Variability of southeast Queensland rainfall and climate indices

Short title: Variability of southeast Queensland rainfall and climate indices
Key words: climate variability, Queensland, rainfall, climate indices, SOI

Bradley F. Murphy and Joachim Ribbe
University of Southern Queensland, Toowoomba, Australia
Corresponding author address: Dr. Joachim Ribbe
Department of Biological and Physical Sciences
University of Southern Queensland
Toowoomba, Qld., 4350
Australia

email: Joachim.Ribbe@usq.edu.au
Ph: +61 7 4631 1452
Fax: +61 7 4631 1530

December 19th, 2003

Murphy, Bradley F. and Ribbe, Joachim (2004) *Variability of southeast Queensland rainfall and its predictors.* International Journal of Climatology, 24 (6). pp. 703-721. John Wiley & Sons Inc.

Abstract

This paper presents a study of variability of climate indices and rainfall in southeast Queensland (SE Qld). Using high-resolution gridded rainfall data for all of Australia and global sea surface temperatures (SST), the relationship between rainfall Australia-wide and in SE Qld in particular with SST indices and the Southern Oscillation Index (SOI) have been investigated. It is found that SE Qld is more subject to the breakdown of correlations between the SOI and rainfall than any other part of Australia. Model predictions suggest that this is probable in the future.

Considering only timescales longer than interannual, it was found that SSTs in the central tropical Pacific Ocean (TPO) (represented by the Nino-4 index) correlated best with SE Qld rainfall. Eastern TPO (Nino-3) SSTs and the SOI produced successively weaker correlations. The time series of the second modes of variability of SSTs over the Pacific and Indian Oceans were shown to have limited impact on SE Qld rainfall variability.

The data was split into periods before and after 1946, when Australian mean rainfall changed (Pittock, 1975). While the SOI correlations with rainfall in SE Australia were similar in both periods, in SE Qld the correlations were very weak in the earlier period (0.06) but very strong in the latter (0.72). The Nino-4 index correlated better than the Nino-3 index in both periods, but they showed smaller changes from the earlier to the latter periods than the SOI.

1. Introduction

Rainfall variability is a major economic factor in Australia. From March to December 2002 rainfall was in the lowest 10% of records over more than half of the Australian continent (e.g.

Nicholls 2003). The drought reduced commodity exports by more than 3.7%, decreasing economic growth by 0.75%. (ABARE, http://www.abare.gov.au/pages/media/2002/16dec.html). In two regions, however, the below-average rainfalls have been much longer-lived. In both southwest Western Australia and in southeastern Queensland (SE Old), mean rainfall for the three years 2000-2002 was also in the lowest 10% on record. While 2002 was a well-defined El Nino year, these longer dry spells are due to additional processes. Most of the continent has seen positive rainfall trends of up to 3 mm yr^{-1} from 1910 to 1999 (Manins et al., 2001), but these two regions are the only in Australia with spatially extensive areas of decreasing rainfall trends. They are therefore exceptional in terms of their long-term rainfall trends and the length of the dry spell that included the 2002 El Nino event. The changes in southwestern Australia have been the focus of several studies to date (e.g. Allan and Hunt, 1999). While Queensland-wide trends in rainfall have been investigated (Lough, 1997), the rainfall trends and long-term deficiencies in SE Qld have yet to be studied in detail. Due to the high agricultural activity in SE Qld, climate forecasting has been linked with agricultural systems modelling for significant economic decision making potential in operational contexts (Meinke et al., 1996, Hammer et al., 2000). This paper aims to provide a systematic study of climate variability in SE Qld and the variations in the climate indices used for monitoring climate variability.

The impact of sea surface temperatures (SST) on Australian rainfall variability has been established previously. Nicholls (1989) showed that winter rainfall in eastern Australia was closely related to SSTs in the central Pacific and Indian Oceans, as well as the waters around Indonesia. Warm SSTs of the Indian and southwest Pacific Oceans are associated with wet years in Australia (Whetton, 1990) and Qld winter rainfall has been linked to SSTs off the northeast of Australia.

Numerous studies have concentrated on the relationships between the El Nino Southern Oscillation (ENSO) and rainfall. These phenomenon is the dominant mode of global climate variability, and it has long been recognised (since Quayle, 1929) that drought conditions in eastern Australia are common during the El Nino phase, when SSTs in the eastern tropical Pacific Ocean are warmer than normal. The Southern Oscillation (SO) is closely related to eastern Australian rainfall, particularly in spring (McBride and Nicholls, 1983). The effect of ENSO on Australian rainfall variability is therefore well established, mostly through the variability of SSTs in the surrounding oceans.

SSTs in the central Tropical Pacific Ocean (TPO) correlate well with rainfall when Qld as a whole is considered (Nicholls, 1989, Lough, 1992, Lough, 1997). A widespread change in eastern Australian rainfall occurred around 1945-46 (Pittock, 1975), and around the same time Qld's-mean rainfall increased and became more variable (Lough, 1991). SE Qld is at the southern limit of monsoon affected Australia, and it is also affected by the position of the subtropical ridge (Lough, 1991). Rainfall variability in the southeast of Qld is therefore affected by atmospheric phenomena other than ENSO.

Rainfall variability is high in SE Qld (Lough 1991), and in contrast to most of the east of the country rainfall persistence is weak even on monthly timescales (Simmonds and Hope, 1997). In northeastern Australia the persistence in rainfall that is evident in late winter and spring is much weaker when the effect of the SO is removed, suggesting that much of the persistence there is ENSO related. It has also been shown that when the effect of ENSO is removed, the link between eastern Australian rainfall and TPO SSTs is much weaker (Nicholls, 1989). Interannual rainfall variability is also amplified in regions that are affected by ENSO (Nicholls, 1988) such as SE Qld.

As well as the reports of long-term changes in the mean rainfall of southern Qld and south-western Australia (Hennessy et al., 1999, Manins et al., 2001), there is also evidence of temporal variations in the links between ENSO, SSTs and eastern Australian rainfall (McBride and Nicholls, 1983, Cordery and Opoku-Ankomah, 1994, Cai et al., 2001). Cai et al. (2001) found that the Southern Oscillation Index (SOI) and northeast Australian rainfall were highly correlated throughout the 20th century ($r \approx 0.7$) except during the period 1930-45 when the relationship was in fact reversed. During this period the global mean surface temperature was warmer than the surrounding periods and the ENSO-rainfall relationship was much weaker then. TPO SST anomalies were weaker during this period, while those in the mid-latitudes of the Pacific Ocean were stronger. At the same time, atmospheric pressure anomalies associated with ENSO were of the opposite sign to usual. The period 1930-45 was one of only two extended periods during the 20th century when the Interdecadal Pacific Oscillation (IPO) was positive. The ENSO signal over Australia is thought to be suppressed during a positive IPO phase, and hence the higher than normal temperatures over the Pacific Ocean during this period seem to be responsible for the temporary disappearance of the correlation between northeast Australian rainfall and the SOI (Power et al., 1999).

In Australia, climate forecasts are mostly based on either large-scale SST patterns or phases of the Southern Oscillation. The SOI phase system (Stone et al., 1996) uses principal component and cluster analysis to identify lag-relationships between changes in the SOI and patterns of rainfall probabilities over Australia. The SST forecasting system used by the Australian Bureau of Meteorology (Drosdowsky and Chambers, 2001) uses the first two rotated principal components of SST patterns over the Pacific and Indian Oceans. While the ENSO/Pacific SST influence is dominant Australia-wide, there is an additional influence that is important for climate variability and climate forecasting exerted by SSTs in the Indian Ocean on rainfall over eastern Australia (Whetton, 1990, Simmonds, 1990, Drosdowsky, 2002). SST variability over the Pacific and Indian Ocean basins therefore has complicated interactions and impacts on Australian rainfall. An important consideration is the effect of changing relationships between ENSO and Australian rainfall when indices of the former are used for forecasting the latter.

This paper investigates the variability of rainfall and its predictors with the main focus on SE Qld. The two interesting aspects of this region are the long-term downward rainfall trends and the persistent dry conditions such as those from 2000-2003. This study's objectives are to investigate in detail the relationships between SE Qld rainfall and climate indices including those of Pacific and Indian Ocean SSTs and the SOI. The variations in these relationships over the previous century are important for SE Qld where the application to agriculture of climate forecasts using these predictors is most advanced. Model data are used to show how these relationships may change in the future and it is argued that forecasting strategies may be vulnerable to such climate changes.

The following section outlines the data that have been used in the study, and section 3 discusses the methods used to analyse them. Results are presented in section 4, followed by a discussion of their significance for SE Qld in section 5. A list of conclusions completes the paper.

2. Data Sources

2.1 Precipitation

The rainfall observations come from gridded analyses of mean monthly rainfall for the period 1891 to the present produced by the Australian Bureau of Meteorology (BoM) National

Climate Centre. The analysis method, described in Jones and Weymouth (1999), is based on the Barnes successive correction analysis technique. It has taken all available Australian stations reporting rainfall, with the number of stations used varying between approximately 2000 and 8000. Data was cross validated and analysed to a regular grid with spacing of 0.25^o .

2.2 Sea surface temperatures

The SST observations used are version 2.3b of the United Kingdom Hadley Centre Global sea Ice Coverage and Sea Surface Temperature (GISST) data (Rayner et al., 1996). This data provide monthly mean SST gridded data at 1^o horizontal resolution for the period 1871-2000. It is reconstructed from ship and satellite observations, and uses several techniques such as empirical orthogonal function analysis to produce global coverage for the entire time series. While the data in the extratropical regions is less accurate, the tropical SSTs have been shown to reproduce realistic ENSO variability from the late 19th century.

2.3 Southern Oscillation Index

We also make use of monthly time series of the SOI from 1876-2002. The SOI has been defined as ten times the standardised difference of the monthly mean surface pressure between Tahiti and Darwin (obtained from the Australian Bureau of Meteorology).

2.4 CSIRO Mark 2 climate model data

The CSIRO (Commonwealth Scientific and Industrial Research Organisation) climate model (Mark 2) is a fully coupled atmosphere/ocean model. It includes dynamic sea ice and soil-canopy models. The atmospheric model is spectral with rhomboidal truncation at wavenumber 21, and has nine vertical levels, while the ocean is a grid point model with 21 levels. Horizontal resolution is 5.6° longitude by 3.2° latitude. Details of the model design can be found in Gordon and O'Farrell (1997) and Hirst (1999). The coupled model is first spun-up for 30 years and the climate change experiment reported in Hirst (1999) begins in a year equivalent to 1881. The atmospheric carbon dioxide concentration was increased in line with that observed until 1990, after which the IPCC climate change scenario IS92a (IPCC, 1994) is followed (often known as the “business-as-usual” scenario). Carbon dioxide levels are increased until three-times the 1880 level is reached in model year 202 (2082) and then held constant. Here we use the first 150 years of the simulation, equivalent to 1885-2035, although individual years should not be considered to correspond exactly. Simulated monthly means of grid point precipitation and the temperature of the first ocean level (which has a depth of 25 m) as an approximation of SSTs, are used. This model simulates present climate realistically (Hirst et al., 1998) and it has been used for several climate studies (e.g. Cai and Whetton, 2000, Cai et al., 2001).

3. Method

The analyses will be performed over the period 1891-2000 as this is the longest period over which the rainfall, SST and SOI observations overlap. A time series of monthly SOI is used. Monthly Nino-3 (N3) and Nino-4 (N4) indices have been calculated as spatial means of the GISST data over the areas 5° S-5° N, 150° -90° W and 5° S-5° N, 160° E-150° W respectively. These represent the mean equatorial SSTs over the east and central tropical Pacific Ocean respectively. Monthly Australian rainfall analyses at 0.25° resolution have been used in all analysis.

The same indices have been calculated from the CSIRO Mark 2 climate model data, although the exact regions used will be slightly different due to model resolution. While modest warming trends were found in the observed tropical SSTs, the warming was much stronger in the model. These strong trends mask the interannual variations in the simulated SSTs in the following analysis. To overcome this, the simulated N3 and N4 indices have been linearly detrended after model year 160 when the warming became pronounced.

This study will concentrate on the rainfall anomalies that persist for periods greater than interannual. In order to do so the time series that are used in the following analysis have usually been filtered with a five-year running mean. In this way it will be possible to isolate the persistent droughts and high rainfall episodes over the observational record and to examine periods of climate-related extreme hardship for primary producers in Australia.

The results section focuses on SE QLD which is defined as the region bounded by 147° E, the eastern coast of Australia, 29° S and 22.5° S.

3.1 Correlation maps

Maps of the coefficient of correlation between the SOI, N3 and N4 time series and the Australian rainfall distributions have been calculated for the entire time period (1891-2000) and for the two 55 year periods 1891-1945 and 1946-2000. The dividing date corresponds to the end of a period of positive IPO when the impact of ENSO on Australian climate was weak (Power et al., 1999; Cai et al., 2001) and when a change was seen in Australian mean rainfall (Pittock, 1975). In this analysis, all time-series have been smoothed with a five-year running mean in order to keep only variations on time scales longer than the interannual. These maps represent the correlations between the indices and rainfall on the five-year time scale over Australia. While maps are produced for all of Australia, we concentrate the analysis of the results on SE Qld.

Stone and Auliciems (1992) have rejected correlation analysis as a basis for seasonal climate forecasting. However, our objective is not to test for the applicability of climate indices for forecasting, but to investigate relationships between the indices and rainfall variability. Our correlation analysis therefore does not reflect on the use of schemes such as the SOI phase system (Stone et al. 1996) that uses instead principal component and cluster analysis to identify lag-relationships between changes in the SOI and rainfall probabilities.

It is useful to give an indication of the significance of the correlation coefficients that are calculated. Given that there would be 22 independent observations when these time series are passed through the five-year running-mean filter, Student's t-test would suggest that at the 5% level correlation coefficients greater that 0.42 are significantly different from zero. It is important to remember in the following analysis that we are not aiming to find new relationships between the variables but to find some new features of relationships that have already been well established.

3.2 Spatial variability of SSTs

Seasonal climate forecasts using SSTs make use of large-scale patterns of SST variability rather than single indices (Drosdowsky and Chambers, 2001). Through the use of such patterns the influence of SSTs over extratropical in addition to tropical regions is included. Therefore, as well as the SOI, N3 and N4 indices for Pacific SST variability, we have examined the leading patterns of variability over the Pacific and Indian Oceans. These patterns, or modes, of variability are the eigenvectors of empirical orthogonal functions (EOFs) that capture the main patterns of variability in the original data. They are found by first detrending the GISST data (to remove the leading mode that is due to global warming) and then performing a singular value decomposition of the annual mean data. The resulting eigenvectors are orthogonal, in that the time series of the modes are not significantly correlated, and the leading modes represent the largest part of the interannual variability in the GISST data set.

The first and second modes of the SSTs covering the entire Pacific and Indian Ocean basins are essentially the same as the superposition of the same modes of each basin calculated separately. The EOF eigenvectors are therefore largely independent of the exact domain used. We therefore examine the spatial structure and time series of the expansion coefficients of the first two modes for SSTs over the tropical and south Pacific Ocean (20^o N-50^o S, 140^o E-70^o W) and the Indian Ocean (20^o N-50^o S, 30^o E-120^o E) in section 4.3.

4. Results

We begin by considering the correlations between rainfall and the N3, N4 and SOI indices for the whole of Australia. The focus will then be shifted to SE Qld.

4.1 Australia-wide correlations

The correlation maps in this section show the coefficient of correlation between the three indices N3, N4 and SOI with Australian rainfall for the period 1891-2000, with all time series passed through a five-year running-mean filter. N3 represents eastern TPO SSTs, and the correlations with rainfall vary widely with location over Australia (Fig. 1a). In the eastern half of the continent the correlations are negative, with only southeast Victoria (around 140° E, 37° S) and parts of coastal Qld having correlations stronger than -0.5. In the west the correlations are positive. The N4 correlations have a very similar spatial distribution, but are generally better, particularly in SE Qld (Fig. 1b). The SOI correlations (Fig. 1c) are again very similar but of opposite sign, but in SE Qld they are weaker than the N4 correlations. There are thus large regions of Australia where rainfall exhibits strong correlations with TPO SSTs and the SOI. Over most of the western half of the country rainfall increases (decreases) with warmer (colder) TPO SSTs. In the eastern states the rainfall is negatively correlated with the SSTs which is in line with El Ninos being associated with below average and La Ninas with above average seasonal rainfall, sometimes leading to drought or flooding. In most eastern regions where the link between ENSO and rainfall has been established (e.g. in New South Wales, see Cordery and Opoku-Ankomah, 1994) the correlations are generally quite weak.

In order to quantify the possible change of these correlations with time, the time series have been divided into two equal periods from 1891-1945 and 1945-2000 (see section 3.1). Our results confirm that the correlations between the three indices discussed above and Australian rainfall were significantly stronger in some regions of Australia in the latter period than in the former. Before 1946 the N3 and N4 indices correlated strongly with rainfall in southeastern Australia, particularly western Victoria and southeastern South Australia, where the N3 index correlations were the strongest and most widely spread. Correlation coefficients were stronger than -0.5 over most of eastern Australia barring coastal SE Qld (Fig. 2a and 2b) for the two SST indices. The SOI correlations were strong in Victoria, Tasmania and southwestern Australia but weak almost everywhere else (Fig. 2c) in this earlier period. The SST indices were much more strongly correlated over more extensive regions of eastern Australia suggesting that the SST variations that were responsible were not entirely due to ENSO variability. Another consideration is that from 1930-45 the appearance of an El Nino did not bring about the typical atmospheric pressure changes (Cai et al., 2001), and hence the SOI did not reflect the state of ENSO during this period.

In the second half of the period (1946-2000) the correlation maps are significantly different (Fig. 3). The N3 correlations weakened in SE Australia and the N4 index generally correlated much more strongly with rainfall over the eastern half of the continent. While N3 correlations were strong in far SE Qld, the N4 correlations were strong over much of eastern Australia, except where the correlations were strongest in the earlier period. The SOI correlation map for this latter period (Fig. 3c)) is remarkably similar to the N4 map. This similarity suggests that the correlations with rainfall on the time scales considered here are closely tied to ENSO and that the N4 index is a very good indicator of the ENSO impact on rainfall in eastern Australia in general. In Qld in particular correlations with rainfall appear to be ENSO related. SOI correlations become much weaker in Western Australia, while in most of eastern Australia the correlations become strongly positive.

The SOI changes between the two periods contrast to some extent to those seen between rainfall and N4. In Victoria and Tasmania the SOI-rainfall relationship persists from the first to the second period while the changes in Qld are much more marked. The correlations with N4 in southeastern Australia weaken in the second period. It is clear that the strongest correlations with rainfall shifted from southeastern Australia to the northern half of the eastern states from the earlier to the latter period (shown previously by Cai et al., 2001). The highest correlations are more spatially extensive between rainfall and the N4 index, and therefore rainfall in southern Qld as a whole is more closely related to SST variations in the central rather than the eastern Pacific.

The relationships between TPO SSTs and Australian rainfall have clearly changed with time. These changes may be due to the changing rainfall distributions at certain locations or to changes in SST variability. Of interest is the spatial pattern of rainfall-N4 correlations in the coastal regions of Qld in the second half of the time series. There are four regions where r is stronger than -0.7, and these are broken by smaller regions where the correlations are much weaker ($r \approx -0.2$). This suggests that there could be stations that are much less influenced by TPO SSTs than those surrounding them. In fact, the stations that do not exhibit strong negative correlations between rainfall and N4 are those that exhibit a large positive rainfall trend over the observational record. For example, the gridded rainfall data at 17.0^{o} S, 145.5^{o} E, where the rainfall correlation with N4 is close to zero, exhibits a positive linear trend of greater than 1 mm day^{-1} per year (see Figures 17 and 18 of Manins et al., 2001). Such a trend completely masks any interannual correlation between the rainfall and the N4 index. Other spatial variations in the correlation maps may be due to variations in the topographical influence on the hydrological cycle or to changes in land use or other factors.

4.2 Large-scale modes of variability

We have shown above that the central TPO SSTs and the SOI produce the same patterns of correlation with Australian rainfall. In addition, the N4 index and the SOI have very similar rainfall correlations in SE Qld in the second half of the observational record. This result suggests, since the SOI is a measure of ENSO, that the central TPO SST variability that leads to strong rainfall correlations is essentially due to ENSO variability. The coefficient of correlation between the time series of the five-year running means of the N4 index and the SOI is -0.72, and for the N3 index and the SOI it is almost identical (-0.73). The N3 and N4 time series are correlated at 0.86. Thus, N3 is as well correlated as N4 to the SOI time series, but the N3 correlations with rainfall, particularly in SE Qld, are weaker than for the SOI and N4 (see Fig. 3). These differences suggest that there may be more than ENSO variability that is related to SE Qld rainfall.

The first two modes of variability of SSTs in the Pacific Ocean both have the central tropical Pacific as an important centre of action. The first mode (not shown) is essentially the pattern associated with ENSO. A tongue of warm SSTs along the equator extends from the Peruvian coast representing the typical SST anomaly pattern associated with an El Nino. The second mode exhibits a centre of action at almost the precise position of the Nino-4 region, although it extends further poleward, and has a centre of action of the opposite sign related to upwelling along the South American coast (Fig. 4a). It therefore represents a mode of variability in central TPO SSTs that is in addition to that directly related to ENSO variability. In these annual mean data the first mode represents 13.0% of the total variability, while the second mode accounts almost half of this (6.1%). The central TPO SSTs that we have found to be highly correlated with the rainfall variability of eastern Australia therefore play a role in both the first and second modes of annual Pacific SST variability. SSTs in both the N3 and N4 regions are active in the first two modes of variability, but the N4 index correlated better with the Australian rainfall.

The Indian Ocean has also been implicated in Australian rainfall variability. The first mode (not shown) has two centres of action in the eastern half of the basin north and south of 30^{o} S, and its variability is closely linked to ENSO (the expansion coefficients of the first Pacific and first Indian Ocean modes correlate at 0.77). While the Indian dipole (Drosdowsky, 1993) has been suggested as an important influence on Australian rainfall variability, it is not evident in this first mode of Indian Ocean SST variability, nor in the second (Fig. 4b). The Indian dipole pattern of variability may therefore have been removed by the detrending of the SST data. The second mode also has two opposing regions to the north and south of 30° S, but extending across essentially the entire basin, and situated south of the equator. As with the Pacific modes, the first and second modes of annual SST variability in the Indian Ocean account for 13% and 6.5% of the total variability, respectively.

Fig. 5 gives the correlations between the time series of the expansion coefficients of the second mode of Pacific Ocean SST variability and the rainfall over Australia. The correlations between Australian rainfall and the time series of this second Pacific mode are quite different to the rainfall correlations with the N4 index that we saw in Figs. 1-3. In fact, the second Pacific mode and N4 index time series correlate at the annual time scale at only 0.14 and at less than 0.1 when five year running means are applied to both time series. As a result, correlations between the second Pacific mode and SE Qld rainfall are weak. The Pacific mode of variability includes influences of SSTs from across the entire Pacific basin, as two other centres of action can be seen in Fig. 4a whereas we have seen that the rainfall variability of much of Australia is very closely related to the SSTs in just the central TPO. The N4 index appears to capture the important variability of the Pacific SSTs that are most relevant to rainfall in SE Qld.

The correlations between the rainfall and the time series of the expansion coefficients of the second Indian Ocean SST mode are seen to vary significantly with location and with time (Fig. 6). In the west of the continent the second Indian Ocean mode is quite poorly correlated with rainfall in the period before 1945, whereas the correlations are quite high in the latter period. In central regions the opposite is the case, with the correlations becoming weaker in the period after 1945. In SE Qld the correlations remain quite weak in the two periods and hence it appears that the influence of this second mode is minimal in this region. To the immediate west and south the correlations were much higher in the earlier period, but SE Qld appears to relatively unaffected by this second, non-ENSO mode of Indian Ocean SST variability.

Of interest, however, are the high positive correlations in the west of the continent in the latter period, where the link with the Indian Ocean SSTs would be expected to be more direct, but also the high negative correlations in the south-east of Australia. This relationship is similar to that given by Drosdowsky (2002), who showed that the Indian Ocean SSTs had the effect of reducing the dry impact of an El Nino in the south-east of the country. The correlations were also weak in the north-east.

4.3 Temporal variations in southeast Queensland

Having examined the relationships between Australia-wide rainfall with SSTs and the SOI, focus is now placed on their impacts on rainfall in SE Qld.

The results presented above show that SE Qld is a region where there have been significant changes in the correlations between rainfall and the three indices of Pacific climate. It is clear that SE Qld rainfall is best correlated on timescales longer than interannual with the SOI and the SSTs in the central tropical Pacific. The results also suggest that this region, along with much of eastern Australia and southwestern Australia, has seen major changes in the links with the variability of the Pacific Ocean. Both the SOI and the N4 index have become much more strongly correlated with rainfall in SE Qld since the middle of the twentieth century. SE Qld also is the area in eastern Australia that exhibits the weakest links with the variability of Indian Ocean SSTs.

Taking the mean rainfall over the SE Qld region, the correlations of monthly values with the indices we have considered are listed in Table 1. The correlations with the N4 index and SOI are the strongest in the second half of records, and SE Qld rainfall has become much better correlated with the SOI in particular. Little change occurs in the two large-scale modes of variability that we have considered, and there has been only a modest increase in the rainfall correlation with the N3 index.

		Period	
Correlations	**1891-2000**	**1891-1945**	**1946-2000**
N4	-0.57	-0.59	-0.65
N3	-0.49	-0.48	-0.53
SOI	0.42	0.06	0.72
PEOF2	-0.33	-0.33	-0.33
IEOF2	-0.39	-0.39	-0.41

Table 1: Correlations between monthly values of SE Queensland rainfall and the time series of the Nino-4 index, Nino-3 index, the SOI and the second modes of variability of Pacific (PEOF2) and Indian (IEOF2) Ocean SSTs.

The five-year running means of SE Qld rainfall (Fig. 7) exhibit significant variations that persist for between five and ten years (as shorter time scales have been filtered out). There have been periods of both positive and negative anomalies of the five-year running means greater than one standard deviation of the unfiltered annual mean rainfall (0.5 mm day^{-1}, annual mean rainfall, being the mean gridded data, of SE Qld, is 2.1 mm day^{-1}), but not since before 1960. Since then there has been only one period of large positive anomalies (the mid-1970s). Most of last 40 years experienced persistent below-average rainfall. Most recently, 1991-95 and 1997 all recording below average rainfall for SE Qld and 2001 and 2002 both recorded negative rainfall anomalies greater than one standard deviation from the mean. Extended dry periods occur in SE Qld approximately once every two decades over the observational record. Dry periods are more prolonged than wet periods, although they are generally less extreme but are becoming more frequent.

The correlations between SE Qld rainfall and the N3, N4 and SO indices since 1946 are very clear when the time series are plotted together (Fig. 7). Throughout this second half of the record, multi-year warm TPO SST (N4) anomalies are concurrent with low rainfall and wet periods coincide with cold TPO SST anomalies. Many of the anomalies in SSTs and rainfall persist for a number of years. The N3 index is also well out-of-phase with the rainfall anomalies, but less so than N4 in the 1960s. Since 1970 the rainfall and SST time series are very well negatively-correlated. The SOI and N4 index are closely related in the second half of the record, and the positive SOI correlation with SE Qld rainfall is very clear. In the period before 1915 the N3 index has the closest relationship with SE Qld rainfall, whereas the SOI was only in phase with rainfall during the brief period from about 1908--1917. It is also evident from Fig. 7 that from around 1915 to 1950 the relationships between the time series were either absent or even reversed. During most of this time the N3/N4 index and the SOI remained out-of-phase, but the relationship with SE Qld rainfall was the opposite of those before and after this period. It is therefore seen that from 1915--50 the ENSO link with SE Qld rainfall was weaker and the correlations were reversed. In this period the IPO was positive and the ENSO signal was weak over Australia (Power et al., 1999).

The interannual variability of SE Qld rainfall was weak quite from 1915-40 and there was a slight downward trend during this period that was reversed in the 1950s. SST and SOI variability was also weaker than during most of the 20th century. In particular, the five-year running mean anomaly of the N4 index remained very close to zero. The horizontal distribution of monthly SST variance in the GISST data (not shown) indicates that tropical SSTs in the second half of the 20th century were much more variable than in the preceding 50 years, and that in the period of weakened TPO SST to Qld rainfall correlations the variance of tropical SSTs was only half that of the post-1945 period. Better data coverage in the latter period may play a role in this enhanced SST variability. The breakdown of the ENSO-rainfall relationship therefore coincides with much lower than normal variability in TPO SSTs. However, there was still some variability in the N3 and N4 indices from 1925-45 that did not result in the normal rainfall variations in SE Qld.

Thus, while the N4 index and therefore central TPO SSTs were best correlated with rainfall in SE Qld throughout most of the observational record, the 1915-50 period is marked by weak central TPO SST and SE Qld rainfall variability. The N4 SSTs remained close to zero, and not greater than the long-term mean, as the higher temperatures that lead to the positive IPO suggest. Even in the eastern TPO SSTs were more often colder than average in this period, while the SOI remained positive from 1915-40. In addition, SE Qld rainfall anomalies were mostly negativ but weak.

As shown in the correlation maps (Fig. 5) there is no clear relationship between the expansion coefficient of the second mode of Pacific Ocean SSTs and SE Qld rainfall (Fig. 8a). The two are quite poorly correlated, in contrast to rainfall and the N4 index. Between 1915-40 this mode appeared to be relatively inactive, when SE Qld multi-annual rainfall (and N4 index) anomalies were modest.

The second mode of Indian Ocean SST variability does have a negative correlation with SE Qld rainfall in certain periods, namely 1891-1905 and 1950-1975. However, as with the second Pacific mode, the relationship is quite different outside these periods. For example, during the late 1920s the very marked positive anomalies in the expansion coefficient for the second Indian mode had little impact on SE Qld rainfall. While the other indices we have correlated with SE Qld rainfall

all exhibit periods of weak correlations, the relationships appear to be more robust than either of the two second modes of SST variability. The impact of these large-scale modes on SE Qld rainfall is therefore much more tenuous. This is true for the Pacific mode since it is lacking important central TPO SST variability due to ENSO and includes SST variability in other sectors of the Pacific Ocean. For the Indian Ocean, the atmospheric mechanisms through which SSTs can affect SE Qld appear too weak to have a lasting significant impact.

5. Discussion

This study has shown the extent of the relationships between Australian rainfall and sea surface temperature variability in the Pacific and Indian Oceans. On timescales greater than interannual, there are large regions of the Australian continent where there are significant links between rainfall and SSTs in the tropical Pacific and the Southern Oscillation Index, a measure of the state of ENSO. In particular, it is seen that in SE Queensland the central TPO SSTs and the SOI have been well correlated with rainfall.

ENSO has long been known to have important impacts on Australian rainfall variability (Quayle, 1929, McBride and Nicholls, 1983, Nicholls 1989 to cite only a few), so some of the results in section 4 merely confirm these relationships. That the impact of ENSO on Australian rainfall has varied over the observational record has also been noted before (Nicholls, 1989, Cai et al., 2001). However, with the current study the relationship on timescales greater than interannual between rainfall and various indices of SST and atmospheric variability have been clarified.

The N4 index and the SOI provide the strongest correlations over the second half of the twentieth century, but before this period they exhibited quite different relationships with rainfall in certain regions. Some of the greatest differences between the correlations in the first and second periods have occurred in SE Qld. In Victoria and Tasmania the SOI-rainfall correlations have remained relatively constant. However, in SE and northern Qld the SOI link was almost non-existent in the earlier period, while it became very strong after 1945. This was also true to a lesser extent for the SST-rainfall correlations in Qld. In the southeastern states the N3/N4-rainfall correlations weakened after 1945 but were still close to -0.5. Qld is therefore the region that has been most prone to disruptions to the relationships of rainfall with tropical Pacific SSTs and atmospheric pressure fluctuations.

While correlation analysis has been discarded for forecasting by Stone and Auliciems (1992) and Stone et al. (1996), there is a risk that the weakening of relationships between rainfall variability and ENSO may also affect the lag-relationships upon which these forecasting schemes are based. We have seen that the correlations were not robust throughout the last century, particularly those between the SOI and rainfall in SE Qld. It is possible that the physical mechanisms that form the basis of the forecasting schemes could change. The investigation of the robustness of these seasonal forecasting models under different climate regimes needs therefore to be addressed.

The correlations were considerably weaker in Qld at least for the period 1915--1945. This weakening has been related to a positive IPO (Power et al., 1999). However, this was one of only two periods on record when the IPO has been consistently positive and so it is difficult to determine whether this weakening of ENSO influence on Australian climate is common. Also, it is interesting to note that from 1980--2000, when the IPO was positive, the SOI correlations with rainfall in SE Qld were as high as at any other time in the observational record and seasonal forecasting models such as the SOI phase system (Stone et al., 1996) performed well. Power et al. (1999) provide time series of correlations between rainfall and the SOI, with the correlations being much stronger when the IPO was negative. However, their analysis does not include the correlations after 1980 and so it is difficult to compare the results with those above. The time series of the SOI and SE Qld rainfall (Fig. 7) indicate that the relationship persisted even though the IPO was positive.

To address the brevity of the observational record, the results of the CSIRO Mark 2 coupled ocean-atmosphere model (described in section 2) have been studied. The model provides an independent source of pseudo-data for which the relationships can be studied. While the model has a relatively coarse resolution, it also simulates multi-decadal periods when the correlations between the N3 / N4 indices and SE Qld rainfall are quite high (Fig. 9). Within the 140 years of the simulation shown, corresponding approximately to 1881 to 2020, there are also long periods when the correlations are very weak. Over the entire 140 model years the correlation between the model N4 index and SE Qld rainfall is insignificant (0.02). However, over the period of model years 0180 to 0220 the correlation is very strong (-0.68) and equivalent to that observed from 1946-2000 (see Table 1). A correlation map for this period produced the same broad features as the observations (Fig.3b). It appears from the observational and model results that the strong correlations that we have shown are not robust over time periods longer than about 50 years. While they have held up for the past fifty-odd years, the prospect of the central TPO SSTs being used as predictors for Australian rainfall into the future must be treated with caution.

6. Conclusions

As one of the major agricultural regions of Australia and with high interannual rainfall variability, southeastern Queensland (northeastern Australia) is economically susceptible to the vagaries of climate. Below average rainfall (in the lowest 10% on record) was recorded from 2000-2002, and SE Qld is one of only two Australia regions to have seen decreasing rainfall trends over the observational record. Considerable energy is currently devoted to climate forecasts and coupling them with operational decision-making models for the region's primary producers. The need for better understanding of climate variability and changes in the predictors used in seasonal forecasting models is therefore of much interest.

The objectives of this study were to carry out a systemic study of rainfall variability in SE Qld and to investigate variations in climate indices that correlate with SE Qld rainfall. The links between Australia-wide and SE Qld rainfall with conditions over the tropical Pacific Ocean have been investigated. The impact of the ENSO phenomenon has been well documented, but SE Qld experienced dry conditions for several years before the appearance of the 2002-3 El Nino event. This suggests that SE Qld rainfall may be affected by factors other than ENSO, such as the latitude of the subtropical ridge, even on interannual and longer time scales. In addition, previous studies have shown that the impact of ENSO on Australian rainfall has weakened considerably for extended periods. The mean rainfall of Australia is known to have changed around 1945-46.

Using monthly observations of the sea surface temperature from the GISST data set and gridded rainfall observations from the Australian Bureau of Meteorology, we have investigated links between SSTs and Australian rainfall on time scales greater than interannual. Two mean SST indices that are commonly referred to, the Nino-3 (mean tropical eastern Pacific SSTs) and Nino-4 (central tropical Pacific) indices, have been used, along with the Southern Oscillation Index. Averaging all data with a five-year running mean, correlation maps between these indices and Australian rainfall were examined. These correlations have also been examined for the periods before (1891-1945) and after (1946-2000) the time of a shift in Australian mean rainfall. The large-scale patterns of variability of SSTs in the Pacific and Indian Ocean have also been correlated with rainfall as these are used in some seasonal forecasting schemes. Emphasis has been placed on the results relevant to the SE Qld region.

The major findings of this study relevant to its objectives are as follows:

1. The strongest correlations across the entire observational record with Qld rainfall on timescales greater than interannual were with central tropical Pacific SSTs (N4 index). SE and coastal northeast Qld showed the strongest correlations in Australia. Rainfall-SOI correlations were of similar strength except in SE Qld.

2. Before 1946 the rainfall-SOI correlations were weak in all eastern regions except Victoria. Tropical Pacific SSTs were better correlated with rainfall in most eastern regions except SE Qld in this period.

3. For the 1946-2000 period the rainfall-SOI correlations were much stronger in coastal Qld, particularly the southeast. Central tropical Pacific SST correlations were very similar, while eastern Pacific SSTs correlations with rainfall were generally weaker. The correlations remained strong from 1980-2000 when the Interdecadal Pacific Oscillation was positive, which has coincided with weakened correlations in the past (1930-45).

4. The second modes of five-year running-mean of Pacific and Indian Ocean detrended SSTs were independent of ENSO, but that of the Pacific showed greatest activity in the Nino-4 region.

5. The correlations of these modes of variability with SE Qld rainfall are minimal. This suggests that the Indian Ocean SSTs have limited impact. The Pacific mode lacks much of the variability due to ENSO, and the high N4 correlations with rainfall come about as this index includes the variability of the first and second modes of Pacific SST variability.

6. Interdecadal rainfall variability in SE Qld is high, with alternating decades of wet and dry periods. Dry periods are less extreme but more prolonged, and most of the last 40 years of the twentieth century were drier than average.

7. SE Qld rainfall and tropical Pacific SST variability were weak from 1915-45. The negative correlation of rainfall with SSTs was weaker or reversed throughout this period, as was that with the SOI.

8. SE Qld is the region of eastern Australia that has experienced the largest change in the relationship between rainfall and the SOI.

On interannual to decadal timescales, the variability of SOI and SSTs in the central tropical Pacific has had the largest influence on SE Qld rainfall since 1946. However, before then this influence, particularly of the SOI, was significantly weaker, while it was relatively unchanged in the southeastern states of Australia. We have shown that the disappearance of the correlations between these climate indices and SE Qld rainfall are also reproduced by a climate model simulation. Both the SOI and SSTs are used as predictors in operational seasonal forecasts of

Australian rainfall. Thus, while these forecasts are not based on correlations analysis as used in this study, this fact may have important implications for forecasting in the future. If the relationships between the indices and rainfall break down again, which our results suggest is probable, then these forecasting models may be affected. Much work is therefore being undertaken to improve climate forecasting tools, and the application of physically-based mechanisms rather than statistical relationships may lead to more robust future seasonal predictions.

Acknowledgments

This paper has been much improved by helpful comments and discussions with Roger Stone of the Queensland Centre for Climate applications and from comments by the two anonymous reviewers who critiqued the original submission. We would like to thank Mark Collier and Wenju Cai of CSIRO Atmospheric Research for providing the CSIRO climate model data, and Peter deVoil of Queensland DPI for the rainfall data. GISST data were provided by the British Atmospheric Data Centre. The graphics for this paper were created using the Ferret program (a product of NOAA's Pacific Marine Environmental Laboratory, www.ferret.noaa.gov). This work was supported by a University of Southern Queensland Team Project Research Program award.

7. References

Allan R, Hunt B. 1999. Climate change modelling for the southern region of Western Australia. CSIRO Atmospheric Research, Aspendale, Victoria, Australia: 64pp.

Cai W, Whetton PH. 2000. Evidence for a time-varying pattern of greenhouse warming in the Pacific Ocean. Geophysical Research Letters. 27: 2577-2580.

Cai W, Whetton PH, Pittock AB. 2001. Fluctuations in the relationship between ENSO and northeast Australian rainfall. Climate Dynamics. 17: 421-432.

Cordery I, Opoku-Ankomah Y. 1994. Temporal variation of relations between tropical sea-surface temperatures and New South Wales rainfall. Australian Meteorological Magazine. 43: 73-80.

Drosdowsky W. 1993. Potential predictability of winter rainfall over southern and eastern Australia using Indian Ocean sea-surface temperature anomalies. Australian Meteorological Magazine. 42: 1-6.

Drosdowsky W. 2002. SST phases and Australian rainfall. Australian Meteorological Magazine. 51: 1-12.

Drosdowsky W, Chambers LE. 2001. Near-global sea surface temperature anomalies as predictors of Australian seasonal rainfall. Journal of Climate. 14: 1677-1687.

Gordon HB, O'Farrell SP. 1997. Transient change in the CSIRO Coupled Model with dynamic sea ice. Monthly Weather Review. 12: 875-907.

Hammer GL, Nicholls, N, Mitchell, C. 2000. Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems. Kluwer Academic Publishers, Netherlands: 469pp.

Hennessy KJ, Suppiah R, Page CM. 1999. Australian rainfall changes, 1910-1995. Australian Meteorological Magazine. 48: 1.

Hirst AC, O'Farrell SP, Gordon HB. 1998. Comparison of a coupled ocean-atmosphere model with and without oceanic eddy-induced advection. Part I: ocean spin-up and control integrations. Journal of Climate. 13: 139-163.

Hirst AC. 1999. The Southern Ocean response to global warming in the CSIRO coupled ocean-atmosphere model. Environmental Modelling and Software. 14: 227-241.

IPCC. 1994. Radiative forcing of climate change and an evaluation of the IPCC IS92 emissions scenarios. Houghton JT, Meira Filho LG, Bruce J, Hoesung Lee, Callander BA, Haites E, Harris N, Maskell K (Eds). Cambridge University Press, UK: 339pp.

Jones DA, Weymouth G. 1997. An Australian monthly rainfall data set. Technical Report 70, Commonwealth Bureau of Meteorology, Melbourne, Australia: 19pp.

Lough JM. 1991. Rainfall variations in Queensland Australia: 1891--1986. International Journal of Climatology. 11: 745-768.

Lough JM. 1992. Variations in sea-surface temperatures off north-eastern Australia and associations with rainfall in Queensland: 1956-1987. International Journal of Climatology. 12: 765--782.

Lough JM. 1997. Regional indices of climate variation: temperature and rainfall in Queensland Australian. International Journal of Climatology. 17: 55-66.

McBride JL, Nicholls N. 1983. Seasonal relationships between Australian rainfall and the Southern Oscillation. Monthly Weather Review. 111: 1998-2004.

Manins P, Allan, R, Beer, T, Fraser, P, Holper, P, Suppiah, R, Walsh, K. 2001. Atmosphere, Australia State of the Environment Report 2001 (Theme Report), CSIRO Publishing on behalf of the Department of the environment and Heritage, Canberra, Australia: 145pp.

Meinke H, Stone, RC, Hammer, GL. 1996. Using SOI phases to forecast climatic risk to peanut production: a case study for northern Australia. International Journal of Climatology. 16: 783-789.

Nicholls N. 1988. El Nino-Southern Oscillation and rainfall variability. Journal of Climate. 1: 418-421.

Nicholls N. 1989. Sea surface temperatures and Australian winter rainfall. Journal of Climate. 2: 965-973.

Nicholls N. 2003. The changing nature of Australian droughts. Climate Change. (accepted).

Pittock AB. 1975. Climatic change and the patterns of variation in Australian rainfall. Search. 6: 498-505.

Power S, Casey T, Folland C, Colman A, Mehta V. 1999. Inter-decadal modulation of the impact of ENSO on Australia. Climate Dynamics. 15: 319-324.

Quayle ET. 1929. Long rand rainfall forecasting from tropical (Darwin) air pressures. Proceedings of the Royal Society of Victoria. 41: 160-164.

Rayner NA, Horton, EB, Parker, DE, Folland, CK, Hackett, R B. 1996. Version 2.2 of the Global sea-Ice and Sea Surface Temperature data set: 1903-1994. Climate Research Technical Note CRTN74, Hadley Centre, Meteorological Office, Bracknell, UK.

Simmonds I. 1990. A modelling study of winter circulation and precipitation anomalies associated with Australian region ocean temperatures. Australian Meteorological Magazine. 38: 151-161.

Simmonds I, Hope P. 1997. Persistence characteristics of Australian rainfall anomalies. International Journal of Climatology.. 17: 597-613.

Stone RC, Auliciems A. 1992. SOI phase relationships with rainfall in eastern Australia. International Journal of Climatology. 12: 625-636.

Stone RC, Hammer GL, Marcussen T. 1996. Prediction of global rainfall probabilities using phases of the Southern Oscillation Index. Nature. 384: 252-255.

Whetton PH. 1990. Relationships between monthly anomalies of Australian region sea-surface temperatures and Victorian rainfall. Australian Meteorological Magazine. 38: 31-41.

Figure Captions

Figure 1: Coefficient of correlation between monthly means of Australian rainfall and (a) the Nino-3 Index, (b) the Nino-4 index and (c) the Southern Oscillation Index for the period 1891-2000. All data have been smoothed with a 5-year running mean. Contour interval is 0.2, negative contours are dashed, and shading is for magnitudes 0.5-0.9 by 0.1.

Figure 2: Same as Figure 1 but for the period 1891-1945.

Figure 3: Same as Figure 1 but for the period 1946-2000.

Figure 4: Second mode of variability of detrended SSTs over the (a) Pacific and (b) Indian Oceans form 1890-2000.

Figure 5: Coefficient of correlation between annual means of Australian rainfall and the second mode of annual mean Pacific Ocean SST variability of the periods (a) 1891-2000, (b) 1891-1945,

and (c) 1946-2000. All data have been smoothed with a 5-year running mean. Contour interval is 0.2, negative contours are dashed, and shading is for magnitudes 0.5-0.9 by 0.1.

Figure 6: Same as Figure 5, but for the second mode of annual mean Indian Ocean SST variability.

Figure 7: 5-year running means of monthly anomalies of southeast Queensland rainfall (heavy shading) (in mm day^{-1}), the Nino-4 (solid line) and Nino-3 (light shading) indices (in ^{o}C), and the SOI (dash-dotted) (in hPa) from Bureau of Meteorology gridded rainfall and GISST.

Figure 8: 5-year running means of annual anomalies of southeast Queensland rainfall (heavy shading (in mm day^{-1}), and the expansion coefficients of the second modes of variability of the Pacific (solid line) and Indian (light shading) Ocean SSTs. All time series have been normalised.

Figure 9: Same as Figure 7, except for data simulated by the CSIRO Mark 2 coupled atmosphere /ocean model (SOI not plotted).