

Towards the prediction of major Australian droughts

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An index of the severity of major Australian drought is defined. Here, major drought is defined as a drought that has severe nation-wide impact, rather than just regional impact. The scores of the first principal component of June to November district average rainfalls over continental Australia provide the drought index which is shown to be closely related to national agricultural production. Years when the principal component score is low (i.e. winter-spring rainfall is low) are also years when mean Australian wheat yield and the value of all Australian crops are lower than usual. The drought index is shown to be closely related to indices of the El Nino — Southern Oscillation and appears to be predictable from changes in tropical Australian air temperature during the preceding summer.

Introduction

Droughts are the most costly natural hazard affecting Australia (Heathcote 1979) and have a major impact on the Australian society and economy. Anderson (1979) identified low rainfall as the climatic variable causing most of the uncertainties and instabilities of the Australian rural sector. The Australian Bureau of Agricultural Economics estimated that the 1982-83 drought (van Dijk et al. 1983) resulted in a drop of 18 per cent in the volume of Australian agricultural production (Campbell et al. 1983) and a 45 per cent reduction in average farm cash operating surplus available for consumption and investment (Purtill et al. 1983). If such droughts could be predicted well in advance some action might be possible to minimise the deleterious consequences. Campbell (1973) suggested that the 'opportunities of minimising drought losses by good management which the availability of reliable long-term predictions would open up would far outweigh all the benefits of investments in agricultural research and irrigation development which has been made in the past with drought mitigation as their objective'.

Much of the variation in Australian rainfall is related to the El Nino — Southern Oscillation (ENSO) phenomenon (e.g. Coughlan 1979; McBride and Nicholls 1983; Pittock 1975; Streten 1981, 1983). Australian rainfall generally is below average when Darwin pressure and east equatorial Pacific sea-surface temperature (SST), two commonly used indices of ENSO, are high (see Rasmusson and Wallace (1983) for a description of the ENSO

phenomenon). Voice and Hunt (1984) in a simulation study with a general circulation model of the atmosphere also found that simulated Australian rainfall anomalies were related to ENSO — like sea-surface temperature anomalies.

The ENSO phenomenon generally has a well-defined life-cycle so that once an ENSO event is detected its future development and decay, over a period of about twelve months, usually can be predicted with some accuracy. This feature has led several researchers to investigate the possibility of using the ENSO phenomenon in the prediction of Australian rainfall (Grant 1954; McBride and Nicholls 1983; Nicholls 1983, 1984a, b; Nicholls and Woodcock 1981; Nicholls et al. 1982; Priestly 1962; Quayle 1929). These studies, using more than a hundred years of data, indicate that in many years a general idea of winter and spring rainfall over much of eastern and northern Australia can be gained some months in advance. McBride and Nicholls (1983) and Pittock (1984) point out, however, that the statistical relationships between ENSO and Australian rainfall have not been completely stable over the historical record, indicating that use of ENSO in prediction will not always produce accurate forecasts.

In this paper the possibilities for using the ENSO phenomenon to predict major Australian droughts are investigated. The following section describes the derivation of an index of Australian drought and demonstrates its validity as a measure of drought severity. Methods for predicting this index are then examined.

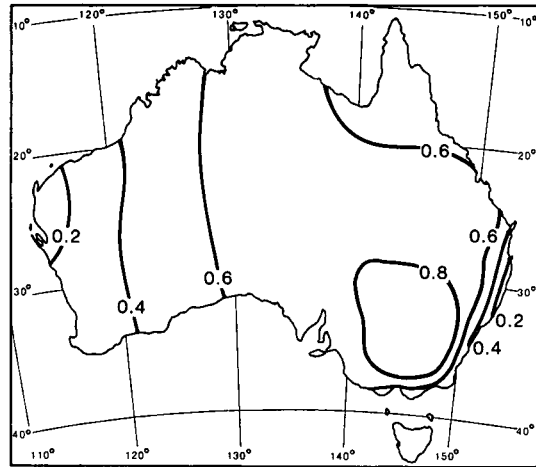
An index of major Australian drought

In almost every year some part of Australia suffers from drought. Even very localised drought can have a substantial impact at the local level but the deleterious effects on the total Australian economy are often offset by better climatic conditions in other parts of the country. On the other hand, in some years a large proportion of the country is drought affected (e.g. 1982-83) and in such cases, as noted above, the consequences to the economy are severe. It is such droughts that are examined here and an index of their severity will now be defined. This drought index differs substantially from the drought indicator, based on rainfall deciles, used by the Bureau of Meteorology in their Drought Watches (Gibbs and Maher 1967). Hounam et al. (1975) list many other drought indices, each derived for a particular purpose.

Pittock (1975) and Coughlan (1979) have demonstrated that the first component (unrotated) of a principal component analysis of Australian annual district average rainfall accounts for a large proportion of the variability of annual rainfall and is related to ENSO. The first principal component is used here to provide a drought index. However, rather than annual rainfall, only winter-spring (June to November) district average rainfall is used. The rationale for this is that winter and spring is the main growing season for the major Australian crops and rainfall in this period should be related to crop yields. Also, rainfall at this time is likely to be more effective in promoting pasture growth than rainfall in summer (when evaporation would be larger), and thus variations in winter-spring rainfall could be expected to have a major impact on the pastoral industry. It will be demonstrated below that the drought index based on winter-spring rain does relate closely to Australian agricultural production. Russell (1967) and Nix (1975) have demonstrated previously the close relationship between wheat yield and rainfall in this period.

The principal component analysis was carried out on district average June to November rainfall totals for continental Australia for the 50 years from 1935 to 1984. The factor pattern (i.e. the correlations of district rainfalls with the scores of the first principal component, henceforth called PCP1) is shown in Fig. 1. Correlations exceeding 0.6 are observed over almost all the eastern two-thirds of the continent. Low correlations (less than 0.2) are found only on the western and eastern seaboard. Very strong correlations (exceeding 0.8) are found over northern Victoria and western New South Wales, where much of Australia's agricultural production occurs. Specifically, considerable proportions of Australia's sheep, beef cattle, and wheat and other cereals are produced within the area with correlations above 0.8. Virtually all Australian production in these extensive and important industries is located within the 0.6 isopleth of Fig. 1 (the exception is the southwest of

Fig. 1 Factor pattern (correlations) of first principal component of June to November district average rainfall. Data from 1935-84.



Western Australia where the correlations are relatively low). It might be expected, because of the correspondence between the location of the major Australian agricultural industries and the high correlations in Fig. 1, that scores of PCP1 would be related to agricultural production.

The relationships between the PCP1 scores and wheat yields (tonnes per hectare) and the total value of Australian crop production have been investigated. Nicholls (1985) examined the time-series of these two indices of Australian production and found they were related to ENSO, after long-term trends were removed. The trends, presumably due in the main to changes in production technology, were removed by fitting cubic splines. The yearly anomalies of wheat yield, after trend removal, are shown in Fig. 2. The anomalies are from Nicholls (1985) and start only from 1951. A typical wheat yield is 1.2 tonnes/hectare so the anomalies of up to 0.5 tonnes/hectare represent substantial inter-annual variability in yield. Also plotted on Fig. 2 are the yearly scores of PCP1. A generally close correspondence between movements in the wheat yield index and the PCP1 score is evident, especially since 1970. The correlation between the two variables is 0.73 ($n = 32$). Callaghan (1973) and Gibbs (1984) noted a close correspondence between falls in Australian wheat yield and the occurrence of major drought. Many other studies of Australian drought have also used sudden drops in wheat yields as evidence of a drought. Thus the strong correlation with wheat yield suggests that PCP1 score can be used as a simple drought index.

Figure 3 shows the anomalies of the total value of Australian crops, in millions of Australian dollars. The long-term trends have been removed and the values inflated to 1983 dollars. The 1982-83 crop value was about 5000 million dollars so the

Fig. 2 Time-series of PCP1 scores (full line) and anomalies of Australian wheat yield in tonnes/hectare (broken line).

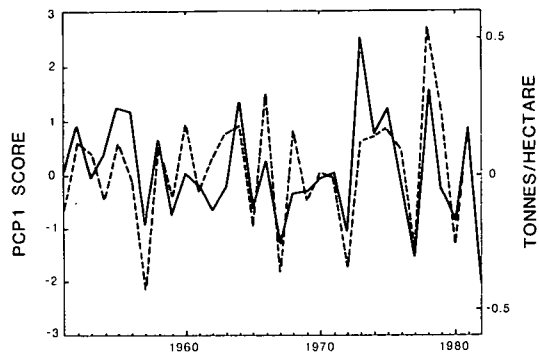
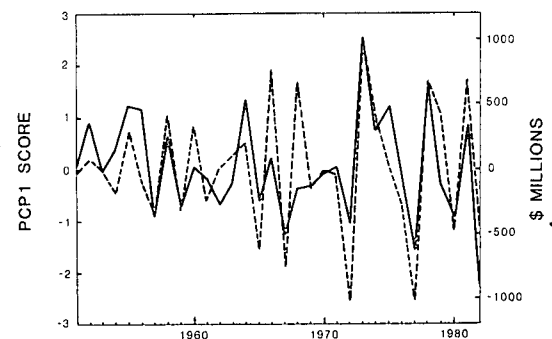


Fig. 3 Time-series of PCP1 scores (full line) and anomalies of the total value of Australian crops in \$millions (broken line).



fluctuations of up to plus or minus 1000 million dollars are relatively important. The scores of PCP1 are also shown in Fig. 3 and again there is close correspondence between the PCP1 scores and the anomalies in the total value of Australian crops, especially after 1970. The correlation in this case is 0.72 ($n = 32$).

The close relationships between winter-spring PCP1 score and wheat yield and the total value of Australian crops confirms that PCP1 is a reasonable index of major Australian droughts. The years with the lowest six values of PCP1 were, in ascending order, 1982, 1977, 1967, 1972, 1957 and 1980. These were also six of the seven years of lowest Australian total crop value (1965 had a low crop value without being one of the six lowest values of PCP1), with an average crop value anomaly of -671 million dollars (1983 dollars). These years were also the six years of lowest wheat yields, after correction for the long-term trend, with an average yield anomaly of -0.36 tonnes/hectare, i.e. an average depression of

yield of about 25 per cent, compared to the long-term average. Thus the years identified as major droughts by the PCP1 scores were also years when Australian agricultural production dropped dramatically.

It should be noted that high PCP1 scores are also related to above average agricultural production. For example, 1973-75, 1978 and 1981 were years when the PCP1 score was relatively high. They were also years when wheat yield was above average (Fig. 2).

ENSO and major Australian droughts

One could expect, from the studies cited in the Introduction, that winter-spring PCP1 scores should be closely related to the ENSO phenomenon. Figure 4 illustrates this relationship by plotting time-series of PCP1 scores and Darwin mean June to November mean sea level pressure. The Darwin pressures have been standardised by subtracting the mean and then dividing by the standard deviation. Fifty years of data are plotted in Fig. 4, although there are three years when the Darwin pressure is missing because one or more months of data were unobtainable. A close relationship is evident, with a correlation coefficient of -0.76 ($n = 47$). As in Figs 2 and 3, the relationship seems especially close since 1970. Darwin pressure is a commonly-used index of ENSO and Fig. 4 confirms that winter-spring PCP1 scores are closely related to ENSO.

There are other indices of ENSO available. One of particular interest is north Australian ($5-15^{\circ}\text{S}$, $120-160^{\circ}\text{E}$) SST which previous studies (e.g. Nicholls 1984c) have demonstrated is closely related, and possibly leads, other ENSO indices. Recently, Wright (1984) has demonstrated that air temperature in the Coral Sea is also related to ENSO. Lead and lag correlations of these two indices, and also of Darwin pressure, to PCP1 scores have been calculated and are plotted in Fig. 5. Correlations of PCP1 score with three-month means for each of the ENSO indices from up to 17 months before and up to 12 months after the winter-spring period have been plotted. The

Fig. 4 Time-series of scores of PCP1 (full line) and June to November mean sea level pressure at Darwin (broken line). The Darwin pressures have been standardised by subtracting the 1935-84 mean and dividing by the standard deviation and the pressure scale is reversed.

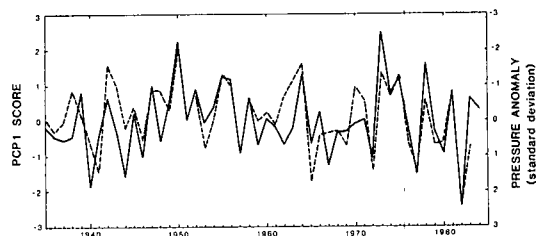
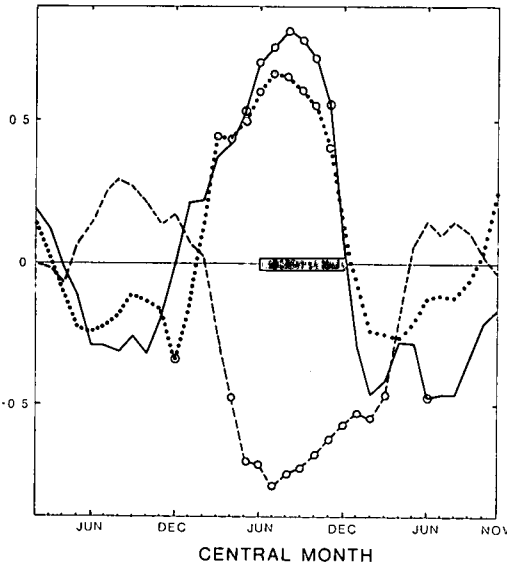


Fig. 5 Lead and lag correlations of PCP1 scores with three-month means of Darwin mean sea level pressure (broken line; data from 1939-82), north Australian sea-surface temperature (full line; data from 1964-82), and Willis I. minimum air temperature (dotted line; data from 1939-82). Correlations significant at the 1% (5%) level denoted by full (open) circle. The thick horizontal bar indicates the period to which the PCP1 score refers. Points to the left of this bar are correlations where the ENSO indices lead the PCP1 score; to the right of the bar PCP1 score leads.



air temperature used was Willis I. (17°S; 150°E) minimum temperature. The rationale behind selecting this variable was that this might be expected to provide a good proxy for SST in the area. Conventional historical SST measurements are poor in this region, thus the correlations with north Australian SST were calculated from only 19 years of data whereas over forty years of data were available for Willis I. air temperatures. Maximum temperature was not selected because it seemed more likely to be influenced by variables such as cloud which might confound its role as a proxy for SST. The similarity of the correlations with SST, calculated from the short data period, and the correlations with Willis I. minimum air temperature, calculated from the longer period, suggests that the latter does provide a good proxy.

The correlations in Fig. 5 indicate that each of the variables is closely related to PCP1 scores. Values of the three indices from before winter, as well as during winter-spring, are significantly correlated with the PCP1 scores. Thus the PCP1 score has a correlation of 0.44 (significant at 1 per cent) with Willis I. minimum temperature averaged over the February to April preceding the winter-spring period.

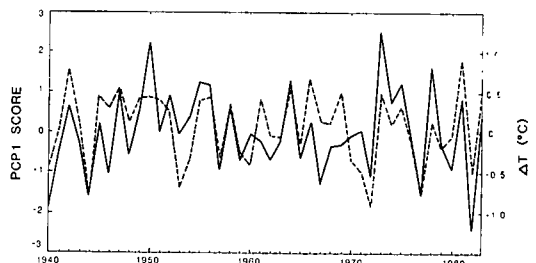
Significant correlations also exist with the other two ENSO indices prior to the winter-spring. It appears that low values of PCP1 score tend to be preceded by the appearance, early in the year, of high Darwin pressures, cold SSTs and low minimum air temperatures around northern Australia.

Although the correlations in Fig. 5 are significant and have been calculated with sufficient data to allow reasonable confidence in their reality, the magnitudes of the correlations with ENSO indices prior to winter-spring, are too low to suggest that accurate predictions with useful lead times could be made using these relationships. However, the possibility of using trends in the ENSO indices to make predictions needs to be considered. Shukla and Paolino (1983) suggested that the trend in Darwin pressure anomaly across the southern hemisphere summer could provide a method for forecasting Indian monsoon rainfall (another atmospheric variable related to ENSO). The correlations in Fig. 5 all show trends around the start of the year prior to the winter-spring PCP1 period. Therefore trends in the three variables, Darwin pressure, northern Australia SST, and Willis I. minimum air temperature, were correlated with PCP1 scores.

The use of trends of the variables resulted in larger correlations, relative to the use of absolute values of the indices. The correlation of PCP1 score with the three-month trend in Willis I. minimum air temperature from November-January to February-April was 0.64. It appears that low values of PCP1 score (i.e. droughts) tend to be preceded by a substantial drop in Willis I. minimum air temperature during summer.

This relationship is illustrated in Fig. 6 which plots time-series of the two variables. A reasonably close correspondence is evident. Once again the best relationship is for the period since 1970. A scatter diagram of the two variables is shown in Fig. 7 and a contingency table relating frequency of occurrence in various ranges of the two variables is provided in Table 1. This figure and table graphically demonstrate the strength of the relationship. Thus of the nine years when the trend in minimum

Fig. 6 Time-series of PCP1 scores (full line) and of change in Willis I. minimum air temperature from November-January to February-April (broken line).



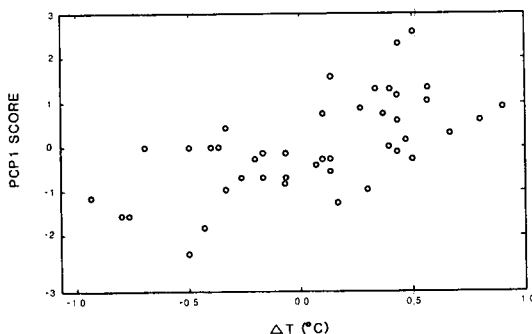
temperature was in the most negative category (i.e. less than -0.35°C) five were in the lowest category of PCP1 scores. On the other hand, of the eight years with largest positive trends in Willis I. minimum temperature (i.e. greater than 0.45°C), seven were in the two highest categories of PCP1 score (i.e. wet). Figure 7 and Table 1 provide convincing evidence that, if the relationships revealed in the past 44 years data are real, then reasonably accurate predictions can be made of PCP1 scores (and thus of major Australian droughts) by monitoring trends in ENSO-related variables across the preceding summer.

Conclusions

The two main conclusions of this study are that the score of the first principal component of continental Australia June to November district average rainfall provides an index of major continental-scale drought and that this drought index appears to be predictable well in advance from temperature changes around tropical Australia. In particular, strong anomalous cooling of the sea surface and air around northern Australia near the start of the calendar year often heralds a major winter-spring drought. About 40 per cent of the variance of the index seems to be accounted for by this predictive relationship, although this needs to be tested on independent data.

Drought probability forecasts could be prepared based on the work reported here. Table 1 can be used to produce approximate probability forecasts of the likelihood of a major drought given a specific value of the change in Willis I. minimum temperature across summer. For instance, of the nine years, since 1940, when the Willis I. temperature dropped more than 0.35°C from early summer to early autumn, five were years of major drought (PCP1 score less than -0.75). Therefore a prediction that a major drought is quite likely when Willis I. has such a drop in temperature seems reasonable. On the other hand, of the nine years when the temperature change over summer exceeded $+0.45$, in no case was a major drought observed, and in only one case was a PCP1 score below zero recorded. In such a case a prediction that major drought was very unlikely seems justified. Figure 7, the scatter diagram of PCP1 score against

Fig. 7 Scatter diagram of PCP1 scores against the change in Willis I. minimum air temperature from November-January to February-April. Data from 1940-83.



the change in Willis I. minimum temperature, could also be used with an observed temperature change to provide a drought prediction in subjective probability terms. Alternatively, logistic regression could be used to produce more formal estimates of drought probability if required.

A number of caveats need to be kept in mind if the work described here is used to prepare drought predictions. First, as noted in the Introduction, correlations between ENSO variables and Australian rainfall are far from perfect and have varied in magnitude over periods of decades, indicating that even though ENSO plays an important role in producing Australian drought it is probably not the only cause. It therefore seems possible that using the technique described here for prediction could produce incorrect forecasts for a period. However, the predictive relationship between rainfall and ENSO has survived, albeit with fluctuations in magnitude, for over fifty years since it was first proposed (Quayle 1929).

A second cause for caution relates to the use of Willis I. minimum air temperature changes in the prediction of the drought index. Only 43 years of data have been used to examine the feasibility of prediction with this variable, and the variable with the highest correlation with PCP1 scores over this

Table 1. Contingency table of frequency of occurrence of categories of PCP1 scores versus category of change in Willis I. minimum air temperature from November-January to February-April. Data from 1940 to 1983.

		Change in Willis I. minimum air temperature				
		< -0.35	-0.35 to 0	0 to 0.3	0.3 to 0.45	> 0.45
PCP1	> 0.85	0	0	2	4	3
	0.1 to 0.85	0	1	1	2	4
	-0.29 to 0.1	4	2	1	2	0
Score	-0.75 to -0.29	0	4	3	0	1
	< -0.75	5	2	1	1	0

period was selected as the predictor. As a result of this selection procedure the apparent skill of the 'predictions' made from the change in Willis I. minimum temperature (e.g. Fig. 7) could be higher than might be achieved operationally, due to selection bias (Miller 1984). Only testing on further data will reveal whether this is a serious problem.

The method for drought prediction outlined in this paper relates only to widespread drought. It is likely, even highly probable, that in a year when there is no widespread drought with severe national effects there might still be pockets of severe local drought causing hardship at a regional level. Similarly, in a year with a major widespread drought there might be small areas not affected by drought. Thus the method described above for forecasting drought cannot be used to predict drought at a local or farm level with anything like the accuracy of the predictions of the major drought index. This clearly limits the value of the drought forecast technique. Nevertheless, advance knowledge of the probability of a major drought, with its likely consequences on the national economy might still be of value to agricultural and economic planners.

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