Observational data reveal significant climate change in and surrounding Australia over the last century. Selected and quality-controlled surface observations from mostly rural sites are used, ensuring that the observed variability and trends reflect those occurring in the broader atmosphere and are generally not due to local factors. Changes in the ocean environment are less abrupt due primarily to the large heat content of the ocean. Further, there have been far less long-term oceanic observations. Therefore determination of ocean climate changes uses indirect evidence in addition to direct observations. To put recent changes in a historical perspective, palaeo-records that go back far beyond the instrumental record are also provided.

2.1 Surface temperature

Australia’s annual mean surface air temperature has increased since 1910 (the time when reliable records in many parts of Australia became available) by about 0.9°C. The first half of last century shows very little overall trend in temperatures, with higher temperatures tending to coincide with major drought years such as 1914-15 and 1938, while wetter periods, such as the 1950s, showed lower temperatures (Figure 2.1). From 1910 to 1950 annual mean Australian temperatures went down slightly, driven largely by increasing rainfall and lower daytime temperatures across eastern Australia. Since 1950, a warming trend of 0.16°C per decade occurred. This rate is nearly double the observed trend over the century as a whole (0.09°C per decade) and is comparable with the global trend since 1970. The year 2005 holds the record as Australia’s warmest year since 1910 with a national average temperature of 22.9°C, 1.1°C above the 1961 to 1990 average, and 2.2°C warmer than the coldest recorded year observed in 1917. The spatial variation in the trends since 1910 is depicted in Figure 2.2. Trends have not been uniform across the country, ranging between 0.05-0.15°C per decade. Largest changes occurred in parts of central Australia, with small pockets of lesser warming in various locations. Spatial variation in temperature trends since 1950 are also evident (Figure 2.2). Maximum warming (exceeding 0.3°C per decade) occurred in central-eastern Australia and minimum warming/slight cooling over north-west Australia.
Accompanying the general warming since 1950 have been changes in the frequency of extremely high and low temperatures across Australia (Figure 2.3). From 1957, the Australian-average shows an increase in hot days, an increase in hot nights, a decrease in cold days and a decrease in cold nights (Nicholls and Collins 2006). The increase in the number of hot days was overlaid on considerable interannual variability largely linked to the swings from wet to dry years. For example, the severe drought year of 2002 was accompanied by a large number of hot days while the wet years from 1999 through 2001 saw relatively few hot days.

2.2 Precipitation, drought, pan evaporation, wind and stream flow

2.2.1 Precipitation

Similar to temperature trends, rainfall trends show a marked contrast between the first half of the last century and the period since 1950. Rainfall trends from 1900 to 1949 were generally rather weak and spatially incoherent. It is unclear whether the lack of substantial trends reflects the weak influence of global warming over this period or if it is simply a product of sampling only 50 years. In contrast, the rainfall trends across Australia since 1950 are both large and spatially coherent (Figure 2.4). North-west Australia has seen an increase in annual rainfall over this period, amounting to more than 30 mm per decade across the north-west third of Australia and exceeding 50 mm per decade on parts of the north-west coast. In marked contrast, eastern and south-western Australia have become drier since 1950, with largest drying along the east coast exceeding 50 mm per decade. Across New South Wales and Queensland these trends partly reflect a very wet period around the 1950s, though recent years have been unusually dry. In the south-west of Western Australia the rainfall decline reflects an apparent step-change to lower rainfall in the 1970s, exacerbated by very low rainfall in recent years. Across Victoria, the trends reflect a combination of a very wet 1950s and an extremely dry last decade. The last decade takes the form of a step-change similar to that which occurred around Perth in the 1970s, with many parts of southern and central Victoria having experienced their driest 10-year period on record.

Figure 2.3: Time series of the annual average number of hot days (>35°C), cold days (<15°C), hot nights (>20°C) and cold nights (<5°C) in Australia. Dotted lines represent linear trends. (Courtesy of National Climate Centre, Bureau of Meteorology.)

Figure 2.4: Trend in annual mean Australian rainfall since 1950. Units are mm per decade.
The last 5 to 10 years mark one of the most severe droughts in Australia’s history (Trewin 2006). Figure 2.5 shows the rainfall deciles for March 2002 to December 2006. (A decile is a proportion of a set of data that has been ranked and divided into ten groups, where each group contains an equal number of data items.) This period starts with the onset of the 2002 El Niño event. Over this period very low rainfall was experienced across eastern Australia, with record low rainfall in key catchment areas of the Murray and Darling rivers and water catchments for Sydney, Canberra and Melbourne.

Australian rainfall shows considerable variability from year-to-year, partly in association with the El Niño – Southern Oscillation (ENSO). Notably dry years such as 1902, 1972, 1982 and 2002 all coincide with major El Niño events, while the very wet years such as 1973, 1974, 1999 and 2000 coincide with La Niña events. Exceptions to this strong ENSO-linked interannual variability are extended periods of above or below average rainfall, such as the Federation Drought, which extended from the mid 1890s through to 1902; the lowest rainfall decade on record during most of the 1940s (in most of the south-east of Australia – Murphy and Timbal 2007); and the very wet period during the early 1970s.

An extreme rain event is defined as an event where the total rain recorded within a period of consecutive days exceeds a nominated threshold value. Annual rainfall variations are primarily caused by variations in intensity of extreme events. Trends in nine daily rainfall indices were examined from January 1910 to August 2005 using an updated high-quality rainfall dataset from the Australian Bureau of Meteorology (Gallant et al. 2007).

Figure 2.5: Rainfall deciles for the drought which commenced in March 2002.

Extreme daily rainfall was defined by the 95th and 99th percentiles for six regions in the east and south-west of Australia. In the eastern central region, from 1910-2005, there have been significant increases in spring and annual rain days and extreme rainfall intensity (95th percentile), but significant decreases in spring and annual rain per rain day and the proportion of rainfall from extreme events. During spring, the New South Wales Tablelands showed a decrease in rain per rain day from 1910-1930 and increases from 1970-2005, most likely due to heavy-rain events. In south-west Western Australia, annual total rainfall has significantly decreased by 21 mm per decade since 1910, and by almost 24 mm per decade since 1950, accompanied by decreases in rain days and extreme rainfall indices. In the eastern coastal region, since 1950, there has been a significant decrease of almost 55 mm per decade in annual total rainfall, along with decreases in rain days and extreme rain, particularly in summer and winter. In the south-east, a significant decrease in annual total rainfall of 20 mm per decade since 1950 stems mainly from decreases during autumn. Generally, the direction of changes in extreme rainfall is consistent with changes in the mean. Trends in the extremes are often greater than the trend in the mean (Alexander et al. 2007).

2.2.2 Drought

In Australia, direct relationships between drought and global warming have been inferred through the extreme nature of high temperatures and heatwaves accompanying recent droughts, i.e. droughts are becoming hotter (Nicholls 2004). Since the start of the 20th century, the period of lowest rainfall across Australia was from the 1930s to the early 1940s. However, in the more recent droughts both the maximum and minimum temperatures have been higher (e.g. 2002 drought), as has potential evaporation.
2.2.3 Pan evaporation

Pan evaporation averaged over 60 high quality sites from 1970-2005 showed large interannual variability, with a small but insignificant decreasing trend of 2.5 mm per yr² (Jovanovic et al. 2007). This 36-year linear trend averaged over the whole of Australia masks the fact that evaporation has changed very little in the south, with increases in recent years. Pan evaporation is often regarded as a surrogate estimate of potential evaporation (the amount of evaporation that would occur if unlimited water were available), but whether this is the case remains to be tested. It is also unclear as to how pan evaporation relates to actual evapotranspiration as the latter is strongly constrained by the amount of water available and so the relevance of pan evaporation in a changing climate regime may be small (Murphy and Timbal 2007). Further analysis of the pan evaporation data suggests that many of the observed changes can be linked to local wind effects caused by changes in the local environments around observation stations (Hayner 2001) or other changes in observational sites (Jovanovic et al. 2007).

2.2.4 Wind

Trends in wind speed are an important aspect of climate change, but they are difficult to determine directly. Records of wind speed at any given station are highly sensitive to changes in the local environment (e.g. construction of buildings, removal of trees), as well as to systematic changes arising from altered instrument types. Considerably more work is needed to produce a dataset useful for determining trends in wind speed across Australia, especially extreme winds. However, it is known that mid-latitude westerly winds appear to have decreased, due to changes in the Southern Annular Mode (see section 2.5.2), with a corresponding increase in wind speed in the polar latitudes in most seasons from 1979 to the late 1990s, manifesting as a poleward displacement of the jet streams and storm tracks (Simmonds et al. 2002; Cai and Cowan 2007). There has been a 20% reduction in the strength of the subtropical jet over Australia and an associated reduction in the likelihood of synoptic disturbances developing over south-west Western Australia since the early 1990s (Frederiksen and Frederiksen 2005).

2.2.5 Changes in stream flow

One of the major impacts of the rainfall decline in southern and eastern Australia has been a reduction in surface water available for storage. The time series of May to April inflows to the south-west Western Australia Integrated Water Supply System is shown in Figure 2.6. The average annual inflow over the period 1911 to 1974 was 338 gigalitres (GL) which is almost twice the average of 177 GL per year over the period 1975 to 1996. Average inflow over the eight years from 1997 to 2005 was even less, at 114 GL per year, or close to a third of the 1911 to 1974 average. Further, for every 1% of rainfall decrease, the percentage reduction in inflow is far greater, and this factor grows as the drying condition persists. This nonlinear relationship is illustrated in Figure 2.7, which shows that the ratio between inflow reduction and rainfall decrease grows with time as the dry conditions persist. The reduction in inflow to dams is also observed in Victoria (Figure 2.8). Victoria has experienced a 20% rainfall decrease since the mid-1990s, translating into an inflow reduction of about 40%.
Figure 2.6: Yearly streamflow into Perth’s dams. Values represent totals for May-April. Averages for 1911-1974, 1975-1996 and 1997-2005 are shown. (Courtesy of the Western Australia Water Corporation.)

Figure 2.7: Yearly streamflow into Perth’s dams. Values represent changes in percentage of mean for May-April. The plot demonstrates the non-linear relationship between rainfall decrease and streamflow reduction. (Data courtesy of the Western Australia Water Corporation and the Bureau of Meteorology’s National Climate Centre.)
2.3 Changes in tropical cyclones, east coast lows, thunderstorms, hail and snow

2.3.1 Tropical cyclones

There has been concern that globally the relative frequency of very strong tropical cyclones may be increasing (Emanuel 2005; Webster et al. 2005; Hoyos et al. 2006; Curry 2006), although these findings have generated significant controversy with the scientific community due to concerns with the quality of the historical tropical cyclone data on which these studies relied (McBride et al. 2006). The IPCC (2007a) summary states: “There is observational evidence for an increase in intense tropical cyclone activity in some other regions where concerns over data quality are greater. Multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity. There is no clear trend in the annual numbers of tropical cyclones.” Recent papers (Klotzbach 2006; Kossin et al. 2007) confirm the upward trend in tropical cyclone intensity for the North Atlantic but are unable to corroborate the presence of upward trends in intensity over the past two decades in other basins. Analysis of the existing Australian tropical cyclone database indicates substantial increases in detected tropical cyclone numbers with the advent of weather radar in the late 1950s, although there have been apparent decreases in east Australian numbers since the 1970s, largely due to increasing numbers of El Niños (Nicholls et al. 1998).

A review of the West Australian tropical cyclone database for 1968-2001 uncovered an artificial bias caused by underestimating tropical cyclone intensities (Harper and Callaghan 2006). After the removal of inconsistencies and biases, a smaller upward trend still remains in the dataset, with the proportion of tropical cyclones that were severe (i.e. ‘category 3 or 4’ cyclones) being larger (41%) during 1989-1998 than during the earlier period 1974-1988 (29%).

2.3.2 East coast lows

Low pressure systems influencing eastern Australia (“east coast lows”) have strong winds and high rainfall, such as the one that flooded the Hunter Valley in June 2007. A consistent dataset of east coast lows based on station rainfall and surface winds from January 1958 to September 1992 showed significant correlations between the occurrence of east coast lows, the Southern Oscillation Index and the latitudinal
position of the subtropical high pressure belt (Hopkins and Holland 1997). There is a strong tendency for east coast lows to occur after El Niño years and in particular when an El Niño is followed by a La Niña. Hopkins and Holland (1997) found a long-term annual trend towards increased numbers of east coast lows over the period of their study, with almost a doubling of the frequency over the 30 years up to the early 1990s. However, there is a great deal of both interannual and decadal variability in the frequency of east coast lows. For example, after the late 1980s there was a decline in frequency up to 2006, while June 2007 saw a near-record monthly total of 5 east coast lows (P. Wiles, personal communication).

2.3.3 Cool-season tornadoes, hail and thunderstorms

About half of all tornadoes in Australia occur during May to October. These ‘cool season tornadoes’ are mostly observed in the southern part of the continent, especially Western Australia and South Australia (Hanstrum et al. 2002). Small-scale phenomena such as tornadoes are very difficult to monitor over a long period and it is therefore difficult to identify possible changes in frequency or intensity. Kounkou et al. (2007) estimated tornado risk during 1958 to 2002 by examining larger scale changes in the atmosphere linked to tornado incidence (Mills 2004). It was not possible to ascertain whether the risk of cool-season tornadoes has increased during the 1958 to 2000 period, despite a marked positive trend, due to an increase of the apparent risk since the introduction of satellite data in 1979.

The largest insured loss from a natural hazard in Australian history was $1.7 billion due to the April 1999 hailstorm in Sydney (Schuster et al. 2000; Insurance Council of Australia 2007). It is therefore important that observed and projected trends in hailstorm frequency and hailstorm intensity are documented and understood.

Schuster et al. (2005) report a decline of about 30% in the number of hailstorms affecting Sydney in the period 1989-2002 compared with 1953-1988. However, the intensity of hailstorms also needs to be considered when assessing the damage potential of hailstorm, and unfortunately there does not appear to be a published work on observed trends in intensity.

Thunderstorms are most frequent over northern Australia, with a secondary maximum in south-east Queensland and over central and eastern New South Wales, extending into north-eastern Victoria. The most severe thunderstorms are found along the eastern coastline, particularly in late spring and summer. ENSO does not appear to have a strong influence of thunderstorm activity, though thunderstorms were less frequent over south-eastern Australia (in Sydney, Adelaide and Canberra) during the strong El Nino year of 1982 and in Perth during the 1994 El Niño. There does not appear to be any evidence of a widespread trend in thunderstorm activity. See Kuleshov et al. (2002) for further details.

2.3.4 Snow

Maximum winter snow depth (Nicholls 2005) at Spencers Creek in the Snowy Mountains of south-eastern Australia has decreased slightly since 1962, and the snow depth in spring has declined strongly (by about 40%). Data from four alpine sites from 1953/4-2002 indicated a weak decline in maximum snow depths at three sites (Spencers Creek, Three Mile Dam and Deep Creek) and a moderate decline in mid-late season snow depths (August-September) at the same three sites (Hennessy et al. 2003).

2.4 Oceans

2.4.1 Sea level

Sea level rise is the result of thermal expansion of ocean water in response to global warming and increases in ocean mass from the melting of glaciers, with smaller contributions from the polar ice sheets. Global sea levels have risen by about 17 cm during the 20th century (Church and White 2006) and there has been a significant increase in the rate of sea level rise during the 20th century. The average rate between 1950 and 2000 was 1.8 ± 0.3 mm per year, and for the period when satellite data are available (i.e. from 1993), the rate was over 3 mm per year (Church and White 2006).

Since 1990, the observed rate of global sea level rise corresponds to the upper limit of the 2001 IPCC projections started from the base year of 1990 (Rahmstorf et al. 2007). While a longer record is needed to ascertain the importance of naturally occurring decadal variability (e.g. from violent volcanic eruptions (Church et al. 2005), this comparison of observed and modelled sea level raises concern that one or more of the model contributions to sea level rise may be underestimated.

Regional sea level reflects both the global mean rise, modulated by local effects of changing ocean currents, and patterns of atmospheric pressure. Knowledge of these combined influences on regional sea level will allow a more rational basis for the regional projection of such levels, their extremes and their likely impacts. For the period 1950 to 2000, sea level rose at all of the Australian coastal sites considered, with substantial variability in trends from location to location (Figure 2.9 (a); Church et al. 2006) and in sea level values from year-to-year. Over the period 1920 to 2000 the estimated average relative sea level rise around Australia was 1.2 mm per year.
Maps of trends in sea level over the region since the early 1990s are depicted in Figure 2.9 (b). These trends are based on data from the Australian Baseline Sea Level Monitoring Array (established in the early 1990s to provide a more accurate, robust national monitoring system for sea level) and the South Pacific Sea Level and Climate Monitoring Project. Figure 2.9 (a) and (b) are consistent in the sense that trends from the early 1990s (to the end of June 2007) are all positive with considerable variability from station to station. Note that Figure 2.9 (a) indicates that year-to-year variability is very important in determining trends over periods as short as the period for which the array in Figure 2.9 (b) has been operating, and that the trends since the early 1990s can differ considerably from trends over longer periods.

**Figure 2.9:** (a) Observed (with coastal tide gauges) and reconstructed sea levels (see Church et al. 2006 for further details) for the period 1920 to 2000 in the Australian region. The observed tide-gauge records are monthly average values. The Gulf St Vincent site is a composite record from three sites and is affected by local land motion. (Courtesy of J. Church, CSIRO). (b) The map shows observed rates of relative mean sea level rise (mm per year, with the vertical motion of the gauge with respect to the land excluded) from the early 1990s to June 2007 only, i.e. for a much shorter period than is depicted in (a). Data used in (b) are from the Australian Baseline Sea Level Monitoring Array (white figures) and the South Pacific Sea Level and Climate Monitoring Project (yellow figures). Trends due to atmospheric pressure changes are retained in both (a) and (b). Instruments that will enable the removal of the influence of additional vertical land movements on the records are currently being installed. (Courtesy of W. Mitchell, National Tidal Centre, Bureau of Meteorology)
2.4.2 Sea surface temperature

Substantial warming has occurred in the three oceans surrounding Australia. In the Pacific, an El Niño-like pattern features prominently in the warming trend with a stronger warming in the eastern Pacific (Figure 2.10). It is not clear whether the pattern is related to greenhouse gas induced global warming, or is caused by the fact that since the mid-1970s, natural variability has resulted in there having been more El Niño years than La Niña years. A feature of the south Pacific, near the east coast of Australia, is a large warming, thought to be associated with the changing East Australian Current. In the Indian Ocean, substantial warming in the tropical and southern subtropical zones contributes to a basin-wide warming rate that is fastest of all oceans. The warming along the West Australian coast is greater than that offshore. Further, the Indian Ocean sector of the sub-Antarctic zone shows the strongest warming of the Southern Ocean. While the gross patterns in Figure 2.10 are reproduced in different datasets, many of the details differ from similar analyses using other surface datasets, and so must be treated with care.

2.4.3 Ocean currents

The Leeuwin Current off Western Australia brings warm water from the tropics and increases the sea surface temperature compared to water offshore. Since the 1960s, sea surface temperatures in the Leeuwin Current have risen by about 0.6°C, less than that offshore but closer to the rise of global average sea surface temperature. The current is stronger during a La Nina year and weaker during an El Niño year (Feng et al. 2003). Since the mid-1970s, there have been more El Niño than La Niña events (see section 2.5), so that the Leeuwin Current is weaker, and its sea surface temperature increase is damped by a shallow thermocline (Feng et al. 2004).

The East Australian Current is the largest ocean current closest to the eastern coastline of Australia and brings warmer water from the tropics. There is indirect evidence suggesting that there has been a significant change of the current. Long-term observations off Maria Island (148°16’E, 42°36’S) near Tasmania reveal a warming trend far greater than the global average, and recent studies suggest that to a large extent this is due to an intensifying East Australian Current. Summer surface wind changes induced by ozone depletion have generated a strengthening flow of the East Australian Current passing through the Tasman Sea (Cai 2006; Figure 2.11). This transports more warm water southwards and contributes to the large warming rate.

![Figure 2.10: Pattern of linear warming rate (°C/50 years) for the period 1950-2006 using updated observed sea surface temperature data (method of Rayner et al. 1996).](image)

![Figure 2.11: Linear trend in the transport stream-function (units are in Sverdrups where, 1 Sv = 106 m³ s⁻¹) calculated using Godfrey's Island Rule model (Godfrey 1989). The model was forced by the linear trend-fitted surface wind stress (Kalnay et al. 1996) averaged over the summer months (December to May) from 1978-2002. The trends depicted include an intensification of both the East Australia Current and the Antarctic Circumpolar Current. The ocean flow directions induced by the wind-stress changes are indicated with arrows. See Cai (2006) for further details.](image)
2.5 El Niño – Southern Oscillation and the Southern Annular Mode

2.5.1 El Niño – Southern Oscillation

The El Niño – Southern Oscillation (ENSO) is strongly related to major Australian anomalies in rainfall, temperature and tropical cyclones. There has been a small downward trend in the annual Southern Oscillation Index (SOI) since 1876 (Figure 2.12), at least partially associated with an increase in the frequency of El Niño events.

Instrumental and palaeo-climate records show large variations in the frequency and intensity of ENSO over time. (e.g. Allan et al. 1996; Power et al. 1999; Van Oldenborgh and Burgers 2005; Tudhope et al. 2001; McGregor and Gagan 2004; Shulmeister and Lees 1995). The impact of ENSO on Australia also varied from decade to decade (Power et al. 1999; 2006). The tropical Pacific Ocean (strongly linked to ENSO) has warmed over recent decades (Figure 2.13 and section 2.4.2).

The relationship between the SOI and both Australian temperature and rainfall has changed (Nicholls et al. 1996; Power et al. 1998a; Power et al. 2006). This is illustrated in Figure 2.14. Temperatures after 1973 were higher for any given value of the SOI than they were previously (Figure 2.14(a)). Rainfall since 1973 has also been higher for any given value of the SOI than it was previously (Figure 2.14(b)). Smith (2004) showed that the recent rainfall increases have been dominated by increases in the north and north-west of the continent during the summer half of the year.
2.5.2 The Southern Annular Mode

The Southern Annular Mode (SAM) can be characterised as a flip-flop in pressure between the high and mid-latitudes of the Southern Hemisphere (Rogers and van Loon 1982; Kidson 1988; Hartmann and Lo 1998; Karoly 1990; Thompson and Wallace 2000; Thompson and Solomon 2002). By convention, when the SAM is in its positive phase, anomalously low pressure occurs over Antarctica and anomalously high pressure over the mid-latitudes (40-55ºS). During the positive phase of SAM, the circumpolar westerlies increase in strength and the circumpolar vortex contracts. These changes are associated with a poleward shift of the mid-latitude storm tracks (Yin 2005; Bengtsson et al. 2006). Although the SAM has largest influence on the surface climate of latitudes further south than Australia, it has been linked to changes in Australian climate (Hendon et al. 2007; Meneghini et al. 2007; Cai and Cowan 2006).

The positive phase of the SAM is associated with significant winter rainfall deficiencies in the southern regions of Australia and significant rainfall increases in the Murray-Darling Basin in summer (Hendon et al. 2007). Approximately 15% of the weekly spring/summer rainfall variance over south-eastern Australia is related to the SAM (Hendon et al. 2007). This is a similar magnitude to that explained by ENSO.

In recent decades, the SAM has increasingly spent more time in its positive phase, with statistically significant positive trends in the summer and autumn seasons and no significant changes in winter and spring (Thompson and Wallace 2000; Marshall 2003). The potential for storm formation over southern Australia has decreased over the last 40 years. In the south-west of the continent, the reduction of wintertime rainfall in the region is associated with both a reduction in the intensity of cyclogenesis and a decrease in the number of some rain-bearing synoptic systems, and a southward deflection of some storms (Hope et al. 2006; Frederiksen and Frederiksen 2006; see also Lim and Simmonds 2007).

2.6 Palaeo-records

In order to help place climatic changes observed over the past century into perspective it is useful to know how Australia’s climate varied before the instrumental period began. This can be achieved through the use of palaeo-records (i.e. proxy records derived from landscape features and biological, chemical and isotopic material stored in sediments, ice sheets, tree rings, cave deposits and corals). Palaeo-records increase our understanding of what climate variations can occur naturally and thus assist in our interpretation of current climate trends. The majority of palaeo-information is from the southern, eastern and northern regions of Australia. Arid areas are not well represented in the records.
2.6.1 Precipitation
Pollen records of past vegetation in eastern Australia indicate precipitation was generally higher than present between 9,000 and 3,500 years ago. Highest levels appear to have occurred between 9,000 and 6,000 years ago in Tasmania, between 7,500 and 4,000 years ago in southern mainland Australia and from 5,000 to 3,700 years ago in northern Australia (Shulmeister et al. 2004). This suggests a regional climatic shift, possibly related to the movement of the subtropical anti-cyclone belt, the westerlies and/or the monsoon.

From around 4,000 years ago onwards, palaeo-records indicate an increase in the seasonality of precipitation in the Australian region (Shulmeister and Lees 1995). Evidence from lakes in Victoria suggest that conditions between about 2,000 years ago to AD 1840 were wetter than present, after which the dry conditions of the recent instrumental period became established (Jones et al. 1998).

2.6.2 Temperature
Palaeo-evidence for temperatures in the Australian region is less widespread than for precipitation and is often debated. What is available indicates that here have been moderate variations in temperature over the past 9,000 years, with some regional variation. Pollen evidence suggests that annual temperatures in south-east Australia may have been slightly higher between 9,000 and 5,000 years ago as the Earth shifted into the Holocene warm phase (Macphail 1979; Lloyd and Kershaw 1997; Anker et al. 2001). However, records from Victoria suggest that it may actually have been winter temperatures that were higher, with summer temperatures being slightly lower (McKenzie and Busby 1992).

Tree ring records from Tasmania indicate cooler conditions than present occurred during the Little Ice Age that occurred from around 1300 to the mid-19th century (Briffa 2000; Cook et al. 2000). This is supported by coral records from New Caledonia, which suggest a 1.4°C cooling around 1/30 (Hendy et al. 2002). However, coral records from northern and western Australia for the same period give evidence of sea surface temperatures as warm as the early 1980s (Gagan et al. 2004), demonstrating that there has been regional variation in past temperature change, possibly as a result of significant shifts in the ocean-atmosphere system (Lough 2001; Hendy et al. 2002; Lough et al. 2006).

2.6.3 Climate variability
Higher resolution, continuous palaeo-records give evidence of decadal and sub-decadal scale climate variation. For example, palaeo-climate data (Mann et al. 2005; Cobb et al. 2003; D’Arrigo et al. 2005; Tudhope et al. 2001; Hughen et al. 1999) indicate that ENSO has operated for many thousands of years. The tropical cyclone palaeo-record for Cairns and the Great Barrier Reef for events spanning the last 5,000 years suggests that the historical record underestimates by a factor of ten the frequency of the most severe tropical cyclones likely to strike the Cairns region, and that the historical record of cyclones in Cairns and the east coast of Queensland coincides with a period of relative quiescence in tropical cyclone activity (Lough 2001; Nott and Hayne 2001; Nott 2003; Lough et al. 2006).