Many conservationists argue that invasive species form one of the most important threats to ecosystems worldwide, often spreading quickly through their new environments and jeopardizing the conservation of native species. As such, it is important that reliable predictions can be made regarding the effects of new species on particular habitats and ecosystems.

This book provides a critical appraisal of ecological theory using case studies of biological invasions in Australasia. Each chapter is built around a set of 11 central hypotheses from community ecology, which were mainly developed in North American or European contexts. The authors examine the hypotheses in the light of evidence from their particular species, testing their power in explaining the success or failure of invasion, and accepting or rejecting each hypothesis as appropriate. The conclusions have far-reaching consequences for the utility of community ecology, suggesting a rejection of its predictive powers and a positive reappraisal of natural history.

"The editors have brought together 34 scientists with solid field experience to write 18 chapters on specific examples of invasions... The results are spectacularly interesting for those of us who are interested in natural history, but they also provide a strong warning for ecologists who think time's arrow always points in the direction of theoretical progress and more precise generalisation."

From the foreword by Charles J. Krebs

This book represents a novel and exciting approach to testing some fundamental ecological ideas such as the niche concept, competition, disturbance, and life history strategy. It does so using invasive alien species, with Australia as both the invaded environment, as well as the source of the invasives. The principal intent of this book is to inform the science of ecology, but it is rich in insights of value to those grappling with the management of this great threat to global biodiversity.

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Invasion Biology and Ecological Theory
Insights from a Continent in Transformation

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12 The development of a climate: an arid continent with wet fringes

Sandra McLaren, Malcolm W. Wallace, Stephen J. Gallagher, Barbara E. Wagstaff and Anne-Marie P. Tosolini

Introduction

The Australian continent is large and therefore exhibits a range of very different climatic zones. Broadly, the continent is characterised by arid climatic regimes: four-fifths of the landmass receiving an annual rainfall of less than 600 mm (Figure 12.1) and one-half of the continent receiving less than 300 mm. These arid and semi-arid regions form the greatest proportion of inland Australia, and are fringed by narrow, wet and temperate climatic zones along the southwestern, southern and eastern coastal zones (Figure 12.1). Tropical monsoonal rainfall characterises the northern coastal zones. Compared to other continents on Earth, Australia has by far the lowest average rainfall. This low precipitation rate is coupled with a high evaporation rate meaning that surface water availability is also anomalously low compared to global averages. Average annual temperature also shows significant variation (Figure 12.1) and in most areas there is also a high diurnal variation in temperature.

It is well known, however, that the currently arid areas of inland Australia were significantly wetter in the geological past, from the early Cenozoic (a period of geological time from c. 65 Ma until the present day; Gradstein et al. 2004) until at least the early Miocene (c. 23 Ma) (e.g. Kenchpatrick et al. 1994; Martin 2006). Much of our current knowledge of climate change from the early Cenozoic to the present is derived from observed variations in the isotopic signature of marine sediments (e.g. deMenocal 1995; Lisiecki and Raymo 2005; Raymo et al. 2006) as well as the distribution, chemistry and palynological assemblages of terrestrial and marine sediments and sedimentary rocks.

Globally, the impact of climatic shifts throughout the geological record has been profound. Numerous examples of changes in species development and/or distribution have been documented in the Cenozoic (e.g. Vezzani et al. 2004; Edwards et al. 2007; Molot et al. 2008; Palombo et al. 2009) and the step-wise aridification of Africa, for example, is thought to have played an important role in forcing the evolution of hominids (e.g. Stanley 1992; Reed 1997; Bobe and Behrensmeyer 2004; Wynn 2004). Notwithstanding the significance of climate change in this interval, the timing of onset of arid climatic regimes in Australia remains poorly constrained and the factors controlling changes in climatic dynamics are still debated (e.g. Cane and Molnar 2001). This chapter summarises the key characteristics of the modern Australian climate and presents a review of our understanding of the timing of the development of this climatic zonation and its origins. We focus particularly on the development of the continent's dominant arid climatic regime. Currently available data suggest that the onset of arid climatic conditions was gradual and step-wise and occurred significantly earlier in southeastern Australia than previously thought. It also seems likely that the onset of acidity was dischronous across the continent, beginning earlier in western and central

Figure 12.1 Climatic features of the modern Australian continent (a) mean annual temperature and (b) mean annual rainfall. Figures modified from the Australian Bureau of Meteorology and reproduced with permission. WA = Western Australia, NT = Northern Territory, Qld = Queensland, SA = South Australia, NSW = New South Wales, Vic = Victoria, Tas = Tasmania.
The development of a climate: an arid continent with wet fringes

In the northern Australian coastal fringes annual rainfall averages 1500–3200 mm (Figure 12.1) and is highly seasonal with significant falls associated with tropical monsoon activity in the summer. Mean annual temperatures are in the range 25–28°C (Australian Bureau of Meteorology, Figure 12.1). This tropical and humid subtropical climate is broadly similar to that of neighbouring landmasses to the north, including the Indonesian archipelago and New Guinea. These regions have typical equatorial climates characterised by high average annual rainfall and small diurnal temperature variations. In contrast, climate conditions in southeastern Australia are temperate with average annual rainfall in the range of 600–2000 mm and mean daily temperatures in the range 12–18°C (Australian Bureau of Meteorology, Figure 12.1). Tasmania, south of the Australian continental landmass, is characterised by average rainfall of 500–3200 mm and average temperatures of 9–12°C (Australian Bureau of Meteorology, Figure 12.1). This climate most closely resembles the maritime climate of Australia’s nearest eastern neighbour, New Zealand.

Over four-fifths of the continent, and almost all of the continental interior, is characterised by arid climatic regimes with average annual rainfall in the range 0–400 mm and average daily temperatures between 19–25°C (Australian Bureau of Meteorology, Figure 12.1). These arid regions are classic subtropical deserts and are situated beneath the downward circulation of the southern hemisphere Hadley Cell (Hesse et al. 2004). Such widespread arid conditions are least like those found in neighbouring landmasses and are a key point of difference between the Australian continent and its neighbours.

The variability of modern climate (rainfall and temperature) across the continent is reflected in the type and distribution of vegetation. Martin (2006) presents a summary of the key modern vegetation types as described by Specht and Specht (2002). These include: (1) closed-forest or rainforest including tropical, subtropical and temperate species, which are generally restricted to high rainfall regions and which generally lack significant Eucalyptus; (2) sclerophyll forest, dominated by Eucalyptus and/or Casuarina, which can be either wet (with a rainforest understorey) or dry (with a sclerophyll understorey); (3) open vegetation, particularly shrublands and grasslands; (4) arid and semi-arid vegetation dominated by Acacia shrublands and low woodlands and which generally lack significant Eucalyptus; and (5) chenopod shrublands dominated by annual and perennial species. Broadly, Australia is dominated by flora that is well adapted to the widespread arid and semi-arid climatic conditions. In these regions, Acacia, Casuarina, chenopods and grasses are dominant (Groves 1999) and Eucalyptus is less dominant. Other vegetation types, particularly tropical and temperate rainforest, are restricted to specific climatic niches characterised by particular humidity, rainfall and/or temperature conditions. The strong relationship between vegetation type and climate means that spore-pollen preserved in sedimentary rocks is one of the best indicators of the nature of past climates.

Climatic history of a continent

Beyond the period of historical meteorological records, our understanding of climatic change is derived largely from the geological record. In particular, sedimentary rocks—those deposited at or near the Earth’s surface—can preserve an extraordinarily detailed
The development of a climate: an arid continent with wet fringes

Late Mesozoic

Prior to the break-up of Gondwana, Australia was characterised by a broadly warm climatic mode (Frakes et al. 1992). Globally, sea level was higher compared to today (100 ± 50 m; Miller et al. 2005) before a significant sea-level drop at the end of the Cretaceous initiated more seasonal climatic conditions (Hays and Pitman 1973). Average global surface temperatures for the Cretaceous were 6°C higher than today resulting in a climate interpreted by many to have been warm, equable and lacking variability (Barron 1983). In general, Cretaceous climates are marked by a warming event around 140 Ma, which was followed by increasing climate instability from around 130 Ma. This trend culminated in a late Aptian cooling episode (Weisert and Erbs 2004) around 110 Ma. Steady warming occurred from this time until around 80 Ma after which time there was another major cooling phase until the Maastrichtian around 67 Ma (Douglas and Savin 1975; Huber et al. 1995; Huber 1998; Clarke and Jenkyns 1999; MacLeod et al. 2001).

Although the Cretaceous climate in Australia broadly follows global trends, the position of the continent at high palaeo-latitude prior to separation from Antarctica resulted in climate extremes, particularly in the south. In the Early Cretaceous lines of latitude increased from the northwest to the southeast across the continent whereas by the Late Cretaceous they increased from north to south (Li and Powell 2001). This shift was due to the change in position of the palaeo south pole. However, throughout the Cretaceous the south of the continent was at least at 65°S (Li and Powell 2001; Chapter 11 of this volume) and a variation in climate regimes occurred across the continent due to a latitudinal spread of approximately 30°.

Cool to cold temperatures are interpreted for the Early Cretaceous of southeastern Australia. Gregory et al. (1989) used oxygen isotope ratios in calcite concretions in the host sediment of fluvial (river deposit) strata in Victoria to suggest mean annual temperatures possibly below zero and certainly below 5°C. Constantine et al. (1998) interpreted cryptoturbation structures (permafrost features) to confirm these temperatures. Rich et al. (1988) regarded preserved Cretaceous dinosaur fauna to have been superbly adapted to high latitude near polar conditions, tolerating at least 3 months of winter darkness and marked seasonality. Cold temperatures are also indicated by the work of Frakes and Kressay (1992) who recorded ice rafted dropstones in Neeccanian–Albian strata in northern Australia in the Carpentaria Basin. Freezing conditions are also suggested by the presence of a tillite in the earliest Cretaceous sequences of the Eromanga Basin (Alley and Frakes 2003). The presence of glendonites in the Eromanga Basin suggests such climatic conditions continued in this basin until the Late Aptian (De Lurio and Frakes 1999) and are also used as evidence for a Late Aptian rise in temperature to 5–8°C. This is in broad agreement with the Western Australian δ18O data of Clarke and Jenkyns (1999) that also shows a significant warming through this time.

Palynological evidence from southeast Australia in the Late Cretaceous suggests that the climate was cool to temperate with high moisture availability (Dettmann 1994). This is in contrast to the north of the continent where Quilty (1994) reports warm to tropical marine faunas on the northwest shelf of Western Australia. Clarke and Jenkyns (1999) suggest a steady cooling on the western continental margin throughout the late Cretaceous. This
pattern is consistent with global oxygen isotope variations that indicate widespread global cooling near the end of the Cretaceous (Huber 1998).

These broad interpretations may be hiding a finer-scale climate story. Gallagher et al. (2008) show that in the latest Cretaceous in the Gippsland Basin conditions were overprinted by Milankovitch eccentricity and obliquity forced alternations of drier and wetter periods. It is suggested that these drier and wetter periods were either related to the waxing and waning of ephemeral ice sheets in Antarctica during times of insolation maxima and minima or were caused by another unknown mechanism (Miller et al. 2003, 2004). The palynological data show a consistent trend to drier conditions culminating around 67 Ma near the Cretaceous/Tertiary boundary. However, angiosperm groups, including Nothofagus, that evolved in the Early Cretaceous and spread rapidly during the Late Cretaceous, not only survived the boundary event but went on to achieve prominence in the Cenozoic (Dettmann 1994). As suggested by Wolfe and Upchurch (1986), this perhaps indicates only a brief duration of the impact of winter in the southern hemisphere. The oldest-known mammal on the Australian continent (a platypus-like species) and Australia’s oldest birds first appeared in the Cretaceous (Archer et al. 1991).

**Palaeogene**

The Palaeogene period includes the Palaeocene, Eocene and Oligocene epochs, and spans the interval from 65.5 Ma to 23.0 Ma. It is a period of dominantly wet and humid conditions in Australia with evidence for only restricted arid conditions in the northwest (Martin, 2006). In the Palaeocene, horses, primates and carnivores radiated worldwide (Archer et al. 1991). In Australia, the first Casuarinaceae appear in the early Palaeocene, and by the late Palaeocene Banksia and Eucalyptus first occur (Hill 1994).

By the Eocene Australia’s marsupials, bats, frogs and snakes became abundant (Archer et al. 1991). Rainforest dominated the continent during this period when the Poaceae first appear (Hill 1994). Temperatures rose into the early Eocene (consistent with a global trend; Zachos et al. 2008) but declined during the mid-late Eocene. The mid-late Eocene was characterised by generally lower average sea-surface temperatures (Gallagher and Holdgate 2000), although intervals of tropical and temperate conditions have been noted in the western half of the continent by Quilty (1994) and Aphthorpe (1988). The late Eocene–early Oligocene was characterised by cool and wet conditions, with many regions characterised by cool temperate rainforest (Benbow et al. 1995). Martin (2006) attributes this change to strengthening of the Antarctic Circumpolar Current reducing heat transfer from the equatorial latitudes to higher latitudes.

The cooling trend continued into the Oligocene, which is characterised by cool and dry ‘icehouse’ conditions (Moss and McGowan 2003), before a significant warming event at the end of the Late Oligocene. By the Oligocene, koalas, kangaroos and other modern marsupials were well established and there is evidence for diverse forest-dwelling fauna at this time (Archer et al. 1991). Evidence suggests that seasonality became important during the Oligocene, particularly in southeastern Australia.

In detail, regions of Australia show different local trends throughout the Palaeogene.

In northwestern Australia, the early Palaeocene was a time of relatively high rainfall, although total rainfall was variable and there is some evidence for local aridity in the north (Truswell and Harris 1982; Aphthorpe 1988). Macphail (1997) suggests the flora, and therefore climatic conditions, in northwestern Australia in the Palaeocene were similar to those in southern Australia. In the early Eocene, mean temperatures in the north increased and the arid conditions that developed in the early Palaeocene were enhanced. At the same time further south temperatures decreased and humidity increased (Martin 2006). Aphthorpe (1988) suggests that rainfall decreased into the late Eocene, although preservation of Nothofagus pollen suggests isolated pockets of rainforest remained at this time (Truswell and Harris 1982). In the middle Oligocene an extensive laterite formed in Western Australia associated with a drop in sea level and possibly a trend to seasonal humidity (Quilty 1994). By the late Oligocene, warm tropical conditions were in place across much of northwestern Australia (Quilty 1994).

In northeastern Australia climatic conditions in the Palaeocene ranged from subtropical to temperate (Feary et al. 1991). Temperatures continued to rise throughout the Palaeocene into the early Eocene until subtropical conditions were widespread. In the mid- to late Eocene mean temperatures began to decrease and temperate conditions prevailed (Feary et al. 1991). Rainforest persisted in isolated pockets. The Oligocene was a period of temperate conditions with decreasing mean annual temperatures. The late Oligocene climatic conditions have been debated in the literature. Arid conditions characterised by high average temperatures and low rainfall have been suggested by Megirian (1992), whereas Creaser (1997) suggested high rainfall conditions. Palynological evidence suggests warm climatic conditions in much of coastal Queensland at this time (Macphail et al. 1994).

In the early Palaeocene of central Australia warm temperate climatic conditions with high seasonal rainfall have been reported by Quilty (1994). Sluiter (1991) suggests mean annual temperature of 18–19°C and mean precipitation in excess of 1400 mm, significantly cooler and wetter than the modern climatic regime (Figure 12.1). The early Eocene basins throughout central Australia, including the Torrens and Lake Eyre Basins, record palynological evidence for rainforest flora but the general absence of Nothofagus suggests rainfall was seasonal and points towards a dry season. By the late Eocene, rainfall had decreased significantly (Truswell and Harris 1982).

In southeastern Australia the late Eocene to early Oligocene was a period of high rainfall conditions, with abundant Nothofagus in cool temperate rainforests (Benbow et al. 1995) and the accumulation of thick peat and coal sequences in the Gippsland Basin (e.g. Holdgate et al. 2009). Pole et al. (1993) suggest that the late Oligocene–early Miocene was the beginning of seasonal conditions in southeastern Australia based on the presence of both open and closed-forest flora in the sediments southeast of Melbourne. In the Murray Basin the presence of Nothofagus and swamp-forest taxa suggests dominantly high rainfall conditions (Martin 1993).

**Neogene**

The Neogene period includes the Miocene, Pliocene, Pleistocene and Holocene epochs, and spans the interval from 23.0 Ma to the present day. The first Acacia appear in the
early Miocene. The Poaceae, that first appeared in the Eocene, became common by late Miocene time (Hill 1994).

Miocene

A number of observations suggest significant warming from the late Oligocene into the early and middle Miocene across Australia. Generally the early to middle Miocene was characterised by widespread warm and wet conditions. Evidence for such early to middle Miocene ‘greenhouse’ conditions includes:

1. the occurrence of tropical foraminiferal taxa in Miocene marine sediments of southeastern Australia (e.g. Li et al. 1996; Gallagher et al. 2001; Gallagher and Gourley 2007) and the observed variation in stable isotope ratios of foraminifera globally (Zachos et al. 2001).

2. the development of a prominent, regionally extensive Miocene–Pliocene ferricrete weathering surface in many parts of Australia. Examples include the Karoonda Surface ferricrete in the Murray Basin (Firman 1973), a prominent ferricrete developed on Cambrian sediments of the Officer Basin of northern South Australia (Drexel and Preiss 1993); ferricretes in the Lake Eyre Basin (Alley 1998) and the Eucla Basin (Drexel and Preiss 1995); silcretes in central Victoria (Webb and Golding 1998); the Timboon surface ferricrete in western Victoria (Kentley 1971) and a prominent saprolite in the Cobar region of NSW (Smith et al. 2009).

3. palynological data suggesting the presence of extensive temperate rainforest (e.g. Kershaw et al. 1994; Macphail et al. 1994), particularly in eastern Australia, and the general absence of grasslands and/or open sclerophyll forest (Kershaw et al. 1994).

These ‘greenhouse’ conditions persisted through the early and middle Miocene. The late Miocene was again characterised by drier icerhouse conditions with a significant decrease in sea-surface temperatures (Gallagher et al. 2001; Zachos et al. 2001). In detail, there is considerable variation across the regions.

In northeastern Australia, Archer et al. (1989), Travouillon et al. (2009) and others use the presence of key rainforest-indicative mammals and high faunal diversity at Riversleigh to argue for a relatively warm and wet forest environment in that area in the early to middle Miocene. In the northwest of the continent, Macphail (1997) estimates that mean annual rainfall in the Miocene was in the range of 600–1500 mm and in parts of north-east Australia was greater than 3000 mm. From the late Palaeogene to the middle Miocene climate is thought to have become more strongly seasonal and there is palynological evidence for around a 50% reduction in mean annual rainfall from the early Miocene to the Pliocene (Macphail 1997). Pollen studies of late-Miocene-aged sediments offshore from northwestern Australia support this, suggesting that coastal vegetation was dominated by Casuarinaceae rather than rainforest species (Martin and McMinn 1994). Archer et al. (1991) suggests that tectonic collisions to the north of the Australian continent during the Miocene permitted the arrival of rodent species for the first time.

Central Australia was characterised by the presence of extensive shallow lakes in the early to middle Miocene (when it was situated around 40°45'S) pointing towards much higher rainfall than present. Evidence from the Lake Eyre Basin suggests widespread freshwater and ephemeral swamps (Alley 1998; Martin 2006). These wet conditions were accompanied by high humidity as indicated bystromatolitic sediments and ooidal grainstones (Martin 2006). Macphail et al. (1994) suggests there was also significant seasonality. By the late Miocene there is palynological evidence for increased dry open woodland and chenopod shrubland (Benbow et al. 1995).

In southeastern Australia pollen studies in the Gippsland Basin suggest a dominantly humid climate in the early-middle Miocene with mean average temperatures around 5°C higher than today and annual rainfall >1500 mm (Kershaw 1997). Similarly, in the Murray Basin the middle-late Miocene was a period of high diversity of plant species, suggesting widespread warm conditions (Martin 1993). In the late Miocene of southern Victoria there were small pockets of Nothofagus rainforest remaining but the general disappearance of rainforest taxa suggests a trend to increasingly arid conditions at this time (Kershaw et al. 1994; Martin 1994). These rainforest communities were replaced by widespread wet sclerophyll forest (Martin 1994).

Pliocene–Pleistocene

Across the continent, the Pliocene–Pleistocene was a time of highly variable climatic conditions and a trend to profound and dramatic long-term climatic change. In general, rainfall declined from the early Pliocene to the middle-late Pliocene and conditions became increasingly arid. This drying trend was briefly reversed in the early Pliocene with a wet and humid interval marked by the re-establishment of some rainforest communities in the Murray Basin (e.g. Martin 1989) and in the area around Lake George in southern New South Wales (e.g. McEwen Mason 1991). As in the late Miocene, rainforest was replaced by wet sclerophyll forest. By the late Pleistocene, fully arid conditions were widespread across much of the Australian continental interior (e.g. Kershaw et al. 1991; Wagstaff et al. 2001) and the first significant grassland communities were established (Hill 1994). Specialist grazing animal species evolved during the Pliocene. By the Late Pleistocene most megafauna species became extinct (Archer et al. 1991).

In southern Western Australia Lake Lefroy, part of a chain of playa lakes in the Yilgarn Craton, was a semi-permanent lake with seasonal dryness in the Pliocene (Zheng et al. 1998) suggesting a greater availability of water surface at that time. The early Pliocene sediments of nearby Lake Tay record a similar set of conditions and a palynological assemblage dominated by sclerophyll woodland with only minor rainforest taxa (Blatt 1981; Hill 1994). A detailed palynological study of paleolake Yallalie in southern Western Australia reveals a dominantly warm and seasonally wet climate in the middle Pliocene, from at least 3.51 Ma until 2.5 Ma (Dodson and Ramrath 2001). This record, however, was one which was interrupted by at least three distinct periods of arid conditions between 2.90 and 2.56 Ma, as indicated by an increase in the abundance of chenopod shrubland pollen (Dodson and Macphail 2004) and observed changes in sediment particle size (Dodson and Lu 2005). Dodson and Ramrath (2001) also suggest periods of greater seasonality between 2.96 and 2.82 Ma.

In central Australia, Lake Amadeus preserves a sequence of fluvial–lacustrine clays (the Uluru Clay) of Pliocene age, suggesting the presence of perennial surface water at that time. The Uluru Clay is overlain by the Winmatt Beds, a sequence of saline
In southeastern Australia, the earliest evidence for early Pleistocene conditions is from around 2.5 million years ago (c. 2.5 Ma). The earliest known flora from this period includes acacias and eucalypts, suggesting a climate similar to modern-day subtropical regions. However, there is some evidence for cooler and wetter conditions in the early Pleistocene, with increased rainfall and cooler temperatures compared to the late Pleistocene and Holocene.

In the early Pleistocene, Australia was characterized by a variety of vegetation types, including savannas, woodlands, and forests. The early Pleistocene climate was warmer and wetter than the late Pleistocene, with increased rainfall and average temperatures. These conditions are reflected in the distribution and diversity of plant species found in the early Pleistocene.

The early Pleistocene is marked by the development of the Nullarbor Plain and the formation of the Murray-Darling Basin. These geological events played a significant role in shaping the landscape and influencing the distribution of plant species and ecosystems.

In conclusion, the early Pleistocene in southeastern Australia was a period of high biodiversity and environmental diversity, with a climate that was generally warmer and wetter than the late Pleistocene and Holocene. The early Pleistocene was a time of significant environmental change, with the development of new ecosystems and the evolution of new species.
suggesting wet and humid conditions until at least 1.6 Ma. By the middle Pleistocene there is evidence for a change to more arid conditions. For example, Wagstaff et al. (2001) present pollen data from western Victoria demonstrating widespread dry land vegetation at this time, while White and Mitchell (2000) suggest the widespread development of coastal dunes at this time in eastern Victoria reflected dry conditions with limited vegetation development. A trend to arid climatic regimes is also suggested by the dominantly carbonate mineralogy of the youngest Lake Bungunnia sediment, the Bungunnia Limestone (McLaren and Wallace 2010). This sediment is younger than the main sedimentary fill of the lake and is therefore younger than 1.2 Ma. Precipitation of evaporitic minerals such as gypsum and magnesite points to profound change in climatic conditions at some time in the Plio-Pleistocene.

Late Pleistocene

There is abundant evidence for pronounced arid glacial and wet interglacial cycles within the late Pleistocene, particularly from high-resolution pollen and isotope records. During glacial episodes increased aeolian sedimentation is noted while from one glacial cycle to the next a trend to increasing severity of aridity is observed. Pollen data reviewed by Kershaw et al. (2003) shows a significant trend towards arid climates beginning around 350 ka. Heise (1994) notes a significant increase in the long-wavelength dust component in sediments of the Tasman Sea, between Australia and New Zealand, at around the same time. Kershaw and Nanson (1993) suggest the greatest aridity occurred between 27 and 17 ka.

Onset of aridity

The development of arid conditions in Australia is thought to largely reflect global cooling in the Cenozoic; however, the nature and timing of the shift to arid climatic conditions across the continent has remained highly controversial. Unfortunately, there are very few continuous sequences that provide a window into the key period from the wet and humid conditions of the late Miocene to the fully arid conditions of the early Pleistocene. Consequently, the timing and mechanism of climatic change in this interval has remained an area of active research endeavour and there has been considerable debate in the literature.

A number of scenarios have been proposed for the timing of initiation and spread of arid climatic conditions. Beard (1977) suggested the arid shift was simply a product of northward tectonic motion bringing the northwest of the continent into high-pressure atmospheric conditions. Kemp (1978) suggested the formation of the Antarctic Circumpolar current following the break-up of Australia and Antarctica was the greatest influence on climate and that arid conditions were initiated soon after break-up and the establishment of this oceanic circulation system. Consequently, Kemp (1978) suggested aridity began in the centre of the continent in the late Eocene and expanded toward the coastal regions.

Our contemporary understanding of the trend to arid climatic regimes in the Cenozoic is based largely on the work of Bowler (1976, 1982) and Martin (1978) together with a large body of more recent work that builds upon and extends these earlier observations (e.g. Chen and Barton 1991; Kershaw et al. 1991; Macphail 1997; Dodson and Macphail 2004; Fujioka et al. 2009). Based principally on the apparent timing of contraction of large lakes, as well as documented vegetation changes, it is now generally accepted that the general trend toward aridification of the Australian continent began sometime in the late Miocene, and increased in amplitude into the Plio-Pleistocene. Bowler (1982) suggested arid climatic conditions developed first in southern Australia with aridity subsequently expanding northwards. Globally, the Plio-Pleistocene is known to be a time of great climatic change (e.g. Clark et al. 2006) and a trend to increasingly arid climates across the globe in this period is reflected by the development of the Atacama Desert around 3 Ma (Hartley and Chong 2002), major step-like increases in aridity in Africa around 2.8 Ma and 1.7 Ma (deMenocal 2004) and the establishment of a permanent northern hemisphere ice sheet (e.g. Lear et al. 2000; Kuhlmann et al. 2006).

In detail, geological observations suggest that there was considerable diachronity in the timing of development of arid conditions across the Australian continent. In this section we summarise current knowledge of the timing and origins of this critical climatic shift.

Northern and western Australia

The identification of three distinct episodes of short-lived aridity, marked by the first appearance of semi-arid zone flora and halophytic diatoms, between 2.50 and 2.56 Ma in palaeolake Yallalie led Dodson and Macphail (2004) and Dodson and Lu (2005) to suggest that a trend to increasing amplitude arid climatic cycles in southern Western Australia began around 2.5 Ma. Lake Lefroy preserves evidence of a significant hydrological transition from the freshwater Revenge Formation to the evaporitic and gypsum-limestone units of the Roysalt Formation; Zheng et al. (1998) reported magnetostratigraphic data to suggest this transition, and by inference the onset of fully arid conditions, occurred within the Brunhes Normal Polarity Chron at <780 ka. However, the Pleistocene age for the onset of arid conditions presented by Zheng et al. (1998) is very different from an early Pliocene age suggested by a palynological study of the same sequence by Clarke (1993) and the magnetostratigraphic constraints continue to be debated (e.g. Clarke and Pflaum 2002).

Central Australia

For central Australia, Chen and Barton (1991) present magnetostratigraphic data for the sediments of Lake Amadeus to constrain the time of onset of aridity, as indicated by the transition from the perennial lacustrine Uluru Clay to the saline sediments of the Winton Beds. Chen and Barton’s (1991) magnetostratigraphic data suggests that arid climatic conditions began at either 0.9 Ma or 1.6 Ma, significantly earlier than the Brunhes–Matuyama transition. English et al. (2001) support the interpretation of a c. 1 Ma age for this change and suggest it is the earliest expression of arid climates in central Australia. In Lake Lewis the transition from perennial lacustrine sediments to saline
sediments seems to occur much later, at a time well into the Brunhes chron. English et al. (2001) suggest this difference reflects local hydrology, including the catchment/lake area ratio, and the type of feeder drainage systems for each of the lakes.

Cosmogenic $^{10}$Be and $^{26}$Al measurements from desert dunes in the western Simpson Desert of central Australia suggest an increase in amplitude of aridity at c. 1 Ma (Fujikawa et al. 2009). In an earlier study, Fujikawa et al. (2005) presented cosmogenic $^{3}$He and $^{10}$Be data to suggest the first stony deserts developed in central Australia around 2–4 Ma.

Southeastern Australia

Two particularly influential contributions to our understanding of the onset of aridity in Australia are those of Bowler (1976, 1982). These contributions use the stratigraphic record of Lake Bungunnia in southeastern Australia (Figure 12.3) to understand the continental shift to arid climatic regimes. Although terrestrial sediments generally provide a more fragmented record of palaeoclimate (Martin 2006) the sediments of Lake Bungunnia provide one of the most continuous records of terrestrial sedimentation in the critical Plio-Pleistocene interval. Lake Bungunnia is also important because it was areally extensive but shallow, and so once formed would have been particularly sensitive to climatic changes in terms of total precipitation and evaporation over the lake as well as volumes and rates of discharge from feeder river systems. Following the work of Bowler (1982) the stratigraphic sequence preserved in Lake Bungunnia has become effectively a type section for understanding the onset of arid conditions in the Australian continent. Sediments of Lake Bungunnia consist of the variable (1–40 m) thickness Blanchetown Clay, the main depositional unit of the lake, and a thin (1–3 m) younger lacustrine carbonate unit, termed the Bungunnia Limestone (Firman 1965; Brown and Stephenson 1991). McLaren and Wallace (2010) have shown that the Blanchetown Clay is comprised of a number of distinct sedimentary units, which can be correlated regionally: (1) well-sorted massive to cross-laminated sands with interbedded clay; (2) grey-green to red-brown laminated to unlaminated clay; and (3) laminated to massive grey-white quartz-silt (Nampoo Member of McLaren et al. 2009; Figure 12.4).

Remnants of megalake Bungunnia remain in the modern environment in the form of small saline playas (Howchin 1929) and it is this dramatic contraction of the lake that has previously been proposed to herald the onset of fully arid climatic regimes (Bowler 1982). The paper by An et al. (1986) subsequently provided magnetostratigraphic data to suggest that the age of the youngest Lake Bungunnia sediments, and hence the time of onset of aridity, was around the Brunhes–Matuyama transition (c. 700–800 ka). However, magnetostratigraphic data presented by McLaren et al. (2009) suggest the Blanchetown Clay was deposited entirely within the Matuyama Reversed Chron. Based on the known thickness of normal polarity sediment within the Blanchetown Clay attributed to deposition during the Olduvai Normal Chron, McLaren et al. (2009) have suggested that the oldest lake sediments were deposited at 2.4 Ma and the youngest Blanchetown Clay is as old as 1.2 Ma; significantly older than the age of reported by An et al. (1986).

In addition to the improved magnetostratigraphic constraints presented by McLaren et al. (2009), a re-evaluation of the stratigraphy of Lake Bungunnia presented by

McLaren and Wallace (2010) highlights two observations that are central to understanding the trend to arid climatic conditions in southeastern Australia. These observations suggest the onset of arid conditions was stepwise and earlier than previously suggested:

1. Recognition of the Nampoo Member aeolian-lacustrine silt as a regionally extensive correlative unit across the Lake Bungunnia basin. The morphology of grains within the Nampoo Member suggest that it represents wind-blown dust and/or loess (Figure 12.4). The major grain size mode around 20 μm is interpreted to represent 'classic' loess (e.g. Pye

Figure 12.4 (a) Stratigraphic section of Blanchetown Clay from Nampoo Station with age information derived from palaeomagnetic analyses (modified from McLaren et al. 2009 and McLaren and Wallace 2010); (b) outcrop of Blanchetown Clay showing Nampoo Member (NMBr) at Lake Tyrrell; (c) outcrop of Blanchetown Clay showing Nampoo Member (NMBr) at Rufus River; (d) average particle size distributions, obtained using a LS Coulter Particle Size Analyser, for the Nampoo Member silt from Nampoo Station.
1987), while the continuum of grains to <1 μm, with secondary mode between 4 μm and 6 μm, may represent a high-level long-wavelength dust component or rainout of finer particles adhered to the coarse silt particles (Hesse and McIntosh 2003). The silt-sized grains may have been sourced from either (1) distal ‘desert loess’, formed and/or stored elsewhere in the continent, possibly in the Central or Western Australian basins or (2) from the floor of Lake Burgunia itself, during a dry, low lake-level episode. Similar origins have been proposed for loess in the Saharan desert (e.g. Evans et al. 2004). Regardless of source mechanism, deposition of the Nampoo Member silt-sized grains must reflect significant climate change, heralding a major transition from the wet climatic regimes responsible for formation of the lake, to cold and arid climatic regimes with high average wind speeds to account for both formation of the desert loess in the basin or in surrounding upland regions and/or its transportation to the Lake Burgunia basin. The loess of the Nampoo Member may be the first sedimentary evidence of the development of extensive desert dune systems in central and/or western Australia. Indeed as noted by Bowler (1976) ‘the presence of aeolian sediments . . . as dust layers deposited from suspension, provides cogent evidence of arid environments’. Its recognition in Lake Burgunia constrains a major step in the aridification of the continent. Constraints from magnetostratigraphy suggest this change occurred around 1.5–1.4 Ma (McLaren et al. 2009). This age is consistent with previously documented evidence of wet climates around 1.6 Ma (Sniderman et al. 2007) and dry climates at 1.2 Ma (Wagstaff et al. 2001).

2. Recognition of distinct terrace levels within the basin, which are capped by an ephemeral lake facies of varying lithology. The Burgunia Limestone is preserved on terraces ranging over 20 m in elevation providing a record of decreasing lake level through time (McLaren and Wallace 2010). This change from clastic to carbonate precipitation records a second major step in the aridification of the continent. The last stages of the evolution of Lake Burgunia are interpreted to reflect fluctuation between (1) a steady-state open lake system where inflow and outflow (via evaporation and fluvial outwash) were matched and shoreline erosion was occurring within the basin to produce the well-formed terraces, and (2) a closed lake system with high evaporation and no overflow that resulted in carbonate precipitating conditions and the deposition of the Burgunia Limestone (McLaren et al. 2012). In this interpretation, (1) is likely to correspond with significantly wetter Late Pleistocene interglacial conditions and (2) with arid glacial conditions. Moreover, the sequence of changing mineralogy of the Burgunia Limestone from calcite and aragonite-dominated to dolomite, gypsum and magnesite-dominated as lake level decreases suggests an increasingly saline and evaporitic influence over time. This is likely to represent an overall trend to increasing aridity, as well as a decrease in the magnitude of fluvial recharge as arid climatic conditions became amplified.

Discussion and conclusion

The Australian continent records a long and complex record of climatic change with many currently arid regions having experienced much wetter conditions in the geological past. To better understand recent ecological and environmental changes, it is essential to understand the timing and origins of this arid shift. Across the continent, a variety of observations give an age of onset of arid climatic conditions between 2.5 Ma and <780 ka. However it is difficult to directly compare previous estimates as definitions of ‘fully arid’ and ‘trend to arid climates’ to which these dates are linked are not necessarily the same from author to author. Moreover, the available data are from a small subset of the area of the continent as a consequence of the limited preservation of sedimentary sequences and/or landforms spanning the appropriate intervals. Available observations do suggest, however, that the onset of arid conditions in the Australian continental interior may have been diachronous. It almost certainly occurred in a step-wise fashion and less rapidly than previously thought.

The stratigraphic sequence represented by the sediments of Lake Burgunia preserves what is at this time the most complete stratigraphic record of climatic change in the Plio-Pleistocene in Australia. It suggests that there was a progressive step-wise increase in aridity in southern Australia. The 1.4–1.5 Ma age of the aeo-lacustrine silts of the Nampoo Member of the Blanchetown Clay dates a major climatic shift across the continent and a major step in the trend to arid climatic regimes. It may also indicate an earlier onset of arid conditions in the centre and west of the continent than in the southeast. Recognition that a major step in the aridification of Australia occurred around 1.5 Ma is consistent with global climate trends and is highly significant for our understanding of climate change in the Plio-Pleistocene. Following this major step toward arid climatic conditions, the record of carbonate precipitation within the Burgunia Limestone suggests a progressive increase in the amplitude of arid climatic cycles, which culminates probably around the middle Pleistocene. Unfortunately, no biostratigraphic or geochronological techniques have yielded precise age constraints for the Burgunia Limestone, however the onset of fully arid conditions must be more recent than c. 1.2 Ma.

The work of Chen and Barton (1991) in central Australia and that of Zheng et al. (1998) in western Australia are the other major studies to attempt to directly date sediments spanning the transition from wet to arid climates. The c. 1.5 Ma age for the onset of arid conditions in southeastern Australia is similar to one interpretation of the magnetostratigraphic data from central Australia presented by Chen and Barton (1991) suggesting isochronous continent-scale climatic change leading up to the mid-Pleistocene transition. However, Chen and Barton’s (1991) alternative interpretation of a 0.9 Ma age for the onset of aridity in central Australia cannot be discounted based on the available data. Moreover, in western Australia a significant range of ages has been presented for the onset of arid conditions. These data suggest that there is at least some spread in the age of onset of arid climatic conditions across the continent and in many ways this is not unexpected given the size of the continent and the number of different climate influences. Importantly, the new data from Lake Burgunia are of a higher sensitivity compared to other datasets and so have the capacity to track step-wise changes that may have been missed in other studies. Moreover, the fact that other studies are less sensitive means that it is not clear whether the age data obtained from them is faithfully recording the age of transition of climatic regime or one step in what may plausibly be a series of step-wise changes.

The cause of the trend to arid climatic conditions in Australia is also debated. The trend to arid climatic regimes must, at least in part, reflect global cooling in the Cenozoic, the
result of increasing total global ice volumes (e.g. Head and Gibbard 2005) as well as changes in relief, such as the uplift of the Tibetan Plateau (e.g. Ruddiman and Kutzbach 1989). In Australia, change in this interval must be closely tied to ice build-up in Antarctica and major changes in atmospheric circulation following intensification of the Antarctic Circumpolar current. Evidence for a step-wise change may suggest a complex interplay between global climate cycles, regional climate drivers, such as ENSO activity, and local factors, including the impact on total rainfall in the continental interior of the retreat of the Miocene sea from the Murray Basin (Kershaw et al. 1994) and the uplift of the Eastern Highlands beginning in the late Eocene and continuing into the Pliocene (Holdgate et al. 2008).

In terms of most recent climate change in the late Pleistocene, Hesse et al. (2004) suggest that in northern Australia changes in the location and intensity of tropical convergence have had the most influence, while in southern Australia changes in the SAM (rather than the subtropical ridge) have had a more significant impact on climate. Kershaw et al. (2003) suggest latest Pliocene and Holocene drying was the result of atmospheric changes due to ongoing collision in southeast Asia, the effect of ice volume induced global glacial-interglacial cyclicity, as well as changes in the frequency and activity of ENSO.

Although the new data from Lake Bungunnia has significantly improved our understanding of the timing of the onset of arid climatic conditions, there remains much work to be done refining the timing of the change across the continent as well as the factors that were responsible for it.

References


The development of a climate: an arid continent with wet fringes


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