NOTES AND CORRESPONDNECE

Dependence of Rainfall Variability on Mean Rainfall, Latitude, and the Southern Oscillation

N. NICHOLLS AND K. K. WONG

Bureau of Meteorology Research Centre, Melbourne, Australia

17 March 1989 and 21 July 1989

ABSTRACT

The relationship between the relative variability of annual rainfall, the long-term mean annual rainfall, the latitude, and the correlation between annual rainfall and the Southern Oscillation Index is examined, using data from 974 stations. A nonlinear relationship between these variables accounts for 94% of the variance in annual rainfall variability. Relative variability typically increases as mean annual rainfall decreases, as latitude decreases, and as the effect of the Southern Oscillation increases. There is an interaction between latitude and the Southern Oscillation so that the effect of the Southern Oscillation on variability weakens as latitude increases.

1. Introduction

Conrad (1941) examined the dependence of interannual rainfall variability on the long-term mean annual rainfall, using data from 384 stations spread across the globe. He defined the relative variability of annual rainfall as the mean of the absolute deviations of annual rainfalls from the long-term mean, expressed as a percentage of the long-term mean. Conrad found that a function relating relative variability to mean precipitation fitted his data very well. The relative variability decreased, in general, as the mean precipitation increased. Over some large areas, however, the relative variability deviated consistently from the global relationship with mean rainfall.

Some of these deviations were due to the influence of the El Niño–Southern Oscillation (ENSO) phenomenon on rainfall. Using Conrad's data, Nicholls (1988) compared the relationship between relative variability and mean rainfall in areas affected by ENSO with the relationship elsewhere. The relative variability was typically one-third to one-half higher for ENSO-affected stations compared with stations with the same mean rainfall in areas not affected by ENSO. McMahon et al. (1987) have shown that rainfall (and streamflow) variability is higher in Australian and southern Africa (both areas affected by ENSO) than elsewhere.

This study extends and confirms the studies of Conrad and Nicholls. More stations have been used, with recent data (the data used by Conrad and Nicholls were from before 1941). A more conventional definition of relative variability, the coefficient of variation, is used in preference to Conrad's definition. The functional dependence of the variability on ENSO's influence is examined in more detail rather than simply dividing stations into a group affected by ENSO and a group not affected [as was done in Nicholls (1988)]. The effect of latitude on variability is also considered. Mean annual rainfall and the effect of ENSO on rainfall tends to be larger in low latitudes so the results of Conrad and Nicholls might just reflect an effect of latitude on variability. Explicit inclusion of latitude, as well as mean rainfall and the effect of ENSO, in this study should allow consideration of this possibility. A nonlinear function relating the coefficient of variation of annual rainfall to mean annual rainfall, latitude, and the effect of the Southern Oscillation is determined.

2. Data and method

The data used here were obtained from the NCAR surface climatology dataset. All stations with at least 25 years of annual rainfall totals post-1950, a total of 974 stations, were used. Their locations are shown in Fig. 1. Three hundred of the stations are from Australia, raising the possibility that any effect specific to Australia might be overrepresented when relationships are calculated with the total dataset. This possibility will be examined later.

For each station the long-term mean annual rainfall (P) and its standard deviation (s) were calculated. The coefficient of variation (V), the ratio of the standard deviation to the long-term mean (s/P), was calculated to provide a measure of the relative variability of annual rainfall.

A quantitative measure of the strength of the relationship between ENSO and the rainfall at each station was needed to examine the dependence of V on ENSO.

Corresponding author address: Dr. Neville Nicholls, Bureau of Meteorology Research Centre, Box 1289 K, G.P.O., Melbourne, Victoria 3001, Australia.

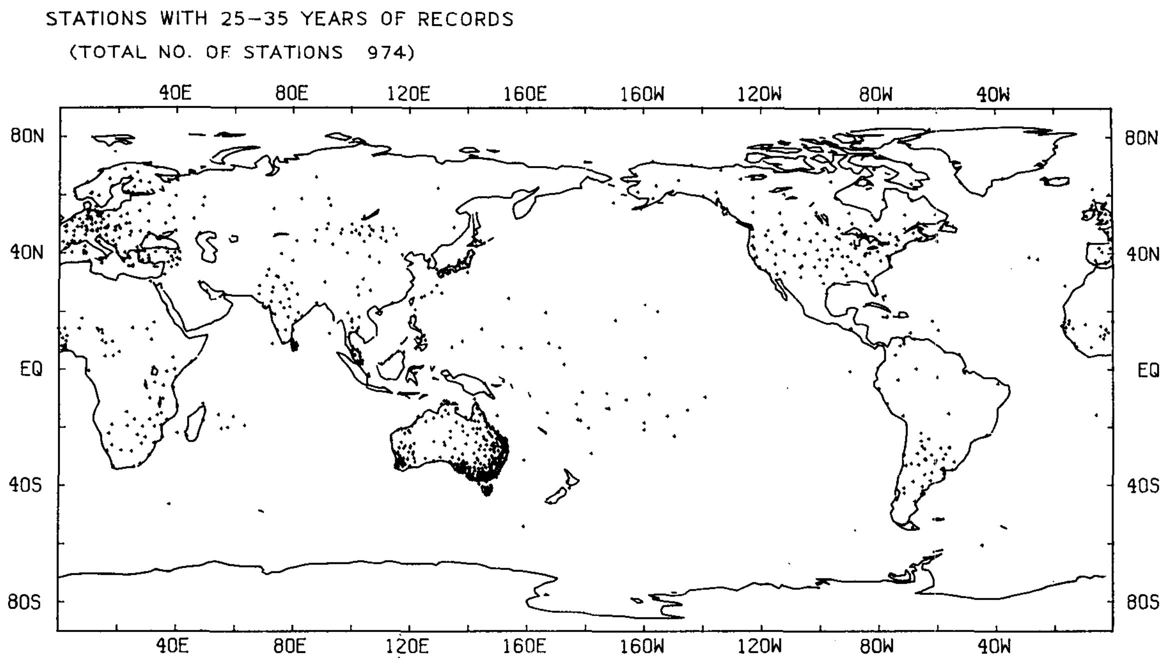

FIG. 1. Locations of the 974 stations used in this study. All stations had at least 25 years of annual rainfall totals since 1950.

The absolute value of the correlation between annual rainfall and annual values of the Southern Oscillation Index (SOI) was used as this measure. The SOI used here was the difference in pressure between Tahiti (17°S, 150°W) and Darwin (12°S, 131°E), standardized to a mean of zero and a standard deviation of 10. Monthly values of the SOI were provided by the National Climate Centre of the Australian Bureau of Meteorology. Annual values were calculated by averaging the 12 monthly values. The annual SOIs were then correlated with the annual rainfalls at the 974 stations and the absolute values of these correlations (R) were noted.

Preliminary work indicated that a relationship between latitude and rainfall variability existed. This relationship was strongest with the absolute value of the latitude (i.e., ignoring whether a station was north or south of the equator), so the absolute value of the latitude of each station (L) was noted. The elevation of the station was also noted since this might affect variability.

The correlations between variability, mean rainfall, latitude (unsigned), elevation, and the correlation of annual rainfall with the SOI (also unsigned) are listed in Table 1. Of the 974 stations with at least 25 years data since 1950, 19 did not have their elevation listed. This left 955 stations to calculate the correlations listed in the table. Elevation was not significantly correlated with variability and was not considered further. The other variables were all significantly correlated with each other, although most correlations were small in magnitude. Mean rainfall had the strongest relationship with variability, followed by latitude and the correlation with the SOI. As noted above, mean precipitation and the correlation of annual rainfall with the SOI are significantly correlated with latitude. The effects of mean rainfall, latitude and ENSO on the coefficient of variation are illustrated in Fig. 2, in which data from subsets of the stations used in this study are plotted. In Fig. 2a the observed coefficients of variation are plotted for two groups of stations; those with little correlation with the SOI and those with relatively strong correlations with the SOI. Stations with intermediate strength correlations (absolute correlations between 0.05 and 0.40) are omitted. Only low-latitude stations are used in this figure, to reduce the effects of latitude and thereby reveal the effect of the SOI more clearly. The figure reveals the strong nonlinear dependence of variability on the long-term mean rainfall noted by Conrad (1941) and Nicholls (1988) on earlier data. The form of this

TABLE 1. Correlations between the coefficient of variation of annual rainfall (V), mean annual rainfall (P), latitude (unsigned) of the station (L), correlation of annual rainfall with the SOI (also unsigned, R), and the elevation of the station (E). Data from 955 stations (all stations with at least 25 years data since 1950 and with station elevation noted in the NCAR surface climatology dataset). Correlations with magnitudes exceeding .11 are significant at the 1% level.

	V	P	L	R
P	−.40			
L	−.22	−.42		
R	.18	−.15	−.15	
E	.05	−.19	−.02	−.02

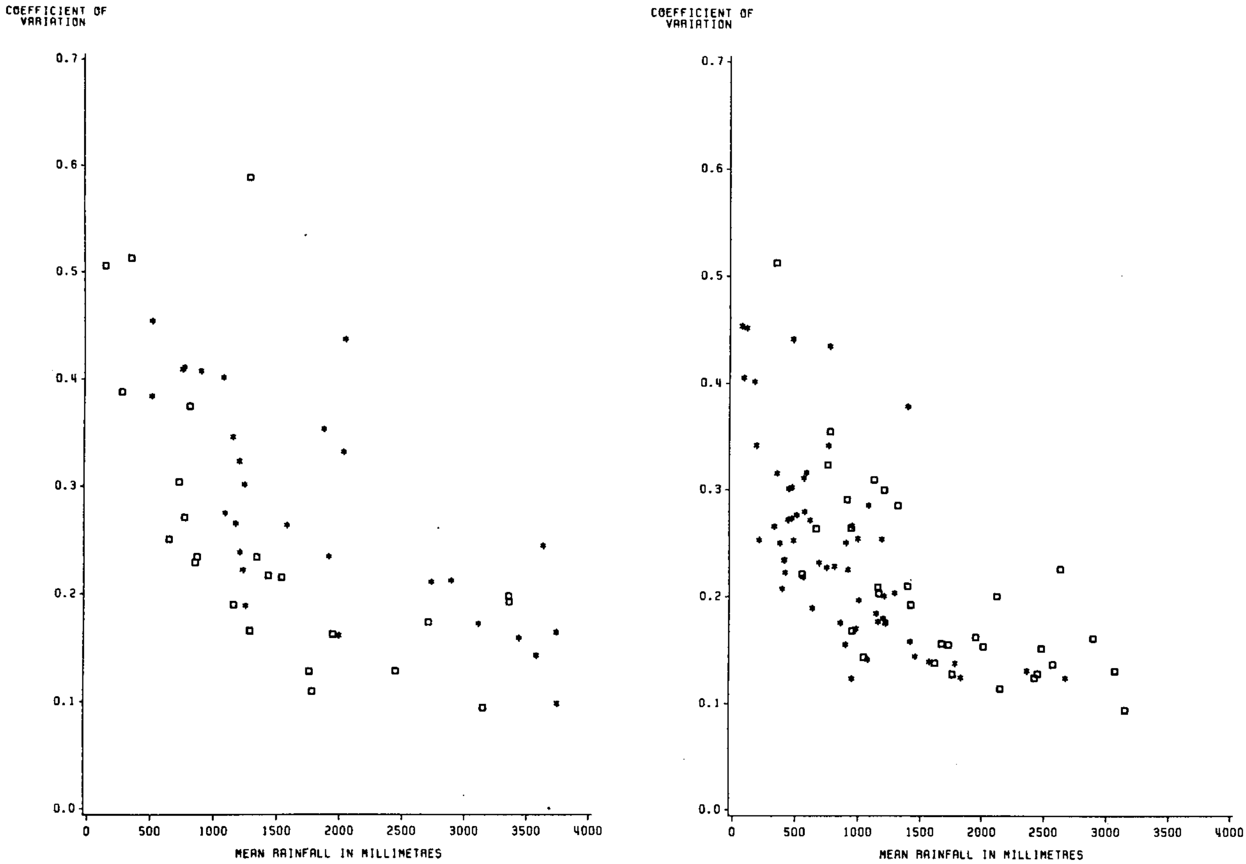

FIG. 2. (a) Observed coefficients of variation plotted against mean annual rainfall. Only stations with latitudes less than 20° have been plotted. Asterisks indicate stations with high correlation (positive or negative) with the SOI ($|R| > 0.4$). Open squares indicate stations with weak correlations with the SOI ($|R| < 0.05$). Stations with intermediate strength correlations with the SOI have not been plotted. (b) Observed coefficients of variation plotted against mean annual rainfall. Only stations with relatively weak correlations with the SOI ($|R| < 0.2$) are plotted. Asterisks indicate midlatitude stations (latitude 35°–40° north or south). Open squares indicate low latitude stations (latitudes less than 10° north or south). Stations with latitudes 10°–35° or greater than 40° are not plotted.

dependence is, of course, to be expected because long-term mean rainfall is the denominator in the definition of the coefficient of variation. A tendency for stations with annual rainfalls strongly correlated with the SOI to have more variable rainfall is also evident in Fig. 2a.

The effect of latitude is illustrated in Fig. 2b. Here only stations with weak correlations with the SOI are used and two groups of stations are plotted; low latitude stations (latitude less than 10° north or south) and midlatitude stations (35°–40° latitude, north or south). The rather narrow range band of latitudes from which the midlatitude stations were chosen was selected so that the numbers of low and midlatitude stations plotted in the figure would be approximately equal. The variability of the low latitude stations tends to be higher than for the midlatitude stations with similar mean rainfall, as expected from the correlations listed in Table 1. The results in Table 1 and Fig. 2 indicate that latitude and the SOI affect rainfall variability. Their explicit inclusion as independent variables is therefore necessary if a model of annual rainfall variability is to be constructed.

The nonlinear relationship between variability and mean rainfall illustrated in Fig. 2 is similar to the relationship found by Conrad (1941). As noted above, such a relationship is to be expected from the definition of the coefficient of variation. The relationship can be fitted to a function:

$$V = c + a/(b + P)$$

where a, b, and c are parameters to be determined. The effects of latitude (L) and the magnitude of the correlation between station rainfall and the SOI (R) have been included in the following analysis in such a way that they can affect the slope of the relationship between V and P and have a multiplicative or additive, or both, effect on V. This variety of possible effects was included because it is not obvious what functional effect L and R should have from inspection of Fig. 2.

So the observed values of V, P, R, and L from the

974 stations were fitted, initially, to the following functional relationship:

$$V = [a/(b + P + g(R, L)) + c + h(R, L)](1 + k(R, L)) \quad (1)$$

where a, b, and c are parameters to be determined. The functions $g(R, L)$, $h(R, L)$, and $k(R, L)$ are each of a similar form, i.e.,

$$tR + uL + wRL,$$

with t, u, and w all parameters to be determined. Different values of t, u, and w could be expected for the three functions g, h, and k. In the absence of the functions g, h, and k, Eq. (1) would be of the form used by Conrad (1941) and Nicholls (1988), i.e., with relative variability increasing nonlinearly with decreasing mean rainfall.

Equation (1) is of a very general form, allowing latitude and the correlation with the SOI to affect the relationship between variability and mean rainfall in several ways. The functions g, h, and k respectively allow the latitude and correlation to affect the slope of the relationship between V and P, allow the possibility of an additive effect of R or L on V, or of a multiplicative effect. Initial fitting of Eq. (1) to the data revealed that six of the nine parameters in the functions g, h, and k were not significantly different from zero. These parameters were therefore dropped, leaving the following simplified version of Eq. (1):

$$V = [a/(b + P + dR + eRL) + c](1 + fL). \quad (2)$$

Here a, b, c, d, e, and f are the parameters to be determined by fitting the equation to the data from the 974 stations. Only the latitude (through the term fL) has a multiplicative effect on V and there is no evidence of any additive effect. The term $dR + eRL$ affects the slope, or more correctly, the rate of change of the slope with P. The eRL term is an interaction effect showing that the effects of latitude and correlation with the SOI are not independent of each other, i.e., the effect of R on V will vary with L.

The above equation was fitted to the data for the 974 stations using the method of false position (Ralston and Jennrich 1979), as was done in Nicholls (1988). The method is available in the SAS statistical analysis system and is described in SAS (1985).

3. Results

The result of fitting the data to Eq. (2) is the following equation, which accounts for 94% of the variance in V:

$$V = (150/(244 + P - 1010R + 23.47RL) + 0.15)(1 - .0068L). \quad (3)$$

Here the mean rainfall, P, is in millimeters, the latitude, L, is in degrees, and V and R are unitless. All of the six fitted parameters in Eq. (3) are significantly different from zero. In the absence of effects from the SOI and latitude this equation indicates that variability decreases as mean precipitation increases, with an asymptote of 0.15. Conrad (1941) and Nicholls (1988) found that a similar relationship between relative variability (as defined by Conrad) and mean precipitation accounted for much of the variance in the relative variability.

The final term in Eq. (3) indicates that latitude has a multiplicative effect on variability. Increasing latitude reduces variability over all values of the mean precipitation. The effect of this term is substantial. At a latitude of 30°, in the absence of effects from the SOI, the multiplicative latitude term indicates that variability would be 80% of the corresponding variability at the equator. Variability at 60° latitude is typically 60% of that at the equator, for the same mean precipitation (again ignoring effects due to the SOI).

The SOI does have a substantial effect on variability. The $-1010R$ term in Eq. (3) indicates that a station with a strong relationship with the SOI will have a steeper relationship between variability and mean precipitation, i.e., the SOI will have little effect on the variability at stations with very large mean annual rainfall but typically enhances the variability substantially at stations with lower annual rainfall. The increased variability associated with strong correlation with the SOI confirms the results of Nicholls (1988).

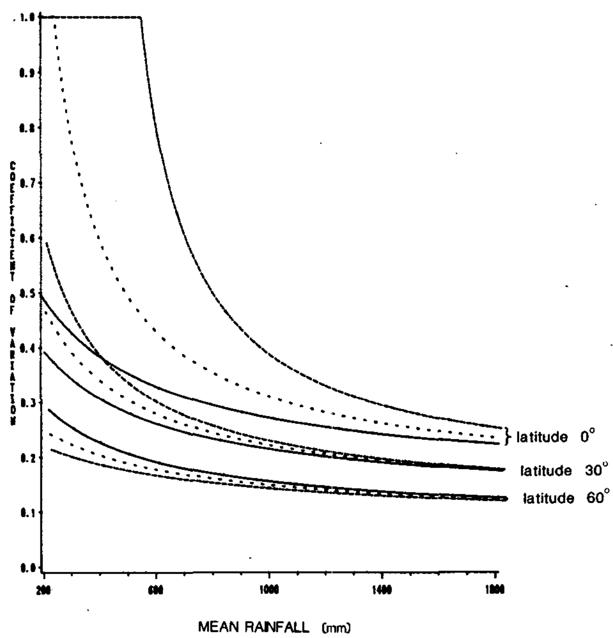

FIG. 3. Relationship between the coefficient of variation and mean annual rainfall for nine combinations of various latitudes and absolute correlations with the SOI. The latitudes are indicated next to each group of three lines. The full lines indicate correlations of zero. The dotted lines and broken lines indicate, respectively, correlations of 0.3 and 0.6. Values of the coefficient of variation exceeding 1.0 have been truncated to 1.0.

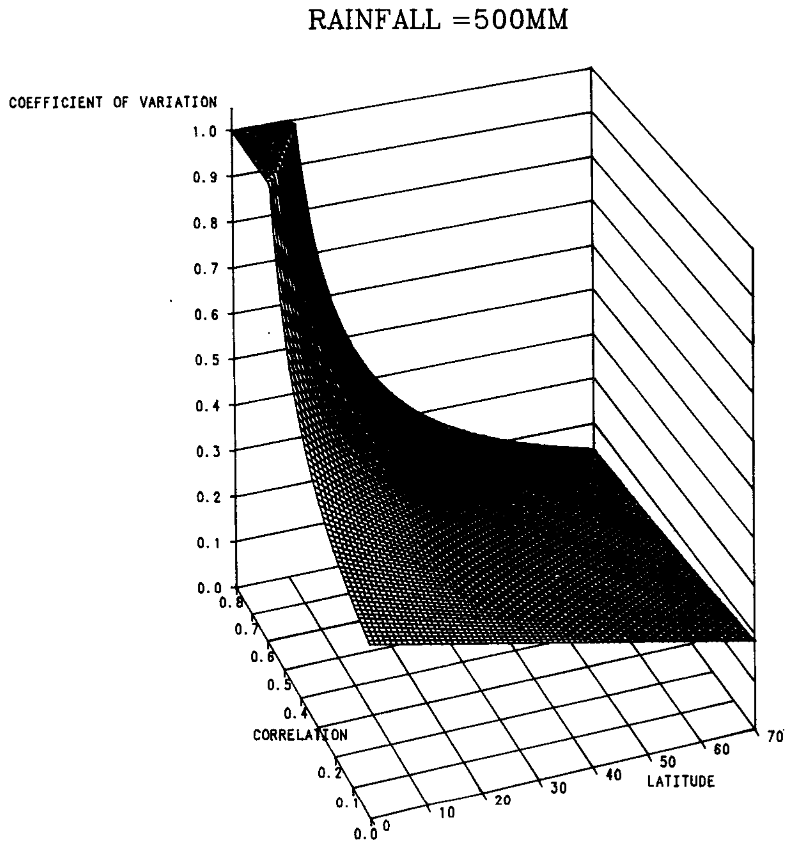

FIG. 4. (a) Dependence of the coefficient of variation of annual rainfall on latitude and absolute correlation with the SOI, for a fixed mean annual rainfall of 500 mm. Values of the coefficient of variation exceeding 1.0 have been truncated to 1.0. (b) Dependence of the coefficient of variation of annual rainfall on latitude and absolute correlation with the SOI, for a fixed mean annual rainfall of 1000 mm. (c) Dependence of the coefficient of variation of annual rainfall on latitude and absolute correlation with the SOI, for a fixed mean annual rainfall of 2000 mm.

The interaction term ($23.47RL$) indicates that increasing latitude weakens the effect of the SOI on variability. The effect of the SOI is strongest at the equator but actually reverses at 43° latitude. Polewards of this latitude an increase in the correlation with SOI, according to Eq. (3), causes variability to decrease. This decrease is very small and few stations polewards of 43° latitude exhibit strong correlations with the SOI anyway, but this term does indicate that the strongest effects of the SOI on variability are at low latitudes.

The relationship between variability, mean rainfall, correlation with the SOI, and latitude is illustrated in Figs. 3 and 4. Figure 3 plots the relationship between variability and mean rainfall for rainfalls between 100 and 2000 mm for nine combinations of latitude (0°, 30° and 60°) and correlation with the SOI (0, 0.3 and 0.6). The figure illustrates that variability increases as mean rainfall decreases, as latitude decreases, and (in low latitudes) as the correlation with the SOI increases. The relative strengths of these effects on variability can be gauged by examining the set of curves in Fig. 3.

A clearer view of the effects of latitude and the SOI on variability may be gained from Fig. 4, which illustrates the relationship between V, R, and L while holding P (the mean rainfall) constant. This is analogous to moving a hypothetical raingauge around, changing its latitude and the degree to which it is affected by ENSO, while not changing its long-term mean annual rainfall. Figures 4a, 4b, and 4c are for the cases where the mean rainfall is 500 mm, 1000 mm, and 2000 mm, respectively. Values of V exceeding 1.0 have been truncated to 1.0 in Fig. 4a, to simplify the figure.

The strong effect of the SOI on variability at relatively low rainfalls, especially at low latitudes, is revealed in Fig. 4a. With zero correlation with the SOI the relationship between V and L is linear but as R increases the relationship between V and L becomes more nonlinear because of the interaction term in Eq. (3). The interaction term also causes the slight reduction in variability evident in Fig. 4a as the correlation with the SOI increases at high latitudes. Figures 4b and 4c illustrate that the dependence of V on R weakens and flattens as mean rainfall increases.

As was noted earlier, Australian stations are overrepresented in the dataset used here. Since rainfall over much of Australia is strongly influenced by the South-

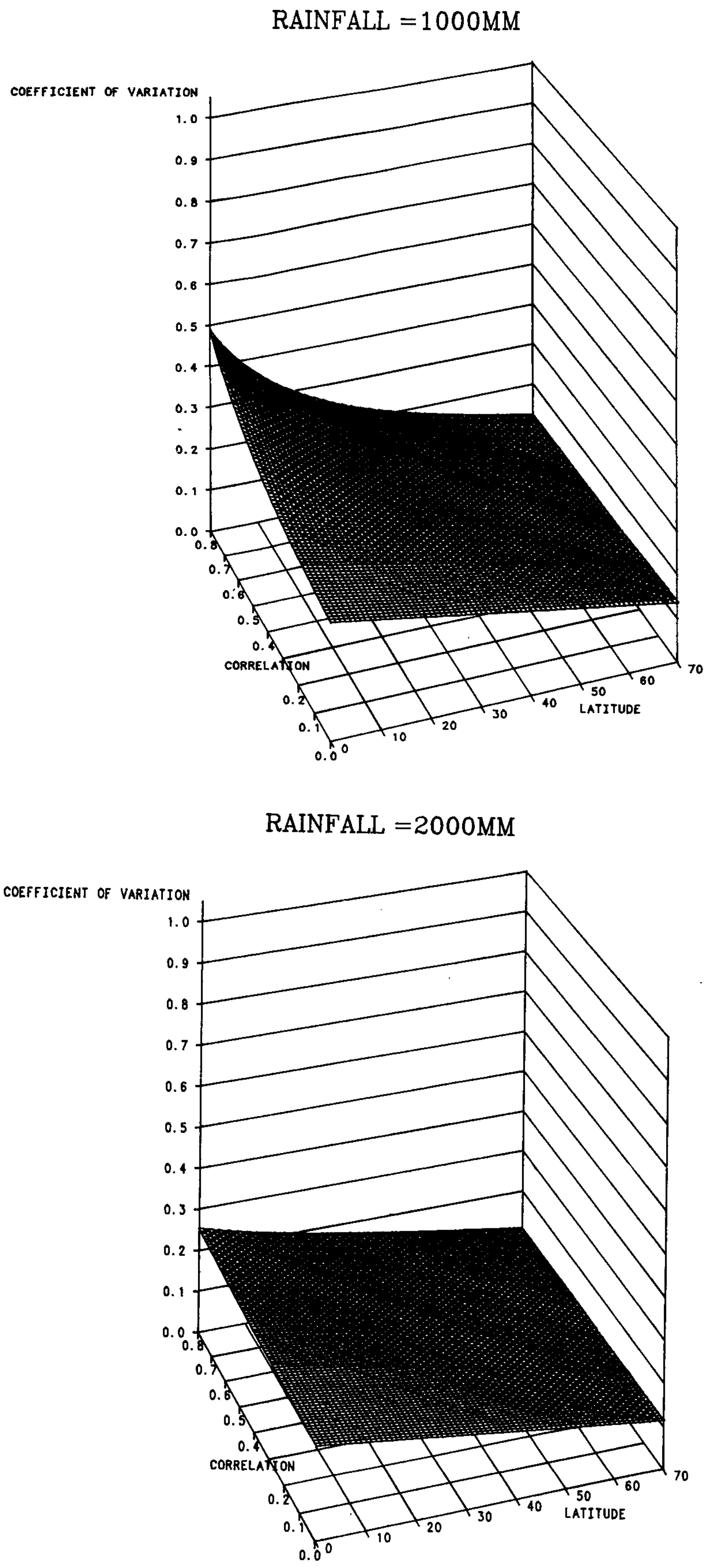

FIG. 4. (*Continued*)

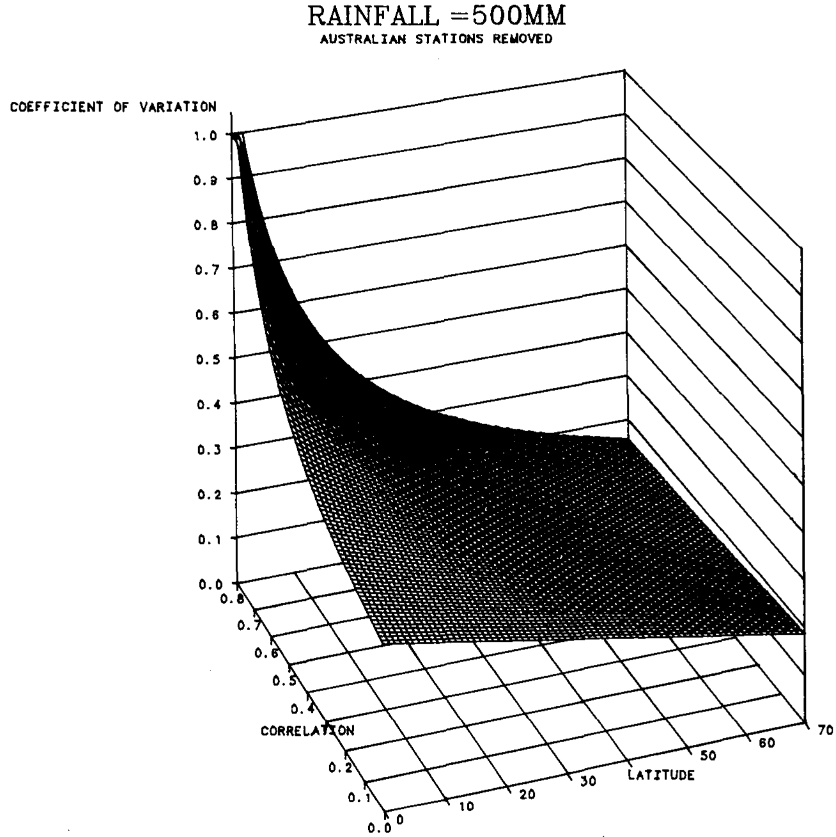

FIG. 5. Dependence of the coefficient of variation of annual rainfall on latitude and absolute correlation with the SOI, for a fixed mean annual rainfall of 500 mm. All Australian stations removed. Values of the coefficient of variation exceeding 1.0 have been truncated to 1.0.

ern Oscillation the dependence of V on R may be largely, or even totally, due to the Australian data. To check this the data were again fitted to Eq. (3) after removal of the 300 Australian stations. The relationship between V, R, and L for a mean rainfall of 500 mm is shown in Fig. 5. A strong dependence of V on R is still evident at lower rainfalls, although the effect was slightly weaker when the Australian data were removed (compare Figs. 4a and 5). There is a slight change in the latitudinal dependence of variability when the Australian data are deleted, but it is too small to be detected in Fig. 5.

The small changes that occur in the fitted function when the Australian data are excluded provide evidence of the stability and reality of the relationship modeled here. Further evidence of this is provided by fitting Eq. (2) separately to the Northern Hemisphere stations and the Southern Hemisphere stations. The fitted values of the parameters in Eq. (2) are listed in Table 2, along with their 95% confidence intervals. Also listed are the values and confidence intervals when all the data are used. The six parameters are all significantly different from zero for all three sets of data and each parameter has the same sign in each set. There are some substantial differences in parameter magnitudes but the fitted functions for the two hemispheres produce similar predictions of V for a wide range of P, L and R. This is shown in Table 3, which lists the predicted coefficients

TABLE 2. Values of the parameters in Eq. (2), and their 95% confidence intervals (in parentheses), when the equation is fitted to all the data, just Northern Hemisphere stations (541 stations) and just Southern Hemisphere stations (412 stations).

Parameter	All data	Northern Hemisphere	Southern Hemisphere
a	150 (130–171)	119 (95–143)	170 (131–210)
b	244 (212–277)	160 (107–213)	288 (235–340)
c	0.15 (0.13–0.17)	0.15 (0.13–0.17)	0.17 (0.14–0.20)
d	−1010 (1200–820)	−621 (893–350)	−1348 (1665–1030)
e	23.47 (17.6–29.3)	15.21 (7.4–23.0)	35.12 (24.5–45.8)
f	−0.0068 (0.008–0.006)	−0.0063 (0.007–0.005)	−0.0080 (0.01–0.006)

TABLE 3. Predicted values of the coefficient of variation (V) calculated from Eq. (2) fitted separately to the Northern Hemisphere data and the Southern Hemisphere data, for selected values of mean annual rainfall (P), latitude (L), and correlation between annual rainfall and annual mean Southern Oscillation Index (R).

			Predicted V	
P (mm)	L (degrees)	R	Southern Hemisphere	Northern Hemisphere
500	0	0	0.39	0.33
500	0	0.3	0.61	0.40
500	30	0	0.29	0.27
500	30	0.3	0.31	0.28
2000	0	0	0.24	0.20
2000	0	0.3	0.26	0.21
2000	30	0	0.19	0.17
2000	30	0.3	0.19	0.17

of variation for a range of values of P, L, and R. The model values of V for the Southern Hemisphere are higher than for the Northern Hemisphere but the effects of the three independent variables are similar in the two hemispheres. However, some of the Northern and Southern Hemisphere parameter estimates fall outside the confidence intervals for the same parameters in the other hemisphere. This may suggest that the relationship between variability and the SOI might be different in the two hemispheres, even though the overall relationship produces similar estimated variability.

4. Concluding remarks

This study has confirmed the conclusion of Conrad (1941) that relative variability of annual rainfall decreases with higher mean rainfall. This dependence is expected because mean rainfall forms the denominator in the definition of relative variability (i.e., the coefficient of variation). The conclusion of Nicholls (1988) that variability is typically higher, for a specific mean rainfall, in areas affected by ENSO has also been confirmed, at least for locations equatorwards of 43°, a region that includes most of the stations strongly affected by ENSO. The Southern Oscillation amplifies climate variability in those areas it affects, even when the effects of latitude and mean rainfall are removed. These conclusions have been confirmed using about three times as many stations as were used by Conrad and Nicholls, on recent data independent of the set used by Conrad and Nicholls, and using a more conventional definition of relative variability.

The study has revealed a clear dependence of variability on latitude with variability decreasing substantially as we move away from the equator, after removal of the effects of long-term mean rainfall and ENSO on variability. The cause of the dependence of variability on latitude requires explanation. It might arise from the tendency for convection to provide a larger proportion of annual rainfall in the tropics, or from the ability of occasional tropical synoptic systems (e.g., tropical cyclones) to produce very large amounts of rainfall.

The study has also revealed an interaction effect between latitude and correlation with the SOI. In the tropics stations strongly correlated with the SOI do tend to be more variable but this tendency weakens as we move polewards. Eventually, at 43° latitude the relationship reverses and polewards of this latitude increasing correlation with the SOI implies slightly lower variability. This reversal of the relationship at higher latitudes is, to some extent, an artifact of the fitting process since few stations are strongly correlated with the SOI at these latitudes.

In summary, variability of annual rainfall increases:

- as mean annual rainfall decreases,
- as latitude decreases, and
- as the influence of the Southern Oscillation increases (at least in tropical and subtropical latitudes).

The regions with the most variable annual rainfalls are tropical deserts strongly affected by the Southern Oscillation.

The function used here to fit the observed variability was prescribed in an ad hoc manner. There are probably better ways to model the effect of latitude and the SOI on variability. Theoretical and further empirical work might refine the results of this study.

The implications of the dependence of variability on latitude and the Southern Oscillation are wide-ranging. Nicholls (1988) suggested that the biota in areas where ENSO amplified variability should be better adapted to frequent climate variations than the biota elsewhere. Human patterns of rainfall usage should also be adapted to the differences in variability in regions of different mean rainfall, latitude, and degree of influence from ENSO, if best use is to be made of this rainfall. The differences in variability in rainfall will lead to differences in frequencies of major droughts and floods, i.e., runoff variability (McMahon et al. 1987). Extrapolating European and North American models and methods for coping with droughts and floods to tropical countries affected by ENSO (and thus with higher relative variabilities, for the same mean rainfall) may not be appropriate.

REFERENCES

Conrad, V., 1941. The variability of precipitation. *Mon. Wea. Rev.*, **69**, 5–11.

McMahon, T. A., B. L. Finlayson, A. Haines and R. Srikanthan, 1987. Runoff variability: A global perspective. *The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources,* IAHS Publication no. 168.

Nicholls, N., 1988. El Niño–Southern Oscillation and rainfall variability. *J. Climate,* **1,** 418–421.

Ralston, M. L., and R. I. Jennrich, 1979. A derivative-free algorithm for nonlinear least squares. *Technometrics,* **1,** 7–14.

SAS, 1985. *SAS User's Guide: Statistics.* SAS Institute Inc., 956 pp. [Available from SAS Institute, Inc., Box 8000, Cary, NC 27522-8000.]