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Observed climate change in Australian marine and freshwater environments

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Abstract. The consequences of human activities increasing concentrations of atmospheric greenhouse gases are already being felt in marine and terrestrial environments. More energy has been trapped in the global climate system, resulting in warming of land and sea temperatures. About 30% of the extra atmospheric carbon dioxide has been absorbed by the oceans, increasing their acidity. Thermal expansion and some melting of land-based ice have caused sea level to rise. Significant climate changes have now been observed across Australia and its coastal seas. The clearest signal is the warming of air and sea temperatures and the rates of warming have accelerated since the mid-20th century. Ocean warming has been higher than the global average around Australia, especially off south-eastern Australia. Changes in Australia's hydrological regime are more difficult to differentiate from the high natural inter-annual variability. Recent trends towards drier winters in south-western Western Australia and part of southern Australia appear, however, to be largely attributable to human-induced climate change. Even without significant changes in average rainfall, warmer temperatures increase evaporative losses, enhance the intensity of recent droughts and reduce river flows. Sustained and coordinated monitoring of the physical environment, especially lacking for Australia's freshwater ecosystems, is important to assess the magnitude and biological consequences of ongoing changes.

Additional keywords: rainfall, temperature.

Introduction

Global climate warming is not a future event – observations and impacts from around the world show that in recent decades, the fingerprint of climate change is apparent (e.g. Root *et al*. 2003). The decade 2000–2009 was the warmest in the instrumental record period globally (Arndt *et al*. 2010) and 2001–2010 the warmest across Australia (Bureau of Meteorology 2011). Humans, and the natural and managed ecosystems that we rely on, are adapted to operate within a limited range of prevailing local climatic conditions – the coping range (Jones and Mearns 2005). These typical conditions are what we expect the weather to be like at a particular location and time of year on the basis of many years of observations and include both the average and the range of variability from year to year (Fig. 1). A climate change is, therefore, a significant change in what we expect the weather to be like at a particular location and season (Mitchell *et al*. 1966). The change could be in the average values and/or in the variability about the average (i.e. the range of extremes), which takes the system outside its coping range. Determining the nature and significance of climate changes requires long, consistent observations of the physical environment (e.g. Manton *et al*. 2001).

Climate change is not new – global and regional climates have varied in the past over a range of timescales because of several causes such as El Niño–Southern Oscillation (ENSO) events, Pacific Decadal Oscillation (PDO), volcanic aerosols and the amount of incoming solar radiation (Le Treut *et al*. 2007). We have, however, entered a new era of rapidly changing global climate as a consequence of human activities, where, unlike previous warming, increases in atmospheric carbon dioxide (CO_2) concentration are preceding temperature change (Jansen *et al*. 2007). Human activities over recent centuries are increasing the concentrations of greenhouse gases in the atmosphere (Forster *et al*. 2007). This is changing the global energy budget (Trenberth *et al*. 2009) and leading to current global warming (Trenberth *et al*. 2007). The atmospheric concentration of the main greenhouse gas, CO_2, has increased by ~40% since the late 18th century and is now at its highest in at least the past 800 000 years (Luthi *et al*. 2008). Not only are atmospheric concentrations of greenhouse gases rising, but the rate of increase is accelerating (Fig. 2*a*). The annual mean growth rate of CO_2 was 2.0 ppm year^{-1} for 2000–2007, compared with an average annual growth rate of 1.5 ppm year^{-1} for 1990–1999 (Canadell *et al*. 2007). In addition, about a third

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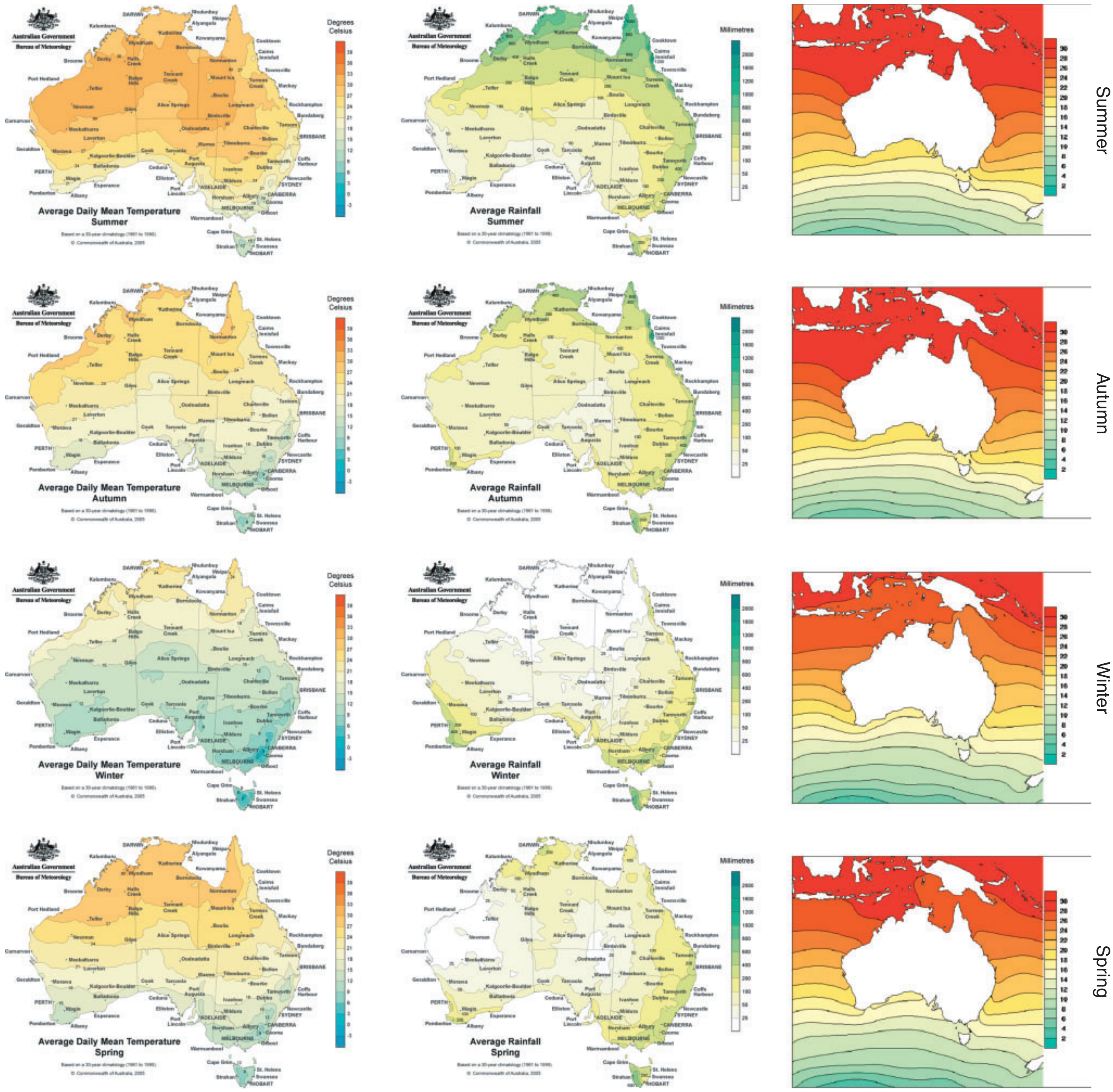

Fig. 1. Climate averages, 1961–1990, for Australia, for summer, autumn, winter and spring and air temperatures, rainfall and sea surface temperatures (data source: Bureau of Meteorology, available at www.bom.gov.au, accessed 18 October 2010).

of the extra CO_2 in the atmosphere has been absorbed by the oceans (if this had not occurred, warming would have been greater) and is changing their chemistry (Fig. 2*b*), with significant consequences for marine calcifying organisms (e.g. Doney *et al*. 2009). Combining instrumental observations of air temperatures over land and sea-surface temperatures (SSTs) clearly shows that the world has been warming since the mid-19th century and that the rate of warming is accelerating (Fig. 3). These trends cannot be explained as artefacts of measurement, despite the best hopes of climate-change deniers (Jones *et al*. 2005).

The high natural variability in the Australian climate means that assessing changes in the physical environment requires long periods of homogeneous instrumental observations. The availability of such data for all components of the physical environment of Australia's aquatic environments varies. The Bureau of Meteorology provides extensive and accessible surface-climate datasets (e.g. air temperature, rainfall, SSTs, sea-level pressure, tropical cyclone activity) that allow examination of temporal and spatial patterns and trends (Jones *et al*. 2009; Alexander *et al*. 2010). Additional observations are available from oceanographic databases; however, the more recently available

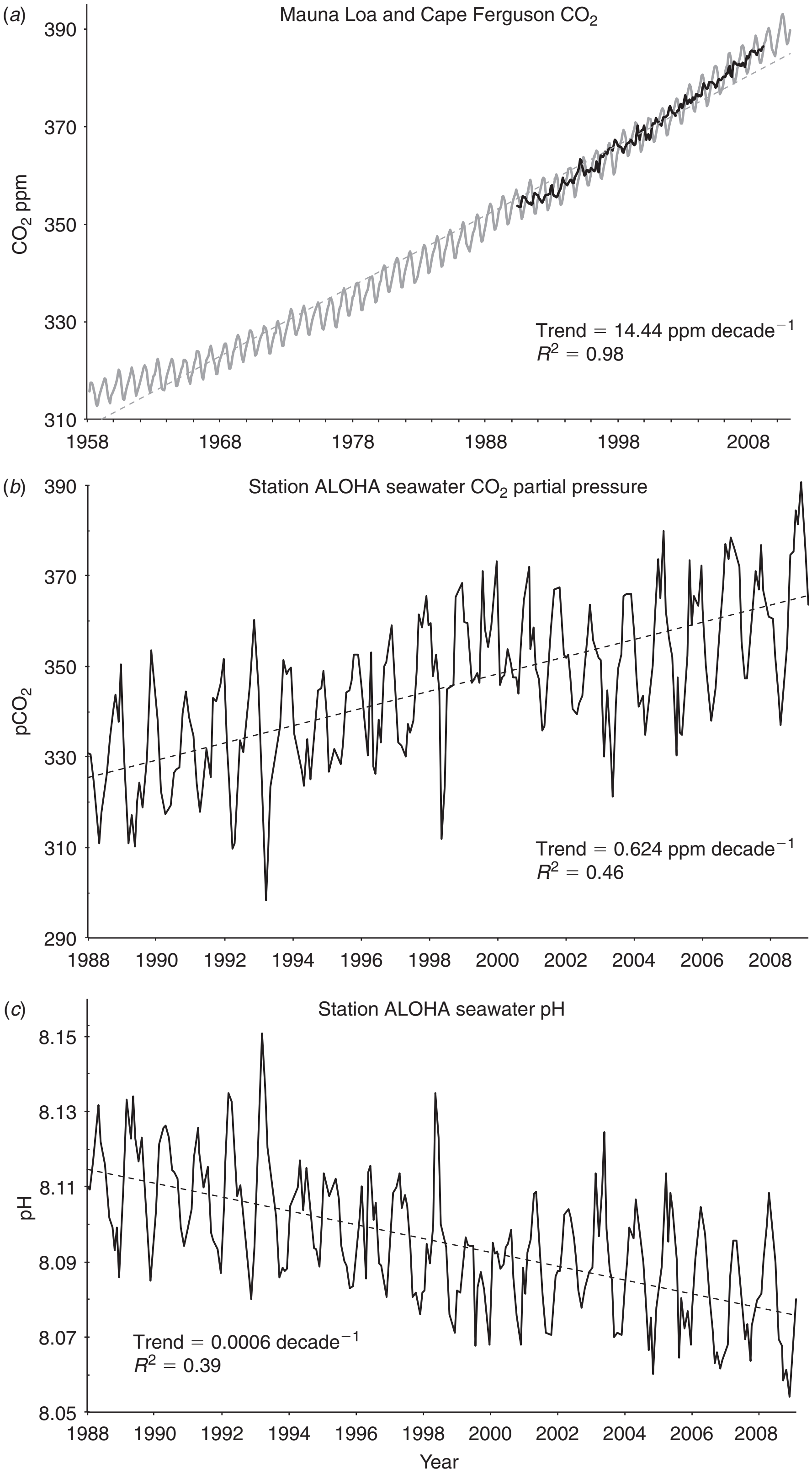

Fig. 2. (*a*) Monthly atmospheric carbon dioxide concentration (ppm) for Mauna Loa, Hawaii (grey, 1958–2010) and Cape Ferguson, Queensland (black, 1991–2009) (data sources: World Data Centre for Greenhouse Gases, available at http://gaw.kishou.go.jp/cgi-bin/wdcgg, accessed 23 June 2011; CSIRO), (*b*) monthly observations of partial pressure of seawater CO_2 and (*c*) pH measured *in situ* at Station ALOHA, northern Pacific, 1988–2009 (adapted from Dore *et al*. 2009).

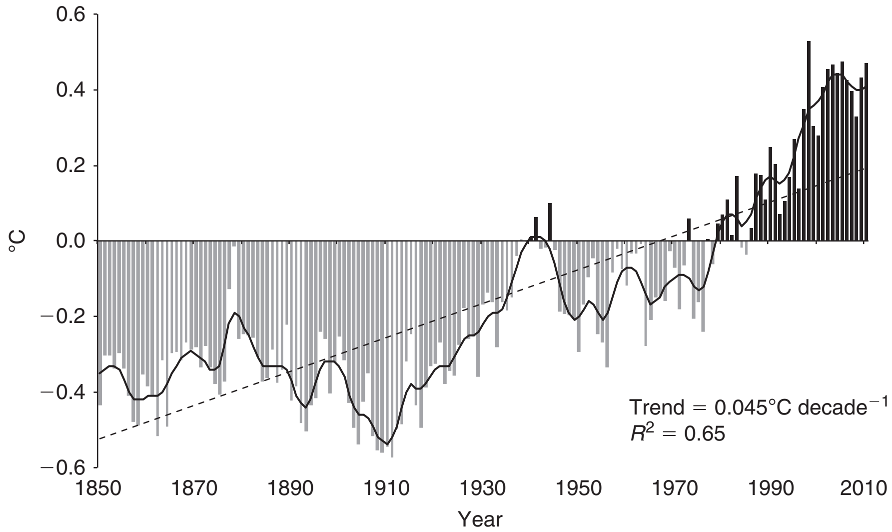

Fig. 3. Annual global land- and sea-temperature anomalies (from the 1961–1990 mean) for 1850–2010. Thick, solid line is 10-year Gaussian filter, emphasising decadal variability; dashed line is linear trend (data source: HadCRUTV3, available at www.cru.uea.ac.uk, accessed 23 June 2011; Jones *et al*. 1999; Brohan *et al*. 2006; Rayner *et al*. 2003, 2006).

satellite observations are too short term to detect robust trends that allow attribution. A centrally coordinated and standardised database for Australian freshwater resources is only now being developed (www.bom.gov.au/water; accessed 29 August 2011) and data are currently scattered amongst various regional archives. We, therefore, use air temperatures and rainfall as 'proxies' for surface-climate conditions that might affect freshwater environments.

Rapid global climate change is already occurring (Allison *et al*. 2009; Steffen 2009), with significant consequences for freshwater resources (Bates *et al*. 2008*a*). What changes have already been observed that might affect Australia's marine and freshwater aquatic environments? In the present paper, we review recent observational evidence for significant changes in Australia's surface climate. Is surface climate already changing, as projected by global climate models (Hobday and Lough 2011)? Current climate changes are set against the backdrop of the driest inhabited continent on Earth, with exceptionally high natural inter-annual rainfall variability, that places Australia on the 'climate change front line' (Palutikof 2010).

Marine environments

Temperature, freshwater input, sea level, ocean chemistry and the frequency of extreme events all control the makeup and physiological processes (e.g. distribution, ranges, community composition, community dynamics, seasonal timing of spawning) of species in Australia's marine ecosystems (e.g. Poloczanska *et al*. 2007; Hobday *et al*. 2008). These ecosystems range from the open ocean to shallow-water coastal regions that encompass complex spatial and temporal variations in their physical environment. Long-term observational studies have tended to be biased to open-ocean conditions. Here, we describe some of the observed physical changes around Australia.

Sea-surface temperatures

Significant warming is already evident in Australia's surrounding oceans (Lough 2009). Globally, SSTs at comparable latitudes to Australian waters have significantly warmed (Fig. 4*a*), with recent average temperatures (1980–2009) 0.41°C higher than those in the early 20th century (1910–1939). Over the same period, the warming of Australian waters has been of greater magnitude, 0.57°C (Fig. 4*b*). The rate of warming around Australia in all seasons has accelerated in recent decades and also shows a spatial signature, with greatest warming off the south-eastern and south-western coasts (Fig. 4*c*). For Australia's coastal waters, between 10.5°S and 29.5°S, this warming has already resulted in southward shifts of climate zones by >200 km along the eastern coast and by ~100 km along the western coast (Lough 2008). The evidence for significant ocean warming both at the surface and through the water column is supported by both global SST compilations, such as those presented in Fig. 4*c*, and continuous *in situ* coastal observations (e.g. Holbrook and Bindoff 1997; Alory *et al*. 2007; Ridgway 2007; Caputi *et al*. 2009; Lough *et al*. 2010). This warming has been accompanied by increasing sea-surface salinity (Pearce and Feng 2007; Thompson *et al*. 2009), which is related to a worldwide signature (Helm *et al*. 2010).

Sea level

Globally, average sea level has risen ~20 cm since the late 19th century (Fig. 5*a*), largely as a result of thermal expansion, with a relatively minor contribution, so far, from melting land ice (Bindoff *et al*. 2007). The rate of sea-level rise has accelerated recently and is now at the upper end of the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) projections (Rahmstorf *et al*. 2007; Church *et al*. 2008). Although, on the basis of monitoring systems that started only in

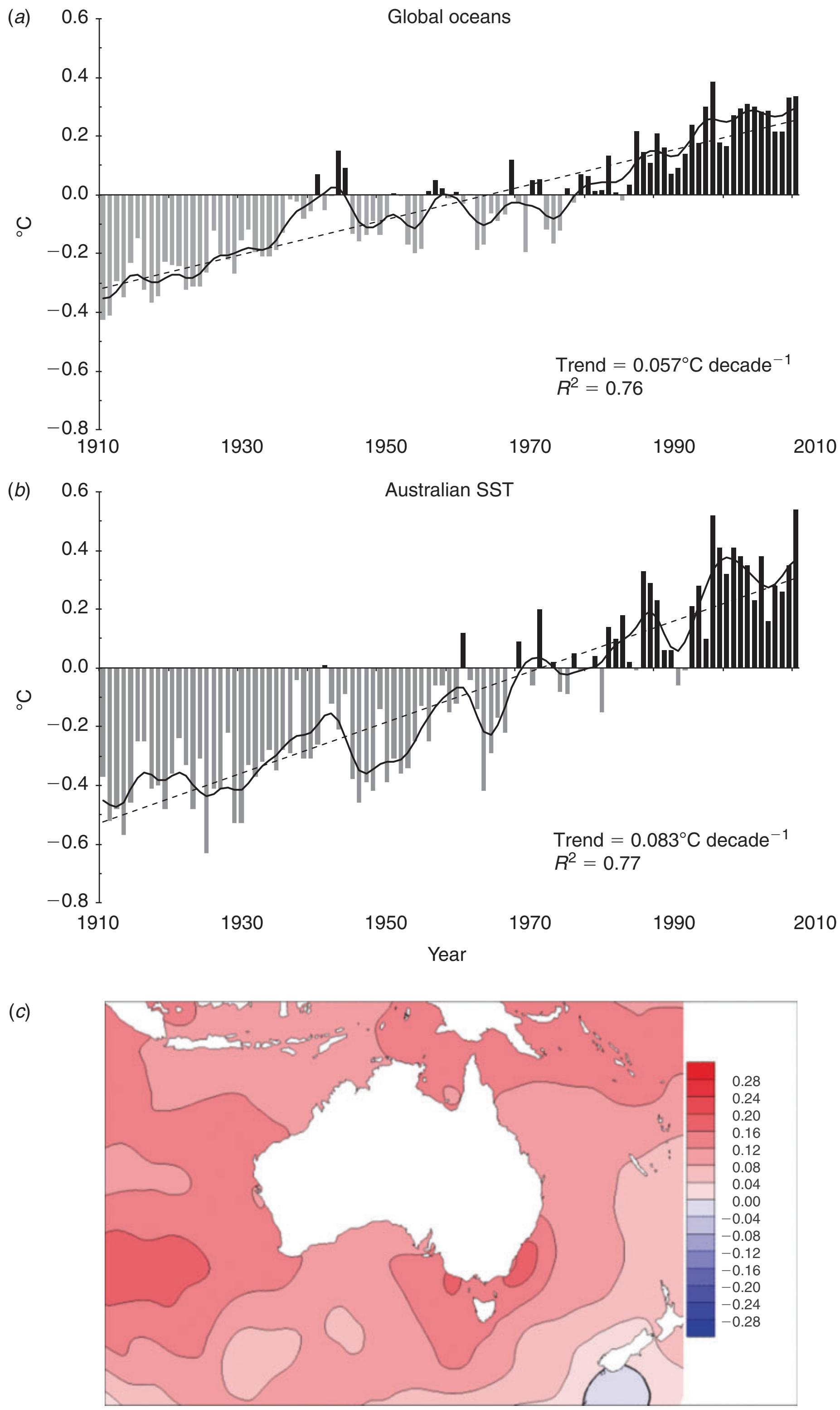

Fig. 4. Annual sea surface-temperature anomalies (from the 1961–1990 mean) for 1910–2010. (*a*) Global oceans, 45°N–45°S, (*b*) Australian region (see Fig. 1) and (*c*) linear trend (°C per decade) of annual sea-surface temperatures, 1950–2010 (data sources: HadISST; Bureau of Meteorology, available at www.bom.gov.au, accessed 22 June 2011). Thick, solid line is 10-year Gaussian filter, emphasising decadal variability; dashed line is linear trend.

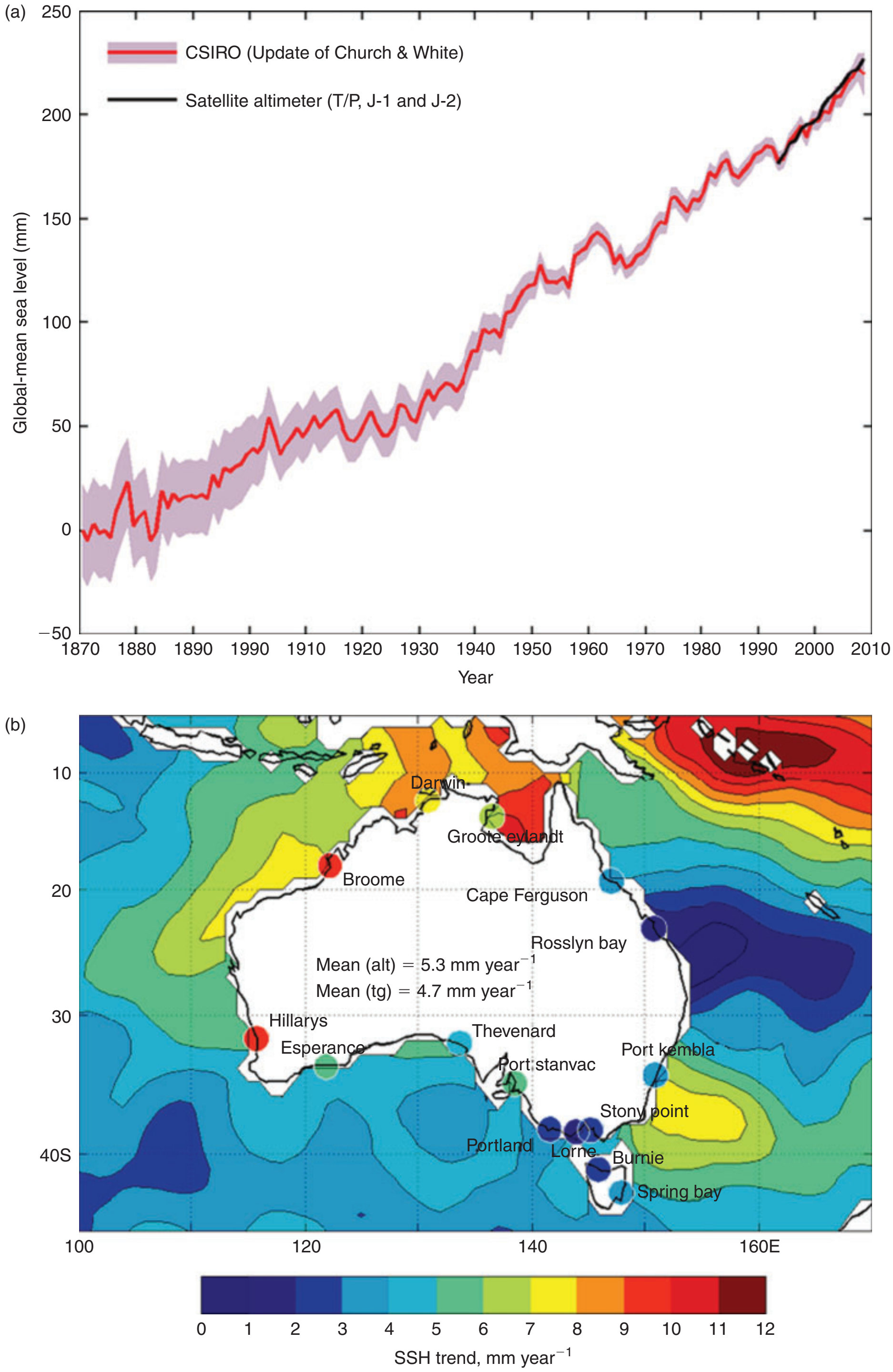

Fig. 5. (*a*) Global sea level, 1870–2008 (Church and White 2006; Church *et al.* 2009; www.cmar.csiro.au/sealevel, accessed 23 June 2011, and (*b*) net relative sea-level trend, mm year^{-1}, from early 1990s through June 2009 (Bureau of Meteorology, available at www.bom.gov.au/oceanography, accessed 23 June 2011; Church *et al.* 2009).

the early 1990s (see National Tidal Centre: www.bom.gov.au/oceanography; accessed 29 August 2011), making the significance of trends difficult to confirm, observed recent sea-level rise around Australia's coastline has been lower along the central eastern coast and greater along the western and northern coasts (Fig. 5*b*). This regional variation in the magnitude of sea-level rise is linked with inter-annual climate variability (e.g. owing to ENSO), and changes in ocean (e.g. increased southward penetration of the East Australian Current, EAC) and atmospheric circulation dynamics (Church *et al*. 2009).

Sea-level rise is not, therefore, uniform. The Indian Ocean, for example, shows considerable spatial complexity in recent observed sea-level changes, partly owing to changes in atmospheric circulation patterns (Han *et al*. 2010). Rising sea level also affects the frequency of extreme sea-level events affecting the coast. Sydney (eastern Australia) and Fremantle (south-western Australia) both have long-term records back to the 1920s and these show that the occurrence of extreme sea-level events (defined by the 0.01 percentile) has become three times more frequent in the period after 1950 than in earlier years (Church *et al*. 2006).

Ocean currents

Australia is unique in having warm, poleward-flowing currents along both its eastern (EAC) and western (Leeuwin Current) coasts, which results in, for example, significant coral reefs and coral communities along both coastlines (Lough 2008). Evidence is emerging for significant changes in the EAC which, over the period 1944–2002, has increased its southward penetration by ~350 km, bringing warmer and saltier waters further south (Ridgway 2007; Hill *et al*. 2008). The oceanography of some of Australia's marine environments, such as the Great Barrier Reef, are especially complex (Steinberg 2007) and requires improved understanding of the linkages between large-scale and meso- and lower-scale processes to begin to document potential changes in circulation patterns (e.g. Weeks *et al*. 2010). The nationally coordinated and standardised ocean-observing systems (integrated marine observing system, IMOS, http://www.imos.org.au/; accessed 29 August 2011) will significantly improve our understanding of changes to ocean circulation.

Ocean chemistry

Changes in water chemistry, as a result of the oceans absorbing about a third of the anthropogenic CO_2 injected into the atmosphere, are highly likely to have significant consequences throughout Australia's marine ecosystems, especially those involving organisms that form skeletons and shells (Kleypas *et al*. 2006; Hoegh-Guldberg *et al*. 2007; Moy *et al*. 2009). The pH of the global oceans has already decreased by 0.1 (termed ocean acidification) and this decline is likely to have also occurred within Australia's marine environments (Feely *et al*. 2004; Sabine *et al*. 2004). Assessing baseline conditions, changes and potential biological consequences requires long-term monitoring of the chemistry of Australia's open-ocean and coastal marine waters (Howard *et al*. 2009). We do not, for example, have the long-term perspective available from the Bermudan (BATS, available at http://bats.bios.edu/; accessed 29 August 2011) or Hawaiian (HOTS, available at http://hahana.soest.hawaii.edu/hot/; accessed 29 August 2011) ocean-chemistry time series (e.g. Dore *et al*. 2009). Assessments of change in Australian and much of the world's oceans have relied on repeated and irregular oceanic observations rather than continuous time series (e.g. Borges *et al*. 2008; Takahashi *et al*. 2009). In addition, most measurements have been made for open-ocean waters, which are not representative of coastal waters (e.g. McNeil 2010). We still know very little about baseline, and variation in, ocean-chemistry conditions in Australian waters, which appear to be particularly complex and variable in both space and time in tropical coral-reef ecosystems (e.g. Gagliano *et al*. 2010). Indeed, coral-reef communities themselves can alter water chemistry (e.g. Anthony *et al*. 2011). Improving the observational record of ocean chemistry around Australia is a significant focus of IMOS.

Freshwater environments

Australia's freshwater environments range from ephemeral billabongs and inland lakes, seasonal creeks and rivers, to permanent tropical rivers. High inter-annual variation in rainfall leads to a range of species and systems that can cope with water shortage. However, the combination of landscape modification as a result of European settlement and agriculture, and climate change is stressing many systems (Balcombe *et al*. 2011). Flow into rivers is related to air temperatures, rainfall and extreme events (tropical cyclones and storms).

Surface air temperatures

Warming of air temperatures over land areas is one of the clearest signals of a rapidly changing climate system, and rates of warming are greater than for the oceans. Globally, air temperatures over the period 1980–2009 were 0.62°C higher than those in 1910–1939 (Fig. 6*a*). Over the same time period, air temperatures over Australia increased by 0.70°C (Fig. 6*b*). As with SSTs in Australian waters, air temperatures over the continent are warming faster than the global average. Warming is evident across almost the entire country (Fig. 6*c*) and the rate of warming has accelerated in recent decades (Lough 2009). Observed warming is now clearly attributable to increases in atmospheric greenhouse-gas concentrations both globally (Trenberth *et al*. 2007) and across Australia (Karoly and Braganza 2005).

Increasing air temperatures across Australia are resulting in changes in temperature extremes, which match model expectations (Alexander *et al*. 2007; Alexander and Arblaster 2009). Higher mean maximum and minimum temperatures are leading to more hot days and warm nights and fewer cool days and cold nights across Australia (Chambers and Griffiths 2008; Hennessy *et al*. 2008). Trewin and Vermont (2010), for example, examined record high and low temperatures over the period 1957–2009, when mean daily maximum and minimum air temperatures increased by ~0.7–0.8°C. They found that record-low temperature extremes dominated the earlier part of the record and record-high temperature extremes dominated the most recent decades. Thus, for example, the most extreme maximum daily temperatures occurred on average 13.3 times per decade (20.4 per decade for extreme lows) from 1957 to 1966, whereas for 1997 to 2009, the highs occurred almost twice as frequently (22.5 per decade) and the lows almost half as frequently (9.3 per decade).

Rainfall and river-flow variability

Rainfall is highly seasonal and exhibits high inter-annual variability across much of Australia. Australian freshwater ecosystems are sensitive to both seasonal flows, e.g. in the dry

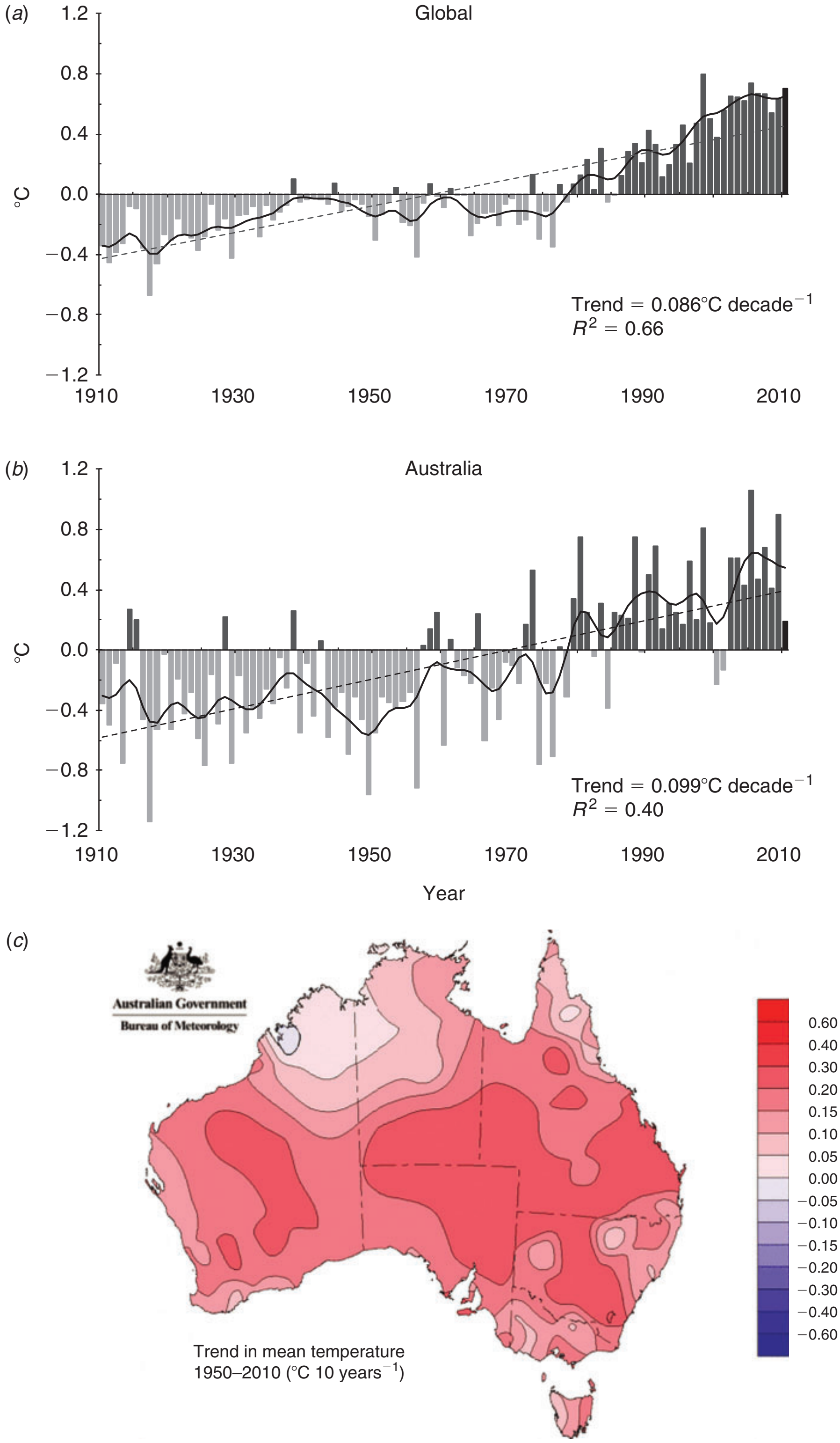

Fig. 6. Annual air-temperature anomalies over land (from the 1961–1990 mean) for 1910–2010, for (*a*) global land area and (*b*) Australia, and (*c*) linear trend (°C per decade), 1950–2010 (data sources: CRUTEMP3v, available at http://www.cru.uea.ac.uk/cru/data/temperature/, accessed 23 June 2011; Bureau of Meteorology, available at http://www.bom.gov.au/cgi-bin/climate/change/trendmaps.cgi, accessed 23 June 2011). Thick, solid line is 10-year Gaussian filter, emphasising decadal variability; dashed line is linear trend.

tropics of northern Australia (Pusey and Kennard 2009; Abrantes and Sheaves 2010), and to recent droughts in southern Australia, the effects of which are being compounded by human interventions in natural river systems (e.g. Bond *et al*. 2008). Highly variable river flows regulate many processes in freshwater environments and the spatial and temporal variability, both seasonally and inter-annually, play a significant role in shaping ecosystem dynamics (e.g. Leigh *et al*. 2010; Puckridge *et al*. 2010). Although of primary interest for freshwater ecosystems, the extent to which we can develop a coherent view of river-flow variations across Australia is still limited by the lack of a nationally integrated and centralised data repository, although this is now being developed (www.bom.gov.au/water; accessed 29 August 2011). We, therefore, focus on the high-quality observations of rainfall provided by the Australian Bureau of Meteorology as a 'proxy' for river flows.

Although clear evidence is now emerging for a recent acceleration in the global hydrological cycle (Helm *et al*. 2010), assessing the magnitude and significance of observed rainfall changes across Australia is hampered by the high inter-annual rainfall variability. High rainfall variability results in Australian river flows being among the most variable in the world (Finlayson and McMahon 1988). Seasonal, inter-annual and longer-term rainfall variability across Australia is largely controlled by several external factors recently summarised by Risbey *et al*. (2009; see also the useful summary of Australian climate influences provided by the Australian Bureau of Meteorology at http://www.bom.gov.au/watl/about-weather-and-climate/australian-climate-influences.shtml; accessed 29 August 2011). ENSO events have long been recognised (e.g. Troup 1965; Allan *et al*. 1996) as the primary source of inter-annual variability across much of the country, although with effects varying across seasons and region. Again, river flows in eastern Australia stand out in a global context as being particularly sensitive to ENSO events (Ward *et al*. 2010).

Additional sources of Australian rainfall variability include the Madden–Julian Oscillation (MJO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM). The MJO operates on within-season (30–60-day) time scales and is an eastward-moving progression, from the western Indian Ocean to the central Pacific Ocean, of enhanced and suppressed deep atmospheric convection, associated with active (high-rainfall) and break (low-rainfall) periods during the northern Australian summer monsoon. (Wheeler *et al*. 2009). The IOD is a coupled ocean–atmosphere phenomenon operating on inter-annual time scales and characterised by opposite-sign sea surface-temperature anomalies in the western and eastern tropical Indian Ocean (Saji *et al*. 1999). The two phases, positive or negative IOD, primarily affect winter and spring rainfall across south-western and south-eastern Australia, bringing drier or wetter conditions, respectively (Ummenhofer *et al*. 2011). The SAM is a significant source of variability of the mid–high-latitude southern hemisphere atmospheric circulation associated with latitudinal shifts in the strength of the mid-latitude westerlies (Thompson and Wallace 2000). Fluctuations between the two phases affect the incidence of storm (rain-bearing) activity across southern Australia (Hendon *et al*. 2007).

The strength of the linkages (teleconnections) between ENSO events and Australian rainfall fluctuates on interdecadal time scales, as modulated by the PDO (Mantua *et al*. 1997; Power *et al*. 1999). During PDO cool phases, the teleconnections between ENSO and eastern Australian rainfall tend to be stronger, with more coherent rainfall anomalies and higher rainfall variability than during PDO warm phases (Kiem *et al*. 2003; Meinke *et al*. 2005). La Niña events that occur during PDO cool phases result in river floods in eastern Australia of twice the magnitude of those during regular La Niña events (Verdon *et al*. 2004).

In addition, although showing several common features, no two El Niño or La Niña events evolve in exactly the same way (Trenberth and Stepaniak 2001). More recently, it has been suggested that ENSO events have shifted from those dominated by warming or cooling centred in the eastern equatorial Pacific to events (termed ENSO–Modoki) characterised by warming or cooling in the central equatorial Pacific (Ashok *et al*. 2007). Whether this is a signal of 'global warming' is not yet clear; however, the two types of ENSO appear to produce different rainfall-anomaly patterns across Australia. ENSO–Modoki events are associated with greater rainfall anomalies across north-western and northern Australia (to the northern Murray–Darling Basin) than are the traditional ENSO events, where the main effects (droughts or floods) are seen in eastern Australia (Cai and Cowan 2009; Taschetto and England 2009*a*).

Rainfall changes

Compilations of reliable observations by the Bureau of Meteorology allow confident assessment of spatial and temporal variations in Australian rainfall back to the early 20th century (Jones *et al*. 2009). Additional insights into Australian rainfall variability over longer timescales than the instrumental observations can also be obtained from high-resolution proxy climate such as tree rings (e.g. Cullen and Grierson 2009) and corals (e.g. Lough 2011). Given the high degree of inter-annual and decadal variability, assessing the reality and significance of frequency of rainfall extremes and changes in average rainfall is more difficult and particularly dependent on the chosen analysis period (CSIRO and Australian Bureau of Meteorology 2007; Gallant *et al*. 2007; Hennessy *et al*. 2008). For example, much of eastern Australia experienced wetter conditions in the 1950s and 1970s (Lough 2011) (Fig. 7). There is, therefore, some disagreement in published analyses of Australian rainfall trends as to the nature and significance of recently observed trends and whether they can be attributed to global climate change. Even if rainfall is unchanged, warmer air temperatures increase rates of evaporation of water; coupled with increased demands by human societies and population growth, climate change will significantly alter inland river systems.

The trend to wetter summer conditions in north-western Australia appears to be a relatively clear (Shi *et al*. 2008; Smith *et al*. 2008), as are declines in winter rainfall in south-western Western Australia (WA) and part of the south-west of south-eastern Australia (Fig. 7). Variations in winter rainfall in the latter two regions are linked because rainfall-bearing disturbances typically track across both regions. The recent declines in winter rainfall in the two areas have been plausibly linked to significant southward shifts in these rainfall-bearing disturbances and storms. This appears to be part of significant changes

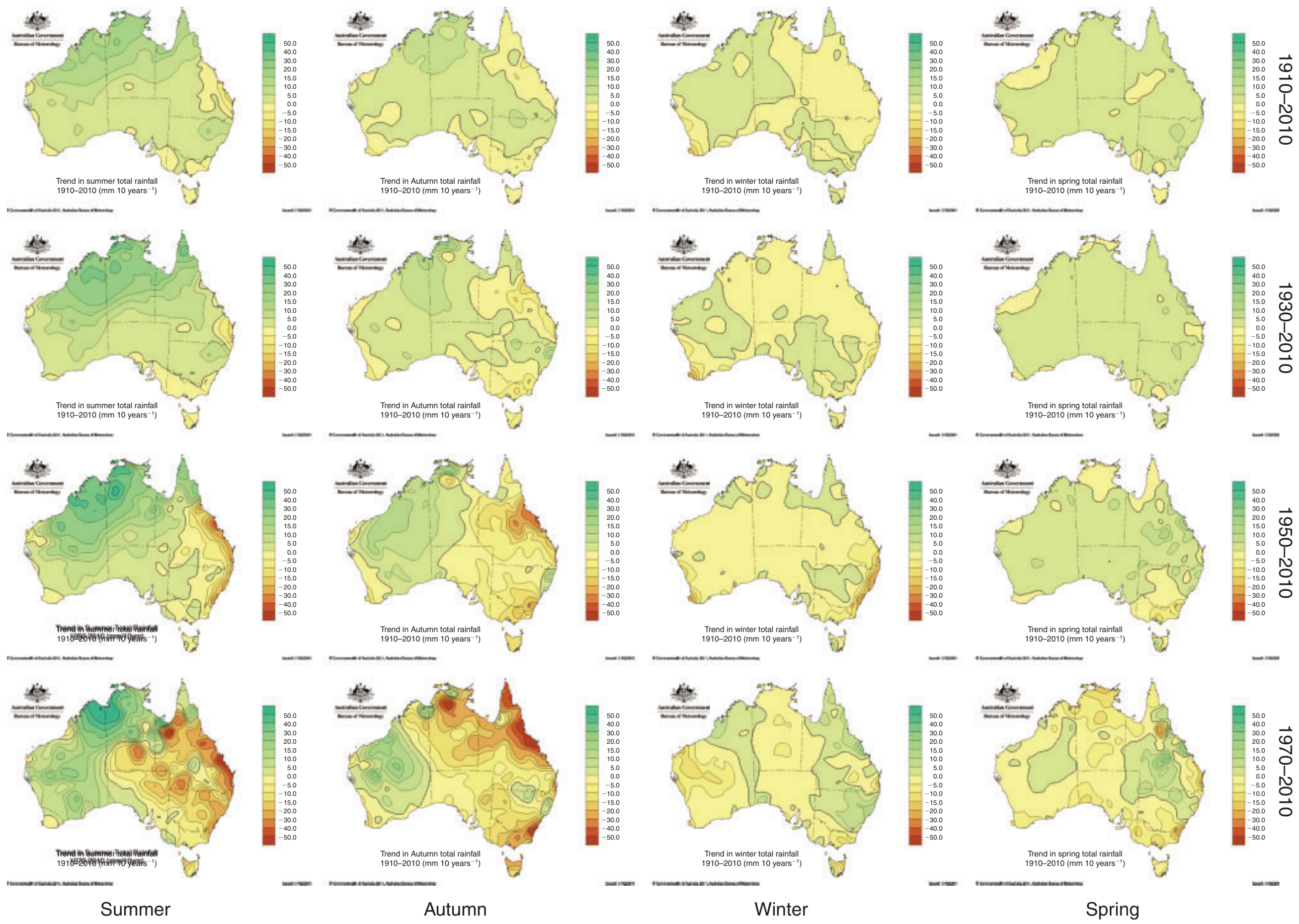

Fig. 7. Linear trends in seasonal rainfall totals (mm per decade) for time periods 1910–2010, 1930–2010, 1950–2010 and 1970–2010 (data source: Bureau of Meteorology, available at http://www.bom.gov.au/cgi-bin/climate/change/trendmaps.cgi, accessed 23 June 2011).

in the larger-scale atmospheric circulation patterns, with a higher sea-level pressure over southern Australia, a more intense subtropical ridge along the eastern coast and a more positive phase of SAM which reflects a contraction southward of the main southern hemisphere westerly wind belt (Larsen and Nicholls 2009; Alexander *et al*. 2010; Hope *et al*. 2010; Nicholls 2010). Another contributing factor to the recent decline in winter and spring rainfall in south-eastern Australia are recent increases, compared with the early 20th century, in the frequency of positive IOD events, which are consistent with projected changes expected with continued global warming (Cai *et al*. 2009). The 15–20% decline in winter rainfall since the 1970s has been suggested to have changed the hydrological regime of south-western WA from perennial to ephemeral streams (Petrone *et al*. 2010) and is also associated with significant (up to 50%) reductions of inflows into dams (Bates *et al*. 2008*b*).

Widely reported declines in eastern Australian rainfall (e.g. CSIRO and Australian Bureau of Meteorology 2007) appear, at least for Queensland, to be largely confined to the south-eastern part of the state and become apparent only when records from the late 20th century are considered (Smith 2004; Taschetto and England 2009*a*, 2009*b*). Steffen (2009) suggested that the 'drying connection' in northern and eastern Australia is 'not yet clear' and that attribution of recent declines in the eastern-coast rainfall are confounded by decadal influences, with higher rainfall characterising the 1950s and 1970s.

Recent reductions in rainfall are, however, compounded by warming air temperatures (Nicholls 2004) and this leads to a greater reduction in river flows than caused by reduced rainfall alone, because of evaporation as water moves across the landscape. For the Murray–Darling Basin, Cai and Cowan (2008) examined the 2001–2007 drought and found that a warming of 1°C resulted in 15% reduction in inflows. A more recent study (Yu *et al*. 2010) suggested that this sensitivity to temperature might be an underestimate. Stream flows decreased by 55% for the Murray–Darling Basin whereas rainfall declined by only 11%, as a result of this temperature effect (Steffen 2009). Similarly, Murphy and Timbal (2008) provided evidence that recent drought conditions in south-eastern Australia were more extreme than earlier rainfall deficits because of warmer air temperatures.

Tropical cyclones

Large volumes of freshwater can be deposited via rainfall during extreme events, such as tropical cyclones, which subsequently floods the landscape and flows into rivers and lakes. There is still debate as to whether we are seeing any significant changes in the occurrence and frequency of tropical-cyclone activity globally (e.g. Emanuel 2005; Elsner *et al*. 2008). Nicholls *et al*. (1998) provided evidence of an apparent decline in numbers of weak tropical cyclones in the Australian region over the period from 1969–1970 to 1995–1996 on the basis of satellite observations. They suggested that this trend was, in part, due to improved discrimination through time of tropical cyclones from other tropical storms, and also noted a weak increasing trend for the most intense tropical cyclones. By comparing the eastern and western Australian tropical-cyclone regions, Hassim and Walsh (2008), while examining the period from 1969–1970 to 2004–2005, provided some evidence that the number, duration and maximum intensity of severe tropical cyclones off WA have been increasing since the 1980s; however, in the eastern region, the number has decreased, with no obvious trend in either intensity or duration. There has been no observed change in the latitudinal distribution of tropical-cyclone activity.

Improved monitoring for Australia's aquatic environments

To predict the biological consequences of ongoing climate change, we need sustained monitoring to determine average conditions, seasonal cycles and inter-annual and longer-term variability and detect trends in Australia's aquatic environments – this information will also be critical in management responses to climate variability and change (e.g. Murray–Darling Basin Authority 2010). The extent to which we can do this varies considerably. Australia has, for example, many high-quality, homogenous and ongoing records of weather elements over land that allows detection and, in some cases, attribution of recent trends in air temperatures and rainfall. Global compilations of ships-of-opportunity measurements at sea (now routinely blended with satellite observations), especially of surface-water temperatures, also provide a high level of confidence in the nature and significance of recent warming trends in Australian marine waters.

There is, however, much room for improvement and we can never underestimate the value of establishing and maintaining long-term monitoring stations with common sampling techniques and data-quality standards (e.g. Pearce and Feng 2007). Maintenance of just four coastal monitoring sites for over 60 years has provided significant insights into both physical and chemical changes in the marine environment (Thompson *et al*. 2009), yet also leaves considerable uncertainty in other regions. Achieving comprehensive geographic coverage in a country the size of Australia is a challenge, but 'necessary if we wish to understand the impacts of climate variability and the consequent implications for our marine ecosystems' (Thompson *et al*. 2009: p. 16).

The IMOS has set a new standard for observing and understanding processes in Australia's varied marine environments that can provide the necessary data to link physical and biological processes (e.g. Lough *et al*. 2010). The value of the IMOS initiative will only increase through time and it is essential that the national commitment for its ongoing support and funding is maintained. The publicly accessible data will be critical not only for attributing changes in the environment, but for interpreting changes in the biology of adjacent systems.

For Australia's freshwater environments, there have been many calls for more organised and integrated monitoring (e.g. Davies *et al*. 2010; Lake *et al*. 2010; Tomlinson and Davis 2010). As noted by Bond *et al*. (2008), the responses by both scientists and resource managers to drought in our freshwater environments have been 'haphazard and uncoordinated'. We are, for example, unable to examine long-term changes in freshwater temperatures, which have been shown to be increasing also in parts of the USA and Europe (e.g. Webb and Nobilis 2007; Kaushal *et al*. 2010). The establishment in New Zealand of the National River Water Quality Network, which undertakes standardised physical and chemical monitoring of 77 sites on 35 rivers, now provides continuous time series back to 1989 (Davies-Colley et al. 2011). As with any monitoring program, the value of sustained high-quality measurements only increases with time, and the New Zealand example allows insights into biological, physical and chemical linkages and changes, which would not be obtainable otherwise (e.g. Scarsbrook *et al*. 2000, 2003).

Australia is not bereft of significant observations of the physical, chemical and biological characteristics of its freshwater environments, some of which extend back to the early 20th century (e.g. river flows). However, such data are scattered through State and Territory water authorities and individual scientists' or scientific organisations' research programs. The future does look brighter with the recent establishment within the Australian Bureau of Meteorology of the Australian Water Resources Information System (AWRIS; www.bom.gov.au/water; accessed 29 August 2011) as a consequence of the *Water Act 2007*. At the core of the AWRIS will be a centralised and nationally consistent system for storage and retrieval of current and historical water data. Among its many objectives, of particular significance for understanding change in Australia's freshwater environments are the commitments to modernise and extend water-monitoring systems and provide a centralised database of river flows and water-quality parameters.

Conclusions

Observational records show that both global climate and that of the Australian region are already significantly changing as a result of human activities changing the composition of the atmosphere and changing the energy balance of the global climate system. The extent to which observed significant changes (detection) can be attributed to human-induced changes in the atmospheric composition of greenhouse gases (attribution) (Hegerl *et al*. 2007) varies between marine and freshwater systems, as well as regionally. It is very likely that the widespread warming of air temperatures across Australia and surface ocean temperatures in the surrounding seas can be attributed to human-induced radiative forcing. Similarly, the observed increase in north-western summer rainfall and decreased winter rainfall in the south-west of Western Australia and south-eastern Australia are consistent with greenhouse-gas forcing (Nicholls 2006, 2010; Cai *et al*. 2009; Steffen 2009). Attribution of recent eastern coast rainfall declines are, however, confounded by decadal influences, with higher rainfall characterising the 1950s and 1970s. Even without significant changes in average rainfall totals, warmer temperatures are already exacerbating the severity of Australian droughts (Ummenhofer *et al*. 2009), significantly affecting the availability of freshwater resources.

Understanding the consequences of rapidly changing environmental conditions for Australia's marine and freshwater ecosystems requires high-quality and sustained physical and biological observations. Australia has a particularly good, by international standards, observational database of terrestrial and open-ocean climate variables, mainly obtained for meteorological purposes. We still, however, lack sufficient historical and ongoing physical observations of shallow-water coastal and freshwater systems to adequately describe baseline conditions for different ecosystems, to determine environmental controls on ecosystem processes, and to assess how these environments may have changed and thus allow projections of future ecosystem responses. In both marine and freshwater systems, the observed physical changes described here are projected to continue for the next 50–100 years (Hobday and Lough 2011) and there are likely to be environmental changes that have not, as yet, emerged from the background of high natural variability in Australia's physical environment. Both human and biological systems will be challenged in their ability to adapt. Without successful greenhouse-gas mitigation, significant disruption to Australia's marine and freshwater environments and their ecosystems is almost certain.

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