CHAPTER FOUR

UNDERSTANDING RECENT AUSTRALIAN CLIMATE

FALLEN ARM AFTER FIRE, VICTORIA, ISTOCK

CHAPTER 4 UNDERSTANDING RECENT AUSTRALIAN CLIMATE

This chapter describes current climate variability over Australia and its drivers (Section 4.1), and observed climate trends and potential causes. The understanding presented in this chapter contributes to the interpretation of the GCM-simulated climate projections and assessing our confidence in the projections (Chapters 5 and 7). Note that this chapter only deals with observed aspects of atmospheric and terrestrial variables. Observations of sea level and the marine climate are discussed in Chapter 8 alongside projections in those variables.

4.1 AUSTRALIAN CLIMATE VARIABILITY

The Australian continent spans over 30° of latitude, from the tropics in the north to the mid-latitudes in the south. As a result, Australia is affected by many different weather systems and climate variability is driven by many significant climate features. Tropical systems affect the north, where there are two main seasons defined by very distinct mean rainfall: the wet season from November to April and the dry season from May to October. To the south the influence of the tropical systems decreases and extra-tropical weather and climate features become dominant. The annual cycle in rainfall becomes weaker but the temperature contrast between winter and summer increases and four distinct seasons exist.

The many different weather and climate features that affect Australia are summarised in Figure 4.1.1 (from Risbey *et al.* 2009b). The main tropical weather features (modes) and their influences are described in section 4.1.1 and the extra-tropical modes are described in Section 4.1.2.

4.1.1 TROPICAL MODES

On the seasonal time-scale most of the northern tropics experience distinct wet and dry seasons, their contrast increasing further north as the influence of the Australian monsoon increases. The monsoon has the strongest influence in northern Australia from late December, when the prevailing easterly winds turn westerly, until March, when it retreats to the north (following the sun) and easterly winds and dry conditions return. The monsoon is driven by the summer heating of the Australian continent and the resulting change in land-sea temperature gradients. It brings high rainfall for much of November to April, but the wet season consists of active (wet) and break (dry) periods of one to several weeks.

The monsoon breaks are partly determined by the phases of the Madden-Julian Oscillation (MJO). The MJO is an eastward moving tropical disturbance of high convection and rainfall with a mean frequency of 40-50 days. As the MJO moves across Australian longitudes it brings enhanced

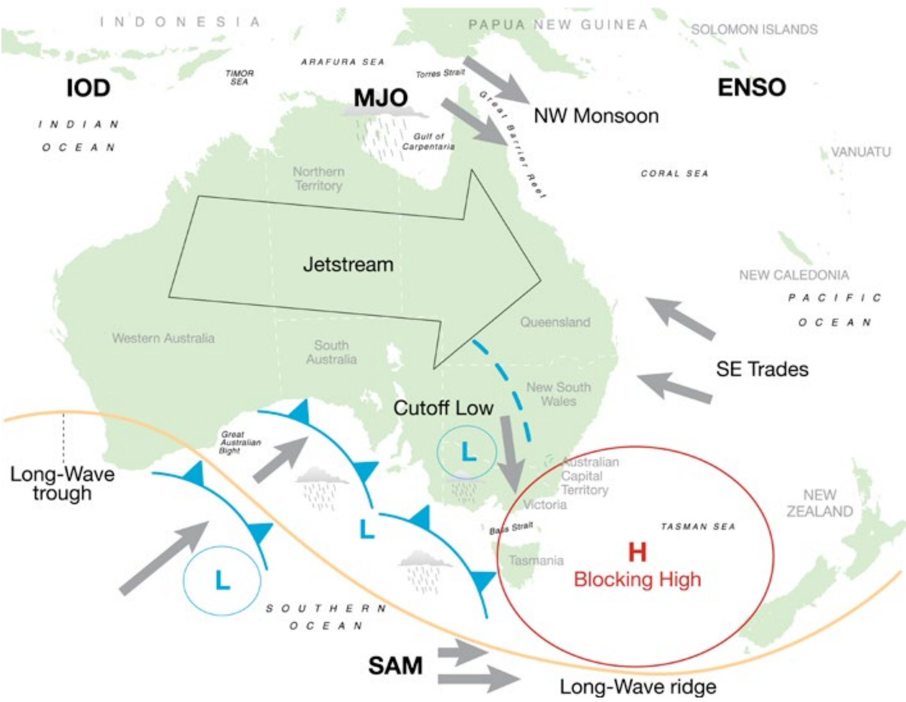

FIGURE 4.1.1: SCHEMATIC SHOWING THE MAIN WEATHER AND CLIMATE FEATURES AFFECTING AUSTRALIAN CLIMATE VARIABILITY (SOURCE: RISBEY *ET AL*. 2009B).

rainfall, and each of its phases have been found to be associated with preferred rainfall anomalies over the continent (Wheeler *et al*. 2009).

The northern wet season is also the tropical cyclone (TC) season in Australia. Most TCs occur between November and April, with a mean of 11 TCs affecting the Australian continent per year during the period from the 1981/1982 wet season to the 2012/2013 wet season (Dowdy *et al*. 2014).

The above weather and climate features are modulated from year to year by the main modes of natural tropical climate variability, namely the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). ENSO originates in the Pacific Ocean and is the major driver of global interannual climate variability (Ropelewski and Halpert, 1989). Its link to Australian climate variability has long been known (*e.g.* McBride and Nicholls, 1983). ENSO is a coupled ocean-atmosphere mode, with strong interaction between the tropical atmospheric circulation and the Pacific Ocean (Philander, 1990). Under normal conditions (the ENSO “neutral” phase), the trade winds and Pacific sea surface temperatures (SST) are in balance. The easterly equatorial trade winds feed into the strong convection over the West Pacific Warm Pool, which in summer brings moisture and rainfall to the tropics. In some years the trade winds weaken or reverse, the Warm Pool expands eastward and convection moves away from Australian longitudes. During these ‘El Niño’ conditions, SSTs are warmer in the eastern Pacific and cooler around northern Australia compared to neutral conditions. As a result rainfall is often below average over much of eastern Australia and TCs are less likely in the Coral Sea. In some other years, the trade winds strengthen, the eastern Pacific cools and SST around northern Australia are warmer than average, leading to enhanced convection over northern Australia and TCs are more likely to form close to Australia. During these ‘La Niña’ conditions the enhanced convection leads to increased moisture availability and so rainfall is often above average over eastern Australia. Australia’s wettest two-year period on record, 2010–11, was associated with a strong, prolonged La Niña in addition to a strong negative phase of SAM (see 4.1.2) (Hendon *et al*. 2014). The effects of ENSO in northern Australia are direct, through changes in SST around Australia and the enhancement or suppression of convection. As ENSO affects SST and surface winds, its phases drive interannual variability in the timing of the onset of the monsoon, and the movement of the MJO. The strongest influences of ENSO on Australian rainfall are in spring and summer. El Niño and La Niña events are natural variations in the climate system and occur on average every 4-7 years, but ENSO and its impacts display significant variability on decadal time scales (Power and Colman, 2006).

The IOD is active in the tropical Indian Ocean but influences interannual climate variability across tropical and extra-tropical Australia. The IOD is characterised by changes in SST off the Sumatra coast in the eastern Indian Ocean basin and changes of the opposite sign in the west of the basin (Saji *et al*. 1999). Low SST in the east (and high in the west) is known as the positive phase of the IOD (see also section 3.5) and comes about when south-east winds off the north-west of Australia induce upwelling in the eastern Indian Ocean (England *et al*. 2006). The IOD is usually active from May to November and is often terminated by the wind reversal accompanying the arrival of the monsoon in northern Australia. A positive IOD has been found to cause heavy rains in eastern Africa and droughts over Indonesia (Yamagata *et al*. 2004), and it can also lead to below average rainfall in winter and spring over central and southern Australia (Risbey *et al*. 2009b). Those regions can receive above average rainfall during the negative phase of IOD, when eastern Indian Ocean SSTs are above average.

Many of the Australian impacts of the IOD are independent of ENSO, but certain ENSO and IOD phases tend to occur concurrently. Meyers *et al*. (2007) found that positive IOD events are more likely during El Niño years and negative IOD events were more frequent during La Niña. They found that a negative IOD event had never been observed during an El Niño.

4.1.2 EXTRA-TROPICAL MODES

Not all climate variability in Australia is due to modes of tropical variability like ENSO and the IOD. The southern part of the Australian continent is affected by a number of extra-tropical weather features and modes of variability in the mid-latitudes. This region is located under the descending (dry) branch of the Hadley circulation, resulting in relatively dry air and little rainfall and the formation of high pressure systems.

The high pressure centres are the predominant extra-tropical weather features and their averaged signature on the climatic time-scale is a band of high pressure: the subtropical ridge (STR). The STR is weaker and located further south in summer but stronger and further north in winter (Drosdowsky, 2005).

A band of strong westerly winds and storms encircles Antarctica (‘the Roaring 40s and 50s’; Sturman and Tapper, 2006), and while the preferred tracks of the centres of the storms (the “storm track”) are generally south of Australia (Simmonds and Keay, 2000), the fronts associated with these storms have a major impact. They are most significant for southern Australian rainfall and temperatures during winter and spring when the STR and the storm track are located furthest north. During summer, they bring the classic ‘cool change’ and the associated strong winds, fire danger (Mills, 2005) and dust events (Trewin, 2002). They, along with cut-off lows, are a major source of rainfall across southern Australia (Risbey *et al*. 2009a,b, Pook *et al*. 2012). Two recent climatologies (Berry *et al*. 2011, Simmonds *et al*. 2012) indicate the prevalence of fronts, particularly cold fronts, across southern Australia.

The northern extent of the westerlies can shift north and south on a range of timescales, influencing rainfall variability across southern Australia. The north-south shift in the westerlies and the low pressure systems is also part of the hemispheric mode of variability known as the Southern Annular Mode (SAM) (Thompson and Wallace, 2000). The SAM reflects the variability in the hemispheric pattern of low pressure around Antarctica and high pressure over Australia. Higher values of the SAM index mean higher pressures over Australia, and a southward shift of the band of westerlies and storm track. The impact of SAM varies with location and season (Hendon *et al*. 2007). In winter in southern Australia a positive SAM phase has low pressure systems shifted to the south, thus shifting rainfall away from south-eastern Australia. In spring and summer a positive SAM phase shifts the westerlies southward so easterly winds are more common over the Eastern Seaboard, bringing above average rainfall. Over recent decades there have been trends towards the positive phase of SAM (primarily in summer), principally due to stratospheric ozone depletion (Arblaster and Meehl, 2006) and a more intense and further southward located STR (primarily during the cooler half of the year: Timbal and Drosdowsky, 2013). These trends have affected rainfall in the south of the country, particularly in the south-west and the south-east where cool season rainfall has fallen significantly since the early 1970s (south-west) and 1990s (south-east). See section 4.2 for more details.

Low pressure systems sometimes develop in the region to the north of the westerlies and the storm track. Known as 'cut-off lows', these bring large rainfall totals to southern Australia (Pook *et al*. 2012). On the eastern Australia coast, cut-off lows are commonly referred to as East Coast Lows. These storms are responsible for some of the most damaging natural disasters in Australia's history due to the extreme winds, waves and rainfall (McInnes *et al*. 2002; Mills *et al*. 2010; Dowdy *et al*. 2014). East Coast Lows can also have positive impacts on the Eastern Seaboard of Australia, being responsible for major inflows to water catchments (Pepler and Rakich, 2010, Dowdy *et al*. 2013b). Large-scale atmospheric and oceanic variability (including ENSO, SAM, the intensity of the subtropical ridge and the strength of the East Australian Current, but excluding blocking) do not appear to have a significant influence on East Coast Low occurrence (Dowdy *et al*. 2013c). The climate of the Eastern Seaboard of Australia is distinct from the rest of eastern Australia in that it is not affected by large-scale environmental influences (such as ENSO) in the same way as other parts of eastern Australia (Risbey *et al*. 2009b; Timbal and Hendon, 2011). Eastern Australia is also a favoured location for the formation of extra-tropical cyclones, as indicated by frequent upper-tropospheric disturbances over this region (Dowdy *et al*. 2013c). These are likely related to phenomena such as persistent high pressure systems known as atmospheric blocking (Pook *et al*. 2013) and a prevalent split in the subtropical jet over eastern Australia during winter (Grose *et al*. 2012).

4.2 OBSERVED TRENDS AND ATTRIBUTION IN THE AUSTRALIAN REGION

4.2.1 TEMPERATURE

AVERAGE SURFACE TEMPERATURE

Australian temperatures have warmed by 0.9 °C since 1910, with more warming in night time minimum temperature than daytime maximum temperature based on the homogenised daily Australian Climate Observation Reference Network – Surface Air Temperature (ACORN-SAT) data (Trewin, 2013, Fawcett *et al*. 2012). Figure 4.2.1 shows mean temperature (the average of maximum and minimum temperature) changes across Australia from 1950 to 2013. Warming has been apparent in all seasons and all States and Territories. 2013 was Australia's warmest year since records began in 1910 (BOM, 2014b).

Regional climate change attribution studies have shown significant consistency between observed increases in Australian temperatures and those from climate models forced with increasing greenhouse gases (Hegerl *et al*. 2007, Karoly and Braganza, 2005). By extension, many aspects of warming over Australia are also attributable to the enhanced greenhouse effect.

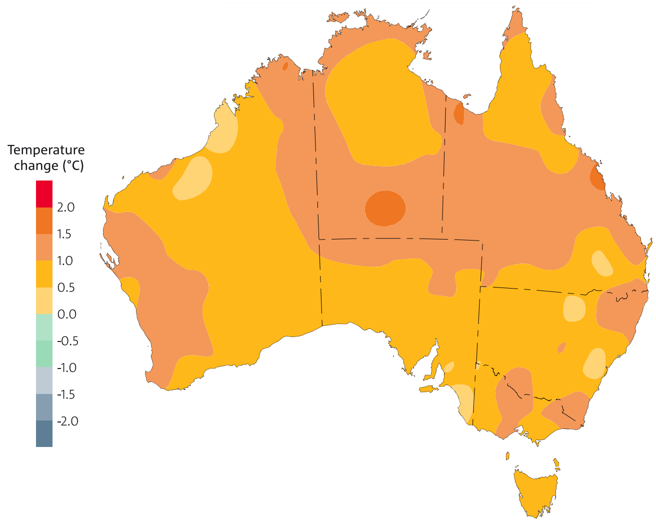

FIGURE 4.2.1: LINEAR TREND IN AUSTRALIAN MEAN TEMPERATURE FROM THE AUSTRALIAN CLIMATE OBSERVATIONS REFERENCE NETWORK (ACORN-SAT) CALCULATED FOR THE ENTIRE PERIOD 1910 TO 2013 (SOURCE: BOM, 2014A).

TEMPERATURE EXTREMES

The mean temperature changes have been accompanied by a large increase in extreme temperatures. Since 2001, the number of extreme heat records in Australia has outnumbered extreme cool records by almost 3 to 1 for daytime maximum temperatures, and almost 5 to 1 for night-time minimum temperatures (Trewin and Vermont, 2010, Trewin and Smalley, 2013). Very warm months (those with monthly averaged temperature above the second standard deviation of monthly temperatures from a 1951-1982 reference period) have increased five-fold in the past 15 years. The frequency of very cool months has declined by around a third over the same period (Fawcett *et al*. 2013). Figure 4.2.2 shows trends in days above 35 °C across Australia, while Figure 4.2.3 shows trends in the temperature of the coldest night since 1950.

The changes in the frequency of temperature extremes have been shown to be directly related to warming trends. These changes include recent, significant increases in the frequency of high-temperature extremes and decreases in the frequency of low temperature extremes (Trewin and Vermont, 2010, Trewin and Smalley, 2013), and increases in the duration, frequency and intensity of heatwaves in many parts of the country (Perkins *et al*. 2012; Alexander and Arblaster, 2009; Alexander *et al*. 2006).

Extreme heat was experienced during the Australian summer of 2012-2013. Near-surface air temperatures and regional sea-surface temperatures for the December to February period were the highest on record for Australia. This period also included Australia's area-averaged hottest month, hottest week and hottest day on record, and the longest and most spatially extensive national heatwave on record (BOM, 2013a). Analysis with forced and unforced climate model simulations show that increasing greenhouse gases lead to a five-fold increase in the odds of Australia recording the temperatures experienced in January 2013 (Lewis and Karoly, 2013; 2014).

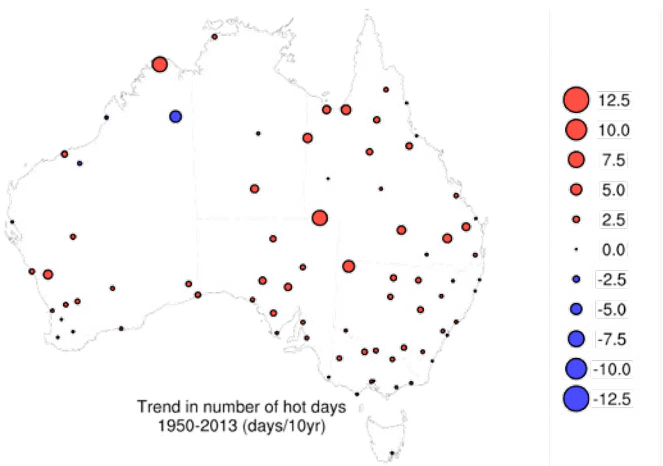

FIGURE 4.2.2: TRENDS IN THE NUMBER OF HOT DAYS (GREATER THAN 35 °C) IN AUSTRALIAN MEAN TEMPERATURE FROM THE AUSTRALIAN CLIMATE OBSERVATIONS REFERENCE NETWORK OF SURFACE AIR TEMPERATURE (ACORN-SAT) FROM 1950 TO 2013 (SOURCE: BUREAU OF METEOROLOGY).

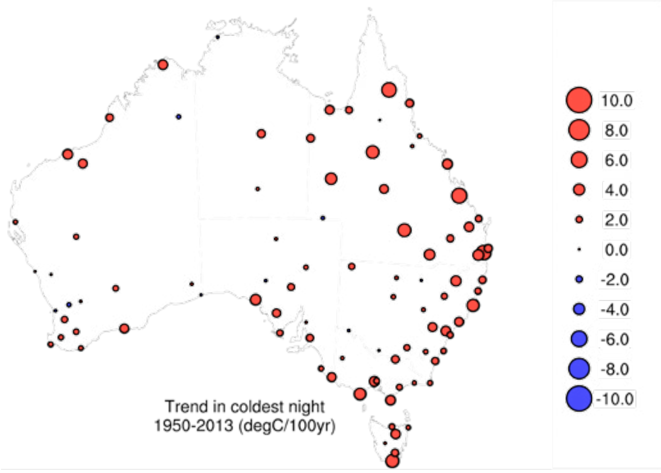

FIGURE 4.2.3: TRENDS IN THE COLDEST NIGHT (°C) IN AUSTRALIAN MEAN TEMPERATURE FROM THE AUSTRALIAN CLIMATE OBSERVATIONS REFERENCE NETWORK OF SURFACE AIR TEMPERATURE (ACORN-SAT) FROM 1950 TO 2013 (SOURCE: BUREAU OF METEOROLOGY).

4.2.2 RAINFALL

Attributing observed regional rainfall changes is a more difficult task than attributing temperature changes. This is especially so in the Australian region, where intrinsic rainfall variability on year to year and decade to decade timescales is large. The following sections cover rainfall in the warmer months (the wet season in northern Australia), the cooler months (the wetter season in much of southern Australia) and heavy rainfall throughout the year. Deciles for the recent period 1997-2013 are shown to illustrate recent changes (linear trends in various seasons and through various periods can be explored at the Bureau of Meteorology Tracker - http://www.bom.gov.au/climate/change).

AUSTRALIAN WARM SEASON RAINFALL

Northern Australian wet season (October to April) rainfall has shown wet and dry decades through the 20 century but with a slight increase indicated in the linear trend in 1900-2012. In recent decades, increases are discernible across northern and central Australia, withthe increase in summer rainfall most apparent since the early 1970s (Figure 4.2.4; Braganza *et al*. 2011), and has been large enough to increase total Australian rainfall (averaged over the entire continent) by about 50 mm when comparing the 1900 to 1960 period with 1970 to 2013. Rainfall during the months of October to April from 1997 to 2013 was very much above average over large parts of the continent (Figure 4.2.5). The period 2010 to 2012 recorded the highest 24-month rainfall totals for Australia as a whole, in conjunction with two strong La Niña events. The statistical significance of trends in monsoonal rainfall is difficult to determine due to high intrinsic variability in the summer monsoon.

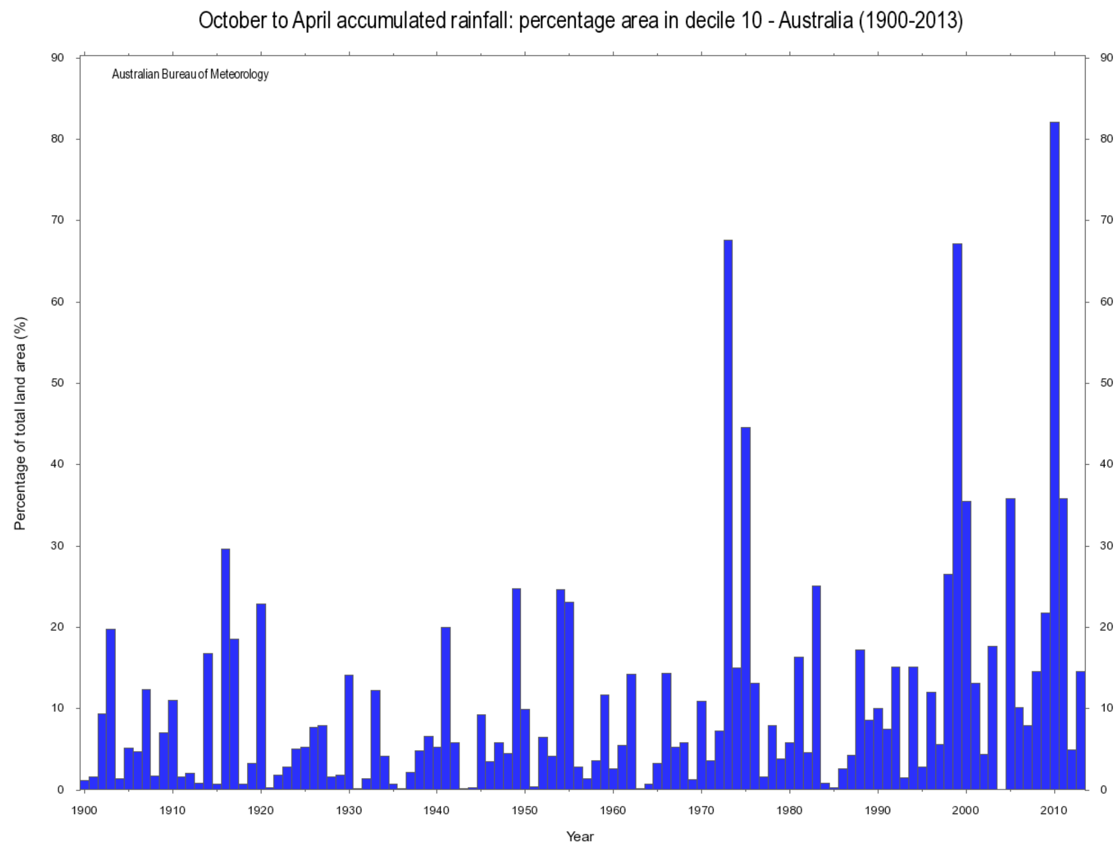

FIGURE 4.2.4: PERCENTAGE OF AUSTRALIA RECEIVING RAINFALL IN DECILE 10 (GREATER THAN 90TH PERCENTILE) DURING WARMER MONTHS OF THE YEAR (DEFINED HERE AS OCTOBER TO APRIL) ACCUMULATED SINCE 1900 (SOURCE: BUREAU OF METEOROLOGY).

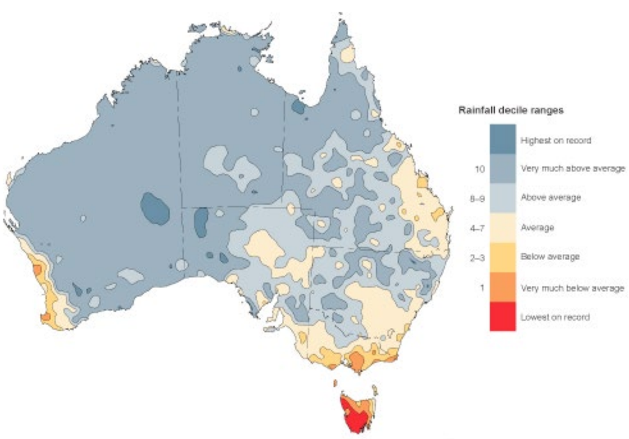

FIGURE 4.2.5: RAINFALL DECILES FOR OCTOBER TO APRIL (THE NORTHERN WET SEASON) 1997 TO 2013, RELATIVE TO THE REFERENCE PERIOD 1900–2013, BASED ON AWAP DATA (SOURCE: BOM, 2014A).

AUSTRALIAN COOL SEASON RAINFALL

Northern Australia is seasonally dry in the cooler months, so the focus here is on southern Australia. Rainfall declines in the south-west and south-east of the continent are apparent over cooler months of the year. These are most significant for the south-west of Western Australia, where a decrease is seen in the linear Trend in rainfall over the entire 20th century. Decreases in some regions of south-east Australia are seen in the linear trend in rainfall through the whole century, with many other regions experiencing a decrease since around 1960. Outside of the tropics, rainfall is the major limiting factor for agriculture and water resource management in the Australian environment, and particular attention is paid here to describing the causes of southern rainfall declines.

The southern drying trends are characterised by a 10-20 percent reduction (expressed as a step change or series of step-changes) in cool season (April –September) rainfall across the south of the continent. The rainfall declines have persisted since around 1970 in the south-west and since the mid-1990s in the south-east (Braganza *et al.* 2011).

These regions typically receive most of their rainfall during the cooler months of the year, and the rainfall declines have occurred in late autumn to early winter in the south-east, and in winter in the south-west (Figure 4.2.6). In

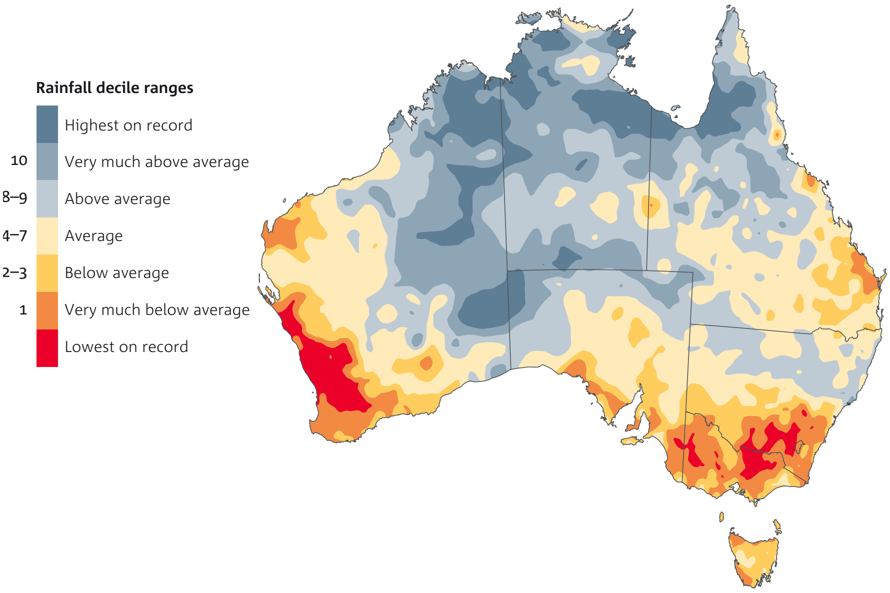

FIGURE 4.2.6: RAINFALL DECILES FOR APRIL TO SEPTEMBER 1997-2013, RELATIVE TO THE REFERENCE PERIOD 1900–2013, BASED ON AWAP DATA (SOURCE: BOM, 2014A).

some regions of the south-west, the decline in cool season rainfall is as much as 40 % over the past fifty years (Cai and Cowan, 2008) with larger decreases in runoff (CSIRO, 2012).

Mean rainfall, and rainfall variability, is dominated by cut-off low pressure systems and cold fronts (Risbey *et al.* 2009a). It has now been reasonably established that the decline in rainfall has been associated with both fewer rain-bearing systems, and less rainfall from those systems that do cross the region (Hope *et al.* 2006, Pook *et al.* 2012, Risbey *et al.* 2013a,b).

Studies have implicated a range of possible drivers of drying trends across southern Australia. To date, this literature could be classified as mostly implied attribution, relying on inferred causality from the attribution of large-scale drivers. More formal model-based attribution has also been attempted; however definitive causes have yet to be firmly established due to a range of uncertainties.

In general, the causes of the rainfall decline can be separated into proximate (local) and ultimate (global atmosphere and ocean) drivers (Nicholls, 2010). While natural variability of Australian rainfall is large, and strongly connected to well-known intrinsic modes of climate variability, it seems likely from the literature to date that drying across southern Australia cannot be explained by natural variability alone. The most notable proximate driver is the frequency and impact of sea-surface temperature variability associated with the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Specifically, a lack of negative-phase IOD events has been identified as a contributing factor to drying and drought in the south-east since the 1990s (Ummenhofer *et al.* 2009).

There is some uncertainty regarding the degree to which variability in Indian Ocean drivers are separate from ENSO variability in the Pacific, though it is notable that Indian Ocean sea surface temperatures have warmed in recent years over a very wide area of the basin. There is also uncertainty as to whether IOD variability can exert much influence on autumn rainfall declines, since both the IOD and ENSO have limited influence on autumn rainfall in south-east Australia (Murphy and Timbal, 2008). The IOD is most important in the June–October period (Risbey *et al.* 2009b). Other studies have suggested that the true forcing by persistent SST is weak, and would account for only a fraction of the observed rainfall trends (Watterson, 2010), while Nicholls (2010) indicates that that long-term rainfall deficiencies do not seem related to changes in the behaviour of ENSO or the IOD.

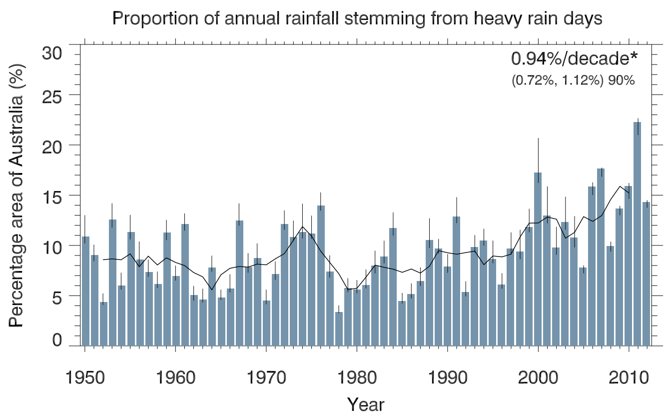

FIGURE 4.2.7: PERCENTAGE AREA OF AUSTRALIA EXPERIENCING A SIGNIFICANT PROPORTION (GREATER THAN 90 %) OF ANNUAL PRECIPITATION ACCUMULATION STEMMING FROM HEAVY ONE-DAY EVENTS. A HEAVY RAIN DAY IS DEFINED AS A DAY WHERE THE RAINFALL TOTAL EXCEEDS THE 90TH PERCENTILE (SOURCE: GALLANT *ET AL*. 2014).

AUSTRALIAN HEAVY RAINFALL

There is recent evidence that extremes of intense precipitation, over various time intervals, are increasing in more places around the globe than not (see for example Donat *et al.* 2013a). Consistent with global studies, an increase in the proportion of heavy rainfall has been detected over Australia. The fraction of Australia receiving a high proportion (greater than the 90th percentile) of annual rainfall from extreme rain days (greater than the 90th percentile for 24 hour rainfall) has been increasing since the 1970s (Figure 4.2.7; Gallant *et al.* 2013). Significant regional variability exists, with the east coast region experiencing a significant decrease in extreme rain events since 1950 (Gallant *et al.* 2014). There is also an increase in the fraction of Australia receiving summer (December to February, accumulated) rainfall that is above the 90th percentile (BOM, 2013b). Detection of changes in heavy rainfall in Australia tends to be sensitive to the indices and thresholds chosen to monitor change over time.

The period 2010 through to 2013 has also seen widespread, individual very-heavy rainfall events, particularly through the warmer months of the year. Based on the linear relationship between Southern Oscillation Index (SOI) values and Australian rainfall (Power *et al.* 2006), the El Niño Southern Oscillation (ENSO) remains the dominant driver of changes in rainfall extremes in Australia (King *et al.* 2013). However the extent to which record rainfall totals during the period 2010 to 2011 are due to natural variability is difficult to determine, since global warming can be expected to influence ENSO itself (*e.g.* Power *et al.* 2013). The La Niña event of 2010-2011 was record breaking as measured by the SOI.

Attribution studies have also found that the warming trend in sea surface temperatures to the north of Australia may have contributed to the magnitude of recent heavy rainfall in 2010-11 in eastern Australia — contributing around 10 to 20 percent of the heavy rainfall anomalies (Hendon et al. 2014, Evans and Bouyer-Sochet, 2012). Another study found that the warm SSTs increased the chances of above average rainfall in eastern Australia in March 2012 by 5-15 % (Christidis *et al.* 2013).

4.2.3 CHANGES IN CIRCULATION IN THE AUSTRALIAN REGION AND THEIR POSSIBLE ASSOCIATION WITH RAINFALL TRENDS

Studies have also looked to the larger, global and hemispheric circulation changes as providing ultimate causality of cool season rainfall declines in Australia. It seems likely that broader-scale circulation changes that are decoupled from local sea-surface temperature variability and trends are the dominant contributing factors to the observed rainfall declines.

In general, the large-scale circulation changes can be described through various dynamical features, each of which share a considerable amount of common variance and dynamical organisation at the hemispheric scale. These can be characterised as expansion of the tropics and a tendency for a contraction of mid-latitude storm tracks toward higher southern latitudes, or movement of the subtropical and polar jet streams. Such a change in circulation would be characterised by a mean decrease in rainfall in mid-latitude regions, and a mean increase in higher latitudes. In the Australian region, this is broadly consistent with cool season rainfall declines described above, and evidence of increased rainfall over the Southern Ocean (Durack *et al*. 2012)

Most studies of changes to these circulation patterns form an inferred attribution of Australian rainfall changes, since this circulation controls changes in the predominant cut-off lows and frontal systems, or storm track, across the south. The basic dynamical reasoning for changes in the Southern Hemisphere circulation is that warming expands the tropics, or Hadley Cell circulation, toward the pole. This is supported by studies of reanalysis and radiosonde data, which show an expansion of the southern Hadley Circulation over the last 30 years (Nguyen *et al*. 2013; Lucas *et al*. 2012).

Warming also reduces the temperature gradient (or baroclinicity) between the equator and pole, reducing the amount of energy available to mid-latitude weather systems. A contraction of mid-latitude weather systems toward the pole, associated with a more positive Southern Annular Mode (SAM), has been attributed to both anthropogenic greenhouse gas warming and springtime Antarctic stratospheric ozone depletion (*e.g.* Arblaster and Meehl, 2006).

While rainfall declines in the south-west have occurred for longer than those in the south-east, and the rainfall regimes in the two regions are not identical, enough similarity between the two regions exists during cooler months to allow some extension of attribution results in one region to be cautiously applied to the other (Hope *et al*. 2010).

For south-west Western Australia, synoptic typing techniques have shown a marked decline in the frequency of troughs associated with rainfall since 1975, along with an increase in weather patterns associated with higher pressure and dry conditions. The decrease in the number of rain-bearing systems accounts for about half of the rainfall decline, while the reduction in rainfall from rain-bearing systems accounts for further drying (Hope *et al*. 2006). These changes are consistent with a general decrease in baroclinicity.

This is consistent with studies showing increased intensity (higher pressure) in the subtropical ridge (STR) in the wider Australian region (Timbal and Drosdowsky, 2013). This is a potentially important attribution step in the research, since the regions of long-term rainfall deficits correspond to those regions where rainfall is well correlated with STR variability during March to October; with increasing pressure potentially explaining two-thirds of the rainfall decline in those regions (Timbal and Drosdowsky, 2013). Figure 4.2.8 shows the correlation between the strength of the STR in the Australian region and January to December rainfall since 1900. There is inconclusive or no evidence

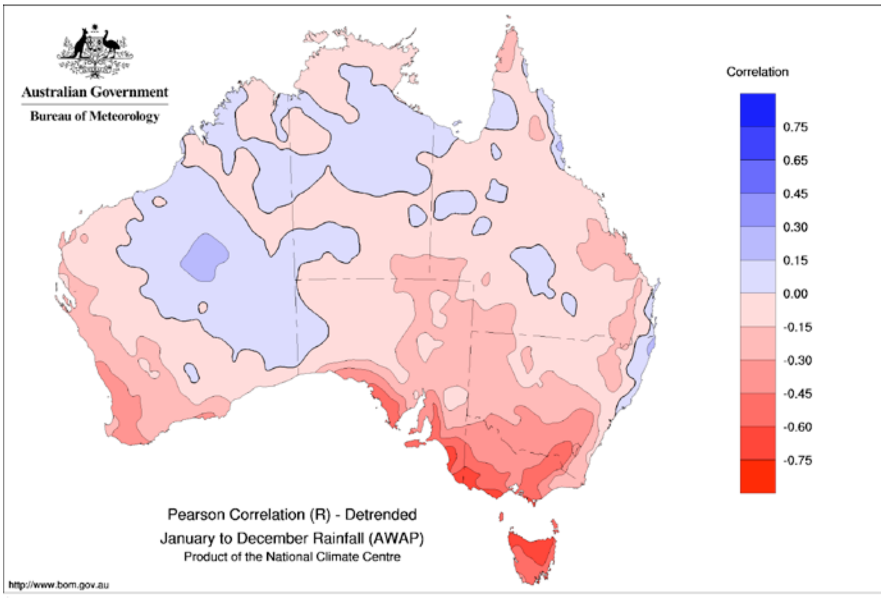

FIGURE 4.2.8: CORRELATION BETWEEN THE STRENGTH OF THE SUBTROPICAL RIDGE (STR) IN THE AUSTRALIAN REGION AND THE JANUARY TO DECEMBER RAINFALL FROM THE AUSTRALIAN WATER AVAILABILITY PROJECT (AWAP, 1900 TO PRESENT) (SOURCE: BUREAU OF METEOROLOGY).

for a poleward shift in the mean position of the STR (Drosdowsky, 2005). Such a shift might be reasonably expected, associated with trends toward a more positive phase of the SAM and expansion of the Hadley circulation. This result does not imply that the storm track across southern Australia has remained constant over time.

Modelling studies have shown a reduction in storm formation in the Australian region since the mid 1970s, and particularly for the period 1997-2006, with storm activity moving from the subtropical jet to the polar jet (Frederiksen *et al*. 2011). This is consistent with a southward movement of the storm track and reduced storminess in the region.

Attribution of the changes in Southern Hemisphere atmospheric circulation has been attempted by several studies. Each of these attribution studies show inconsistencies between climate models and the real world, mostly related to the magnitude of the observed circulation and rainfall changes as well as the seasonality of the relationships between circulation and rainfall changes.

While poleward expansion of the Hadley circulation is consistent with anthropogenic forcing simulations, comparison between those experiments and reanalysis data show observed changes are much larger, as a function of latitudinal movement per decade, than the models (Hu *et al*. 2013, Lucas *et al*. 2014). Similarly, observed increases in the intensity of the subtropical ridge are consistent with anthropogenic simulations and inconsistent with natural variability, but very much less than pressure increases that have been observed in the Australian region (CSIRO, 2012).

The southward contraction of SAM (or trend toward an increasingly positive phase) in the last several decades has been associated with both greenhouse gas increases and stratospheric ozone decreases. The majority of studies have found that stratospheric ozone depletion is the biggest contributor to the poleward contraction of SAM during summer in the second half of the twentieth century (Polvani *et al*. 2011, Son *et al*. 2010, Arblaster and Meehl, 2006, Gillett and Thompson, 2003). Increases of greenhouse gases are also likely to be a factor, and are necessary for the simulation of the observed trends at the surface. Since the 1950s, the greenhouse gas driven contribution to total SAM changes is estimated to be two to three times smaller than the contribution ozone reductions in summer, but larger than ozone contributions during winter (Arblaster and Meehl, 2006). More recent studies in the Northern Hemisphere show that increased atmospheric aerosols may also play a part in poleward movement of storm tracks (Allen *et al*. 2012; Lucas *et al*. 2014). It is important to note that stratospheric ozone depletion may be expected to stabilise and possibly recover in coming decades, but that greenhouse gas forcing is likely to increase.

While the connection between anthropogenic forcing and circulation changes is relatively clear, seasonality issues remain in connecting changes in the SAM and rainfall declines over southern Australia. The influence of Southern Hemisphere ozone depletion and trends in the SAM at the surface are most apparent in summer (Thompson *et al*. 2011), while declining rainfall trends occur in autumn and winter. Timbal *et al*. (2010) find that the trend in the SAM can account for rainfall declines during May, June and July in the south-east, but that the mechanism could only account for around half of the observed drying.

Complicating that comparison is the fact that the local surface pressure signal from trends in SAM is largest prior to the period of observed rainfall decline (Timbal *et al*. 2010). However modelling studies (Cai and Cowan, 2006) show the possibility that a SAM-south-west Western

Australia relationship exists in winter, with anthropogenic forcing contributing to about 50 % of the observed rainfall decline since the late 1960s.

Simulations of rainfall changes over the south-west of Western Australian and south-eastern Australia consistently show declines during cooler months of the year. The largest modelled declines, in response to increasing greenhouse gases, occur in winter and spring rather than autumn and winter. Similar to other atmospheric variables discussed here, rainfall simulations from climate models also show changes that are much smaller than those observed. For drying over Australia, observed changes are around two to five times larger than model simulations for a 1 °C global warming.

There are a range of potential reasons for the discrepancy in the magnitude of observed and modelled response. It is possible that natural variability superimposed on anthropogenic forced changes is causing larger, transient changes in the real world. Similarly, it is possible that unaccounted forcings are present and of a similar direction to anthropogenic forced changes. It is also possible that the model response is too small compared to the real world. The discrepancy between observed rainfall and modelled rainfall locally in southern Australia is consistent with some global studies suggesting that the models underestimate the amplification of the hydrological cycle under the enhanced greenhouse effect (see for example Durack *et al*. 2012 and Wentz *et al*. 2007).

While much discussion of rainfall variability and trends focuses on zonal mean (north-south) changes, it should be noted that zonal asymmetries (east-west differences in circulation) also play a role in setting rainfall variability and trends across southern Australia.

For many parts of south-east Australia, rainfall variability and trends are more strongly determined by variation in rain from cut-off low systems than from frontal systems (Risbey *et al*. 2013b). The frontal component of rainfall declines is associated with north-south shifts in the storm tracks as discussed above. However, the cut-off low contribution reflects both north-south shifts in the storm tracks and east-west shifts in the zones of preferred blocking. The Millennium Drought (section 4.2.4) in the south-east was at least partly associated with a reduction in cut-off rainfall and blocking activity in the Tasman Sea region (Risbey *et al*. 2013a).

In south-west Australia the rainfall reductions are more strongly driven by frontal rain than cut-off rain, but variations in blocking and cut-off rain also play a role there (Pook *et al*. 2012). A fuller understanding of the causes of rainfall changes in southern Australia needs to account for longitudinal as well as latitudinal shifts in the preferred storm track regions (Risbey *et al*. 2013b).

4.2.4 DROUGHT

Australia has experienced three major dry periods over the last century or more, including the "Federation drought' (1895-1903), the "World War II drought" (1939-1945), and the so-called "Millennium drought" (1996-2010). These major droughts have been related to variability of large-scale drivers including ENSO, the monsoonal circulation over northern Australia, Indian Ocean sea surface temperatures, and the large-scale circulation in the Southern Hemisphere (*e.g.* Risbey *et al*. 2003, Timbal and Hendon, 2011). On the decadal scale, the Interdecadal Pacific Oscillation (IPO) may modulate droughts by changing the regional impact of ENSO (Power *et al*. 1999, Verdon-Kidd and Kiem, 2009).

Assessment of changes in the behaviour of droughts over time is complex, with the IPCC *Fifth Assessment Report* finding that results varied greatly between studies, depending on the drought indicator used (in particular, whether it was purely rainfall-based or incorporated other variables) and the timescale of drought considered (IPCC, 2013). Major studies in Australia include those of Hennessy *et al*. (2008), which considered rainfall and soil moisture below the 5th percentile at the 12-month timescales, and Gallant *et al*. (2013), which considered rainfall and soil moisture below the 10th percentile over rolling 3-month periods. Observed trends in the areal extent and frequency of exceptionally low rainfall years over Australia are highly dependent on the period of analysis due to large variability between decades, with those trends which exist superimposed on those decadal-scale variations (Hennessy *et al*. 2008).

The recent period has included a significant drought that coincided with seasonal rainfall declines in the south-east (described above). The Millennium Drought, running from about 1996 to 2010, saw a reduction of annual rainfall associated with declines in autumn and winter months, and a lack of significant rainfall outside of those months. The Millennium Drought is likely the result of coincident timing of separate, but potentially correlated, climate drivers. These include the drivers of the cool-season rainfall decline (discussed above), including the decline of cyclone frequency, (McGrath *et al*. 2012).

A comparison of the Millennium Drought with previous drought in the Murray Darling Basin has shown that the most recent dry period was larger in spatial extent, and that the depth of the drought during late autumn and winter was more severe, perhaps influenced by coincident rainfall trends (Timbal and Drosdowsky, 2013, Timbal and Fawcett, 2013). However, little evidence for trends in episodic drought has been found for Australia, using a variety of metrics (Hennessy *et al*. 2008). Amongst the most robust trends has been an increase in various drought-related variables in the south-west of Western Australia, where there has been an increase in the frequency of exceptionally low rainfall totals covering large areas, particularly in winter (Hennessy *et al*. 2008, Gallant and Karoly, 2010); although this is again conflated with a long-term seasonal rainfall decline. A significant increase in the area of south-east Australia experiencing exceptionally low rainfall during autumn was largely due to a substantial increase since the turn of the 21st century (Gallant and Karoly, 2010). On the other hand, many other parts of the continent, particularly in the tropics, show a decrease in drought frequency and intensity at various timescales since the early 20th century (Gallant *et al*. 2013), although the exact nature of these results is sensitive to the period used for analysis, with the 1900-1920 period having a particularly high frequency of droughts in many regions.

4.2.5 SNOW

In 2003, CSIRO and the Australian National University published a report titled *The impact of climate change on snow conditions in mainland Australia* (Hennessy *et al*. 2003). One of the key findings was that snow depths at four alpine sites (Rocky Valley Dam, Spencers Creek, 3-Mile Dam and Deep Creek) have declined from the 1950s to 2001. In 2012, an updated analysis of snow measurements at Rocky Valley Dam in Victoria from 1954–2011 (Bhend *et al*. 2012) indicated an ongoing trend to lower maximum snow depths and an earlier end of the snow season. The long-term changes are superimposed on considerable year to year variability. The variability in maximum snow depth can be well explained by maximum temperature and precipitation from June to August. The earlier end of the snow season is dependent on changes in temperature.

4.2.6 SURFACE WINDS OVER CONTINENTAL AUSTRALIA

Wind fields across Australia are associated with large-scale circulation patterns and their seasonal movement. Across the southern half of Australia, average wind conditions are influenced by the seasonal movement of the subtropical high pressure belt which separates the mid-latitude westerly winds to the south and the south-east trade winds to the north. From November to March, the Asian-Australian monsoon interrupts the trade winds, bringing a north-westerly flow across northern Australia.

Trends in terrestrial near-surface winds (2 to 10 metres above the ground) determined from anemometers over recent decades have been found to be declining in the tropics and mid-latitudes globally (Vautard *et al*. 2010, McVicar *et al*. 2012) and this has been attributed mainly to an increase in land surface roughness arising from increased vegetation cover (Vautard *et al*. 2010). Over Australia, the trend at 2 m is of the order -0.01 m/s/year or metres per second per year (McVicar *et al*. 2008). However at 10 m, an increasing trend of the order of 0.03 m/s/year has been detected (Troccoli *et al*. 2012). Over the oceans, increasing trends have been found in mean and extreme 10 m wind speeds based on two decades of satellite altimeter data (Young *et al*. 2011). Wind trends in the Australian region are related to the poleward shift in the Hadley circulation. This has been associated with a declining trend in pressure in the sub-tropics and an increasing trend in mean sea level pressure (MSLP) in the mid-latitudes over 1989–2006 in the NCEP–NCAR reanalysis (Troccoli *et al*. 2012).

Due to the sparseness of long-term, high quality wind measurements from terrestrial anemometers, a high quality gridded data set for wind is not available over Australia (Jakob, 2010). Therefore 10 m winds from reanalysis products are commonly used as a baseline against which climate model winds are compared. Although constrained by observations, reanalysis products are also derived from models and so may contain biases. For example, McInnes *et al*. (2011) found that average wind speeds between the NCEP-DEO AMIP-II (Kanamitsu *et al*. 2002) and ERA40 (Uppala *et al*. 2005) reanalysis products over 1981–2000 exhibited spatial differences between each other that were greater than the differences between these products and some CMIP3 climate models. This was particularly the case in the southern hemisphere in winter (McInnes *et al*. 2011).

4.2.7 TROPICAL CYCLONES

Tropical cyclones are relatively small-scale weather phenomena that affect the tropical coasts of Western Australia, the Northern Territory and Queensland from late November through to April. The most severe impacts of tropical cyclones in Australia are characterised by catastrophic wind speeds, storm surges and extreme heavy rainfall and flooding. Natural variability in the number of tropical cyclones making landfall in Australia is strongly influenced by ENSO, with more tropical cyclones during La Niña years and fewer in El Niño years.

The relatively short time span of consistent records, combined with high year to year variability, makes it difficult to discern any clear trends in tropical cyclone frequency or intensity for the Australian region. For the period 1981 to 2007, no statistically significant trends in the total numbers of cyclones, or in the proportion of the most intense cyclones, have been found in the Australian region, South Indian Ocean or South Pacific Ocean (Kuleshov *et al*. 2010). However, observations of tropical cyclone numbers from 1981–82 to 2012–13 in the Australian region show a decreasing trend that is significant at the 93-98 % confidence level when variability associated with ENSO is accounted for (Dowdy, 2014). Only limited conclusions can be drawn regarding tropical cyclone frequency and intensity in the Australian region prior to 1981, due to a lack of data. However, a long-term decline in numbers on the Queensland coast has been suggested (Callaghan and Power, 2010).

4.2.8 EAST COAST LOWS

Observational studies provide some indication of a small decreasing trend in the number of East Coast Lows, based on reanalysis data (Dowdy *et al*. 2013c). There is a strong connection between heavy rainfall and East Coast Low occurrence in the eastern Australian region (Pepler *et al*. 2014, Dowdy *et al*. 2013b) and a decrease in extreme rain events along the east coast has been observed since 1950 (Gallant *et al*. 2007). East Coast Lows are also the primary cause of large ocean waves in NSW coastal regions (Dowdy *et al*. 2014).

4.2.9 SOLAR RADIATION

The downward solar radiation at the Earth's surface is a key parameter for the Earth-atmosphere climate system. It also plays an important role in many physical, chemical and biological processes. Its variation relates to factors including cloud cover, air pollution, latitude and the season. In Australia, there is a close connection, or covariability, at continental scales between rainfall, cloudiness, temperature and solar radiation at the surface.

Estimates of solar radiation from a cloud-based model using data from 29 stations across Australia from 1967 to 2004 show no significant changes at the majority of stations, with only eight stations showing significant decreases and two stations showing significant increases (Nunez and Li, 2008). Specifically, the notable changes in solar radiation over time are concentrated over the south of the continent. High quality cloud observations show that the Australian mean annual total cloud amount is characterised by high year to year variability, with a weak increase over the 1957 – 2007 period (Jovanovic *et al*. 2011). Attribution of small changes in solar radiation over time is difficult, due to the range of complex influences. These include changes in cloud associated with high rainfall variability in the Australian region and the direct and indirect effect of changes in aerosols.

4.2.10 SURFACE HUMIDITY

Humidity describes the relative amount of water vapour in an air parcel. Surface humidity in Australia is an important component of local weather. Very high or low humidity is associated with ecological and agricultural impacts, the severity of fire weather and the impact of heat waves on human health.

Changes in humidity across Australia are closely connected to rainfall variability, and are not well described by linear trends over time. Instead, large interannual and decadal variability is apparent in Australian dewpoint temperatures (the saturation temperature for an air parcel cooled at a constant pressure and moisture content). However most sites across Australia have shown increases in dewpoint temperature from 1957 to 2003, with the largest increases in the interior of the continent (Figure 4.2.9) (Lucas, 2010a). Specific attribution of these changes has not been performed.

4.2.11 PAN EVAPORATION

Pan evaporation is a direct measurement of the evaporative loss from a uniform (standard) small body of water placed within the environment at the surface. Pan evaporation is mostly utilized for estimating evapotranspiration, or the transfer of water vapour from vegetation and the land surface. Evapotranspiration is a key variable in determining the water balance of a system.

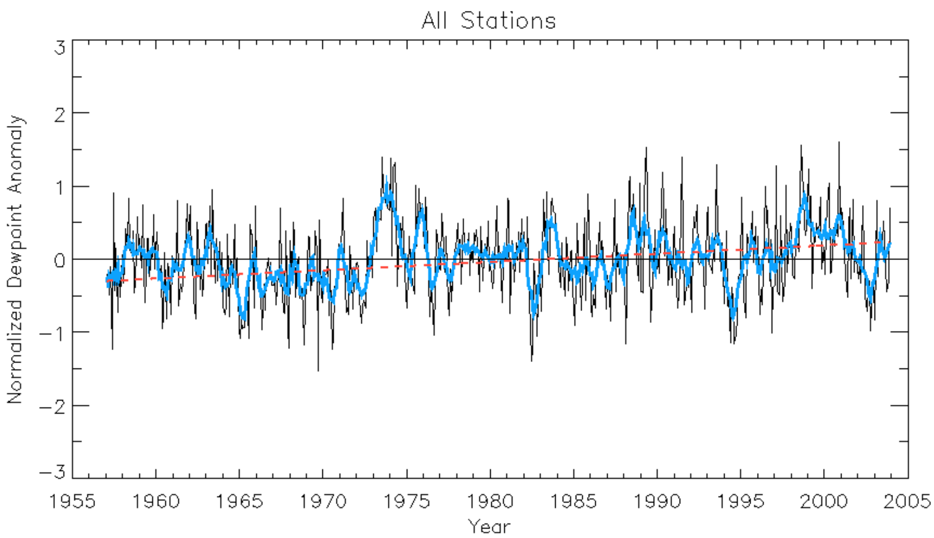

FIGURE 4.2.9: AVERAGE MONTHLY NORMALIZED DEWPOINT ANOMALY ACROSS ALL 58 HIGH QUALITY STATIONS OVER AUSTRALIA. BLUE LINE IS THE 7-MONTH SMOOTHED VALUE (SOURCE: LUCAS, 2010A).

There are no clear changes observed in pan evaporation across Australia in data available since 1970 (Jovanovic *et al*. 2008). Uncertainties in pan evaporation changes over time are largely due to sensitivity to wind speed at pan height, which in turn is highly sensitive to changes in site exposure. There is a broad-scale pattern of decreases in pan evaporation across northern Australia in regions which have seen recent increases in monsoonal rainfall.

4.2.12 FIRE WEATHER

Australia is one of the most fire prone regions in the world. The fire season is distinctly different for different parts of the continent; during the dry season for northern Australia, spring and summer for the sub-tropics and middle to late summer for southern regions. Fire potential at a given place depends on four ‘switches’: 1) ignition, either human-caused or from natural sources such as lightning; 2) fuel abundance or load (a sufficient amount of fuel must be present); 3) fuel dryness, where lower moisture contents are required for fire, and; 4) suitable weather conditions for fire spread, generally hot, dry and windy (Bradstock, 2010). The settings of the switches depend on meteorological conditions across a variety of time scales, particularly the fuel conditions.

Fire weather is monitored using a McArthur Forest Fire Danger Index (FFDI), which is calculated from daily temperature, wind speed, humidity and a drought factor, at sites with consistent data across Australia (Lucas, 2010b). An increase in the annual (July-June) cumulative FFDI is observed across all 38 sites analysed in Australia from 1973 to 2010, and is statistically significant at 16 of those sites. (Figure 4.2.10; Clarke *et al*. 2013), particularly in the south-eastern part of the country. This increase across south-east Australia is characterised by an extension of the fire season further into spring and autumn (Clarke *et al*. 2013). There has also been an increase in high FFDI values (90th percentile) from 1973–2010 at all 38 sites, with a statistically significant increase at 24 sites, indicating that extreme fire weather days have become more frequent over time (Clarke *et al*. 2013).

The FFDI increases are partly driven by temperature increases that are attributable to climate change. Similarly, temperature changes alone have been shown to contribute significantly to evaporation and surface evapotranspiration in drier catchments of the Murray Darling Basin (McVicar *et al*. 2012). However, no studies explicitly attributing the Australian increase in fire weather to climate change have been performed at this time.

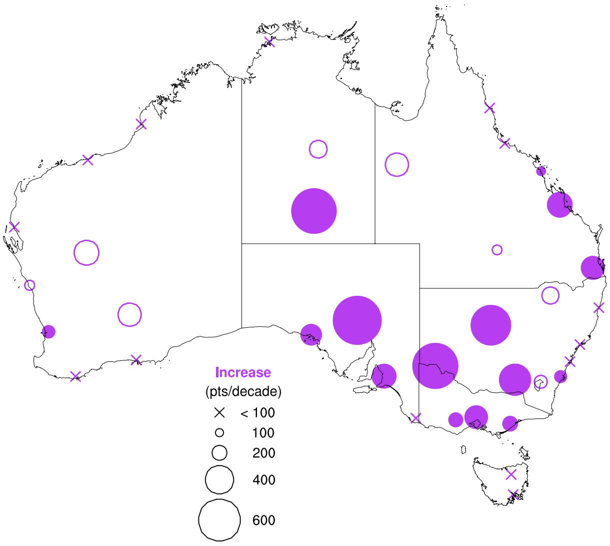

FIGURE 4.2.10: MAP OF TREND IN ANNUAL 90TH PERCENTILE FFDI. MARKER SIZE IS PROPORTIONAL TO THE MAGNITUDE OF TREND. REFERENCE SIZES ARE SHOWN IN THE LEGEND. FILLED MARKERS REPRESENT TRENDS THAT ARE STATISTICALLY SIGNIFICANT. THE MARKER FOR LAVERTON HAS BEEN MOVED WEST TO AVOID OVERLAP WITH MELBOURNE AIRPORT (SOURCE: CLARKE *ET AL*. 2013).