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Queensland Climate Change Centre of Excellence

Research Report

Department of Environment and Resource Management

Rainfall in Queensland

Part 1: A literature survey of key rainfall drivers in Queensland, Australia: Rainfall variability and change

Prepared by Nicholas Klingaman

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Walker Institute

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Toward Q2 Tomorrow's Queensland

Queensland Government

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1 Executive Summary

Queensland’s climate experiences considerable natural inter-annual and decadal variability in its rainfall. To determine how Queensland's rainfall is going to change in the coming decades as the planet warms, it is critical to establish which global and regional climate phenomena are driving this variability.

Understanding the potential impacts of climate change is essential to inform strategies and actions to avoid or manage dangerous levels of change. The impacts of these changes are important especially for those sectors that are vulnerable to changes in rainfall, such as water-resource management and agriculture. In 2007, the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, 2007) confirmed that there is currently substantial uncertainty in rainfall projections for the Australian region for the coming century. This reinforces the urgent need to reduce that uncertainty. Improving the current understanding of key processes and phenomena that influence Queensland rainfall on timescales from days to decades will help to address that uncertainty, as there may be greater confidence in the impacts of climate change on these phenomena than for rainfall. A reduced uncertainty in rainfall changes would support effective planning to address potential changes in the hydrological cycle at the regional and local level.

Part of the uncertainty in future rainfall changes arises from the various competing and interacting influences on Queensland rainfall, which are associated with synoptic and climate drivers across various time scales, such as tropical cyclones, the Madden-Julian Oscillation (MJO), the El-Niño Southern Oscillation (ENSO) and the Inter-decadal Pacific Oscillation (IPO). The MJO controls the sub-seasonal variations in the summer monsoon rainfall with a period of 30-60 days. It primarily affects northern Queensland and modulates the monsoon and trade-wind circulations. Active periods of the MJO also increase the probability of tropical cyclone formation in the Coral Sea.

On inter-annual timescales, Queensland's rainfall is heavily influenced by ENSO: wet conditions prevail in La Niña (cold equatorial Pacific Ocean temperatures) years, while El Niño (warm equatorial Pacific Ocean temperatures) promotes drought. Rainfall is sensitive to both the magnitude and position of El-Niño and La Niña events. Central Pacific ENSO events have a much stronger impact on Queensland than eastern Pacific events. The link between Queensland's rainfall and the ENSO can fluctuate from one decade to the next, but shows no long-term trend.

The IPO describes the slowly evolving variations in Pacific Ocean temperatures, with a period of about 20-30 years. Its positive (warm) phase resembles an expanded El-Niño, while its negative (cool) phase resembles an expanded La Niña. El-Niño and La Niña events canoccur in either phase of the IPO. The IPO influences the relationship between ENSO and Queensland rainfall: warm phases show a weak connection, while cold phases display a strong connection.

Knowledge and prediction of the influence of these drivers on regional and local rainfall will help improve the understanding of climate changes at those smaller scales. This may also result in more-accurate predictions of climate variability and change over the next 20 years - a key period for climate-change adaptation efforts.

This report reviews existing studies of observed changes in Queensland rainfall - its mean, variability and extreme events - to determine the dominant remote synoptic and climate drivers of rainfall. The review found that although many studies have described variations in rainfall in Queensland and across Australia, only a few have explained these changes as due to variations in the impact of known remote rainfall drivers. Even fewer studies have provided plausible physical mechanisms for the variability in the influence of those drivers. Analysis has often focused on annual-or seasonal-mean rainfall, neglecting the spatial and temporal characteristics of rainfall. Little research had been undertaken on the interactions between temporal scales of variability, despite strong indications that these interactions are key to determining the character of Queensland’s rainfall.

2 Introduction

2.1 The objective of this report

This report describes the current body of knowledge concerning rainfall variability and change in Queensland, Australia. The primary objective is to comprehensively survey potential remote synoptic and climate drivers of rainfall variability; the secondary objective is to examine how these drivers might change in a warming world. No novel analysis is presented here, although the author does comment, where appropriate, on links between studies - particularly on interactions between modes of variability acting at separate temporal scales - and to point out opportunities for further research. After a brief justification for investigating remote drivers of Australian rainfall variability (Section 2.2), this report reviews studies of observed changes in Queensland rainfall, both in its mean (Section 2.4.1) and variability (Section 2.4.2), including extreme events. The bulk of the report assesses the literature surrounding the dominant synoptic (Section 3) and climate (Section 4) drivers of Queensland rainfall. These sections are organised by phenomenon, which are organised on a temporal scale, from shortest period to longest. Sections are summarized separately (Sections 2.4.3, 3.4 and 4.6); a synopsis concludes the report (Section 5).

2.2 The case of examining remote drivers of rainfall variability in Australia

Australian rainfall varies considerably on temporal scales ranging from one day to several decades. This variability is greater than that of other regions with similar mean climates (Nicholls et al. 1997). While local-scale processes such as mesoscale thunderstorms, the land-ocean thermal contrast and local sea surface temperature (SST) gradients cause a portion of this variability, Australian rainfall is heavily influenced by phenomena that extend far beyond the continent and that vary on intra-seasonal, seasonal, decadal and inter-decadal temporal scales (Risbey et al. 2009). These include, in order of lengthening period, the Madden-Julian Oscillation (Madden and Julian 1971; Wheeler et al. 2009), the Southern Annular Mode (Baldwin 2001; Hendon et al. 2007), the Indian Ocean Dipole (Saji et al. 1999; Ashok et al., 2003a), the El Niño Southern Oscillation (Allan 1988; Wang and Hendon 2007) and the Inter-Decadal Pacific Oscillation (IPO) (Power et al. 1999). These slowly evolving, broad-scale climatic drivers are valuable, as they are likely predictable at longer lead times - in reality and in general circulation models (GCMs) - than the more-stochastic local weather. These climatic drivers modulate regional synoptic patterns, including the temporal and spatial distribution of extreme rainfall events; knowledge of changes to those patterns could be improved by analysing their interactions with lower-frequency phenomena (Pook et al. 2006).

In addition to identifying these remote drivers, a few past studies have attempted to examine the interactions between them (Fig. 1). The abundance of arrows in Fig. 1 suggests the complexity of these cross-temporal-scale interactions and the difficulty involved in isolating any single one. For example, the Madden-Julian Oscillation, the El Niño Southern Oscillation and the Inter-decadal Pacific Oscillation have all been found to affect the number of tropical cyclones that affect Queensland, yet these processes themselves interact on everything from intra-seasonal to inter-decadal temporal scales. Some climate drivers and some interactions are less well defined or understood than others; these tenuous links are indicated by dashed boxes or dashed arrows in Fig.1. The drivers and their connections to one another will be examined in Sections 2 and 3, Figure 1 is placed here for easy reference.

Climate change compounds the natural variability of Australian rainfall, not only by potentially altering mean rainfall, but also by affecting the synoptic and climate processes responsible for that variability. For example, Pacific Ocean warming may create a more El Niño-like basic state that, judged against the present-day mean state, could result in an increased (decreased) frequency of El Niño (La Niña) events (Federov and Philander 2000). Power and Smith (2007) implied that climate change may disrupt teleconnections between El Niño or La Niña and regional climate variability around the globe. It is extremely difficult to partition observed trends or fluctuations in rainfall into that which is the result of climate change and that which is the result of natural variability, especially since variability on decadal and longer scales is often poorly resolved by the spatially and temporally limited observed record. Attribution at the regional scale has typically been performed with GCMs instead (e.g. Timbal et al. 2006), but GCMs are not always able to reproduce observed regional changes, particularly in derived parameters such as precipitation; there are also questions as to the models' capacity to represent teleconnections between large-scale climatic drivers and local weather.

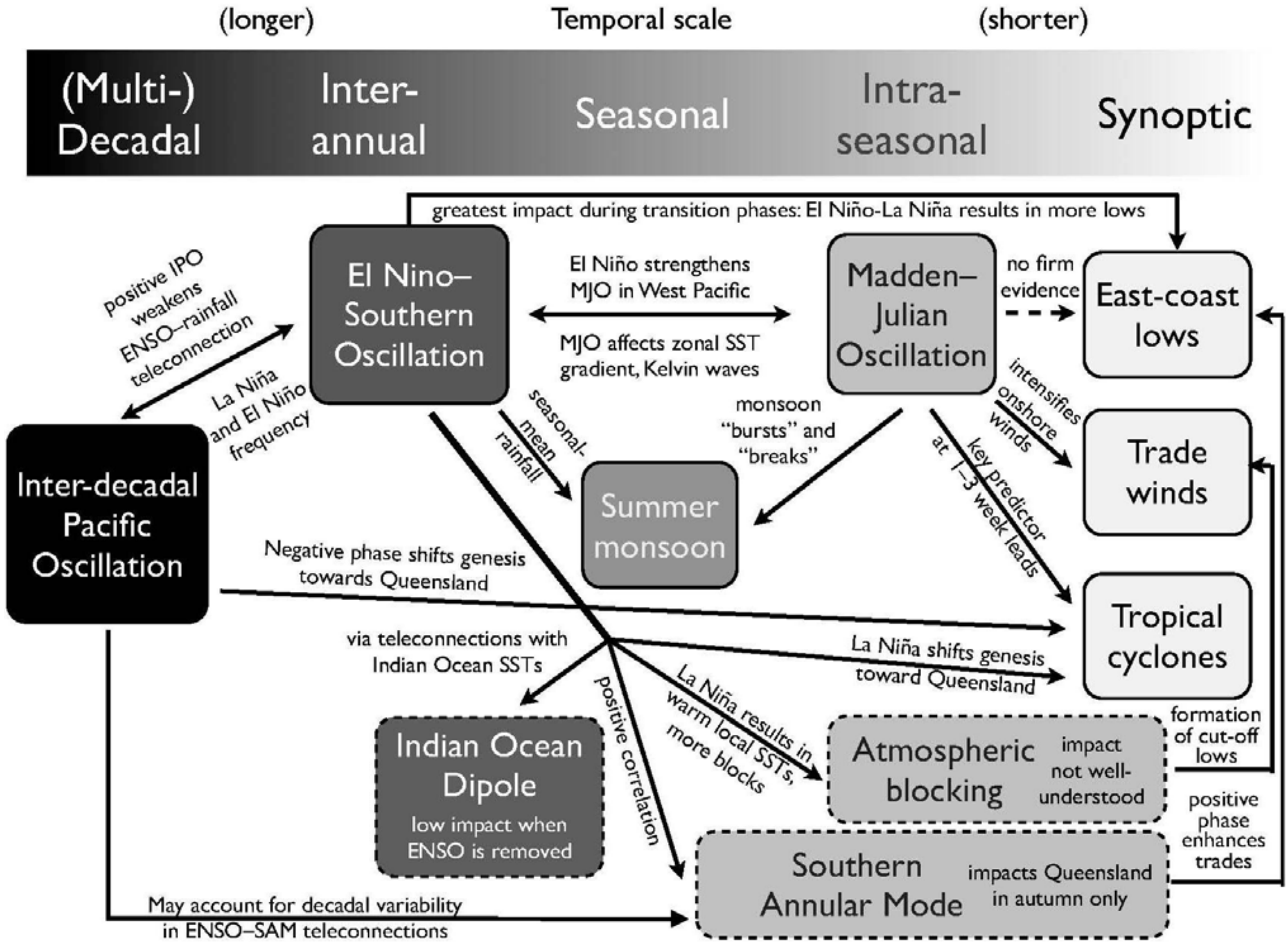

Figure 1: Conceptual diagram indicating the remote drivers of Queensland rainfall (in boxes) and the interactions between those drivers (arrows), as discussed in the following sections. The shade of gray in the background of each box corresponds to the temporal scales at the top of the figure. The temporal scales are organized from longest to shortest. Double-headed arrows identify two-way interactions between the drivers they connect. Remote drivers and interactions that are poorly defined or understood are shown in dashed boxes and arrows, respectively.

2.3 Mean annual and seasonal rainfall in Queensland

The 1979-2007 climatology of annual rainfall totals from the Center for Merged Analysis of Precipitation (CMAP) dataset shows that the highest rainfall amounts in Queensland are found near the coasts (Fig. 2a); such coastal maxima are found throughout most of Australia. These maxima are poorly resolved, however, by the 2.5 degree horizontal resolution of the CMAP dataset. The Tropical Rainfall Measuring Mission (TRMM) climatology extends only over 1999–2007, but is available at the much finer 0.25 degree resolution. The broad patterns of the TRMM climatology (Fig. 2b) compare well against CMAP, but the precipitation maxima are stronger and closer to the coastline. A qualitative comparison against images of gauge-based annual precipitation from the Australian Bureau of Meteorology (not shown) demonstrated that the TRMM maxima had similar magnitude and spatial location, while the CMAP maxima were generally too low in magnitude and extended too far inland. The TRMM climatology will be used to explore the mean seasonal cycle of Queensland rainfall.

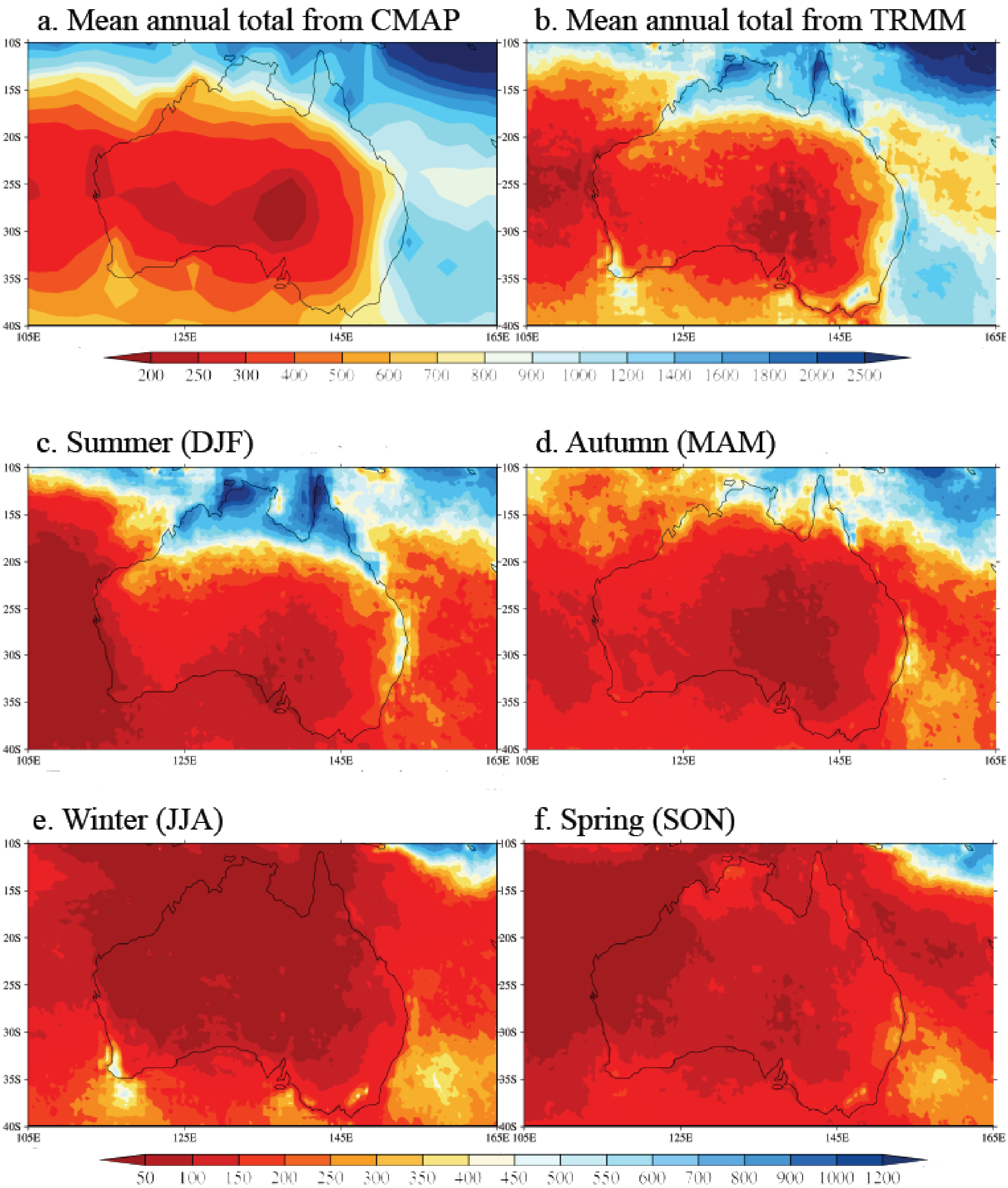

Figure 2: (a–b) Mean annual rainfall (mm)from (a) the Centre for Merged Analysis of Precipitation dataset (CMAP; 1979–2007) and (b) the Tropical Rainfall Measuring Mission dataset (TRMM; 1999–2008). (c–f) Mean seasonal rainfall (mm) from TRMM for (c) December–February, (d) March–May, (e) June–August and (f) September–November.

Queensland obtains the vast majority of its rainfall in austral summer (December-February; Fig. 2c). The northern peninsula receives 800-1200 millimetres during this season, most of which is due to the Australian monsoon and its associated synoptic-scale disturbances (Section 4.1.1). The remaining fraction comes from the south-easterly trades (Section 3.1). Rainfall along the east coast of Queensland is in excess of 500 millimetres in summer; that region is affected more by extra-tropical coastal cyclones (Section 3.2.2) than by the monsoon. The monsoon circulation often lingers into March, leading to moderate autumn totals for the north coast (Fig. 2d). Extra-tropical systems continue to affect the east coast in autumn and do so rarely in winter (Fig. 2e). Winter and spring (Fig. 2f) are very dry seasons, particularly in the north where the monsoonal circulation reverses and warm, dry southerlies dominate.

2.4 Observed changes in Queensland rainfall and its variability

This section reviews studies of observed changes in Queensland rainfall in both the mean and variability. The latter subsection emphasises on modifications to the frequency of extreme daily precipitation, which are critical to determine how a warmer world may alter flooding patterns.

2.4.1 Trends in mean rainfall

Queensland - as much of inhabited Australia - has a relatively long record of continuous observations of rainfall across a wide network (Lavery et al., 1992, 1997). Many records in the state extend back to the early 20th century; some reliable records exist from the mid-to-late 19th century, but these are few and rarely included in analyses. Lavery et al. (1997) determined that the 1890s was the first decade in which a sufficient number of stations existed, covering much of the continent, to justify creating an area-averaged all-Australia rainfall index. The length of this record enables detection of variability on scales of up to several decades, as well as changes in long-term mean rainfall.

When the entire 20th century is considered, Queensland has not experienced a statistically significant trend in seasonal rainfall. Lough (1997) examined rainfall at 17 stations across the state for 1890–1994 which were deemed to have the highest quality records, with little missing data and no discontinuities from shifts in location or sensor height (Fig. 3). That study determined that there was no statistically significant linear trend in rainfall in any season, although there was substantial inter-annual and decadal variability, confirming the findings of Lough (1991). Section 4 examines the underlying causes of this variability. Lough (1997) concluded that while the early 1990s were a dry period in Queensland - particularly in summer, when the state receives most of its rainfall - they were not “particularly unusual” in the context of the 105-year record. The early 1990s appeared dry only because mean summer rainfall had increased sharply over much of eastern Australia around 1950, the cause of which is presently unknown. When the early 1990s were compared against the longer-term (1890–1995) mean, the dry anomalies were of similar magnitude to those in the 1930s and 1960s and were not as severe as the “Federation drought” of 1896–1902 (Fig. 3).

Hennessy et al. (1999) analysed a modified form of the Lavery et al. (1997) dataset to evaluate rainfall trends in Australia. In keeping with Lough (1997), Hennessy et al. (1999) found a shift to wetter summers in eastern Australia around 1950. The increase in Queensland summer rainfall over 1910–1995 was approximately 15 per cent, but was not statistically significant; the 17 per cent increase in neighboring New South Wales was significant. There was no significant trend in Queensland winter rainfall. Nicholls and Lavery (1992) obtained similar results: the mean summer rainfall abruptly increased in coastal eastern Australia near 1950, with a slight drying over 1950–1990. Nicholls and Lavery (1992) clustered the continent into ten regions with homogeneous rainfall trends, then identified a "representative station” for each. The coastal Queensland representative station - Gatton Lawes - exhibited substantial decadal variability, with a declining trend from 1970-1990 due to drier summers. Nicholls and Lavery (1992) made no rigorous attempt to evaluate their trends’ statistical significance, but in Queensland the trends were far smaller than the inter-annual or decadal variability.

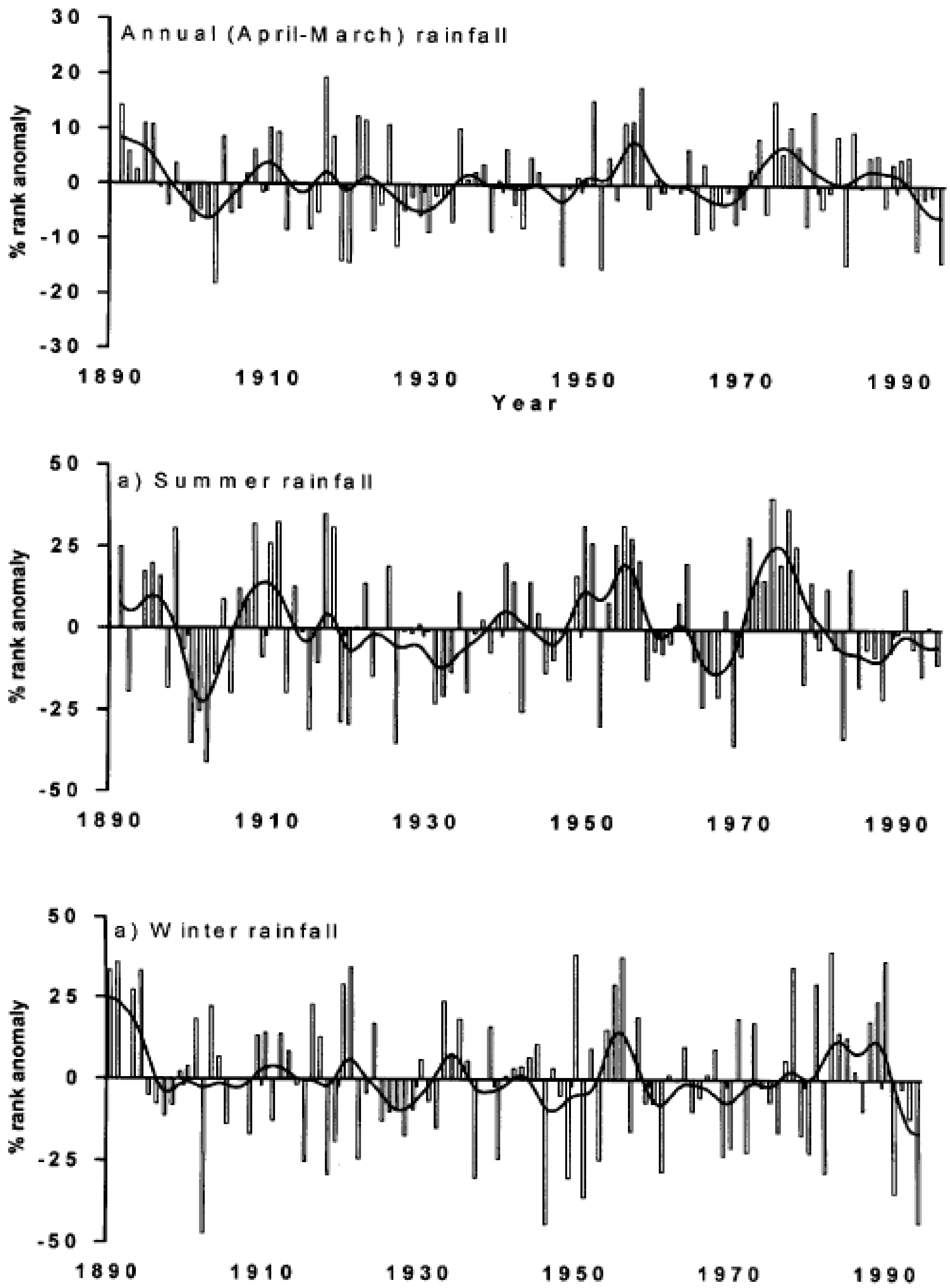

Figure 3: Observed rainfall anomalies in Queensland from 17 stations, expressed as rank anomalies, for (top) annual, (middle) summer half-year (October–March) and (bottom) winter half-year (April– September) rainfall. Ranks were calculated by sorting all years from lowest to highest, assigning each year a number corresponding to its position in the series, normalizing each value by the total number of years and multiplying by 100. The rank anomaly for each year is then its rank minus the average rank (50). Figure reproduced from Figs. 4, 2a and 3a, respectively, in Lough (1997).

2.4.2 Changes to extreme events and variability

These results do not mean that climate change has not affected Queensland rainfall. First, these studies are based on only observations, which contain signals of natural variability and the mean climate; climate change may influence both of these independently, as well as their interaction (Section 1.2). Second, these studies have focused on the linear trend in mean rainfall. This sort of analysis neglects any alterations to the spatial and temporal character of precipitation, such as frequency and intensity, the occurrence of severe storms and the fractional contribution of heavy events to the annual total.

Suppiah and Hennessy (1998) studied changes in the frequency and intensity of heavy rain over 1910-1990, defined separately at each of 125 stations over Australia as the long-term-mean 90th and 95th percentiles of daily precipitation amounts. That study concluded that coastal Queensland displayed an increase in both the occurrence of heavy rain events and in the amount of rain that fell in those events. The number of dry days - rainfall less than the reporting threshold of 0.1 millimetres - had decreased. Inland regions of Queensland, however, showed changes of the opposite sign in those parameters (i.e. a decrease in the frequency and intensity of extreme precipitation and an increasing number of dry days), suggesting spatially complex modifications to the state’s flood and drought risk. Despite this regional variability, Suppiah and Hennessy (1998) demonstrated that same-signed changes were spatially coherent, leading the authors to conjecture that synoptic weather patterns had shifted (i.e. storms that had previously tracked inland were remaining closer to the coast).

In a related earlier study, Suppiah and Hennessy (1996) concluded that a relationship existed between the frequency of extreme precipitation-defined as daily rainfall exceeding the long-term mean 90th percentile-and the Southern Oscillation Index (SOI): positive SOI values-consistent with La Niña-were associated with an increased frequency of extreme rainfall. The authors also found that the winter SOI could predict the number of summer extreme events in tropical Australia, including Northeast Queensland. Section 4.4 discusses the SOI - Queensland rainfall relationship.

Haylock and Nicholls (2000) confirmed these results for Queensland for 1910–1998. Queensland showed a high positive correlation between the annual-mean rainfall and the frequency of daily rainfall above the long-term-mean 95th percentile, indicating that the annual rainfall was dependent upon the occurrence of only a few extreme precipitation events. Therefore, any impact of climate variability or change on the synoptic conditions responsible for these extreme events would almost certainly have a substantial impact on the annual mean. Haylock and Nicholls (2000) found that the contribution of extreme events to the annual total had grown over 1910 - 1998. If this trend continues in the 21st century, it will have profound hydrological implications for the region in terms of surface runoff, river flows and flooding frequency. Similar trends in the contribution of daily extreme events have been found in other regions for the second half of the 20th century (e.g. the USA; Karl et al. 1995). Many GCMs in the IPCC Fourth Assessment Report (2007) simulated a higher frequency of daily extreme rains in a warmer world (Tebaldi et al. 2006), particularly in the tropics (e.g. India; Kripalani et al. 2007; Turner and Slingo 2009).

Several studies have discovered modulations in the variability of Queensland and all-Australia rainfall, particularly on inter-annual and longer scales, at which the El Niño Southern Oscillation (ENSO) and the Inter-decadal Pacific Oscillation (IPO) are the dominant controls (Lough 1991; Suppiah and Hennessy 1996; Hennessy et al. 1999; Power et al. 1998, 1999). Lough (1991) showed that the relationship between Queensland rainfall and ENSO exhibited substantial decadal variability. Periods when this relationship was weak (e.g. 1930–1945) corresponded to low inter-annual rainfall variability; the spatial coherence of rainfall anomalies was also reduced, presumably due to the lack of a large-scale, low-frequency driver. For all-Australia rainfall, Power et al. (1999) demonstrated that seasonal anomalies became much less predictable during periods of weak correlations between ENSO and Australian precipitation, which the authors ascribed to the influence of the IPO; Section 4.5 contains further information on the impact of the IPO on ENSO and its teleconnections. Power et al. (1998) also found decadal and multi-decadal variability in the ENSO–Australia rainfall relationship. The relationship had become stronger since 1970, such that a higher-magnitude rainfall anomaly could be expected for the same SOI value. Suppiah and Hennessy (1996) indicated that a stronger SOI-heavy-precipitation relationship existed in 1950–1989, relative to 1910–1949.

These studies confirm that linear changes in the mean rainfall-while useful at the initial stage of an analysis-cannot stand alone as a metric for changes in regional-, national-or global-scale rainfall. One must also consider the spatial and temporal characteristics of that rainfall, its variability on all temporal scales and how changes to the key drivers of rainfall may alter those characteristics and that variability. Sections 3 and 4 explore the relationship between Queensland rainfall variability and synoptic and climate processes on all temporal scales in greater detail. At this stage, it is important to note that previous studies have found modulations of Queensland rainfall and its variability.

2.4.3 Summary of observed changes in Queensland rainfall

Many studies of changes in Queensland rainfall over the 20th century have focused on only the long-term-mean seasonal or annual rainfall (e.g. Lough, 1991; Nicholls and Lavery 1992; Lough 1997; Hennessy et al. 1999). Queensland has not experienced a statistically significant trend in rainfall in any season. Summers have become somewhat wetter over the 20th century, mostly due to an abrupt increase in the mean around 1950; winter-mean rainfall has not substantially changed.

Restricting an analysis to mean rainfall neglects any changes in extreme events on temporal scales shorter than the meaning period, as well as the substantial inter-annual and decadal variability that exists around the mean (Lough 1993). The frequency of daily extreme rainfall is strongly positively correlated with the annual mean; this relationship has strengthened over the 20th century (Haylock and Nicholls 2000). This suggests that shifts in local synoptic patterns could have potentially damaging consequences for the state. Inter-Annual variability is highly correlated to the El Niño–Southern Oscillation (e.g. McBride and Nicholls 1983; Lough 1991), but the magnitude of this correlation varies on decadal and multi-decadal scales; the Inter-decadal Pacific Oscillation has been implicated in this variability (Power et al. 1999).

3 Synoptic drivers of Queensland rainfall variability

This section surveys literature that has analysed remote synoptic drivers of Queensland rainfall variability. It does not consider processes such as local land-atmosphere interactions or mesoscale convection, except where those are relevant to the actions of the remote drivers. The relevant remote synoptic drivers for Queensland are trade winds (Section 3.1), extra-tropical disturbances such as atmospheric blocking and cut-off lows (Section 3.2.1) and east-coast cyclones (Section 3.2.2) and tropical cyclones (Section 3.3). Figure 4 shows these drivers and their typical spatial patterns.

3.1 Trade winds

Trade-wind-driven rainfall occurs along the coast of tropical Northeast Queensland, where the predominantly onshore, south-easterly winds are forced to rise over a coastal plain broken by granite hills of 100-500 meters (Fig.4; Lyons and Bonnell 1992; Connor and Bonnell 1998). This region receives some of the highest annual-mean rainfall in Australia, with about 1.5 metres falling near Cooktown (Fig.2b). Lyons and Bonnell (1992) constructed a spatially dense network of 133 gauges to observe trade-wind precipitation during one wet season, October 1988–June 1989. The authors identified 13 distinct synoptic weather types that produced rainfall during that season. Flow over orography was the most common circulation feature associated with these types, followed by the orientation of the moist trade flow to the land surface (i.e. onshore winds). Orography provided both a direct control on rainfall—forcing local upward motion and triggering convection—and an indirect control: the orography forced the airstream to separate horizontally to flow around the orography; this local divergence induced convergence downstream, producing upward motion and rainfall.

In a related study, Connor and Bonnell (1998) derived a statistical model to predict trade-wind rainfall, based on rain-gauge data in Northeast Queensland for three autumns in the early 1990s. Parameters considered for the statistical model were separated into “air-mass” (e.g. relative humidity, inversion strength, lapse rates) and “dynamic” (e.g. vorticity, wind speed and direction, divergence) categories. The dynamic parameters proved better predictors of trade-wind rainfall than the air-mass parameters: the vertically averaged onshore wind below 850 hPa was the strongest single predictor, with 850 hPa relative humidity the best air-mass parameter.

These studies agree, then, that the direction and strength of the onshore flow provides a key control over trade-wind precipitation along the north-eastern coast of Queensland. Any large-scale modes of variability that modulate this flow should thus be able to exert an influence over the synoptic-scale trade-wind precipitation regime. Wheeler et al. (2009) suggested that the Madden–Julian Oscillation (MJO) may be one such large-scale mode (Fig. 1). Section 4.1 discusses MJO–trade-wind interactions.

3.2 Extra-tropical blocking and cyclones

Extra-tropical cyclones can cause heavy precipitation along Queensland’s east coast (Sinclair, 1994), although no precise quantification exists of the fraction of annual rainfall attributable to these systems. Past studies have identified two types of extra-tropical cyclones that affect Queensland (Fig.4): “cut-off lows” that form to the south of Australia during periods of atmospheric blocking (Section 3.2.1; Qi et al. 1999) and “east-coast lows” that develop in regions of strong zonal SST gradients and track along the eastern coastline (Section 3.2.2; Sinclair 1994). The distinction between these may not be as clear in reality as the literature makes it seem, as both types of systems have a closed circulation and strong baroclinic development. It is unknown whether the conditions that have been identified as leading to one type of system could apply to the other (i.e. whether there is any association between blocking and east-coast lows, or SST gradients and cut-off lows). Since east-coast lows and cut-off lows have been considered separately in the literature, this report considers them separately as well, but notes that they may be the same type of system with a separate genesis regions (Fig. 4).

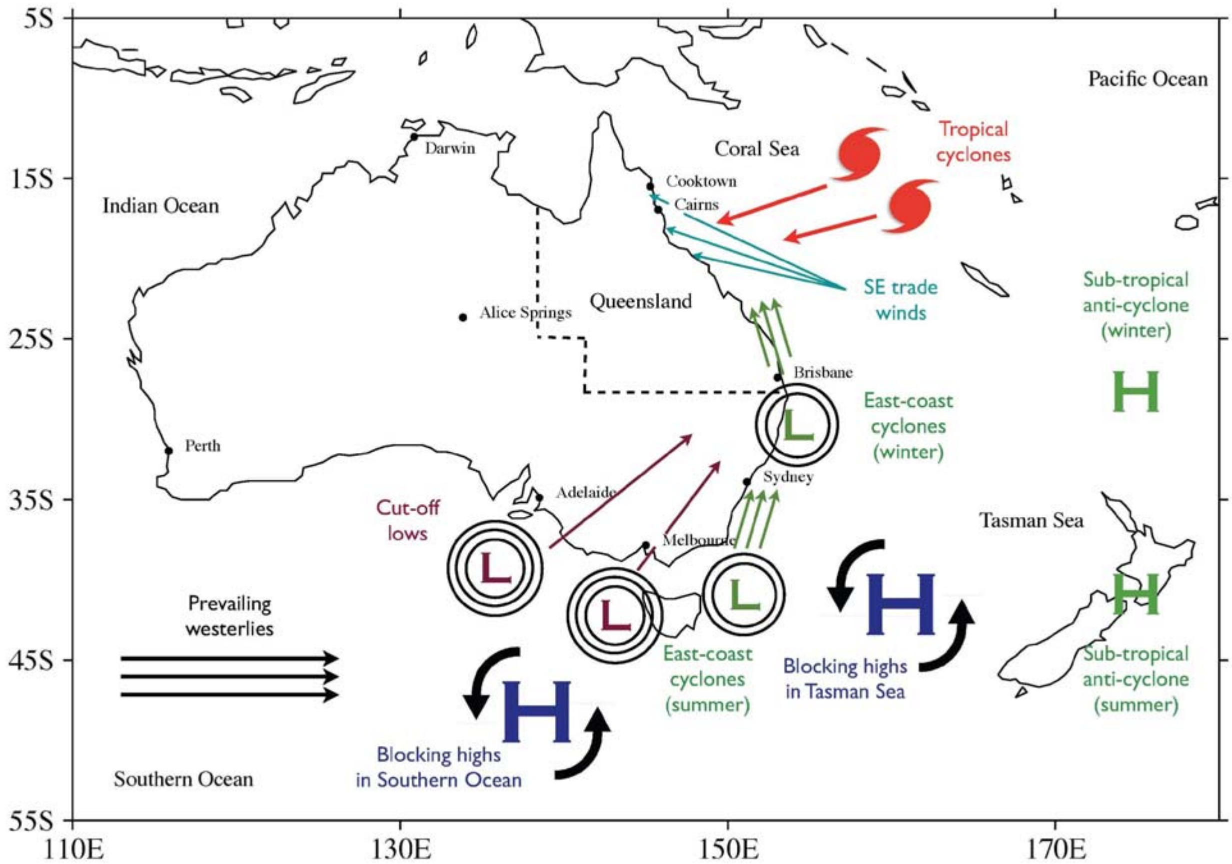

Figure 4: The dominant synoptic drivers of rainfall variability in Queensland: trade winds (aquamarine), atmospheric blocking (blue) and cut-off lows (purple), east-coast cyclones (green) and tropical cyclones (red). The colours in parentheses indicate the colour of the text used in the figure to describe that synoptic driver. Blocking is shown in its two preferred locations: the Tasman Sea and the Southern Ocean. The typical positions and tracks of east-coast cyclones are shown for summer and winter separately, as is the approximate latitude of the sub-tropical high; the shifts in the position of the high are associated with the changes in the east-coast cyclonegenesis region (Hopkins and Holland 1997).

3.2.1 Blocking and cut-off lows

Blocking anticyclones are nearly stationary areas of high surface pressure that form as a result of perturbations to the hemispheric atmospheric long-wave pattern. Near Australia, blocks occur most frequently in the Tasman Sea south of New Zealand and in the Southern Ocean (Fig.4; Trenberth and Mo 1985); while blocks form in all seasons, approximately two-thirds occur in April-August (Lejenäs 1984; Pook and Gibson 1999). When a block forms, the upper-tropospheric westerly winds in the Tasman Sea bifurcate and recurve around the block. This distortion steers eastward-moving surface synoptic features (e.g. air-mass fronts and cyclones) southeast, such that they avoid Southeast Australia (Risbey et al. 2009) causing dry conditions (Pook and Gibson 1999) in Southeast Australia and more surface depressions reach Antarctica.

Contrary to Pook and Gibson (1999), several studies have found that blocking can lead to heavy rainfall along the southern and eastern coasts of Australia. From Bureau of Meteorology gridded analyses for 1983-1996, Qi et al. (1999) determined that blocks favoured the development of cut-off lows: areas of low surface pressure, closed circulation and intense mid-and upper-tropospheric baroclinic development. These lows formed most often in May-October, consistent with frequent blocking in that period. Nineteen percent of these lows moved northeast to produce rain along the eastern and southern coasts of Australia (Fig. 4). Pook et al. (2006) used a longer record (1970– 2002) to determine that cut-off lows accounted for 50-60 per cent (40-45 per cent) of rain in Victoria in autumn and spring (winter). Subsequent paragraphs will demonstrate that these lows also affect Queensland.

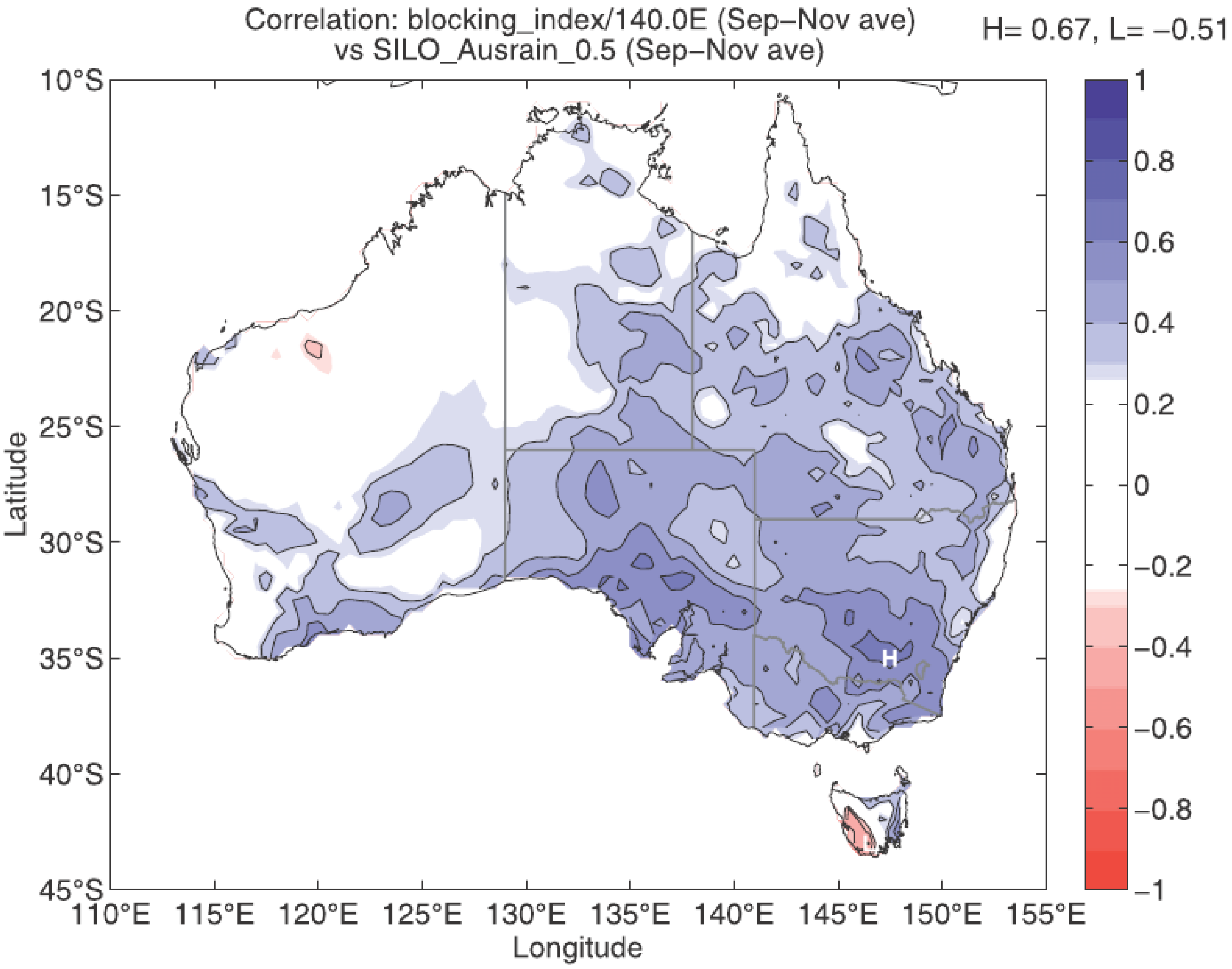

Figure 5: For September–November, the correlation between the Bureau of Meteorology blocking index at 140°E and observed rainfall from the SILO dataset at 0.5° resolution. Figure reproduced from Fig. 13d in Risbey et al. (2009).

Risbey et al. (2008) confirmed these results for the Southeast Australia agricultural region. Tropical SST anomalies explained most of the inter-annual variability in cut-off lows, with La Niña - cool equatorial Pacific SST anomalies - and the negative phase of the Indian Ocean Dipole - warm SST anomalies in the eastern Indian Ocean - associated with more cut-off lows and rainfall. La Niña and the negative IOD resulted in warm SST anomalies south of Australia; thermal air–sea coupling resulted in a positive correlation between SST and atmospheric thickness anomalies; the warm atmospheric thickness anomalies promoted the development of cut-off lows via the thermal wind.

Atmospheric blocking and cut-off lows affect rainfall in southern and south-eastern Queensland, particularly in June-November. Risbey et al. (2009) applied the Bureau of Meteorology’s blocking index 1 to the NCEP–NCAR reanalysis. The analysis considered blocking only at 140°E, just west of Tasmania; the authors noted that blocking at other longitudes may have substantially different impacts on rainfall. Risbey et al. (2009) found statistically significant positive correlations between blocking and winter and spring rainfall in southern Queensland. Indeed, blocking was the dominant remote driver of spring rainfall for south-eastern Queensland of all drivers considered, including the SOI, the IOD and the SAM.

While these results suggest that blocking may be a driver Queensland rainfall on synoptic and intra-seasonal temporal scales, the links between blocking and rainfall have not been explored as extensively for Queensland as for Victoria and New South Wales. Substantial scope remains to determine the impact of Tasman-Sea blocking and the development of cut-off lows on the inter-annual variability of Queensland rainfall, particularly given the strong relationship between the frequency of heavy rainfall and the annual mean (Section 2.4.2; Lough 1993; Haylock and Nicholls 2000).

3.2.2 East-coast lows

East-coast lows are areas of closed circulation that form near the eastern coast of Australia south of 20°S and move parallel to the coast (Fig. 4; Hopkins and Holland 1997). Hopkins and Holland (1997) identified 80 such cyclones in the period 1958-1992 by examining rainfall records from 28 east coast stations. The cyclones typically formed in regions of strong local zonal SST gradients, which could be in excess of 4 degrees Celsius. Simulations with a regional model demonstrated that the absolute value of SST was also critical for cyclone intensity (McInnes et al. 1992). In Queensland, east coast lows produced heavy precipitation events only in winter, when the subtropical anti-cyclone - a persistent area of high pressure in the southwest Pacific - was at its most northerly position (Hopkins and Holland 1997). The poleward movement of the subtropical anti-cyclone in spring and summer shifted the genesis region to off the southeast coast of Australia, confining the influence of the lows to Tasmania and southern Victoria (Fig. 4). While high-resolution GCMs have skilfully predicted rainfall associated with individual lows in case studies (e.g. Qi et al. 2000), numerical weather prediction models have typically under-predicted these storms' intensities (McBride and Ebert, 2000).

Hopkins and Holland (1997) found substantial inter-annual variability in the number of east-coast cyclones, with approximately 10 per cent of years containing no cyclones and another 10 per cent containing five or more. When using partial correlations to remove the influence of heavy-rain events, there were no statistically significant correlations between east-coast cyclones and either the Southern Oscillation Index (SOI) or the latitude of the subtropical anti-cyclone. The partial correlation was deemed necessary because of strong correlations between extreme precipitation frequency and each of the SOI (positive correlation), the number of east-coast cyclones (positive) and the latitude of the subtropical anti-cyclone (negative). The number of east-coast lows was significantly correlated to ENSO transition phases, however: the shift from El Niño to La Niña (La Niña to El Niño) conditions in the equatorial Pacific resulted in more (fewer) east-coast lows. Hopkins and Holland (1997) hypothesized that this resulted from longitudinal shifts of "conducive synoptic conditions" for development during the ENSO transition phases, but offered no evidence in support. The physical mechanism linking shifts in ENSO phase to east-coast lows has not yet been determined.

Finally, Hopkins and Holland (1997) detected an increasing trend in east-coast lows from the 1950s through the 1990s, but again could offer no physical explanation. There has also been a decreasing trend in the SOI from the mid-1970s through the early 2000s (Federov and Philander 2000; Power and Smith 2007). Given the weak in-phase correlation between east-coast lows and the SOI, one cannot attribute the trend in cyclone numbers to the trend in tropical Pacific forcing.

3.3 Tropical Cyclones

3.3.1 Background and impact on annual-mean rainfall

Historical analyses (1910–2005) from the Bureau of Meteorology indicate that, on average,1 or 2 tropical cyclones with a minimum central pressure of at most 990 hPa make landfall in Queensland each year (Flay and Nott 2007). The vast majority of these cyclones formed in the Coral Sea, to the northeast of Queensland, in January–March (Fig. 4). Flay and Nott (2007) showed inter-annual variability in the number of landfalling cyclones in that many years had no landfalling cyclones and a few years had as many as three. Not all tropical cyclones that form in the Coral Sea make landfall in Queensland; the Queensland Tropical Cyclone Database indicates a mean of about 4 cyclones per year in the Coral Sea, with large inter-annual variability (Grant and Walsh 2001; Walsh et al. 2004).

Lough (1993) found a positive correlation between years with positive annual-mean rainfall anomalies and years with greater numbers of land falling tropical cyclones. This correlation was higher than the correlation with the combined number of cyclones that either made landfall or merely approached the coast, indicating that coastapproaching cyclones were less likely to produce heavy rainfall than landfalling cyclones. The author also demonstrated a statistically significant correlation between the frequency of heavy (>25 millimetres per day) and very heavy (>50 millimetres per day) rainfall and the annual-mean rainfall anomaly, consistent with the findings of Haylock and Nicholls (2000) (Section 2.4). These studies are complementary: an increase in the number of land falling tropical cyclones is likely to produce more extreme rainfall events, which in turn lead to a wet annual-mean precipitation anomaly.

3.3.2 Inter-Annual variability

Inter-annual variability in tropical-cyclone genesis east of Australia has been repeatedly linked to the El Niño-Southern Oscillation (e.g. Nicholls, 1979, 1984; Hastings 1990; Walsh and Syktus 2003; Flay and Nott 2007). During El Niño, warm SST anomalies occur in the eastern and central equatorial Pacific and cold SST anomalies are found near the Australian east coast. Since tropical cyclones preferentially form over warmer SSTs, these anomalies shift the primary genesis region to the central Pacific (Fig. 1). Under La Niña the SST anomaly pattern has the opposite sign and the genesis region moves west, favouring development in the Coral Sea and near Queensland. Walsh and Syktus (2003) found that there were about five times more cyclone-days near the Queensland coast under La Niña (or positive SOI) than El Niño (or negative SOI; Fig. 6); employed a generalized linear model to fit tropical-cyclone numbers to values of the SOI in preceding seasons, with a Bayesian technique for estimating the model parameters. Cross-validation analysis by Flay and Nott (2007) using a generalized linear model demonstrated that the model captured the observed relationship, but there was substantial inter-annual variability in tropical-cyclone numbers that the SOI and their model could not explain.

Basher and Zheng (1995) suggested that ENSO-driven variations of the strength and location of the monsoon trough contributed to inter-annual fluctuations in tropical-cyclone genesis and tracks. The monsoon trough typically and its associated low-level westerly winds typically extended eastward to about 175°E; during El Niño years, however, the westerlies continued far into the central and eastern Pacific, reaching 110°W during the El Niño of 1983 (Chu, 2002). These near-equatorial westerlies interacted with the easterly trade winds south of the equator to produce low-level cyclonic wind shear and cyclonic relative vorticity, conditions favourable for the development of tropical cyclones. Combined with the thermodynamic effects of the anomalously warm SSTs in the equatorial central and eastern Pacific, these dynamic factors produced more tropical cyclones over the open central Pacific, far from the Australian coast. Due to the strongly zonal orientation of the favourable development region, the tracks of these cyclones tended to be zonal as well. During La Niña years, cyclones form further south of the equator and track south and west, increasing the chances of landfall in Queensland (Fig. 6; Evans and Allan 1992; Chu 2002).

Leroy and Wheeler (2008) developed a statistical forecasting model for weekly Southern Hemisphere tropical-cyclone formation in the Indian and Pacific Oceans, at lead times as long as seven weeks. The authors considered ENSO, the IOD, the daily climatology of genesis and the MJO as predictors. The model was evaluated on a binary skill metric, based on whether the model correctly predicted whether a cyclone formed; since the model forecast only the presence or absence of tropical cyclones, multiple tropical cyclones in observations were considered as a single cyclone. For all forecast zones and at all lead times, climatology was the single best predictor. At lead times longer than three weeks, ENSO (the IOD) was the second most-skilful predictor for zones in the Pacific (Indian) Ocean. The MJO often provided more skill than ENSO or the IOD at leads shorter than three weeks. Section 4.1 considers the impact of the MJO on tropical cyclones.

Some of the remaining non-ENSO inter-annual variability may be the result of modulations of the SOI–tropical-cyclone relationship on decadal scales. Indeed, Flay and Nott (2007) noted there was a weaker correlation between landfalling tropical cyclones and the SOI during the first half of the 20th century than in 1950–2005. Grant and Walsh (2001) discovered a relationship between the Inter-decadal Pacific Oscillation (IPO) and annual tropical-cyclone counts, whereby the negative (positive) IPO phase—in which SSTs were cooler (warmer) across the equatorial East Pacific—produced more (fewer) cyclones in the Coral Sea. Flay and Nott (2007) suggested that the IPO might explain variations in the strength of the SOI–tropical-cyclone relationship, since positive IPO phases sometimes weakened this correlation while negative phases strengthened it. This relationship is questionable, however, given that there was a robust SOI–tropical-cyclone correlation during the positive IPO phase in the 1980s. The overall SOI - Queensland-rainfall relationship exhibits similar decadal variability (e.g. Lough 1991; Cai et al. 2001). Section 4.5 discusses this relationship in more detail.

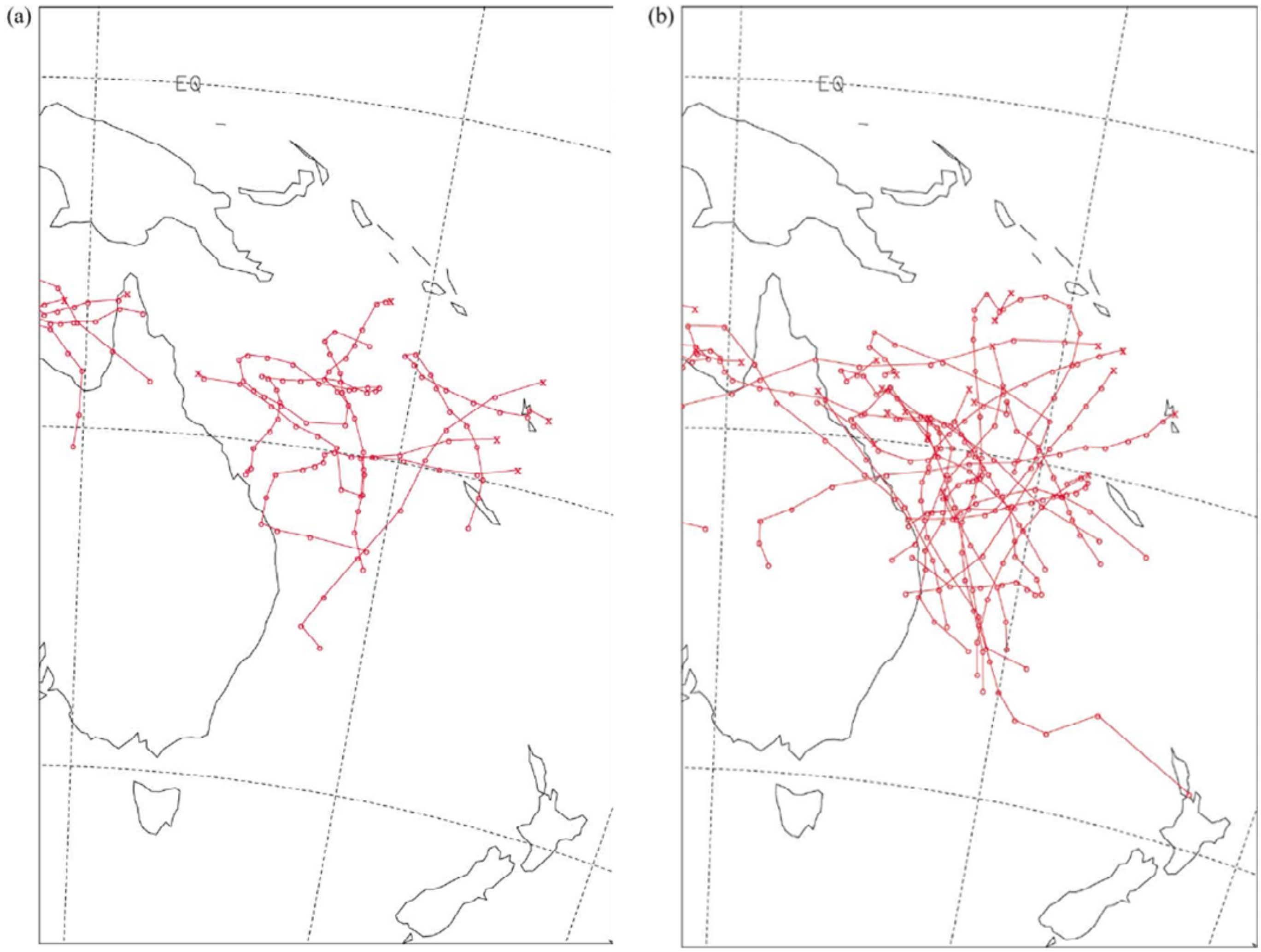

Figure 6: Observed tracks of tropical cyclones during (left) El Niño and (right) La Niña years in the period 1967–1996, where La Niña (El Niño) was defined as a value of the Southern Oscillation Index above +10 (below -10). Figure reproduced from Figs. 4a and 4b in Walsh and Syktus (2003).

3.3.3 Projections of tropical-cyclone activity

There is substantial uncertainty in projections of tropical-cyclone activity and intensity with climate change (e.g. Walsh 2004). While warmer tropical SSTs and a greater atmospheric capacity for water vapour should lead to more and stronger tropical storms, several authors have found that indirect effects of climate change (e.g. increased vertical wind shear in the tropics (Vecchi and Soden 2007) will limit the direct influences of warming on tropical cyclones. Increases in the intensity of the strongest tropical cyclones (i.e. categories 4 and 5 on the Saffir-Simpson scale) have been detected in most ocean basins over the last century, along with growing tropical-cyclone numbers in the Atlantic (Webster et al. 2005; Trenberth and Shea 2006; Hoyos et al. 2006; Mann et al. 2007). Several studies have questioned these results, based on uncertainty in pre-satellite-era cyclone counts (e.g. Kossin et al. 2007; Landsea 2007; Vecchi and Knutson 2008).

The GCMs that contributed projections to the IPCC Fourth Assessment Report (AR4) employed resolutions that were too coarse to allow direct simulation of tropical cyclones. Walsh and Syktus (2003) demonstrated that even a 75km regional model - a resolution finer than most GCMs used in AR4 - under-predicted observed tropical-cyclone numbers near Queensland, even when the threshold wind speed used to detect such cyclones was reduced; Walsh et al. (2004) had some success with a 30 kilometre regional model. In that latter study, the authors analysed tropical cyclones forming east of Australia in a simulation with three times the pre-industrial concentration of CO_2. While the number of cyclones remained similar to the present day, the intensity of the storms increased by up to 56 per cent. In an earlier study with the same model, Walsh and Ryan (2000) concluded that intensity also increased under CO_2 concentrations twice the pre-industrial level, but that the simulated increase was less than the theoretical Maximum Potential Intensity, which is computed from changes in thermodynamic parameters (Emanuel 1998; Holland 1997). The authors hypothesised that increases in vertical wind shear acted against the more-favourable thermodynamic conditions for tropical-cyclone development, similar to the later conclusions of Vecchi and Soden (2007) described above.

Studies of global tropical-cyclone frequency and intensity have noted pronounced inter-model variability in projected changes under increased CO_2. Emanuel et al. (2008) developed a statistical downscaling method for detecting tropical cyclones in the coarse-resolution AR4 GCMs; while the authors drew broad conclusions concerning changes in cyclone occurrence and strength in each basin, there was no consistent global signal among the models. Southern Hemisphere cyclones decreased in number, at odds with Walsh and Ryan (2000) and Walsh et al. (2004). Bengtsson et al. (2007) also found a decrease in tropical-cyclone occurrence in the Southern Hemisphere, using the Hamburg (ECHAM5) GCM at relative low (T63, approximately 100 kilometre) and higher (T213, approximately 50 kilometre) resolutions, with only slight changes in cyclone intensity compared to the present day.

3.4 Summary of synoptic drivers of Queensland rainfall variability

Key synoptic drivers of Queensland rainfall variability include trade winds (Section 3.1), atmospheric blocking and the cut-off lows that form as a result (Section 3.2.1) and extra-tropical and tropical cyclones (Section 3.3). Variability in the strength and direction of the low-level trade winds affects the north-eastern coast in October-June, where orographic forcing exerts both a direct and an indirect control on rainfall (Lyons and Bonnell 1992; Connor and Bonnell 1998). Blocking anti-cyclones in the Tasman Sea can cause cut-off lows to form off southeast Australia; some of these move along the east coast, producing heavy rain in south-eastern Queensland in winter (Qi et al. 1999; Risbey et al. 2008).

Other extra-tropical weather systems also affect Queensland's southern coast in winter, including east-coast cyclones - areas of closed circulation that form in regions of strong SST gradients and track north along the coastline (Hopkins and Holland 1997). These systems have become more frequent in recent years, but the physical mechanism for this is unclear. Most of the tropical cyclones that make landfall in Queensland form in the Coral Sea in January-March (Flay and Nott, 2007). There is a strong positive correlation between the number of cyclones making landfall and the annual-mean rainfall anomaly (Lough 1993). La Niño years are associated with more (fewer) tropical cyclones (e.g. Hastings 1990; Walsh and Syktus 2003), while the transition from La Niña to El Niño (El Niño to La Niña) leads to more east-coast lows (Hopkins and Holland 1997).

4 Climatic drivers of Queensland rainfall variability

This section reviews potential remote climatic drivers of Queensland rainfall variability, which operate on scales ranging from sub-seasonal to inter-decadal. There are considerable interactions among these temporal scales, which are indicated in the text. In order of lengthening period, the potential remote drivers of Queensland rainfall are the Madden–Julian Oscillation (Section 4.1), the Southern Annular Mode (Section 4.2), the Indian Ocean Dipole (Section 4.3), the El Niño Southern Oscillation (Section 4.4) and the Interdecadal Pacific Oscillation (Section 4.5). The Indian Ocean Dipole has a negligible impact on Queensland, but it is considered as a potential driver due to its impact on other broad regions of Australia. Figure 7 displays the typical spatial patterns of the climate drivers considered in this section.

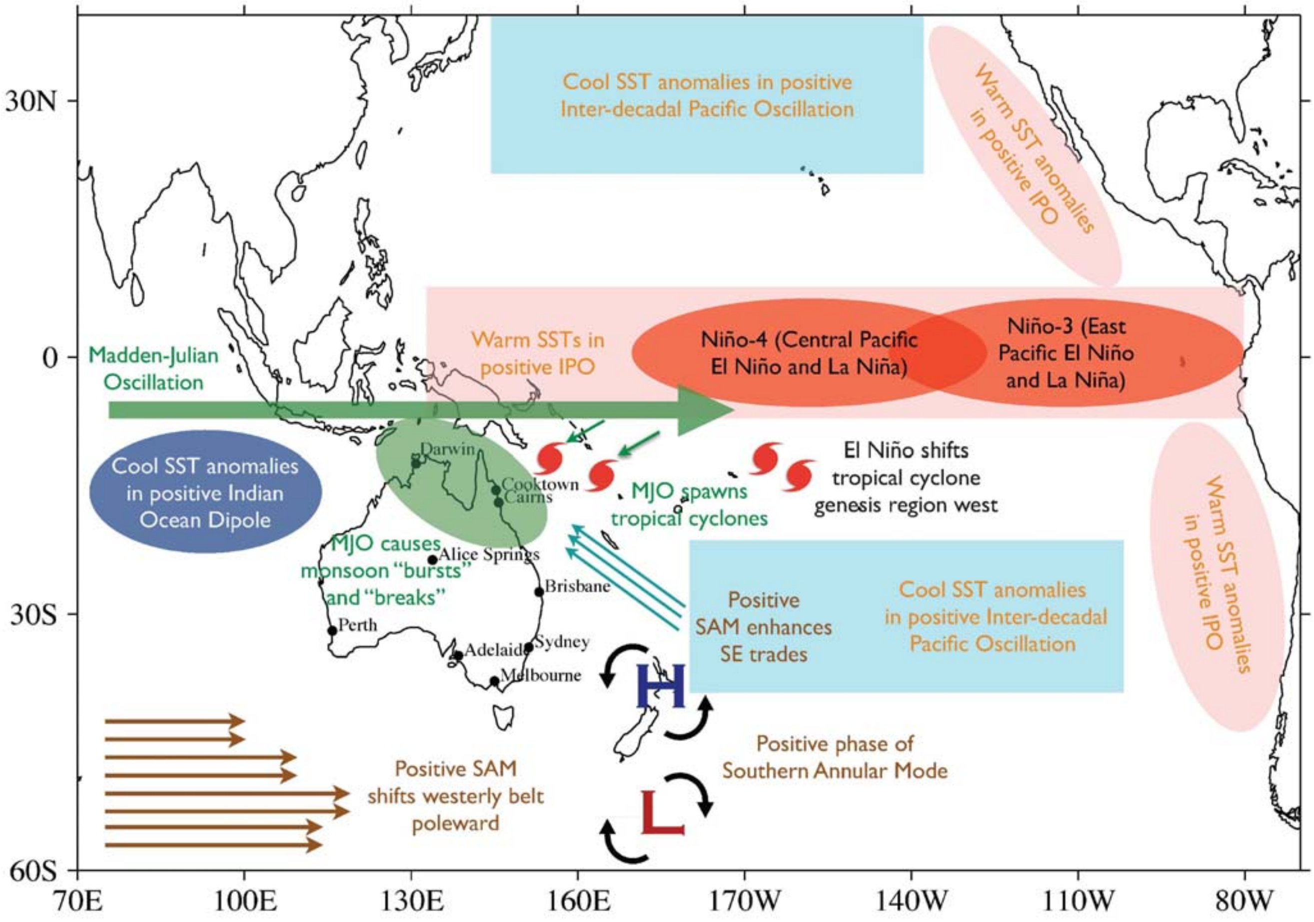

Figure 7: The climate drivers of Queensland rainfall variability discussed in this report: the Madden–Julian Oscillation (green), the Southern Annular Mode (brown), the Indian Ocean Dipole (white), the El Niño-Southern Oscillation (black) and the Inter-decadal Pacific Oscillation (orange). The colours in parentheses indicate the colour of the text used in the figure to show the impacts of that phenomenon. The IOD, ENSO and the IPO are shown as regions of SST anomalies, although in reality ocean-temperature anomalies associated with these modes extend below the surface.

4.1 The Madden-Julian Oscillation (MJO)

The MJO is a global, tropical, eastward-propagating, quasi-regular circulation anomaly with a 30–60 day period. Convection is strongly coupled to the MJO in the Indian Ocean and the West Pacific (Madden and Julian 1971). In all seasons, the signal of MJO active phases is typically seen first in the western or central Indian Ocean; enhanced convection then moves east along the equator to the Maritime Continent and into the Pacific (Fig.7; Madden 1986). Once there, the MJO can modulate activity along the South Pacific Convergence Zone (SPCZ) east of Australia, via the propagation of Rossby waves and air with anomalously high potential vorticity (Matthews et al., 1996). In austral winter the MJO also propagates north from the Indian Ocean to India, causing monsoon active and break phases there (e.g. Annamalai and Slingo 2001; Lawrence and Webster 2002; Waliser 2006). During summer in Queensland, the MJO causes one-half (at most) of the intra-seasonal variability in the monsoon (Section 4.1.1) and modulates tropical-cyclone genesis in the Coral Sea (Section 4.1.2). The MJO may also affect synoptic variability in Queensland in other seasons via its influence on the south-easterly trades and the frequency of east-coast cyclones (Section 4.1.3).

4.1.1 The MJO and the monsoon intra-seasonal variability

Northern Australia, including tropical North Queensland, receives as much as 80 per cent of its annual precipitation during the summer monsoon (Lough 1997; Suppiah and Hennessy 1998). The mean onset date is 24 or 25 December, depending on whether low-pass filtered low-level winds are used alone (Holland 1986) or in conjunction with low-pass filtered rainfall (Hendon and Liebmann 1990a) to define the onset. During the onset, strong westerly winds replace the trade easterlies that prevail in autumn, winter and spring (e.g. Drosdowsky 1996; Wheeler and McBride 2005). The monsoon rains and the associated circulation typically withdraw from northern Australia by the end of March.

Within each season, the monsoon rains exhibit variability that is at least as large as, if not larger than, the magnitude of the seasonal cycle (Hendon and Liebmann 1990a, b; Wheeler and McBride 2005). Troup (1961) first characterized this intra-seasonal variability, referring to sub-seasonal periods of heavy rainfall and strong low-level westerlies as monsoon “bursts”. Holland (1986) determined that the active phases of the monsoon were separated by approximately 40 days, which provided circumstantial evidence for a connection to the 30–60 day MJO.

Hendon and Liebmann (1990b) were one of the first to link the passage of active MJO events to the sub-seasonal “bursts” of Troup (1961). The authors analysed lead-lag composites of anomalies in satellite-derived outgoing longwave radiation (OLR) in the Indian and Pacific Oceans, centred on the dates of monsoon active phases at Darwin. Prior to active conditions at Darwin, coherent regions of enhanced convection were propagating east through the Indian Ocean at 5 metres per second along 5-10°S, a clear MJO signal. Active phases at Darwin were associated with increased rainfall throughout northern Australia, including tropical Queensland, south to near 20°S (Fig. 7). As the envelope of enhanced convection moved into the central Pacific, “break” conditions of clear skies, slack winds and patchy rainfall took hold over northern Australia. Hendon and Liebmann (1990a) suggested a close association between the monsoon onset and the first MJO active event of the season, a connection that Drosdowsky (1996) disputed. Wheeler and McBride (2005) showed that Hendon and Liebmann (1990a) had overstated the impact of the MJO by using a restrictive filter on Australian rainfall that eliminated all frequencies but those of the MJO. However, Wheeler and McBride (2005) concluded that the MJO set the onset date to a resolution of one or two weeks, while local synoptic conditions determine the precise date.

Not all of the monsoon intra-seasonal variance is associated with the MJO. Cross-spectrum coherence calculations between OLR and 850 hPa zonal wind over northern Australia have revealed that only half of the 30-80 day variance can be attributed to any coherent mode (Hendon et al. 1999; Wheeler and McBride, 2005). In other words, the MJO can explain at most one-half of the intra-seasonal variance - and most likely some what less, given that there are other coherent modes of sub-seasonal variability that influence the monsoon, such as convectively coupled equatorial Rossby waves (Matsuno 1966; Hendon et al. 1989; Wheeler and Kiladis 2000) and fast-moving equatorially trapped Kelvin waves (Dunkerton and Crum 1995; Wheeler and Kiladis 2000).

Even so, the MJO has a considerable impact on summer rainfall in North Queensland. Robertson et al. (2006) developed a Hidden Markov Model to categorize spatial patterns of daily rainfall at 11 stations in North Queensland into five discrete synoptic types. Three of those five states were spatially coherent across the region - representing heavy, moderate and light rainfall - while two described heavy or moderate coastal rains and dry conditions inland. The authors then matched their synoptic states to MJO phases, based on the Real-time MJO Multivariate (RMM) indices of Wheeler and Hendon (2004). The coherent heavy-rainfall state of Robertson et al. (2006) was associated with RMM phases 6–7, which Wheeler and Hendon (2004) showed were associated with enhanced convection over Queensland; phases 6–7 corresponded to an active MJO over the West Pacific. Conversely, the coherent dry state in Robertson et al. (2006) was most likely to occur in MJO Phases 8 and 1, in which the MJO was suppressed over the West Pacific and active in the Western Hemisphere. Wheeler et al. (2009) found that phases 5–6 led to an enhanced probability of heavy rainfall - defined as the upper tercile of weekly rainfall - over North Australia, while phases 1–2 had much smaller probabilities (Fig.8); phases 2 and 6 affect Queensland most strongly.

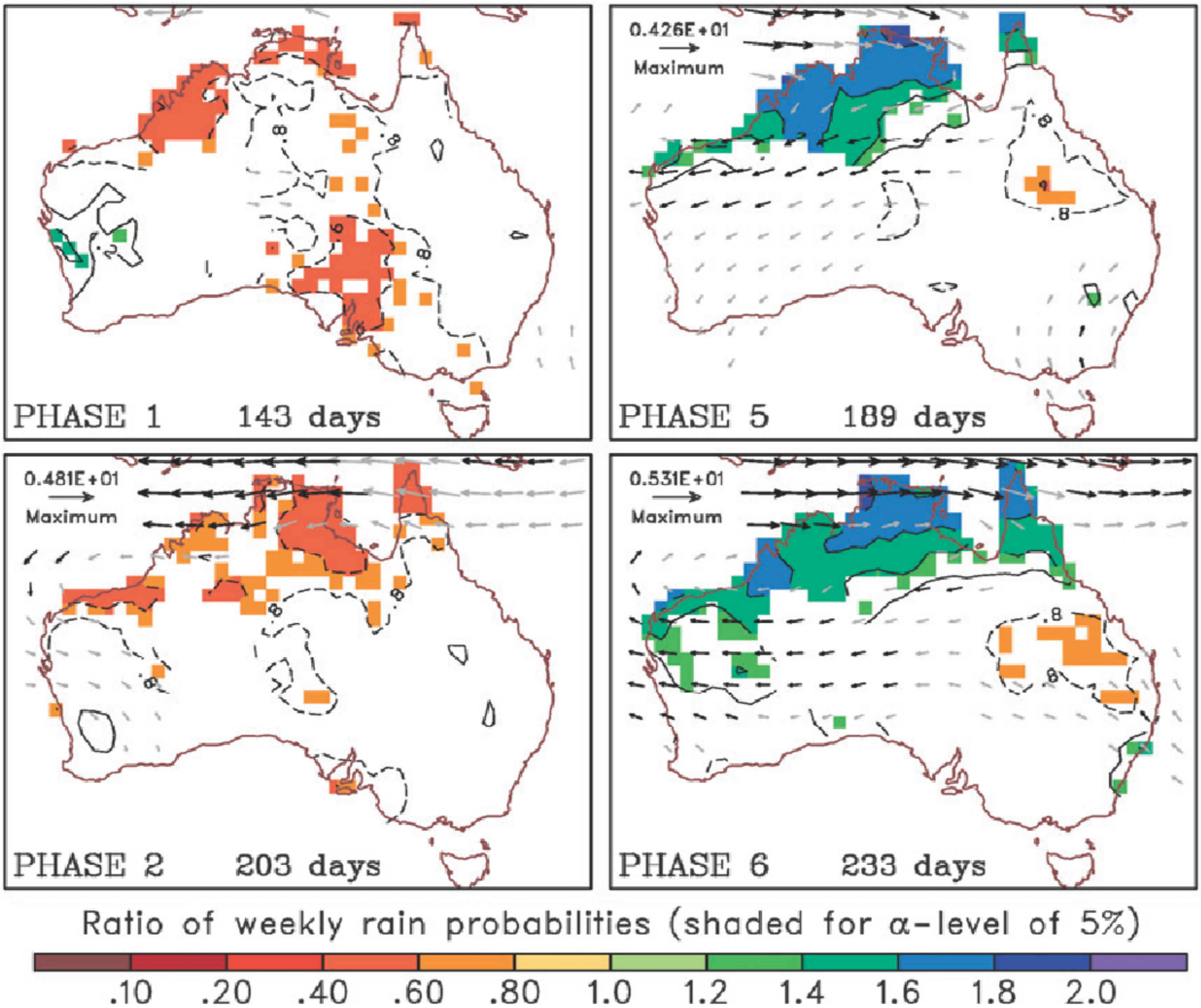

Figure 8: Rainfall probabilities for December-February. Contours represent the probability of heavy rainfall - defined as the upper tercile of weekly precipitation - during each RMM MJO phase shown, divided by the mean probability (33 per cent). Vectors show the mean anomalous 850-hPa wind for each phase. Dark vectors and all shaded contours are statistically significant at the 5 per cent level. Figure reproduced from Fig. 3 in Wheeler et al. (2009).

4.1.2 The MJO and tropical cyclones

Active phases of the MJO can also increase the probability of tropical-cyclone genesis (Hall et al. 2001; Wheeler and McBride 2005; Leroy and Wheeler 2008). Typically, tropical cyclones form to the west of the eastward-moving MJO convective envelope. Hall et al. (2001) found a four-fold increase in the probability of cyclone genesis for storms affecting Northwest Australia as the active phase of the MJO passed through the Maritime Continent. Using the RMM index, Wheeler and McBride (2005) found that the preferred region for tropical-cyclone formation followed the active phase of the MJO as it propagated through the Indian Ocean, the Maritime Continent and the West Pacific (Fig. 7). In the Coral Sea - the primary formation region for cyclones that make landfall in Queensland (Section 3.3) - probabilities of tropical-cyclone genesis were highest during enhanced intraseasonal convection in the West Pacific (MJO Phases 6–7); probabilities were lowest once the MJO crossed the dateline (Phases 8–1).

Further evidence of a link between the MJO and tropical cyclones comes from Leroy and Wheeler (2008), the results of which were discussed in Section 3.3. The authors designed a statistical forecast model for tropical cyclone genesis south of the equator in the Indian and Pacific Oceans. They considered the El Niño Southern Oscillation (ENSO), the MJO (defined by the Wheeler and Hendon (2004) RMM indices), the Indian Ocean Dipole (IOD) and the daily climatology of tropical-cyclone genesis as potential predictors. For shorter lead times (1-3 weeks), the MJO indices displayed skill equal to or greater than the inter-annual SST variability (i.e. ENSO or the IOD) in all four of forecast zones. The value of the MJO as a predictor declined after three weeks. Hindcasts with the statistical model were most accurate when the amplitude of the MJO was large, suggesting that the influence of the MJO on tropical cyclone genesis scaled with the strength of the MJO itself.

4.1.3 The MJO and tropical-extratropical interactions

Recent studies have demonstrated MJO impacts on Queensland rainfall outside of the summer season (Donald et al. 2006; Wheeler et al. 2009). In an analysis of global MJO - rainfall teleconnections using Monte Carlo-based statistical techniques, Donald et al. (2006) showed that in austral winter heavy rainfall in North Queensland was linked to the enhanced MJO phase in the Indian Ocean and the Maritime Continent (RMM phases 2–4). The active MJO there was associated with lower sea-level pressures in the Indian Ocean and higher pressures in the West Pacific and east of Australia. The latter anomaly enhanced the south-easterly onshore winds and promoted trade-wind-driven rainfall along the north-eastern Queensland coast (Section 3.1). Wheeler et al. (2009) confirmed this amplification of the trade winds by MJO-induced circulation anomalies using NCEP–NCAR reanalysis winds.

Wheeler et al. (2009) also found that in autumn and spring, active MJO phases increased the probability of Tasman-Sea blocking. The active MJO over the eastern Maritime Continent (phases 5–6) displayed a statistically significant positive correlation with the probability of heavy rain - defined as the upper tercile of the probability distribution of daily values - over central and southern Queensland. Wheeler et al. (2009) suggested that this was due to a weak, low-level cyclonic circulation in their composites, which may have been a signal of more-frequent east-coast cyclones (Section 3.2.2). This is circumstantial evidence, though; further investigation into links between the MJO and extra-tropical storm tracks is clearly needed (Fig. 1; Wheeler and McBride 2005, Wheeler et al. 2009).

4.2 The Southern Annular Mode (SAM)

The SAM is the dominant mode of circulation variability in the extra-tropics and high latitudes of the Southern Hemisphere (Rogers and van Loon 1982; Gong and Wang 1999; Thompson and Solomon 2002), accounting for the greatest fraction of variance in daily, zonal-mean sea-level pressure anomalies (Baldwin 2001). It is zonally symmetric and has an equivalent barotropic structure; it represents shifts in mass between Antarctica and the mid-latitudes (Thompson and Wallace 2000). During its positive phase, positive (negative) sea-level pressure anomalies appear in the mid-latitudes (Antarctica), which are associated with a poleward shift of the Southern Ocean westerly wind belt (Fig. 7).

There are only weak relationships between the SAM and Queensland rainfall. Hendon et al. (2007) computed a SAM index based on the projection of daily 700 hPa height anomalies onto the first empirical orthogonal function of monthly mean 700 hPa height. (Empirical orthogonal functions identify the dominant, unrelated patterns of spatio-temporal variability in a field such as geopotential heights). When the authors correlated that index with rainfall, they found that SAM influenced only south-western and south-eastern Australia, where it explained nearly 15 per cent of the variance in weekly-mean rain. The poleward shift of the westerly wind belt during the positive SAM phase reduced rainfall for the south coast. For the east coast, Hendon et al. (2007) found an association between the positive SAM and enhanced spring and summer rainfall, due to a low-level onshore circulation. The SAM had a greater impact in New South Wales than Queensland, but statistically significant correlations extended into southern Queensland.

These results have been confirmed by other studies with independent SAM indices (Meneghini et al. 2007; Risbey et al. 2009). Meneghini et al. (2007) calculated two indices: one using the traditional Gong and Wang (1999) definition of the difference in normalized, zonal-mean sea-level pressure anomalies at 40°S and 65°S; the other using the same formula but employing data from only the Australian region (90–180°E) for the zonal mean. Both SAM indices were highly negatively correlated with rainfall in southern Australia, but only weakly positively correlated with rainfall in the north and east. The authors also found that the SAM had its greatest influence on inter-annual variability; there was no evidence that the SAM had contributed to long-term trends in Australian rainfall. Risbey et al. (2009) calculated the Gong and Wang (1999) SAM index and found that the SAM and Queensland rainfall were correlated only in spring, due to an enhanced onshore flow.

4.3 The Indian Ocean Dipole

A coupled atmosphere–ocean mode of variability in the Indian Ocean, the Indian Ocean Dipole (IOD) typically reaches its peak amplitude in austral spring (Saji et al. 1999). During the positive IOD phase, warm SST anomalies occur in the equatorial West Indian Ocean, with cool SST anomalies in the tropical Southeast Indian Ocean (Fig. 7). Whether the IOD is independent from the El Niño Southern Oscillation (ENSO) is debatable (e.g. Saji et al. 1999; Allan et al. 2001; Ashok et al. 2003b; Meyers et al. 2007), but this is outside the scope of this report since - as will be described - the IOD has no impact on Queensland once any influence of ENSO on the IOD is removed (Fig. 1).

In an analysis of climatic drivers of Australian rainfall, Risbey et al. (2009) demonstrated that the IOD had nearly no impact on eastern Australia. While the Saji et al. (1999) “Dipole Mode Index” showed statistically significant positive correlations with June-October Queensland rain, these signals dropped to near zero when the effect of ENSO on the IOD was removed via a partial correlation. The IOD-rainfall relationship existed only because ENSO modulated both the IOD and rainfall. Risbey et al. (2009) also obtained near-zero IOD-rain partial correlations for Queensland - removing the effect of ENSO - using the Meyers et al. (2007) IOD index. Nicholls (1989) found that Indian Ocean SSTs had no significant association with eastern Australia rain; Murphy and Ribbe (2004) concluded that Southeast Queensland rain had no statistically significant correlation with any Indian Ocean SST variability that was unrelated to ENSO. The IOD has little impact on Queensland.

4.4 El Niño, La Niña and Southern Oscillation

El Niña no and La Niño are the oppositely-signed phases of an irregular oscillation of equatorial Pacific Ocean upper-ocean temperatures, which occurs due to unstable atmosphere–ocean interactions (Federov and Philander 2000). Anomalous SSTs associated with this oscillation commonly peak in austral summer, although the evolutions of individual events differ markedly. These ocean-temperature anomalies cause variations in sea-level atmospheric pressure, termed the Southern Oscillation (Troup 1965). The Southern Oscillation index (SOI) is traditionally defined as normalized sea-level pressure anomalies at Tahiti minus those at Darwin; positive (negative) values correspond to La Niña (El Niño) (e.g. Chen 1982; Ropelewski and Jones 1987). As tropical rainfall is tightly coupled to SSTs, the El Niña–Southern Oscillation (ENSO) explains much of the inter-annual rainfall variance in the tropics (e.g. Allan 1988; Suppiah 1992; Wang and Hendon 2007). ENSO also has teleconnections to the extra-tropics around the globe (e.g. Ropelewski and Halpert 1987).

The most easily discernible impact of ENSO on Queensland rainfall is in seasonal-or annual-mean rainfall (Section 4.4.1), although rain fall is sensitive not just to the strength of Pacific SST anomalies, but also their zonal position (Section 4.4.2). ENSO can modulate rainfall variability on synoptic and sub-seasonal scales, via its impacts on tropical-cyclone genesis frequency (Section 3.3) and the MJO (Section 4.4.3).

4.4.1 Broad relationships between ENSO and Queensland rainfall

Numerous studies have documented the negative correlation between equatorial Pacific SSTs and rainfall across most of Australia, including Queensland: rainfall is typically deficient (in excess) during El Niña) years (e.g. McBride and Nicholls 1983; Allan 1988; Lough 1991; Murphy and Ribbe 2004). Lough (1991) examined 96 years (1891-1986) of station rainfall in Queensland and found that the strongest correlations between rainfall and the SOI occurred during the pre-monsoon months of October and November in spring, although correlations were also statistically significant in summer and winter. Few regions of Queensland had a statistically significant relationship between autumn rainfall and the SOI. ENSO is often weak and incoherent in this season, which is called the ENSO "predictability barrier" (Webster and Yang 1992; Latif et al. 1998). Perhaps most interestingly, Lough (1991) found that summertime Queensland rainfall was substantially affected by ENSO only for values of the SOI in the highest or lowest decile. In other words, it was only Fig 9: Correlations between monthly means of Australian rainfall and (top) the extreme values of the monthly mean SOI - where "extreme" is defined to be the highest or lowest 10 per cent - that caused widespread, statistically significant rainfall anomalies over Queensland.

4.4.2 Why ENSO strength is an insufficient predictor of its impact on Queensland rainfall

Recent studies have gone beyond considering the over all impact of ENSO on rainfall, to focus on how variations in the spatial location of equatorial Pacific SST anomalies influence their teleconnections. Murphy and Ribbe (2004) examined monthly mean observed rainfall from the Bureau of Meteorology and monthly mean observed and reconstructed SSTs from the Hadley Centre HadISST dataset, both for the period 1891–2000. The authors considered separately the impact on Australian rainfall of SSTs in the Niño-3 (eastern equatorial Pacific) and Niño-4 (central equatorial Pacific) regions. Queensland was heavily influenced by Niño-4 SSTs and displayed substantially smaller correlations with Niño-3 SSTs (Figs.7 and 9). The correlations with Niño-4 SSTs were much stronger in the second half of the 20th century than in the first, which the authors took to imply multi-decadal variability in the ENSO-rainfall link. Queensland showed high correlations with the SOI that were also stronger in the second half of the 20th century. Murphy and Ribbe (2004) concluded that Southeast Queensland had the largest multi-decadal variability in Australia in the ENSO-rainfall relationship.

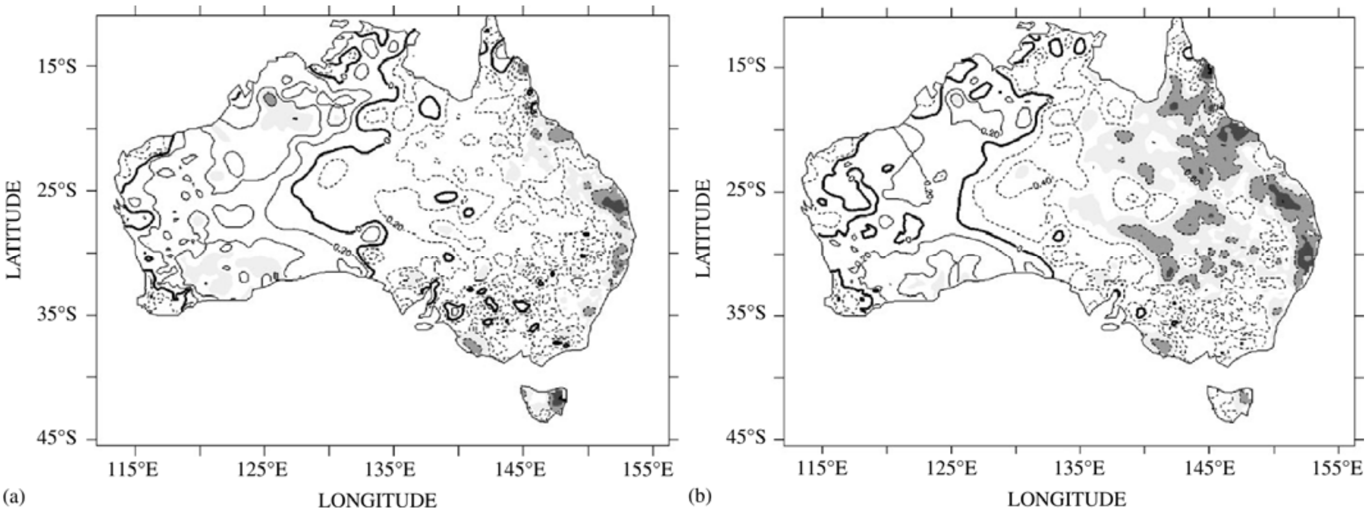

Figure 9: Correlations between monthly means of Australian rainfall and (top) the Niño-3 and (bottom) the Niño-4 index for the period 1946-2000. The contour interval is 0.2, with the zero line doubly thick and negative values dashed. Shading begins at 0.5; progressively darker shades mark every interval of 0.1. Figure reproduced from Figs. 3a and 3b of Murphy and Ribbe (2004).

Wang and Hendon (2007) obtained similar results as Murphy and Ribbe (2004) in a study focused on the difference in the response of Australian rainfall to the El Niños of 1997 and 2002. The former was a strong El Niño in the East Pacific, yet Australian rainfall was near-to above-normal; the latter was a weak El Niño in the Central Pacific and produced near-record drought over much of the continent. Statistical seasonal forecasting systems failed to predict these rainfall anomalies, due to their reliance on a linear relationship between El Niño strength and precipitation deficits. Wang and Hendon (2007) concluded that the zonal distribution of SST anomalies during an El Niño, not their magnitude, determined rainfall anomalies. Warm SST anomalies on the edge of the West Pacific warm pool had a far greater impact on rainfall than warm SST anomalies in the East Pacific. The authors hypothesised that East Pacific El Niño events forced an anomalous Walker Circulation that was centred too far east to affect Australia, whereas Central Pacific El Niños generated an anomalous Walker Circulation whose descending branch was much nearer Australia, suppressing rainfall there. This sensitivity to the zonal position of SST anomalies may explain why Power et al. (2006) found that annual-mean, all-Australia rainfall anomalies did not scale linearly with El Niño amplitude.

These studies strongly suggest that predicting the strength of an El Niño is necessary, but not sufficient, to predict its impact on Queensland; the location of the warm SST anomalies must also be correctly forecast. Further evidence comes from studies of the utility of statistical forecasting systems based on SOI phases or equatorial Pacific SST anomalies within a single box (e.g. Niño-3 or Niño-4; Syktus et al. 2003; Vizard and Anderson 2009). Syktus et al. (2003) found that seasonal rainfall forecasts for Queensland from a statistical model based on SOI phases were less valuable when processed through the AussieGRASS grazing simulator than similar forecasts from a high-resolution, double-nested regional climate model driven by a global GCM. The dynamical forecasts contained biases, such as an overly strong SOI-rainfall relationship, but the results implied that the interactions between equatorial Pacific SSTs and Queensland rainfall were more complex than could be captured by one metric alone (i.e. the SOI). Hansen et al. (2004) drove a wheat-yield forecast model for Northeast Australia with rainfall data from the Hamburg (ECHAM4) GCM and from statistical SOI- and Pacific-SST-based models. The GCM-based forecasts out performed those based on the SOI or Pacific SSTs, particularly at long leads. Vizard and Anderson (2009) created a cost/loss model to assess the economic value to agriculture of statistical seasonal rainfall forecasts based on SOI phase. The forecasts consistently predicted smaller rainfall anomalies than were observed, producing little value for users who would act only when the forecast deviated widely from climatology.

4.4.3 ENSO-MJO interactions

Beyond the annual and seasonal means, ENSO influences Queensland rainfall variability on synoptic and sub-seasonal scales via interactions with blocking and cut-off lows, tropical cyclones and the MJO. The ENSO modulations of blocking, east-coast lows and tropical cyclones have been discussed in Sections 3.2.1, 3.2.2 and 3.3, respectively. This section summarises known ENSO-MJO interactions.

In the last decade, there has been a growing acknowledgment that the MJO can influence the development of an ENSO event (e.g. Moore and Kleeman 1999; Kessler and Kleeman 2000; Bergman et al. 2001; Kutsuwada and McPhaden 2002; Shinoda and Hendon 2002; Roundy and Kiladis 2006; Roundy and Kravitz 2009). As the active MJO phase moves through the Pacific, strong low-level westerly winds that trail just behind the enhanced convection force down welling oceanic Kelvin waves. These waves can both depress the thermocline in the Central and East Pacific and move warm water east from the West Pacific warm pool (Federov and Melville, 2000; Roundy and Kiladis, 2006). Additionally, the low insolation and strong winds associated with the convection can cool the West Pacific SSTs, reducing the Pacific zonal SST gradient (Fig.1; Woolnough et al. 2000, 2001). A prolonged suppressed MJO phase in the Pacific has the opposite impact on the SST gradient. These processes influence the timing and growth of an El Niño or La Niña; whether the MJO alone can trigger or terminate an ENSO event is debatable (Bergman et al. 2001; Roundy and Kiladis 2006).

Conversely, ENSO is able to modulate MJO activity. Roundy and Kiladis (2006) concluded that the MJO and its associated rainfall anomalies propagated more slowly during developing El Niño events than during developing La Niña events. The developing El Niño events were also associated with enhanced Kelvin-wave activity in the East Pacific, which formed a positive feedback onto the SST anomalies. Roundy and Kravitz (2009) separated ENSO into six phases - growing, mature and decaying El Niño - and created an MJO composite for each. Certain ENSO phases were found to "prefer" certain MJO patterns; the authors suggested that these MJO patterns contributed to the evolution of ENSO. For example, there was weak coupling between the MJO-driven westerlies and downwelling Kelvin waves in the East Pacific during decaying El Niños, which accelerated the termination of those events. The MJO was weaker in the Pacific during La Niña (Fig.1) than during El Niño.

These MJO–ENSO interactions have implications for Queensland rainfall variability. For example, La Niña and the active phase of the MJO both result in a greater frequency of tropical cyclones in the Coral Sea (Sections 3.3 and 4.1, respectively), but Roundy and Kravitz (2009) suggested that MJO activity is suppressed during La Niña. Similarly, seasonal-mean monsoon rainfall in North Queensland is enhanced during La Niña years (Murphy and Ribbe, 2004) but its intra-seasonal variability maybe reduced due to a weaker MJO. This suggests complex and competing influences on synoptic-scale rainfall patterns from intra-seasonal and inter-annual variability. Since Queensland's annual-mean rainfall is tightly coupled to the frequency of extreme precipitation (Haylock and Nicholls, 2000), these results imply that MJO–ENSO interactions play a key role in determining the annual rainfall.

Many studies have noted that the ENSO-Queensland rainfall correlation varies on decadal and multi-decadal temporal scales (e.g. Lough 1991; Cai et al. 2001). Section 4.5 considers these variations and what relationship they may have to the dominant mode of decadal Pacific SST variability, the Inter-decadal Pacific Oscillation (IPO).

4.5 The Inter-decadal Pacific Oscillation

Throughout the observed record, the ENSO-Australian rainfall relationship has fluctuated in magnitude and even occasionally in sign (e.g. Troup 1965; McBride and Nicholls 1983; Elliott and Angell 1988). Lough (1991) and Cai et al. (2001), among others, demonstrated that these fluctuations affected Queensland; Murphy and Ribbe (2004) argued that Southeast Queensland had the largest variability of any region in Australia in the strength of the connection between its rainfall and ENSO. Variability in the ENSO-Queensland rainfall correlation is strongest on decadal temporal scales (Cai et al. 2001). It is worth noting that this decadal variability is not unique to Australia: globally, teleconnections to ENSO wax and wane on decadal and inter-decadal periods (e.g. Wang and Ropelewski 1995; Wang and Wang 1996; Zhang et al. 1997; Gershunov and Barnett 1998).

ENSO and Queensland rainfall became uncorrelated during 1920-1950, the only such period in the observed record. During these years, Queensland rainfall became less variable on inter-annual scales, presumably due to the lack of a large-scale climate driver (Lough, 1991). Annual rainfall anomalies were also less spatially coherent; this suggests that absent the ENSO influence, the tracks of synoptic systems such as tropical and extra-tropical cyclones became less organised spatially and produced a less predictable spatial distribution of rainfall. This mechanism is only conjecture; there is substantial scope for examining drivers of Queensland rainfall during periods of weak ENSO forcing.

Power et al. (1999) found that the Inter-decadal Pacific Oscillation (IPO) modulated the influence of ENSO on rainfall across Australia. The IPO is a low-frequency mode of variability in Pacific SSTs; in its positive phase, SSTs are warmer in the East Pacific and in the central equatorial Pacific and cooler in the subtropical and extra-tropical West Pacific in both hemispheres (Fig. 7). Thus the positive phase of the IPO resembles, to some extent, a much-prolonged, zonally stretched El Niño. The IPO is linked to the Pacific Decadal Oscillation (PDO), which affects the North Pacific on decadal and inter-decadal temporal scales (e.g. Mantua et al. 1997; Power et al. 1999; Folland et al. 2002; Power et al. 2006). Folland et al. (2002) described the PDO as the North-Pacific manifestation of the Pacific-wide IPO. Many studies have defined indices for the IPO, most of which rely on empirical orthogonal function (EOF) analysis of low-pass filtered SSTs (e.g. Zhang et al. 1997; Folland et al. 1998, 2002). Power et al. (1999) defined the IPO using indices based on a 13-year lowpass filter, suggesting that the IPO is somewhere between a decadal and a multi-decadal phenomenon.

Power et al. (1999) concluded that the positive IPO phase resulted in a weakening of ENSO-Australian-rainfall teleconnection. Since most statistical seasonal forecasting models for Australian rainfall rely heavily on the ENSO signal, hindcasts with these models displayed substantially lower skill in years when the IPO was in its positive phase. It was unclear whether including information on the IPO phase could improve statistical prediction schemes, or whether the climate system itself was less predictable in an IPO positive phase. All four of the IPO indices in Power et al. (1999) indicated that a positive phase of the IPO occurred in 1920-1945, consistent with the lack of correlation between ENSO and Queensland rainfall then. Cai et al. (2001) also noted that 1931-1945 was a period of warm SSTs in the East Pacific and reduced ENSO variability, which are compatible with a diagnosis of a positive IPO phase. The authors hypothesised that the reduced ENSO variability was due to cool SST anomalies in the mid-latitude Pacific, which strengthened the atmospheric equator-to-pole heat transport and prevented equatorial Pacific SSTs from warming; no evidence was supplied to support this hypothesis, however. The authors further conjectured that the low ENSO variability caused the weak ENSO-Australian rainfall correlations, but again this was unsupported.

There is little understanding of the mechanisms that led to a weak ENSO-Queensland-rainfall teleconnection during the positive IPO of 1920-1950. Further, there is limited knowledge of the IPO’s impact on Queensland beyond its modulation of the influence of ENSO. As discussed in Section 3.3, Grant and Walsh (2001) demonstrated that the IPO affected tropical-cyclone numbers in the Coral Sea, with negative (positive) phases associated with more (fewer) cyclones. Folland et al. (2002) found that the South Pacific Convergence Zone (SPCZ) migrated further south during summer in negative IPO phases, as well as during La Niña, confirming the results of Salinger et al. (1995); the superposition of La Niña and the negative IPO caused the SPCZ to shift even further south. Verdon et al. (2005) showed that this migration increased rainfall and streamflow in Queensland and New South Wales, again finding that the negative - IPO - La Niña superposition had the greatest impact.

It is questionable whether decadal and multi-decadal variability in the Pacific can explain all, or even a large fraction, of the decadal variability in Australian rainfall. Despite the strong association between the IPO and the

ENSO - rainfall correlation for much of the 20th century, the IPO has recently been in a positive phase (approximately 1980–2000) and the ENSO - rainfall relationship has remained relatively robust in Queensland (Murphy and Ribbe, 2004). The mechanism for this behaviour remains as unclear as that for the weak ENSO-rainfall relationship during 1920–1950.

It is clear that much work needs to be done to elucidate not only the impacts of decadal and multidecadal variability in Pacific SSTs on Queensland rainfall and its variability on shorter temporal scales, but also the mechanisms that underlie those impacts. A clear physical understanding of the influence of the IPO-PDO on Queensland would be of great benefit, particularly if GCMs were able to predict the evolution of the decadal oceanic signal. This has already been attempted in a relatively coarse-resolution coupled model by Power et al. (2006), with limited success. Improved and higher-resolution models with refined techniques for assimilating information on the current state of the ocean are now available (e.g. Smith et al. 2007), however, so analysis of these simulations may lead to a better understanding of whether predictable decadal variability exists in Queensland rainfall.

4.6 Summary of climate drivers of Queensland rainfall variability

Queensland is heavily influenced by the MJO on intra-seasonal scales, ENSO on inter-annual scales and the IPO on decadal and multi-decadal scales (Fig. 1). The MJO provides at most one-half of the sub-seasonal variance in the summer monsoon, which is considerable given that the total sub-seasonal variance is often as large as, or larger than, the seasonal cycle (Hendon and Liebmann 1990a; Wheeler and McBride 2005). Active MJO phases in the West Pacific enhance tropical-cyclone genesis in the Coral Sea (Wheeler and McBride 2005; Leroy and Wheeler 2008). The active MJO also increases trade-wind rainfall in Northeast Queensland; it may induce blocking anticyclones in the Tasman Sea in autumn and spring (Wheeler et al. 2009).

El Niño (La Niña) events tend to cause deficient (excess) rainfall in Queensland, but this relationship is neither simple nor linear. Queensland rainfall is sensitive not only to the magnitude of ENSO events, but also to their zonal position. Central Pacific SST anomalies have a stronger impact than those in the East Pacific (Murphy and Ribbe, 2004; Wang and Hendon, 2007). This link has strengthened since 1950, consistent with the finding of Power et al. (1998) that the rainfall anomaly for a given SOI value increased after 1970 (Section 2.4.2). El Niño (La Niña) is associated with fewer (more) tropical cyclones and a stronger (weaker) MJO, the latter of which suggests complex and competing interactions between intra-seasonal and inter-annual variability for synoptic weather patterns.

Considerable decadal and multi-decadal variability exists in Queensland rainfall, as well as in its correlation to ENSO. ENSO and Queensland rainfall became uncorrelated during 1920–1950 (Lough, 1991; Cai et al., 2001), a period of warm equatorial Pacific SSTs due to a positive IPO phase (Power et al. 1999). Positive IPO phases have also been associated with periods of weak ENSO variability (Cai et al., 2001), low spatial coherence in Queensland rainfall (Lough 1991), fewer Coral Sea tropical cyclones (Grant and Walsh, 2001) and a northward migration of the SPCZ (Folland et al. 2002). The physical mechanisms underlying these cross-temporal-scale correlations are poorly understood. Further analysis must be done to determine the sources of decadal variability in Queensland rainfall, the mechanisms behind it and to what extent it is predictable.

Queensland rainfall and the SAM are connected only weakly: the positive SAM phase may bring increased spring rainfall due to a stronger onshore flow (Hendon et al. 2007; Risbey et al. 2009). The IOD has no discernible impact on Queensland (Murphy and Ribbe 2004; Risbey et al. 2009).

5 Conclusion

This report has reviewed the dominant remote synoptic and climatic drivers of Queensland rainfall on temporal scales from days to several decades. Changes in large-scale, remote drivers are likely to be more predictable than changes in local weather conditions. Thus, information on how these drivers influence regional and local rainfall may improve the understanding of changes on those smaller scales. Any predictable inter-annual or decadal signals with a known relationship to Queensland rainfall would lead to more-accurate predictions of climate variability and change over the next one or two decades, a key period for climate-change adaptation efforts.

Many studies have described changes in rainfall in Queensland and across Australia, but only a few have explained these changes to variations in the impact of known remote drivers of rainfall. Even fewer studies have provided plausible physical mechanisms for the variability in the influence of those drivers. Analysis has often focused on annual-or seasonal-mean rainfall, neglecting the spatial and temporal characteristics of rainfall within the year or season. Changes in rainfall frequency and intensity can have larger impacts (e.g. in agriculture and flood-risk management) than shifts in the mean. Linear trends have been fitted to observed rainfall data that contain clear evidence of inter-annual, decadal and multi-decadal variability. With some exceptions (e.g. Robertson et al. 2006), little research exists on the interactions between temporal scales of variability, despite strong indications that these interactions are key in determining the character of Queensland’s rainfall.

6 Glossary

Baroclinic - Refers to a condition and type of motion in which pressure is not constant on surfaces of constant density, e.g. internal tides and other internal waves.

Blocking anticyclone - Large scale patterns in the atmospheric pressure field that are nearly stationary, effectively "blocking" or redirecting migratory cyclones. They are also known as blocking highs or blocking anticyclones.

Cut-off lows - Areas of low surface pressure, closed circulation and intense mid-and upper-tropospheric baroclinic development that form to the south of Australia during periods of atmospheric blocking.

East-coast lows - Areas of closed circulation that form near the eastern coast of Australia south of 20°S and move parallel to the coast. They develop in regions of strong zonal SST gradients and track along the eastern coastline of Australia.

El Niño Southern Oscillation (ENSO) - An irregular oscillation of equatorial Pacific Ocean upper-ocean temperatures, which occurs due to unstable atmosphere–ocean interactions. These ocean-temperature anomalies cause variations in sea-level atmospheric pressure, termed the Southern Oscillation

General Circulation Models (GCM) - Computer models designed to help understand and simulate global and regional climate, in particular the climatic response to changing concentrations of greenhouse gases. GCMs aim to include mathematical descriptions of important physical and chemical processes governing climate, including the role of the atmosphere, land, oceans, and biological processes. The ability to simulate sub-regional climate is determined by the resolution of the model.

Indian Ocean Dipole (IOD) - The difference between sea surface temperature in the western and eastern tropical Indian Oceans. A positive IOD occurs when the western basin is warmer than average and the eastern basin is cool.

Inter-decadal Pacific Oscillation (IPO) - A low-frequency mode of variability in Pacific SSTs; in its positive phase, SSTs are warmer in the East Pacific and in the central equatorial Pacific and cooler in the subtropical and extra-tropical West Pacific in both hemispheres.

Madden-Julian Oscillation (MJO) - A tropical atmospheric phenomena, with a timescale ranging from 40 to 60 days which develops over the Indian Ocean and travels eastwards through the tropics.

Southern Annular Mode (SAM) - The north-south movement of the band of westerly winds south of Australia. SAM is positive when there is a poleward shift of the westerly wind belt and is associated with enhanced spring and summer rainfall in New South Wales and Queensland.

Southern Oscillation - Traditionally defined as normalised sea-level pressure anomalies at Tahiti minus those at Darwin; positive (negative) values correspond to La Niña (El Niño).

Synoptic - Pertaining to a general view of the whole, hence a synoptic variable is one used to describe the state of system over a wide geographical area.

Trade winds - Steady easterly surface winds found in the tropics and blowing towards the equator from the northeast in the northern hemisphere or the southeast in the southern hemisphere, especially at sea. They blow from the tropical high-pressure belts to the low-pressure zone at the equator.

Tropical cyclone - A storm system characterised by a large low-pressure centre and numerous thunderstorms that produce strong winds and heavy rain. Tropical cyclones feed on heat released when moist air rises, resulting in condensation of water vapour contained in the moist air.

Walker Circulation - The east-west movement of the trade winds across the tropical Pacific Ocean, bringing moist surface air to the west with dry air returning along the surface to the east.

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