

# Climate change and Australia: Trends, projections and impacts

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**Abstract** This review summarizes recent research in Australia on: (i) climate and geophysical trends over the last few decades; (ii) projections for climate change in the 21st century; (iii) predicted impacts from modelling studies on particular ecosystems and native species; and (iv) ecological effects that have apparently occurred as a response to recent warming. Consistent with global trends, Australia has warmed  $\sim 0.8^{\circ}\text{C}$  over the last century with minimum temperatures warming faster than maxima. There have been significant regional trends in rainfall with the northern, eastern and southern parts of the continent receiving greater rainfall and the western region receiving less. Higher rainfall has been associated with an increase in the number of rain days and heavy rainfall events. Sea surface temperatures on the Great Barrier Reef have increased and are associated with an increase in the frequency and severity of coral bleaching and mortality. Sea level rises in Australia have been regionally variable, and considerably less than the global average. Snow cover and duration have declined significantly at some sites in the Snowy Mountains. CSIRO projections for future climatic changes indicate increases in annual average temperatures of  $0.4\text{--}2.0^{\circ}\text{C}$  by 2030 (relative to 1990) and  $1.0\text{--}6.0^{\circ}\text{C}$  by 2070. Considerable uncertainty remains as to future changes in rainfall, El Niño Southern Oscillation events and tropical cyclone activity. Overall increases in potential evaporation over much of the continent are predicted as well as continued reductions in the extent and duration of snow cover.

Future changes in temperature and rainfall are predicted to have significant impacts on most vegetation types that have been modelled to date, although the interactive effect of continuing increases in atmospheric  $\text{CO}_2$  has not been incorporated into most modelling studies. Elevated  $\text{CO}_2$  will most likely mitigate some of the impacts of climate change by reducing water stress. Future impacts on particular ecosystems include increased forest growth, alterations in competitive regimes between C3 and C4 grasses, increasing encroachment of woody shrubs into arid and semiarid rangelands, continued incursion of mangrove communities into freshwater wetlands, increasing frequency of coral bleaching, and establishment of woody species at increasingly higher elevations in the alpine zone. Modelling of potential impacts on specific Australian taxa using bioclimatic analysis programs such as BIOCLIM consistently predicts contraction and/or fragmentation of species' current ranges. The bioclimates of some species of plants and vertebrates are predicted to disappear entirely with as little as  $0.5\text{--}1.0^{\circ}\text{C}$  of warming.

Australia lacks the long-term datasets and tradition of phenological monitoring that have allowed the detection of climate-change-related trends in the Northern Hemisphere. Long-term changes in Australian vegetation can be mostly attributed to alterations in fire regimes, clearing and grazing, but some trends, such as encroachment of rainforest into eucalypt woodlands, and establishment of trees in subalpine meadows probably have a climatic component. Shifts in species distributions toward the south (bats, birds), upward in elevation (alpine mammals) or along changing rainfall contours (birds, semiarid reptiles), have recently been documented and offer circumstantial evidence that temperature and rainfall trends are already affecting geographic ranges. Future research directions suggested include giving more emphasis to the study of climatic impacts and understanding the factors that control species distributions, incorporating the effects of elevated  $\text{CO}_2$  into climatic modelling for vegetation and selecting suitable species as indicators of climate-induced change.

**Key words:** Australia, climate change, climate projections, rainfall, species impacts, temperature.

## INTRODUCTION

Climate change as a result of the enhanced greenhouse effect is no longer a hypothesis. The global average surface temperature of the Earth has increased by  $0.6 \pm 0.2^{\circ}\text{C}$  since 1900 and it is likely that the rate and

duration of the warming are greater than at any time in the past 1000 years (IPCC 2001a). The warming trends, together with changes in rainfall and sea level, appear to be now discernible above natural decadal- and century-scale variability. The most recent report from the Intergovernmental Panel on Climate Change (IPCC 2001a) concluded 'most of the observed warming over the past 50 years is likely to have been

due to the increase in greenhouse gas concentration'. There is also clear evidence that recent climate trends have already had significant impacts on species and ecosystems.

This review summarizes recent Australian research on: (i) climate and geophysical trends over the last century; (ii) projections of future climate change; (iii) potential impacts of climate change for particular species and ecosystems; and (iv) recent impacts of climate change on biological systems. It also identifies some of the major gaps in our knowledge to date and highlights some potential research directions for the future.

The review focuses on research for particular locations and native species. It does not cover all the potential impacts climate change may have on Australian ecosystems as several general reviews of this nature have previously been published (Bouma *et al.* 1996; Basher *et al.* 1998; Pittock & Wratt 2001). For managed ecosystems and related areas readers are also referred to the following reviews: agriculture (Campbell *et al.* 1996; Howden *et al.* 1999f; CSIRO 2001b), forestry (Howden & Gorman 1999; Howden *et al.* 1999e), and pests and diseases (Sutherst *et al.* 1996; Chakraborty *et al.* 1998; Russell 1998; Walker 1998; Sutherst 2001). The implications of climate change for conservation and conservation policy have also been reviewed (Hughes & Westoby 1994; Williams *et al.* 1994; Pouliquen-Young & Newman 2000).

## RECENT CLIMATE AND GEOPHYSICAL TRENDS IN AUSTRALIA

### Temperature

Australia's continental average temperature has increased by approximately 0.8°C since 1910 (Collins 2000). Most of this rise occurred after 1950, with 1998 being the warmest year, and the 1990s and 1980s being the warmest and second warmest decades, respectively (Collins 2000). These trends are consistent with those measured globally. Since 1951, mean temperatures have increased 0.1–0.2°C per decade over most of Australia, with the greatest warming inland, particularly in Queensland and the southern half of Western Australia (WA), although some cooling has occurred in southern Queensland and New South Wales (NSW) (Suppiah *et al.* 2001). The recent warming has been greatest in winter and spring (Hulme & Sheard 1999).

Night-time temperatures have increased more than daytime temperatures (~0.96°C per century for minima *vs.* ~0.56°C per century for maxima; Suppiah *et al.* 2001), especially in the northern half of the continent. Consequently, the diurnal temperature range (DTR) has decreased, consistent with global

trends (Easterling *et al.* 1997). There is a suggestion that increased overnight temperatures are associated with increased nocturnal cloud cover (Collins & Della-Marta 1999).

Associated with increases in average temperatures, occurrences of extreme warm events have generally increased over the period 1957–1996, whereas the numbers of extremely cool events have decreased (Plummer *et al.* 1999; Collins *et al.* 2000). The trend to warmer temperatures appears to have already reduced frost frequency and duration (Stone *et al.* 1996). Further, high temperatures may have contributed to the severity of the 2002 drought. Maximum temperatures during 2002 were more than 1°C higher than during any of the five major droughts since 1950 (Karoly *et al.* 2003). At Griffith, in the Murray–Darling Basin, for example, a combination of temperatures 2.14°C higher than the annual average, coupled with the lowest March–November rainfall recorded (45% of the annual average) resulted in the highest rates of evaporation on record, 10% higher than in previous droughts (Karoly *et al.* 2003).

### Rainfall

Australian rainfall has increased slightly over the past century, and more so in summer than winter (Collins & Della-Marta 1999; Hennessy *et al.* 1999). On a continent-wide basis, this trend is not statistically significant because of high interannual variability. On a regional and seasonal basis, trends in rainfall are clearer. Annual total rainfall has risen by approximately 15% in NSW, South Australia (SA), Victoria and the Northern Territory (NT), with little change in the other states. South-west WA has become 25% drier in winter, with most of the decline between 1960 and 1972 (Hennessy *et al.* 1999; Hennessy 2000).

Higher Australian rainfall since 1910 is linked to increases in both heavy rainfall events and the number of rain days, with some regional exceptions (Hennessy *et al.* 1999; Haylock & Nicholls 2000). On average, the number of wet days has increased by approximately 10% (despite the significant 10% decline in south-west WA), although this figure rises to nearly 20% in parts of NSW and NT (Hennessy *et al.* 1999). Significant increases of heavy rainfall events in summer, especially in the east and north, and decreases in south-west WA have occurred (Hennessy *et al.* 1999). In central Australia, reconstruction of ancient flood sequences from sediment deposits in the gorge of the Finke River show that four of the eight largest flood events in the last 800 years have occurred since 1967 (Pickup 1991).

Regional decreases in rainfall in western Victoria have apparently affected the hydrological budgets of several enclosed lakes (Jones *et al.* 2001). Levels of three lakes have fallen 15–20 m since the 1840s.

Historical surveys show that the fall in water levels preceded the major land use change after European occupation and are likely to be due to local decreases in rainfall, together with increases in solar radiation.

### Sea temperature

Sea surface temperatures in many tropical regions have increased by almost 1°C over the past 100 years (some tropical seas up to 2°C) and are currently increasing ~1–2°C per century (Hoegh-Guldberg 1999). In the Great Barrier Reef, sea surface temperatures have increased 0.46°C per century in the north to 2.59°C per century in the waters off Townsville. Sea surface temperatures on the Great Barrier Reef in early 1998 were the warmest in the past 95 years of instrumental record (Lough 2000) and were associated with significant coral bleaching (see 'Recent impacts' section).

### El Niño Southern oscillation

The El Niño Southern Oscillation (ENSO) phenomenon has a strong influence on climate and sea level variability in many parts of Australia (Suppiah *et al.* 2001). Since the 1970s, El Niño events have apparently increased and La Niña events decreased. Analyses by Trenberth and Hoar (1996, 1997) indicate that both this trend, and the prolonged 1990–1995 ENSO, have a probability of natural occurrence of about once in 2000 years. These authors concluded that global warming is a more likely explanation for the observed trends than natural decadal-scale variability, although others (e.g. Allan & D'Arrigo 1999) have questioned this interpretation.

In addition to possible changes in the frequency of ENSO, the relationship between ENSO, annual temperature and rainfall also changed in the early 1970s (Nicholls *et al.* 1996). Since then, for any value of the Southern Oscillation Index (SOI) or rainfall, maximum temperature has tended to be higher than previously recorded. Likewise rainfall, for any value of SOI, has tended to be greater than would have been expected for such an SOI value previously. Nicholls *et al.* (1996) concluded that differential warming in the Indian Ocean, relative to the Pacific Ocean, may be the cause of these changes.

### Tropical cyclones

The number of tropical cyclones in the Australian region has apparently declined since the start of reliable satellite observations (1969/1970) but the number of more intense cyclones has increased slightly (10–20%; Nicholls *et al.* 1998).

### Sea level

Recent analyses of sea level trends from 23 locations around Australia indicated values from  $-0.95 \text{ mm year}^{-1}$  for Geraldton to  $+2.08 \text{ mm year}^{-1}$  for Port Adelaide (Mitchell *et al.* 2000). The average trend from these analyses was  $+0.3 \text{ mm year}^{-1}$  and that for the Pacific region was  $0.8 \text{ mm year}^{-1}$ , substantially less than the Intergovernmental Panel on Climate Change (IPCC) global estimate of  $1\text{--}2 \text{ mm year}^{-1}$  (Mitchell *et al.* 2000). Mitchell *et al.* (2000) found no evidence yet of a substantial acceleration of sea level rise, in contrast to expectations from global circulation models. Another study that focused only on SA data also found sea level rises thus far to be very modest ( $+0.08$  to  $+0.76 \text{ mm year}^{-1}$ ) once adjustments for geological, isostatic and local anthropogenic effects had been made (Harvey *et al.* 2002).

### UV-B and ozone

Surface UV-B radiation has increased by approximately 6% in Southern Hemisphere mid-latitudes and by 130% in the Antarctic, relative to 1970s values (Madronich *et al.* 1998). Over the Antarctic, the springtime ozone 'hole' expanded to its largest size on record in the spring of 2000, peaking at 28 million km<sup>2</sup> early in the season (Watkins 2001). Current best estimates suggest a slow recovery to preozone depletion levels during the next half-century (Madronich *et al.* 1998).

### Snow

A significant decline in mean snow cover between the periods 1960–1974 and 1975–1989 was recorded at Spencers Creek, in the NSW alpine region (Osborne *et al.* 1998). At this location there were a total of 2283 metre-days of snow in the 1960s, with a 20% reduction in the 1970s (1843 metre-days) and a further 10% in the 1980s and 1990s (1655 and 1706 metre-days, respectively; Green & Pickering 2002). The last 5 years of the 1990s had the lowest 5-year average of the series, 7.5% less than the previous lowest 5 years, and 53% less than the highest 5 (Green & Pickering 2002).

## PROJECTIONS OF FUTURE AUSTRALIAN CLIMATE

The Climate Impact Group published the following climate projections in 2001 (CSIRO 2001a). For details on the methods used to construct the projections see Whetton 2001). Finer resolution models

have also been developed for some regions (see Mitchell *et al.* 1994 for WA; Hennessy *et al.* 1998 for NSW; Suppiah *et al.* 1998 for northern Australia; Walsh *et al.* 2001 for Queensland; Whetton *et al.* 2002 for Victoria; and Whetton *et al.* 2001 for south-eastern Australia).

### Temperature

By 2030, annual average temperatures are projected to be 0.4–2.0°C higher over most of Australia (relative to 1990), with slightly less warming in some coastal areas and the potential for greater warming in the north-west. By 2070, annual average temperatures may increase by 1.0–6.0°C. The range of warming is projected to be greatest in spring and least in winter. The models suggest that increases in daily maximum and minimum temperature will be similar to the changes in average temperature. This contrasts with the greater increase in minima than maxima observed over Australia in the 20th century, as described in the previous section. Along with changes in average temperatures, changes in extreme temperatures are also predicted.

### Rainfall and El Niño Southern oscillation

There is a wide range of uncertainty in predictions by CSIRO of future rainfall trends, because of disagreement between the two types of global circulation models used. Whereas slab-ocean models indicate increases in summer rainfall, coupled-ocean models indicate decreases, except in the south-east and south-west where wetter conditions are predicted to be equally likely. Another limitation in predicting future rainfall is that global circulation models are yet to fully incorporate accurate simulations of ENSO (IPCC 2001a). Some modelling, however, indicates greater hydrological extremes as a result of more intense rainfall in La Niña years and more intense drought resulting from higher rates of evaporation in El Niño years (Walsh *et al.* 2001).

Overall, the CSIRO (2001a) scenarios indicate that annual average rainfall may decrease in the south-west (–20 to +5% by 2030 and –60 to +10% by 2070), and in parts of the south-east and Queensland (–10 to +5% by 2030 and –35 to +10% by 2070). In some other areas, including much of eastern Australia, projected ranges are –10 to +10% by 2030 and –35 to +35% by 2070. The ranges for the tropical north (–5 to +5% by 2030 and –10 to +10% by 2070) represent little change from current conditions. In winter and spring most locations tend towards decreased rainfall (or are seasonally dry) with typical ranges of –10 to +5% by 2030 and +5 to +10% by 2070. Projected decreases are stronger in the south-west (–20 to +5% by 2030 and –60 to +10% by 2070). Tasmania tends toward

increases in winter (–5 to +20% by 2030 and –10 to +60% by 2070). In summer and autumn, projected rainfall ranges from 10 to +10% by 2030 and –35 to +35% at most locations.

Modelling also indicates that return times for heavy rainfall events will decrease (Groisman *et al.* 1999) and flooding will increase in some regions (Whetton *et al.* 1993). For example, increases in the magnitude and frequency of flood events in the Parramatta and Hawkesbury-Nepean Rivers are predicted (Schreider *et al.* 2000); return times for a one in a 100-years flood may be reduced to one in 44 years in the Upper Parramatta, one in 35 years for the Hawkesbury-Nepean and one in 10 years for the Queanbeyan River.

### Evaporation, moisture balance and runoff

The CSIRO models indicate increases in potential evaporation of up to 8% per degree of global warming over most of Australia, and up to 12% over the eastern highlands and Tasmania with increases tending to be larger where there is a corresponding decrease in rainfall. The resulting scenario is a decrease in annual moisture balance over the continent averaging from ~40–120 mm per degree of global warming, depending on the model used. This represents decreases of 15–160 mm by 2030 and 40–500 mm by 2070 and indicates that much of the continent will be subject to greater moisture stress in the future (CSIRO 2001a). Previous modelling by Kothavala (1999) also indicates more severe drought in north-east and south-east Australia. Arnell (1999) found marked decreases in runoff over most of mainland Australia but some increases for Tasmania. For the Murray–Darling Basin, Arnell found decreases in mean flow of 12–35% by the 2050s. More recent modelling of the Murray–Darling catchment indicates decreases in streamflow to Burrendong Dam of 0–15% by 2030 and 0–35% by 2070 (Jones *et al.* 2002). Modelling by Chiew and McMahon (2002) suggests that the annual runoffs to catchments on the north-east coast and east coast could change by –5 to +15% and ±15%, respectively, by 2030. The annual runoff in the south-east could decrease by up to 20%, and in Tasmania a ±10% change by 2030 is possible. A decrease in the annual runoff in catchments in the Gulf of St Vincent, SA, of up to 25% by 2030, and a change of –25 to +10% in the runoff on the south-west coast are also indicated (Chiew & McMahon 2002).

### Snow

A number of modelling studies in Australia have indicated that marked reductions in snow cover and duration are likely in the future (Galloway 1988; Whetton *et al.* 1996; Whetton 1998). Whetton (1998)

defined a best case scenario as +0.3°C by 2030, and +1.3°C by 2070, with no change in precipitation (CSIRO 1996). Under this scenario, the area covered by snow was projected to contract 18% by 2030, and 39% by 2070. Under a worst case scenario, defined as +1.3°C by 2030 with -8% precipitation, and +3.4°C and -20% precipitation by 2070, snow cover was projected to contract 66% by 2030 and 96% by 2070.

Snow duration may also decline. Currently, the Australian Alps experience a significant winter snow cover lasting, in most years, from a few weeks at elevations of 1200–1400 m, and up to 4 months on the higher peaks (1800–2200 m). Under the best case scenario, snow duration in 2030 is projected to decline by approximately 10 days in 2030 and 20 days in 2070. Under the worst case scenario, snow duration is projected to be zero days of snow cover at ~1400 m and approximately 40–50 days shorter than current duration at higher sites. By 2070, simulated durations were approximately zero up to 1800 m and approximately 100 days shorter than present at higher elevations (Whetton 1998). Under this scenario there would be insufficient natural snow for viable ski operations by 2030 at the lower Australian resorts (e.g. Mt Baw Baw), and at all resorts by 2070 (Whetton 1998).

### Tropical cyclones

The behaviour of tropical cyclones under enhanced greenhouse conditions has been the subject of considerable speculation but projections are difficult because tropical cyclones are not well resolved by global or regional climate models (Pittock *et al.* 1996; Walsh & Pittock 1998). Present indications are that modest to moderate (0–20%) increases in average and maximum cyclone intensities are expected by the end of the century in some regions (Walsh & Ryan 2000). Future changes in frequency will be modulated by changes in ENSO. Tropical cyclones are associated with the occurrence of oceanic storm surges, gales and flooding rains in northern Australia and the frequency of these events would rise if the intensity of tropical cyclones increases. Projected rises in average sea level will also contribute to more extreme storm surges (CSIRO 2001a). Modelling by McInnes *et al.* (2000) indicates that if tropical cyclone intensity around Cairns increased up to 20% by 2050, the flood level associated with a one in 100 years flood would increase from the present height of 2.3 to 2.8 m.

### Sea level

The most recent IPCC projections are for the global average sea level to rise by 9–88 cm by 2100, or 0.8–8 cm per decade (IPCC 2001a). The central value of these projections is 48 cm, which is an average rate of

2.2–4.4 times the rate for the 20th century. There is low confidence in the regional distribution of sea level change except that the range is substantial compared with the average. Nearly all models project a greater than average rise in the Arctic and a less than average rise in the Southern Ocean. Trends in Australian sea levels detected over the last 25 years, described in the previous section (Mitchell *et al.* 2000), suggest that sea level rise in Australian and the Pacific might also be considerably less than the global average.

### Fire

Changes in fire regimes are highly likely in the future. Increased fuel load is expected under higher CO<sub>2</sub> levels because of increased plant growth, particularly if reductions in wood and litter nitrogen concentrations reduce decomposition rates (Howden *et al.* 1999d). Increased temperatures will increase fuel dryness and reduce relative humidity, and this will be exacerbated in those regions where rainfall decreases (Howden *et al.* 1999d). Beer and Williams (1995) used the Macarthur Forest Fire Danger Index and CSIRO (1992) climate scenarios to predict changes in future fire incidence. The Macarthur Index incorporates climatic parameters such as air temperature, relative humidity and days since rain and fuel load, to predict fire danger. The models indicate an increase in fire danger over much of Australia. More quantitative modelling by Williams *et al.* (2001) confirmed this general result, indicating an increase in the number of days of very high and extreme fire danger.

## PREDICTED IMPACTS FOR SPECIFIC ECOSYSTEMS

### Vegetation: general

A range of different modelling methods has been used to investigate the potential impacts of temperature and rainfall change on Australian vegetation. In general, the additional impact of elevated CO<sub>2</sub> has not been included in these exercises, although most authors acknowledge its potential importance. Controlled experiments have consistently shown that under optimal growing conditions, plant growth is enhanced by elevated CO<sub>2</sub>: known as the ‘CO<sub>2</sub> fertilization effect’. The magnitude of this effect is, however, highly dependent on water and nutrient availability and under conditions of limiting nutrients such as N or P, enhanced growth at elevated CO<sub>2</sub> may not occur at all. As much of Australia’s vegetation is subject to nutrient and/or water limitation, considerable uncertainty remains as to the magnitude of CO<sub>2</sub> fertilization on this continent. A further difficulty for predicting the

future response of vegetation is that elevated CO<sub>2</sub> enhances water use efficiency in many plant species by reducing stomatal conductance. Enhanced CO<sub>2</sub> may therefore mitigate some of the potential negative impacts of warmer, drier conditions in some areas (Farquhar 1997; Wullschlegel *et al.* 2002). A comparison of the following two studies illustrates the influence of including CO<sub>2</sub> effects. Woodward and Rochefort (1991) predicted that under a global 3°C warming and +10% precipitation change, the number of plant families in eastern Australia may decline, that is, an increase of 10% precipitation will fail to offset the decrease in diversity caused by increased evapotranspiration at the higher temperature. Woodward and Rochefort concluded that eastern Australia will be very sensitive to environmental change because precipitation currently limits vegetation phenology and productivity over much of the region. By contrast, a later study using the same model, but incorporating the effects of doubling CO<sub>2</sub> indicated no change in Australian plant family diversity because the increased CO<sub>2</sub> offset the deleterious effects of increased evapotranspiration (Rochefort & Woodward 1992).

The forest growth model CenW (Kirschbaum 1999a) has been used to simulate growth responses of a generic forest to doubling CO<sub>2</sub> and a warming of 3°C (Kirschbaum 1999b). The model predicted increases of 25–50% in growth for forests in southern Australia. Negative impacts in the north and some marginal inland areas were also predicted, with growth reductions of more than 50% in many regions. In general, responses were inversely related to the magnitude of the temperature increase and there was a strong sensitivity to changes in rainfall. The same model predicted that net primary productivity of Australian forests would decline by ~6% for a scenario of doubled CO<sub>2</sub>, +3°C and –20% rainfall. Net primary productivity was predicted to increase ~21% under the same scenario if rainfall increased by 20% (Lucas & Kirschbaum 1999).

### Tropical rainforests

Analysis using an artificial neural network (ANN) model suggests that the tropical forests of north Queensland are highly sensitive to climate change within the range that is likely to occur within the next 50–100 years. Hilbert *et al.* (2001a) estimated the extent and distribution of 10 structural rainforest types using 10 climate scenarios with up to 1°C warming and altered precipitation from –10 to +20% (but with no change in CO<sub>2</sub> incorporated). The area of lowland mesophyll rainforest was predicted to increase with warming, whereas the upland complex notophyll vine forest responded either positively or negatively to temperature, depending on precipitation. Highland rainforest environments, which are the habitat of many

of the region's endemic vertebrates, were predicted to decrease by 50% with only a 1°C warming. The overall conclusion of the study was that most of the forest types examined will experience climates in the future that are currently more appropriate to some other structural forest type.

### Arid and semiarid rangelands

The interaction between elevated CO<sub>2</sub> and water supply will be especially critical for grasslands and rangelands where approximately 90% of the variance in primary production can be accounted for by annual precipitation (Campbell *et al.* 1997). Sensitivity studies by Hall *et al.* (1998) have indicated that a doubling of CO<sub>2</sub> may mitigate the potentially negative effects of a combined warmer temperature/reduced rainfall scenario on the carrying capacity of rangelands. Simulations by Howden *et al.* (1999c) for native pastures showed that the beneficial effects of doubling CO<sub>2</sub> are relatively stronger in dry years, but that nitrogen limitations may reduce the potential benefits. Positive effects of CO<sub>2</sub> are predicted to balance a 10% reduction in rainfall but greater rainfall decreases will result in reduced productivity (Howden *et al.* 1999b,c). Some limited changes in the distributions of C3 and C4 grasses are also suggested (Howden *et al.* 1999b,c), although this will be moderated by any temperature change. Any increase in pasture growth is likely to increase burning opportunities that in turn will affect carbon stores and future greenhouse gas emissions (Howden *et al.* 1999d).

Climate change scenarios developed for Australia's arid and semiarid regions have assumed that both variability and unpredictability will increase (Stafford Smith *et al.* 1994; Graetz *et al.* 1988; Pickup 1998). Individual rainfall events may be larger and more frequent with a threefold reduction in the return period of 100-year events and longer dry spells between rainfall events (Stafford Smith *et al.* 1994). Any enhanced runoff redistribution will intensify vegetation patterning and erosion cell mosaic structure in degraded areas (Stafford Smith & Pickup 1990) and there may also be an increase in dryland salinity. Major changes in vegetation composition will come through shifts in rainfall pattern and increased runoff distribution, and will favour the establishment of woody vegetation and encroachment of unpalatable woody shrubs in many areas. Changes in rainfall variability and amount will also have important impacts on fire frequency, which greatly increases after wet periods (Griffin & Friedel 1985).

### Mangroves and wetlands

The fate of mangrove habitats will depend on a number of factors, including current tidal range, sedimentology,

salinity regime, community composition and shore profile (see Semeniuk 1994 for a detailed discussion). For example, the macrotidal shores of King Sound, in north-western WA, are already eroding naturally at 1–3 cm year<sup>-1</sup>, a rate that simulates the effect of a rising sea. The mangroves in this area are migrating landwards, generally keeping pace with the retreat. Thus, sea-level rise in a system such as King Sound would most likely result in the migration of mangroves, with similar composition and structure, into habitats made available by increased inundation. By contrast, in microtidal locations, such as those around Shark Bay and Exmouth Gulf, a predicted rise of 50 cm will completely inundate the existing mangrove zones (Semeniuk 1994).

In northern Australia, extensive seasonally inundated freshwater swamps and floodplains extend for approximately 100 km along rivers. The low relief of these areas means that even small rises in sea level could result in relatively large areas being affected by salt-water intrusion, with expansion of the estuarine wetland system at the expense of present-day freshwater wetlands (Woodroffe & Mulrennan 1993; Bayliss *et al.* 1997; Eliot *et al.* 1999). Any increase in rainfall, especially if the wet season is extended, will also enhance both the spread and productivity of mangrove, saltflat and samphire communities, although increased storminess will inflict some damage (Bayliss *et al.* 1997). There is some evidence that these changes are already occurring (see 'Recent impacts' section). In the longer-term, a sea level rise of 1–2 m could see a return of the 'big swamp' conditions of 2000–3000 years BP when most of the freshwater wetlands in the Alligator River Region were saline and supported mangrove communities (Woodroffe *et al.* 1986).

Elevated CO<sub>2</sub> is expected to increase the growth of mangrove species, as for other plants, although experimental studies by Ball *et al.* (1997) have indicated that these effects may occur only when mangrove species are not limited by either humidity or salinity. Elevated CO<sub>2</sub> is therefore unlikely to allow mangroves to expand into areas where salinities are currently too extreme to support growth.

Predictions of increased drought frequency (Kothavala 1999; Walsh *et al.* 2001) and reduced river flows for many Australian rivers (Schreider *et al.* 1997; Arnell 1999), have serious implications for inland wetlands. For example, regional scenarios of reduced rainfall and increased evaporation in the Macquarie Valley area indicate that mean annual runoff to Burrendong Dam may be reduced 12–32% by 2030, resulting in an annual reduction in water flow to the Macquarie Marshes (Hassall & Associates 1998; Herron *et al.* 2002). Assuming that water allocation practices do not change, Johnson (1998) suggested that this will reduce both semipermanent and ephemeral wetland vegetation

in the Marshes by 20–40% of their original area by 2030 and subsequently reduce breeding events for colonial nesting bird species.

Wetland ecosystems in the arid zone are dependent on infrequent heavy rainfall events. Extraction and diversion of water has already had adverse impacts on these systems (Kingsford 2000) and any climatic change that results in drying or reduced flood frequency will have serious consequences for wetland-dependent taxa, particularly waterbirds (Roshier *et al.* 2001). Alternatively, even a relatively small (10%) increase in annual rainfall would increase mean annual inflows into Lake Eyre from 4 to 6 km<sup>3</sup> and transform it into a permanent water body with concomitant effects on the wetland community of the region (Roshier *et al.* 2001).

### Coral reefs

Corals in subtropical and tropical locations exist within 1 or 2°C of their upper thermal limit during the summer months (Jones *et al.* 1997). When corals are exposed to higher than normal seawater temperatures during the warm season their algal symbiosis is disrupted, leading to a phenomenon known as bleaching. This physiological symptom of stress is followed by large-scale mortality if temperatures are high enough or exposure long enough. In 1998, an estimated 16% of the world's living coral died, with some regions such as the Indian Ocean experiencing more than 40% mortality (Wilkinson 2000).

In the region around the Great Barrier Reef, mean annual sea surface temperatures may increase 2–5°C by 2100 (IPCC 2001b). The impact of predicted temperature increases on the frequency and intensity of bleaching events in the Great Barrier Reef over the next 100 years has been modelled by Hoegh-Guldberg (1999). Results for relatively conservative scenarios like that of IS92a (IPCC 1992) suggest that the current upper thermal tolerance limit of corals will be exceeded every year by about 2030 and bleaching events as severe as that in 1998 are likely to become commonplace within the next 20 years. On this basis, reefs are likely to be maintained in an early successional state or shift to communities dominated by organisms other than corals, such as macroalgae (Hoegh-Guldberg 1999). Unprecedented rates of species turnover on coral reefs in the Caribbean following the 1998 bleaching event (Aronson *et al.* 2002) provide a picture of potential change in the future.

Coral reefs are also vulnerable to a number of other threats including hypo-osmotic stress if the magnitude of extreme floods increases (Coles & Jokiel 1992), and physical damage from increased cyclone intensity. Increased sea levels will favour some reef-top communities currently limited by sea level, but smother

others, as a result of redistribution of reef-top sediments. Increased atmospheric CO<sub>2</sub> concentration will reduce the alkalinity of reef waters, causing an increase in the rate of chemical dissolution of existing reef limestone, and a decrease in deposition rate and/or strength of new limestone deposited by reef organisms (LeClerq *et al.* 2002).

### Alpine areas

Alpine systems are generally considered to be among the most vulnerable to future climate change. The extent of true alpine habitat in Australia is very small (0.15% of the Australian land surface) with limited high altitude refuge (Green & Pickering 2002). Interannual temperature variation is narrow compared with anticipated warming (Pittock & Wratt 2001), and modelling studies by Whetton *et al.* (1996) and Whetton (1998) point to a high degree of sensitivity of seasonal snow cover and depth.

The distribution of high mountain vegetation is related primarily to summer temperatures, as in other alpine, arctic and subantarctic regions of the world. Tree growth is limited to areas where the mean temperature of the warmest month is 10°C or greater. Elevated summer temperatures may not only increase the growth rates of extant shrubs but promote the expansion of woody vegetation into areas currently dominated by herbaceous species (Williams & Costin 1994). The rate of expansion will depend on the availability of bare ground for the establishment of seedlings, which will be greater if grazing by stock continues (Williams & Costin 1994).

The future importance of snow cover for populations of alpine vertebrates can be gauged from the response of species to years of shallow cover (Green & Pickering 2002). In such years there is evidence for a reduction in populations of dusky antechinus, broad-toothed rats and the mountain pygmy possum. The first two species are active under the snow throughout winter (Green 1998) and are therefore subject to increased predation by foxes when snow is reduced (Green & Osborne 1981). The pygmy possum depends upon snow cover for stable, low temperatures during hibernation (Walter & Broome 1998).

### PREDICTED IMPACTS OF CLIMATE CHANGE FOR SELECTED AUSTRALIAN TAXA

Climate mapping, using programs such as CLIMEX (Sutherst *et al.* 1998) and BIOCLIM (Busby 1991), has been the principal method for predicting potential distributions of individual species under current and future climates. In general, although species are

expected to respond individually to future climate change, the consistent message from these modelling exercises is that the distributions of most species will contract and/or become increasingly fragmented. Although this type of modelling currently provides the only predictive tool available for many species (see review by Baker *et al.* 2000), it has several important limitations. First, the estimation of the bioclimatic envelope that a species currently inhabits is extremely sensitive to the accuracy of the distributional data used. If these observations do not cover the entire geographic range of the species, the climatic profile produced may underestimate the climatic range that the species can inhabit. Second, the models assume that the present day distribution of the species is in equilibrium with present climate. Third, the models assume that climate is the only factor affecting a species distribution and do not take into account other potentially important influences such as elevated CO<sub>2</sub>, microclimate, soil, competition and natural enemies. Finally, the differential abilities of species to disperse, and thus track shifting climate zones, are not included. Predictions by the models as to changes in distributions of species should therefore be considered as indicators of potential change, rather than accurate forecasts. Recent studies that have incorporated information on soil and vegetation distributions with bioclimatic estimates represent important steps forward in improving the utility of predictions (Chapman & Milne 1998; Pouliquen-Young & Newman 2000).

### Plants

Many Australian plant species are restricted in geographic and climatic range and may therefore be predisposed to early extinction or displacement under climate change (Pouliquen-Young & Newman 2000). Many species in the genus *Eucalyptus*, for example, which dominates more than 90% of Australian forests and woodlands (Pryor & Johnson 1981), have sharply defined, narrow geographic ranges that are closely associated with local environmental conditions such as soil and drainage. BIOCLIM modelling indicated that 53% of 819 eucalypt species have current ranges spanning less than 3°C of mean annual temperature, with 41% having a range less than 2°C and 25% with less than 1°C (Hughes *et al.* 1996). In addition, 23% of species have ranges of mean annual rainfall that span less than 20% variation (Hughes *et al.* 1996). Although the actual climatic tolerances of many species may be wider than the climatic envelope they currently occupy, if even a modest proportion of present day boundaries reflect thermal or rainfall tolerances, substantial changes in the Australian tree flora may be expected in the future.



Pouliquen-Young and Newman (2000) assessed the effects of three climate scenarios (CSIRO 1996) for 92 species of the endemic WA genus *Dryandra* and 27 species of *Acacia* using BIOCLIM. The bioclimates of 55% of the *Dryandra* species were predicted to decline to less than half their current distribution. Twenty-eight per cent of *Dryandra* species, all of which have current geographic ranges of less than 1000 km<sup>2</sup>, were predicted to disappear completely with a 0.5°C warming. With a 2°C warming, the bioclimates of 91% of the *Dryandra* species are predicted to decline by more than half of their current distribution and 66% to disappear completely. The *Acacia* species were found to be more robust to modest warming, with only one species having a bioclimate predicted to disappear with a 0.5°C increase. However, the bioclimates of 59% of *Acacia* species would disappear with a 1°C increase (all species with a range less than 20 000 km<sup>2</sup>) and the rest suffer a decline in distribution of more than 75%. The bioclimates of all *Acacia* species were predicted to disappear with a 2°C warming. In general, species were not predicted to track moving climate zones across the landscape because of soil constraints, but instead, to shrink to a smaller range within their current distribution.

BIOCLIM modelling by Chapman and Milne (1998) also highlighted the importance of considering potential constraints due to soil type. Suitable and marginal bioclimates for Curley Mitchell Grass, *Astrebla lappacea*, for example, were predicted to decrease in northern areas by 23 and 44%, respectively. However, only approximately 50% of the area projected to remain climatically suitable occurs on the cracking clay soils to which this species is restricted.

As detailed earlier, any response of plant species to climatic change will interact with their response to increasing CO<sub>2</sub>. The few published studies that have investigated the response of Australian plant species to elevated CO<sub>2</sub> have mostly focused on woody species grown under non-limiting conditions of light, nutrients and water: *Eucalyptus* spp. (Duff *et al.* 1994; Roden & Ball 1996; Lawler *et al.* 1997; Gleadow *et al.* 1998; Roden *et al.* 1999), *Acacia* spp. (Atkin *et al.* 1998, 1999; Evans *et al.* 2000), *Rhizophora* (Ball *et al.* 1997), and rainforest trees (Berryman *et al.* 1993; Kanowski 2001). Several C4 grasses have also been tested (Ghannoum *et al.* 2001). Under these conditions, the impacts of elevated CO<sub>2</sub> on plant growth have been consistent with studies for Northern Hemisphere species; elevated CO<sub>2</sub> generally enhances photosynthesis and growth, improves water use efficiency, increases C : N ratios and reduces the concentration of nitrogen. With the exception of a study by Kanowski (2001), all plants tested have been grown in potting mix or hydroponic solution. To my knowledge, there have been no published studies testing the response of native plant species grown as mixed stands or under the

range of nutrient-limited conditions typical of many Australian soils.

### Vertebrates

The potential impacts of climate change on Australian vertebrates have been reviewed by Stott (1994), including possible changes in competitive regimes, sex ratios, and parasite transmission. Most recent studies have modelled the impacts of rainfall and temperature changes using BIOCLIM and have generally focused on threatened and vulnerable species.

Brereton *et al.* (1995) examined the impact of five greenhouse climate scenarios (CSIRO 1992) on the distribution of 42 vertebrate species, most with threatened status, from south-east Australia. Range reductions were predicted for 41 of the species, with 15 predicted to have no suitable bioclimate available in south-east Australia with a 3°C rise in temperature under the most likely rainfall scenario. The most dramatic impact was predicted for the mountain pygmy possum *Burramys parvus*, whose bioclimate may disappear completely with a 1°C rise in temperature. The bioclimates of a further five species disappeared at +2°C and another nine at +3°C. Although the bioclimates of six species increased with a 1°C rise, that of only one species, the eastern bristlebird, increased with a +3°C rise. Of the 42 species studied, 24 were predicted to lose 90–100% of their bioclimate with a 3°C rise in temperature. Similar general conclusions were reached by Dexter *et al.* (1995) for 58 species of threatened vertebrates, with more than 80% of species predicted to suffer contractions of their core climatic habitat under each of the three scenarios used.

Chapman and Milne (1998) broadened the previous vertebrate studies by including several common species, in addition to those with threatened status, and using bioclimatic modelling in conjunction with vegetation and soil maps. The range of the kowari, *Dasyuroides byrnei*, for example, was predicted to contract by 92–98%, but the areas that remained climatically suitable occur in vegetation and soil types where the species does not presently occur. In contrast, the numbat, *Myrmecobius fasciatus*, showed very little predicted change in total habitat after climate change and under some scenarios showed an increase in suitable area. A similar exercise by Pouliquen-Young and Newman (2000) indicated that the bioclimates of the three frog species studied, plus 15 species of endangered or threatened WA mammals, would either disappear or be restricted to small areas with only a 0.5°C warming. Rainfall changes will also be important. For example, the habitat of the northern bettong, *Bettongia tropica*, in the wet tropics is predicted to decline if warming is accompanied by greater precipitation, but

to increase in geographic range if rainfall decreases (Hilbert *et al.* 2001b).

In addition to the direct impacts of changes in temperature and rainfall, some vertebrates will be indirectly affected by elevated CO<sub>2</sub>. Folivorous mammals are considered especially sensitive to foliage chemistry as a consequence of their high mass-specific metabolic requirements (Cork & Foley 1991). Kanowski (2001) found that the nitrogen levels of two rainforest tree species important in the diet of folivorous mammals in north-east Queensland were reduced by 25–29% at double-ambient CO<sub>2</sub>. Unlike phytophagous insects, arboreal folivores cannot compensate for a decline in foliage quality by increasing consumption, because such a strategy would lead to elevated and unsustainable losses of faecal nitrogen (Cork 1996). On the basis of previous mammal surveys, Kanowski (2001) estimated that the abundance of the lemuroid ringtail possum, *Hemibelideus lemuroides*, might decline by 30–40% in the higher elevation rainforest of the Atherton Tablelands if foliar nitrogen concentrations fall by 15–20% under elevated CO<sub>2</sub> conditions (Kanowski 2001).

### Invertebrates

The potential impact of climate change on Australian invertebrates has received far less attention than that for vertebrates. Beaumont and Hughes (2002) used BIOCLIM to determine the current climatic ranges of 77 butterfly species restricted to Australia and found that the majority of species had fairly wide climatic ranges with only 8% having a mean annual temperature range spanning less than 3°C. Despite the wide ranges, the predicted extent of suitable climate by 2050 for 24 species modelled under four different climate change scenarios suggested that even species with wide ranges may still be vulnerable. Under a very conservative climate change scenario (with a temperature increase of 0.8–1.4°C by 2050) 88% of species bioclimates were predicted to decrease, with 54% reduced by at least 20%. Under an extreme scenario (temperature increase of 2.1–3.9°C by 2050), 92% of species bioclimates were predicted to decrease, with 83% declining by at least 50%. Furthermore, the proportion of the current climate range that was contained within the predicted range decreased from an average of 63% under a very conservative scenario, to less than 22% under the most extreme scenario. Beaumont and Hughes also identified seven of the 77 species as being particularly at risk because of a combination of life history characteristics (e.g. being obligate myrmecophiles) and narrow climatic ranges (the hesperiids *Exometocea nycteris* and *Trapezites heteromacula*, and the lycaenids *Hypochryps*

*halyaetus*, *H. piceata*, *Jalmenus clementi*, *J. lithchroa* and *Nesolyceana urumelia*).

Many herbivorous invertebrates are also likely to be affected by reductions in plant quality as atmospheric CO<sub>2</sub> increases. Reduced nitrogen content and increased C:N ratios in eucalyptus foliage, for example, were associated with reduced digestive efficiency, smaller pupal size and increased mortality in the chrysomelid beetle *Chrysophtharta flaveola*, consistent with studies for non-Australian insect species (Lawler *et al.* 1997). Similarly, the moth *Dialectica scalarisella*, introduced into Australia to control the weed Paterson's Curse, suffered longer development times, higher mortality and had reduced adult weight when fed on foliage grown at elevated CO<sub>2</sub> (Johns & Hughes 2002).

Surveys of marine invertebrates along the coastline of Victoria identified 3.7% as being endemic to the region (O'Hara 2002). Of these, approximately 4–6% of the decapods and echinoderms and 9–17% of the molluscs are currently limited to the cool temperate waters of south-eastern South Australia, Victoria and Tasmania. O'Hara (2002) suggested that at least a proportion of these species may become locally extinct from Victorian waters with an increase in temperatures of 1–2°C. Whether this decline would be balanced by range extensions of northern species is uncertain. At even more risk is the cluster of species endemic to south-eastern Tasmania that cannot retreat to more southerly latitudes (Edgar *et al.* 1997).

### HAS CLIMATE CHANGE ALREADY AFFECTED AUSTRALIAN SPECIES AND COMMUNITIES?

There is now clear evidence that the relatively modest climatic changes over the past century have already had significant impacts on the abundance, distribution, phenology and physiology of a wide range of species. Recent reviews have documented many instances of shifts in species distributions toward the poles or upward in elevation, and progressively earlier life cycle events such as flowering, reproduction and migration (Hughes 2000; McCarty 2001; Walther *et al.* 2002; Parmesan & Yohe 2003; Root *et al.* 2003). Australian examples are, however, notably lacking from these compilations. As climate changes in Australia are consistent with global trends, the lack of documented impacts is presumably not because Australian species have been unaffected, but rather because long-term datasets in which such trends could be detected are scarce (Westoby 1991). The following list of examples of species and ecosystems where there is evidence of recent, climate-associated change, is therefore modest compared to those compiled in North America and Europe and in many cases, the relative role of climate change versus other factors is poorly understood.

## Vegetation

Australian vegetation has been profoundly altered during the last 200 years of European colonization. Century-scale changes in vegetation have been documented in various vegetation types in Australia, including open forests, grassy woodlands, tussock grasslands and rainforests, but few studies have involved repeated sampling at the same sites (reviewed by Lunt 2002). Although the potential role of recent climate and atmospheric change has been noted, most changes in composition and age structure have been attributed to grazing or to changes in fire regimes following European settlement (e.g. Lunt 1998; Lunt 2002).

A marked increase in woody biomass at the landscape scale has been reported for a wide variety of arid and semiarid environments, as well as tropical savannas and open woodlands (Archer *et al.* 1995 and references therein). This phenomenon, known as 'vegetation thickening', has been generally viewed as an example of vegetation recovery and succession following episodic disturbance events such as drought, fire and clearing (Gifford & Howden 2001). Although not the primary cause, atmospheric change may also be involved in thickening (Archer *et al.* 1995).

Vegetation thickening over the last 50–100 years has been recorded in Australia in a number of environments such as semiarid woodlands (Henry *et al.* 2002), and eucalypt savannas (Bowman *et al.* 2001). Where this has occurred in grazed rangelands it is known as the 'woody weed' problem. The potential role of CO<sub>2</sub> fertilization in these changes has been investigated by Berry and Roderick (2002). They described landscapes in terms of the abundance of three different functional types of leaves and estimated the proportion of natural vegetation made up of each type using climatic and satellite data. Using continental scale maps of past and present vegetation, they estimated the change in proportion of the three leaf types that has occurred as a result of increased CO<sub>2</sub>, as opposed to land use change. They concluded that increasing CO<sub>2</sub> would have exacerbated the woody weed problem.

Changes in rainfall patterns have also been implicated in some vegetation trends. For example, a historical survey of eucalypt savannas in Litchfield National Park, NT, where less than 1% of the study area has been modified by humans, showed that forest coverage has increased from 5% to nearly 10% over ~50 years, whereas areas of grassland have decreased from approximately 7 to 2.5% (Bowman *et al.* 2001). Although the cessation of Aboriginal landscape burning may be the primary cause, the period of increased rainfall in the 1970s may also have been an influence. Above average rains in eastern Australia favour the increase of woody biomass in savannas. Climatic records over the past 125 years show that there was a trend of above-average rainfall in the second half of the

study period (i.e. 1965/66–1994/95), although there was considerable variation in the total amount of rainfall for any wet season. It is possible that this wetter-than-average period has favoured the increase in woody biomass by increasing supplies of groundwater accessible to tree roots (Bowman *et al.* 2001). Similarly, Fensham *et al.* (in press) documented a general increase in overstorey cover in central Queensland over the second half of the 20th century, during a period of higher than average rainfall. A contrasting trend in Tasmania toward an increased incidence of drought and alterations in seasonal rainfall patterns has been implicated in eucalypt dieback (Kirkpatrick *et al.* 2000). A positive relationship between the magnitude of drought and eucalypt dieback was also found in north Queensland savanna (Fensham & Holman 1999).

Expansion of rainforest at the expense of eucalypt forest and grasslands in Queensland over the past two centuries has been well documented (Harrington & Sanderson 1994; Hopkins *et al.* 1996). In the Bunya Mountains in south-east Queensland, aerial photographs over a 40-year period (1951–1991) demonstrated that both eucalypt forest and rainforest had invaded and in some cases, completely engulfed, grasslands that occur in a range of landscapes (Fensham & Fairfax 1996). In North Queensland, comparisons of aerial photographs from the 1940s and the early 1990s indicated that rainforest had invaded large areas of wet sclerophyll eucalypt forest (Harrington & Sanderson 1994) with widespread thickening of the canopy across both vegetation types. Once again, cessation of active traditional Aboriginal land management has been suggested as the primary cause, but climatic changes cannot be discounted. Recent invasions of warm temperate rainforest species to higher elevations in northern NSW and expansion of *Nothofagus* into eucalypt woodland on plateaus in the Barrington Tops region have also been documented (Read & Hill 1985). At present it is unclear whether this migration is a response to recent warming or whether the vegetation is still responding to the major climate changes following the last glacial maximum.

Australia's alpine vegetation has been the subject of several long-term studies. Increases in cover of *Sphagnum* and decreases in shrub cover in sphagnum bogs in Kosciuszko National Park have occurred over a 32-year period (1959–1973 sites resampled in 1991, Clarke & Martin 1999). A similar trend in shrub senescence has been reported for shrublands in the Victorian Alps in plots fenced to exclude grazers since 1945 (Wahren *et al.* 1994). These trends have been interpreted mainly as slow recovery from grazing disturbance and postfire regeneration (Wahren *et al.* 1994). Other trends in the alpine zone, however, have been more confidently ascribed to recent warming trends. Encroachment by *Eucalyptus pauciflora* into

subalpine grasslands near Mt Hotham, Victoria, has been documented by Wearne and Morgan (2001). All invading saplings were estimated to be less than or equal to 31 years old and the majority (54%) established between 1991 and 1995. Most sapling establishment (66%) occurred within 5 m of the forest–grass–land boundary and some of the recently established plants are now reproductively mature trees (1–8 m in height), suggesting an ecotonal change is underway.

Warming trends have also been implicated in agricultural changes. The average yield of wheat has increased by 0.5 tonnes per ha since 1952, representing a rise of ~45% of the average annual yield (Nicholls 1997). Over the same period, the frequency of severe frosts decreased in eastern Australia (Stone *et al.* 1996) and median annual temperatures, averaged across Australia, increased by 0.58°C (1952–1992). Nicholls (1997) estimated that climate trends were responsible for 30–50% of the observed increase in wheat yields, with increases in the minimum temperature being the dominant influence, although other authors (Godden *et al.* 1998) have offered alternative explanations.

Some of the most compelling evidence that recent warming has already affected life cycles comes from long-term phenological monitoring of various species of plants, birds, insects and amphibians in the Northern Hemisphere (Hughes 2000; Parmesan & Yohe 2003; Root *et al.* 2003). Unfortunately, there are few comparable datasets in Australia, with the exception of several compilations of reproductive phenology of eucalypts in four Australian states (NSW, Queensland, Victoria and WA), collected by state forestry organizations for varying periods from 1925 to 1981 (Keatley *et al.* 2002). Records for four eucalypt species in Victoria, collected from 1940 to 1962, indicate that temperature accounted for greater variation in flowering commencement date than rainfall, but that over this period, no statistically significant trends in flowering date were evident (Keatley *et al.* 2002). One identified problem with the dataset, however, was that flowering observations took place only monthly, so it is possible that each observed flowering date may be up to 30 days later than the actual commencement date. Relationships between flowering date, temperature and rainfall for the dataset indicated that a warming of 1°C may result in earlier flowering for two of the four species, *E. microcarpa* and *E. polyanthemos*, by 41 and 43 days, respectively, and later flowering in *E. leucoxylon* and *E. microcarpa* (Keatley *et al.* 2002).

### Wetlands

The landward transgression of mangroves into salt-marsh environments in the estuaries of Queensland,

NSW, Victoria and SA over the past five decades is a widespread trend with saltmarsh losses ranging up to 80% (Saintilan & Williams 1999). This process is occurring in a range of geomorphic settings, and in some cases is reversing the trend of longer-term vegetation change. Although direct human disturbance is undoubtedly a factor in these trends (e.g. revegetation of areas cleared for agriculture, increases in nutrient levels and sedimentation), increases in rainfall and altered tidal regimes have also been implicated (Saintilan & Williams 1999). Along the eastern shore of the Gulf of St Vincent, SA, for example, mangroves extended at a rate of 17 m per year from 1949 to 1979 (Fotheringham 1994, cited in Saintilan & Williams 1999). One explanation for this trend is that increased average annual precipitation since 1945 in the area may have diluted salts within saltmarsh soils to the extent that mangrove colonization was enhanced (Saintilan & Williams 1999).

In some areas of the NT, dramatic expansion of some tidal creek systems has occurred since the 1940s. In the Lower Mary River system, two creeks have extended more than 4 km inland, invading freshwater wetlands (Woodroffe & Mulrennan 1993; Bayliss *et al.* 1997; Mulrennan & Woodroffe 1998). Rates of extension of saltwater ecosystems inland in excess of 0.5 km year<sup>-1</sup> have been measured (Knighton *et al.* 1992). The tidal networks are still expanding and only in their lower reaches does the maximum extension appear to have been reached. The smallest tributaries are being eliminated as mangroves (*Avicennia* sp.) spread along creek boundaries and trap large quantities of fine sediment. The saltwater intrusion has had dramatic effects on the vegetation of formerly freshwater wetlands with more than 17 000 ha adversely affected and a further 35–40% of the plains immediately threatened (Mulrennan & Woodroffe 1998). These changes most likely have multiple causes, but both sea level rise and increases in rainfall may have contributed (Woodroffe & Mulrennan 1993; Bayliss *et al.* 1997).

### Terrestrial vertebrates

One of the few long-term datasets for Australian fauna is that for the sleepy lizard, *Tiliqua rugosa*, collected in mid-north SA by Bull and colleagues since 1983. Over the study period 1983–1997, the last months of winter (July and August) have become warmer and drier, and the spring months when lizard activity is highest (September and October) have become wetter (Bull & Burzacott 2002). These climatic shifts have been associated with changes in the timing of lizard pairing behaviour. Specifically, pairing tended to start earlier following the warmer, drier winters of the later years of the study and persisted for longer. As part of the same

study, distributions of two reptile ticks for which the sleepy lizard is a host have also been monitored. The abrupt parapatric boundary between the two species has shifted 1–2 km over the same period, with the more mesic-adapted *Aponomma hydrosauri* advancing into the distribution of the more arid-adapted *Amblyomma limbatum*. The density of ticks on lizards in regions flanking the boundary zone has also increased for *Ap. hydrosauri* and decreased for *Am. limbatum* (Bull & Burzacott 2001).

In the alpine zone, there is evidence of shifts in vertebrate ranges to higher elevations over the 30-year period to 1999. Wildlife Atlas records indicate a higher maximum altitudinal distribution for all three macropod species and for four species of feral mammals (Green & Pickering 2002). Other evidence for increasing activity by feral mammals at higher altitudes supports this trend. In the 1970s, Snowy Plains (1370 m a.s.l.) was regarded as climatically marginal for rabbits, yet during the summer of 1998–1999 the National Parks and Wildlife Service was forced to institute a rabbit control program at Perisher Valley (Green & Pickering 2002). During the period 1980–1988, Green (1988) conducted regular small-mammal trapping near the treeline on the South Ramshead with access up a spur from Dead Horse Gap (1580 m a.s.l.) without once recording evidence of horses above the gap. This route is now regularly used by horses to gain access to the alpine zone (K. Green, pers. obs.).

A trend toward earlier arrival of migratory bird species in the alpine zone in the 1980s and/or 1990s, compared with the 1970s, has also been documented (Green & Pickering 2002). For the 11 bird species for which there are sufficient data, the earliest record was in the 1990s for five species and in the 1980s for four. The particular foraging techniques and biology of the individual bird species were associated with the trends in their arrival. The species recorded as arriving earlier include three species of honeyeaters that depend on the flowering of shrubs. The Australian kestrel *Falco cenchroides* is largely dependent on snow-free ground for foraging. The ground-feeding flame robin, *Petroica phoenicea*, and Richard's pipit, *Anthus novaeseelandiae*, arrive early in spring and feed on insects immobilized on snow; the earlier presence of these insects is associated with sufficient warmth at their point of origin for metamorphosis and flight. Olive whistlers, *Pachycephala olivacea*, and striated pardalotes, *Pardalotus striatus*, glean active insects off shrubs and trees and movements of fan-tailed cuckoos, *Cuculus flabelliformis*, are attuned to the breeding timetable of their hosts. The two species that appear not to arrive earlier despite changes in snow cover over the three decades are the grey fantail, *Rhipidura fuliginosa*, which catches insects in flight, and the silvereve, *Zosterops lateralis*, which is involved in long migratory flights, the timing

of which may be independent of local events (Green & Pickering 2002).

Baxter *et al.* (2001) have documented recent observations of the black-necked stork, *Ephippiorhynchus asiaticus*, in north-east South Australia, well to the south of its customary range, and suggested that monsoon-flooding in Queensland and far northern SA during the summer–autumn of 2001 may be an explanation. Recent observations of the magpie goose, *Anseranas semipalmata*, a vagrant well outside its usual range, have also been noted (Baxter *et al.* 2001). Although annual floods down the major rivers in the Channel Country in the summers of 1999–2001 were much larger than average annual flows and were linked to a La Niña phase, they were not as great as the largest floods experienced in previous La Niña periods such as 1974–1976 and 1989–1991. No records of magpie goose or black-necked stork were reported from north-eastern SA during these previous La Niña events. Baxter *et al.* (2001) conclude that the intrusion of these species into the area is highly unusual and may not have occurred in the recent past.

The range of *Pteropus poliocephalus*, the grey-headed flying fox, has contracted south from its northern boundary by approximately 750 km since the 1930s (Tidemann 1999). *Pteropus poliocephalus* was a common breeding species in the Rockhampton area in 1930 but by the early 1960s the northern extent of its breeding range had contracted to Maryborough. Although satellite camps still extend to around Maryborough, most camps in this area are now dominated by *P. alecto*, the black flying fox, a more tropical species. Along with the southward contraction in range by *P. poliocephalus*, *P. alecto* has apparently extended its range south by a similar distance, with its southern limit progressively extending from Maryborough, to the NSW–Queensland border and then to Bowraville, NSW; its breeding range now extends to Maclean, NSW. Increases in rainfall and temperature in eastern Australia over the period have possibly favoured *P. alecto*, which cannot tolerate frosts (Tidemann 1999). The range shifts of both species have occurred such that the area of sympatry between them has remained much the same.

### Marine birds

There have been some major changes in seabird breeding distribution since the late 19th century in the transition zone between tropical and temperate seabird species in the region between the Houtman Abrolhos and the Naturaliste and Leeuwin Capes, off the coast of WA (Dunlop 2001). At least eight species have formed new breeding locations well to the south of their historical range and/or have seen marked population increases at their more southerly colonies. Such

changes have occurred in the wedge-tailed shearwater (*Puffinus pacificus*), bridled tern (*Sterna anaethetus*), roseate tern (*Sterna dougalli*), crested tern (*Sterna bergii*) and brown noddy (*Anous stolidus*). Some of the shifts began as early as the 1920s (bridled tern), others in the 1950s and 60s (roseate tern, red-tailed tropicbird), whereas others did not begin until the last decade of the 20th century (brown noddy, sooty tern). The rate of establishment and/or growth of new colonies seems to have accelerated since the early 1980s. Long-term monitoring studies at three wedge-tailed shearwater colonies suggest that their fisheries decline during El Niño conditions. Brown noddies and sooty terns also fare poorly on the Abrolhos during periods when the Leeuwin Current is weak. During the 1996–1997 El Niño event there was almost complete breeding failure in hundreds of thousands of brown and lesser noddies, sooty terns and roseate terns on Pelsaert Island due to an ENSO-triggered collapse in the pelagic seabird fisheries. Although the records are patchy, there is also some evidence that the prospecting behaviour by the birds that precedes the colonization of new, more southerly breeding sites, tends to occur in association with the major El Niño events. The El Niño phase of the Southern Oscillation increased in frequency with every couple of decades of the 1900s such that what was once an unusual climatic pattern has become more common in the last two decades of the century, with major events in 1982–1983, 1987–1988, 1991–1994 and 1996–1997. Because the behaviour of the Leeuwin Current is strongly influenced by ENSO, it is likely that this is the ultimate cause of the shifts in the seabird fisheries and changing population dynamics (Dunlop 2001).

Since 1980, the Australasian gannet (*Morus serrator*) population has increased threefold in Australian waters, from 6600 breeding pairs to approximately 20 000 pairs in 1999–2000, a rate of 6% per year (Bunce *et al.* 2002). In colonies where nesting space is not limiting, the breeding population has expanded at rates as high as 24% per year. Bunce *et al.* (2002) suggest that the population increase may be associated with the increased ENSO activity over this time because increased upwellings of nutrient-rich cold subantarctic waters during ENSO events are positively correlated with increases in several commercially important fish stocks. A gradual long-term warming trend in Bass Strait and waters off south-eastern Australia may also have positively affected the distribution and local availability of pilchards and other prey species, as has been shown in other parts of the world (Bunce *et al.* 2002). Although these correlations are suggestive of a climate influence on gannet populations, it is possible that changes in the fishing practices of several major commercial fisheries in south-eastern Australia, resulting in an increase in discarded bycatch, may also be important (Bunce *et al.* 2002).

## Coral reefs

Since the late 1970s there has been a global increase in the number and scale of coral-bleaching events and the extent, timing and severity of many such events have been correlated with warmer than normal seawater temperatures (Jones *et al.* 1997; Lough 2000). In 1998, tropical sea surface temperatures were the highest on record, topping off a 50-year trend for some tropical oceans (Reaser *et al.* 2000). In the same year, coral reefs around the world suffered the most extensive and severe bleaching on record. The mortalities that followed these events were higher than any in the previous 3000 years (Aronson *et al.* 2002). The geographic extent, increasing frequency, and regional severity of mass bleaching events are an apparent result of a steadily rising baseline of marine temperatures, combined with regionally specific El Niño and La Niña events (Hoegh-Guldberg 1999; Lough 2000).

One of the best records of recurrent bleaching events comes from the inshore fringing reefs of Magnetic Island on the Great Barrier Reef, where bleaching has been observed in the summers of 1979–1980, 1981–1982, 1986–1987, 1991–1992 and 1993–1994 (Jones *et al.* 1997). Average daily seawater temperatures exceeded 31°C for 14 days and 31.5°C for 2 days during the bleaching event of 1991–1992 and exceeded 31°C for 10 days and 31.5°C for 2 days during the 1993–1994 event.

A severe and widespread bleaching on the Great Barrier Reef occurred from February to April, 1998 with inshore reefs being the worst affected (Berkelmans & Oliver 1999). Although Australian reefs were less affected than many elsewhere (3% loss compared with 46% in the Indian Ocean; Wilkinson 2000) damage was nonetheless severe at many sites. At the worst affected sites, most staghorn and other fast-growing corals were killed, whereas the very old corals had high rates of survival. The level of thermal stress at the majority of bleaching sites was unmatched in the period 1903–1999 (Lough 2000). Reefs elsewhere around Australia were similarly affected. Lowered seawater salinity as a result of river flooding between Ayr and Cooktown early in 1998 probably exacerbated the effects of warming on the inshore reefs (Berkelmans & Oliver 1999). At Scott Reef off the north-west coast, most corals died to a depth of 30 m and have since recovered only slightly (Sweatman *et al.* 2002).

Extensive coral bleaching re-occurred in the summer of 2001–2002 and the Great Barrier Reef was again subject to a complex mosaic of relatively hotter and cooler areas. Bleaching was more extensive than in 1998 and the inshore reefs were again the most affected. In the cooler areas no damage was found but significant coral mortality was seen in the hottest patches (T. J. Done, unpubl. obs., Sweatman *et al.* 2002). Surprisingly, the ubiquitous hard corals previ-

ously thought to be the most sensitive (e.g. family Pocilloporidae) survived relatively well whereas others (Acroporidae and Faviidae) suffered significant injury and mortality (T. J. Done, cited in Sweatman *et al.* 2002)

Evidence of warming oceans also comes from examination of annual variation in the density of calcium carbonate (CaCO<sub>3</sub>) skeletons in some massive coral species such as *Porites* (Lough & Barnes 1997; Lough 2000). Some of these corals live several hundred years and can be used retrospectively to monitor coral growth in an analogous way to the study of tree-rings. For each 1°C of temperature increase, calcification increases by ~0.3 g cm<sup>-2</sup> year<sup>-1</sup> and linear extension of the coral increases by ~3 mm year<sup>-1</sup>. Average calcification rates of *Porites* measured in more than 200 small coral colonies from 29 reefs along the Great Barrier Reef show decreases from north to south as the average annual seawater temperature decreases. When examined over 50-year periods, a more than two-centuries long record shows constant rates of calcification until the most recent period, when calcification significantly increases by ~4%, matching the observed rise in seawater temperatures (Lough 2000).

### SOME RESEARCH DIRECTIONS

The potential impact of climate change on species and ecosystems is becoming increasingly well recognized as an important scientific, economic, political and conservation issue. Policy frameworks and associated administrative arrangements to co-ordinate implementation are already in place including the National Strategy for Conservation of Australia's Biological Diversity, the National Greenhouse Response Strategy and the Environment Protection & Biodiversity Conservation Act of 1999. Despite the existence of this legislative framework to implement strategies to understand and mitigate the effects of climate change, many potential impacts are very poorly understood. The following is a partial and fairly general list of research and policy directions that could be undertaken or re-emphasized to try to fill some of the gaps. A more extended discussion of climate-change research needs and their integration with policy can be found in Howden *et al.* (1999a) and Pittock and Wratt (2001).

#### Emissions versus impacts

Current Australian government policies regarding climate change are largely focused on mitigation strategies, which have been developed in response to both international pressure and to the potential economic significance of future carbon trading. Considerable efforts have been put into developing an

integrated, but largely voluntary, system of inducements to reduce the high level of greenhouse gas emissions from the energy sector in particular. The total contribution of these policies to a long-term reduction in global greenhouse gas concentrations is difficult to ascertain. Although Australia is one of the world's highest producers of greenhouse gases on a per capita basis, it produces only just over 1% of global emissions and ~3% of the emissions from industrialized countries (Australian Greenhouse Office 2001). Therefore, although controlling emissions is of fundamental importance, even a substantial reduction on Australia's part will not appreciably alter the inexorable impact of climate change unless the rest of the industrialized world follows suit. The scientific reality is that profound impacts of climate change will be felt over the next century in this continent regardless of how effectively Australian emissions are modified. Identifying and ameliorating these impacts must be given as high a priority as emissions control. Further, the range of taxa and communities studied needs to go beyond the current focus on threatened vertebrates to include introduced and aquatic species, invertebrates and a broader range of vegetation types.

#### Back to basics

Predicting what will happen to species distributions in the future must rely heavily on understanding the factors by which they are currently limited. Although the question 'What determines the distribution and abundance of species?' is one of the most fundamental in ecology, we do not know the answer to it for any more than a handful of Australian taxa.

#### Interaction of CO<sub>2</sub>, temperature, nutrients and water

Broad-scale changes in terrestrial vegetation, which will in turn affect the habitats of animal species, will result from interactions between the effects of elevated CO<sub>2</sub>, temperature and rainfall. We know a great deal about how elevated CO<sub>2</sub> affects the growth of pot-grown (mostly) Northern Hemisphere plant species, growing under optimal conditions. But we know very little about the response of Australian plant species, especially growing under conditions of water stress and/or nutrient limitation. We know even less about the response of natural, mixed plant communities.

#### Shifts in vegetation zones

Changes in vegetation distributions are expected to be most rapid and extreme at ecotones. Focusing research

on boundaries between vegetation types (woodland/grassland, rainforest/woodland) may give us the best chance of understanding early impacts.

### Monitoring change; early warning systems

Although long-term monitoring programs are in place for physical indicators such as sea level and climate variables, programs that cover vulnerable animals, plants and ecosystems are also needed. Species for which reliable historical records are available, and whose biology suggests may be sensitive indicators of climatic change, need to be identified and monitored. An excellent model for such a program is the set of 34 climatic, environmental and socioeconomic indicators selected in the UK (Cannell *et al.* 1999). A major goal for the future will also be to tackle the difficult task of untangling the signal of anthropogenic-induced climate impacts from the noise of background variation and land use change.

### Integration of research effort

The information compiled in this review indicates that climate change research in Australia has been somewhat fragmented. There is little collaboration between climate modellers and ecologists, although there is increasing recognition within the climate modelling community that incorporating biospheric feedback into climate models is important (A. Pitman, pers. comm.). But even within the ecological community, there is little integration between those monitoring long-term change, those modelling impacts on particular species and those doing experimental work on the direct physiological effects of changes in CO<sub>2</sub>, temperature and water availability. Interdisciplinary collaboration between climatologists, modellers, physiologists, palaeoecologists and resource managers, to name just a few, is urgently needed.

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