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Local and remote causes of the southern Australian autumn-winter rainfall decline, 1958–2007

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Abstract The 1958–2007 decline in March–August rainfall over southern Australia (south of 30°S) is very closely related to an increase in surface atmospheric pressure over Australia. Sea surface temperatures around northern Australia are strongly correlated with southern Australian rainfall but the recent warming of the ocean should have led to increased rainfall rather than the observed rainfall decline. The relationships between the rainfall and indices of several modes of the atmosphere/ocean system are investigated to determine a cause of the rainfall decline. Indices of the modes that only use data remote from the Australian region are used to avoid the possibility that a relationship between the mode and Australian rainfall is simply reflecting the behaviour of "local" portions of the index. Thus a climate mode index that incorporates Australian pressure would, of course, be related to southern Australian rainfall, even if the remote parts of the mode were unrelated to Australian rainfall. Unless the remote contributions to the mode index were also related to Australian rainfall it seems physically unrealistic to consider that the mode, per se, was affecting Australian rainfall (rather than simply reflecting the influence of the local pressure changes). The rainfall decline does not appear to be explainable by a change in the behaviour of the El Niño-Southern Oscillation (remote indices of this phenomenon do not exhibit a trend over this period) or the Indian Ocean Dipole (which is not strongly correlated with Australian rainfall on detrended data). The strong 1958–2007 trend in the southern annular mode (SAM) appears able to explain much of the rainfall decline since its year-to-year variations are correlated with year-to-year variations in southern Australian rainfall, and the sense of the correlation and the SAM trend would lead to a decline in rainfall (and an increase in pressure over Australia). The observed trend in SAM can reproduce over 70% of the observed rainfall trend. All these conclusions also apply to the rainfall declines in the southeast and southwest sub-regions.

Keywords Australia · Climate change · Rainfall · El Niño

1 Introduction

Rainfall during the March–August period (the cooler part of the year) over southern Australia (defined here as the land areas of Australia located south of 30°S) has declined about 15% over the last 50 years (Fig. 1; also see http://www.bom.gov.au/silo/products/cli_chg/). The correlation between the rainfall time series and the year, which provides a guide to the strength of the trend, is −0.26 over the past 50 years. Although several studies have examined rainfall trends across Australia, and have reported associations between rainfall and various atmospheric circulation indices (e.g., Nicholls and Lavery 1992; Nicholls et al. 1997; Ashok et al. 2003; Smith 2004; Cai and Cowan 2006; England et al. 2006; Gallant et al. 2007; Hendon et al. 2007; Williams and Stone 2008; Taschetto and England 2008; Murphy and Timbal 2008; Shi et al. 2008; Evans et al. 2008), the underlying cause of the southern Australian rainfall decline has not been clearly established. This partly reflects that observed rainfall trends are seasonally, temporally, and spatially variable across this region. For example, the rainfall decline in southwestern

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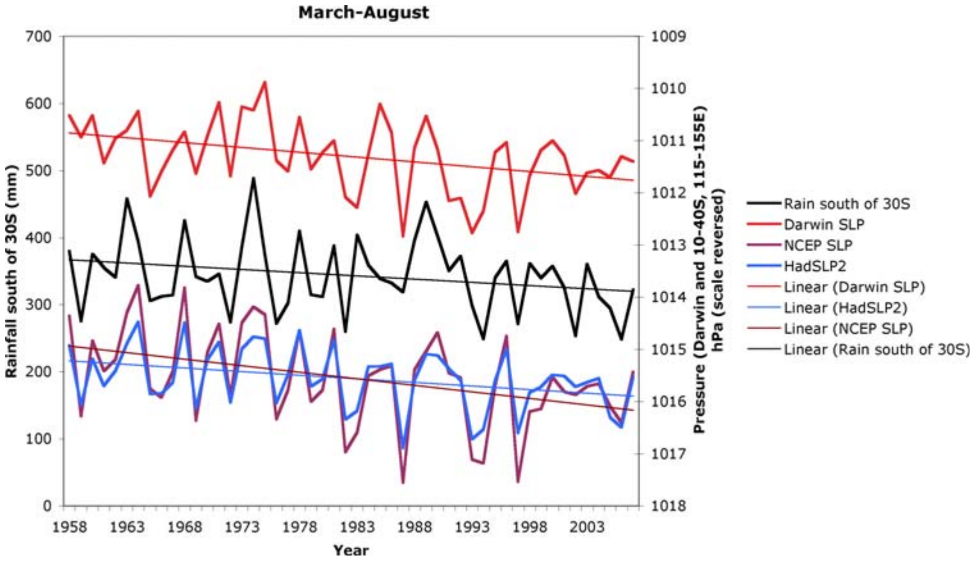

Fig. 1 Timeseries (1958–2007) of March–August rainfall south of 30°S, and mean sea level pressure averaged over the region 10–40°S, 115–155°E, from the HadSLP2 and NCEP datasets. The timeseries of Darwin mean sea level pressure for March–August is also shown. Linear trends are shown for all variables (thin lines). Note pressure scale (right-hand axis) is reversed

Australia appears to have commenced a decade or more prior to the southeast Australian decline. These spatial and temporal variations in the trends means that most studies have focussed on sub-regions of southern Australia (e.g., Ummenhofer et al. 2008; Evans et al. 2008), but even for these smaller regions there are competing theories regarding the underlying causes of the rainfall declines (Nicholls 2006). However, rainfall across nearly all the region has declined over the past 50 years, so it may be useful to investigate whether a single underlying cause is contributing to this decline across all longitudes, rather than focussing initially on the smaller sub-regions.

One phenomenon that might well cause a rainfall trend over such a large region would be a widening of the tropical belt (cf., Seidel et al. 2008) perhaps associated with a polewards shift in the subtropical ridge (cf., Larsen 2008; Williams and Stone 2008) or the subtropical jet (cf., Archer and Caldeira 2008). If such a shift was taking place, one might well expect a consistent trend in rainfall across all southern Australian longitudes. Similarly, a trend in the strength of the southern annular mode (SAM), a zonally oriented, annular mode of variability known to be associated with southern Australian rainfall variations (Hendon et al. 2007; Meneghini et al. 2007), might also lead to a consistent trend in this region. Because of the known role of the El Niño-Southern Oscillation (ENSO) in influencing rainfall in the same sense across most of Australia (i.e., El Niño events are generally associated with decreased rainfall, although the strength of the relationship varies spatially, e.g. McBride and Nicholls 1983) a trend in the El Niño-Southern Oscillation could also lead to a trend in rainfall across southern Australian longitudes. There is evidence of a recent trend in some indices of the El Niño-Southern Oscillation, although the strength of the trend varies seasonally and between the various indices of the phenomenon (Nicholls 2008). Changes in the Indian Ocean Dipole (IOD) might also play a role in the observed rainfall decline, since variations in the IOD appear to be related to winter rainfall variations over much of southern Australia (Ashok et al. 2003). Finally, sea surface temperatures around northern Australia are also related to Australian rainfall variations (e.g., Nicholls 1989) so trends in these temperatures might be causing rainfall trends.

For the above reasons, this study commences with an examination of the spatially averaged rainfall across the southern Australian region, to determine if the decline in this spatial average rainfall can be explained by trends in one or more modes or indices of climate variability. If a trend in one or more climate mode indices can account for the average rainfall decline across the region, this may simplify the determination of the ultimate, underlying cause of this decline. Then further work may identify the causes of the spatial and temporal variations in the rainfall decline across the region.

2 Materials and methods

The monthly rainfall in each year 1958–2007, averaged across Australian land areas south of 30°S was calculated from the DIAGNOSE software (Jones et al. 2004) using gridded rainfall data prepared by the Australian Bureau of Meteorology. Surface atmospheric pressures across the Australian region were related to southern Australian rainfall. The pressures used were from Darwin (obtained from ftp://ftp.bom.gov.au/anon/home/ncc/www/sco/soi/

darwinmslp.html), and the Hadley Centre gridded sea level pressure analysis (HadSLP2; Allen and Ansell 2006), and the NCEP/NCAR reanalysis (Kistler et al. 2001). The gridded pressure data and reanalysis data were obtained from the Climate Explorer web site (http://climexp.knmi.nl/; Oldenborgh and Burgers 2005). Monthly values of the NINO3 index, and sea surface temperatures for calculating an index of the Indian Ocean Dipole (IOD) and an index of sea surface temperatures around northern Australia (NAsst) were also obtained via Climate Explorer. The HadSLP2 pressures were also used to calculate a regional southern annular mode (SAM) index.

This study first establishes that a simple index of atmospheric circulation over Australia (spatially averaged sea level pressure across Australia) can reproduce the interannual variability and trends in the southern Australian rainfall index. Then, having established this "local" explanation of the decline in rainfall, several atmospheric circulation modes are investigated known to affect the Australian region, to determine whether they can be held responsible for the observed trend. The approach employed here to determine whether specific modes of climate variability might explain the observed rainfall trend uses partial correlations and analysis of residuals from linear least squares regression, as well as examination of relationships calculated from detrended data. The underlying philosophy is that a mode of variability could only be considered a possible explanation for the decline if the mode has exhibited a clear trend over the 1958–2007 period, and if variations in the mode are also associated with variations in rainfall over southern Australia. However, strong trends in variables may produce artificial correlations between variables, so for parts of the analysis the data are detrended by taking year-to-year differences prior to correlating the rainfall and climate mode indices. If such detrending removes the correlation between the climate mode and rainfall then it seems unlikely that the trend in the mode could be physically linked to the rainfall decline. Another aspect of the approach adopted here is to use remote indices of the climate modes, rather than examining indices that incorporate climate variables from Australia and its immediate surrounds. This is because (as is demonstrated below) the rainfall decline is very closely associated with local changes in the Australian local atmospheric circulation. So any climate mode index that incorporates local Australian climate data in its index will necessarily be related to the rainfall decline, even if the remote "pole" of the circulation mode is unrelated to Australian climate. If the mode really is to be considered a cause of the rainfall decline then indices of the mode that are located remote from the Australian region should also be related to the Australian rainfall decline, in their own right.

One approach used here is to calculate the partial correlations between rainfall and the "year" of observation, controlling for the influence of the remote index of a specific climate mode (e.g., ENSO). If the partial correlations, after controlling for the variations in the mode, are close to zero this means that much of the rainfall decline is related to trends in the climate mode. If, however, the partial correlation between rainfall and "year" is still clearly negative after controlling for the climate mode, this indicates that the mode is unlikely to be contributing appreciably to the rainfall decline. This analysis is supplemented by plotting time series of the residuals from the linear regressions between the climate mode indices and rainfall, to illustrate whether or not a trend remains in the residuals. A final approach used here is to calculate the linear regression between year-to-year differences (also known as first-order differences) of the variables, and using this regression to estimate the rainfall decline that could be associated with the observed trend in the climate mode. This approach assumes that only if there is a relationship between the climate mode and rainfall on interannual time scales could long-term changes in the mode be a potential explanation of trends in the rainfall. This approach complements the approach of plotting residuals from the regressions calculated on the original data, but removes the possibility that any relationship between the climate mode index and the rainfall is simply due to the trends in the variables rather than reflecting a relationship that works on all climate time scales.

There are several issues regarding the approach taken in this study to separate possible causes of the rainfall decline. For instance, the assumption that year-to-year differences in variables should be related if we want to attribute trends in one variable to another variable ignores the possibility that a physical mechanism might operate only at time scales longer than a year. If this were the case, then the approach adopted here would not identify this causal relationship. It is quiet challenging, however, to postulate a physical climate mechanism that links variables at long time scales but not on the year-to-year time scale. The approach of using year-to-year variations also implicitly assumes the existence of linear relationships and causal links between variables. This is, of course, likely to be too simplistic, although there is no evidence in the following of obvious non-linearities that might confound the analysis.

3 Results

Preliminary work investigating trends in pressure revealed that over all of Australia and its immediate surround, there had been a consistent trend towards higher pressures, over the period 1958–2007. Large-scale spatial averages of pressure were prepared to compare with the observed trend and variations in southern Australian rainfall. Variations in March–August rainfall south of 30°S are closely related to variations in sea level pressure averaged across the Australian continent over the same period (10–40°S, 115–155°E), irrespective of whether the pressures are taken from NCEP or HadSLP2 (Fig. 1). Correlations between the rainfall and the pressures are listed in Table 1.

The trend in rainfall exhibited in Fig. 1 is in the same sense (decline) as would be expected if it was due to the increase in pressures also seen in Fig. 1. In fact, the entire decline in rainfall can be attributed to the increase in pressure seen in the figure. This can be demonstrated by calculating the partial correlation between rainfall and "year", controlling for the relationships of pressure with rainfall and "year". These partial correlations are also listed in Table 1. The partial correlations between rainfall and "year", after controlling for pressure, are close to zero. This indicates that there is essentially no trend in rainfall, except for that related to the trend towards higher pressures across Australia.

Because of possible biases in reanalysis data sets and even in the HadSLP2 pressure gridded data, the above analysis was repeated using Darwin sea level pressure as the explanatory variable. Southern Australia March–August rainfall is also closely associated with Darwin March–August pressure (Fig. 1 and Table 1), and Darwin pressures also exhibit an upward trend over 1958–2007. The partial correlation between rainfall and "year", controlling for Darwin pressure, is close to zero, indicating that the decline in southern Australian March–August rainfall is explainable by the increase in Darwin pressures. This confirms that the attribution of the rainfall decline to the increase in atmospheric pressure, determined from the HadSLP2 and NCEP data, is not reflecting artificial biases in these gridded data sets.

A more visual demonstration that the decline in rainfall reflects the increase in pressure is in Fig. 2, which shows again the time-series of March–August southern Australian rainfall and a linear trend of these data, showing the rainfall decline. The figure also shows residual March–August rainfall from a linear fit of rainfall to March–August

Table 1 Correlations of March–August rainfall south of 30°S with mean sea level pressure averaged over the region 10–40°S, 115–155°E, from the HadSLP2 and NCEP datasets, with Darwin sea level pressure, with NINO3, with indices of the IOD and SAM, and with North Australian sea surface temperatures (0–15°S, 110–150°E, from HadSST1), for March–August

	HadSLP2	NCEP	Darwin	NINO3	IOD(west)	SAM(south)	NAsst
Correlation with rainfall	−0.72	−0.72	−0.54	−0.31	−0.21	0.37	0.37
Correlation with "year"	0.34	0.40	0.39	0.13	0.69	−0.59	0.47
Partial correlation	−0.02	0.04	−0.06	−0.23	−0.16	−0.06	−0.53

Data from 1958 to 2007. Correlations of each variable with "year" are also listed. The partial correlations between rainfall and "year", after adjusting for the association of "year" and rainfall with the variable at the head of each column are also listed. Correlations exceeding 0.33 are statistically significant at 1% level; correlations exceeding 0.24 are statistically significant at 5% level

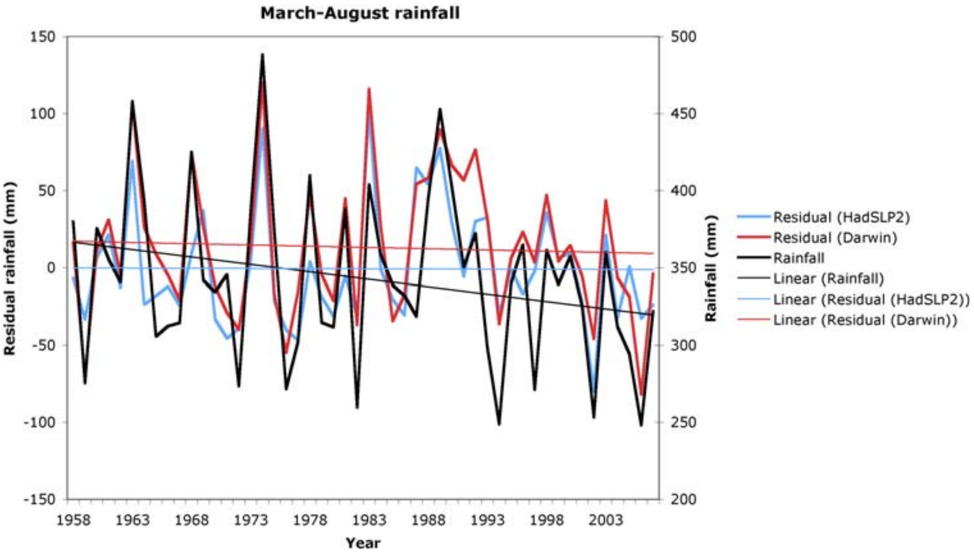

Fig. 2 Timeseries (1958–2007) of March–August rainfall south of 30°S, and timeseries of residual rainfalls from rainfalls predicted with linear regressions using the HadSLP2 and Darwin March–August pressures as predictors. Linear trends are shown for all variables (thin lines)

HadSLP2 pressures, and the linear trend of these residuals. The span of the scale for the residuals (300 mm; left hand axis) is the same as for the actual rainfalls (right hand axis), so the magnitude of the trends can be directly compared visually. It is clear that removing the influence of the pressures on rainfall (using either HadSLP2 or Darwin pressures, or NCEP—not shown), removes virtually the entire drying trend in rainfall. The trend lines for the residuals are close to horizontal, not exhibiting the downward trend seen in the original rainfall data. Thus the "local", immediate "cause" of the observed southern Australian rainfall decline is simply the fact that atmospheric pressure has increased over Australia over the last 50 years. This pressure increase is Australia-wide, and thus does not represent a trend in the latitude of the sub-tropical ridge, which does not appear to have shifted substantially over the period studied here (Larsen 2008).

But what could be the underlying cause of this increased pressure (and thus be the underlying cause of the decline in rainfall)? The influence of three "modes" of Southern Hemisphere variability, ENSO, SAM, and the IOD, is considered here. However, as discussed in the previous section, care needs to be taken in selecting which indices of these modes of variability to relate to Australian pressure and rainfall. For instance, a commonly used index of ENSO is the Southern Oscillation Index, the difference between standardized pressures at Tahiti and Darwin. This index necessarily includes Australian atmospheric pressures, which, as shown above, are the local cause of the rainfall decline. Selecting the SOI as an index of ENSO would prejudice any investigation as to whether ENSO was the underlying cause of the rainfall decline. So a remote index of ENSO has been employed—if this is also related to Australian rainfall the argument that ENSO is contributing to the rainfall decline would be much stronger than would be the case if the SOI were used in the analysis. The IOD and SAM also are conventionally measured with indices involving the difference in a variable (pressure for SAM; sea surface temperature for the IOD) measured in two locations, one of which is close to Australia. As is the case with ENSO, it would be surprising if the use of these conventional measures, because of the proximity of one of their "poles" to Australia, did not lead to strong correlations with Australian rainfall and pressures. Behera and Yamagata (2003) in fact do report a strong link between the IOD and Australian pressures. The existence of such correlations would not necessarily mean that the physical mechanisms underlying the IOD or SAM were affecting Australian rainfall. It might simply be that the index was conflating the real variability associated with this mode and local Australian changes unrelated to the physical mechanism of the mode. For this reason, remote indices of each of the modes have been selected for analysis (e.g., western Indian Ocean sea surface temperatures to represent the IOD)—if these remote indices are related to Australian rainfall one could be confident that the mode is indeed affecting rainfall, and that the relationship does not simply reflect the relationship of local, Australian-region pressures and sea surface temperatures with rainfall. If, however, the remote index is not related to Australian rainfall it would be difficult to conclude that a real physical link exists between the mode of variability and Australian rainfall, and thus that a change in the mode is the cause of the rainfall decline. So, the NINO3 index (sea surface temperatures averaged over 5°S–5°N, 90–150°W) was selected to represent ENSO; the western pole of the IOD (sea surface temperatures averaged in the box 50–70°E, 10°S–10°N; hereafter referred to as "IOD(west)") to represent the IOD; and, following Meneghini et al. (2007), atmospheric pressures averaged over the box 60–70°S, 90–180°E (hereafter referred to as "SAM(south)") were chosen to represent the southern pole of SAM. Note that this is a regional index, rather than an average across all longitudes. Meneghini et al. (2007) used a regional index defined over this range of longitudes (although they used an index based on the latitudinal difference of pressure, rather than the remote index based on only high-latitude average pressures employed here).

The selection of a single "pole", e.g. IOD(west) to describe what are conventionally defined as gradients in pressure (SAM, or ENSO) or sea surface temperatures (IOD), might be considered to result in an incomplete measure of these phenomena. What we are testing in this study, however, is not whether or not the IOD or SAM exist as important climate modes of variability. Rather, what is being tested is whether these modes are affecting southern Australian rainfall variations and trends. This is tested here by checking whether the gradients in either pressure or sea surface temperature are more closely related to Australian rainfall than are local, Australian-region pressures or sea surface temperatures. The gradients would only be more closely related to Australian rainfall if the "remote" part of the gradient was also correlated with Australian rainfall. If this is not the case, then one can assume that any apparent relationship between these gradient-type indices and rainfall simply reflects the relationship between rainfall and local, Australian-region ocean temperatures or atmospheric pressures. If, on the other hand, the remote "pole" of a mode of variability such as the IOD is related to Australian rainfall variations this indicates that the gradient would likely be more closely related to Australian rainfall than would be the local "pole" variable by itself. This would imply that the mode, as measured by the gradient, really does impact on Australian rainfall.

NINO3 is related to southern Australian rainfall (Table 1), although less strongly than is the case with

Australian atmospheric pressure. NINO3 also exhibits a trend, although this is weaker than the trend exhibited by pressures over Australia (Nicholls 2008). The partial correlations of rainfall with "year", controlling for NINO3, are not, however, close to zero, indicating that the trends in NINO3 cannot account for the declining rainfall. Figure 3 repeats the analysis undertaken for Fig. 2, but using the NINO3 as a "predictor" of southern Australian rainfall. The downward trend in the residuals, in this case, is still clear although it is somewhat weaker than the downward trend in the original rainfall data (also shown in Fig. 3). It is clear that the weaker trends in NINO3 cannot account for the rainfall decline, whereas the increases in pressures over Australia can do so (compare Figs. 2 and 3). However, the period March–August is not the time of year when the NINO indices reach their maxima and minima, so perhaps trends at the time of year (December–February) when these indices are most variable may account for the decline in rainfall? Nicholls (2008) showed that there were no clear trends in indices of the El Niño-Southern Oscillation outside March–September over the 1958–2007 period, so the behaviour of the El Niño-Southern Oscillation at other times of the year cannot be the cause of the decline in southern Australian rainfall.

IOD(west) is also correlated with southern Australian rainfall (Table 1) with warmer western Indian Ocean sea surface temperatures tending to occur with a drier southern Australia, although the correlation does not quite reach the 5% statistical significance level. IOD(west) has also exhibited a very strong warming trend over the past 50 years (Table 1). However, the partial correlation between rainfall and year (controlling for IOD(west)) is weaker than the correlation between the original values of rainfall and year. Figure 3 also shows the time series of the residual rainfalls after use of the IOD(west) to predict rainfall with the linear relationship between the variables. The trend of the residuals is still towards declining rainfall, although the downward trend in the residuals is somewhat less than the trend in the original rainfall data. Thus the trend in the IOD(west) index does not account for all of the declining rainfall trend, although it appears that the IOD may account for more of the rainfall trend than is the case with NINO3.

SAM(south) is more strongly correlated with southern Australian rainfall (Table 1) than are either NINO3 or IOD(west). SAM(south) has also exhibited a strong trend, in the same sense that would imply a declining trend in rainfall, since 1958. The partial correlation between rainfall and year, after removal of the influence of the SAM(south) is close to zero (Table 1), indicating that most of the declining rainfall is associated with the trend in SAM. The residuals of the rainfall time series after removal of the rainfall predicted using the linear regression on SAM(south) exhibit almost no trend (Fig. 3), as is expected from the near-zero partial correlation. So, unlike the NINO3 or IOD(West), the trend in the SAM(south) index appears to be able to account for (i.e., "explain") the decline in southern Australian rainfall over the last 50 years.

Since the explanatory variables (pressures, NINO3, IOD(west), SAM(south)) used here exhibit trends over the 1958–2007 period, it is possible that much of the relationship between each of these variables and the rainfall may be reflecting these trends, rather than relationships between the interannual variability. In such a case, any correlation between rainfall and the explanatory variable could be artificially inflated, if the trends actually arose by

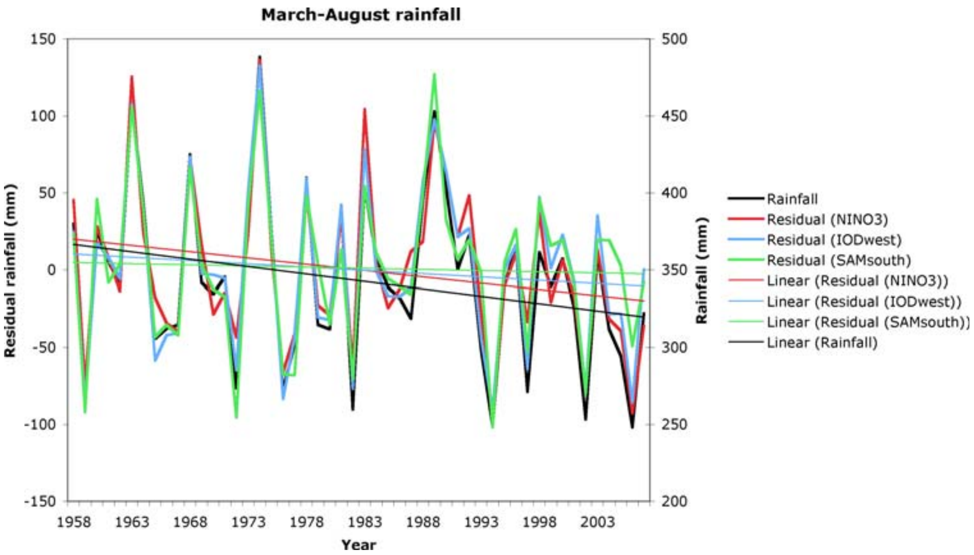

Fig. 3 Timeseries (1958–2007) of March–August rainfall south of 30°S, and timeseries of residual rainfalls from rainfalls predicted with linear regressions using either NINO3, IOD(west) or SAM(south) in March–August as predictor. Linear trends are shown for all variables (thin lines)

chance. To investigate if such confounding or inflating due to the trends is the case, year-to-year differences were calculated for all the variables and linear regressions and correlations calculated between the variables. The linear regressions between these year-to-year differences then allow the estimation of the rainfall trend that should be expected from the relationship between the variables, given the observed trend in the explanatory variables. Table 2 lists the correlations of each of the explanatory variables with rainfall (the correlations between the original data and also the year-to-year differences are listed for comparison—the correlations on the original data are repeated from Table 1). Also shown in the table are the rainfall declines that could be expected from the observed trend in each explanatory variable, assuming that the relationship derived from the year-to-year values operates on multidecadal timescales as well. These rainfall trends were calculated by applying the linear regression (slope) between year-to-year changes in the explanatory variable and rainfall, to the linearly estimated trend in the explanatory variable from 1958 to 2007. The trends in rainfall estimated in this way should be compared with the actual trend of −48 mm in rainfall over the 1958–2007 period.

Trends in either of the local pressure indices (i.e. the Australian average from HadSLP2 and also Darwin pressure) can account for the virtually all the decline in rainfall over southern Australia, as would be expected from the earlier results and discussion. NINO3 can only reproduce a small amount (12%) of the observed rainfall trend, because there is little trend in NINO3 over the 1958–2007 period.

There is a strong trend in the IOD(west), as noted earlier, but there is almost no correlation between the year-to-year differences of southern Australia rainfall and the IOD(west) index. This indicates that the correlation between the undifferenced rainfall and IOD(west) index is almost entirely reflecting the fact that there are trends in both indices. This suggests that this correlation is most likely artificial—why should the correlation not be seen in year-to-year data if there was a real physical mechanism relating the two variables? Whatever the explanation, the absence of even a modest correlation between rainfall and the IOD(west) means that almost no rainfall trend can be attributed to the trend in the IOD index. So the results in Table 1 and Fig. 3, suggesting a possible influence of the IOD on the rainfall trend, are misleading and are due to the fact that the IOD and rainfall both exhibit trends over the 1958–2007 period. The absence of a clear correlation between the year-to-year variations of rainfall and IOD(-west) implies that the correlation on undetrended data is spurious.

The correlation between SAM(south) and rainfall is also weaker when the year-to-year differenced data are used (Table 2). But this correlation, with the strong observed trend in SAM(south), is still strong enough to reproduce most of the observed rainfall trend (an estimated trend of 34 mm, compared with an observed trend of 48 mm). So, this analysis suggests that a physical process associated with changes in SAM is contributing much of the observed decline in March–August southern Australia rainfall.

A final variable considered here as a possible contributor to the observed decline in southern Australian rainfall is sea surface temperature around northern Australia, a variable known to be related to Australian rainfall (e.g., Nicholls, 1989). An index of sea surface temperatures, averaged across the region 0–15°S, 110–150°E and labelled NAsst, was calculated from the HadSST1 gridded data. NAsst is indeed correlated with southern Australian March–August rainfall (Table 1), and has exhibited a strong warming trend. The partial correlation between rainfall and "year", after adjusting for the relationships with NAsst is −0.53. That is, removal of the influences of NAsst exacerbates the observed trend of declining rainfall. In other words, the observed warming trend in NAsst should have contributed to increased rainfall, in the

Table 2 Correlations of March–August rainfall south of 30°S with mean sea level pressure averaged over the region 10–40°S, 115–155°E from the HadSLP2, with Darwin sea level pressure, with NINO3, with indices of the IOD and SAM, and with North Australian sea surface temperatures (0–15°S, 110–150°E, from HadSST1), for March–August (from Table 1)

	HadSLP2	Darwin	NINO3	IOD(west)	SAM(south)	NAsst
Correlation (original data)	−0.72	−0.54	−0.31	−0.21	0.37	0.37
Correlation (year-to-year differenced data)	−0.73	−0.56	−0.28	−0.02	0.27	0.60
Estimated rainfall trend (mm), 1958–2007, using linear regression between year-to-year differenced data and observed trend in explanatory variable.	−46	−46	−6	−4	−34	53

Data from 1958 to 2007. Correlations between the year-to-year differences of each "explanatory" variable and year-to-year differences of rainfall are also listed. Also shown are the estimated rainfall changes, 1958–2007, estimated from the linear regression between each explanatory variable and rainfall, using the observed 1958–2007 trends in the explanatory variables absence of other factors. Not only has the warming of the ocean around northern Australia NOT contributed to the rainfall decline, the rainfall decline might have been even stronger in the absence of the warming tropical sea surface temperatures. This is further exemplified in Table 2, which lists the correlations between year-to-year variations in NAsst and the rainfall. The correlation of 0.60 is substantially stronger than the correlation on the undifferenced data, indicating that the trends in the two variables have acted to weaken the correlation. The warming of NAsst of approximately 0.45°C observed over the period 1958 to 2007 should have led to an *increase* in rainfall of about 53 mm, rather than the *decline* of 48 mm actually observed. This is evident in Fig. 4 which plots the time series of rainfall (from Fig. 1) and NAsst. The strong positive correlation between the two time series on an interannual time-scale is clear. But it is also clear that the divergence of the trends in the two time series runs counter to the positive correlation evident from year-to-year.

Why are the two time series in Fig. 4 diverging, despite their strong positive correlations from year-to-year? Since pressures over Australia have already been shown to be a strong driver of the decline in rainfall, the relationship between NAsst and pressures was investigated. NAsst and HadSLP2 pressures (from Fig. 1) are correlated at −0.26, i.e. warmer tropical sea surface temperatures lead to decreased pressures. But this correlation is much stronger (−0.63) if it is calculated using the year-to-year differences. Thus, trends in the time series are also weakening the correlation between the time series, relative to correlations calculated in the absence of these trends. This is again evident in Fig. 5, which plots the time series of NAsst and the HadSLP2 pressures over Australia. Note that on interannual time scales the two time series are negatively correlated, yet they both exhibit positive trends. The very strong negative correlation between NAsst and pressures on interannual time scales implies that the warming trend in NAsst should have led to decreased pressures (if the tropics were driving the observed pressure trend) which in turn would have led to increased rainfalls (because of the strong negative correlation between pressure and rainfall on interannual time scales—Table 2). The fact that pressures and sea surface temperatures have both exhibited positive trends over the past 50 years indicates that the pressure trend is NOT being driven by north Australian sea surface temperature trend, and thus that the decline in southern Australian rainfall is similarly NOT driven by the tropical sea surface temperature changes.

The above analyses were repeated using time series of rainfall from two sub-regions: southeast Australia (east of 135°E) and southwest of Australia (west of 120°E). In both regions March–August rainfall exhibited a decline over the period 1958 to 2007, although these declines were weaker than in the average rainfall across all longitudes. Table 3 lists the correlations between year-to-year differences of the two regional rainfall indices and the explanatory variables. The correlations are all similar to those between the explanatory variables and rainfall across the entire region south of 30°S. In the southeast, virtually the entire downward rainfall trend of 39 mm was related to the increase in pressure across Australia (using either the HadSLP2 or Darwin pressures) over 1958–2007, while most, but not all, of the decline in the southwest rainfall (of 44 mm) could be accounted for by the increase in pressure. The near-zero correlations between the IOD(west) year-to-year differences and rainfall in both sub-regions means that the strong

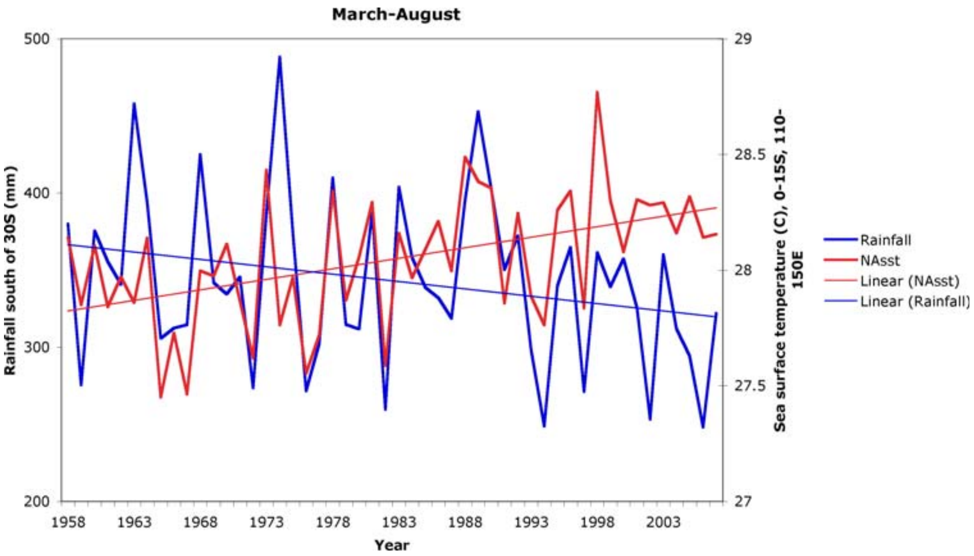

Fig. 4 Timeseries (1958–2007) of March–August rainfall south of 30°S, and northern Australia sea surface temperatures averaged over the region 0–15°S, 110–150°E, from the HadSST1 dataset. Linear trends are shown for both variables (thin lines)

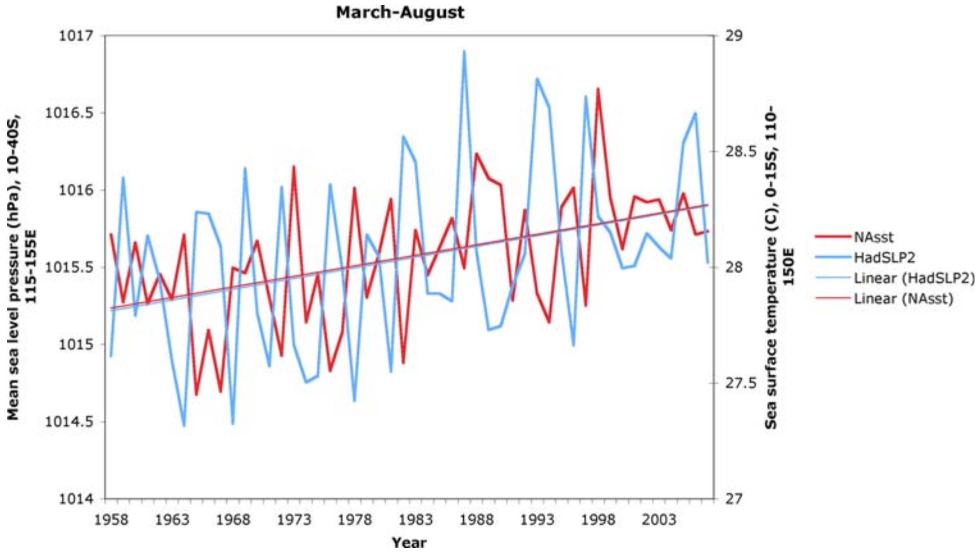

Fig. 5 Timeseries (1958–2007) of March–August northern Australia sea surface temperatures averaged over the region 0–15°S, 110–150°E, from the HadSST1 dataset, and mean sea level pressure averaged over the region 10–40°S, 115–155°E, from the HadSLP2 dataset. Linear trends are shown for both variables (thin lines)

Table 3 Correlations between year-to-year differences of southeast Australia rain (east of 135°E and south of 30°S) and southwest Australia rain (west of 120°E and south of 30°S) with year-to-year differences of mean sea level pressure averaged over the region 10–40°S, 115–155°E from the HadSLP2 gridded data, with Darwin sea level pressure, with NINO3, with indices of the IOD and SAM, and with North Australian sea surface temperatures (0–15°S, 110–150°E, from HadSST1), for March–August

	HadSLP2	Darwin	NINO3	IOD(West)	SAM(south)	NAsst
Southwest Australia rainfall	−0.51	−0.34	−0.22	−0.05	0.24	0.33
Southeast Australia rainfall	−0.61	−0.50	−0.22	0.02	0.22	0.61

Data from 1958 to 2007. Correlations exceeding 0.33 are statistically significant at 1% level; correlations exceeding 0.24 are statistically significant at 5% level

trend in the IOD (as measured with IOD(west)) cannot be the cause of the rainfall declines. Nor can changes in the El Niño-Southern Oscillation be causing the rainfall declines, since even though year-to-year changes in NINO3 are related to year-to-year rainfall variations in both sub-regions, the lack of a strong trend in NINO3 precludes this as an explanation of the rainfall trends. The year-to-year variations in the SAM index, however, are correlated to the year-to-year differences in the two rainfall sub-regional time series (although the correlations are slightly weaker than was the case with the rainfall averaged across all longitudes). The trend in SAM, along with the relationship between SAM and the sub-regional rainfall series, is sufficiently strong to have resulted in a downward trend of rainfall of 32 mm for the southwest and 31 mm for the southeast (i.e. more than 70% of the observed trend in both sub-regions) over the 1958–2007 period.

All the above conclusions are, of course, dependent on the approaches used in this study, and some potential problems associated with these approaches are outlined in Sect. 2. The implicit assumptions of linearity, and that physical mechanisms that affect trends should also be operating at interannual time scales, are just two such issues that reduce the confidence in which we can hold the above conclusions. Other, complementary approaches could lead to more definitive conclusions. For instance, modelling experiments can be designed to test some of the conclusions reached here, and it is intended to do this in the future.

4 Discussion

In summary, the above analysis shows that the 1958–2007 decline in rainfall over southern Australia is very closely related to an increase in surface atmospheric pressure over Australia. The association of the decline in March–August rainfall over southern Australia with the increase in atmospheric pressures over Australia simplifies the question of attribution of the rainfall decline to an ultimate cause. That is, if we wish to determine the cause of the observed rainfall decline, we simply need to understand the cause of the trend towards higher pressures observed across Australia. The rainfall decline does not appear to be explained by any change in the behaviour of the El Niño-Southern Oscillation because even though rainfall is correlated with indices of this phenomenon, the El Niño-Southern Oscillation has not exhibited a sufficiently strong trend over the 1958–2007 period (Nicholls 2008). The Indian Ocean Dipole does not appear to be the cause of the rainfall decline (despite a strong trend in indices of this phenomenon) because it is not strongly correlated with southern Australian rainfall once the long-term behaviour of the IOD is removed by filtering (at least if an index of the IOD remote from the immediate Australian region is used). Sea surface temperatures around northern Australia are also correlated with southern Australian rainfall but the sense of the relationship is such that the strong warming of the ocean should likely have led to increased rainfall (through a decline in atmospheric pressures over Australia), rather than the observed rainfall decline. So, tropical sea surface temperatures around northern Australia are also presumably NOT the cause of the observed rainfall decline. However, the 1958–2007 trend in the southern annular mode (SAM) does appear to be a candidate for explaining much of the rainfall decline. The SAM has exhibited a strong trend and its year-to-year variations are correlated with year-to-year variations in the southern Australian rainfall, even if an index of SAM remote from the Australian continent is used. The relationships and trends are in the correct sense and are sufficiently strong, so that the observed trend in SAM can be associated with over 70% of the observed rainfall trend. All these conclusions also apply to the rainfall declines in the southeast and southwest subregions.

How do these conclusions match the conclusions reached in other recent studies of the causes of these rainfall declines? Hendon et al. (2007) were unable to attribute winter rainfall declines in southern Australia to trends in SAM, because of an absence of winter-time trends in SAM. However, they examined a shorter period (1979–2005) than was studied here, and did not combine autumn and winter. Meneghini et al. (2007) also concluded that trends in the SAM could not explain the decline in southwest rainfall in winter, but may be partly responsible for the decline in southeast Australia. However, they did not disentangle the relationships between the SAM and Australian rainfall in the way that has been done here. On the other hand, the portion of the rainfall decline attributed here to trends in the SAM might be an overestimate, because of the likelihood that trends in indices of the SAM derived from reanalyses (as has been done here) are exaggerated (e.g., Marshall 2003).

If the strong trend in SAM is the cause of much of the decline in southern Australian rainfall observed over the past half century, what has caused the SAM trends? Have models been able to reproduce this decline in rainfall, and for the correct reasons (i.e., associated with a trend in SAM and not, for instance, in the El Niño-Southern Oscillation)? Raphael and Holland (2006) showed that climate models had reproduced the trend in the SAM over the period examined here, implying that this trend was due to either reduced stratospheric ozone concentrations and/or increased greenhouse gases.

An important question this study raises is why have both tropical sea surface temperatures around northern Australia and sea level pressures across the continent, increased over the past 50 years, when their interannual variations are strongly and negatively correlated? Determining the underlying cause for this unexpected behaviour is a crucial question, if we are to comprehensively attribute the causes of regional Australian climate changes. It may be this behaviour that has caused changes in the relationships between the El Niño-Southern Oscillation and Australian rainfall over recent decades (Nicholls et al. 1996), and the unrelated changes in sea surface temperatures and pressures in this region may be the cause of the strange trends in some (but not all) indices of the El Niño-Southern Oscillation noted by Nicholls (2008). Changes in the SAM appear to have been able to at least offset the pressure decline (and rainfall increase) we could have expected from the warming of the oceans around northern Australia. But what has caused the changes in SAM, and are these changes sufficient to explain the entire rainfall decline that has occurred, despite the warming of the oceans? And is the SAM trend the underlying cause of the observed changes in rainfall-ENSO relationships and the distinct trends in some indices of ENSO (Nicholls et al. 1996; Nicholls 2008)?

Finally, what does the attribution of the rainfall decline to the trend in SAM portend for the future? Shi et al. (2008) examined projections of climate over the Australian region, from a climate model. The model projections for the middle of the 21st century showed a decline in rainfall across southern Australia. The projections also were for increased atmospheric pressures over the country, and this presumably was associated with the rainfall decline.

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