East Australian Rainfall Events: Interannual Variations, Trends, and Relationships with the Southern Oscillation

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ABSTRACT

The number, average length, and average intensity of rain events at five stations located in eastern Australia have been calculated for each year from 1910 to 1988, using daily rainfall totals. A rain event has been defined as a period of consecutive days on which rainfall has been recorded on each day. Inter-relationships between the rain-event variables (at each station and between stations), along with their relationships with annual rainfall and the El Niño–Southern Oscillation, have been investigated. Trends in the time series of the rain-event variables have also been examined. Annual rainfall variations are found to be primarily caused by variations in intensity. Fluctuations in the three rain-event variables are essentially independent of each other. This is due, in some cases, to inter-relationships at interdecadal time scales offsetting relationships of the opposite sense at shorter time scales. The large-scale geographical nature of east Australian rainfall fluctuations mainly reflects interstation correlations in the number of events. The El Niño–Southern Oscillation affects rainfall mainly by influencing the number and intensity of rain events. Twentieth century increases in east Australian rainfall have been due, primarily, to increased numbers of events. Intensity of rain events has generally declined, offsetting some of the increase in rainfall expected from more frequent events.

1. Introduction

Many studies have considered the relationship between Australian rainfall and the Southern Oscillation (e.g., Walker and Bliss 1930; Quayle 1929; Priestley 1962; Troup 1965; Pittock 1975; Coughlan 1978; Nicholls and Woodcock 1981; McBride and Nicholls 1983; Nicholls et al. 1982; Ropelewski and Halpert 1987, 1989; Allan 1988; Drosdowsky and Williams 1991). All these studies have used monthly, seasonal, or annual rainfall *totals* as their dependent variable. Some have demonstrated that seasonal rainfall totals in some parts of the country, in certain seasons, can be predicted from prior observations of the Southern Oscillation index (SOI), the normalized difference in pressure between Tahiti and Darwin. The general relationship, that drier-than-normal conditions usually occur during periods with large negative SOI values (El Niño episodes) is well known, as are its consequences for Australian agriculture and native vegetation and wildlife (Nicholls 1984, 1986, 1989, 1991; Limpus and Nicholls 1988). None of the studies has, however, discussed how rain *events* might be related to the Southern Oscillation, that is, are negative values of the SOI associated with fewer than normal rain events, or shorter events, or less intense events? Information about SOI relationships with such variables might lead to increased understanding of the mechanisms by which the Southern Oscillation affects Australia's climate.

Numerous studies have also documented historical rainfall trends in Australia (e.g., Deacon 1953; Kraus 1954; Wright 1974a, 1974b; Pittock 1975, 1983; Cornish 1977; Coughlan 1978; Russell 1981; Srikanthan and Stewart 1991; Nicholls and Lavery 1992). Again, these studies have concentrated on trends in total rainfall, for example, in annual rainfall totals. Little attention has been given to trends in the parameters describing rain events, apart from Yu and Neil (1991), who examined the relationship between east Australian rainfall totals, high-intensity rain events, and global temperatures. Studies of trends in rain-event characteristics would be useful, especially in the context of a continuing discussion on the possibility that an enhanced greenhouse effect may lead to regional rainfall changes. Some examinations of rainfall events in numerical models with doubled CO_2 (e.g., Mearns et al. 1990) have suggested that increased intensity of rain events might be expected from an enhanced greenhouse effect. Information about recent historical trends in Australian rain events might provide a basis for determining if a particular regional rainfall change was due to an enhanced greenhouse effect. Thus, if the models predict greater intensity of rain events, and no evidence of this is found in the recent record, this might suggest that the recent changes are *not* due to the enhanced greenhouse effect, if the predicted change to date was

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large enough to anticipate detection against the natural variability.

In this paper the secular trends and relationships between rain events and the SOI are examined for five stations in east Australia. The stations have been chosen because another study (Lavery et al. 1992) determined that their daily rainfall data were of high quality and were unlikely to have been contaminated through changes in exposure, observational apparatus or techniques, or shifts in location. The observers operating these stations were also determined, through a series of statistical tests and careful searches of station documentation, to have been accurate and thorough. Nicholls and Lavery (1992) identified these stations as representative of large areas of eastern Australia because of the strong correlations between annual rainfall variations.

2. Data and methodology

The stations selected for analysis are listed in Table 1. Their locations are shown in Fig. 1. They are at approximately the same longitude, but their latitudes range from the tropics to midlatitudes. The stations are all located in an area where rainfall is strongly affected by the El Niño–Southern Oscillation (e.g., McBride and Nicholls 1983). Eastern Australian rainfall is affected by a variety of synoptic systems, including tropical cyclones and monsoonal depressions in the north, and frontal activity and midlatitude depressions in the south. Of these, only tropical-cyclone activity has clearly been demonstrated to be related to the El Niño–Southern Oscillation (e.g., Nicholls 1992). Each station has daily rainfall data from at least 1910. The data record is almost complete at each station, with very few missing days, or periods when the data was accumulated over more than a single day. These data are, therefore, suitable for examination of the behavior of rain events, where events are defined in terms of daily data. The data cannot, of course, be used to examine rain events of shorter duration.

One possible source of systematic bias in the rainfall records relates to the change from imperial (British) to metric units. This occurred at the start of 1974. With respect to rainfall this means that rain amounts were recorded before 1974 if at least 0.005 inches (0.127 mm) fell; from 1974 on, a fall of only 0.1 mm was required to register rainfall. This may have caused an upward trend in the number and length of rain events, artificially biasing the results of this paper, especially the trends. Two approaches were adopted to check if a bias did result from the change in units. First, Lavery et al. (1992) examined frequency distributions of rain amounts before and after metrication and concluded that no obvious bias had occurred as a result of the change in units. Second, for the purposes of the present study, trends of the various rain-event characteristics were calculated using all available data and repeated using only data up to 1973 (Tables 7 and 8). The results of these calculations are discussed later but, in summary, there was little evidence that the change of units caused discontinuities in trends. Despite these checks the possibility remains that some of the results of this paper are affected by the change of units. Similarly, changes in observers could confound the results. For example, a change to a more competent observer might result in more rain days and a change in the number of events. Over the total period examined, the techniques employed by Lavery et al. (1992) to select high-quality stations would have eliminated stations where poor observing practices were the rule. These techniques would not, however, eliminate the possibility that shorter periods of poor practices exist in the data.

TABLE 1. Locations of stations used in analysis.

Station	Number	Latitude	Longitude
Winton Post Office	37051	22°23′S	143°02′E
Gatton–Lawes	40082	27°33′S	152°20′E
Peak Hill Post Office	50031	32°43′S	148°11′E
Canary Island	80004	35°58′S	143°51′E
Carrick	91013	41°33′S	147°00′E

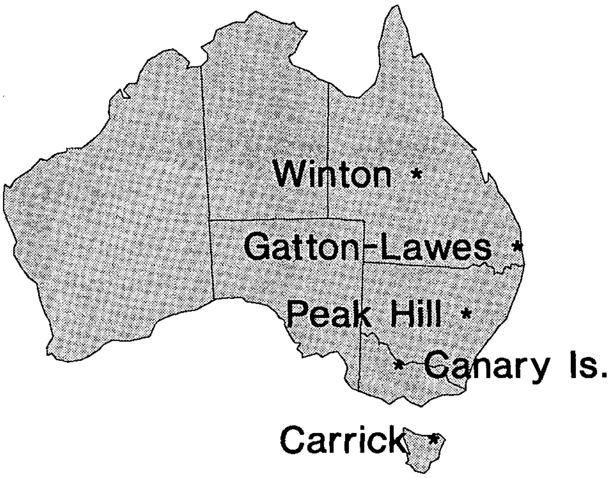

FIG. 1. Locations of the five stations used in this study.

For the purposes of this study, a rain event was defined as a continuous period with recorded rainfall on each day. The length of an individual event was the number of contiguous days with recorded rainfall. Three variables were used to describe interannual variations in rain events:

(i) Number: the number of rain events in a year;

(ii) Length: average length of events (raindays/event); and

(iii) Intensity: average rainfall per rainday (mm day^{-1}).

These three variables were calculated for each year from 1910 to 1988, for each of the five stations. Only annual

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TABLE 2. Mean annual rainfall (mm), mean number, length (days), and intensity of rain events (mm/day) for each station. Data from 1910–1988.

Station	Annual	Number	Length	Intensity
Winton	415.0	22.3	1.8	10.3
Gatton-Lawes	791.5	46.0	2.0	8.7
Peak Hill	562.5	42.4	1.6	8.0
Canary Island	367.6	41.5	1.6	5.4
Carrick	708.5	60.5	2.1	5.6

totals and averages were calculated for this study. The total annual rainfall in a year is the product of these three variables (i.e., number × length × intensity) for that year.

The interannual variations of the three variables, and the annual rainfall, at the five stations were correlated with each other, with the corresponding variable at the other stations, and with the year (to examine linear trends) and the SOI. Values of the SOI were provided by the National Climate Centre of the Australian Bureau of Meteorology (the SOI used here differs from that sometimes used, in that it is standardized to a standard deviation of ten, not to a standard deviation of one), as were the original daily rainfall data. The results are discussed below in the following order: means and frequency distributions of annual rainfall and mean number, length, and intensity of rain events; intrastation correlations between the four variables; interstation correlations for each of the four variables; correlations of each variable at each station with the annual SOI; and trends in each of the variables at each station. Unless otherwise stated correlations denoted as "significant" were statistically significant at the 5% level. No adjustment to the significance testing was made to take account of serial correlations in the variables. Serial correlations were generally small. The average lag-one autocorrelation for the four variables (annual rainfall, number, length, and intensity of rain events) at the five stations was only 0.12. Only five of the lag-one autocorrelations exceeded +0.2. Only one (intensity at Canary Island) reached a magnitude (0.44) at which it would have caused substantial reduction in the effective degrees of freedom. The smallness, in general, of the serial correlations indicated that calculation of effective degrees of freedom would not have appreciably altered the significance levels.

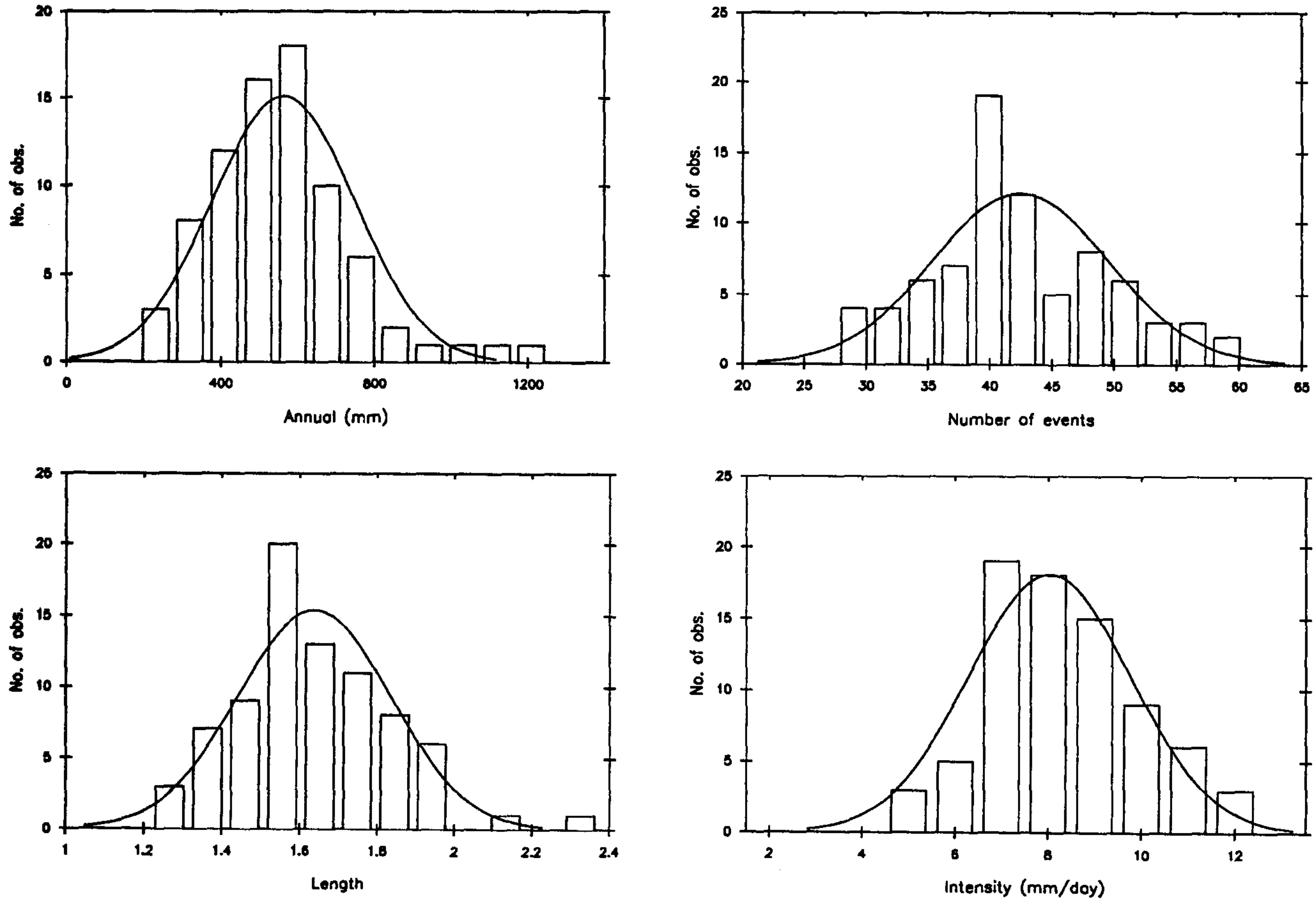

FIG. 2. Frequency distributions of each variable at Peak Hill. The thin line indicates fitted normal distribution.

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TABLE 3. Correlations of annual total rainfall with the number of rain events, their average length in raindays, and the average intensity per rainday, for each station. All correlations are significant at 5%. Data from 1910–1988.

Station	Number	Length	Intensity
Winton	0.55	0.64	0.71
Gatton–Lawes	0.48	0.54	0.59
Peak Hill	0.62	0.58	0.66
Canary Island	0.63	0.34	0.71
Carrick	0.29	0.57	0.76

3. Results

a. Mean values and frequency distributions

Table 2 lists the mean annual rainfall at each station, along with the mean number, length, and intensity of rain events. The mean number of events ranges between 22 and 60, with the largest number at Carrick, the station located at the highest latitude. The events tend to last about two days, and their intensity decreases poleward.

The frequency distribution of the annual rainfall totals and the annual values of the three rain-event characteristics were examined. The distributions for Peak Hill are shown in Fig. 2. All four variables show reasonably close correspondence to a normal distribution, at this station. Inspection of the distributions of the variables at the other stations (not shown) indicated that with few exceptions the distributions closely approximated normal. The exceptions included annual rainfall at Winton, which is positively skewed with many years of low rainfall. This is due to positive skewness in the number of events and in the length of events. The number of events at Carrick is negatively skewed, that is, in many of the years there are more than the long-term mean number of events.

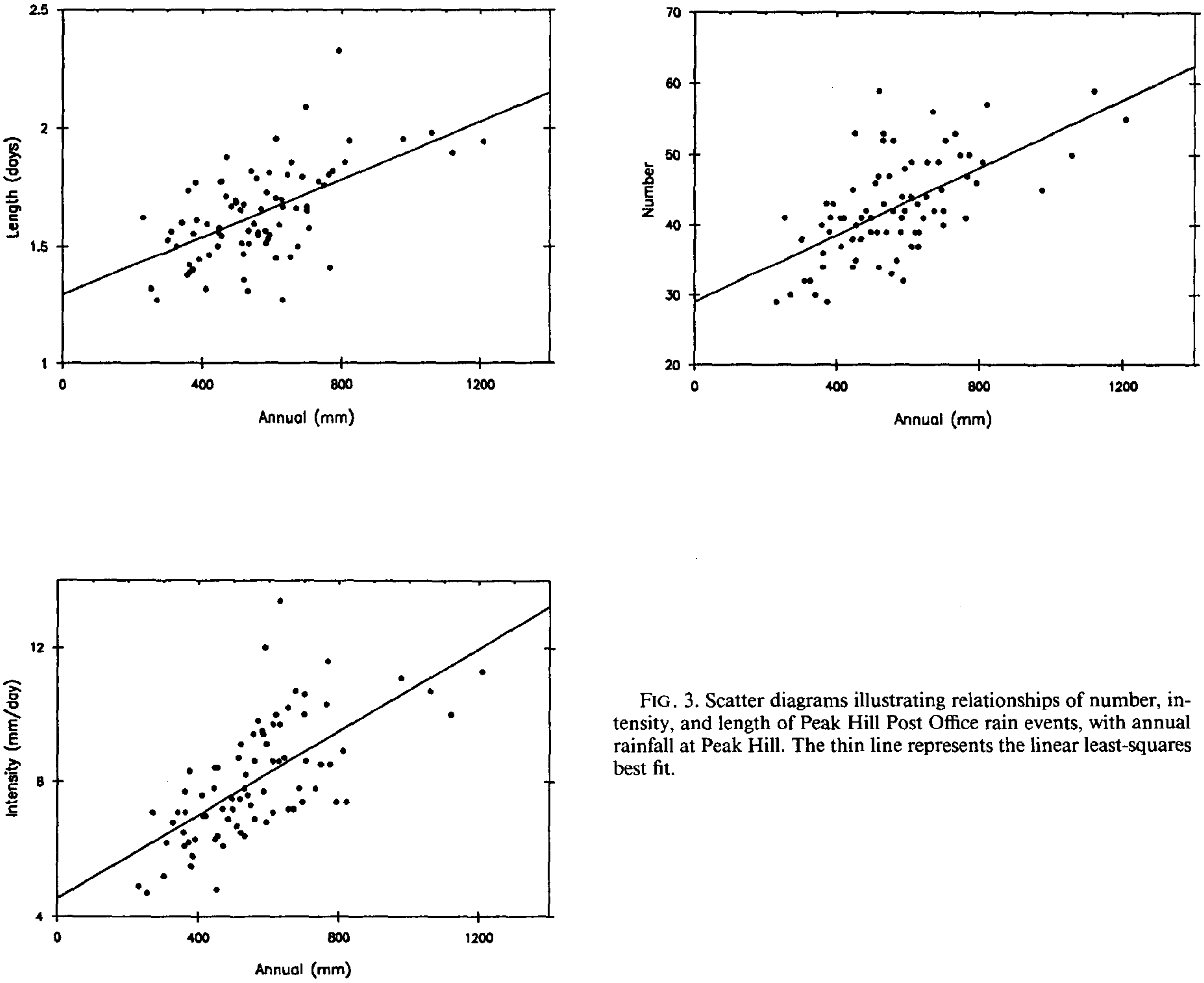

FIG. 3. Scatter diagrams illustrating relationships of number, intensity, and length of Peak Hill Post Office rain events, with annual rainfall at Peak Hill. The thin line represents the linear least-squares best fit.

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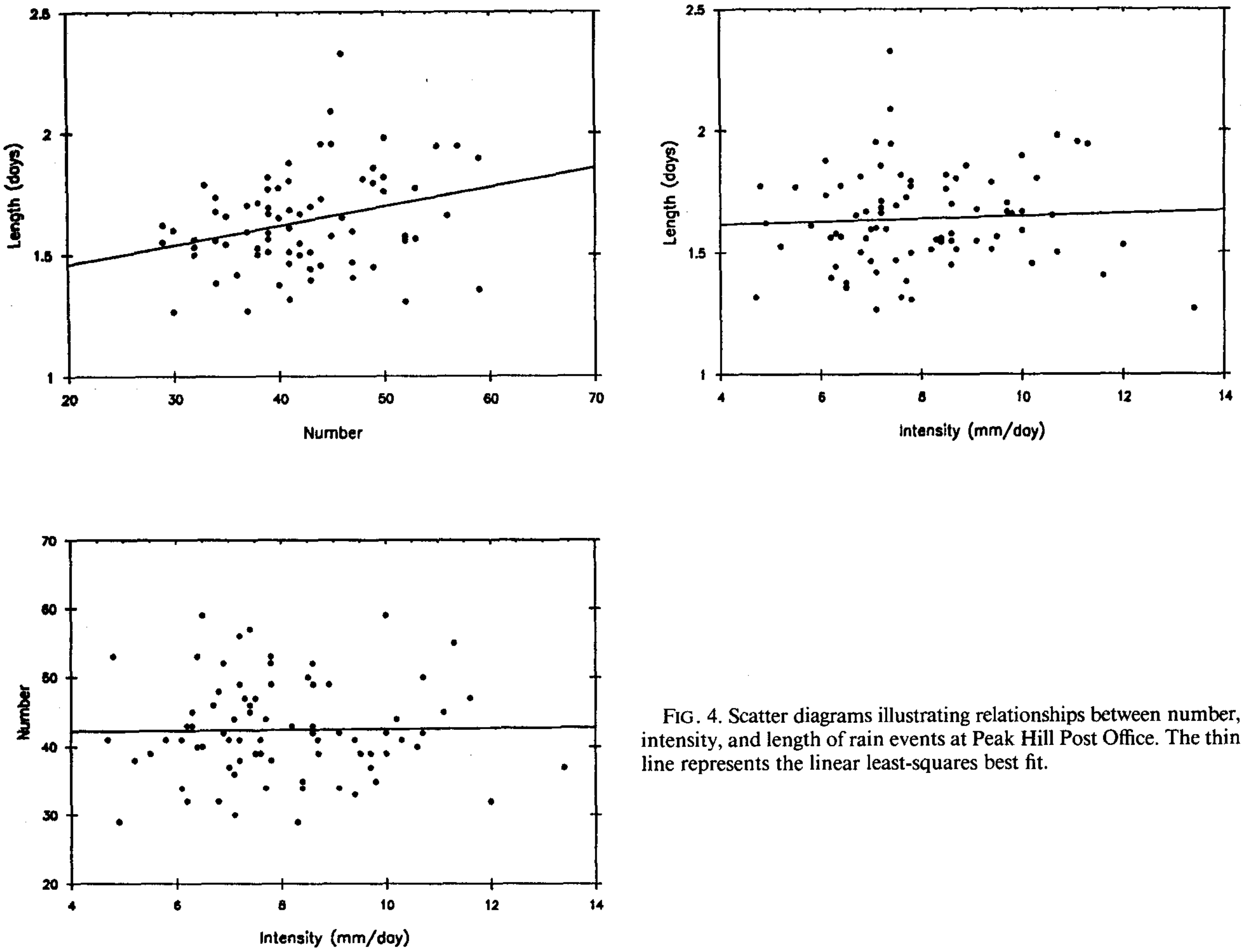

FIG. 4. Scatter diagrams illustrating relationships between number, intensity, and length of rain events at Peak Hill Post Office. The thin line represents the linear least-squares best fit.

b. Intrastation relationships

As was noted above, the annual total rainfall is the product of the number, length, and average intensity of rain events for the particular year. All three variables do not, however, contribute equally to the interannual variations in annual rainfall. Their respective contributions depend on the correlations between them, and their variability. In Table 3, the correlations of annual rainfall with the other three variables are listed for each station.

At each station, the average intensity (i.e., the average rainfall per rainday) is the major determinant of the interannual variations in annual rainfall totals. The relative contributions of the average length of events and the number of events vary, with no obvious pattern.

Scatter diagrams illustrating the relationships between the four variables are shown in Figs. 3 and 4, for Peak Hill. The relationships at Peak Hill are generally representative of the behavior at the other stations. Lines of the linear best fit between the variable pairs are included in each diagram. The positive, significant correlations of number, length, and intensity with annual rainfall (Table 3) are clear in Fig. 3. The absence of significant relationships between the other three rain-event variables is also clear in Fig. 4, apart from the number and length of events. The three event variables were generally poorly correlated at the other stations (Table 4). Thus, the number, length, and intensity of rain events can be considered to be independent variables at each station.

TABLE 4. Correlations between number, intensity, and length of rain events at each station. The correlations significant at 5% level are underlined. Data from 1910–1988.

Station	Number–Intensity	Number–Length	Length–Intensity
Winton	0.02	0.12	0.29
Gatton-Lawes	−.08	−.02	−.04
Peak Hill	0.02	0.29	0.05
Canary Island	0.05	0.15	−.12
Carrick	−.09	−.20	0.16

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TABLE 5. Interstation correlations. Correlations in each box are, in order, between annual rainfall totals, number of rain events, length of rain events, and intensity of rain events. The correlations significant at 5% level are underlined. Data from 1910–1988.

Station	Winton	Gatton–Lawes	Peak Hill	Canary Island
Gatton–Lawes	0.26 0.47 0.12 −.11			
Peak Hill	0.42 0.29 0.03 0.15	0.57 0.32 0.32 0.02		
Canary Island	0.42 0.34 0.11 −.03	0.34 0.05 −.10 0.04	0.60 0.41 0.12 0.26	
Carrick	0.33 0.18 0.05 0.18	0.21 0.26 0.07 0.24	0.37 0.26 0.13 0.23	0.58 0.31 0.22 0.14

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Annual
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c. Interstation correlations

Correlations between the four variables at the five stations are listed in Table 5. The relationships between Gatton–Lawes and Peak Hill are presented, in Fig. 5, to illustrate their form and strength. The annual rainfalls at all stations are positively and significantly correlated with annual rainfall at all the other stations (except between Gatton–Lawes and Carrick where the correlation of 0.21 is significant at 7%). Strong positive correlations between rainfall totals at eastern Australian stations have been noted before (e.g., Pittock 1975). These interstation relationships of annual rainfall result mainly from interstation relationships in the numbers of rain events (Table 5). All these correlations are positive, and most are significant. The relationships between Gatton–Lawes and Peak Hill are strongest for annual rainfall, followed by the number of events (Fig. 5).

The other two variables (length and intensity) reveal little consistency between stations (Fig. 5, Table 5).

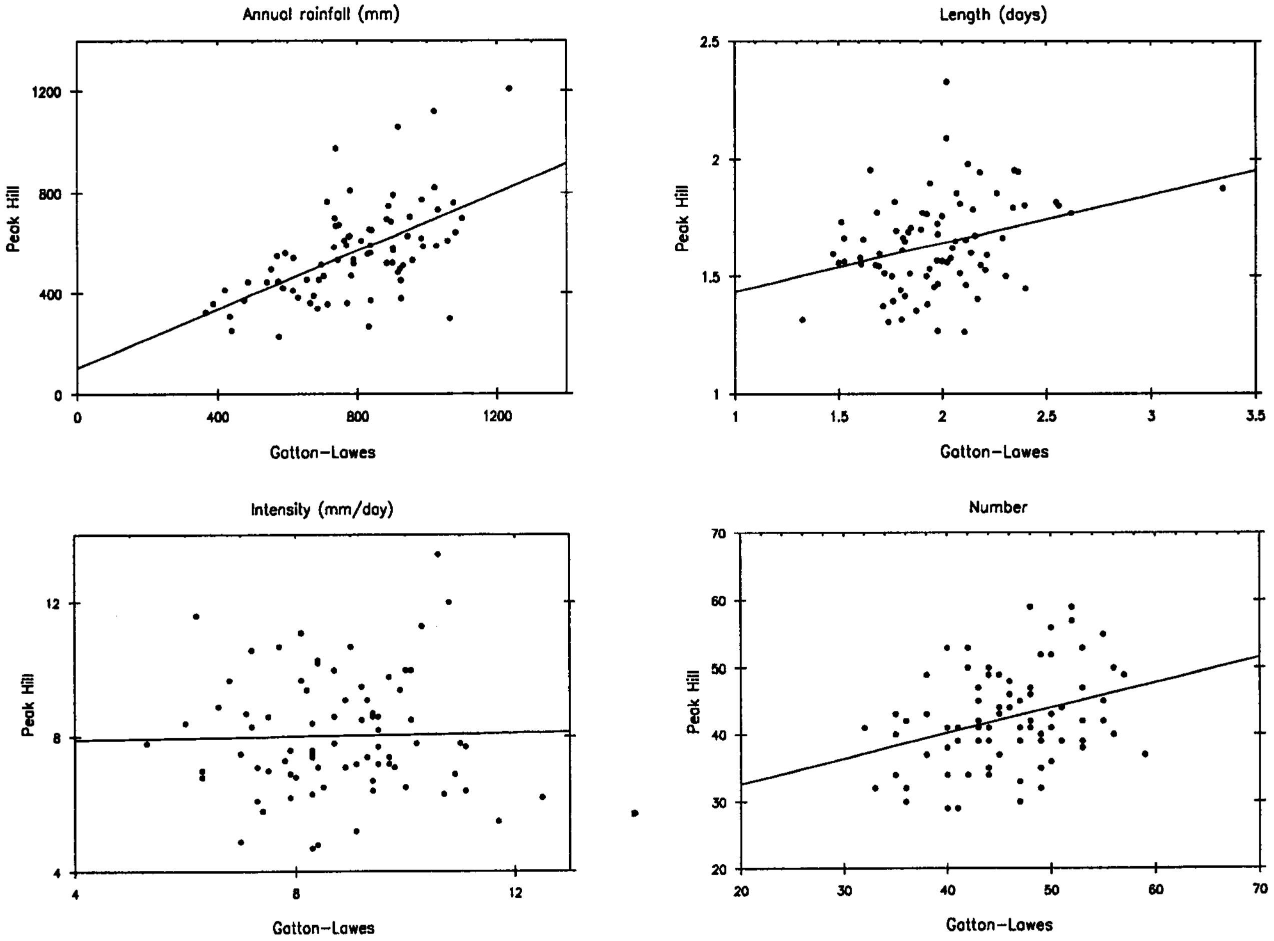

FIG. 5. Scatter diagrams illustrating relationships between variables at Gatton–Lawes and Peak Hill Post Office. The thin line represents the linear least-squares best fit.

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TABLE 6. Correlations of annual SOI with number, length and intensity of rain events, and annual total rainfall, at five stations. The correlations significant at 5% are underlined.

	Number	Length	Intensity	Annual
Winton	0.35	0.13	0.27	0.44
Gatton–Lawes	0.33	0.12	0.24	0.47
Peak Hill	0.30	0.15	0.38	0.44
Canary Island	0.37	0.22	0.19	0.45
Carrick	0.19	0.37	0.41	0.58

Very few of the relationships are significant and some are even negative. So, we can conclude that the large-scale nature of Australian rainfall fluctuations is largely caused by an influence operating on the number of rainfall events. However, most of the interstation relationships for intensity and length are positive, although generally weak. This indicates that they are contributing, to some small extent, to the large-scale relationships between rainfall totals at the various stations. This is also indicated by the fact that the correlations between the annual rainfalls are generally larger than the correlations between the number of events at the different stations.

d. Relationships with the Southern Oscillation

Correlations between the annual mean SOI and the four variables at each station are presented in Table 6. Scatter diagrams of the SOI and the four variables are shown for Peak Hill in Fig. 6. All correlations are positive, indicating that the El Niño–Southern Oscillation affects the number, length, and intensity of rain events at all stations, as well as influencing annual rainfalls. The correlations with annual totals are the largest, followed at three stations by the correlations with the number of rain events. Intensity is also significantly correlated with the SOI at some stations (e.g., Peak Hill, Fig. 6). The correlations with length are small

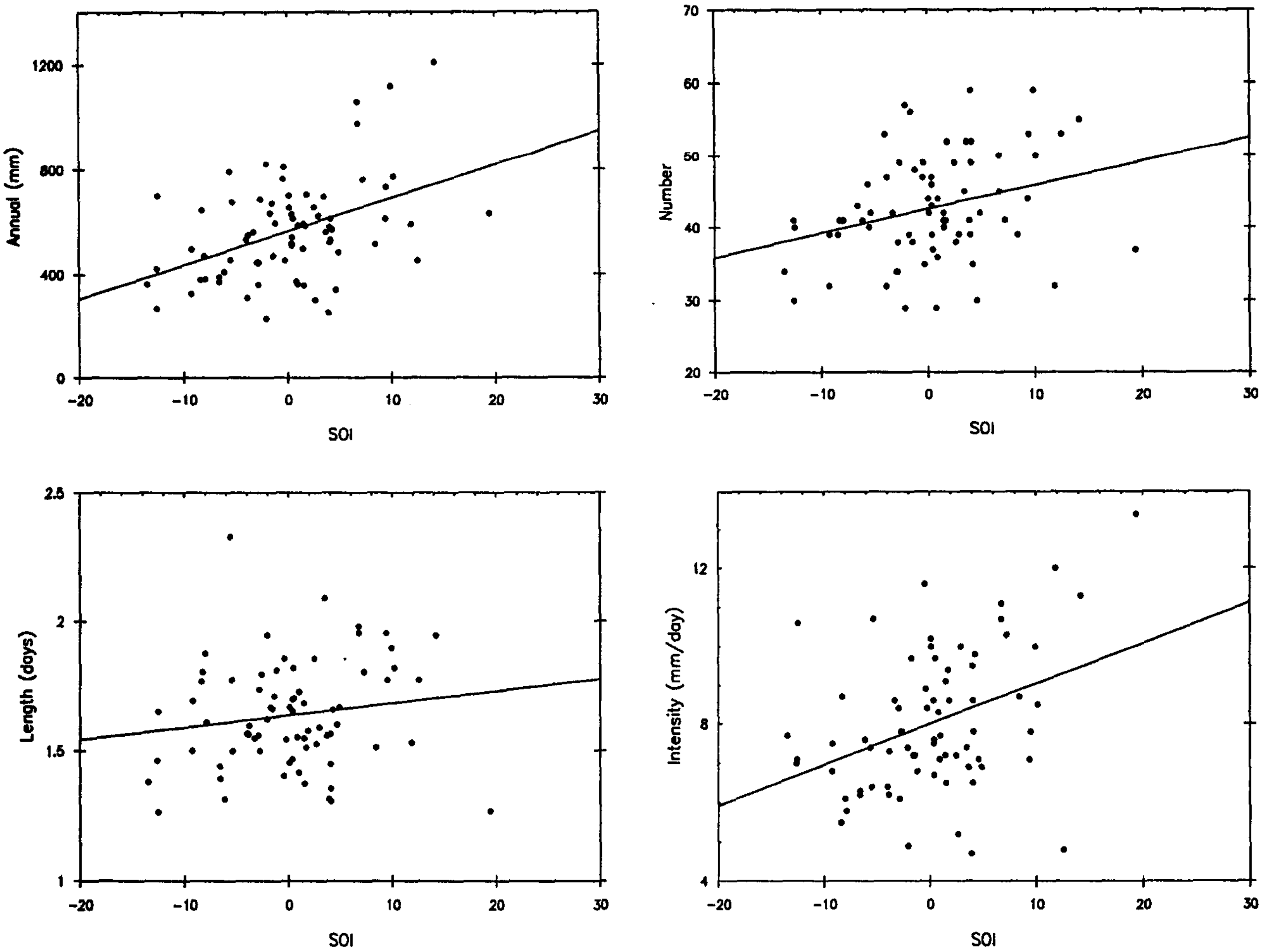

FIG. 6. Scatter diagrams illustrating the relationships between SOI and annual rainfall, number, length, and intensity of rain events at Peak Hill Post Office. The thin line represents linear least-squares best fit.

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and not significant, except at Carrick. Carrick's relationships with the SOI are rather different from the other four stations. At Carrick the number of events displays the weakest correlations with the SOI, whereas elsewhere this variable is significantly correlated with the SOI. The influence of the SOI on the length of events appears to increase with latitude, only at Carrick reaching significance.

The correlations between the SOI and annual rainfall reflect the combined influence of the SOI on all three event variables: number, length, and intensity. At every station each of these three variables is positively correlated with the SOI and, therefore, contributes to the SOI-annual rainfall correlation. So the SOI does *not* just affect annual rainfall by influencing just one index of rain events (e.g., number of events).

e. Trends

Time series of the four variables at the five stations from 1910 are shown in Figs. 7–11. To facilitate identification of secular trends each figure includes (as a thin line) a distance-weighted, least-squares smoothed fit to the data. The method used to do this smoothing

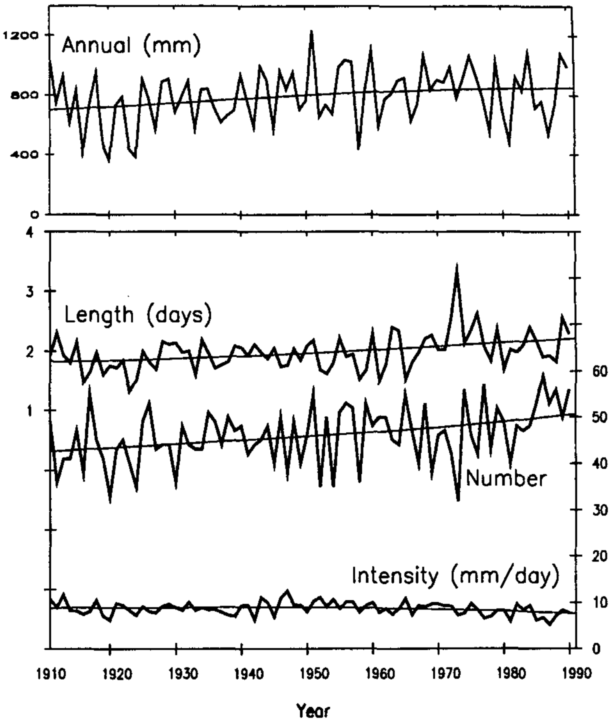

FIG. 8. As in Fig. 7 but for Gatton–Lawes.

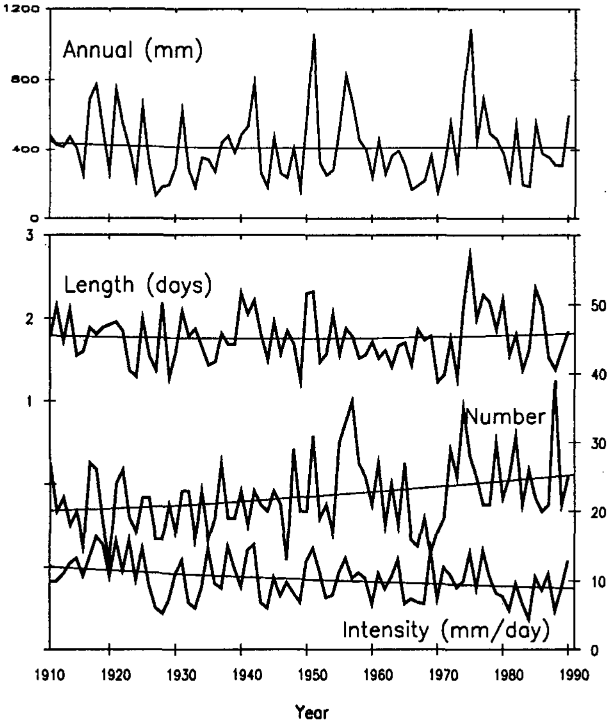

FIG. 7. Time series of annual rainfall, and the intensity, number, and length of rain events at Winton Post Office. Data from 1910 to 1988. The thin line represents a distance-weighted least-squares fit to the data, to illustrate longer-term variations. Scales for annual rainfall and for the length of events are on the left of the figure; scales for number and intensity are on the right. Units are indicated next to the individual plots.

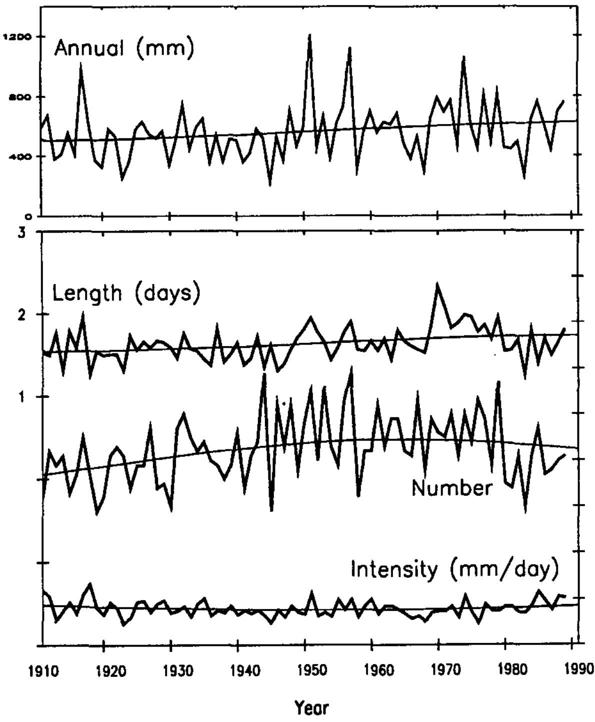

FIG. 9. As in Fig. 7 but for Peak Hill Post Office.

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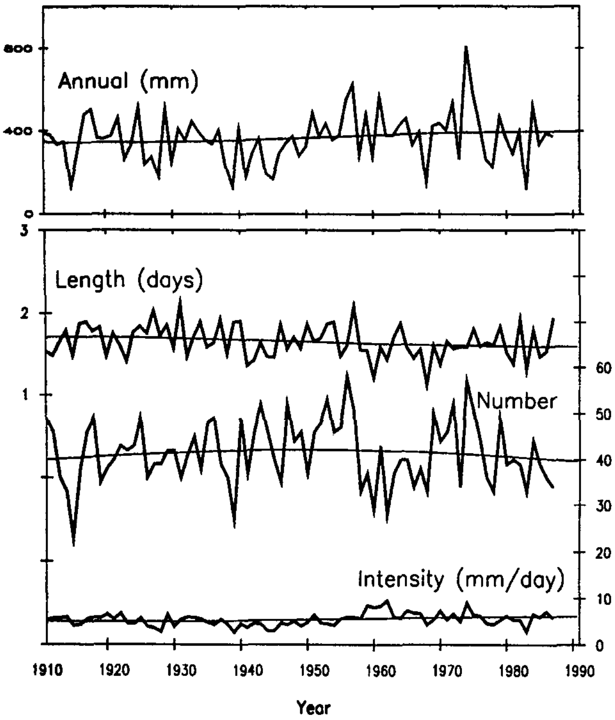

FIG. 10. As in Fig. 7 but for Canary Island.

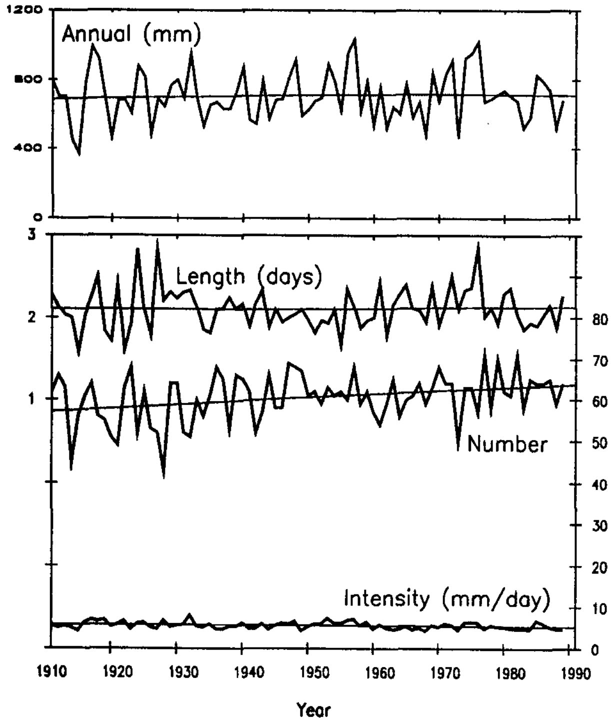

FIG. 11. As in Fig. 7 but for Carrick.

TABLE 7. Correlations between year and the number, length, and intensity of rain events, and annual rainfall totals, at five stations. The correlations significant at 5% are underlined. Data from 1910 to 1988.

Station	Annual	Number	Length	Intensity
Winton	−.03	0.29	0.02	−.29
Gatton–Lawes	0.26	0.36	0.38	−.21
Peak Hill	0.21	0.25	0.31	−.07
Canary Island	0.16	0.00	−.20	0.28
Carrick	0.05	0.33	0.03	−.18

is described in the user manual for CSS:STATISTICA (published by StatSoft, Inc.). Correlations with year were calculated to identify significant linear trends. These correlations are listed in Table 7. In Table 8 the correlations with year, using only data prior to 1974, the year when metric units were introduced, are listed for comparison. The similarity between the correlations using the total period and those calculated from only the pre-1974 data provide some indication of whether the trends are real or artificial. In fact, the two sets of correlations (using all data and pre-1974 data only) are substantially different for only a few station-variable pairs. These include intensity at Gatton–Lawes and Peak Hill, where the correlations change sign when only pre-1974 data are used. The sign changes at the two stations are opposite in sense. The correlations with the number of events at the three most northern stations also change substantially, although the signs of the correlations do not change. At two stations, the correlations become more positive when the later data is added; at the other station, the correlation becomes less strongly positive. Finally, the sign of the correlation with length at Winton also changes. There seems little consistency in the way the correlations change when only pre-1974 data are used, relative to the correlations calculated with all the data. This suggests that the change of units in 1974 has not had a major effect on the rain event characteristics. The trends described below occur in both the total dataset and the pre-1974 data. This is evident in Figs. 7–11.

There is no evidence of a general increase in intensity of rain events. In fact, four of the stations show negative

TABLE 8. Correlations between year and the number, length, and intensity of rain events, and annual rainfall totals, at five stations. The correlations significant at 5% are underlined. Only data before 1974 are used in this table.

Station	Annual	Number	Length	Intensity
Winton	−.11	0.19	−.19	−.26
Gatton–Lawes	0.31	0.19	0.33	0.07
Peak Hill	0.25	0.46	0.39	−.24
Canary Island	0.24	0.12	−.27	0.35
Carrick	0.06	0.25	0.03	−.12

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correlations between intensity and year. Four of the five stations exhibit significant positive correlations between year and the number of events. The weak positive trends in rainfall at most of the stations are due, in general, to these increases in the number of events. The increases in annual rainfall are weaker than the number of events case because decreases in the intensity of events tend to offset the increases in rainfall caused by the increased numbers of events. This is particularly the case at Winton where the strong decrease in intensity completely offsets the increased numbers of events, resulting in no trend in annual rainfall.

Canary Island is the only station without a significant positive trend in numbers of events. It is also the only station with a positive trend in intensity, and this trend results in a weak positive trend in rainfall total.

At Peak Hill and Gatton–Lawes there are significant positive trends in the length of events. These positive trends enhance the increased annual rainfall caused by the increases in the numbers of events. As a result the positive trends in annual rainfall are strongest at these two stations. Nicholls and Lavery (1992) identified positive trends in rainfall, mainly summer rainfall, in the region, including these two stations.

The relationships between the variables on longer time scales, as revealed by the weighted least-squares smoothed fits shown in Figs. 7–11, differ from the relationships found that include all time scales. For instance, the long time-scale variations of numbers and intensity of events at Peak Hill (Fig. 9) are out of phase. But when all the data from the individual years are plotted (Fig. 4), no relationship is discernable (correlation = 0.02). Careful inspection of the fluctuations about the trend lines in Fig. 9 indicates that at interannual time scales the number and intensity of rain events tend to be in phase. This is also the case at Canary Island.

4. Discussion

a. *Rainfall trends and the "greenhouse" effect*

As was noted earlier, some numerical-model studies of the climatic effects of increased atmospheric concentrations of carbon dioxide have suggested that intensity of rain events might increase. In east Australia, the intensity of synoptic-scale rain events has not, in general, increased through the twentieth century, despite rainfall totals increasing. Indeed, intensity has tended to decrease, offsetting some of the increased rainfall due to the higher frequency of rain events. Thus, the pattern of rain-event trends does not appear to coincide with that expected from the atmospheric model studies, implying that the twentieth-century rainfall trends in east Australia (see Nicholls and Lavery 1992) may *not* be the result of an enhanced "greenhouse" effect, or that any such effect has, so far, been overwhelmed by other sources of variation. Yu and Neil (1991) examined high-intensity rainfall events in eastern Australia and concluded that they did not exhibit a simple and consistent relationship with global temperatures and rainfall totals. High rainfall intensities have occurred during periods of low or average rainfall and low temperature, as well as high temperature and rainfall.

b. *The Southern Oscillation and rain events*

The results noted earlier indicate that the Southern Oscillation produces the large-scale nature of east Australian rainfall fluctuations by influencing, primarily, the *number* of rain events. That is, during El Niño episodes, the number of rain events at most stations is generally below normal. The Southern Oscillation also affects the length and intensity of rain events at all the stations examined here (Table 6). However, other factors must also affect the length and intensity of rain events in different ways at each station, leading only to weak interstation correlations between these variables (Table 5). By contrast, the interstation correlations of the number of events are significant for most station pairs (Table 5), suggesting that other factors do less to disrupt the Southern Oscillation influence on the numbers of events.

The Southern Oscillation does, however, affect annual rainfall at *individual* stations through its influence on all three characteristics of the rain events: number, length, and intensity. The correlations of SOI with annual rainfall are greater than the correlations with the individual rain-event characteristics (Table 6). The strength of the SOI–rainfall correlations in this area forms the basis of the seasonal-outlook service provided by the Australian Bureau of Meteorology. This service uses the significant lag correlations between the SOI and seasonal rainfall (McBride and Nicholls 1983). It might be possible to improve the SOI–rainfall lag relationships (and, thus, the outlooks) by predicting number, length, and intensity of rain events separately and then combining the predicted characteristics to produce a "predicted" total rainfall.

c. *Confounding of interannual relationships by trends*

The trends in the rain variables appear to confound the relationships with the El Niño–Southern Oscillation, leading to weaker correlations than would be the case in the absence of trends. Figure 12 shows time series of annual SOI values and the number of rain events at Gatton–Lawes. The number of events at this station is positively correlated with the SOI (Table 6), but there is also a significant positive trend in the number of events (Table 7) *not* matched by a positive trend in the SOI. In fact there is a weak *negative* trend in the SOI (Fig. 12). Figure 12 indicates that the interannual variations in the SOI are positively related with the number of events (i.e., the fluctuations about the trend

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line tend to be in phase), but the positive trend in the number of events is not matched by an increase in the SOI. The strong trend in the number of events, since it is not matched by a trend in the SOI, would lead to a substantial reduction in the correlation between the SOI and the number of events.

A simple method for estimating the confounding effect of the trends on the SOI–rain event correlations is to calculate correlations between first differences (i.e., the difference between the current year and the previous year) of the SOI and the rain-event characteristics. First differences are often used to remove nonstationarity in time series. The correlation between the first differences of the SOI and the number of events at Gatton–Lawes is 0.46, substantially larger than the correlation of 0.33 between the original values of the SOI and the number of events. Thus, the SOI is more closely related with the interannual variations in the number of events, after the removal of trends. The relationship between the first differences of the variables is shown in Fig. 13. The relevance, to seasonal prediction, of these stronger relationships after the removal of trends, assuming the same situation arises with regard to lag relationships between the SOI and rainfall and rain events, is that removal of the trend may lead to more accurate seasonal predictions. Nicholls (1992) suggested this was appropriate for the prediction of Australian, seasonal tropical-cyclone activity from the SOI. The SOI–cyclone relationship is also affected by the secular trend.

Trends also confound the relationships between the variables describing rain events. It was noted earlier that the relationships between the rain-event characteristics vary with time scale. So, the long time-scale variations of numbers and intensity of events at Peak Hill (Fig. 9), as revealed by the weighted least-squares smoothed fit lines, are out of phase, but the short time-scale variations tend to be in phase. Peaks and troughs in the short time-scale fluctuations around the two "trend" lines for the variables often align. When all time scales are considered, for example in the scatter diagrams of Fig. 4, the different relationships at the long and short time scales negate each other, leading to a very weak overall relationship. The same phenomenon occurs at Canary Island. This suggests that a similar process of removal of trends, by taking first differences, could produce different results in the relationships between variables, as well as their relationships with the SOI. At Peak Hill the correlation between the first differences of intensity and the number of events is 0.23, significant at 5%. At Canary Island the correlation is 0.35, significant at 1%. The interstation relationships between interannual fluctuations of the rain-event variables, as well as the intrastation relationships, might also be disguised, or exaggerated, by qualitatively different relationships at longer time scales.

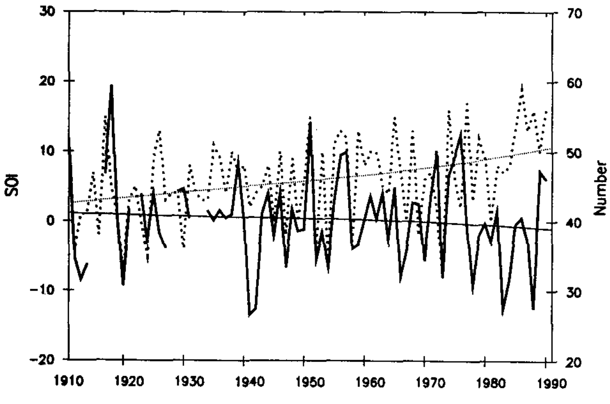

FIG. 12. Time series of the SOI (continuous lines) and the number of rain events at Gatton–Lawes (dotted lines). The thin lines are distance-weighted least-squares fits to the data to illustrate trends. Note that some SOI values are missing.

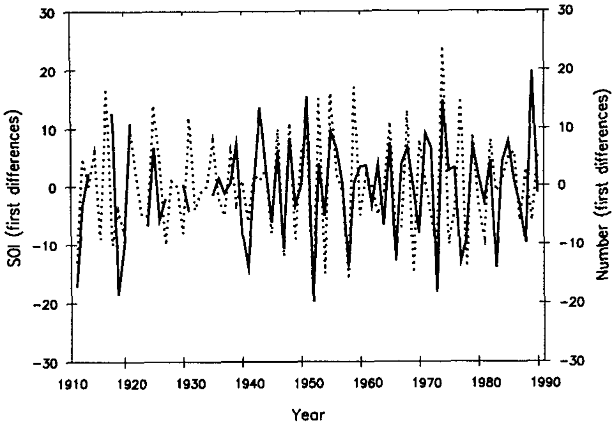

FIG. 13. Time series of the first differences of the SOI (continuous line) and the number of rain events at Gatton–Lawes (dotted line).

The different relationships between the numbers and the intensity of events at long and short time scales should provide further information about the cause of the long-term trends. Clearly, a different mechanism is influencing rain events at long time scales, compared with the influences at interannual time scales. The El Niño–Southern Oscillation appears to be a major influence at the shorter time scales. The physical mechanism through which the El Niño–Southern Oscillation affects Australian rain events must then be different in character to the mechanisms producing longer time-scale variations.

5. Concluding remarks

This study of east Australian rain events at five stations has found that

(i) Annual rainfall variations are primarily caused by variations in intensity.

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(ii) The number, length, and intensity of rain events are essentially independent of each other, at each station. This is due, at some stations, to interrelationships between the variables at different time scales offsetting or masking each other. Thus, the number and intensity of events tend to be negatively related at long time scales, but positively correlated at short time scales.

(iii) The large-scale geographical nature of east Australian rainfall fluctuations is mainly due to strong interstation correlations in the *number* of rain events.

(iv) The Southern Oscillation affects rainfall mainly by influencing the number and the intensity of rain events. Its influence on the length of events is, in general, weaker. Long-term trends confound some of the relationships with the Southern Oscillation.

(v) Twentieth-century increases in rainfall have been due, primarily, to increased numbers of rain events. Intensity of rain events has generally declined, offsetting some of the increase in rainfall expected from the increased numbers of events.

These conclusions have been derived from a study of rain events at only five stations. Although these stations are probably representative of conditions across much of east Australia [indeed Nicholls and Lavery (1992) selected these stations because their interannual rainfall variations were representative of substantial regions], more extensive investigations, using all the high-quality stations identified by Lavery et al. (1992), could be informative. This study could also be extended by applying different definitions of a rain event. Examination of changes in extreme daily rainfalls may be more useful in deciding whether rainfall trends can be attributed to an enhanced "greenhouse" effect. Calculation of seasonal lag correlations between the SOI and the rain-event characteristics might provide methods for seasonal prediction of these characteristics. Finally, relating the characteristics of rain events to other indicators and influences of the atmospheric circulation, for example, global sea surface temperature patterns, might provide further information on the causes of variations in rain events and their characteristics.

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