Rainfall declines over Queensland from 1951-2007 and links to the Subtropical Ridge and the SAM

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Rainfall declines over Queensland from 1951-2007 and links to the Subtropical Ridge and the SAM

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Abstract. Much of southern and eastern Australia including Queensland have experienced rainfall declines over recent decades affecting agricultural production and accelerating water infrastructure development. Rainfall declines from southern Australia have now been directly related to changes in the Southern Annular Mode (SAM) and the subtropical ridge. In southern and coastal Queensland, the rainfall declines have occurred mostly in the austral summer and autumn. Observations from this region reveal the rainfall decline is correlated to an increase in the mean sea level pressure (MSLP) at many stations. The largest increases in MSLP are over southeast Queensland and coastal regions, where some of the largest rainfall declines occur. This study indicates the subtropical ridge as one of the main factors in the rainfall decline over this region. SAM is also likely to be important, although its seasonal influence, apart from winter, is harder to determine.

1. Introduction

Rainfall declines over much of Queensland began in ~1951 and although there have been about four La Niña events since 1996, the rainfall declines have now intensified and cover most of the state [1,2]. Rainfall has decreased over coastal as well as inland regions of Queensland and also during the La Niña events, although useful rains have occurred over the last three years or so in some areas. Negative decadal trends in annual rainfall (up to 200 mm decade^{-1}) have occurred along the Queensland coast and over half of Queensland is now affected by decreasing rainfall of 20 mm decade^{-1} or greater (figure 1). If the rainfall trends from 1951–2007 are compared to the climatological mean (1961–1990), over half of inland Queensland, as well as coastal areas have had a significant rainfall decline of 20% or higher, with some areas, such as north of Mackay, a 50% or higher decrease in rainfall (figure 2).

Although the El Niño-Southern Oscillation (ENSO) and tropical sea surface temperatures are important factors on the year to year rainfall variability in Queensland [3-5], other factors on decadal time scales must be underpinning the long-term rainfall decline. Over southern Australia, some of the long-term rainfall declines have been attributed to increases in the mean sea level pressure (MSLP) and to changes in the Southern Annular Mode (SAM), and are less likely related to changes in ENSO or the Indian Ocean Dipole (IOD)[6,7]. However, it has been argued that the key driver of major droughts over Victoria is the IOD [8]. These studies and others, indicate the causes of the rainfall declines (and associated droughts) in Australia are likely to be complex and vary between regions.

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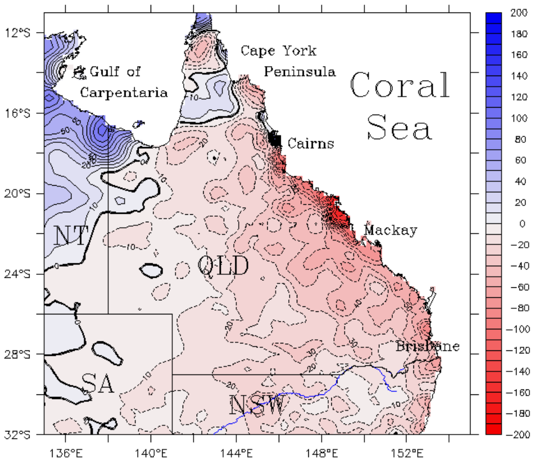

Figure 1. Decadal trends in annual rainfall (mm decade $^{-1}$) over Queensland from 1951–2007. Gridded data (0.25° by 0.25°) from the Australian Bureau of Meteorology.

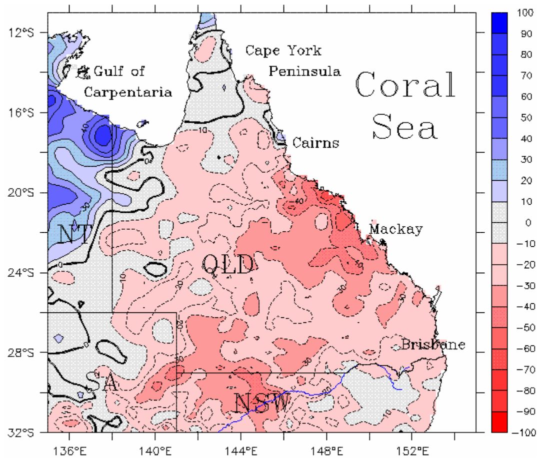

Figure 2. Decadal trends in annual rainfall over Queensland (1951–2007) as a percentage of the annual mean (1961–1990).

2. Data and Method

Monthly rainfall and MSLP data were obtained from the Australian Bureau of Meteorology (BoM) from 25 stations from across the Queensland and adjacent regions including Lord Howe and Norfolk Islands. Although several stations have reliable records starting in the 1880s and 1890s, no significant rainfall or MSLP changes occur prior to ~1950, and so the focus of this study is on the period from 1951–2007. Stations were selected based on the continuity of rainfall and MSLP data and the location to provide statewide coverage. The monthly MSLP data consist of 9am and 3pm readings and both have been averaged to calculate the mean MSLP value over the time series at each station. Linear regression analysis is used to calculate the change in MSLP from the start to the end of each time series for seasonal and annual values. The decadal trend in seasonal and annual MSLP is calculated from the mean MSLP change. All time series of the MSLP exhibit considerable year to year variability and shows an increase from the start to the end of each time series.

A correlation analysis between the seasonal and annual rainfall and MSLP across the Queensland region was completed to investigate the relationship between lower rainfall and higher surface pressure. Since many of the time series start in a different year, the level of significance (using the 5% level) varies slightly for each and these values are shown in the corresponding tables (tables 1 and 2). Only results from ten stations are shown in the tables to provide broad spatial coverage.

A correlation analysis between the MSLP from Queensland and the SAM from 1957–2007 using data from the Southern Hemisphere Annular Mode Index located at http://www.antarctica.ac.uk/met/gjma/sam.html (and links therein) is completed to indicate any relationships to the SAM, such as over southern Australia. This SAM dataset was selected as it has been corrected by a number of observational based stations around the South Polar Region and the mid-latitudes [9].

A correlation analysis between an ensemble mean of the annual MSLP from fourteen stations (identified by having an annual correlation value above the 5% level to the SAM) from the Queensland region and Norfolk Island for the period 1957–2007 highlights MSLP changes and the links to the subtropical ridge. Norfolk Island is located in the north Tasman Sea, east of southern Queensland and changes in the MSLP in the austral spring, summer and autumn should be unaffected by the Australian land mass and continental heating. The correlation between the annual MSLP from fourteen stations in an ensemble mean and the SAM index is provided to show the overall teleconnections between the two regions.

3. Changes in the MSLP across the Queensland Region

Contoured plots of the decadal trend in seasonal and annual MSLP from the Queensland region are shown in figure 3. In DJF, the increase in MSLP is highest over southeast Queensland (SE QLD)(> 0.3 hPa decade^{-1}) and the north Tasman Sea, with the largest values at Toowoomba, Norfolk Island, Lord Howe Island, Burketown and Longreach. A small decrease in MSLP occurs over far southwestern Queensland around Thargomindah. In MAM, all of Queensland is covered by an increase in MSLP, the highest values (>0.5 hPa decade^{-1}) over SE QLD at Toowoomba and at Norfolk and Lord Howe Islands. The coastal regions south of Rockhampton and parts of the Cape York Peninsula also show moderate increases in MSLP (>0.3 hPa decade^{-1}). In JJA, the increase in MSLP is slightly stronger over Queensland than in MAM, with a larger region covered by an increase in MSLP of 0.3 hPa decade^{-1} or higher. The largest increase (>0.5 hPa decade^{-1}) occurs at Toowoomba and Norfolk and Lord Howe Islands. In SON, the increase in MSLP is lower over most of Queensland compared to other seasons, with the largest increases (>0.3 hPa decade^{-1}) over SE QLD at Toowoomba and the Tasman Sea (Norfolk and Lord Howe Islands). A small decrease in MSLP occurs over southwest Queensland and the Mount Isa region. The strongest increases in seasonal MSLP occur in MAM and JJA. The decadal trend in the annual MSLP shows nearly the entire region is covered by small to moderate increase (>0.2 hPa decade^{-1}) in MSLP, strongest over SE QLD and the north Tasman Sea (southeast of Brisbane and south of the Coral Sea).

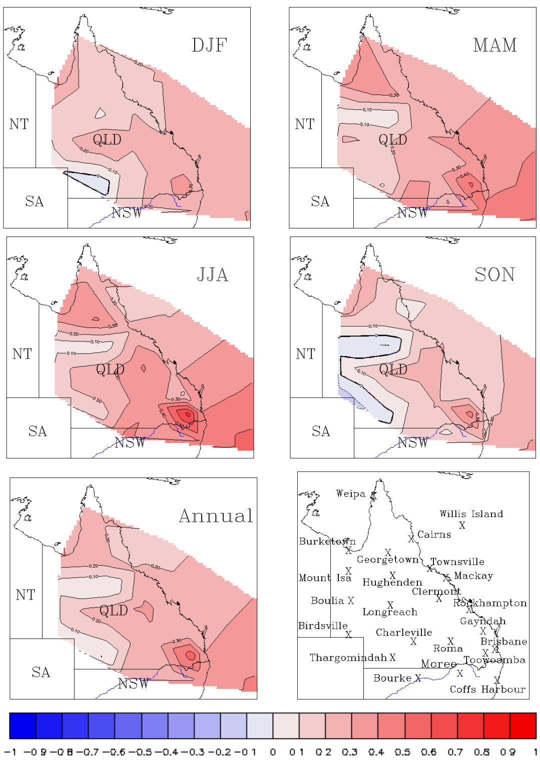

Figure 3. Contoured seasonal and annual decadal MSLP trends (hPa decade^{-1}) from BoM observations over the Queensland region (1951–2007) in DJF, MAM, JJA, SON and annual periods. Regions shaded in red show increasing MSLP and blue decreasing MSLP. Bold contour line is zero MSLP change. Station locations - lower right plot.

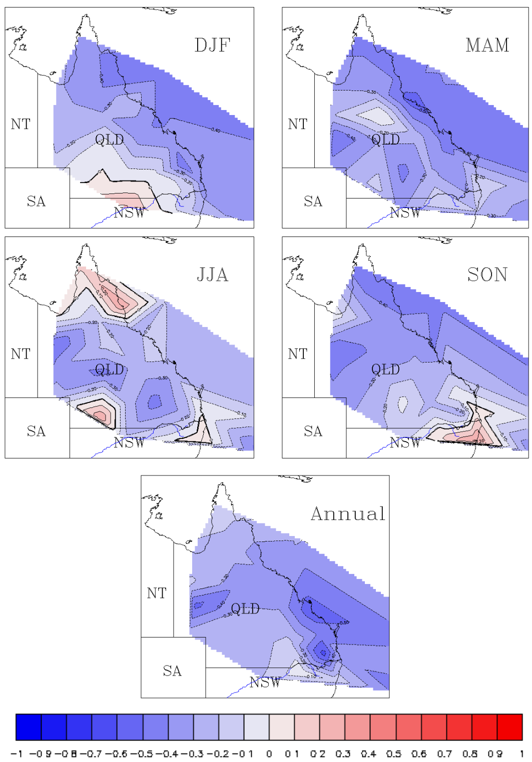

Figure 4. Contoured seasonal and annual correlation between rainfall and MSLP from BoM observations over the Queensland region (1951–2007) in DJF, MAM, JJA, SON and annual periods. Regions shaded in red show positive correlation and blue negative correlation. Bold contour line is zero correlation.

4. Correlation between MSLP and Rainfall

A summary of the correlation values between rainfall and MSLP over the Queensland region from ten selected stations are shown in table 1. In DJF, the locations with the highest negative correlation are Gayndah (-0.50), Cairns (-0.49), Willis Island (-0.49) and Mackay (-0.43). Eleven out of 25 stations have correlation values which are statistically significant above the 5% level of significance. In MAM, the highest negative correlation values occur at Townsville (-0.54), Norfolk Island (-0.50), Boulia (-0.50) and Mackay (-0.49). Sixteen stations have correlations which are statistically significant (above the 5% level) and this is the largest number of stations for all seasons. In JJA, four stations have negative correlations between -0.4 and -0.6 including Lord Howe Island (-0.51), Mount Isa (-0.51), Roma (-0.45) and Longreach (-0.43). Eight stations have correlation values above the 5% level. In SON, the highest negative correlations occur at Weipa (-0.50), Lord Howe Island (-0.46), Willis Island (-0.43) and Boulia (-0.43). Thirteen out of 25 stations have correlation values above the 5% level of significance. The annual correlation is highest (negative) at Toowoomba (r=-0.65) and r^2 indicates ~42% of the rainfall decrease can be explained by an increase in MSLP. Other large annual negative correlations are at Rockhampton (-0.56), Boulia (-0.54) and Lord Howe Island (-0.45). Twelve out of the 25 stations have correlation values which are statistically significant above the 5% level.

Regionally (figure 4), in DJF, the highest negative correlation values (>-0.3) are located over eastern, central and northern coastal Queensland. A small region over the southwest border of Queensland with New South Wales (NSW) shows a small positive correlation (>0.1). In MAM, the negative correlation covers the entire Queensland region, with the highest values (>-0.3) along the east coast regions and southern and western Queensland. In JJA, the negative correlation covers most of Queensland and is highest in western and south-central Queensland, except for a small positive correlation over southwest parts and the Cape York Peninsula. In SON, the negative correlation covers nearly the entire Queensland region, highest over northern Queensland. A small positive correlation occurs in northeast NSW. The highest correlations occur in MAM, followed by SON and DJF. The annual correlation shows the entire Queensland region is covered by negative values, with the largest values (>-0.4) over western, central and coastal SE QLD. We have shown there is a significant relationship between the increasing MSLP and lower rainfall over Queensland in all seasons, generally strongest in coastal areas and SE QLD.

Table 1. Seasonal and annual correlation between the MSLP and rainfall from a selection of ten stations across the Queensland region and the north Tasman Sea.

Location	Level of Significance at 5%	Seasonal Correlation				Annual Correlation
		DJF	MAM	JJA	SON	
1. Toowoomba	0.35	-0.12	-0.36	-0.24	-0.24	-0.65
2. Brisbane Aero	0.27	-0.35	-0.13	0.01	0.06	-0.36
3. Norfolk Island	0.27	-0.35	-0.50	-0.33	-0.42	-0.32
4. Lord Howe Island	0.27	-0.38	-0.44	-0.51	-0.46	-0.45
5. Burketown	0.33	-0.28	-0.32	0.04	-0.01	-0.24
6. Longreach	0.33	-0.07	-0.29	-0.43	-0.29	-0.29
7. Rockhampton	0.27	-0.36	-0.45	-0.27	-0.22	-0.56
8. Mackay PO	0.29	-0.43	-0.49	-0.13	-0.41	-0.41
9. Townsville	0.27	-0.23	-0.54	-0.25	-0.36	-0.31
10. Cairns	0.27	-0.49	-0.42	0.29	-0.43	-0.31

5. Correlation between MSLP and the SAM

A summary of the correlation values between MSLP and the SAM index from ten selected stations over the Queensland region are shown in table 2. In DJF, only three stations, Townville (0.32), Cairns (0.29) and Gayndah PO (0.29) have significant correlation values above the statistically significant level of 5%. In MAM, no stations have correlations statistically significant at the 5% level of significance. In JJA, nineteen stations have correlation values greater than the statistically significant level of 5%, with Coffs Harbour (0.46), Lord Howe Island and Burketown (0.44), Bourke (0.43) and Toowoomba (0.41) above 0.40. This indicates nineteen stations show an increase in the MSLP that may be related to the decrease in MSLP in the South Polar Region, with higher MSLP in the mid–latitudes. In SON, only one station (Coffs Harbour) has a correlation value above the statistically significant level of 5%. The annual correlation between the MSLP and the SAM index shows fourteen stations have correlation values greater than the statistically significant level of 5%, with the highest values at Bourke, Coffs Harbour and Lord Howe Island (0.46). Thus the signal from the SAM is strong enough to be significant in the annual correlation, even though only the austral winter season has a significant correlation at a number of stations.

Table 2. Seasonal and annual correlation between MSLP and the SAM from a selection of ten stations across the Queensland region and the north Tasman Sea.

Location	Level of Significance at 5% Level	Seasonal Correlation				Annual Correlation
		DJF	MAM	JJA	SON	
1. Toowoomba	0.35	0.21	0.07	0.41	0.08	0.43
2. Brisbane Aero	0.27	0.26	0.12	0.39	0.20	0.43
3. Norfolk Island	0.27	0.24	0.18	0.39	0.09	0.44
4. Lord Howe Island	0.27	0.19	0.18	0.44	0.14	0.46
5. Burketown	0.33	0.29	0.08	0.44	-0.08	0.26
6. Longreach	0.33	0.28	0.03	0.28	0.04	0.32
7. Rockhampton	0.27	0.21	0.03	0.34	0.15	0.40
8. Mackay PO	0.29	0.22	-0.02	0.32	0.04	0.34
9. Townsville	0.27	0.32	-0.03	0.37	0.03	0.34
10. Cairns	0.27	0.29	-0.10	0.33	0.07	0.25

6. Relationship of MSLP to the Subtropical Ridge and the SAM

A time series of the annual MSLP at Norfolk Island and an ensemble mean using fourteen stations from the Queensland region is shown in figure 5. This shows there has been an increase in MSLP by ~2 hPa in both regions, with a strong correlation of 0.89 (r^2 =79%). The correlations from the ensemble mean for the austral summer is 0.78, autumn (0.67), winter (0.88) and spring (0.80) and indicates all seasons are well correlated to the changes in the MSLP at Norfolk Island. Seasonal global MSLP data shows the strongest MSLP changes are in the Tasman Sea [1] and this indicates the subtropical ridge is the most likely cause of the increase in MSLP over the Queensland region.

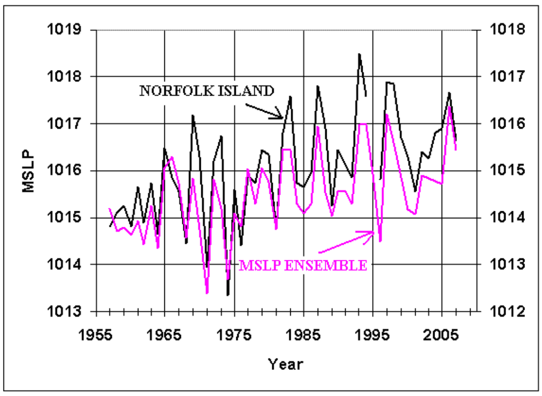

Figure 5. Time series of the annual MSLP at Norfolk Island (black) and ensemble mean (purple) from the Queensland region for 1957–2007. Correlation = 0.89.

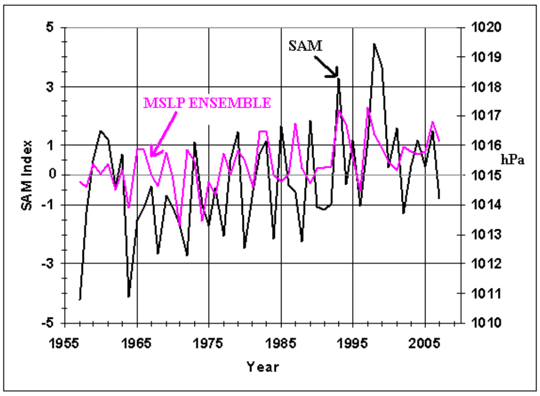

Figure 6. Time series of the annual SAM mode index (black) and the annual MSLP ensemble (purple) over the Queensland region for 1957-2007. Correlation = 0.44.

A time series of the annual SAM index and an ensemble mean of annual MSLP are shown in figure 6. The SAM index shows considerable variability from year to year and varies between ~2–4 hPa. A long–term increase in the MSLP in the SAM index from negative to positive values is evident. The MSLP ensemble from the Queensland region has a lower year to year variability (~1–2 hPa) but has many peaks and troughs in phase with the SAM index. The MSLP ensemble also shows an increase in the MSLP over the 50 year period from 1015 hPa to 1016 hPa. Similar peaks between the SAM index and the MSLP ensemble occurred in 1963, 1965/66, 1969, 1982/1983, 1993 and 2006 and troughs in 1962, 1964, 1968 and 1996 respectively. Several other periods (1971/72, 1980/81 and 1997/98) show the MSLP ensemble from the Queensland region leads or lags the SAM index peak or trough by one year. From 1984 to 1990, the changes in the SAM index and the MSLP ensemble are distinctly opposite to one another, for reasons which remain unclear. The correlation between the SAM index and the ensemble mean for the entire period (1957–2007) is 0.44, indicating ~19% of the variance in the MSLP can be explained at these stations by changes in the annual SAM index.

7. Conclusions

Although ENSO plays an important role in year to year rainfall variability over the Queensland region, it is unlikely to be playing a major role in the rainfall declines. This study shows the subtropical ridge and to a lesser degree the SAM are important factors in the rainfall declines over southern Queensland, well north of previous studies from southern Australia [7] and New Zealand [10]. Increases in MSLP are significant across much of the Queensland region, especially SE QLD and the coastal regions, with the largest increases in austral autumn and winter, indicating the subtropical ridge is driving some of the MSLP changes over the region. The strongest impacts from the SAM on MSLP were shown to be in the austral winter and for the annual period, with lower impacts in the other seasons. Although we have not investigated direct links to the descending region of the Hadley circulation over the Australian region, changes during this time may have enhanced the drying trend through increased subsidence in association with the subtropical ridge [12]. We have demonstrated changes in the MSLP have directly altered rainfall in the Queensland region, however further studies are required to identify the significant synoptic features which have led to the rainfall decline over the Queensland region, which are clearly different from those in southern regions of Australia.

In this paper, we have shown the rainfall declines have been accompanied by an increase in the mean sea level pressure (MSLP) over the region. The increases in the MSLP are directly linked to changes in the behaviour of the subtropical ridge in the southeast Australian region and at least partially due to the positive polarity of the SAM. Since the changes in the SAM are directly related to ozone depletion and rising greenhouse gases [6,11], the changes in rainfall over much of Queensland are could be at least partly anthropogenic in origin and may represent climate change that has developed and persisted in rainfall trends for now over half a century.

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