Frost in Northeast Australia: Trends and Influences of Phases of the Southern Oscillation

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ABSTRACT

A forecast method capable of estimating date of last frost and number of frosts per season in northeastern Australia some months in advance is described. Forecast "skill" is achieved using either Southern Oscillation index (SOI) patterns (phases) during the previous austral autumn or a linear discriminant approach and the SOI. When applying these systems, it is possible to provide significantly different probability distributions of day of last frost and number of frosts, depending on the SOI patterns observed during the previous season. An analysis of the time series of frost frequency and date of last frost suggests an apparent warming trend in the data, resulting in a trend toward earlier dates of last frost and fewer numbers of frosts at many of the locations analyzed. The beneficial implications of the proposed frost forecasting system for enterprises such as winter agriculture in the region are believed to be significant.

1. Introduction

Frost affects many natural and managed ecosystems in northeastern Australia by direct effects on plants and animals. The management of such systems is often tuned to frost occurrences. For example, wheat crops in northeastern Australia are managed to avoid frost at flowering. Predicted changes of only a few days in date of last frost would have important implications in wheat-cropping management. Appropriate varietal changes and earlier sowing could improve potential yield by approximately 1% for each day flowering is advanced (Woodruff and Tonks 1983; Woodruff 1992). Severe and untimely frosts can have severe effects on enterprises ranging from fruit crops to livestock, and various strategies are employed to minimize frost damage. Although the relationship between minimum temperature and frost occurrence is not exact, risk associated with critical threshold minimum temperatures has been used as an indicator of frost risk to aid primary producers in making management decisions (Hammer and Rosenthal 1978).

In northeast Australia, considerable variability exists in dates of both the first and last frosts of the year and in the number and severity of frosts (Foley 1945). A mechanism responsible for significant seasonal climate variability in Australia is the El Niño–Southern Oscillation phenomenon (ENSO) (McBride and Nicholls 1983; Nicholls and Wong 1991). Coughlan (1979) identified relationships between maximum temperature variations in Australia and the Southern Oscillation index (SOI) and Jones (1991) correlated daily mean temperature with the SOI. Certain relationships between the Southern Oscillation and mean global temperature variability have been extensively investigated by Kiladis and Diaz (1989) and Halpert and Ropelewski (1992). These authors have identified large-scale global temperature patterns associated with extreme states of ENSO, which suggests possible global application of a frost forecasting method that utilizes ENSO or the SOI. Thus, although this paper, in part, seeks to identify relationships between the Southern Oscillation and frost likelihood in eastern Australia, it is believed the method may have application generally wherever significant relationships between ENSO and temperature variability exist. In most studies emphasis has been placed on identifying relationships between *mean* temperature and ENSO. A link between frost forecasting and ENSO has not been established.

Some studies have documented historical trends in minimum and maximum temperatures and diurnal temperature range over eastern Australia (Coughlan 1979; Jones 1991; Karl et al. 1993). However, possible trends in critical temperature thresholds near the freezing point have not, so far, been considered. The prime aim of this study was to develop a system for seasonal forecasting of frost likelihood. The secondary aim was to examine the historical record for any trend in frost occurrences.

2. Data and methodology

a. Data

Dates of last "frost" and number of frosts each year were identified for minimum temperature thresholds

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between 3°C and −3°C in steps of 1°C from long-term daily temperature data (1894 to 1992) compiled for a number of locations in northeast Australia (Fig. 1). Frost in this study refers to screen temperatures falling below certain near-zero temperatures. Minimum temperature thresholds were not met in all years at all sites. As this study was part of a project on evaluating the role of seasonal forecasts in managing crop production in northeastern Australia (Stone and Hammer 1992), stations used in the analysis were in major wheat production areas in that region.

Temperature data used were from minimum temperature thermometers housed in a Stevenson Screen. Data quality and consistency of record varied a little from station to station so that some trade-off between spatial representativeness and record quality eventuated. A qualitative assessment of consistency in station records was made to gauge the type and techniques of measurement, the sampling interval, and the manner of processing. Changes in exposure or location, changes of procedure in collecting and processing data were also examined to provide evidence of station suitability (cf. Srikanthan and Stewart 1991; Nicholls and Kariko 1993; World Meteorological Organization 1994). Some station records gave evidence of either occasional poor instrument maintenance or some shift in position of the Stevenson Screen to a nearby but slightly less than ideal environment. Emerald and Dalby station records suggested occasional problems with screen site over their 100-year period of record. Records at other locations suggested little problem with site environment, although Goondiwindi had a few problems with site quality in the late 1980s. The known site inconsistencies or inhomogeneities were not severe enough to significantly affect the results of this study.

An initial appraisal of the variability in both number of frosts and day of last frost each year was achieved by producing frequency distributions of the long-term data. Regression equations were calculated for each dataset to produce a simple linear fit to the data to gain an appreciation of the significance of any apparent trends.

b. *Correlation analysis*

Relationships between a predictor (SOI) and predictand (date of last frost and number of frosts) were first investigated via correlation analysis of both the May SOI and the day of last frost and the May SOI and total number of frosts. May SOI was initially chosen as a potential predictor as it preceded the timing of frost occurrences. SOI values used were supplied by the Australian Bureau of Meteorology National Climate Centre and follow the calculations of Troup (1965); that is,

$$\mathrm{SOI} = 10 \times [dp(\mathrm{Tahiti}) - dp(\mathrm{Darwin})]/\text{standard deviation of the difference},$$

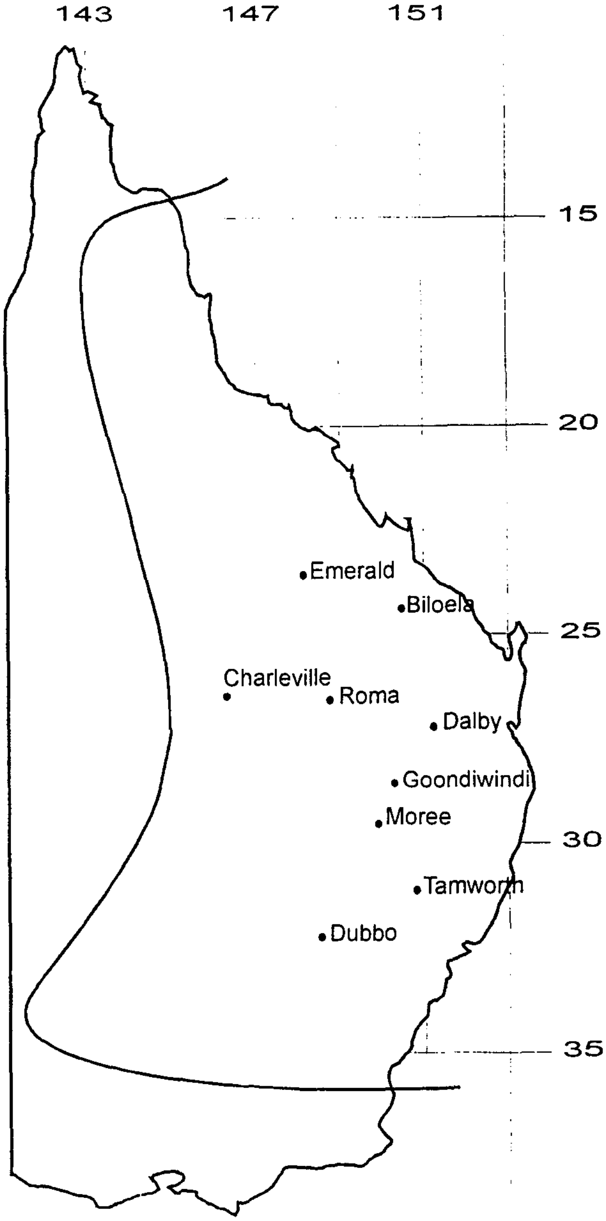


FIG. 1. Location of stations used in the analyses.

where $dp(\ )$ = pressure anomaly

= monthly mean−long-term mean.

c. *Linear discriminant analysis*

Linear discriminant analysis is a technique for determining whether the "predictor" variables (in this case the SOI and also the year to allow for any possible trend) can discriminate between two or more groupings of the "predictand" variable. The basic idea was to determine whether groups differed with regard to the

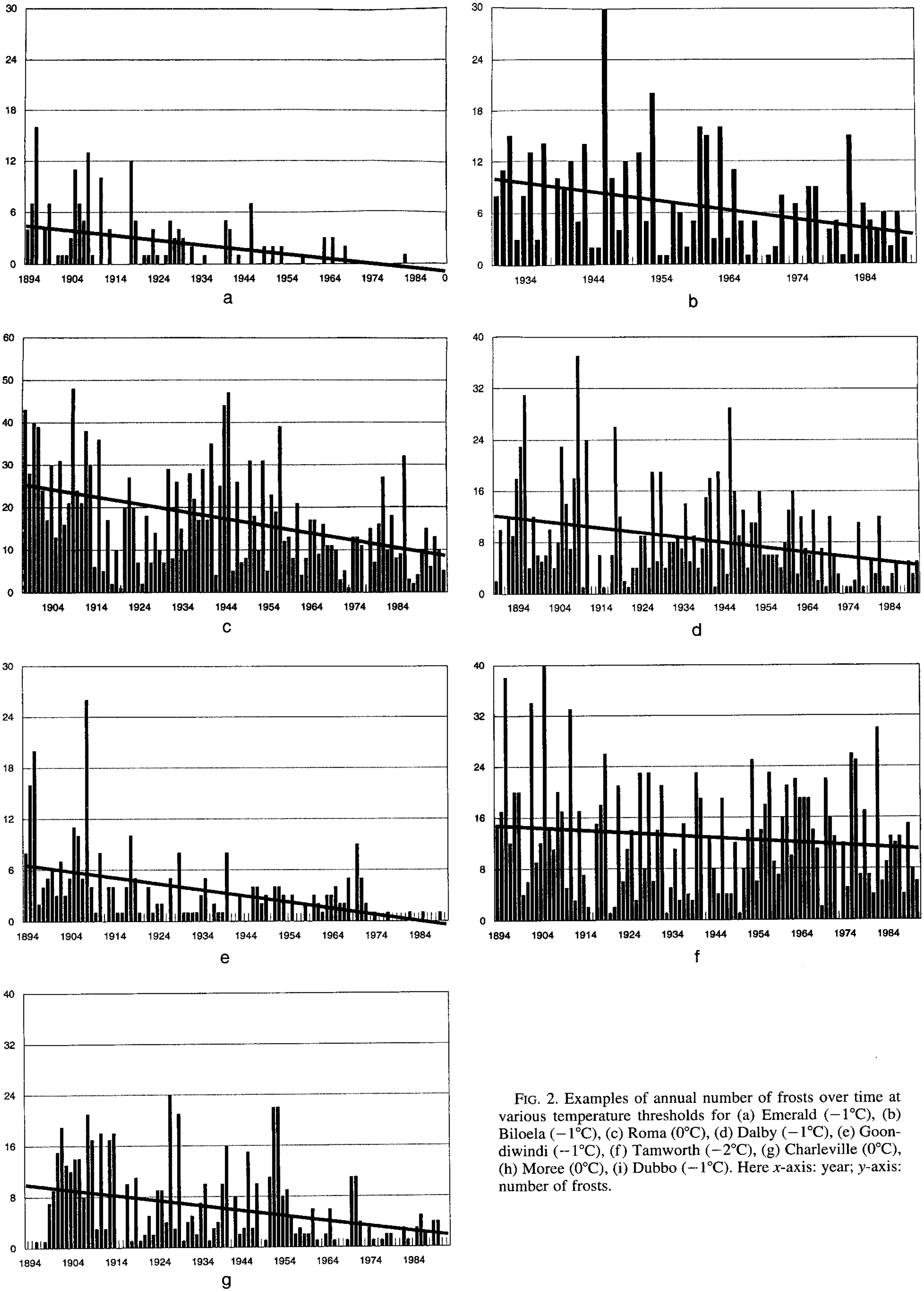


FIG. 2. Examples of annual number of frosts over time at various temperature thresholds for (a) Emerald (−1°C), (b) Biloela (−1°C), (c) Roma (0°C), (d) Dalby (−1°C), (e) Goondiwindi (−1°C), (f) Tamworth (−2°C), (g) Charleville (0°C), (h) Moree (0°C), (i) Dubbo (−1°C). Here *x*-axis: year; *y*-axis: number of frosts.

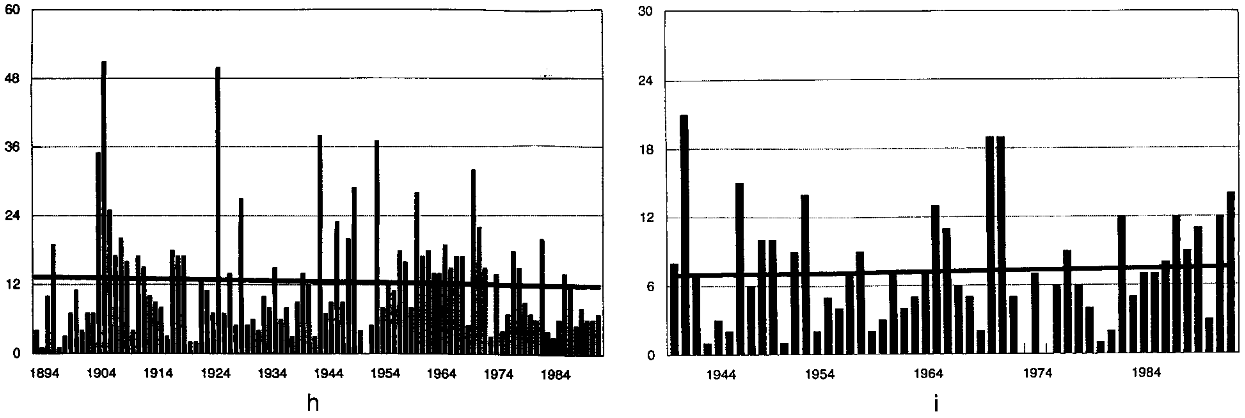


FIG. 2. (*Continued*)

mean of the year and the SOI and then to use those variables to predict group membership (e.g., of new cases). Here the two groups of the predictand variable are simply whether or not a temperature lower than the specified threshold was observed in the year under consideration. The threshold selected for this analysis was the minimum temperature that was reached in only approximately half the years on record. This threshold varied between stations.

d. SOI phase analysis

Simple correlation analysis may mask otherwise important relationships existing between the SOI and rainfall or temperature. For example, it is known that change or trend in SOI can have significant effects on rainfall in Australia (Rimmington and Nicholls 1993). An established method of categorizing SOI *behavior* into SOI phases or types (Stone and Auliciems 1992) that has already been applied to rainfall analysis in Australia (Stone and Hammer 1992) was also used in this study to assess the usefulness of SOI categories in frost prediction.

The SOI phases of Stone and Auliciems (1992) were derived using a combination of principal components analysis (PCA) and *k-means* (iterative partitioning) cluster analysis to classify patterns of SOI behavior using monthly SOI data from 1882 to 1991 (obtained from the National Climate Centre, Bureau of Meteorology). (Analysis was also made using only SOI data between 1936 and 1991 and similar SOI phases were produced.) Either monthly or seasonal SOI data may be employed to construct SOI phases, depending on eventual application. However, seasonal SOI values may mask important tropospheric responses, especially during the austral autumn and spring and so monthly SOI data were used in this analysis. It was also noted contamination from the intraseasonal oscillation on monthly SOI was minimal (Williams 1987). A full description of the method is found in Stone and Auliciems (1992).

Briefly, to obtain SOI phases, various data matrices comprising current and varying lag SOI values for the SOI history were used with the aim of producing principal components and principal component scores that best represented the time series of the SOI. For example in this analysis, each SOI case or observation used in the analysis represented the current SOI, the immediately preceding SOI, and the difference in value in SOI between the current month and the immediately preceding month. The use of PCA was primarily to create *orthogonal* factor scores for further analysis. An iterative partitioning cluster algorithm was then applied to the component scores to provide distinct clusters or "phases." Similar methods have been applied by Kalstein and Corrigan (1986) to obtain a "temporal index" in synoptic climatology, while Stone (1989) used a similar technique to temporally group synoptic weather observations.

Five SOI clusters were identified according to certain cluster "stopping rules" (e.g., Mojena 1977). These five phases comprise

1) consistently negative SOI, with a mean SOI value over a two-month period of −12.2 and mean difference between the two months of +2.3,
2) consistently positive SOI, with a mean SOI value over a two-month period of +9.5 and mean difference between the two months of −1.7,
3) rapidly falling SOI, where the mean SOI value the initial month is +2.7, the value in the subsequent month is −9.9, and the mean difference in values is −12.7,
4) rapidly rising SOI, where the mean SOI value the initial month is −4.4, the mean SOI value the subsequent month is +6.6, and the mean difference in values is +11.0,

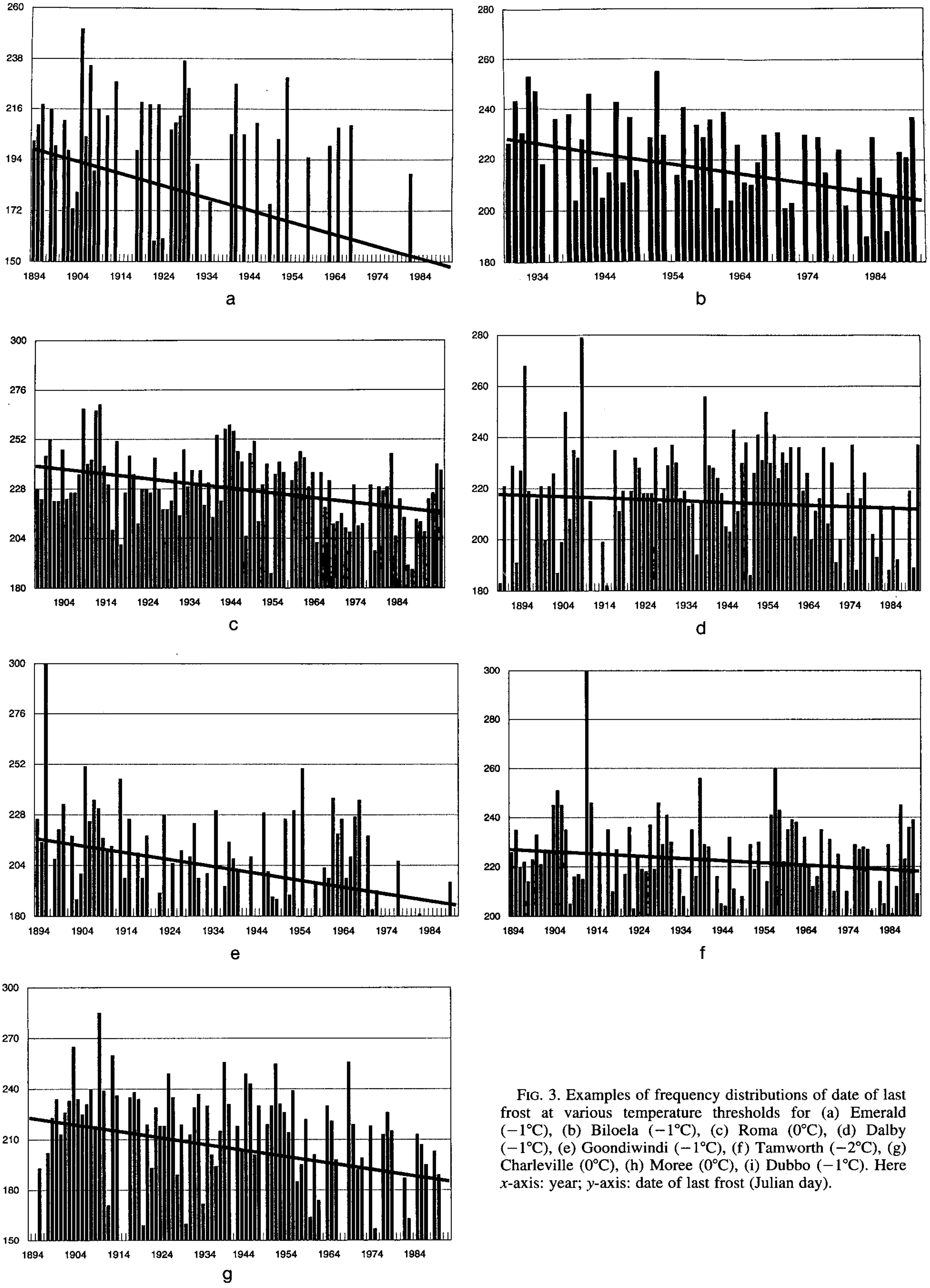


FIG. 3. Examples of frequency distributions of date of last frost at various temperature thresholds for (a) Emerald (−1°C), (b) Biloela (−1°C), (c) Roma (0°C), (d) Dalby (−1°C), (e) Goondiwindi (−1°C), (f) Tamworth (−2°C), (g) Charleville (0°C), (h) Moree (0°C), (i) Dubbo (−1°C). Here *x*-axis: year; *y*-axis: date of last frost (Julian day).

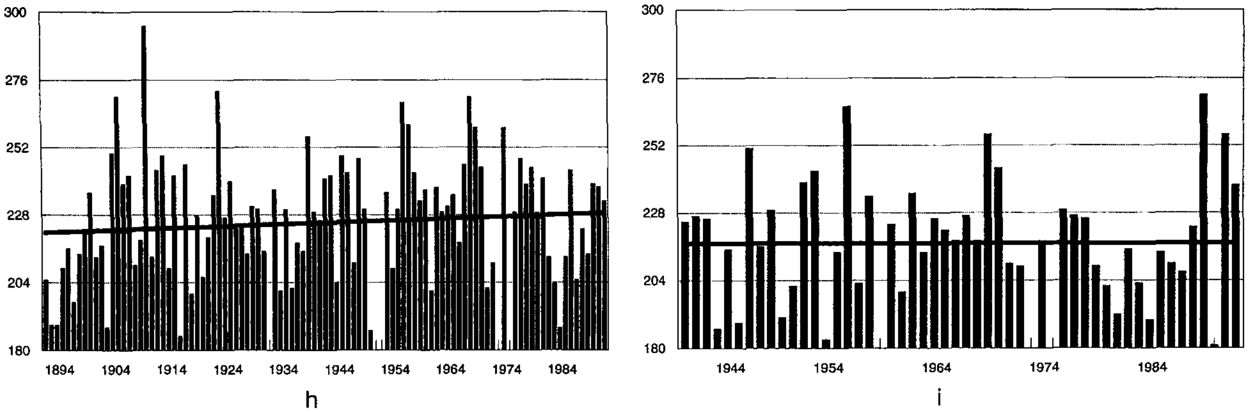


FIG. 3. (*Continued*)

5) SOI values consistently near zero with little change over the preceding month—mean SOI −1.7, mean difference −1.3.

Stone and Hammer (1992) demonstrated the value of the SOI phase approach when investigating *lag* relationships between SOI phases and rainfall probability distributions in eastern Australia. They were able to demonstrate that

1) either a falling or a consistently negative SOI pattern in the late austral autumn was associated with a high probability of below-average rainfall during the following winter–spring period at many locations in eastern Australia (especially at locations where wheat was grown during winter),

2) either a rapidly rising or a consistently positive SOI during the late austral autumn period was associated with a high probability of above-average rainfall during the following winter–spring season.

Since a period of below-average rainfall may also be associated with increased longwave radiation output, and hence greater likelihood of low minimum temperatures, it was considered this approach may be useful in developing a method for assessing probability distributions of late frosts. SOI phases chosen for this analysis were for the April–May, March–April, February–March, and January–February periods.

3. Results

a. Frequency distributions

Considerable variability was found in both the number of frosts and in date of last frost at the locations analyzed. Figure 2 describes variation in annual number of frosts for a selection of temperature thresholds, and a simple regression line suggests possible trends in the data. At most locations analyzed, depending on the temperature threshold analyzed, the number of frosts per year has varied from 0 to 65 in the period from 1894 to 1992. Further, the plots also suggest a downward trend in yearly numbers of frosts at many of the stations. At most of the northeastern stations (e.g., Tamworth, Dalby, Roma, Goondiwindi, Biloela, and Emerald) there has been a tendency toward fewer frosts over the historical record.

Figure 3 describes variation in the date of last frost for a selection of temperature thresholds. Date of last frost has varied from before Julian day 180 to day 300, depending on the temperature threshold being analyzed. Inspection of Fig. 3 suggests a shift or downward trend (i.e., a tendency over the record toward an earlier date) in day of last frost at most locations, but with the exception of the more southwestern stations of Moree and Dubbo. Simple regression equations suggest a downward trend in numbers of frosts over the period of record (at the 95% confidence level) at six of the nine stations analyzed: Emerald, Biloela, Roma, Dalby, Goondiwindi, and Tamworth. Regression equations calculated for dates of last frost over the period of record suggest a downward trend (95% confidence level) (i.e., trend towards earlier last date of frost) at five of the stations: Emerald, Biloela, Roma, Goondiwindi, and Tamworth.

Earlier work by Jones (1991) and Jones and Henderson-Sellers (1992) show increase in minimum temperature for 256 out of 316 Australian stations analyzed over the period from 1890–1990 with a mean trend of 0.12°C decade^{-1}. Jones (1991) further demonstrated a downward trend in daily *mean* temperature in Australia over the 100-yr period to 1990. Both increase in minimum temperature and decrease in daily mean temperature have been attributed to an increase in mean cloud cover, which has been further related to increase in sea surface temperatures (SST) in waters to the northeast of Australia (also see Cooper et al. 1989; Lough 1992, 1993).

Jones (1991) also found moderate positive correlation between the trend in SOI and trend in cloud cover over Australia and a moderate negative correlation be-

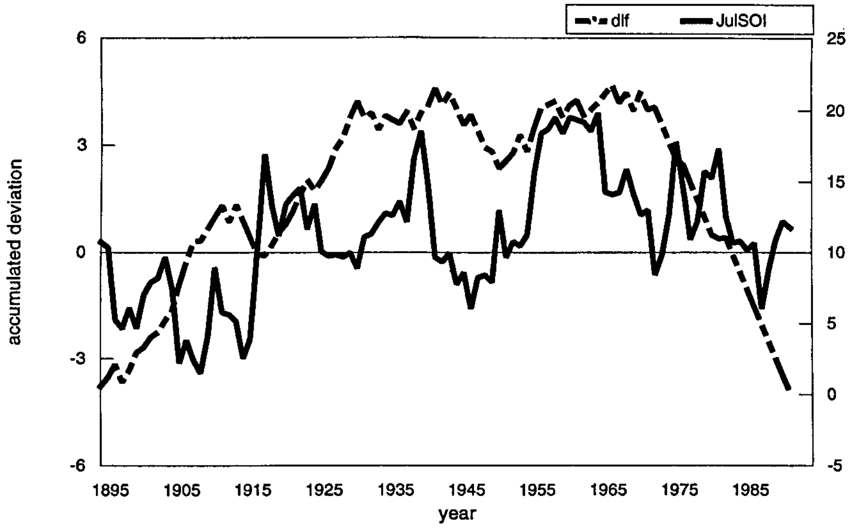


FIG. 4. Accumulated deviations from the mean of date of last frost at Emerald, June SOI. Here *x*-axis: year; *y*-axis: accumulated deviation. Solid line depicts June SOI, dashed–dot line the date of last frost.

tween trend in SOI and trend in diurnal *temperature range* over the same region. Figure 4 describes, as an example, the accumulated deviation from the mean (residual mass curves) of the date of last frost at Emerald (0°C in the screen) for the period of historical record together with accumulated deviations from the mean of the July SOI (the month in which most last frosts occur). There is a moderate positive correlation between May, June, and July SOI trend and trend in date of last frost (correlation between trend in July SOI and trend in date of last frost: $r = +0.46$; sig at $p = 0.001$). This result suggests a dissimilar finding to Jones (1991), although closer inspection of the accumulated deviations from the mean since about 1960 indicates a decline in date of last frost (increase in minimum temperature) at Emerald since about 1963 (since 1954 at Roma), while the trend in June SOI also fell. Similar results were found for relationships between SOI and date of last frost at other northeastern stations.

Correlations between trend in *numbers of frosts* and trend in SOI were opposite in sign to those between trend in *date of last frost* and trend in SOI. Figure 5

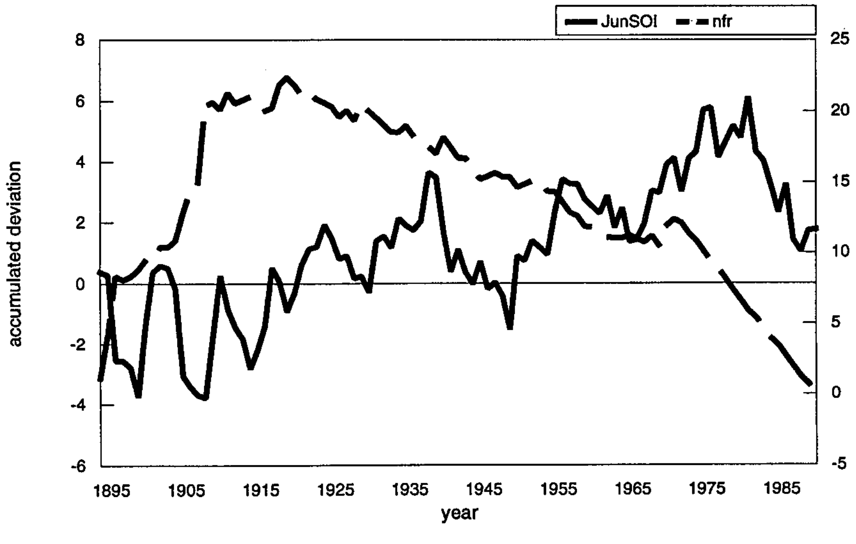


FIG. 5. Accumulated deviations from the mean of numbers of frosts at Goondiwindi, June SOI. Solid line depicts June SOI, broken line numbers of frosts. Here *x*-axis: year; *y*-axis: accumulated deviation.

TABLE 1. Correlation of annual number of frosts with May SOI for selected sites in northeast Australia (correlation values significant at the 5% level indicated as [a]; at the 1% level as [b]).

Screen temperature	−2°C	0°C	2°C
Emerald	−0.28[b]	−0.34[b]	−0.34[b]
Biloela	−0.33[b]	−0.29[a]	−0.23
Dalby	−0.28[b]	−0.27[b]	−0.20[a]
Charleville	−0.33[b]	−0.36[b]	−0.32[b]
Roma	−0.40[b]	−0.40[b]	−0.33[b]
Goondiwindi	−0.24[a]	−0.33[b]	−0.34[b]
Moree	−0.11	−0.27[b]	−0.23[a]
Tamworth	−0.08	−0.17	−0.17
Dubbo	−0.22	−0.40[b]	−0.37[b]

TABLE 2. Correlation of date of frost in the year May SOI for selected sites in northeast Australia (correlation values significant at the 5% level indicated as [a]; at the 1% level as [b]).

Screen temperature	−2°C	0°C	2°C
Emerald	−0.31[b]	−0.20[a]	−0.22[a]
Biloela	−0.23[a]	0.19	0.22[a]
Dalby	−0.08	0.12	0.05
Charleville	−0.25[b]	−0.17	−0.19[a]
Roma	−0.11	−0.16	−0.24[b]
Goondiwindi	−0.35[b]	−0.16	−0.22[a]
Moree	−0.11[a]	−0.17	−0.12
Tamworth	−0.04	−0.08	−0.08
Dubbo	−0.03	−0.19	−0.21

describes relationships between accumulated deviations from the mean in numbers of frosts (example for Goondiwindi, minus 1°C in the screen) and June SOI (the most common month of occurrence of that frost at Goondiwindi). There is a strong negative correlation between trend in number of frosts and trend in SOI at most locations (at Goondiwindi $r = -0.71$; $p = 0.001$) and this result supports the suggestion (Jones 1991) of a positive correlation between SOI trend and minimum temperature trend. However, the trend in numbers of frosts appears to become the same as trend in SOI (i.e., downward) from about 1976. Similar results are found for other locations.

b. *Correlation analysis*

Results of correlation analyses of number of frosts and SOI during the preceding May are presented in Table 1. Moderate, negative correlations between SOI and number of frosts were obtained for most locations and most temperature thresholds. Results were significant at $p < 0.05$ in most instances.

Table 2 shows an example of results of correlation analysis of date of last frost with May SOI (temperature thresholds −2°C, 0°C, 2°C). For most locations, weak to moderate negative correlations were found between May SOI and date of last frost. However, the results were significant at $p < 0.05$ for most temperature thresholds at Emerald, Charleville, Goondiwindi, Moree, and Roma. An interesting result of this analysis was the varying correlation values at Biloela (and to a lesser extent at Dalby) with increase in temperature threshold. At Biloela (Fig. 6), there was a moderate (significant at $p < 0.05$) negative correlation between the SOI during May and the date of last frost at colder temperatures. However, the sign of the correlation changed with progression toward higher temperatures. At a threshold of 1°C or 2°C, the correlation was positive and significant at $p < 0.05$. We cannot offer an explanation for this effect.

c. *Linear discriminant analysis*

It was considered that application of a correction for the presence of the trends may result in improved SOI-frost relationships. For station–threshold pairings in which there was at least one frost every year, the date of last frost could be detrended prior to analysis using the SOI phases described above. For many station–threshold pairings, however, not all years record a frost so it was not simple to detrend the date of last frost. The different approach used here took account of the trends in frost occurrence. It involved the use of the SOI and the year as predictors in a linear discriminant analysis (LDA) approach to forecasting frost occurrence.

The results of the LDA shown in Table 3 indicate that a small increase in the accuracy of predicting whether a specific year will record a frost is possible using May SOI and the year as predictors. In Table 3 the column with the percentage of years with no day recording a minimum temperature below the threshold provides an indication of the accuracy of "unskilled" or climatological forecasts. Thus for Emerald, a simple "forecast" every year of "no frost," that is, no temperature below −1°C, would be correct 61% of years. The next column provides an indication of the accuracy obtainable by using the year and the May SOI as pre-

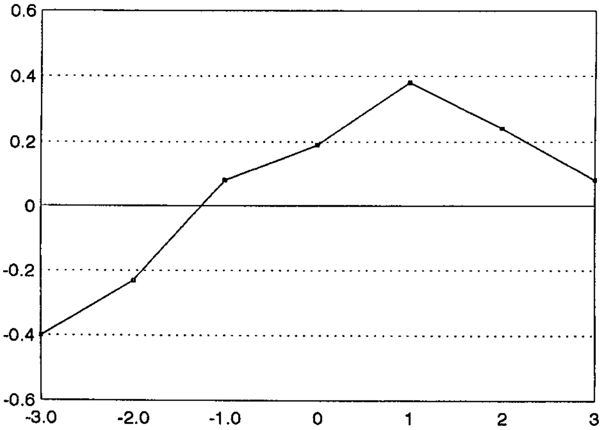


FIG. 6. Correlation May SOI with date of last frost—Biloela. Here *x*-axis: frost threshold (°C); *y*-axis: correlation.

TABLE 3. Summary of linear discriminant analysis with year and May SOI as predictors of whether at least one day of specific year will have temperature below threshold.

Station	Threshold (°C)	Percentage of years with no day below threshold	Percentage of years correctly allocated by LDA	Significance level
Emerald	−1	61	72	0.00001
Biloela	−3	57	67	0.004
Dalby	−3	56	62	0.01
Goondiwindi	−2	66	72	0.003
Roma	−3	56	63	0.02
Charleville	−3	58	64	0.006

dictors to discriminate between no frost years and frost years. LDA calculates the probability of the two groups (frost and no frost) and allocates each year to the group with the higher probability. The percentage of years correctly allocated in this way can be compared with the unskilled forecast. At Emerald LDA results in a correct allocation 72% of the time, compared to 61% for an unskilled forecast.

Application of the LDA approach shows the increased percentage of years allocated to the correct group is between 6% and 11%, relative to the climatological forecast. These increases are small but statistically significant. The last column in Table 3 shows the significance level of the LDA in discriminating the two groups. The discrimination for each station–threshold pair was clearly significant. At some of the stations, however, most of the skill arose from the trend (year) variable, with little contribution from the May SOI. This was the case for Emerald and Biloela. For the other stations the influence of the May SOI was at least as strong as that of the trend. LDA was also used with the April SOI replacing the May SOI. This was an attempt to determine whether earlier predictions of frost occurrence or nonoccurrence appeared to be feasible using this approach. The ''year'' was again used as the second predictor in the LDA. The results were generally disappointing. Most station–threshold combinations did not result in statistically significant results.

The generally small increases in the percentage of correct allocations obtainable by using LDA with the year and May SOI as predictors may appear disappointing. The percentage correct allocation does not, however, reveal all the utility of the LDA approach. LDA provides a simple method for predicting classification probabilities. These may be more useful in decision making than a simple allocation to one of two groups. The posterior classification probabilities for Charleville −3°C are shown in Fig. 7, along with an indication of the actual observed category, for the years 1971–1990. The years when temperatures below −3°C were recorded are indicated with a square at the top of the figure; years when no temperature below this threshold was observed are indicated by a square on the bottom axis.

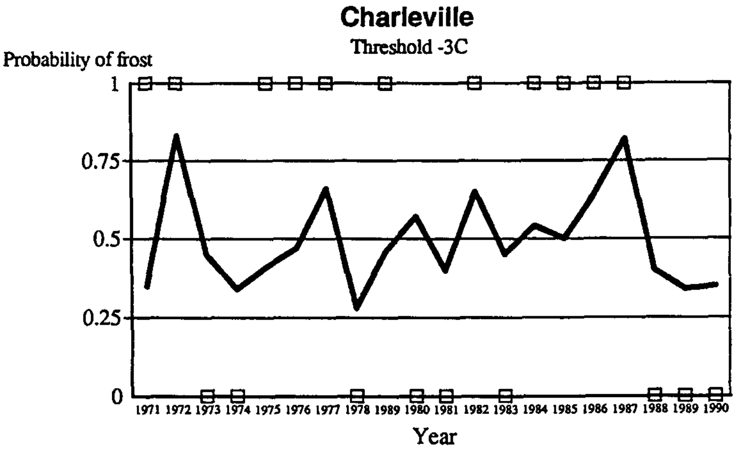
In some years, notably the El Niño years of 1972, 1977, 1982, and 1987, the probability of at least one day with a minimum temperature below −3°C at Charleville exceeded 0.65 (compared with a climatological probability of 0.42). In other years (e.g., 1978) the probability of a frost fell to less than 30%. The substantial changes in probability predicted by LDA, from year to year, suggests that this approach may be useful for some decision making purposes.

d. SOI phase analysis—date of last frost

Probability distributions of date of last frost at Roma provide an example of variation in dates of last frost corresponding to the SOI phase structure applied in the study. Figure 8 shows the probability distributions of date of last frost at Roma using all temperature thresholds in one degree steps from 3°C to −3°C (in the screen) following negative or rising SOI phases (phases 1 and 4) or negative or positive SOI phases (phases 1 and 2) in April–May.

Nonparametric significance tests (Kolmogorov–Smirnov, Walf–Waldowitz, Kruskall–Wallis) were applied to the probability distributions over all sites. Most significant discrimination occurred between SOI phases 1 and 2, phases 1 and 4, and phases 3 and 4, depending on location and temperature threshold being examined. An exception occurred at Goondiwindi where significant differences were more likely to occur between SOI phases 2 and 5, rather than between phases 1 and 2.

Differences in median date of last frost of 10 to 20 days were common between at least two of the phases at most locations, with the largest differences more likely to occur at the lowest temperature thresholds. Most significant differences in the distributions occurred between phases 1 and 4 and phase 1 and 2 (i.e., between a consistently negative and either a rapidly rising or consistently positive SOI pattern the previous April–May). Also, for example, the distributions indicate the risk of receiving a last damaging frost (e.g., 2°C in the screen) after day 250 (7 September) is 30%



Predictors: May SOI; year.

FIG. 7. Posterior classification probabilities and categories observed—Charleville −3°C. Here x-axis: year; y-axis: probability of frost.

following SOI phase 4 in April–May but rises to 80% following SOI phase 1.

A common and significant result across all locations and threshold temperatures was that a consistently negative SOI phase in April–May resulted in a high probability of a late date of last frost. Conversely, there was a high probability of an early date of last frost when a consistently positive or rising SOI phase occurred in April–May. Also, there tended to be greater discrimination at colder temperature thresholds (e.g., −2°C) than at warmer temperature thresholds (e.g., 2°C).

SOI phases for other time periods besides April–May suggested useful discrimination in date of last frost although, generally, not to the same degree of discrimination as the April–May phases. At Roma, for example, median dates of last frost associated with negative and rising SOI phases in April–May differed by 20 days and by 10 days according to the distributions associated with March–April phases.

Perhaps surprisingly, useful information on discrimination in date of last frost is provided by SOI phases known as early as February in the late austral summer. This suggests that, at most locations, considerable lead time (i.e., seven months) in forecast information is possible. At Dubbo, for example (Fig. 9) (1°C in screen) significant discrimination (at $p < 0.05$) is provided by SOI phases 2 and 4 in January–February, where differences of 28 days exist between the probability distributions. Note that the probability of latest date of last frost occurs following phase 2 in January–February (consistently positive SOI) suggesting La Niña-type austral summers (opposite conditions to the "warm" ENSO phase or El Niño) are frequently followed by negative SOI periods the following winter and consequent greater probability of a late frost. This result reflects the quasibiennial nature of ENSO or the tendency for warm (El Niño) events to alternate with cold (La Nina) events in adjacent years, with associated global reflection in climatic signals extending to remote regions (Kiladis and Diaz 1989).

Although median date of last frost has been used in this description of results, probabilities of exceeding a certain date on, say, 30% of occasions may be more appropriate where application to agricultural enterprises are concerned, reflecting a farmer's acceptable level of risk. In many instances the split in distributions of date of last frost according to the SOI phases was greater at the 30% level of exceeding than at the median level.

e. SOI phase analysis—number of frosts

Considerable variability occurred in numbers of frosts depending on which SOI phase occurred the pre-

TABLE 4. Median number of occasions temperature threshold of 0°C in the screen (i.e., number of days of frost) associated with April–May SOI phases 1, 3, and 4. (Distributions significantly different at the 5% level are shown as [a], at the 1% level as [b].)

	SOI phase 1	SOI phase 3	SOI phase 4
Emerald	1	3	0
Biloela[a]	15	14	6
Dalby[a]	13	17	10
Charleville	13	14	7
Roma[b]	29	18	10
Goondiwindi[a]	6	8	2
Moree	12	15	7
Tamworth	17	24	14
Dubbo[a]	17	19	10

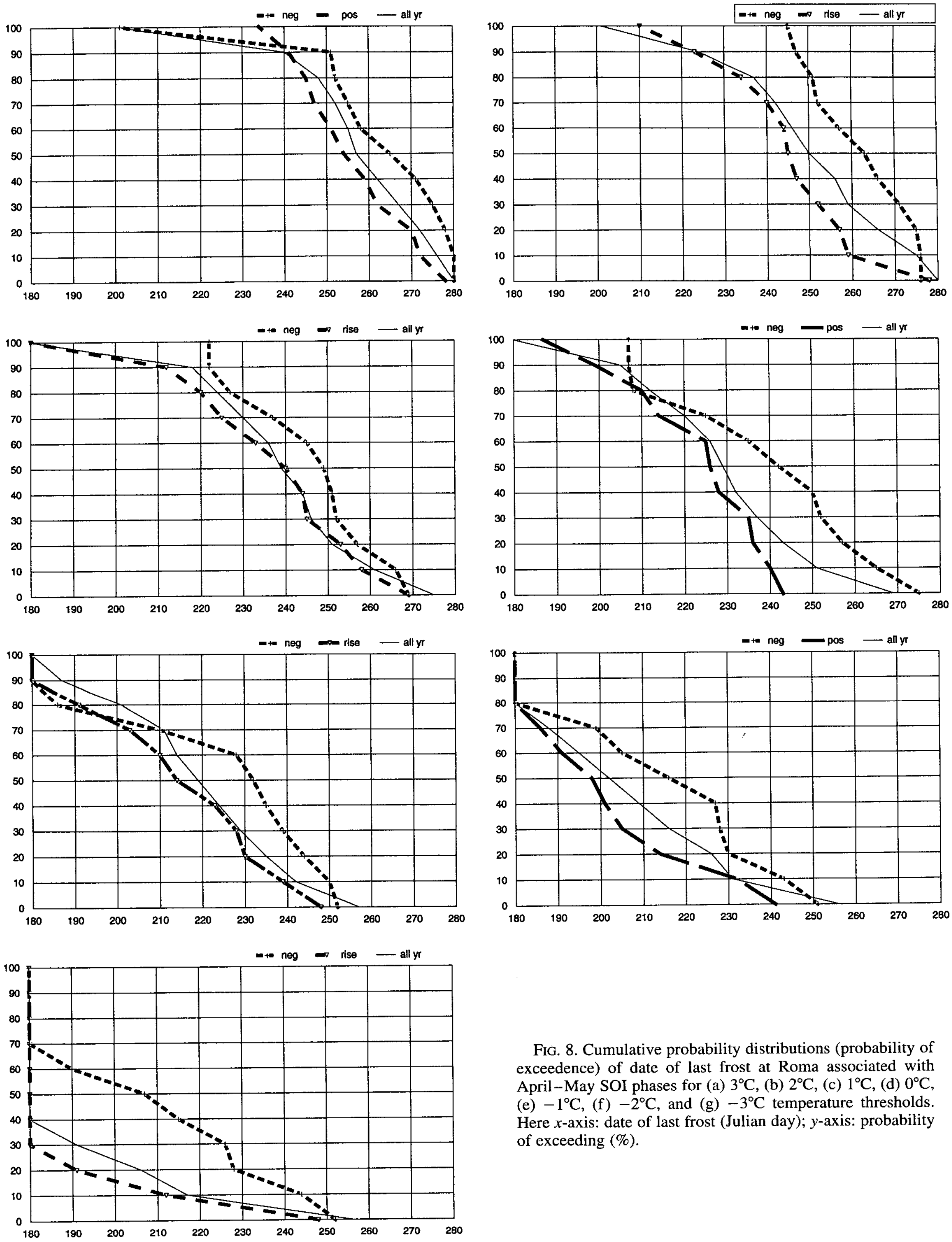


FIG. 8. Cumulative probability distributions (probability of exceedence) of date of last frost at Roma associated with April–May SOI phases for (a) 3°C, (b) 2°C, (c) 1°C, (d) 0°C, (e) −1°C, (f) −2°C, and (g) −3°C temperature thresholds. Here *x*-axis: date of last frost (Julian day); *y*-axis: probability of exceeding (%).

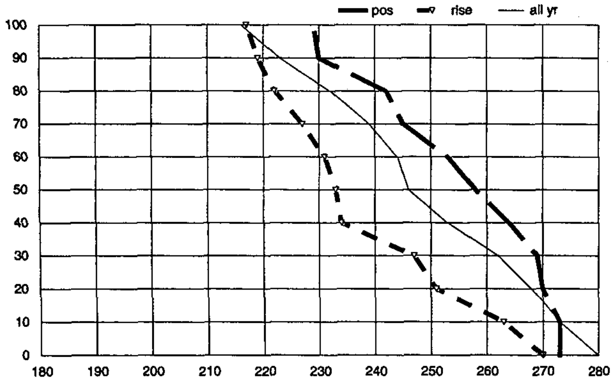


FIG. 9. Cumulative probability distributions (probability of exceedence) of date of last frost at Dubbo (1°C threshold in the screen) associated with January–February SOI phases 2 and 4. Here *x*-axis: date of last frost (Julian day); *y*-axis: probability of exceeding (%).

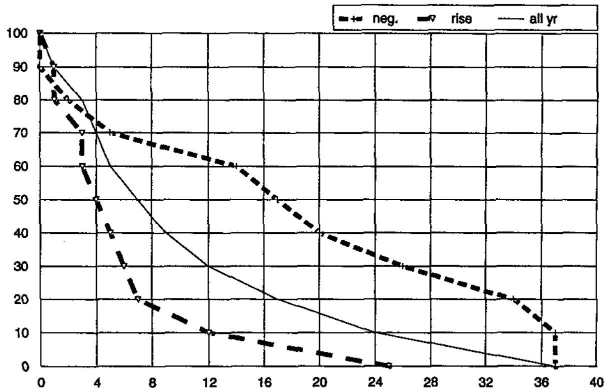


FIG. 10. Cumulative probability distributions (probability of exceedence) of numbers of frosts at Roma (−1°C threshold) associated with April–May SOI phases 1 and 4. Here *x*-axis: date of last frost (Julian day); *y*-axis: probability of exceeding (%).

vious April–May (Table 4). Figure 10 shows the cumulative probability distributions for number of frosts associated with consistently negative (phase 1) and rapidly rising SOI (phase 4) for a temperature threshold of −1°C in the screen at Roma. The median number of frosts varied between 4 following SOI phase 4 and 17 following SOI phase 1. Figure 11 shows the level of discrimination in number of frosts following phases 3 and 4 in April–May for Charleville. The example shown is representative for most of the stations analysed. The figure shows the median number of frosts following a rapidly falling SOI phases is 35, while the number of frosts following a rapidly rising SOI phase is 22. Furthermore, the figure shows the probability of receiving 30 frosts a year increases from 20% following a rapidly rising SOI phase to 70% following a rapidly falling SOI phase (significant at $p < 0.05$).

4. Discussion and conclusions

a. SOI phase frost prediction

While not a perfect predictor, the SOI, and particularly SOI phases, appear to provide modest skill in predicting date of last frost and number of frosts. Lead times of three to four months or more appear to be feasible. This would provide useful, timely information for agricultural and other enterprises. For example, the SOI phases for January–February provide skill in partitioning probability distributions of date of last frost seven or more months in the future. Updated forecast information would be available using April–May SOI phases, available at the end of May.

SOI phases representing either consistently negative or rapidly falling SOI during late austral autumn appear to provide most of the forecast skill as probability distributions that follow these phases indicate the highest probability of a late date of last frost, depending on the temperature threshold being analysed. Conversely, a rapidly rising SOI pattern in late autumn suggests an earlier date of last frost. These results may suggest the developing stage of an El Niño event and subsequent high probability of below long-term median rainfall over much of the study area is associated with a *high* probability of late date of last frost and greater numbers of frost events. Conversely, a rapidly rising (or consistently positive) SOI pattern in late autumn may suggest the decaying stage of an El Niño event, an associated high probability of at least the long-term median rainfall, and a consequent *low* probability of a (damaging) late frost or large numbers of frosts in the winter–spring season. Indeed, for many station–threshold combinations, more than 50% of years recorded no frost.

The reasons for forecast skill existing for many locations as early as the end of February is not clear. The occasional association between a positive SOI

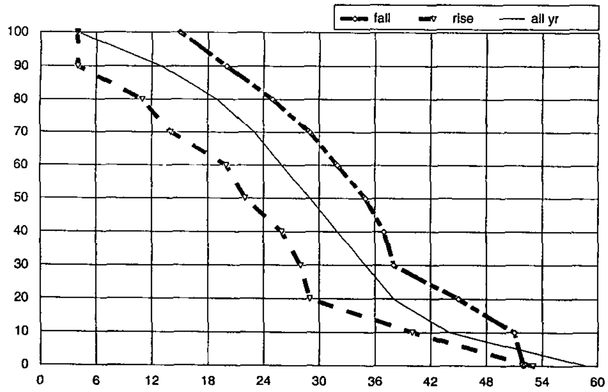


FIG. 11. Cumulative probability distributions (probability of exceedence) of numbers of frosts (2°C threshold) at Charleville associated with SOI phases 3 and 4 in April–May. Here *x*-axis: number of frosts; *y*-axis: probability of exceeding (%).

pattern in January–February and late date of last frost the subsequent autumn implies a changeover from positive SOI periods in the austral summer to negative SOI patterns in the austral winter (cf. Rimmington and Nicholls 1993). At most locations, the highest probability of an *early* date of last frost is following a rapidly rising SOI pattern the previous January–February.

The association of number of frosts in the winter–spring period with previously occurring SOI values or patterns is both consistent and significant. Negative or falling SOI patterns late in autumn suggest a subsequent greater number of frosts than normal, while rapidly rising or consistently positive SOI patterns suggest a winter with fewer numbers of frosts. In application to an operational forecasting system, we suggest combining SOI phases (e.g., in April–May combining phases 1 and 3, in January–February combining phases 1 and 5) may be useful to increase number of cases and statistical significance of results.

b. Trend in frost data

We were surprised by the trend or shift toward fewer numbers of frosts and earlier date of last frost at many of the locations, especially those more northeastern stations. However, earlier work by Jones (1991) and Jones and Henderson-Sellers (1992) suggested minimum temperatures were rising over much of northeastern Australia and our results tended to confirm that finding. Trends at the locations analyzed may reflect the influence of their proximity to a warming Coral Sea. Lough (1992, 1995) identified significant (at 1% level) warming in waters close to the Queensland coast between 1956 and 1987, while waters to the north of New Guinea showed a cooling trend. SST warming was especially marked in the austral winter, although it was less evident in summer SST. Nevertheless, association of increase in winter SST with decrease in date of last frost and numbers of frosts at the more northeastern stations in Australia may be significant. Trends in date of last frost and numbers of frosts also appear to be similar to world trends in minimum temperature (e.g., Karl et al. 1993). The trend in numbers of frosts appears to be negatively correlated with the trend in winter (July) SOI.

Station records suggest site location and observation standard were mostly of high quality, although Emerald and Dalby have suffered from the occasional problem over the past 100 years. However, it is suggested these trends, where they occur, are real. The significance of these trends in frost number and date of last frost (if they continue) for enterprises such as agriculture is high since frost damage is responsible for many millions of dollars in lost production for winter crops in Australia, especially wheat.

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