, using four tree-ring and coral records for the 1787–2002 period, were able to successfully capture around 40% of observed variability in the Palmer Drought Severity Index (PDSI; Figure 10).

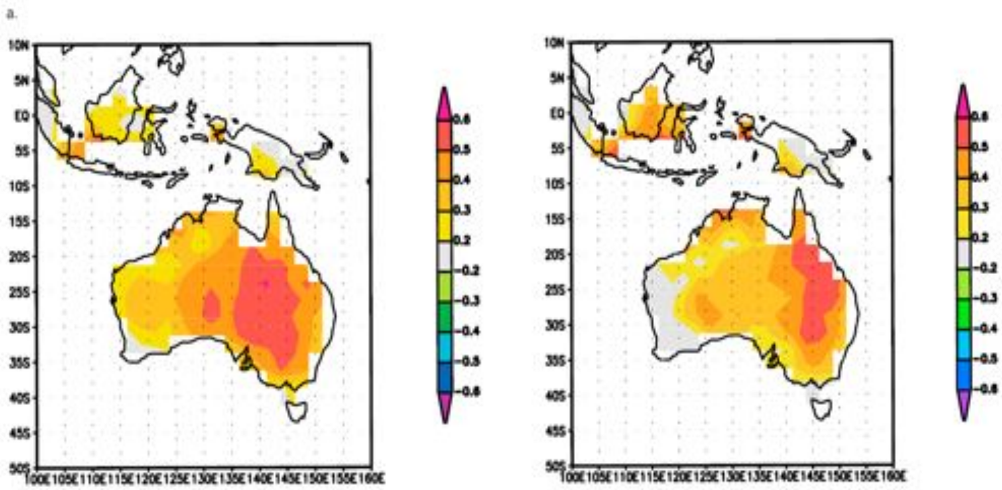

Figure 10. Spatial correlation fields comparing observed (left) and reconstructed (right) September-January Australasian Palmer Drought Severity Index (PDSI), 1925-2000.Note the PDSI reconstruction (right) is only based on four palaeoclimate indicators. The authors conclude that an expanded network of proxy records could improve spatial variability estimates of the regional drought index. *Source:* D'Arrigo *et al*. (2008).

Similarly, Nicholls *et al*. (2006) showed that around 40% of observed Australian mean annual maximum temperature variability could be estimated from three palaeoclimate records, suggesting that even a small number of proxies for the Australian region may be able to provide a useful reconstruction.

Researchers at the University of Melbourne are currently undertaking research to directly target the south-east Australian region, including the MDB. This project fills a critical gap in Australian climate science by assembling a range of pre-20th century data to develop annual, climate spatial field reconstructions (temperature, rainfall, atmospheric pressure) for south-east Australia for the past 200–500 years.

The data sources can be broadly classified as follows:

- **Palaeoclimate records** e.g. tree-ring, coral, ice-core, speleothem records
- **Documentary accounts** e.g. early European settler/explorer accounts, government correspondence, early newspapers
- **Early weather station data** e.g. weather diaries, station observations and ship logbooks

Pilot study results of the palaeoclimate records suggest that it is possible to provide annual climate reconstructions, covering the 1565–1990 period, are possible using 14 records from the Australasian region. This confirms the conclusion of the team's previously developed El Nino–Southern Oscillation (ENSO) reconstructions that considerable skill is achievable using a few, well-dated proxy records back to A.D. 1525 (Gergis *et al.*, 2006; Braganza *et al.*, 2009; Gergis and Fowler, 2009). For example, Braganza *et al*. (2009) showed that up to 52% of observed ENSO variability, which greatly influences climate variability in the MDB region, could be captured by fewer than eight palaeoclimate records.

Comparing regional temperature, rainfall and pressure reconstructions from the southeastern Australia region with independent reconstructions of large-scale climate modes (e.g., ENSO, Southern Annular Mode, Indian Ocean Dipole, Pacific Decadal Oscillation, Sub-tropical Ridge) will be helpful for characterising the long-term stability of the dominant drivers of Southern Hemisphere climate variability in the Australian region (Murphy and Timbal, 2008) and, more specifically, in the MDB.

This project will also assemble early instrumental data from south-eastern Australia for the international Atmospheric Circulation Reconstructions over the Earth (www.met-acre.org) 'data rescue' program (Page *et al.*, 2004). This has direct relevance to the MDB region as these three-dimensional reanalysis products (e.g. gridded mean sea level pressure and sea surface temperature fields) are 'downscaled' for climate impacts, projections and natural resource management applications (Allan and Ansell, 2004; Compo *et al*., 2006).

Developing annual reconstructions of pre-20th century climate variability, using palaeo-proxies, historical documentary records and early weather station data, will be the first study of its kind in Australia (Gergis, 2008; Gergis *et al*., in press). It will contribute to the rectification of the spatial and temporal coverage deficiencies that currently characterises the Australian region. While the limited number of palaeoclimate proxies currently available directly from the MDB hampers a specific reconstruction for the area, broad scale climate spatial field reconstructions will go a long way towards improving the description of the large-scale, circulation features that influence climate variability in the MDB region.

High-resolution palaeoclimatology can fulfil a recognised management need of agencies like the Murray-Darling Basin Authority for extended estimates of regional-scale climate variables by providing estimates of pre-20th century climate variability. Given the large number of extreme climate events that the region has experienced recently, this review advocates the collection of new palaeoclimate data directly in the MDB to provide a more detailed understanding of recently observed changes, and an opportunity to constrain regional climate change projections using extended estimates of natural climate variability.

In summary, high-resolution climate records make important contributions towards understanding climate variability and the management of Australia's natural resources by:

1. assisting in the evaluation of contemporary water management policies adopted by government agencies, e.g. the rules determining irrigation allocations by providing a long-term baseline of pre-20th century climatic information that will assist in the evaluation of contemporary water management;

2. testing, calibrating and constraining the reliability of the global circulation and regional climate models;

3. providing opportunities to statistically distinguish intrinsic, natural climate variability from anthropogenic climate change using detection and attribution techniques;

4. Determine the changes in regional rainfall and temperature patterns under a range of future climate change scenarios based on the examination of large-scale atmospheric and ocean circulation patterns and how these have changed historically, and what such changes mean for regional patterns under a range of future climate change scenarios.

5. RECOMMENDATIONS

This review identifies several research needs directed at increasing the capacity of palaeoclimate science to better inform the natural resource policy and management needs of the MDB:

1. Assemble and coordinate established knowledge:

A considerable body of research current exists on the past climates of south-eastern Australia; however, this has not been collated and validated over large spatial scales. There is a clear need to consolidate the palaeoclimate science relevant to natural resource management in the MDB. This would allow the assessment of the extent of: (a) data coverage; (b) the reliability of the data; (c) the confidence with which conclusions can be made about past climate change and variability; and (d) the responsiveness of the system to such change. Understanding the trajectories of change can be improved by the development of a co-ordinated network of researchers who can synthesise and evaluate the research, and generate management recommendations from the current knowledge base.

2. Establish new palaeoclimate research within the MDB

Whilst much palaeoclimatic research has been undertaken, there remains a paucity of climate records developed across the MDB itself. Most available evidence is from the periphery of the MDB, or in catchments of contrasting geomorphic and hydroclimatological conditions. Whilst marginal sites are relevant to the MDB, there is a need to develop high-quality, high-resolution records of climate change and variability from within the MDB to evaluate the responsiveness of within-basin climates to regional atmospheric circulation patterns.

3. Co-ordinate climate change and response research

There are potentially many records of wetland, river and landscape change available from within the MDB. Sites located in the upper reaches are 'response' sites that record the effect of climate change and variability, to a degree distilled by catchment processes. Many of the sites in the MDB are affected by the influence of anthropogenic catchment changes, so their records contain accounts of changes most relevant to the natural resource management of the MDB. However, in these sites,

particularly those in the lower reaches of the system, distinguishing between climate and catchment drivers can be problematic. This can be overcome by co-ordinating a suite of research endeavours on sub-catchment scales that have climate sensitive archives, usually located in the upper catchment, with matching downstream response sites.

4. Research focus in catchments sensitive to changing circulation patterns

The study of sub-catchments that lie in latitudes sensitive to atmospheric circulation changes could supply managers with information useful for determining the likely response of hydrological systems to shifts in future patterns of rainfall and evaporation by understanding those that have existed in the past. This will then inform debates over appropriate measures to be taken under present and futures climate regimes

5. Clearly communicate past climate science for policy-relevant natural resource management

There is a perception amongst the palaeoclimate science community that the management and policy makers have not fully acquired the value of understanding past climate change and variability and its application to the management of natural systems.

Most research on past climatic changes and variability takes the form of peer-reviewed journal articles that are not particularly suited to management needs. There is a clear need for the palaeoclimate science community to actively interpret its findings in a manner accessible and relevant to the natural resource management community. Improved estimates of past climate variability will help contextualise future change scenarios and the natural resource management measures required to address them.

6. REFERENCES

Adamson, D.A., Williams, M.A.J., Baxter, J.T. (1986). Complex Late Quaternary alluvial history in the Nile, Murray-Darling and Ganges Basins: three river systems presently linked to the Southern Oscillation. In: Gardiner, V. (Ed.). *Proceedings of the First International Conference on Geomorphology*, John Wiley & Sons, Chichester, pp. 875-887.

Allan, R.J., Ansell, T. 2006. A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2): 1850-2004. *Journal of Climate*, **19**, 5816-5842.

Allen, K.J., Cook, E.R., Francey, R.J., Michael, K. 2001. The climatic response of *Phyllocladus aspleniifolius* (Labill.) Hook. f in Tasmania. *Journal of Biogeography*, **28**, 305-316.

Allen, K.J., Ogden, J., Buckley, B.M., Cook, E.R. In prep. Characteristics of the climate response evident in ring-widths of *Athrotaxis* spp., Tasmania, Australia.

Argent, R.M., McMahon, T., Bowler, J.M., Finlayson, B.L. 2004. The dendroecological potential of *Eucalyptus camaldulensis* Denhardt (river red gum) from the Barmah Forest, Victoria, Australia. *Australian Geographical Studies*, **42**, 89-102.

Armstrong, W., Webb, T., Darwent, M., Beckett, P.M. 2009. Measuring and interpreting respiratory critical oxygen pressures in roots. *Annals of Botany*, **130**, 281-293.

Arnell, N.W., 1999. Climate change and global water resources. *Global Environmental Change*, **9**, S31-S46.

Ayliffe, L.K., Marianelli, P.C., Moriarty, K.C., Wells, R.T., McCulloch, M.T., Mortimer, G.E., Hellstrom, J.C. 1998. 500 ka precipitation record from southeastern Australia: Evidence for interglacial relative aridity. *Geology*, **26**, 147-150.

Baker, A., Ito, E., Smart, P.L., McEwan, R.F. 1997. Elevated and variable values of ^{13}C in speleothems in a British cave system. *Chemical Geology*, **136**, 263-270.

Baker, P.J., Palmer, J., D'Arrigo, R.D. 2008. The dendrochronology of Callitris intratropica in northern Australia: Annual ring structure, chronology development, and climate correlations. *Australian Journal of Botany*, **56**, 311-332.

Banerjee, D., Page, K., Lepper, K. 2002. Optical dating of palaeochannel deposits in the Riverine Plain, Southeastern Australia: testing the reliability of existing thermoluminescence dates. *Radiation Protection Dosimetry*, **101**, 327-332.

Banks, J.C.G. 1988. A history of forest fire in the Australian Alps. In: Good, R. (Ed). *The scientific significance of the Australian Alps: Proceedings of the first Fenner Conference on the Environment*. The Australian Alps Liaison Committee, Canberra, pp 265-280

Barrows, T.T., Juggins, S. 2005. Sea-surface temperatures around the Australian margin and Indian Ocean during the Last Glacial Maximum. *Quaternary Science Reviews*, **24**, 1017-1047.

Barrows, T.T., Stone, J.O., Fifield, L.K., Cresswell, R.G. 2001. Late Pleistocene glaciation of the Kosciuszko Massif, Snowy Mountains, Australia. *Quaternary Research*, **55**, 179-189.

Barrows, T.T., Stone, J.O., Fifield, L.K., Cresswell, R.G. 2002. The timing of the Last Glacial Maximum in Australia. *Quaternary Science Reviews*, **21**, 159-173.

Battarbee, R.W., Binney, H. (2008). Natural climate variability and global warming: A Holocene perspective. John Wiley & Sons, Chichester, pp. 288.

Bickford, S. Gell, P. 2005. Human impact on Holocene environments: Vegetation History and Aboriginal wetland use as recorded in a microfossil profile from a wetland in the Fleurieu Peninsula, South Australia. *The Holocene*, **15**, 200-215.

Bickford, S., Gell, P., Hancock, G.J. 2008. Wetland and terrestrial vegetation change since European settlement on the Fleurieu Peninsula, South Australia. *The Holocene*, **18**, 425-436.

Black, M.P., Mooney, S.D. 2006. Holocene fire history from the Greater Blue Mountains World heritage area, New South Wales, Australia: the climate, humans and fire nexus. *Regional Environmental Change*, **6**, 41-51.

Bowler, J.M. 1967. Quaternary chronology of Goulburn Valley sediments and their correlation in southeastern Australia. *Journal of the Geological Society of Australia*, **14**, 287-292.

Bowler, J.M. 1973. Clay dunes: their occurrence, formation and environmental significance. *Earth Science Reviews*, **9**, 315-338.

Bowler, J.M. 1976. Aridity in Australia: age, origins and expressions in aeolian landforms and sediments. *Earth-Science Reviews*, **12**, 279-310.

Bowler, J.M. 1986. Spatial variability and hydrologic evolution of Australian lake basins: analogue for Pleistocene hydrologic change and evaporite formation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **54**, 21-41.

Bowler, J.M., Wasson, R.J. 1984. Glacial age environments of inland Australia. In: Vogel, J.C. (Ed.), *Late Cainozoic Palaeoclimates of the Southern Hemisphere*. Balkema/Rotterdam/Boston, pp 183-208.

Bowler, J.M., Thorne, A.G., Polach, H.A. 1972. Pleistocene man in Australia: Age and significance of the Mungo skeleton. *Nature*, **240**, 48-50.

Bowler, J.M., Stockton, E., Walker, M.J. 1978. Quaternary stratigraphy of the Darling River near Tilpa, New South Wales. *Proceedings of the Royal Society of Victoria*, **90**, 79-88.

Bowler, J.M., Johnston, H., Olley, J.M., Prescott, J.R., Roberts, R.G., Shawcross, W., Spooner, N.A. 2003. New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature*, **421**, 837-840.

Bradley, R.S., Alverson, K., Pedersen, T.F. 2003.Challenges of a changing earth: past perspectives, future concerns. In: Alverson, K.D., Bradley, R.S., Pedersen, T.F. (Eds.). *Paleoclimate, Global Change and the Future.* Springer-Verlag, Heidelberg, Berlin, pp 163-167.

Braganza, K., Gergis, J., Risbey, J., Fowler, A., Mooney, S. 2009. A multiproxy index of the El Nino–Southern Oscillation, A.D. 1525–1982. *Journal of Geophysical Research*: D05106, doi:10.1029/2008JD010896: p1-17.

Brookhouse, M. 2006. Eucalypt dendrochronology: past, present, and potential. *Australian Journal of Botany*, **54**, 435-449.

Brookhouse, M., Bi, H. In Press. Elevation dependent climate sensitivity in *Eucalyptus pauciora* Sieb. Ex Spreng. tree-ring chronologies. *Trees: structure and function*.

Brookhouse, M., Lindesay, J., Brack, C. 2008. The climatological and hydrological potential of tree rings in *Eucalyptus pauciora*. *Geographical Research*, **46**, 421-434.

Bryan, B.A., Marvanek, S. 2004. Quantifying and valuing land use change for Integrated Catchment Management evaluation in the Murray-Darling Basin 1996/97 - 2000/01. Stage 2 report to the Murray-Darling Basin Commission. CSIRO Land and Water Client Report November 2004. Adelaide: CSIRO Land and Water.

Burke, E.J., Brown, S.J., Christidis, N. 2006. Modelling the recent evolution of global drought and projections for the 21st century with the Hadley Centre climate model. Journal of Hydrometeorology, **7**, 1113-1125.

Butler, B.E. 1950. A theory of prior streams as a causal factor of soil occurrence in the riverine plain of S.E. Australia. *Australian Journal of Agricultural Research*, **1**, 231-252.

Butler, B.E. 1956. Parna-An aeolian clay. *Australian Journal of Science*, **18**, 145-151.

Butler, B.E., Baldwin, J.G., Penman, F., Downes, R.G. 1942. Soil survey of part of County Moira, Victoria. Bulletin, **152**, CSIR, Melbourne.

Butler, B.E., Hutton, J.T. 1956. Parna in the Riverine Plain of south-eastern Australia and the soils thereon. *Australian Journal of Agricultural Research*, **7**, 536-553.

Cai, W., Whetton, P.H. 2000. Evidence for a time-varying pattern of greenhouse warming in the Pacific Ocean. *Geophysical Research Letters*, **27**, 2577-2580.

Cai, W., Cowan, T. 2008. Evidence of impacts from rising temperatures on inflows to the Murray-Darling Basin. *Geophysical Research Letters*, **35**, L07701, doi: 10.1029/2008GL033390.

Calvo, E., Pelejero, C., De Deckker, P., Logan, G.A. 2007. Antarctic deglacial pattern in a 30 kyr record of sea surface temperature offshore South Australia. *Geophysical Research Letters*, **34**, L13707, doi: 10.1029/2007GL029937.

Cann, J.H., Bourman, R.P., Barnett, E.J. 2000. Holocene foraminifera as indicators of relative estuarine-lagoonal and oceanic influences in estuarine sediments of the River Murray, South Australia. *Quaternary Research*, **53,** 378-391.

Cattle, S.R., McTainsh, G.H., Elias, S. 2009. Aeolian dust deposition rates, particle-sizes and contributions to soils along a transect in semi-arid New South Wales, Australia. *Sedimentology*, **56**, 765-783.

Chen, X.Y. 1995. Geomorphology, stratigraphy and thermoluminescence dating of the lunette dune at Lake Victoria, western New South Wales. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **113**, 69-86.

Compo, G., Whitaker, J., Sardeshmukh, P. 2006. Feasibility of a 100-year reanalysis using only surface pressure data. *Bulletin of the American Meteorological Society*, *87*, 175-190.

Cook, E.R., Bird, T., Peterson, M., Barbetti, M., Buckley, B., D'Arrigo, R., Francey, R., Tans, P. 1991. Climatic change in Tasmania inferred from a 1089-year tree-ring chronology of subalpine huon pine. *Science*, **253**, 1266-1268.

Cossart, R. 2008. An environmental history of the Narran system. Unpublished Masters Thesis, University of Canberra.

Cossart, R., Thoms, M.C., Reid, M.A. 2008. Determination and interpretation of sediment provenance in a sedimentary sequence affected by post-depositional changes. In: Schmidt, J., Cochrane, T., Phillips, C., Elliot, S., Davies, T., Basher, L. (Eds). *Sediment Dynamics in Changing Environments*. IAHS Press: Wallingford, Oxfordshire. pp. 60-67.

Craik, W. 2005. *Weather, climate, water and sustainable development. Bureau of Meteorology.* Australian Government. Commonwealth of Australia, pp 16.

Croudace, I., Rindby, A., Rothwell, R.G. 2006. ITRAX: description and evaluation of a new multi-function X-ray core scanner. In: Rothwell, R.G. (Ed.) *New Techniques in Sediment Core Analysis*, Geological Society, London, Special Publications, **267**, 51–63.

Cullen, L., Grierson, P.F. 2008. Multi-decadal scale variability in autumn-winter rainfall in south-western Australia since 1655 BP as reconstructed from tree rings of Callitris columellaris. *Climate Dynamics*, DOI 10.1007/s00382-008-0457-8.

Cunningham, S.C., MacNally, R., Read, J., Baker, P.J., White, M., Thomson, J.R., Griffioen, P. 2009. A robust technique for mapping vegetation condition across a major river system. *Ecosystems*, **12**, 207-219.

Cupper, M.L. 2005. Last glacial to Holocene evolution of semi-arid rangelands in southeastern Australia. *The Holocene*, **15**, 541-553.

Cupper, M.L., Drinnan, A.N., Thomas, I. 2000. Holocene palaeoenvironments of salt lakes in the Darling Anabranch region, southwestern New South Wales, Australia. *Journal of Biogeography*, **27**, 1079-1094.

D'Arrigo, R.D., Baker, P.J., Palmer, J., Anchukaitis, K., Cook, G. 2008. Experimental reconstructions of Australasian and East African monsoon variability using tree rings and corals from Indonesia. *Geophysical Research Letters*, **35**, L12709.

Davies, J.A., Baker, P.J. In Prep. Snow gum (*Eucalyptus pauciora*) stand dynamics and the historical relationship between climate and fire in western New South Wales.

Desmarchelier, J., Goede, A., Ayliffe, L., McCulloch, M.T., Moriarty, K. 2000. Stable isotope record and its palaeoenvironmental interpretation for a late Middle Pleistocene speleothem from Victoria Fossil Cave, Naracoorte, South Australia. *Quaternary Science Reviews*, **19**, 763-774.

Dickson, B.L., Scott, K.M. 1998. Recognition of aeolian soils of the Blayney district, NSW: implications for mineral exploration. *Journal of Geochemical Exploration*, **63**, 237-251.

Dodson, J.R., Wright, R.V.S. 1989. Humid to arid to subhumid vegetation shift on Pilliga Sandstone, Ulungra Springs, New South Wales. *Quaternary Research*, **32**, 182-192.

Falconer, I.R. 1997. Blue-green algae in lakes and rivers: their harmful effects on human health. *Australian Biologist*, **10**, 107-110.

Fischer, M. J., Treble, P.C. 2008. Calibrating climate-$\delta^{18}O$ regression models for the interpretation of high-resolution speleothem $\delta^{18}O$ time series. *Journal of Geophysical Research*, **113**, D17103, doi:10.1029/2007JD009694.

Fischer, M.J., Treble, P.C. 2009. A model and the fidelity of climate reconstructions from speleothems. *Geophysical Research Abstracts*, Vol. 11, EGU2009-6287, EGU General Assembly 2009.

Fitzsimmons, K.E., Rhodes, E.J., Magee, J.W., Barrows, T.T. 2007. The timing of linear dune activity in the Strzelecki and Tirari Deserts, Australia. *Quaternary Science Reviews*, **26**, 2598-2616.

Flohn, H. 1986. Singular events and catastrophes now and in climatic history. *Naturwissenschaften*, **73**, 136-149.

Fluin, J., Gell, P., Haynes, D., Tibby, J. 2007. Paleolimnological evidence for the independent evolution of neighbouring terminal lakes, the Murray Darling Basin, Australia. *Hydrobiologia*, **591**, 117-134.

Fritz, S.C.1999. Twentieth-century salinity and water-level fluctuations in Devils Lake, North Dakota: Test of a diatom-based transfer function. *Limnology and Oceanography*, **35**, 1771-1781.

Galloway, R.W. 1965. Late Quaternary climates in Australia. *Journal of Geology*, **73**, 603-618.

Gardner, G.J., Mortlock, A.J., Price, D.M., Readhead, M.L., Wasson, R.J. 1987. Thermoluminescence and radiocarbon dating of Australian desert dunes. *Australian Journal of Earth Sciences*, **34**, 343-357.

Gatehouse, R.D., Williams, I.S., Pillans, B.J. 2001. Fingerprinting windblown dust in south-eastern Australian soils by uranium-lead dating of detrital zircon. *Australian Journal of Soil Research*, **39**, 7-12.

Gell, P.A. 1997. The development of diatom database for inferring lake salinity, Western Victoria, Australia: Towards a quantitative approach for reconstructing past climates. *Australian Journal of Botany*, **45**: 389-423.

Gell, P., Little, F. 2006. Long Term Water Quality Changes in Murrumbidgee Floodplain Wetlands Revealed by Fossil Diatom Assemblages. In: Taylor, I.R., Murray, P.A., Taylor, S.G. (Eds). *Wetlands of the Murrumbidgee River catchment: Practical management in an altered environment*. Presented at the Murrumbidgee Wetlands Forum, Leeton, November, 2006. Fivebough and Tuckerbil Wetlands trust: 43-65.

Gell, P.A., Stuart, I-M., Smith, J.D. 1993. The response of vegetation to changing fire regimes and human activity in the Delegate River catchment, East Gippsland, Victoria. *The Holocene*, **3**, 150-160.

Gell, P., Bulpin, S., Wallbrink, P., Bickford, S., Hancock, G. 2005a. Tareena Billabong – A palaeolimnological history of an ever changing wetland, Chowilla Floodplain, lower Murray-Darling Basin. *Marine and Freshwater Research*, **56**, 441-456.

Gell, P., Tibby, J., Fluin, J., Leahy, P., Reid, M., Adamson, K., Bulpin, S., MacGregor, A., Wallbrink, P., Hancock, G., Walsh, B. 2005b. Accessing limnological change and variability using fossil diatom assemblages, south-east Australia. *River Research and Applications*, **21**, 257-269.

Gell, P., Baldwin, D., Little, F., Tibby, J., Hancock, G. 2007. The impact of regulation and salinisation on floodplain lakes: the lower River Murray, Australia. *Hydrobiologia*, **591**, 135-146.

Gentilli, J. 1971. Climatic fluctuations. In: Gentilli, J. (Ed.). *Climates of Australia and New Zealand*. Elsevier, Amsterdam, pp 189-211.

Gentilli, J. 1986. Climate. In: Jeans, D. (Ed), *The Natural Environment*. A Geography of Australia, 1. Sydney University Press, Sydney, pp. 14-48.

Gergis, J. 2008. Documentary accounts of the impacts of past climate variability on the early colony of New South Wales, 1788–1791: a preliminary analysis. *Bulletin of the Australian Meteorological and Oceanographic Society*, **21**, 103-107.

Gergis, J., Braganza, K., Fowler, A., Risbey, J., Mooney, S. 2006. Reconstructing El Nino-Southern Oscillation (ENSO) from high-resolution palaeoarchives. *Journal of Quaternary Science*, **21,** 707-722.

Gergis, J., Fowler, A. 2009. A history of El Niño–Southern Oscillation (ENSO) events since A.D. 1525: implications for future climate change. *Climatic Change*, **92**, 343-387.

Gergis, J., Karoly, D., Allan, R. In Press. A climate reconstruction of Sydney Cove, New South Wales, using weather journal and documentary data, 1788–1791. *Australian Meteorological and Oceanographic Journal***.**

Gingele, F., De Deckker, P., Norman, M. 2007. Late Pleistocene and Holocene climate of SE Australia reconstructed from dust and river loads deposited offshore the River Murray Mouth. *Earth and Planetary Science Letters*, **255**, 257-272.

Goodrick, G.N. 1984. *Wetlands of north-western New South Wales*. National Parks and Wildlife Service, Sydney.

Goss, K.F. 2003. Environmental flows, river salinity and biodiversity conservation managing trade-offs in the Murray-Darling basin. *Australian Journal of Botany*, **51**, 619-625.

Harle, K., Etheridge, D., Barbetti, M., Jones, R., Brooke, B., Whetton, P., van Ommen, T., Goodwin, I., Fink, D. Haberle, S. 2007. *Building a future on knowledge from the past: what palaeo-science can reveal about climate change and its potential impacts in Australia*. Australian Greenhouse Office, Department of the Environment and Water Resources, Canberra, Australia.

Harrison, S.P. 1993. Late Quaternary lake-level changes and climates of Australia. *Quaternary Science Reviews*, **12**, 211-231.

Heinrich I, Gärtner H, Monbaron M, Schleser G. (Eds.). 2006. TRACE - Tree Rings in Archaeology, Climatology and Ecology, pp 313.

Heinrich, I., Weidner, K., Helle, G., Vos, H., Lindesay, J., Banks, J.C.G. 2009. Interdecadal modulation of the relationship between ENSO, IPO and precipitation: insights from tree rings in Australia. *Climate Dynamics*, **33**, 63-73.

Hennessy, K., Fitzharris, B., Bates, B.C., Harvey, N., Howden. S.M., Hughes, L., Salinger, J., Warrick, R. (2007). Australia and New Zealand. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.). Climate Change 2007: Impacts, Adaptations and Vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp 507-540.

Hesse, P.P. 1994. The record of continental dust from Australia in Tasman Sea Sediments. *Quaternary Science Reviews*, **13**, 257-272.

Hesse, P.P. Submitted. The Australian desert dunefields: formation and evolution in an old, flat, dry continent. In: Bishop, P., Pillans, B. (Eds), *Australian landscapes*. Geological Society London, London.

Hesse, P.P., McTainsh, G.H. 1999. Last Glacial Maximum to Early Holocene wind strength in the mid-latitudes of the Southern Hemisphere from aeolian dust in the Tasman Sea. *Quaternary Research*, **52**, 343-349.

Hesse, P.P., McTainsh, G.H. 2003. Australian dust deposits: modern processes and the Quaternary record. *Quaternary Science Reviews*, **22**, 2007-2035.

Hesse, P.P., Humphreys, G.S., Smith, B.L., Campbell, J. and Peterson, E.K. 2003. *Age of loess deposits in the Central Highlands of New South Wales*. Australian Journal of Soil Research, **41**, 1115-1131.

Hesse, P.P., Magee, J.W., van der Kaars, S. 2004. Late Quaternary climates of the Australian arid zone: A review. *Quaternary International*, **118-119**, 87-102.

Hope, J.H., Dare-Edwards, A., McIntyre, M.L. 1983. Middens and megafauna: stratigraphy and dating of Lake Tandou lunette, western New South Wales. *Archaeology in Oceania*, **18**, 38-45.

Hughes, L. 2003. Climate change and Australia: Trends, projections and impacts. *Austral Ecology*, **28**, 423-443.

Hutton, J.T. 1980. Chemical analyses of samples of parna from the Riverine Plain of South-Eastern Australia. In: Wasson, R.J. (Ed), *Quaternary Dust Mantles of China, New Zealand and Australia*. Australian National University, Canberra, pp. 149-152.

Jansen, E., Overpeck, J., Briffa, K., Duplessy, J., Joos, F., Masson-Delmotte, V., Olago, D., Otto-Bliesner, B., Peltier, W., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina, O., Villalba, R., Zhang, D. 2007. Palaeoclimate. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*: 433-497. Cambridge University Press, Cambridge, United Kingdom.

Jones, R.N., Pittock, A.B. 2002. Climate change and water resources in an arid continent:managing uncertainty and risk in Australia. In: Beniston. M. (Ed.). *Climatic Change:Implications for the Hydrological Cycle and for Water management*, *Advances in Global Change Research*, Kluwer Academic Publishers, Dordrecht and Boston, 465-501.

Jones, R.N., Pittock, A.B., Whetton, P.H. 2000. The potential impacts of climate change. In: Gillespie, A., Burns, W.C.G. (Eds.). *Climate change in the South Pacific: impacts and responses in Australia, New Zealand, and Small Island States.* Kluwer Academic Publishers, Dordrecht, pp 7-33.

Jones, P., Briffa, K., Osborn, T., Lough, J., van Ommen, T., Vinther, B., Luterbacher, J., Wahl, E., Zwiers, F., Mann, M., Schmidt, G., Ammann, C., Buckley, B., Cobb, K., Esper, J., Goose, H., Graham, N., Jansen, E., Kiefer, T., Kull, C., Kuttel, M., Mosley-Thompson, E., Overpeck, J., Riedwyl, N., Schulz, M., Tudhope, A., Villalba, R., Wanner, H., Wolff, E., Xoplaki, E. 2009. High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects. *The Holocene*, **19,** 3-49.

Karoly, D., Risbey, J., Reynolds, A., Braganza, A. 2003. Global Warming Contributes to Australia's Worst Drought. *Australasian Science*, **24**, 14-17.

Kawahata, H. 2002. Shifts in oceanic and atmospheric boundaries in the Tasman Sea (Southwest Pacific) during the Late Pleistocene: Evidence from organic carbon and lithogenic fluxes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **184**, 225-249.

Kemp, J., Spooner, N.A. 2007. Evidence for regionally wet conditions before the LGM in southeast Australia: OSL ages from a large palaeochannel in the Lachlan Valley. *Journal of Quaternary Science*, **22**, 423-427.

Kershaw, A.P. 1986. Climatic change and Aboriginal burning in north-east Australia during the last two glacial/interglacial cycles, *Nature*, **322**, 47-49.

Kershaw, A.P., Nanson, G.C. 1993. The last full glacial cycle in the Australian region. *Global and Planetary Change*, **7**, 1-9.

Kershaw, A.P., Clark, J.S., Gill, A.M. and D'Costa, D.M. 2002. A history of fire on Australia. In: Bradstock, R., Williams, J., Gill, M. (Eds), *A History of Fire in Australia*. Cambridge University Press, Cambridge.

Kershaw, A.P., McKenzie, G.M., Porch, N., Roberts, R.G., Brown, J., Heijnis, H., Orr, L.M., Jacobsen, G., Newall, P.R. 2007. A high resolution record of vegetation and climate through the last glacial cycle from Caledonia Fen, south-eastern highlands of Australia. *Journal of Quaternary Science*, **22**, 481-500.

Kershaw, A.P., van der Kaars, S. In Press. Tropical Quaternary climates in Australia and the south-west Pacific. In Metcalfe, S.E. and Nash, D.J. (Eds.). *Quaternary Environmental Change in the Tropics*. Blackwell Scientific Publishers, Oxford.

Kingsford, R.T., Porter, J. 1999. Wetlands and waterbirds of the Paroo and Warrego Rivers. In: Kingsford, R.T. (Ed), *A Free-Flowing River: The ecology of the Paroo River*. National Parks and Wildlife Service, Sydney, pp. 23-39.

Kothavala, Z., 1999. The duration and severity of drought over eastern Australia simulated by a coupled ocean-atmosphere GCM with a transient increase in CO_2. *Environmental Modelling and Software*, **14**, 243-252.

Kraus, E.B. 1954. Secular changes of tropical rainfall regime of southeast Australia. *Quarterly Journal of the Royal Meteorological Society*, **80**, 591-601.

Kraus, E.B. 1955. Secular changes of east-coast rainfall regimes, *Quarterly Journal of the Royal Meteorological Society*, **81**, 430-439.

Luly, J.G. 1993. Holocene palaeoenvironments near Lake Tyrell, semi-arid northwestern Victoria, Australia. *Journal of Biogeography*, **20**, 587-598.

Lynch, A.H., Beringer, J., Kershaw, P., Marshall, A., Mooney, S., Tapper, N., Turney, C., van der Kaars, S. 2007. Using the paleorecord to evaluate climate and fire interactions in Australia. *Annual Review of Earth and Planetary Science*, **35**, 215-239.

MDBC. 1999. *The Salinity Audit of the Murray-Darling Basin.* Murray-Darling Basin Ministerial Council, pp 48.

MDBC, 2003: *River Murray System – Update*. 6 February 2003. Murray-Darling Basin Commission, Canberra, Australia, pp 6.

McCarthy, J. J., Canziani, O. F., Learty, N. A., Dokken, D. J., White, K. S. (Eds.). 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Intergovernmental Panel on

Climate Change, Geneva. Cambridge University Press, Cambridge, UK and New York, USA, pp 1032.

Macumber, P.G. 1969. Interrelationship between physiography, hydrology, sedimentation, and salinization of the Loddon River Plains, Australia. *Journal of Hydrology*, **7**, 39-57.

Macumber, P. 1991. *Interaction between groundwater and surface systems in northern Victoria*. Department of Conservation and Environment, Victoria, Melbourne.

Marlon, J.R., Bertlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E. Joos, F., Power, M.J., Prentice, I.C. 2008. Climate and human influences on global biomass burning over the past two millennia. *Nature Geoscience*, **1**, 697-702.

Maroulis, J.C., Nanson, G.C., Price, D.M., Pietsch, T. 2007. Aeolian-fluvial interaction and climate change: source-bordering dune development over the past ~100 ka on Cooper Creek, central Australia. *Quaternary Science Reviews*, **26**, 386-404.

McDermott, F. 2004. Palaeo-climate reconstruction from stable isotope variations in speleothems: a review. *Quaternary Science Reviews*, **23**, 901-918.

McDonald, J. 2000. Late Quaternary palaeoclimate reconstruction of central NSW as inferred from the stable isotope and trace element geochemistry of speleothems. BSc Hons. Unpublished Thesis., University of Newcastle.

McDonald, J., Drysdale, R., Hill, D. 2004. The 2002-2003 El Niño recorded in Australian cave drip waters: Implications for reconstructing rainfall histories using stalagmites. *Geophysical Research Letters*, **31**, L22202, doi:10.1029/2004GL020859.

McDonald, J., Drysdale, R. Hill, D., Chisari, R., Wong, H. 2007. The hydrochemical response of cave drip waters to subannual and interannual climate variability, Wombeyan Caves, SE Australia. *Chemical Geology*, **244**, 605-623.

McGowan, H.A., Petherick, L.M., Kamber, B.S. 2008. Aeolian sedimentation and climate variability during the late Quaternary in southeast Queensland, Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **265**, 171-181.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingsteing, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., Zhao, Z.-C. 2007. Global Climate Projections. In: *Climate Change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.). Cambridge University Press, Cambridge, United Kingdom, pp 747-845.

Miller, G.H., Magee, J.W., Jull, A.J.T. 1997. Low-latitude glacial cooling in the Southern Hemisphere from amino-acid racemization in emu eggshells. *Nature*, **385**, 241-244.

Miller, G.H., Mangan, J., Pollard, D., Thompson, S.L., Felzer, B.S., Magee, J.W. 2005. Sensitivity of the Australian monsoon to insolation and vegetation: implications for human impact on continental moisture balance. *Geology*, **33**, 65-68.

Mooney, S.D. 1997. A fine-resolution palaeoclimatic reconstruction of the last 2000 years, from Lake Keilambete, southeastern Australia. *The Holocene*, **7**, 139-149.

Moss, P.T., Kershaw, A.P. 2007. A late Quaternary marine palynological record (Oxygen isotope stages 1-7) for the Humid Tropics of northeastern Australia based on ODP Site 820. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **251**, 4-22.

Murphy, B., Timbal, B. 2008. A review of recent climate variability and climate change in southeastern Australia. *International Journal of Climatology*, **28**, 859-879.

Nicholls, N. 2004. The changing nature of Australian droughts. *Climatic Change*, **63**, 323-336.

Nicholls, N., Collins, D., Trewin, B., Hope, P. 2006. Historical instrumental climate data for Australia – quality and utility for palaeoclimatic studies. *Journal of Quaternary Science*, **21**, 681-688.

Norris, R.H., Liston, P., Davies, N., Coysh, J., Dyer, F., Linke, S., Prosser, I.P., Young, W.J. 2001. *Snapshot of the Murray-Darling Basin river condition*. Report to the Murray Darling Basin Commission. Cooperative Research Centre for Freshwater Ecology, and CSIRO Land and Water, pp 50.

Ogden, R.W. 2000. Modern and historical variation in aquatic macrophyte cover of billabongs associated with catchment development. *Regulated Rivers-Research and Management*, **16**, 487-512.

Ogden, R., Spooner, N., Reid, M., Head, J. 2001. Sediment dates with implications for the age of the conversion from palaeochannel to modern fluvial activity on the Murray River and tributaries. *Quaternary International*, **83-85**, 195-209.

Olago, D.O., Odada, E.O. 2004. Palaeoreserach in Africa: relevance to sustainable environmental management and significance for the future. In: Past climate variability through Europe and Africa. Battarbee, R.W., Gasse, F., Stickley, C.E. (Eds.). *Developments in Palaeoenvironmental Research*. Volume 6. Springer, Dordrecht, The Netherlands, pp 551-565.

Olfield, F., Alverson, K. 2003. The societal relevance of palaeoenvironmental research. In: Alverson, K.D., Bradley, R.S., Pedersen, T.F. (Eds.). *Paleoclimate, Global Change and the Future.* Springer-Verlag, Heidelberg, Berlin, pp 1-12.

Page, K.J., Nanson, G.C. 1996. Stratigraphic architecture resulting from Late Quaternary evolution of the Riverine Plain, south-eastern Australia. *Sedimentology*, **43**, 927-945.

Page, K.J., Nanson, G.C., Price, D.M. 1991. Thermoluminescence chronology of late Quaternary deposition on the Riverine Plain of south-eastern Australia. *Australian Geographer*, **22**, 14-23.

Page, K., Dare-Edwards, A., Nanson, G., Price, D. 1994. Late Quaternary evolution of Lake Urana, New South Wales, Australia. *Journal of Quaternary Science*, **9**, 47-57.

Page, K., Nanson, G., Price, D. 1996. Chronology of Murrumbidgee River palaeochannels on the Riverine Plain, southeastern Australia. *Journal of Quaternary Science*, **11**, 311-326.

Page, K.J., Dare-Edwards, A.J., Owens, J.W., Frazier, P.S., Kellett, J., Price, D.M. 2001. TL chronology and stratigraphy of riverine source bordering sand dunes near Wagga Wagga, New South Wales, Australia. *Quaternary International*, **83-85**, 187-194.

Page, C., Nicholls, N., Plummer, N., Trewin, B., Manton, M., Alexander, L., Chambers, L., Choi, Y., Collins, D., Gosai, A., Della-Marta, P., Haylock, M., Inape, K., Laurent, V.,

Maitrepierre, L., Makmur, E., Nakamigawa, H., Ouprasitwong, N., McGree, S., Pahalad, J., Salinger, J., Tibig, L., Tran, T., Vediapan, K., Zhai, P. 2004. Data Rescue in the Southeast Asia and South Pacific Region: Challenges and Opportunities. *Bulletin of the American Meteorological Society*, **85**, 1483-1489.

Pant, G.B., Rupa Kumar, K., Parthasarathy, B., Borgaonkar, H.P. 1988. Long-term variability of the Indian summer monsoon and related paramenters. *Advances in Atmospheric Sciences*, **5**, 469-481.

Petherick, L., McGowan, H.A., Moss, P. 2008. Climate variability during the Last Glacial Maximum in eastern Australia: evidence of two stadials? *Journal of Quaternary Science*, **23**, 787-802.

Petherick, L.M., McGowan, H.A., Kamber, B.S. 2009. Reconstructing transport pathways for late Quaternary dust from eastern Australia using the composition of trace elements of long traveled dusts. *Geomorphology*, **105**, 67-79.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzmann, E., Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, **399**, 429-436.

Pietsch, T.J. 2005. *Fluvial geomorphology and late Quaternary geochronology of the Gwydir fan-plain*. Unpublished PhD Thesis, University of Wollongong, pp. 313.

Pitman, A.J., Hesse, P.P. 2007. The significance of large scale land cover change on the Australian palaeomonsoon. *Quaternary Science Reviews*, **26**, 189-200.

Pittock, A.B. 1975. Climate change and the pattern of variation in Australian rainfall. *Search*, **6**, 498-503.

Pittock, B. 2003. *Climate Change: An Australian guide to the science and potential impacts.* Australian Greenhouse Office.

Radke, L.C., 2000. Solute divides and chemical facies in south-eastern Australian salt lakes and the response of ostracods in time and space. Unpublished Thesis, Australian National University, pp. 232.

Ralph, T.J. and Hesse, P.P. In press. Downstream hydrological and morphological changes in the Macquarie River, New South Wales, and the formation of floodout wetlands. *Geomorphology*.

Readhead, M.L. 1988. Thermoluminescence dating study of quartz in aeolian sediments from southeastern Australia. *Quaternary Science Reviews*, **7**, 257-264.

Reid, M.A. 2008. Evidence for catastrophic shifts in the trophic structure of floodplain lakes associated with soil erosion. In: Schmidt, J., Cochrane, T., Phillips, C., Elliot, S., Davies, T., Basher, L. (Eds). *Sediment Dynamics in Changing Environments*. IAHS Press, Wallingford, UK, pp. 584-590.

Reid, M.A, Fluin, J., Ogden, R., Tibby, J., Kershaw, P. 2002. Long-term perspectives on human impacts on floodplain-river ecosystems, Murray-Darling Basin, Australia. *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie*, **28**, 710-716.

Reid, M.A., Sayer, C.D., Kershaw, A.P., Heijinis, H. 2007. Palaeolimnological evidence for submerged plant loss in a floodplain lake associated with accelerated catchment erosion (Murray River, Australia). *Journal of Paleolimnology*, **38**, 191-208.

Ryan, A.L., Cattle, S.R. 2006. Do sand dunes of the lower Lachlan floodplain contain the same dust that produced parna? *Australian Journal of Soil Research*, **44**, 769-781.

Schumm, S.A. 1968. River adjustment to altered hydrologic regimen - Murrumbidgee River and paleochannels, Australia. *Geological Survey Professional Paper*, **598**, 1-65.

Seager, R., Harnik, N., Robinson, W.A., Kushnir, Y., Ting, M., Huang, H.P., Velez, J. 2005. Mechanisms of ENSO-forcing of hemispherically symmetric precipitation variability. *Quarterly Journal of the Royal Meteorological Society,* **131,** 1501-1527.

Shao, Y., Leslie, L.M. 1997. Wind erosion prediction over the Australian continent. *Journal of Geophysical Research*, **102**, 30,091-30,105.

Scheffer, M., Westley, F.R. 2007. The evolutionary basis of rigidity: locks in cells, minds, and society. *Ecology and Society*, **12**, 36.

Simkin, R., Baker, P.J. 2008. Catastrophic fire and historical forest dynamics in Victorias Central Highlands. *Austral Ecology*, **33**, 747-760.

Singh, G., Geissler, E.A. 1985. Late Cainozoic history of vegetation, fire, lake levels and climate, at Lake George, New South Wales, Australia. *Philosophical Transactions of the Royal Society of London*, **B 311**, 379-447.

Singh, G., Kershaw, A.P., Clark, R. 1981. Quaternary vegetation and fire history in Australia. *In*: Gill, A.M., Groves, R.A., Noble, I.R. (Eds), *Fire and the Australian Biota*. Australian Academy of Science, Canberra, pp. 23-54.

Smith, I.N., McIntosh, P., Ansell, T.J., Reason, C.J.C., McInnes, K. 2000. Southwest western Australian winter rainfall and its association with Indian Ocean climate variability. *International Journal of Climatology*, **20**, 1913-1930.

Spooner, N.A., Olley, J.M., Questiaux, D.G., Chen, X.Y. 2001. Optical dating of an aeolian deposit on the Murrumbidgee floodplain. *Quaternary Science Reviews*, **20**, 835-840.

State of the Environment, Australia. 1996. Independent report to the Commonwealth Minister for the Environment by the State of the Environment Advisory Council. CSIRO publishing, Collingwood, Victoria, pp. 544

State of the Environment, Australia. 2006. Independent report to the Government Minister for the Environment and Heritage, Department of the Environment and Heritage, Canberra, pp. 141.

Stone, T. 2006. Last glacial cycle hydrological change at Lake Tyrrell, southeast Australia. *Quaternary Research*, **66**, 176-181.

Thomas, I., Enright, N.J., Kenyon, C.E. 2001. The Holocene history of Mediterranean-type plant communities, Little Desert National Park, Victoria, Australia. *The Holocene*, **11**, 691-697.

Thorne, A., Grun, R., Mortimer, G., Spooner, N.A., Simpson, J.J., McCulloch, M., Taylor, L., Curnoe, D. 1999. Australia's oldest human remains: age of the Lake Mungo 3 skeleton. *Journal of Human Evolution*, **36**, 591-612.

Tibby, J. 2004. Development of a diatom-based model for inferring total phosphorus in southeastern Australian water storages. *Journal of Paleolimnology*, **31**, 23-36.

Tibby, J., Reid, M.A., Fluin, J., Hart, T., Kershaw, A.P. 2003. Assessing long-term pH change in an Australian river catchment using monitoring and palaeolimnological data. *Environmental Science and Technology*, **37**, 3250-3255.

Timms, B.V. 1999. Local runoff, Paroo floods and water extraction impacts on the wetlands of Currawinya National Park. In: Kingsford, R.T. (Ed), *A Free-Flowing River: The ecology of the Paroo River*. National Parks and Wildlife Service, Sydney, pp. 51-66.

Treble, P., Shelley, J.M.G., Chappell, J. 2003. Comparison of high resolution sub-annual records of trace elements in a modern (1911-1992) speleothem with instrumental climate data from southwest Australia. *Earth and Planetary Science Letters*, **216**, 141-153.

Treble, P.C., Chappell, J., Gagan, M.K., McKeegan, K.D., Harrison, T.M. 2005. In situ measurement of seasonal $\delta^{18}O$ variations and analysis of isotopic trends in a modern speleothem from southwest Australia. *Earth and Planetary Science Letters*, **233**, 17-32.

Turney, C., Duncan, R., Nicholls, N., Moberg, A., Pollack, H. 2008. Towards an Australasian climate reconstruction for the past two millennia. *PAGES News*, **16**, 34.

Turney, C., Kershaw, P., Lynch, A. 2006. Introduction: Integrating high-resolution past climate records for future prediction in the Australasian region. *Journal of Quaternary Science*, **21**, 679-680.

Vivés B, Jones R. 2005. *Detection of abrupt changes in Australian decadal rainfall (1890-1989)*. CSIRO Atmospheric Research Technical Paper no. 73. CSIRO Atmospheric Research, Aspendale, Victoria, Australia, pp 54.

Walker, B., Salt, D. 2007. *Resilience Thinking: Sustaining ecosystems and people in a changing world*. Island Press, pp. 174.

Walker, K.F. 2006. Serial weirs, cumulative effects: the Lower River Murray, Australia. In: Kingsford, R.T. (Ed.). *Ecology of Desert Rivers.* Cambridge University Press, Cambridge. pp 248-279.

Walsh, K., Allan, R., Jones, R., Pittock, B., Suppiah, R., Whetton, P. 1999. *Climate Change in Queensland UnderEnhanced Greenhouse Conditions*. First Annual Report, 1997-1998, CSIRO Atmospheric Research, Aspendale, Victoria, Australia, pp 84.

Walsh, K., Hennessy, K., Jones, R., Pittock, B., Rotstayn, L., Suppiah, R., Whetton, P. 2000. *Climate Change in Queensland Under Enhanced Greenhouse Conditions*. Second Annual Report, 1998-1999, CSIRO Atmospheric Research, Aspendale, Victoria, Australia, pp 130.

Ward, W.T. 1992. *Soils and landscapes near Narrabri and Edgeroi, NSW , with data analysis using fuzzy k-means*. Soils and Land Use Series, **63**, Division of Soils, CSIRO, Melbourne.

Warner, R.F. 1987. The impacts of alternating flood- and drought-dominated regimes on channel morphology at Penrith, New South Wales, Australia. *IAHS Publication*, **68**, 327-338.

Warner, R.F. 1995. Predicting and managing channel change in southeast Australia. *Catena*, **25**, 403-418.

Wasson, R.J. 1976. Holocene aeolian landforms in the Belarabon area, southwest of Cobar, N.S.W. *Journal and Proceedings of the Royal Society of New South Wales*., **109**, 91-101.

Wasson, R.J., Donnelly, T.H. 1991. *Palaeoclimatic reconstructions for the last 30 000 years in Australia - a contribution to prediction of future climate*. Technical Memorandum, **91/3**, CSIRO Division of Water Resources.

Watkins, J.J. 1993. Thermoluminescence dating of Quaternary sediments from the Nyngan - Walgett area. *Geological Survey of New South Wales*, *Quarterly Notes*, **89**, 23-29.

Whetton, P.H., Adamson, D. and Williams, M. 1990. Rainfall and river flow variability in Africa, Australia, East Asia linked to El Niño – Southern Oscillation events, *Geological Society of Australia Symposium Proceedings*, **1**, 71-82.

Williams, M.A.J., Adamson, D.A., Baxter, J.T. 1986. Late Quaternary environments in the Nile and Darling Basins. *Australian Geographical Studies*, **24**, 128-144.

Williams, O.B., Oxley, R.E. 1979 Historical aspects of chenopod grasslands. In: Graetz, R.D., Howes, K.M.W. (Eds.). *Studies of the Arid Zone. IV Chenopod Shrublands*. CSIRO, Melbourne, pp 5-16.

Williams, A., Karoly, D., Tapper, N. 2001. The sensitivity of Australian fire danger to climate change. *Climate Change*, **49**, 171-191.

Wray, R.A.L. 2009. Palaeochannels of the Namoi River floodplain, New South Wales, Australia: the use of multispectral Landsat imagery to highlight a Late Quaternary change in fluvial regime. *Australian Geographer*, **40**, 24-49.

Yonge, D., Hesse, P.P. 2009. Geomorphic environments, drainage breakdown and channel and floodplain evolution on the lower Macquarie River, central-western New South Wales. *Australian Journal of Earth Sciences*, **56**.

Young, R.W., Young, A.R.M., Price, D.M., Wray, R.A.L. 2002. Geomorphology of the Namoi alluvial plain, northwest New South Wales. *Australian Journal of Earth Sciences*, **49**, 509-523.

7. ADDITIONAL RESOURCES

Adger, W.N. 2003. Social capital, collective action, and adaptation to climate change. *Economic Geography*, **79**, 387-404

Aerts, J., Renssen, H., Ward, P.J., de Moel, H., Odada, E., Bouwer, L.M., Goosse, H. 2006. Sensitivity of global river discharges under Holocene and future climate conditions. *Geophysical Research Letters*, **33**, L19401, doi:10.1029/2006GL027493.

Andronova, N.G., Schlesinger, M.E. 2001. Objective estimation of the probability density function for climate sensitivity. *Journal of Geophysical Research-Atmospheres*, **106**, 22605-22611.

Annan, J.D., Hargreaves, J.C. 2006. Using multiple observationally-based constraints to estimate climate sensitivity. *Geophysical Research Letters*, **33**, L06704, doi:10.1029/2005GL025259.

Bourman, R.P., Murray-Wallace, C.V., Belperio, A.P., Harvey, N. 2000. Rapid coastal geomorphic change in the river Murray Estuary of Australia. *Marine Geology*, **170**, 141-168.

Bowler, J.M. 1981. Australian salt lakes: a paleohydrologic approach. *Hydrobiologia* **82**, 431-444.

Brewer, G.D. 2007. Inventing the future: scenarios, imagination, mastery and control. *Sustainable Science*, **2**, 159-177.

Burton, I. 1997. Vulnerability and adaptive response in the context of climate and climate change. *Climatic Change*, **36**, 185-196.

Burton, I., Huq, S., Lim, B., Pilifosova, O., Schipper, E.L. 2002. From impacts assessment to adaptation priorities: the shaping of adaptation policy. *Climate Policy*, **2**, 145-159.

Canadell., J.G., Le Quéré, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P., Houghton, R.A., Marland, G. 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks *Proceedings of the National Academy of Sciences*, **104**, 18866-18870.

Carter, T.R., Parry, M.L., Harasawa, H., Nishioka, S. 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. University College, London and Centre for Global Environmental Research, Japan, pp. 59.

Carter T.R., Parry, M.L. 1998. *Climate impact and adaptation assessment: a guide to the IPCC approach*. Earthscan, London, pp. 166.

Carter, T.R., Jones, R.N., Lu, X., Bhadwal, S., Conde, C., Mearns, L.O., O'Neill, B.C., Rounsevell, M.D.A. Zurek, M.B. 2007. New Assessment Methods and the Characterisation of Future Conditions. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds). *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Collins, M., Booth, B.B.B., Harris, G.R., Murphy, J.M., Sexton, D.M.H., Webb, M.J. 2005. Towards quantifying uncertainty in transient climate change. *Climate Dynamics*, **27**, 127-147.

Conway, D. 2005. From headwater tributaries to international river: Observing and adapting to climate variability and change in the Nile Basin. *Global Environmental Change*, **15**, 99-114.

Cox, P., Stephenson, D. 2007. A changing climate for prediction. *Science*, **317**, 207-208.

CSIRO and BOM (Bureau of Meteorology). 2007. *Climate Change in Australia - Technical Report 2007*. CSIRO and the Bureau of Meteorology, Melbourne, pp. 148.

CSIRO and Melbourne Water. 2005. *Melbourne Water Climate Change Study*, Melbourne Water, Melbourne.

Dessai, S., Hulme, M. 2004. Does climate adaptation policy need probabilities? *Climate Policy*, **4**, 107-128.

Dessai, S., Hulme, M. 2007. Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the East of England. *Global Environmental Change*, **17**, 59-72.

Dessai, S., Lu, X., Risbey, J.S. 2005. On the role of climate scenarios for adaptation planning, *Global Environmental Change*, **15**, 78-97.

DSE. 2007. *Our Water Our Future: the Next Stage of the Government's Water Plan*. Department of Sustainability and Environment, Melbourne, pp. 28.

Enting, I.G., Wigley, T.M.L., Heimann, M. 1994. *Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses*, CSIRO Division of Atmospheric Research Technical Paper No. 31, CSIRO, Melbourne.

Feenstra, J.F., Burton, I., Smith, J.B., Tol, R.S.J. (Eds.), 1998. *Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies*, Version 2.0. UNEP/IVM, The Netherlands.

Field, J., Dodson, J.R., Prosser, I.P. 2002. A Late Pleistocene vegetation history from the Australian semi-arid zone. *Quaternary Science Reviews*, **21**, 1023-1037.

Forbes, M.S., Bestland, E.A. 2007. Origin of the sedimentary deposits of the Naracoorte caves, South Australia. *Geomorphology*, **86**, 369-392.

Forest, C.E., Stone, P.H., Sokolov, A.P., Allen, M.R., Webster, M.D. 2002. Quantifying uncertainties in climate system properties with the use of recent climate observations. *Science*, **295**, 113-117.

Frame, D.J., Stone, D.A., Stott, P.A., Allen, M.R. 2006. Alternatives to stabilization scenarios. *Geophysical Research Letters*, **33**, L14707, doi:10.1029/2006GL025801.

Garnaut, R. 2008. *Garnaut Climate Change Review: Draft Report June 2008*. Garnaut Climate Change Review, Melbourne, pp. 537.

Gingele, F., De Deckker, P., Hillenbrand, C.D. 2004. Late Quaternary terrigenous sediments from the Murray Canyons area, offshore South Australia and their implications for sea level change, palaeoclimate and palaeodrainage of the Murray-Darling Basin. *Marine Geology*, **212**, 183-197.

Gregory, J.M., Stouffer, R.J., Raper, S.C.B., Stott, P.A., Rayner, N.A. 2002. An observationally based estimate of the climate sensitivity. *Journal of Climate*, **15**, 3117-3121.

Groves, D.G., Lempert, R.L. 2007. A new analytic method for finding policy-relevant scenarios. *Global Environmental Change*, **17**, 73-85.

Grübler, A., Nakicenovic, N. 2001. Identifying dangers in an uncertain climate. *Nature*, **412**, 15.

Haberle, S.G. 2005. A 23,000-yr pollen record from Lake Euramoo, wet tropics of NE Queensland, Australia. *Quaternary Research*, **64**, 343-356.

Hansen, J. 2007. *How Can We Avert Dangerous Climate Change?* Written testimony to the Select Committee on Energy Independence and Global Warming, United States House of Representatives, 26 April 2007, Arxiv preprint arXiv:0706.3720

Henderson-Sellers, A. 1993. An Antipodean climate of uncertainty. *Climatic Change*, **25**, 203-224.

Hill, P.J., De Deckker, P., von der Borch, C., Murray-Wallace, C.V. 2009. Ancestral Murray River on the Lacepede Shelf, southern Australia: Late Quaternary migrations of a major river outlet and strandline development. *Australian Journal of Earth Sciences*, **56**, 135-157.

IPCC. 1990. *Climate Change: The IPCC scientific assessment*. Houghton, J.T., Jenkins, G.J., Ephraums, J.J. (Eds). Cambridge University Press, Cambridge, pp 365.

IPCC. 1992. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*. Houghton, J.T., Callander, B.A.,Varney, S.K. (Eds.). Cambridge University Press, Cambridge, pp 200.

IPCC. 1996a.*Climate Change 1995: The Science of Climate Change*. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Houghton, J.T., Meiro Filho, L.G., Harris, N., Callander, B.A., Kattenburg, A., Maskell, K., (Eds). Cambridge University Press, Cambridge, pp 572.

IPCC. 1996b. *Climate Change 1995: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Watson, R.T., Zinyowera, M.C., Moss, R.H. (Eds). Cambridge University Press, Cambridge, pp 880.

IPCC. 2001a. *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.). Cambridge University Press, Cambridge, pp 881.

IPCC. 2001b. *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.). Cambridge University Press, Cambridge, pp 1032.

IPCC. 2001c. *Climate Change 2001: Mitigation*. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Metz, B., Davidson, O., Swart, R., Pan, J., (Eds.). Cambridge University Press, Cambridge, pp 702.

IPCC. 2007a. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.). Cambridge University Press, Cambridge, pp 996.

IPCC. 2007c. *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Cambridge University Press, Cambridge, pp 851.

IPCC-TGICA. 2007. *General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment*. Version 2. Prepared by T.R. Carter on behalf of the Intergovernmental Panel on Climate Change, Task Group on Data and Scenario Support for Impact and Climate Assessment, pp 66.

Jones, R.N. 1995. Modelling Hydrologic and Climatic Controls of Closed Lakes Western Victoria. Ph. D. Thesis, University of Melbourne, Melbourne (unpublished).

Jones, R.N. 2001. An environmental risk assessment/management framework for climate change impact assessments, *Natural Hazards*, **23**, 197-230.

Jones, R.N. 2004. Incorporating agency into climate change risk assessments. *Climatic Change*, **67**, 13-36.

Jones, R.N. 2004. Managing Climate Change Risks. In Agrawal, S., Corfee-Morlot, J. (Eds.). *The Benefits of Climate Change Policies: Analytical and Framework Issues*, OECD, Paris, 249-298.

Jones, R., Durack, P., Page, C., Ricketts, J. 2005. Climate change impacts on the Water Resources of the Fitzroy River Basin. In Cai, W. (Ed). *Climate Change in Queensland under Enhanced Greenhouse Conditions: Final Report 2004-2005*. CSIRO Marine and Atmospheric Research, Melbourne, 19-58.

Jones, R.N., Page, C.M. 2001. Assessing the risk of climate change on the water resources of the Macquarie River Catchment. In Ghassemi, F., Whetton, P., Little, R., Littleboy, M. (eds.), *Integrating Models for Natural Resources Management across Disciplines, issues and scales* (Part 2), Modsim 2001 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand, Canberra, 673-678.

Kane, S., Shogren, J.F. 2000. Linking adaptation and mitigation in climate change policy. *Climatic Change*, **45**, 75-102.

Kenny, G.J., Warrick, R.A., Campbell, B.D., Sims, G.C., Camilleri, M., Jamieson, P.D., Mitchell, N.D., McPherson, H.G., Salinger, M.J. 2000. Investigating climate change impacts and thresholds: an application of the CLIMPACTS integrated assessment model for New Zealand agriculture. *Climatic Change*, **46**, 91-113.

Knutti, R., Tomassini, L. 2008. Constraints on the transient climate response from observed global temperature and ocean heat uptake. *Geophysical Research Letters*, **35**, L09701, doi:10.1029/2007GL032904.

Knutti, R., Stocker, T.F., Joos, F., Plattner, G.-K. 2002. Constraints on radiative forcing and future climate change from observations and climate model ensembles. *Nature*, **416**, 719-723.

Lövbrand, E. 2004. Bridging political expectations and scientific limitations in climate risk management - on the uncertain effects of international carbon sink policies. *Climatic Change*, **67**, 449-460.

Maronna, R., Yohai, V.J. 1978. A bivariate test for the detection of a systematic change in mean. *Journal of the American Statistics Association*, **73**, 640-645.

McDonald, J., Drysdale, R., Hodge, E., Hua, Q., Fischer, M., Frisia, S., Hellstrom, J., Kinsey, L., Greig, A. 2009. One thousand year palaeohydrological record derived from SE Australian stalagmites. *Geophysical Research Abstracts*, Vol. 11, EGU2009-11554, EGU General Assembly 2009.

Mearns, L.O., Hulme, M. 2001. Climate scenario development. In Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Van Der Linden, P.J. Xioaosu, D. (Eds.). *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 739-768.

Miller, G.H., Fogel, M.L., Magee, J.W., Gagan, M.K., Clarke, S.J., Johnson, B.J. 2005a. Ecosystem collapse in Pleistocene Australia and a human role in megafaunal extinction. *Science*, **309**, 287-290.

Mix, A.C., Pisias, N.G., Rugh, W., Wilson, J., Morey, A., Hagelberg, T. 1995. Benthic foraminiferal stable isotope record from Site 849, 0-5 Ma, Local and global climate changes. In: Pisias, N.G., Mayer, L., Janecek, T., Palmer-Julson, A., van Andel, T.H. (Eds), *Proceedings of the Ocean Drilling Project, Scientific Results, Leg 138*. Ocean Drilling Project, College Station, TX, pp. 371-412.

Moss, R., Babiker, W., Brinkman, S., Calvo, E., Carter, T., Edmonds, J., Elgizouli, I., Emori, S., Erda, L., Hibbard, K., Jones, R., Kainuma, M., Kelleher, J., Lamarque, J.F., Manning, M., Matthews, B., Meehl, J., Meyer, L., Mitchell, J., Nakicenovic, N., O'Neill, B., Pichs, R., Riahi, K., Rose, S., Runci, P., Stouffer, R., van Vuuren, D., Weyant, J., Wilbanks, T., van Ypersele, J.P., Zurek, M. 2008. *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies*. Intergovernmental Panel on Climate Change, Geneva, pp 132.

Murphy, J.M., Sexton, D.M.H., Barnett, D.N., Jones, G.S., Webb, M.J., Collins, M., Stainforth, D.A. 2004. Quantifying uncertainties in climate change from a large ensemble of general circulation model predictions, *Nature*, **430**, 768-772.

Nakićenović, N., Swart, R. (Eds.). 2000. *IPCC Special Report on Emissions Scenarios*. A Special Report of IPCC Working Group III. Cambridge University Press, Cambridge, pp 599.

New, M., Hulme, M. 2000. Representing uncertainty in climate change scenarios: a Bayesian Monte-Carlo approach. *Integrated Assessment*, **1**, 203-213.

New, M., Lopez, A., Dessai, S., Wilby, R. 2007. Challenges in using probabilistic climate change information for impact assessments: an example from the water sector. *Philosophical Transactions of the Royal Society A*, **365**, 2117-2131

O'Brien, K.L., Leichenko, R.M. 2000. Double exposure: assessing the impacts of climate change within the context of economic globalisation. *Global Environmental Change*, **10**, 221-313.

O'Neill, B.C., Oppenheimer, M. 2002. Dangerous climate impacts and the Kyoto Protocol, *Science*, **296**, 1971-1972

Pepper, W., Leggett, J., Swart, R., Wasson, J., Edmonds, J., Mintzer, I. 1992. *Emission Scenarios for the IPCC, an Update, Assumptions, Methodology and Results*. Prepared for the Intergovernmental Panel on Climate Change, Working Group I, pp 115.

Reid, M.A. 2002. A diatom-based palaeoecological study of two billabongs on the Goulburn River floodplain, southeast Australia. In: John, J. (Ed). *Proceedings of the15th international diatom symposium*. Gantner Verlag, Ruggell, pp. 237-253.

Risbey, J., Kandlikar, M., Dowlatabadi, H., Graetz, D. 1999. Scale, context, and decision making in agricultural adaptation to climate variability and change. *Mitigation and Adaptation Strategies for Global Change*, **4**, 137-165.

Robertson, G.B., Prescott, J.R. 2006. Luminescence dating at the archaeological and human burial site at Roonka, South Australia. *Quaternary Science Reviews*, **25**, 2586-2593.

Schneider, S.H. 1983. CO_2, Climate and Society: A brief overview. In Chen, R.S., Boulding, E., Schneider, S.H. (Eds.). *Social Science Research and Climate Change: In Interdisciplinary Appraisal*. D. Reidel, Boston, 9-15.

Schneider, S.H. 2001. What is 'dangerous' climate change? *Nature*, **411**, 17-19.

Sheehan, P. 2008. The new global growth path: implications for climate change analysis and policy. *Climatic Change*, 10.1007/s10584-008-9415-z

Sheehan, P., Jones, R.N., Jolley, A., Preston, B.L., Clark, M., Durack, P.J., Islam, S., Sun, F., Whetton, P.H. 2008. Climate change and the new world economy: implications for the nature and timing of policy responses. *Global Environmental Change*, doi:10.1016/j.gloenvcha.2008.04.008.

Smit, B., Pilifosova, O. 2003. From adaptation to adaptive capacity and vulnerability reduction. In: Smith, J. B., Klein, R. J. T., Huq, S. (Eds.). *Climate Change, Adaptive Capacity and Development*, Imperial College Press, London, 9-28.

Smit, B., Burton, I., Klein, R.J.T., Wandel, J. 2000. An anatomy of adaptation to climate change and variability. *Climatic Change*, **45**, 223-251.

Smith, D.M., Cusack, S., Colman, A.W., Folland, C.K., Harris, G.R., Murphy, J.M. 2007. Improved Surface Temperature Prediction for the Coming Decade from a Global Climate Model, *Science*, **317**, 796-799.

Smithers, J. Smit, B. 1997. Human adaptation to climatic variability and change. *Global Environmental Change*, **7**, 129-146.

Stone, T. 2006. The late-Holocene origin of the modern Murray River course, southeastern Australia. *The Holocene*, **16**, 771-778.

Suppiah, R., Whetton, P.H. 2007. *Observed and projected changes in effective degree-days in Melbourne*, 2008-2012. CSIRO, Melbourne, pp 62.

Tebaldi, C. Knutti, R. 2007. The use of the multi-model ensemble in probabilistic climate projections. *Philosophical Transactions of the Royal Society A*, **365**, 2053-2075.

The International Ad Hoc Detection and Attribution Group. 2005. Detecting and Attributing External Influences on the Climate System: A Review of Recent Advances. *Journal of Climate*, **18**, 1291-1314.

Tol, R.S.J., de Vos, A.F. 1998. A Bayesian statistical analysis of the enhanced greenhouse effect. *Climatic Change*, **38**, 87-112.

Treble, P.C., McDonald, J. 2008. Speleothem research unlocking rainfall archives. *Quaternary Australasia,* **25**, 27-29.

Troccoli, A., Palmer, T.N. 2007. Ensemble decadal predictions from analysed initial conditions. *Philosophical Transactions of the Royal Society A*, **365**, 2179-2191.

Turney, C.S.M., Kershaw, A.P., Lowe, J.J., van der Kaars, S., Johnston, R., Rule, S., Moss, P., Radke, L., Tibby, J., McGlone, M.S., Wilmshurst, J.M., Vandergoes, M.J., Fitzsimons, S.J., Bryant, C., Branch, N.P., Jacobsen, G., Fifield, L.K. 2006. Climatic variability in the southwest Pacific during the Last Termination (20-10ka BP). *Quaternary Science Reviews*, **25**, 886-903.

Twidale, C.R., Bourne, J.A., Spooner, N.A., Rhodes, E.J. 2007. The age of the palaeodunefield of the northern Murray Basin in South Australia: Preliminary results. *Quaternary International*, **166**, 42-48.

van Vuuren, D.P., O'Neill, B.C. 2006. The consistency of IPCC's SRES scenarios to 1990-2000: Trends and recent projections. *Climatic Change*, **75**, 9-46.

Ward, P.J., Aerts, J., de Moel, H., Renssen, H. 2007. Verification of a coupled climate-hydrological model against Holocene palaeohydrological records. *Global and Planetary Change*, **57**, 283-300.

Watterson, I.G. 2008. Calculation of probability density functions for temperature and precipitation change under global warming. *Journal of Geophysical Research* - *Atmospheres*, **113**

Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J., Grubb, M. 1996. Integrated assessment of climate change: an overview and comparison of approaches and results. In: Bruce, J.P., Lee, H., Haites, E.F. (Eds.). *Climate Change 1995: Economic and Social Dimensions of Climate Change*. Contribution of Work Group III to 2nd Assess. Rep. IPCC. Cambridge University Press, Cambridge, UK.

Weyant, J.P. 2004. EMF 19 Alternative Technology Strategies for Climate Change Policy *Energy Economics*, **26**, 501-755.

Whetton, P.H., Macadam, I., Bathols, J.M., O'Grady, J. 2007. Assessment of the use of current climate patterns to evaluate regional enhanced greenhouse response patterns of climate models. *Geophysical Research Letters*, **34,** L14701, doi:10.1029/2007GL030025.

Wigley, T.M.L. 2005. The climate change commitment. *Science*, **307**, 1766-1769.

Wigley, T.M.L., Raper, S.C.B. 2001. Interpretation of high projections for global-mean warming. *Science*, **293**, 451-454.

Wigley, T.M.L., Richels, R., Edmonds, J.A. 1996. Economic and environmental choices in the stabilization of atmospheric CO2 concentrations. *Nature*, **379**, 240-243.

Willows, R., Connell, R.K. 2003. *Climate Adaptation: Risk, Uncertainty and Decision-making*. United Kingdom Climate Impacts Programme, Oxford UK.

Yohe, G.W., Andronova, N.G., Schlesinger, M.E. 2004. To hedge or not. against an uncertain climate future. *Science*, **306**, 416-417.

Yohe, G.W., Lasco, R.D., Ahmad, Q.K., Arnell, N.W., Cohen, S.J., Hope, C., Janetos, A.C., Perez, R.T. 2007. Perspectives on climate change and sustainability. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.). *Climate Change 2007: Impacts, Adaptation and Vulnerability*. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, 811-841.