Quart. J. R. Met. Soc. (1979), **105**, pp. 707–719

551.524.34 (94)

Recent variations in annual-mean maximum temperatures over Australia

By M. J. COUGHLAN
Bureau of Meteorology, Melbourne, Australia

(Received 18 July 1978; revised 27 November 1978)

SUMMARY

A data set of annual-mean maximum temperature variations over the Australian continent, including Tasmania, for the period 1946 to 1975 has been prepared, using all available data. From this data set, trends over the 30-year period indicate a space scale of variability typically less than 1500 km. Most of Australia has experienced a rise in annual-mean maximum temperature over the period although the proportion which has experienced a fall is not insignificant. This has implications for the determination of hemispheric trends in temperature south of the equator.

Comparisons between annual-mean maximum temperature anomalies and annual rainfall are made, which show that there is no strong overall relationship. Typically negative correlations do emerge, however, when comparisons are made between temperature variations and the two major patterns of rainfall derived from a principal component analysis. It is further demonstrated that the pattern of trends in temperature can be related to a large extent to the trends in circulation features to which these two major patterns have been ascribed: the Southern Oscillation, and the mean latitude of the high pressure belt over eastern Australia.

1. INTRODUCTION

Investigations of climatic temperature fluctuations in Australia to date have been carried out, using selections of station records from the total available. Deacon (1953), in a review of climatic change in southeast Australia from 1880 to 1950, noted that inland annual-mean maximum temperatures during the second half of the period were appreciably lower than during the first half. He found that the change was due largely to a fall in daytime summer temperatures.

Unfortunately, exposure of thermometers in Australia prior to 1910 varied from state to state, and many stations were using the open-fronted Greenwich screen which generally leads to higher daily maximum temperatures being recorded than would be the case with the fully enclosed Stevenson screen. The latter was introduced as the standard when meteorological services throughout the country became a Federal responsibility.

More recently, Tucker (1975) investigated annual-mean temperature trends from 1957 to 1973 and noted that there had been a tendency for a rise in the average of the annual-mean temperature for some thirty stations. He noted further the spatial coherence on a sub-continental scale of fairly large trends which can be observed over time intervals of five to seven years. Damon and Kunen (1976) and Salinger and Gunn (1975) looking at annual-mean temperatures, and Coughlan (1978) looking at annual-mean maximum temperatures, also noted that warming trends appeared to dominate in recent years in the station records chosen for their studies.

The space scale of variability which can be described by a sample of observations from an area is determined firstly by the number of observations in the sample, secondly by the distribution of the sample over the area. The fewer the observations and the less evenly they are distributed, the greater the chance of bias in the representativeness of the data sample. In addition, where there are doubts about the reliability of the records, one cannot be confident that the station records chosen will reflect only climatic variations and not also those due to changes in site conditions, instrument types or observing practices. Little work has been carried out on Australian climatological records into this problem of reliability. Ideally one should employ the techniques described by Mitchell (1961) to determine the most accurate record for a locality. For a country the size of Australia such a task would be formidable.

In each of the studies mentioned above, the records were chosen chiefly on the basis of completeness in a series and also with due regard to the increasing urban 'heat island' effect at major centres of population. The present study set out to use as many station records of annual surface temperature as were available in the Australian Bureau of Meteorology data bank to prepare a continuous data set for the whole country over the period 1946 to 1975. Recognizing that daily maximum temperature and daily minimum temperature are to a large extent measurements related to different atmospheric processes, it was decided from the outset not to consider daily mean temperature, i.e. the arithmetic average of maximum and minimum. As explained below, ultimately only maximum temperature was considered.

The purpose of this paper is to use the data set to determine the space scales of climatic variability of surface temperature, to ascertain the proportion of Australia which has experienced the warming trend detected in earlier studies, and also to identify and investigate the probable mechanisms underlying this variability of temperature.

2. PREPARATION OF DATA SET

An initial scan through the primary data set of annual-mean temperature records for Australia revealed that fewer than thirty stations had a complete record for the thirty years 1946–1975; most of these were clustered in the more densely populated southeast corner of the country. It was then decided to build up a data set of inter-annual differences in

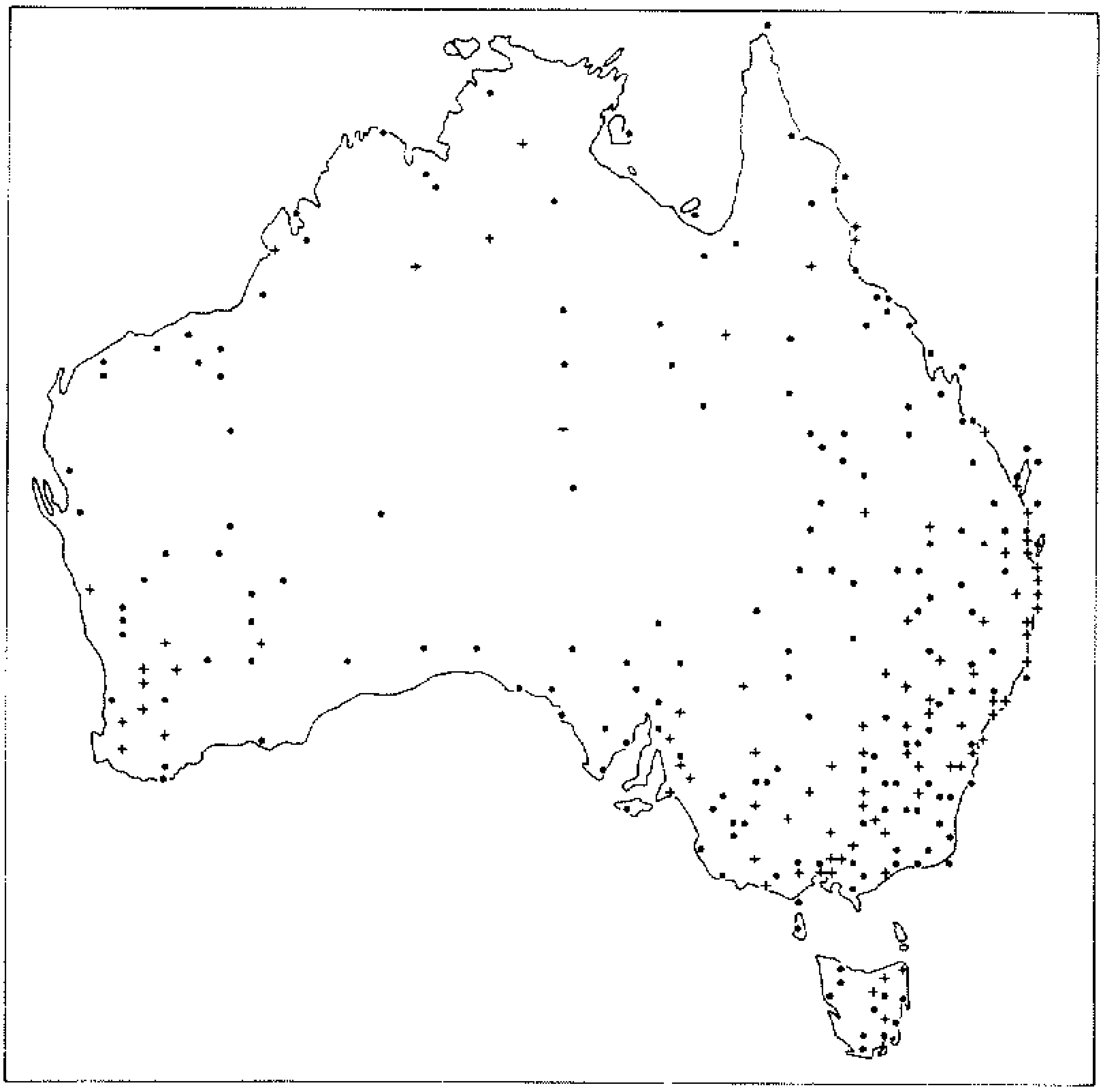

Figure 1. Typical distribution of stations obtained for each set of inter-annual mean-maximum temperature difference maps. Dots are individual stations, crosses denote more than one station within a 50 km radius.

temperature. These differences were calculated for all stations wherever and whenever possible, plotted on large scale maps, and isopleths drawn at 0·5 degC intervals. From these maps it was possible to detect any inconsistencies between nearby or adjacent stations where the resulting network allowed such comparisons.

Figure 1 shows a typical distribution of data points for each map. After 1956 there was an abrupt decrease in the number of station records available for each map (~450, down to around 300). This decrease was due to an administrative decision to reduce the number of records stored in computer-compatible form for climatological purposes. Fortunately, most of the reductions were in the more densely represented areas so that the overall representativeness did not deteriorate as much as one might have expected.

From the twenty-nine maps of inter-annual temperature differences, spot values on a 2° latitude–longitude grid were extracted. With the exceptions of the Gulf of Carpentaria, Bass Strait and other minor bays, etc., no attempt was made to infer air temperature changes over the sea. For each gridpoint, annual temperature anomalies for the thirty-year period were obtained as follows:

The series of n annual-mean temperatures at any gridpoint can be given as

$$T_1, T_1+t_1, T_1+t_1+t_2, \ldots, T_1+\sum_{i=1}^{n-1} t_i,$$

where $t_1, t_2 \ldots, t_n$ are the inter-annual differences. The average temperature for the whole period is

$$\bar{T} = (1/n)\{nT_1+(n-1)t_1+(n-2)t_2+\ \ldots\ +t_{n-1}\} = T_1+Q,$$

where $Q = (1/n)\{(n-1)t_1+(n-2)t_2+\ \ldots\ +t_{n-1}\}$. Thus yearly anomalies are given by: $\Delta T_1 = -Q$; $\Delta T_2 = t_1-Q$; $\Delta T_3 = t_1+t_2-Q; \ldots$; $\Delta T_n = \sum_{i=1}^{n-1} t_i - Q$.

With this procedure, spatial coherence in the maps of inter-annual-mean maximum temperature differences was sufficient to enable values to be extracted to an order of accuracy of around ±0·2 degC. However, in the corresponding minimum temperature maps, spatial coherence was so poor that it was difficult to draw meaningful isopleths at anything less than a 1 degC spacing; subsequent extraction of spot gridpoint values carried an accuracy of up to ±0·5 degC. It was evident that minimum temperatures are much more influenced by immediate local topography than are maximum temperatures, and that it would not be possible to use this technique on the former to obtain quantitative information about larger-scale atmospheric variability. For this reason it was decided to concentrate on annual maximum temperature anomalies.

It might be argued that maximum temperatures are also subject to local influences. For example, topography or land–sea differences may lead to greater variability in cloud cover and consequently in maximum temperatures. While this may be valid up to a point, the variations induced in daytime temperatures as a result of local influences can still be largely related to forcing by the broader-scale atmospheric circulation, with the exception of some sea breeze circulation systems. On the other hand, with more stable conditions generally prevailing at night, it is the topography itself which is more likely to be the dominant factor 'driving' the local circulation. The investigation of minimum temperatures on a seasonal basis may prove to be less troublesome.

It should be borne in mind that since large-scale year-to-year differences in mean weather patterns can lead to annual-minimum temperature anomalies that are ultimately as much a function of topography, then so too will topographic effects be incorporated into annual mean temperature anomalies.

One aspect of the method of preparation of the data set requires some comment. The use of first differences to derive anomalies introduces a potential for cumulative error which in the worst possible case, i.e. of a consistent error of one sign at a gridpoint, would lead to a gross error in the calculation of Q. This could be overcome by using the first differences only to fill in gaps where necessary due to missing station data for any particular year. Analysis of actual annual maximum temperature maps could then be carried out. However, this approach would introduce significant topographical effects at some gridpoints and it would be difficult to interpolate with confidence at these points. An alternative would be to concentrate, as in earlier studies, on a sample of the more complete station records, and not to attempt the derivation of gridpoint values. However, it was felt that this alternative would compromise one of the main aims of the paper, that is, to ascertain a best estimate of the space scale of variability. All care was taken in the analysis and interpolation of the first differences, and, where possible, $T_n - T_1$ was checked against the total of the first differences. The subsequent results would appear to have justified use of the technique; however, they must be viewed in the light of this potential deficiency in areas where this check was not possible, notably in the sparse data regions.

3. TEMPERATURE TRENDS

To investigate the temperature trend over the thirty-year period at each gridpoint, Kendall's rank statistic, τ, was used: $\tau = 4P/n(n-1) - 1$. Here P is the total number of cases in a series $T_1 \ldots T_n$ in which $T_j > T_i$ for $j > i$. The coefficient τ may vary from -1 to $+1$. Its expected value in a random series is zero, and its variance is given by $\sigma_\tau^2 = 2(2n+5)/9n(n-1)$ (Kendall 1973).

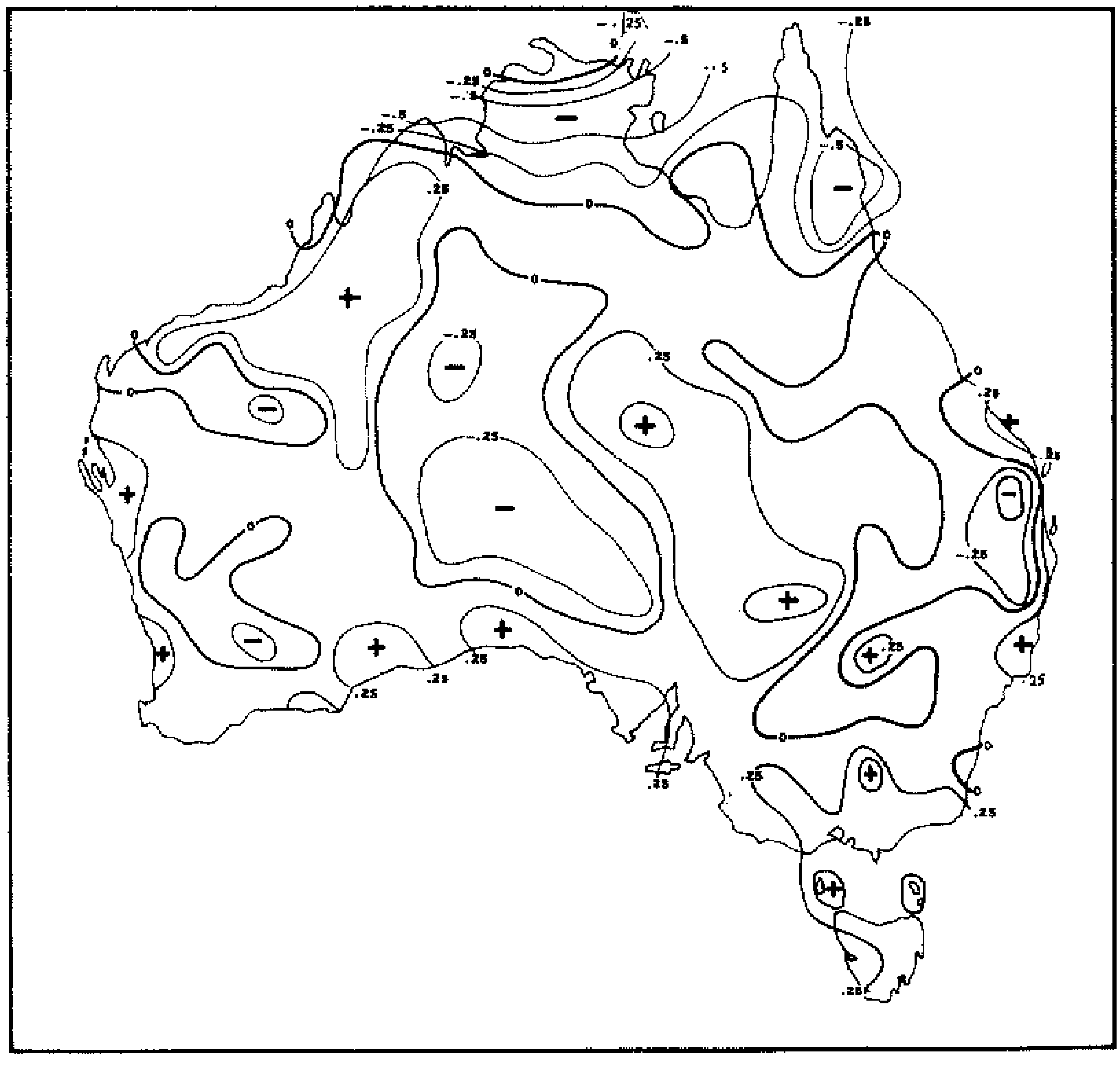

Figure 2. Value of Kendall's rank statistic giving the trend of annual-mean maximum temperature for the period 1946 to 1975. 95% confidence limits are approximately ±0·25.

The advantages of the rank statistic are that it is an equally good indicator of both linear and non-linear trend and is less affected by individual extreme values, particularly at the extremities of a series, than is simple linear regression. However, for a series of 30 elements the value of ±0·25 for the rank statistic (95% confidence level) is approximately equal to a slope of ±0·03 degC/year in a linear regression line, i.e. equivalent to a change of around ±1 degC over the 30-year period.

Figure 2 shows that between 1946 and 1975 about 62% of the country experienced an increase in annual-mean maximum temperature. If one considers only those areas with a rank statistic exceeding the 95% level, the assumption being that trends in all other areas could very well change sign with the addition of a few extra values at either end of the series, the proportions are as follows:

Significant rise	No significant rise or fall	Significant fall
22%	65%	13%

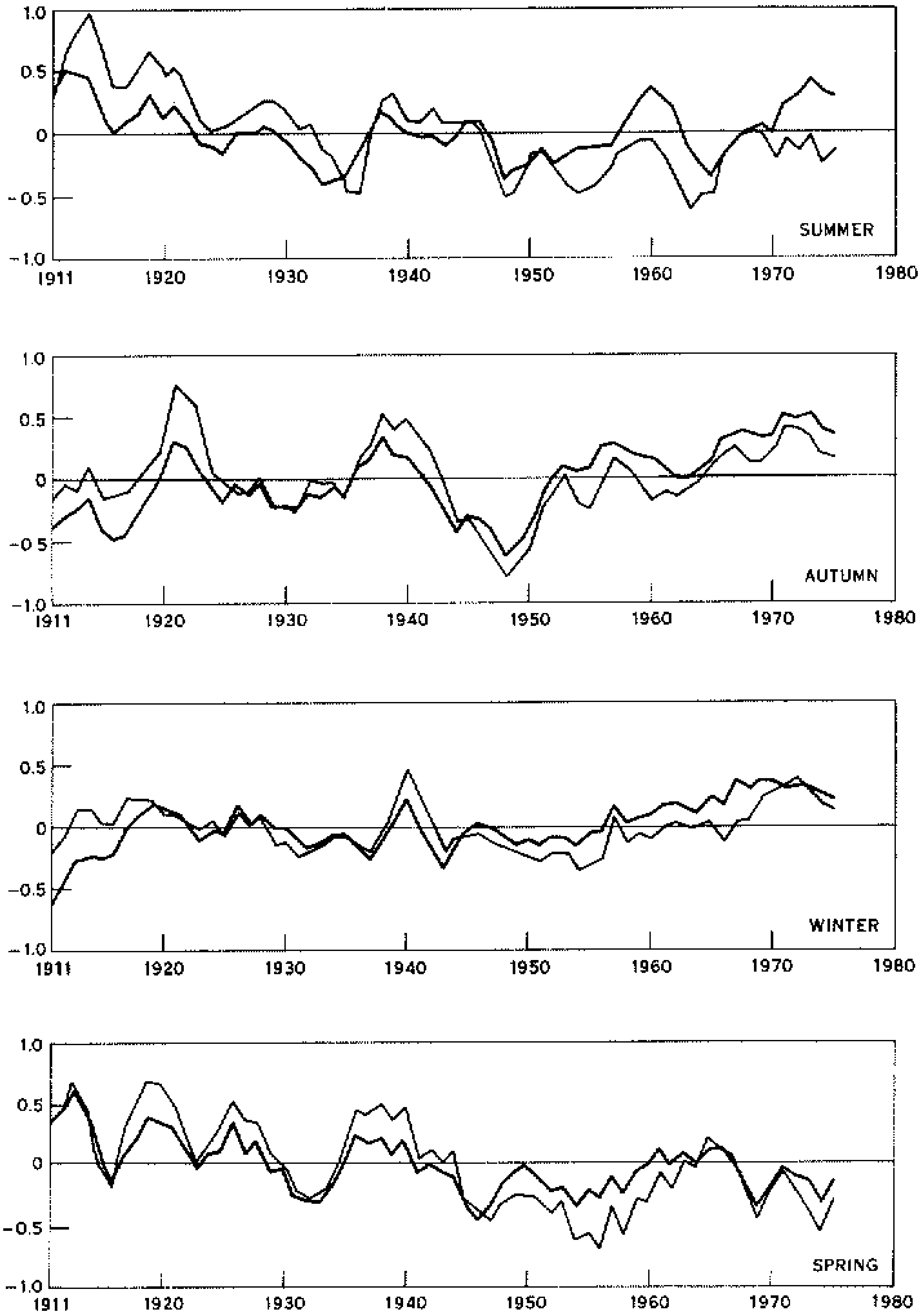

Figure 3. Five-year running means of seasonal mean-maximum temperature anomalies from 1911 to 1975 (deg C). Thick line: average of four major cities; thin line: average of nine provincial centres. End values are estimates only (Kendall 1973).

There is no doubt that the larger proportion of Australia has experienced a rise in annual-mean maximum temperature over this 30-year period. However, the area experiencing falls and the overall scale of variability (notwithstanding that the scale of variability over the oceans may be greater than that observed here over a land mass) would seem to confirm the reservations expressed by Kukla *et al.* (1977) and Streten (1977): that the necessarily selective samples of temperature records which have been used to date are insufficient to infer hemispheric trends of temperature south of the equator, e.g. Damon and Kunen (1976), Angell and Korshover (1977).

It is interesting to note that there has been a significant fall in annual-mean maximum temperature through much of the northern Australian tropical regions, while the far southern regions have experienced a significant rise. One would like to know whether such changes are a feature of one particular season or are spread throughout the year. An earlier, unpublished study by the author showed that for the southeastern part of the country, the major rises for the period 1946 to 1975 appear to have occurred in autumn (March–May) and winter (June–August). Figure 3 shows separately 5-year running means of seasonal maximum temperature anomalies from 1911 to 1975 for four major cities and nine provincial centres with small populations. While the urban heat island effect is more evident in the minimum temperature curves (not shown) it is probably still reflected here by the generally greater rate of increase in the urban curves. The records from the relatively few major urban centres in Australia were eliminated from this present study.

4. TEMPERATURE AND RAINFALL

A direct comparison between the annual-mean maximum temperature anomalies and annual rainfall totals was made, using a data set of district averages for the latter (Fig. 4).

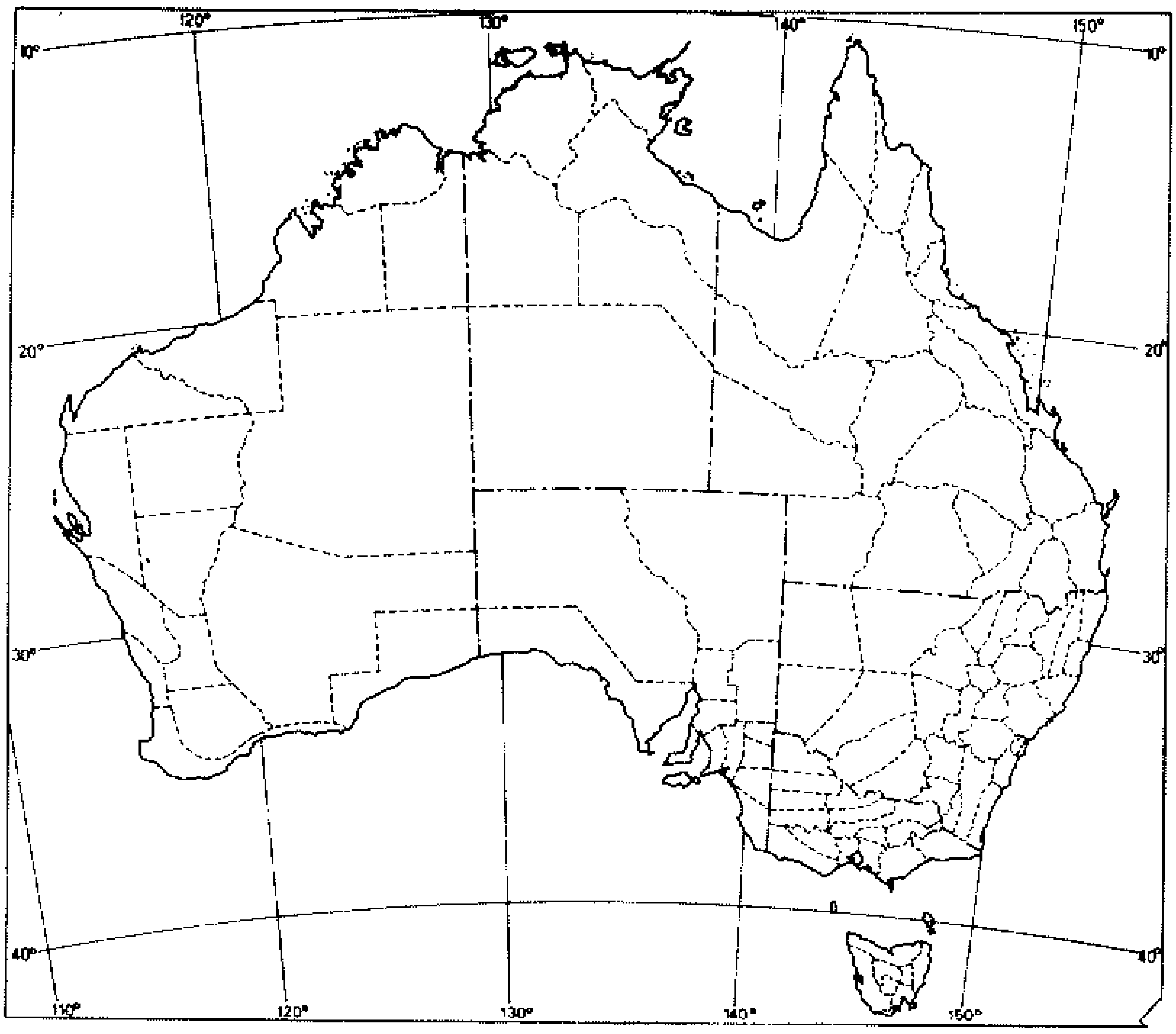

Figure 4. Disposition of rainfall districts in Australia. Annual-mean maximum temperature anomalies at gridpoints enclosed by each district were correlated with the annual totals of the district average rainfall to produce Fig. 5.

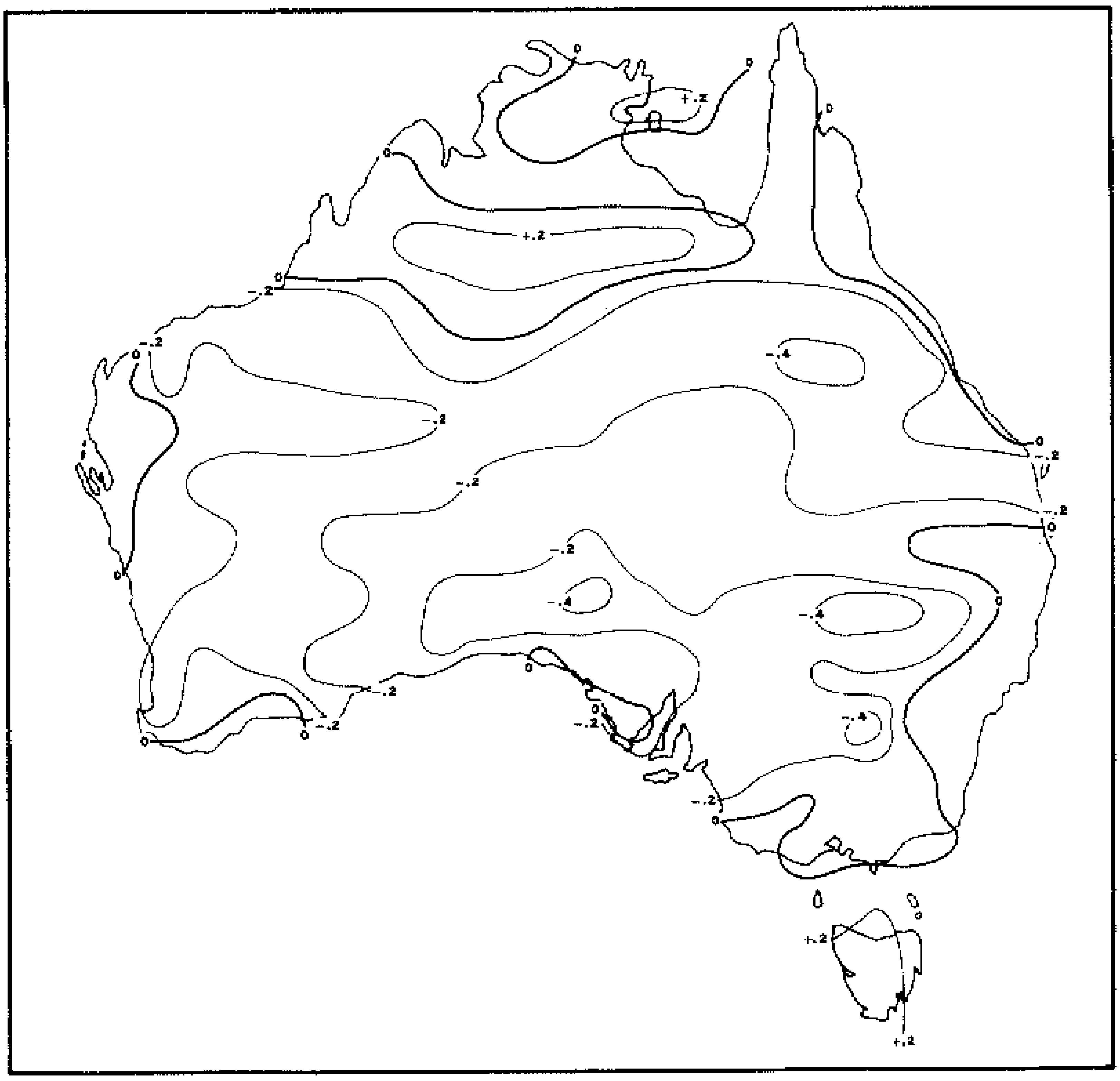

Figure 5. Correlation between annual rainfall and annual-mean maximum temperature anomalies from 1946 to 1975 after linear components have been removed. 95% confidence limits are approximately ±0·4.

The pattern of correlations which emerged (not shown) was similar in its gross characteristics to the trend pattern for temperature. This indicated that while, overall, there was a tendency for an inverse correlation between annual rainfall and mean maximum temperature, much of it could be attributed to the long-term trend. After removal of the linear trend, the pattern in Fig. 5 shows that correlation between annual rainfall and maximum temperature is mostly negative inland with a tendency for positive correlations nearer the coast, although the overall pattern is rather weak. Correlations carried out on a seasonal basis, such as Madden and Williams (1978) have derived for the United States and Europe, may lead to more meaningful patterns.

If, however, one takes the two major characteristic patterns of annual rainfall derived from a principal component analysis of the same data set over the period 1913–1975 (Figs. 6(a) and (b)) and correlates the annual coefficients for each pattern for the years 1946 to 1975 with the temperature anomalies for each gridpoint, clearer evidence of negative correlations between rainfall and temperature emerges (Figs. 7(a) and (b)).

Pittock (1975) has described the relationships between these first two characteristic patterns of annual rainfall and the Southern Oscillation (S) and the mean latitude of the high pressure belt along the east coast of Australia (L), respectively. The index S employed here is the mean sea level pressure difference, Papeete minus Darwin, normalized for each calendar month to a standard deviation equal to ten, and averaged again to obtain a mean annual value (Troup 1965). The importance of the index S as a measure of a rain-producing regime for Australia is further demonstrated by the fact that its annual value correlates with the area of above-average yearly rainfall at value of $r = +\cdot 66$ (significant at $<0\cdot 1\,\%$). In the same context, it is interesting to note that L acts in opposite senses on two approxi-

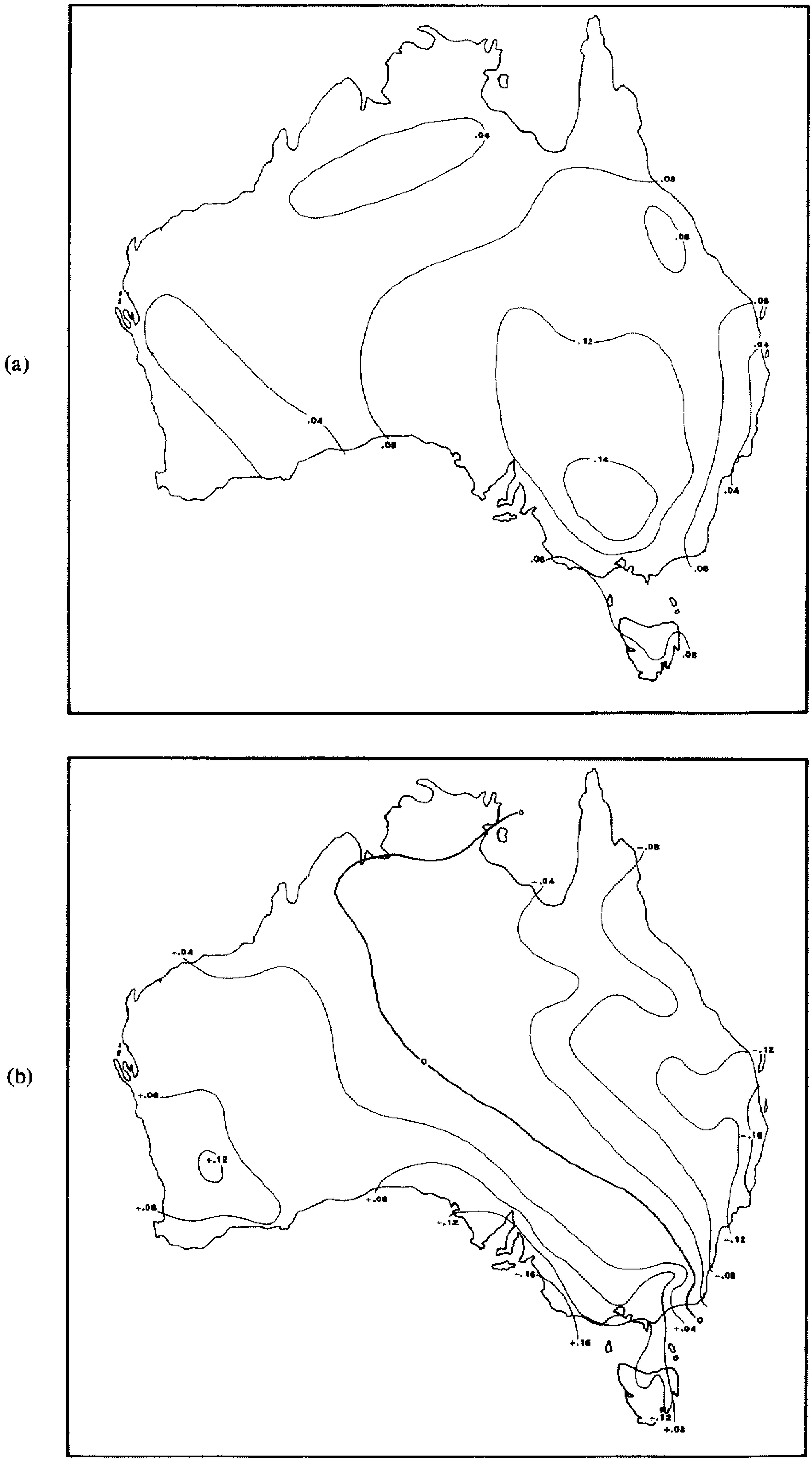

Figure 6. The first two characteristic patterns (CP) derived from a principal component analysis of the rainfall district annual averages (Fig. 4) for the period 1913 to 1975. (a) CP1 accounts for 38% of the normalized variance; (b) CP2, 16% (updated from Pittock 1975).

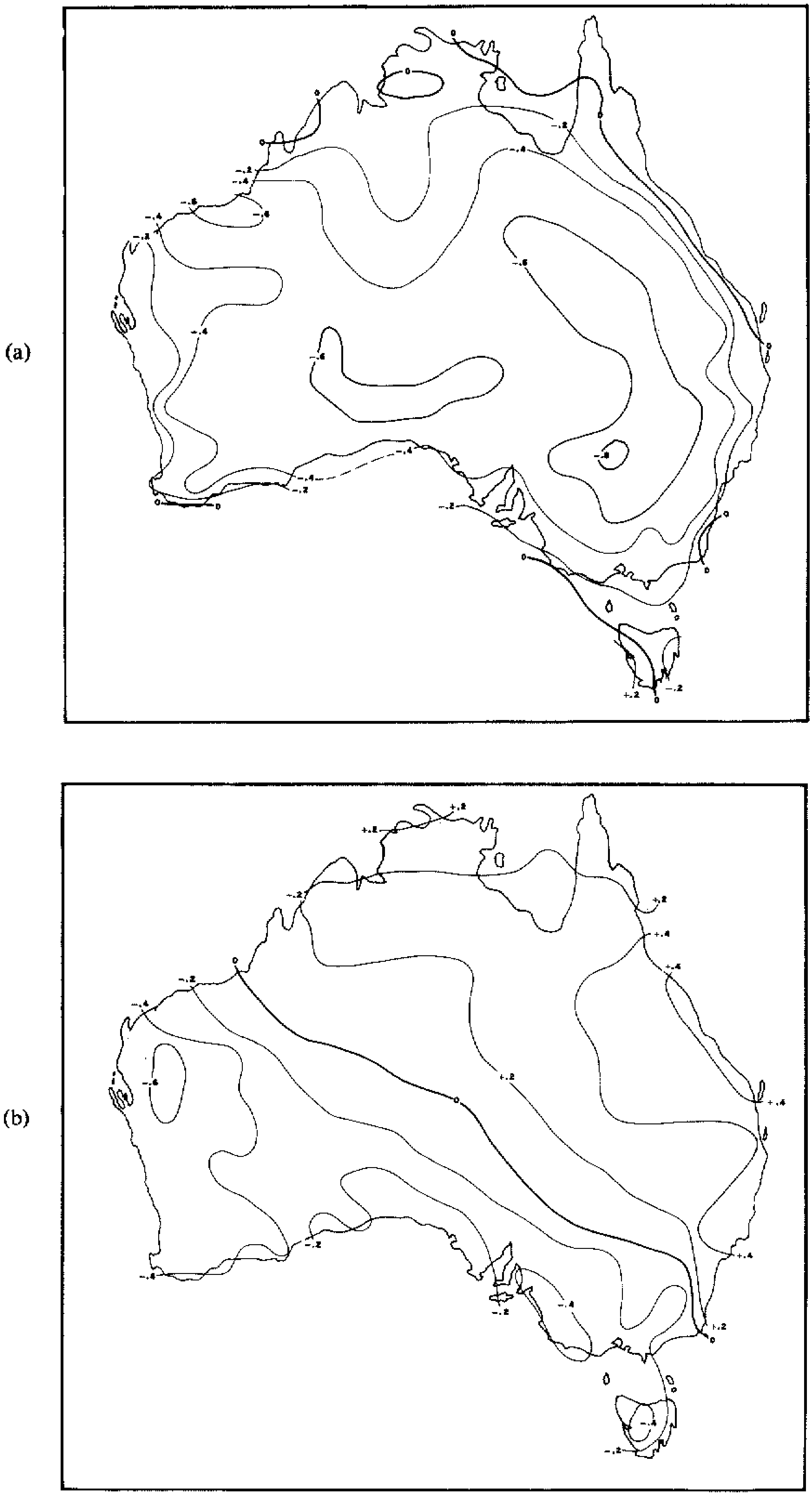

Figure 7. Correlations between annual-mean maximum temperature anomalies at each gridpoint and the coefficients of (a) CP1, (b) CP2, for the period 1946 to 1975. 95% confidence limits are approximately ±0·4.

mately equal areas of the country, the dividing line roughly corresponding to the boundary between winter and summer rainfall regimes; a correlation between L and the area of above-average yearly rainfall leads to a value of $r = +{\cdot}07$.

5. TEMPERATURE, S and L

S and L have been suggested to be indices of the standing wave pattern and the intensity of the Hadley circulation in the Australian region, respectively, although there has been some discussion of the exact nature of the latter relationship (Trenberth 1975, see also concurrent correspondence). If one correlates them directly with temperature anomalies, the patterns (Figs. 8(a) and (b)) are similar to those in Figs. 7(a) and (b), respectively. Thus the Southern Oscillation in its positive mode, which means a strengthening of the east-to-west Walker circulation between the eastern Pacific and Australia at low levels, results generally in lower temperatures (and higher rainfall) over much of inland Australia, particularly in the eastern half of the continent. There is, however, an interesting exception. It can be seen in Fig. 8(a) that in the far southeast of mainland Australia, and in particular over Tasmania, the correlation is positive (cf. Fig. 7(a)). A positive value of S is associated with generally low pressure over the Australian mainland; the reversal in sign of r in the far southeast is presumably due to a reduction in cloud cover as a result of:

(a) a greater prevalence of anticyclonic conditions there; or
(b) a drying out and warming, especially south of the low ranges lying east–west across central Victoria, of a mean flow from between north and east which could be associated with low pressure over the continent.

Correlations along the east coast are not significant probably because of the local and more random occurrences of sea breezes, which would affect maximum daytime temperatures, particularly in the warmer months.

Turning to the pattern of correlation between the latitude of the high pressure belt, L, and temperature anomaly, it can be seen that a poleward movement of its mean position will lead to low temperatures in the north and east of the country and high temperatures in the south and west and vice versa. The only exception is the small, non-significant, positively correlated area along the far north central coast. It will be remembered that this area also appeared anomalous in the pattern of trends in Fig. 2. Removal of the linear trend from L ($\tau = +0{\cdot}25$ is just significant at 95% confidence limit) and from the temperature anomalies, eliminated this area of weak positive correlation, although the overall pattern remained essentially unchanged. This could mean that there are errors in the data set in this area, which relies on one or two stations around Darwin. Subsequent enquiries into the history of the Darwin observing site did not reveal any indication of a major site change over the period, although there was some evidence of an increase in the number of buildings in the vicinity of the enclosure.

Another possibility for this area of positive correlation, somewhat speculative, is that a sufficient southward movement of the mean latitude of the high pressure belt could in fact result in higher temperatures in this area since the equatorial trough, which lies across the north of Australia in summer, may also be farther south in this season, while in winter the relatively cool southeast trades may be weaker. An analysis of pressure pattern variations over the period may clarify this point.

It is evident that the trend towards a more poleward position of the mean annual latitude of the high pressure belt would result in the observed temperature trends in southern and northern Australia shown in Fig. 2. In fact, if one superimposes the likely pattern of trend that would follow from a more positive Southern Oscillation index onto the one

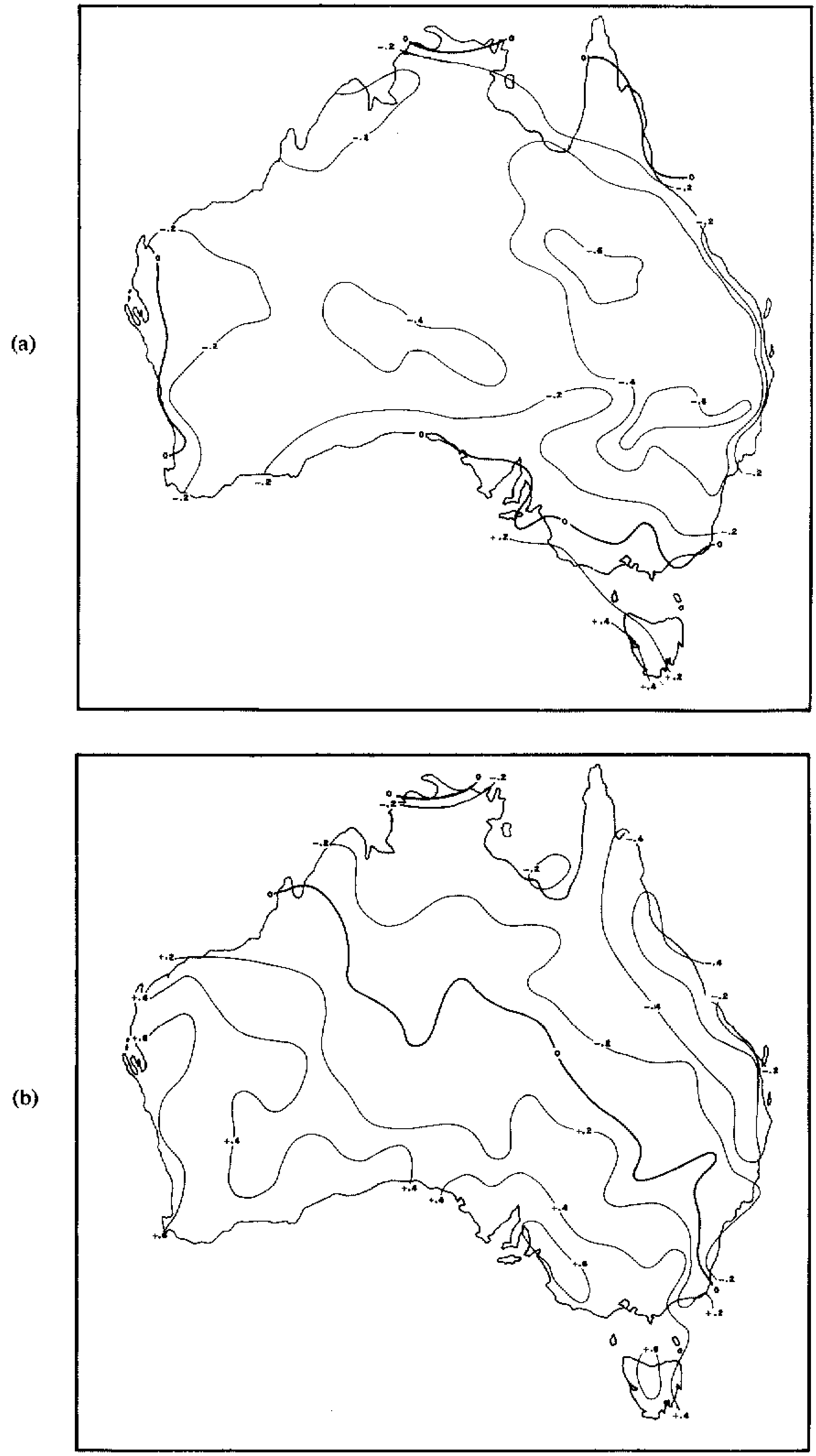

Figure 8. Correlations between annual-mean maximum temperature at each gridpoint and the mean annual values of (a) the Southern Oscillation index (*S*), (b) latitude of the high pressure belt along the east of Australia (*L*), for the period 1946 to 1975. 95% confidence limits are approximately ±0·4.

expected from a positive trend in *L*, the overall gross features of Fig. 4 are consistent. While the trend of *S* has not been statistically significant (95% confidence limit) over the period, it is none the less positive ($\tau = +0{\cdot}19$).

The patterns of variability in temperature and rainfall which can be ascribed to the two indices are of importance in attempts to derive extensions of the records of past atmospheric circulations in this region using proxy data, e.g. tree rings. For example, in Western Tasmania it would appear that while rainfall variations are determined more by changes in *L* than in *S*, temperature variations are determined more equally by both *L* and *S*. However, it must be remembered that this study has used annual calendar means; the growing season for this area overlaps the end of one year into the next. A similar analysis to the one carried out here using maximum temperatures averaged and rainfalls summed over a period more related to the growing season may prove to be of more value.

6. Conclusions

The technique employed in this study has enabled the preparation of a relatively homogeneous data set of annual-mean maximum temperature anomalies for Australia on a sufficient scale to determine a pattern of temperature trends for the period 1945 to 1975. Hitherto, studies have shown that the southern hemisphere, and Australia in particular, appears to have experienced a warming during this period. The results presented here show that while this does appear to be the case for Australia taken as a whole, the space scale of rises and falls confirms doubts about quoted hemispheric temperature trends, given the necessarily selective and limited data which have been investigated to date.

The two circulation indices identified by Pittock (1975) as being important for explaining the variance of annual rainfall over much of Australia are shown to be probably of comparable importance in determining the variability of annual-mean maximum temperature. The trends in *L* and *S* over the period 1946–1975 would appear to go a long way towards explaining the patterns of observed trends in this parameter. On the other hand, annual-mean minimum temperatures would seem to be as much, if not more, influenced by secondary effects of local topography.

Acknowledgment

Permission from the Director of Meteorology in Australia to publish this paper is gratefully acknowledged.

References

Angell, J. K. and Korshover, J. 1977 Estimate of the global change in temperature, surface to 100 mb between 1958 and 1975, *Mon. Weath. Rev.*, **105**, 375–385.

Coughlan, M. J. 1978 Changes in Australian rainfall and temperature, in *Climatic change and variability, a southern perspective*, Camb. Univ. Press 194–199.

Damon, P. E. and Kunen, S. M. 1976 Global cooling, *Science*, **193**, 447–453.

Deacon, E. L. 1953 Climatic change in Australia since 1880, *Aust. J. Physics*, **6**, 209–218.

Kendall, M. G. 1973 *Time series*, Griffin, London.

Kukla, G. J., Angell, J. K., Korshover, J., Dronia, H., Hoshiai, M., Namias, J., Rodewald, M., Yamamoto, R. and Iwashima, T. 1977 New data on climatic trends, *Nature*, **270**, 573–580.

Madden, R. A. and Williams, J. 1978 The correlations between temperature and precipitation in the United States and Europe, *Mon. Weath. Rev.*, **106**, 142–147.

Mitchell, J. M., Jr. 1961 The measurement of secular temperature change in the Eastern United States. *Res. Paper No. 43*, U.S. Dept. of Commerce, Weather Bureau.

Pittock, A. B. 1975 Climatic change and the patterns of variation in Australian rainfall, *Search*, Sydney, **6**, 498–504.

Salinger, M. J. and Gunn, J. M. 1975 Recent climatic warming around New Zealand, *Nature*, **256**, 396–398.

Streten, N. A. 1977 Aspects of the year-to-year variation of seasonal and monthly mean station temperature over the southern hemisphere, *Mon. Weath. Rev.*, **105**, 195–206.

Trenberth, K. E. 1975 A quasi-biennial standing wave in the southern hemisphere and interrelations with sea surface temperature, *Quart. J. R. Met. Soc.*, **101**, 55–74.

Troup, A. J. 1965 The Southern Oscillation, *Ibid.*, **91**, 490–506.

Tucker, G. B. 1975 Climate: Is Australia's changing?, *Search*, Sydney, **6**, 323–328.