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

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 subtropical 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).

![Map of runoff by sub-catchment, box highlights the MDB.](image)

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 °C and 1.74 °C 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 GI (preventing good bird breeding) 48% of the time, and storage in the largest dam was below 500,000 GI 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 (32° S, 143° 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 et 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).
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 glacial 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, southeast 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. *Lagarostrobus franklinii*, Huon Pine; Cook *et al*., 1991), *Phyllocladus asplenifolius* (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 palaeoclimatic 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 hydroclimatic 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.
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7. ADDITIONAL RESOURCES


