INTERNATIONAL JOURNAL OF CLIMATOLOGY, VOL. 17, 1155–1168 (1997)

RAINFALL VARIABILITY OVER SOUTH-EAST ASIA—CONNECTIONS WITH INDIAN MONSOON AND ENSO EXTREMES: NEW PERSPECTIVES

R. H. KRIPALANI* AND ASHWINI KULKARNI
Indian Institute of Tropical Meteorology, Pashan, Pune 411008, India
email: rhksup@tropmet.ernet.in

Received 13 September 1996
Revised 5 March 1997
Accepted 14 March 1997

ABSTRACT

Seasonal and annual rainfall data for 135 stations for periods varying from 25 to 125 years are utilized to investigate and understand the interannual and short-term (decadal) climate variability over the South-east Asian domain. Contemporaneous relations during the summer monsoon period (June to September) reveal that the rainfall variations over central India, north China, northern parts of Thailand, central parts of Brunei and Borneo and the Indonesian region east of 120°E vary in phase. However, the rainfall variations over the regions surrounding the South China Sea, in particular the north-west Philippines, vary in the opposite phase. Possible dynamic causes for the spatial correlation structure obtained are discussed.

Based on the instrumental data available and on an objective criteria, regional rainfall anomaly time series for contiguous regions over Thailand, Malaysia, Singapore, Brunei, Indonesia and Philippines are prepared. Results reveal that although there are year-to-year random fluctuations, there are certain epochs of the above- and below-normal rainfall over each region. These epochs are not forced by the El Niño/La Nina frequencies. Near the equatorial regions the epochs tend to last for about a decade, whereas over the tropical regions, away from the Equator, epochs last for about three decades. There is no systematic climate change or trend in any of the series. Further, the impact of El Niño (La Nina) on the rainfall regimes is more severe during the below (above) normal epochs than during the above (below) normal epochs. Extreme drought/flood situations tend to occur when the epochal behaviour and the El Niño/La Nina events are phase-locked. © 1997 by the Royal Meteorological Society. *Int. J. Climatol.*, 17: 1155–1168 (1997).

(No. of Figures: 9 No. of Tables: 2 No. of References: 30)

KEY WORDS: South-east Asia rainfall; Indian monsoon; teleconnections; ENSO; epochs; phase locking.

INTRODUCTION

South-east Asia consists of the mainland lying to the east of India and south of China, together with the islands to the south and east (Figure 1). This extensive area consists of Myanmar (formerly Burma), Thailand, Indo-China (Vietnam, Laos, Kampuchea), Malaysia, Singapore, the islands forming the Republic of Indonesia, Borneo, Brunei, the Philippine islands, Portuguese Timor and the western New Guinea.

Monsoon-related droughts and floods have an enormous social and economic impact on the people of India, China and the countries of South-east Asia, which form a large segment of the world's population. A large amount of scientific literature on the Indian and the East Asian monsoon is available (reviews available in Fein and Stephens, 1987; Chang and Krishnamurti, 1987; Lau and Li, 1984). However, possible connections between rainfall anomalies over the countries in the Asian domain are not well documented. Most of the previous studies on rainfall variability in the monsoon belt have focused on regional monsoon areas such as India, China, Indonesia, etc. By comparison, possible connections within the Asian monsoon have received little attention. Some work in this direction has been done by investigating the relationship between rainfall variations over India with variations over China (Kripalani and Singh, 1993), over Thailand (Kripalani *et al.*, 1995) and over Bangladesh and Nepal (Kripalani *et al.*, 1996a). These studies have shown that the rainfall variations over central India, north China and north-west Thailand are in-phase with Indian monsoon rainfall (IMR), whereas the rainfall variations from north-east India up to south-east China are out of phase with IMR (Kripalani, 1997).

* Correspondence to: R. Kripalani, Indian Institute of Tropical Meteorology, Pashan, Pune 411008, India.

CCC 0899-8418/97/111155-14 $17.50
© 1997 by the Royal Meteorological Society

Figure 1. Map showing the region of South-east Asia. Dots represent the location of the stations used in this study

It is now well recognized that the ENSO (El Niño–Southern Oscillation) phenomenon is the single most important mode to the Earth's year-to-year climatic variability. Normally, during the El Niño events the Indian region experiences drought conditions (Ropelewski and Halpert, 1987). Further, there have been distinct epochs of above (1880–1895, 1930–1963) and below (1895–1930, 1963–1990) normal rainfall over India. In a recent study, Kripalani and Kulkarni (1997a) have shown that the impact of El Niño is more severe during the below normal epochs and that the epochal behaviour of IMR is not forced by the El Niño/La Niña frequencies. The general climatological and environmental information and the circulation features over this region are available (e.g. Hastenrath, 1991; Martyn, 1992).

In view of the above, the purpose of the present empirical study is:

(i) to explore possible spatial connections of rainfall variations over the South-east Asian domain with those over the Indian region;
(ii) to prepare time series of areally averaged rainfall over contiguous regions in this sector and to determine the epochs of above and below normal rainfall;
(iii) to investigate whether these epochs are forced by the El Niño/La Niña events and whether the impact of El Niño/La Niña on rainfall regimes over this region is the same or different during these epochs.

DATA

The monthly station rainfall data for 135 stations (Figure 1) has been extracted from the Numeric Data Package *The Global Historical Climatology Network: Long-term Monthly Temperature, Precipitation, Sea-level Pressure,*

 © 1997 Royal Meteorological Society

and Station Pressure Data. This data package has been prepared by the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, USA. This data set has been subjected to thorough quality control checks. For details the reader may refer to Voce *et al.*, (1992).

Out of the 135 stations, 20 stations had data for 100 to 125 years, 82 stations for 50 to 100 years, and for the remaining stations the data period was 25 to 50 years. For 65 stations, missing data was less than 10 per cent, whereas for 41 stations the missing data was between 10 and 20 per cent. The remaining stations had 20–40 per cent of data missing.

The time series for IMR (June to September) has been taken from Parthasarathy *et al.*, (1994)).

SPATIAL CONNECTIONS WITH IMR

The search for teleconnections usually involves the calculation of a sample cross-correlation function for the pairs of time series. The existence of autocorrelation can lead to apparent leading or lagging relationships when none are actually present. Further, the effect of autocorrelation of the individual time series is to 'smear out' any contemporaneous cross-correlation that might be present (Katz, 1988). Cross-correlation functions are frequently presented for variables without first removing or correcting for the effects of autocorrelation (Kulkarni and Storch, 1995). However, all the rainfall series used here are free from autocorrelation because the lag-1 autocorrelations are insignificant. The common data period available for this analysis was 1951–1975. For a sample of 25 values the significant correlation is *ca.* 0·5 (0·4) at the 1 (5) per cent significance level.

The time series of IMR is correlated with the seasonal (June to September) rainfall of each of the 135 stations and with rainfall of 52 blocks (Kulkarni *et al.*, 1992) over India. This spatial pattern of contemporaneous correlations is shown in Figure 2. For completeness, this figure also includes the spatial correlations with Chinese rainfall (Kripalani and Singh, 1993), which are also based on the same data period.

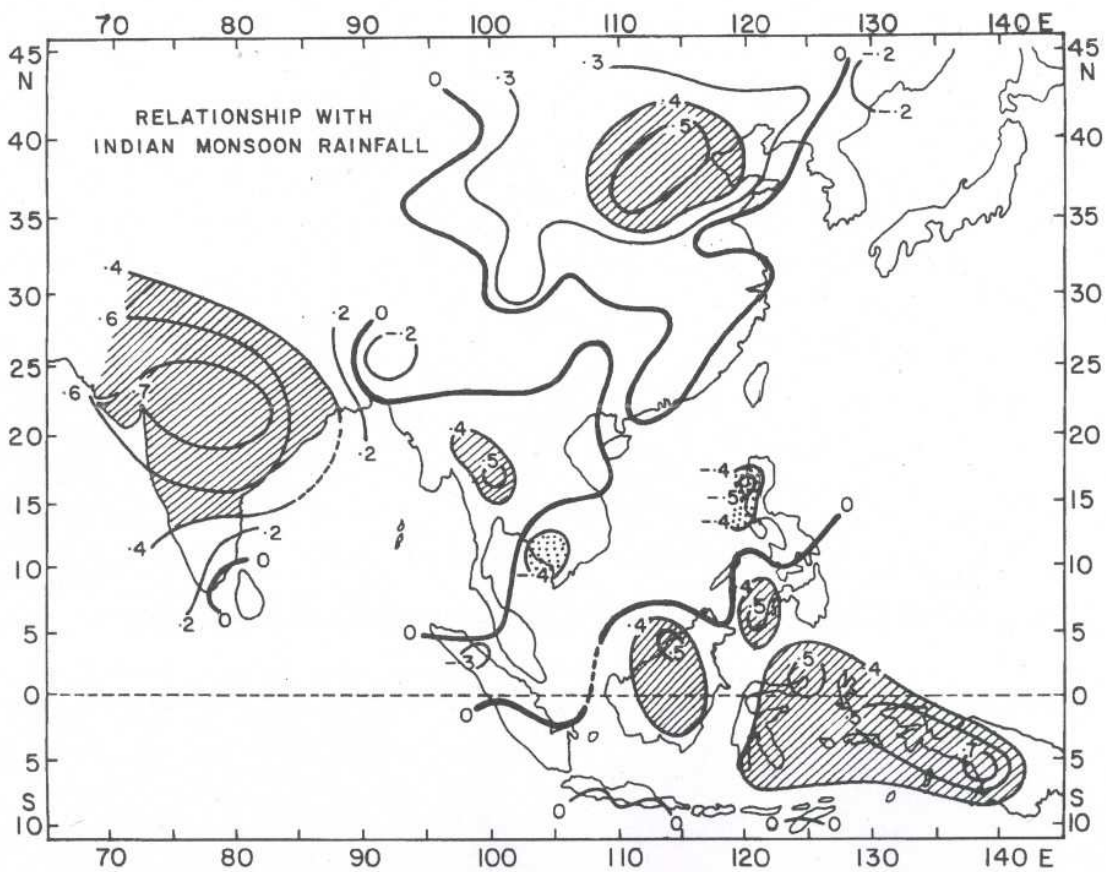

Figure 2. Spatial distribution of the correlation coefficients of IMR with seasonal rainfall (June–September) of each of the 135 stations. Regions that show significant positive (negative) correlation with IMR have been hatched (stippled)

© 1997 Royal Meteorological Society

Figure 2 reveals that the rainfall variations over central India, north China, north-west Thailand, central parts of Brunei and Borneo and the Indonesian region lying between 120° to 140°E are in phase, and show a high significant positive relationship with IMR. Although Brunei and Borneo's main rainy months are during the winter period (November through to February), they do receive rainfall during the summer monsoon months (Kripalani and Kulkarni, 1997b). The Indonesian region (showing high positive significant relationship with IMR) lying south of the equator between Celebes and New Guinea gets high rainfall during the northern summer monsoon period also (Kripalani and Kulkarni, 1997b). Thus extensive coherent regions showing in-phase variations with IMR occur over north China and the Indonesian region lying between 120° and 140°E. It is well known that the monsoon over north China is greatly influenced by the West Pacific subtropical high (Tao and Chen, 1987). Even the Indian monsoon is affected by changes over the West Pacific (Kripalani *et al.*, 1997). This may be one of the reasons for in-phase variations over the northern parts of China. The strong correlations with IMR between 110° and 140°E, north and south of the Equator, may be due to the impact of the Southern Oscillation phenomenon on both these regions.

The most intriguing feature is that the region surrounding the South China Sea, namely Kampuchea, southern Vietnam, Malaysia and north-west Philippines, is out of phase and shows a negative relationship with IMR. However, the out-of-phase relationship is significant over southern parts of Kampuchea and north-west Philippines only, in particular over north-west Philippines. This out-of-phase relationship over the Philippines region has been noted earlier using outgoing longwave radiation data (Kripalani *et al.*, 1991).

The South-east Asian summer monsoon has its low-level branch of the local Hadley circulation, with substantial convergence, pronounced updraft and vigorous rain, around 10°–20°N over the Bay of Bengal region,

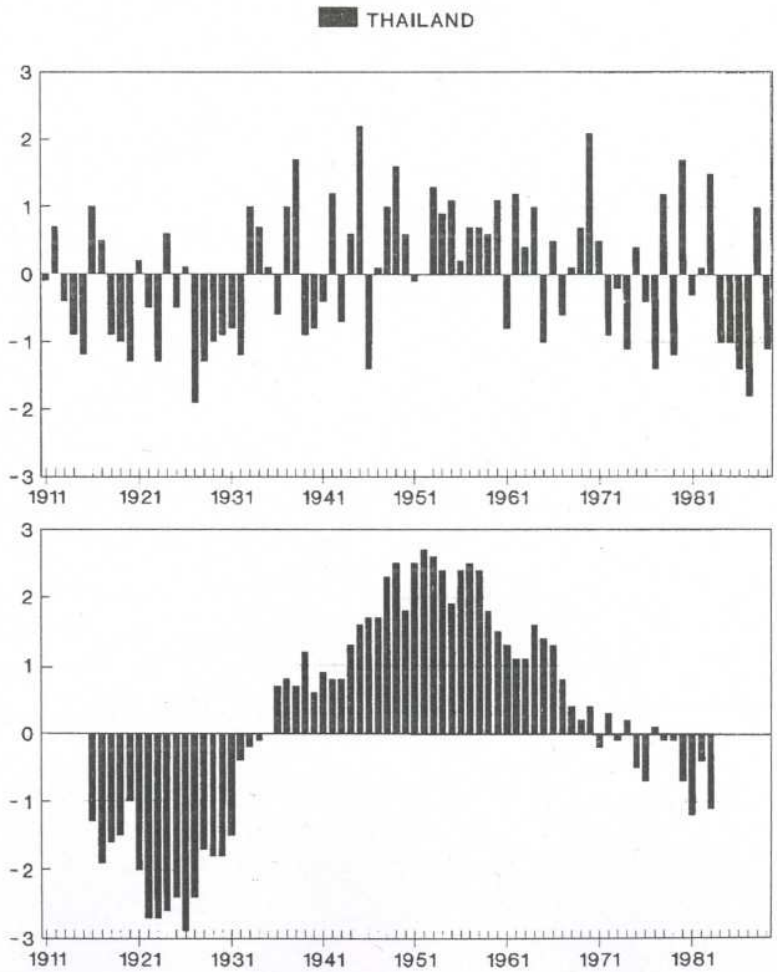

Figure 3. Year-to-year standardized monsoon rainfall over Thailand (top panel). Values of the Cramer's t statistic for the 11-year running means (bottom panel). The t values are plotted at the centre of the 11-year period

© 1997 Royal Meteorological Society

Figure 2 reveals that the rainfall variations over central India, north China, north-west Thailand, central parts of Brunei and Borneo and the Indonesian region lying between 120° to 140°E are in phase, and show a high significant positive relationship with IMR. Although Brunei and Borneo's main rainy months are during the winter period (November through to February), they do receive rainfall during the summer monsoon months (Kripalani and Kulkarni, 1997b). The Indonesian region (showing high positive significant relationship with IMR) lying south of the equator between Celebes and New Guinea gets high rainfall during the northern summer monsoon period also (Kripalani and Kulkarni, 1997b). Thus extensive coherent regions showing in-phase variations with IMR occur over north China and the Indonesian region lying between 120° and 140°E. It is well known that the monsoon over north China is greatly influenced by the West Pacific subtropical high (Tao and Chen, 1987). Even the Indian monsoon is affected by changes over the West Pacific (Kripalani *et al.*, 1997). This may be one of the reasons for in-phase variations over the northern parts of China. The strong correlations with IMR between 110° and 140°E, north and south of the Equator, may be due to the impact of the Southern Oscillation phenomenon on both these regions.

The most intriguing feature is that the region surrounding the South China Sea, namely Kampuchea, southern Vietnam, Malaysia and north-west Philippines, is out of phase and shows a negative relationship with IMR. However, the out-of-phase relationship is significant over southern parts of Kampuchea and north-west Philippines only, in particular over north-west Philippines. This out-of-phase relationship over the Philippines region has been noted earlier using outgoing longwave radiation data (Kripalani *et al.*, 1991).

The South-east Asian summer monsoon has its low-level branch of the local Hadley circulation, with substantial convergence, pronounced updraft and vigorous rain, around 10°–20°N over the Bay of Bengal region,

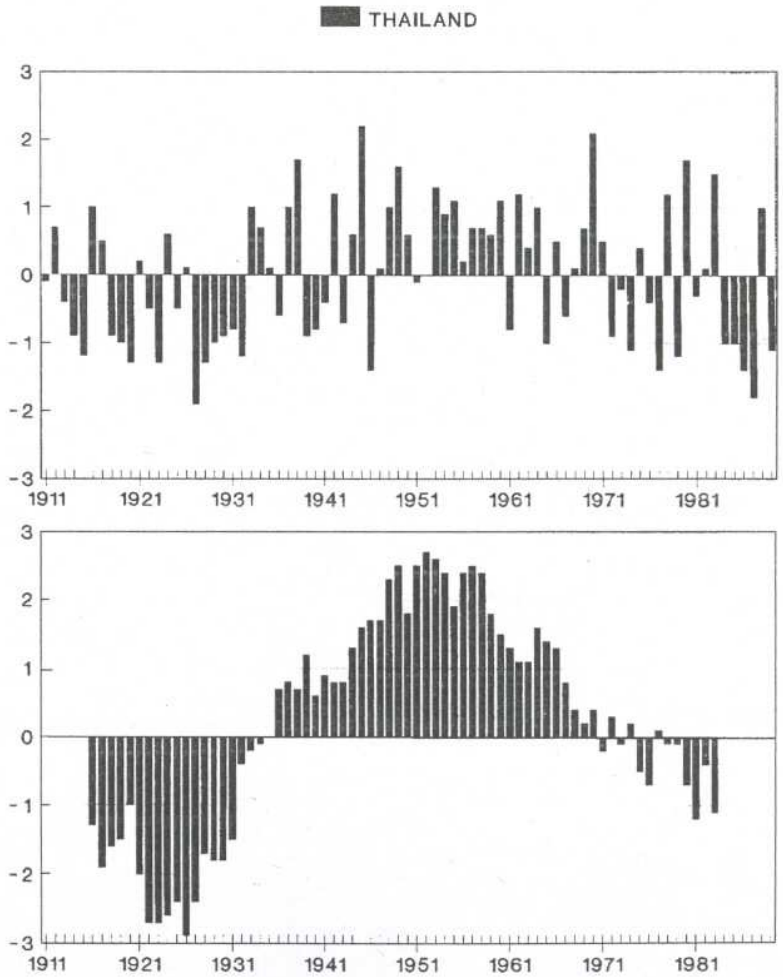

Figure 3. Year-to-year standardized monsoon rainfall over Thailand (top panel). Values of the Cramer's t statistic for the 11-year running means (bottom panel). The t values are plotted at the centre of the 11-year period

 © 1997 Royal Meteorological Society

whereas the western North Pacific summer monsoon has its active convection and updraft centre occurring over the key domain (10°–20°N, 130°–150°E) of the world's highest sea-surface temperatures. The boundary between these two monsoon regimes appears to exist somewhere over the South China Sea, where relatively dry weather persists and where the downdraft portion of both these monsoons occurs (Murakami and Matsumoto, 1994). This may have led to the out-of-phase relationship surrounding the South China Sea. Further, north-west Philippines is influenced by the pressure changes over the South China Sea. During the low pressure phase, enhanced cloudiness is found in the vicinity of the Philippines. In the phase change from low to high pressure a remarkable decrease in cloudiness is found near the Philippines, and the intensity of the Indian monsoon increases (Tao and Chen, 1987). Thus the intensity of the monsoon in the South China Sea does not necessarily correlate positively with the Indian monsoon. Recent simulations of the East Asian monsoon with atmospheric general circulation models have also noted that the monsoon over the Indian region (60°–90°E, 6°–22°N) and over the East Asian region (110°–125°E, 12°–22°N) seem to be negatively correlated (Wang and Xun-Qiang, 1995). Thus the empirical results obtained in this study are consistent with earlier studies and with model simulated results.

INTERANNUAL AND DECADAL VARIABILITY

Based on the available instrumental data, time series of areally averaged rainfall amounts are prepared using the simple arithmetic mean of station rainfall data for a particular region. However, because the rainfall over one location may differ to another location within a country, the stations selected for averaging are based on an

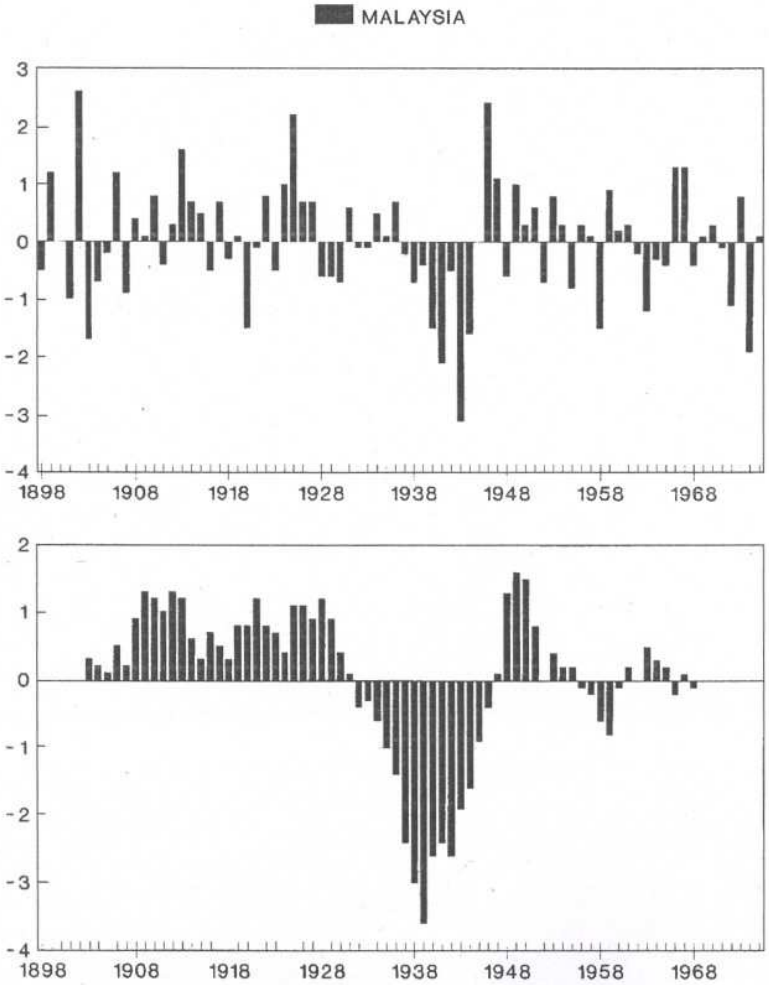

Figure 4. Same as Figure 3, but for annual rainfall over Malaysia

© 1997 Royal Meteorological Society

objective criteria. Correlation coefficients are computed between station rainfall series within a country. Only the stations having a positive significant correlation between each other are retained for averaging. The average time series is again correlated with the rainfall series of each station selected, to confirm that the average series does represent the region. With this method, rainfall series for the following contiguous regions only could be prepared:

(i) Thailand (monsoon period) region lying between 12·5° and 19·0°N, 99° and 104°E — average of eight stations for the period 1911–1989 (Figure 3);
(ii) Malaysia (annual) — 25 stations for the period 1898–1975 (Figure 4);
(iii) Singapore (annual) — two stations for the period 1872–1980 (Figure 5);
(iv) Brunei (annual) — seven stations for the period 1908–1980 (Figure 6);
(v) Indonesia (annual) region lying between 5° and 10°S, 105° and 120°E — 19 stations for the period 1898–1975 (Figure 7);
(vi) Philippines (monsoon period) region over the north-west sector — six stations for the period 1903–1975 (Figure 8);
(vii) Philippines (annual) — 19 stations for the period 1903–1975 (Figure 9);

Such series could not be prepared for Myanmar, Laos, Kampuchea, Vietnam, Sumatra, Borneo, Celebes, Papua/New Guinea and the Indonesian region lying east of 120°E owing to limited data. The results presented are based on the available length of data for a region, because the features based on the common data period are similar.

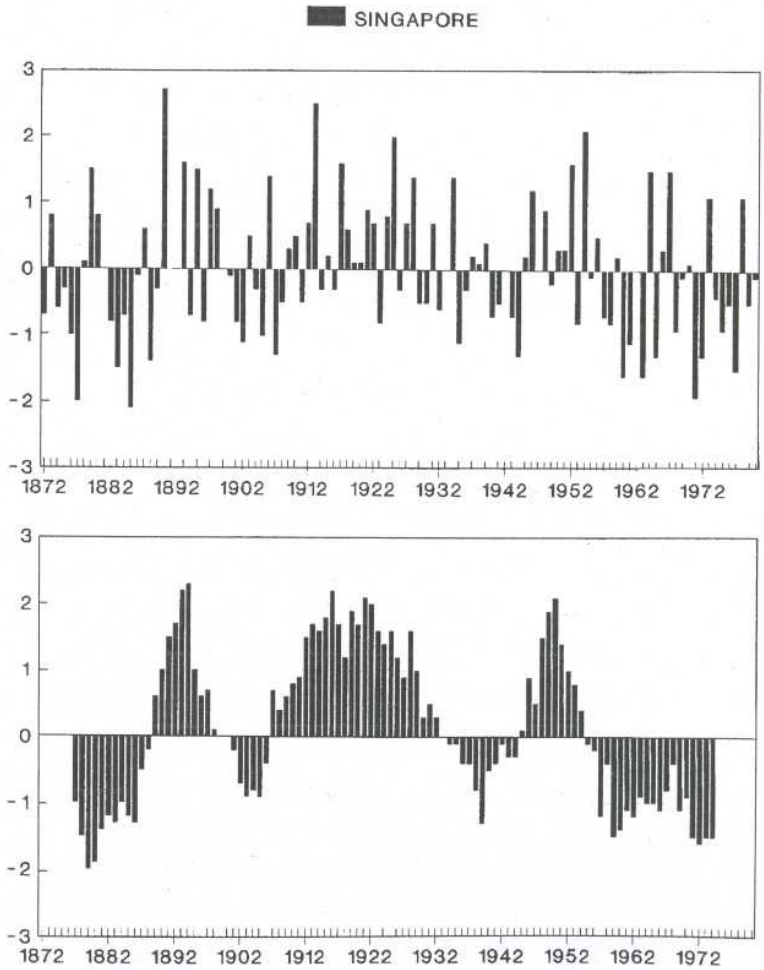

Figure 5. Same as Figure 3, but for annual rainfall over Singapore

© 1997 Royal Meteorological Society

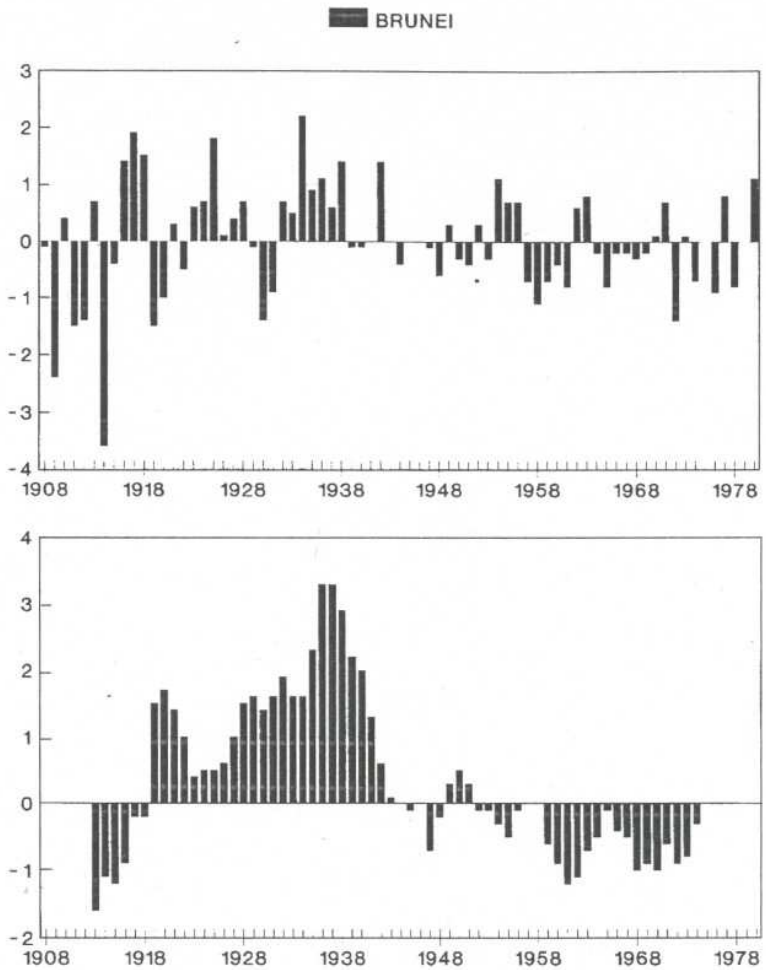

Figure 6. Same as Figure 3, but for annual rainfall over Brunei

All the above series have been subjected to statistical tests. The frequencies of these series are Gaussian according to chi-square and Kolmogorov–Smirnov (K–S) tests (WMO, 1966a). These series are also free from Markovian type of persistence, because the lag-1 autocorrelations are insignificant. Long-term changes are examined with the Mann–Kendall rank statistic (WMO, 1966b). No trends are detected. The short-term climatic fluctuations have been studied by applying Cramer's test for the 11-year (since decadal) running means (WMO, 1966b). This statistic compares the means of the subperiods with the mean of the whole period. Here this statistic has been used to isolate periods of above and below average rainfall only, and not to examine their significance.

Figures 3 to 9 show the year-to-year standardized rainfall (top panel) along with the values of the Cramer's statistic for the 11-year running means (bottom panel) for each series defined above. Although there are year-to-year random fluctuations, the most striking features seen are the epochs of above and below normal rainfall in each series. However, there is no systematic climatic change or trend in any of the series. There appears to be an inherent epochal variability in each of the series. The average length of the period between the turning points (from an epoch of above to below normal or from an epoch of below to above normal) over the equatorial regions (Singapore, Indonesia) is about one decade (oceanic influence), whereas over the tropical regions, away from the Equator (India, Thailand), it is about three decades (continental influence).

Impact of ENSO

The ENSO phenomenon is the most dominant pattern of the short-term climatic variations over the globe. It accounts for a greater proportion of variance of climatic and oceanic fields on time-scales from a season to a

© 1997 Royal Meteorological Society

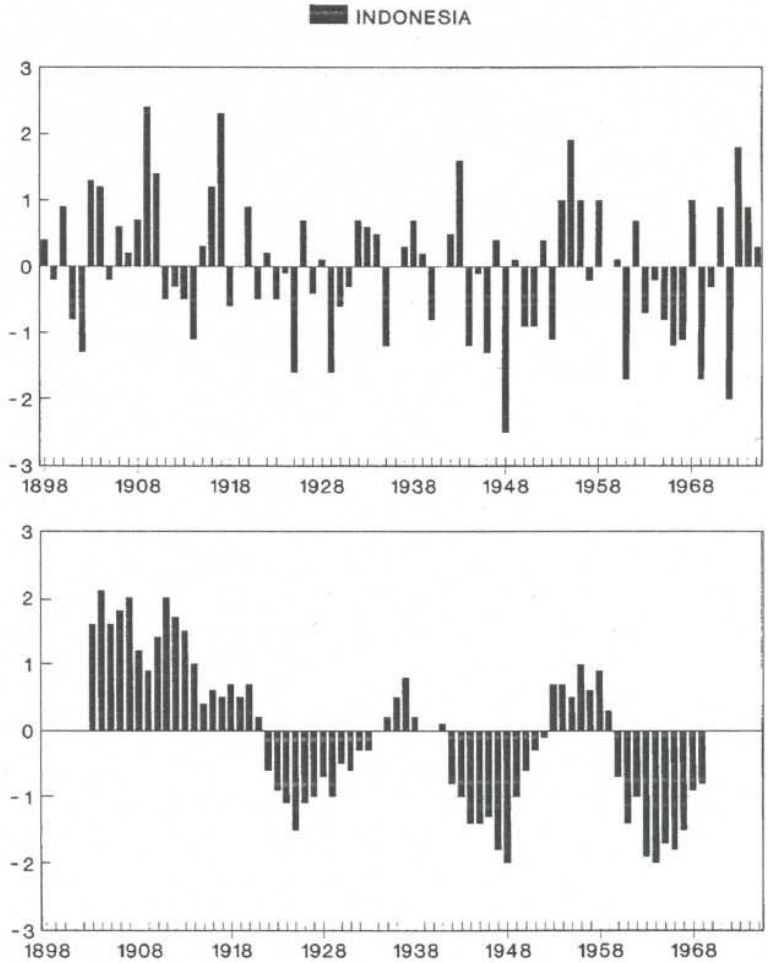

Figure 7. Same as Figure 3, but for annual rainfall over Indonesia

decade than any other single phenomenon, except only the annual cycle. Further, a majority of the warm (cold) extremes, i.e. the El Niño (La Niña) events cause below (above) normal rainfall over the Indo-Australian region (Ropelewski and Halpert, 1987). Whether the impact of these episodes is the same or different during the above- and below-normal epochs remains to be examined. Hence the influence of ENSO warm extremes (Rasmusson and Carpenter, 1983) and the cold extremes (Van Loon and Shea, 1985) on the rainfall regimes is assessed separately during these epochs. However, it would be worthwhile to determine first whether the epochal behaviour is forced by the El Niño/La Niña frequencies.

Epochal behaviour and El Niño/La Niña frequency

The importance of the Southern Oscillation has varied during the last century, with epochs of strong and weaker variations (Trenberth and Shea, 1987). These Pacific decadal time-scale variations have been linked to the recent changes in the frequency and intensity of the El Niño versus La Niña events (Trenberth and Hurrel, 1994). Hence to examine whether the epochal behaviour over the South-east Asian domain is also triggered by the frequency of the El Niño/La Niña events, the 11-year *t*-statistics have been recomputed by deleting the (i) El Niño cases, (ii) La Niña cases, and (iii) El Niño plus the La Niña cases. The running means are now computed depending on the values available during a particular 11-year period. Results show that the major epochs of above- and below-normal rainfall and the turning points have remained the same (figures not presented). However, although the series are not altered fundamentally by this removal, for some regions, in some time

 © 1997 Royal Meteorological Society

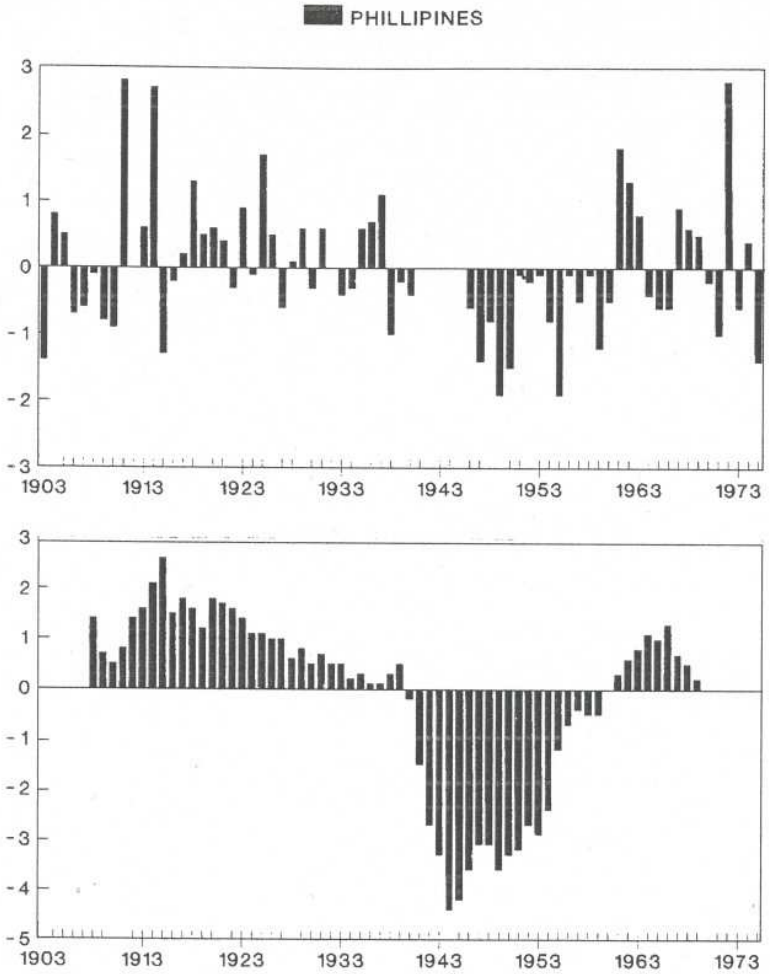

Figure 8. Same as Figure 3, but for seasonal (June–September) rainfall over north-west Phillipines

periods, the details are slightly different. Thus this analysis suggests that the epochal behaviour is slightly modified but not fundamentally forced by the El Niño/La Niña frequency. Because the epochal behaviour is not forced by these episodes, El Niño/La Niña events can be considered as an external forcing and the epochal behaviour as an internal variability.

Epochal behaviour and ENSO extremes

The epochs of above- and below-normal rainfall for each region can be inferred from the bottom panel of the respective figures (Figures 3 to 9). The years of the El Niño (La Niña) events during the above- and below-normal epochs, along with the standardized rainfall for each episode for the respective regions, are tabulated in Table I (Table II). Certain El Niño/La Niña cases occurring around the turning points or during the periods where the epochal variability appears damped, could not be classified either in the above- or below-normal epochs. These have been shown separately.

A critical examination of Table I reveals interesting results. It is seen that during the below normal epochs practically all the cases for all the regions have resulted in below normal rainfall. However, in only 50 per cent (on average) of the cases the rainfall has been below normal during the above normal epochs. Even the average standardized rainfall during the below normal epochs for all the regions is negative. However, the average standardized rainfall during the above normal epochs is positive (except for Indonesia). The differences between

© 1997 Royal Meteorological Society

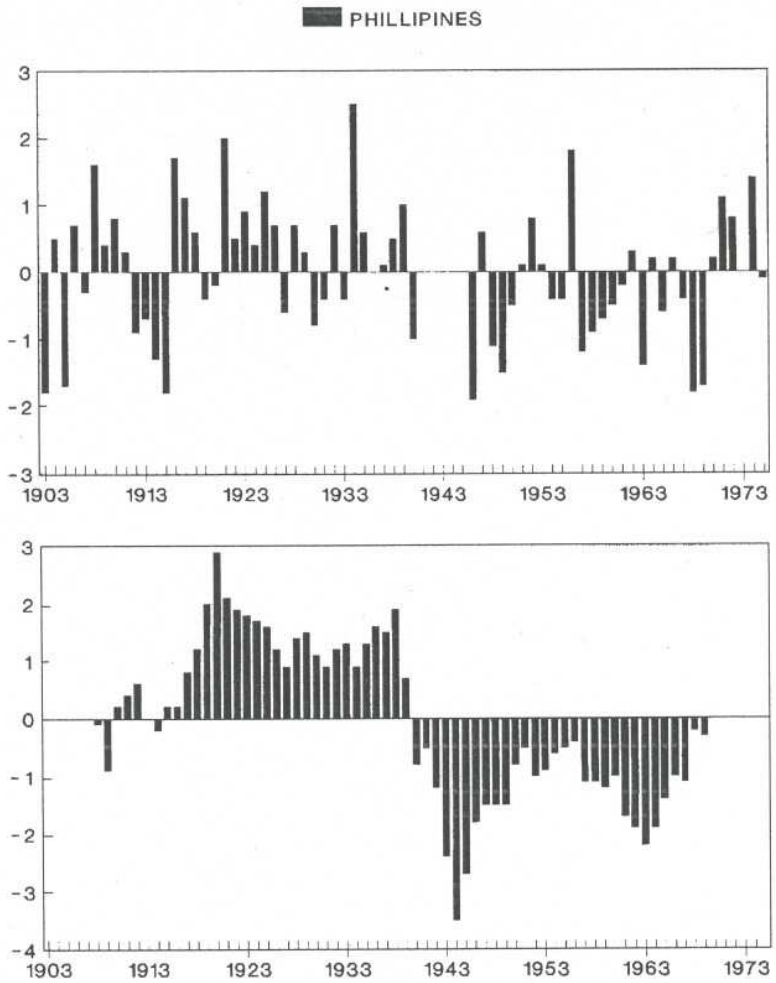

Figure 9. Same as Figure 3, but for annual rainfall over Philippines

the means of the standardized rainfall for the above- and below-normal epochs are significant at the 5 per cent level for Thailand, Malaysia, Singapore and Brunei. Further, severe droughts related to the El Niño events have occurred during the below normal epochs only, e.g. Thailand (1923, 1932), Malaysia (1941), Singapore (1877, 1902, 1905, 1965, 1972), Brunei (1911, 1914, 1972), and Indonesia (1925, 1972). Most of the El Niño cases that have not resulted in below normal rainfall are the ones which have occurred during the above normal epochs, e.g. the El Niño during 1925 resulted in above normal rainfall over Malaysia, Singapore and Brunei. Hence the major drought situations occur when the epochal variability and the El Niño events occur in-phase (phase-locking), i.e. the impact of El Niño is more severe during the below normal epochs than during the above normal epochs. Indonesia lies at the centre of action of the Southern Oscillation phenomenon, this may be the reason that the impact of El Niño is practically the same during the above normal as well as the below normal epochs.

A similar inference can be drawn for the La Niña cases shown in Table II, however, the results are not as spectacular as for the El Niño cases. On average, 70 (50) per cent of the La Niña cases have resulted in above (below) normal rainfall during the above (below) normal epochs. The differences between the means are highly significant (at the 1 per cent level of significance) for Indonesia and significant (5 per cent) for Thailand only. Majority of the La Niña related floods have occurred during the above normal epochs, e.g. Thailand (1938, 1970) and Singapore (1954). Hence the major extreme events of rainfall (severe floods/droughts), in particular droughts, may be due to the phase-locking between the internal epochal variability and the external forcings of the El Niño/La Niña events.

 © 1997 Royal Meteorological Society

Table I. Years of the El Niño events.

Region		El Niño years and SR										ASR	Student's t statistic
Thailand (monsoon)	B	1918	1923	1925	1930	1932							
Figure 3	5	−0·9	−1·3	−0·5	−0·9	−1·2						−1·0	2·60*
	A	1939	1941	1951	1953	1957	1965	1969					
	7	−0·9	−0·4	−0·1	+1·3	+0·7	−1·0	+0·7				+0·0	
	T	1972	1976										
	2	−0·9	−0·4										
Malaysia (annual)	B	1939	1941										
Figure 4	2	−0·4	−2·3									−1·4	2·32*
	A	1905	1911	1914	1918	1923	1925	1951	1953				
	8	−0·2	−0·4	+0·7	−0·3	−0·5	+2·2	+0·6	+0·8			+0·4	
	T	1930	1932	1957	1965	1969	1972						
	6	−0·8	−0·1	+0·1	−0·4	+0·1	−1·0						
Singapore (annual)	B	1877	1884	1902	1905	1939	1941	1957	1965	1969	1972		
Figure 5	10	−2·0	−0·7	−1·2	−1·1	+0·4	−0·6	−0·8	−1·2	−0·1	−1·4	−0·9	2·60*
	A	1891	1911	1914	1918	1923	1925	1951					
	7	0·0	−0·6	−0·4	+0·7	−0·8	+2·2	+0·3				+0·2	
	T	1887	1896	1899	1930	1932	1953						
	6	+0·7	−0·8	0·0	−0·5	−0·6	−0·8						
Brunei (annual)	B	1911	1914	1965	1969	1972							
Figure 6	5	−1·5	−3·6	−0·8	−0·2	−1·4						−1·5	2·55*
	A	1923	1925	1930	1932	1939	1941						
	6	+0·6	+1·9	−1·3	+0·7	−0·1	0·0					+0·3	
	T	1918	1951	1953	1957								
	4	+1·5	−0·4	−0·3	−0·7								
Indonesia (annual)	B	1923	1925	1930	1951	1965	1969	1972					
Figure 7	7	−0·6	−1·6	−0·6	−0·8	−0·8	−1·5	−2·0				−1·1	1·58
	A	1902	1905	1911	1914	1918	1957						
	6	−1·3	−0·2	−0·5	−1·2	−0·6	−0·2					−0·7	
	T	1932	1939	1941	1953								
	4	+0·8	+0·2	0·0	−1·1								
Philippines (monsoon)	B	1941	1951	1953	1957								
Figure 8	4	0·0	−0·1	−0·1	−0·5							−0·2	1·86
	A	1911	1914	1918	1923	1925	1930	1932	1965				
	8	+2·8	+2·7	+1·4	+1·0	+1·6	−0·3	0·0	−0·6			+1·1	
	T	1939	1969	1972									
	3	−0·2	+0·5	+2·8									
Philippines (annual)	B	1951	1953	1957	1965								
Figure 9	4	+0·1	+0·1	−1·2	−0·5							−0·4	1·93
	A	1918	1923	1925	1930	1932							
	5	+0·6	+1·0	+1·2	−0·8	+0·8						+0·6	
	T	1911	1914	1939	1941	1969	1972						
	6	+0·3	−1·3	+1·0	0·0	−1·6	+1·0						

Values below the years are the standardized rainfall (SR) for that year. A, Above normal epochs; B, below normal epochs; T, around the turning points or where the epochal variability appears damped; ASR, average standardized rainfall for that particular epoch. Values below B, A and T are frequencies. * (**) significant at 5 (1) per cent level

For Indonesia it appears that the impact of the external forcing plays a more dominant role than the internal epochal behaviour. However, for the Philippines, the epochal behaviour appears to be more important than the impact of the El Niño/La Niña events. Whereas the summer monsoons over Thailand, Indo-China and Malaysia–Indonesia are due to the land–ocean heat contrast, the Philippines is distinctly different due to less significant continentality. Basically this is an oceanic monsoon supported by disturbance activity, with the role of the north–south heat contrast minimal (Murakami and Matsumoto, 1994). As over India (Kripalani and Kulkarni, 1997a), the concept of phase-locking plays a dominant role in determining the extreme situations over Thailand, Malaysia, Singapore and Brunei.

© 1997 Royal Meteorological Society

Table II. Same as Table I but for La Niña events

Region		La Niña years and SR							ASR	Student's t statistic
Thailand (monsoon)	A	1938	1942	1949	1954	1964	1966	1970		
Figure 3	7	+1·7	+1·2	+1·6	+0·9	+1·0	+0·5	+2·1	+1·3	2·90*
	B	1916	1920	1924	1931					
	4	+1·0	−1·3	+0·6	−0·8				−0·1	
	T	1973	1975	1978						
	3	−0·2	+0·4	+1·2·						
Malaysia (annual)	A	1906	1908	1916	1920	1924	1949			
Figure 4	6	+1·2	+0·4	−0·5	−1·5	+1·0	+1·0		+0·3	1·15
	B	1938	1942							
	2	−0·8	−0·5						−0·7	
	T	1931	1954	1964	1966	1970	1973			
	6	+0·7	+0·3	−0·3	+1·5	+0·3	+0·8			
Singapore (annual)	A	1892	1916	1920	1924	1949	1954			
Figure 5	6	0·0	−0·4	+0·1	+0·9	−0·2	+2·3		+0·5	0·06
	B	1886	1903	1938	1942	1964	1966	1970 1973		
	8	−0·1	+0·5	+0·1	0·0	+1·6	+0·3	+0·1 +1·3	+0·5	
	T	1889	1898	1906	1908	1931				
	5	−0·3	+0·9	+1·4	−0·5	+0·8				
Brunei (annual)	A	1920	1924	1931	1938	1942				
Figure 6	5	−1·0	+0·7	−0·9	+1·5	+1·4			+0·3	0·16
	B	1916	1964	1966	1970	1973				
	5	+1·4	−0·2	−0·2	+0·1	+0·1			+0·2	
	T	1949	1954							
	2	+0·3	+1·2							
Indonesia (annual)	A	1903	1906	1908	1916	1920	1954			
Figure 7	6	+1·3	+0·5	+0·7	+1·2	+1·0	+1·2		+1·0	4·91**
	B	1924	1931	1942	1949	1964	1966	1970		
	7	−0·1	−0·3	+0·5	+0·1	−0·2	−1·2	−0·3	−0·2	
	T	1938								
	1	+0·8								
Philippines (monsoon)	A	1908	1916	1920	1924	1931	1964	1966		
Figure 8	7	−0·1	−0·2	+0·6	−0·1	+0·6	−0·3	−0·6	0·0	1·98
	B	1942	1949	1954						
	3	0·0	−1·8	−0·7					−0·8	
	T	1938	1970							
	2	−1·0	−0·2							
Philippines (annual)	A	1920	1924	1931	1938					
Figure 9	4	−0·2	+0·5	−0·5	+0·5				+0·1	0·88
	B	1942	1949	1954	1964	1966				
	5	0·0	−1·5	−0·4	+0·2	+0·2			−0·3	
	T	1908	1916	1970	1973					
	4	+1·7	+1·8	+0·2	0·0					

CONCLUSIONS

The relationship with IMR has revealed that within the Asian monsoon regime, not only are there regions (north China, some northern parts of Thailand, Borneo, Brunei and Indonesia) which are in-phase with IMR, but there are regions (surrounding the South China Sea) which are out-of-phase also. These types of teleconnections lack physical explanation but are important topics for future research and climate dynamics.

This study has fostered some new insights in the connections between the ENSO extremes and the rainfall variability. First, the analysis of the short-term fluctuations of seasonal and annual rainfall time series show distinct epochs of above- and below-normal rainfall, which are not forced by the El Niño/La Niña frequencies. Second, the epochs tend to last for about one decade over the equatorial oceanic regions and about three decades

 © 1997 Royal Meteorological Society

over the continental regions. Third, the impact of El Niño is more severe during the below normal epochs than during the above normal epochs. In fact a majority of the El Niños that have occurred during the above normal epochs have caused positive rainfall anomalies. The impact of La Niña appears to be more severe during the above normal epochs. Extreme drought and flood situations tend to occur when the internal epochal behaviour and the external forcings of El Niño/La Niña events are phase-locked.

After examination of the epochal behaviour of rainfall over India for recent years, Kripalani and Kulkarni (1997a) have speculated that India is almost invulnerable to severe droughts during the next two decades. Further Kripalani and Kulkarni (1996) have shown that, although severe droughts over India are linked with El Niño, severe floods are linked with events other than the La Niña events. Besides the ENSO phenonemon, other factors also are believed to be important for the interannual behaviour of the IMR and for the rainfall variability over South-east Asia. A recent study by Kripalani *et al.*, (1996b) suggests that snow depth over Russia is better related to the Indian monsoon than the Eurasian snow cover. All these aspects will be looked into once the recent data over this region are available to the authors.

ACKNOWLEDGEMENTS

The authors express their thanks to Professor R. N. Keshavamurty, Director, Indian Institute of Tropical Meteorology and Dr S. S. Singh, Deputy Director, for the encouragement and for the facilities provided. The authors also wish to thank sincerely the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, USA, for the station rainfall data without which this research would not have been possible. Finally thanks are due to the anonymous reviewers for constructive suggestions and to Dr Brian D. Giles for painstaking editorial work.

REFERENCES

Chang, C. P. and Krishnamurti, T. N. (eds) 1987. *Monsoon Meteorology*, Oxford University Press, Oxford, 544 pp.

Fein, J. S. and Stephens, P. L. (eds) 1987. *Monsoons*, John Wiley and Sons, New York, 632 pp.

Hastenrath, S. 1991. *Climate Dynamics of the Tropics* (updated Edition from *Climate and Circulation of the Tropics*), Kluwer Academic Publishers, Dordrecht, 488 pp.

Katz, R. W. 1988. 'Use of cross correlations in the search for teleconnections', *J. Climatol.*, **8**, 241–253.

Kripalani, R. H. 1997. 'Connections of Indian monsoon rainfall within the Asian monsoon regime', *First WMO International Workshop on Monsoon Studies*, Bali, Indonesia, 24–28 February 1997, WMO/TD No. 786, pp. 104–106.

Kripalani, R. H. and Kulkarni, A. 1996. 'Assessing the impacts of El Niño and Non-El Niño-related droughts over India', *Drought Network News*, **8** (3), 11–13.

Kripalani, R. H. and Kulkarni, A. 1997a. 'Climatic impact of El Niño/La Niña on Indian Monsoon: a new perspective', *Weather*, **52**, 39–46.

Kripalani, R. H. and Kulkarni, A. 1997b. 'Relationship between some large-scale atmospheric parameters and rainfall over southeast Asia: comparison with features over India', *Theor. Appl. Climatol.*, in press.

Kripalani, R. H. and Singh, S. V. 1993. 'Large scale aspects of India–China summer monsoon rainfall', *Adv. Atmos. Sci.*, **10**, 71–84.

Kripalani, R. H., Singh, S. V. and Arkin, P. A. 1991. 'Large scale features of rainfall and outgoing longwave radiation over Indian and adjoining regions', *Cont. Atmos. Phys.*, **64**, 159–169.

Kripalani, R. H., Singh, S. V., Panchawagh, N. and Brikshavana, M. 1995. 'Variability of the summer monsoon rainfall over Thailand — Comparison with features over India', *Int. J. Climatol.*, **15**, 657–672.

Kripalani, R. H., Inamdar, S. and Sontakke, N. A. 1996a. 'Rainfall variability over Bangladesh and Nepal: comparison and connections with features over India', *Int. J. Climatol.*, **16**, 689–703.

Kripalani, R. H., Singh, S. V., Vernekar, A. D. and Thapliyal, V. 1996b. 'Empirical study on Nimbus-7 snow mass and Indian monsoon rainfall', *Int. J. Climatol.*, **16**, 23–34.

Kripalani, R. H., Kulkarni, A. and Singh, S. V. 1997. 'Association of the Indian summer monsoon with the Northern Hemisphere mid-latitude circulation', *Int. J. Climatol.*, in press.

Kulkarni, A., Kripalani, R. H. and Singh, S. V. 1992. 'Classification of summer monsoon rainfall patterns over India', *Int. J. Climatol.*, **12**, 269–280.

Kulkarni, A. and Storch, H. V. 1995. 'Monte-Carlo experiments on the effect of serial correlation on the Mann-Kendall test of trend', *Meteorol. Zeitschrift.*, N.F.4.Jg., 82–85.

Lau, K. M. and Li, M. T. 1984. 'The monsoon of east Asia and its global association — a survey', *Bull. Am. Meteorol. Soc.*, **65**, 114–125.

Martyn, D. 1992. *Climates of the World. Developments in Atmospheric Sciences*, Vol. 18, Elsevier, Amsterdam, 435 pp.

Murakami, T. and Matsumoto, J. 1994. 'Summer monsoon over the Asian continent and western North Pacific', *J. Meteorol. Soc. Jpn.*, **72**, 719–745.

Parthasarathy, B., Munot, A. A. and Kothawale, D. R. 1994. 'All-India monthly and seasonal rainfall series 1871–1993', *Theor. Appl. Climatol.*, **49**, 217–224.

Ropelewski, C. F. and Halpert, M. S. 1987. 'Global and regional scale precipitation associated with ENSO', *Mon. Wea. Rev.*, **115**, 1606–1626.

© 1997 Royal Meteorological Society

Rasmusson, E. M. and Carpenter, T. H. 1983. 'The relationship between eastern equatorial Pacific sea surface temperature and rainfall ov India and Sri Lanka', *Mon. Wea. Rev.*, **111**, 517–528.

Tao, S. and Chen, L. 1987. 'A review of recent research on the East Asian Summer Monsoon in China', in Chang, C.-P. and Krishnamur T. N. (eds), *Monsoon Meteorology, Oxford Monographs on Geology and Geophysics*, No. 7, Oxford University Press, New York, pp. 6 92.

Trenberth, K. E. and Hurrel, J. W. 1994. 'Decadal atmosphere-ocean variations in the Pacific', *Climate Dyn.*, **9**, 303–319.

Trenberth, K. E. and Shea, D. J. 1987. 'On the evolution of the Southern Oscillation', *Mon. Wea. Rev.*, **115**, 3078–3096.

Van Loon, H. and Shea, D. J. 1985. 'The Southern Oscillation. Part IV: the precursors south of 15 deg. S to the extremes of the oscillatio *Mon. Wea. Rev.*, **113**, 2063–2074.

Vose, R. S., Schmoyer, R. L., Steurer, P. M., Peterson, T. C., Heim, R., Karl, T. R. and Eischeid, J. K. 1992. *The Global Historic Climatology Network: Long-term Monthly Temperature, Precipitation, Sea Level Pressure and Station Pressure Data*, Prepared by t Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 300 pp.

Wang, H.-J. and Bi, X.-Q. 1995. 'Some results of East Asian Monsoon simulation with IAP AGCMs', *Proceedings, The First Internation AMIP Scientific Conference*, May 1995, California, WCRP-92, WMO/TD No. 732, pp. 187–191.

WMO, 1966a. *Some methods in climatological analysis*, WMO Technical Note No. 81, WMO NO. 199-TP-103, World Meteorologic Organization, Geneva, 53 pp.

WMO, 1966b. *Climatic Change*, WMO Technical Note No. 79, WMO NO. 195-TP-100, World Meteorological Organization, Geneva, 53 p

© 1997 Royal Meteorological Societ