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The El Niño Southern Oscillation and the historic malaria epidemics on the Indian subcontinent and Sri Lanka: an early warning system for future epidemics?

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Summary The recurrent great malaria epidemics which occurred in the Punjab province of former British India and Ceylon before the introduction of residual insecticides have been related to excessive and failing monsoon rains respectively. In the arid Punjab, rainfall facilitated breeding and increased the lifespan of the mosquito vector and, in the wet part of Ceylon, failing monsoon rains caused rivers to pool, creating more favourable breeding conditions. The periodic fluctuations in monsoon rainfall and epidemic malaria are here explained in relation to the El Niño Southern Oscillation. In the Punjab, epidemic malaria between 1868 and 1943 correlates significantly (r=0.34, P<0.005) with the sea surface temperature anomalies in the Eastern Equatorial Pacific, a parameter of the oscillation, and epidemics were significantly more prevalent in a year with a wet monsoon following a dry El Niño year than in other years. In Ceylon, epidemics were significantly more prevalent during El Niño years, when the same south-west monsoon tends to fail. With the reduced reliance on residual insecticides and the recurrence of epidemic malaria on the Indian subcontinent, advances made in predicting El Niño events may be used to forecast high and low risk years for future malaria epidemics.

keywords malaria, epidemic, El Niño, ENSO, Punjab, India, Sri Lanka

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Introduction

With the predicted changes in the world's climate, the effects of weather on the epidemiology of diseases have received increasing attention in recent years. Malaria, as a vector borne disease, is thought to be particularly influenced by climate change (WHO 1990). The development of the parasite in the mosquito—the sporogonic cycle—is temperature dependent (Macdonald 1957), and the population dynamics of the mosquito vector are sensitive to small climate variations (Molineaux 1988). Rainfall affects breeding conditions, and the vector's lifespan, affected by the relative humidity, needs to be sufficiently long to pass on the infection. Malaria in areas of low endemicity is particularly sensitive to climate variations. In these areas of 'unstable' malaria the population lacks protective immunity, and is prone to epidemics when climate conditions facilitate transmission.

The natural boundaries of the geographical distribution of malaria are determined by temperature and rainfall. Low temperatures can restrict transmission in tropical highlands ('highland fringe malaria') or at higher latitudes, and 'desert fringe malaria' (Najera *et al.* 1992) is found where low rainfall restricts the vector population. It was particularly in these fringe areas with unstable malaria, that insecticides used on a large scale since the 1940s had their greatest impact. However, with the reduced reliance on residual insecticides as a result of vector resistance and limited health budgets in many tropical countries, the classic malaria epidemiology is resurfacing and epidemics have reappeared which have been described as 'post eradication epidemics' (WHO 1979).

Before the introduction of residual insecticides the Punjab province[1] and parts of Ceylon saw dramatic malaria epidemics. The death toll in the great 1908 Punjab epidemic was over 300 000 within a few months. These epidemics recurred at regular intervals and were related to excessive monsoon rains and the consequent above average humidity in the arid Punjab (Christophers 1911; Gill 1923; Yacob & Swaroop 1945; 1946). In the wet part of Ceylon epidemics were usually observed after a failing South-West monsoon which reduced rivers to strings of pools suitable for vector breeding (Carter 1927; Briercliffe 1935; Gill 1935). Both areas share similar features in that famine conditions were identified as a factor contributing to malaria mortality (Christophers 1911; Gill 1923; 1935), that *Anopheles culicifacies* was found to be the main malaria vector, and that *Plasmodium falciparum* and *P. vivax* were the two main malaria species.

Since 1921, forecasts of malaria epidemics in the districts of the Punjab have been issued (Gill 1923) based mainly on established correlations between rainfall and malaria mortality. Swaroop (1946) showed that this system, using actual rainfall early in the transmission season as the main variable, was fairly accurate, and it was probably the first mathematically supported early warning system ever used. The great impact of insecticides since the 1940s has rendered this system obsolete. However, with the resurgence of malaria on the subcontinent, including its epidemic form, the present control programmes may benefit from a review of these earlier efforts. Advances made in forecasting rainfall in recent years may help to develop a system to identify high risk years before the rain actually falls, allowing more time to prepare for epidemics.

[1] The Punjab province of former British India is now divided between Pakistan and India. In the text, 'Punjab' refers to the original area.

The Southern Oscillation is an unstable atmospheric system in the Pacific with a period of approximately 5 years which has been known for over 50 years (Walker & Bliss 1932). This system, now intimately linked with 'El Niño', an oceanographic phenomenon, is referred to as the 'El Niño Southern Oscillation' (ENSO). It has worldwide weather implications (Ropelewski & Halpert 1987) and has been suspected to affect vector-borne diseases (Nicholls 1993) and periodic malaria epidemics in particular (Bouma *et al.* 1994a). The historical data on malaria mortality and climate from British India, known for its high standards of administration and record keeping, provide unique material to analyse the effect of climate and climate change on malaria in an era when the epidemiology of the disease was not affected by the use of insecticides.

Geography, climate and malaria epidemiology

Punjab

The Punjab of former British India, in existence until 1947, consists roughly of the present-day Punjab province in Pakistan, and the Punjab, Haryana and Himachal Pradesh provinces in India. The alluvial plains of the Indus have an arid climate, with large areas with less than 25 cm of annual rainfall (Figure 1a). These areas were liable to inundation during years with heavy monsoon rainfall, and prone to periodic malaria epidemics (Figure 1b). Epidemic malaria was not seen in the hilly tracts, including the north-eastern part of the old Punjab, now Himachal Pradesh, with annual rainfall in excess of 100 cm. The fringe of the desert, an area with annual precipitation of between 25 and 50 cm (Figure 1a), has been described by Nájera (1970) in Pakistan's Punjab as an area conducive to epidemic malaria. Lower rainfall restricts the vector population and, in the area with more rainfall, malaria is more endemic and the level of malaria transmission less subject to climate fluctuations (Zulueta *et al.* 1980). The belt with rainfall between 25 and 50 cm stretches further south to the Indian ocean (Figure 1a), and covers areas where epidemics have been described in recent decades; these are Rajasthan (Figure 1c) (Mathur *et al.* 1992) and Gujarat (J. A. Najera, personal communication, 1992).

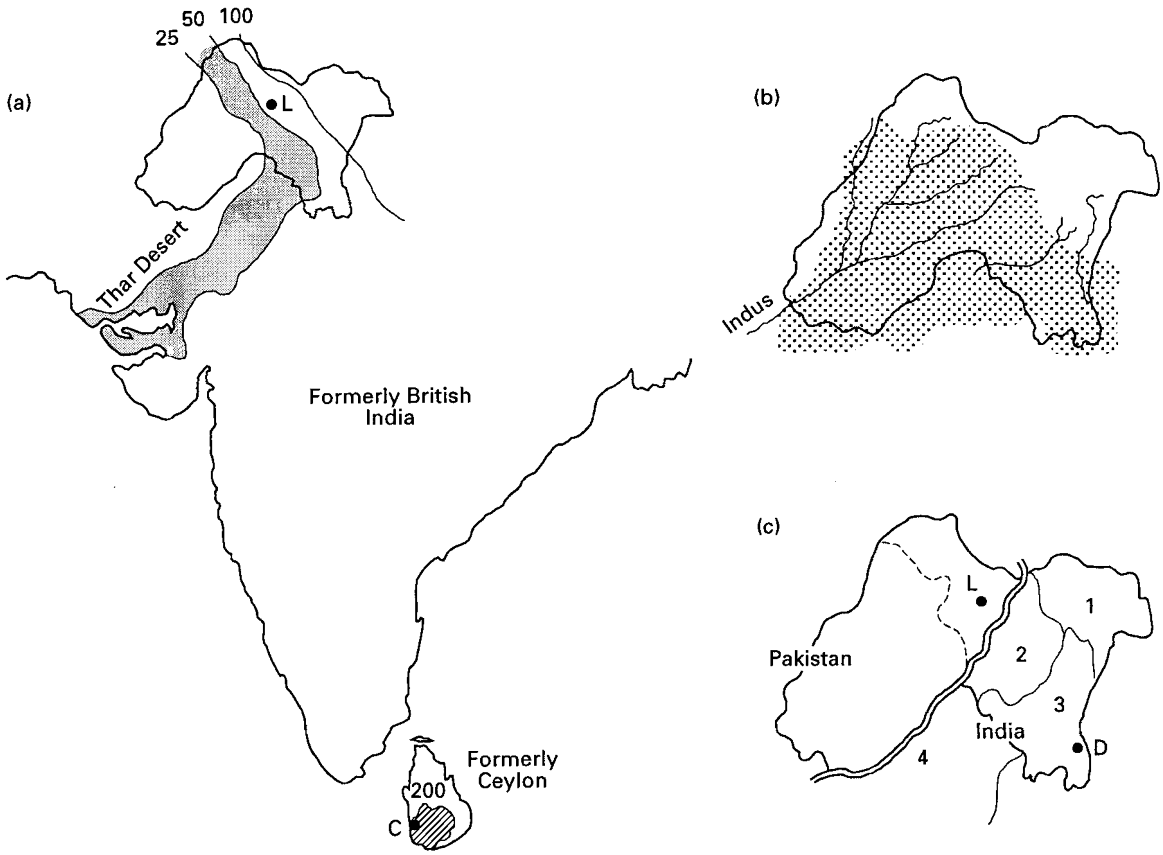

Figure 1 a, Annual rainfall in the Indian Subcontinent (Batholomew & Herbertson 1899). Isohyets of 25, 50, 100 cm in formerly British India (grey: 25–50 cm belt), and 200 cm in formerly Ceylon (hatched area: 200–500 cm) (L, Lahore; C, Colombo). b, the old Punjab province with the Indus river and tributaries. The dotted area is that described by Gill (1921) as prone to severe malaria epidemics in the period 1901–1917. c, The old Punjab province with the border between the East and West Punjab (broken line) and the present Pakistan–Indian border (double line). Indian provinces shown are: Himachal Pradesh (1), Indian Punjab (2), Haryana (3) and West Rajasthan (4), and the cities shown are Lahore (L) and Delhi (D).

Excessive rainfall during the summer (SW) monsoon, and related higher relative humidity, have been recognized as the most important factors in the genesis of epidemics in the plains of the Punjab by Christophers (1911), Gill (1923) and Yacob and Swaroop (1945; 1946). Strong correlations were found between monsoon rainfall and malaria related mortality (Christophers 1911; Yacob & Swaroop 1946). Rainfall in May, before the monsoon, showed a significant correlation with mortality (Yacob & Swaroop 1946). Interannual fluctuations of monsoon rainfall resulted in periodic epidemics, with a cycle estimated between five (Gill 1923) and eight (Yacob & Swaroop 1945) years. Prevailing famine conditions before a heavy monsoon ('economic stress') were identified as an important cofactor by all these early investigators. This was inferred from the positive correlation found between the prevailing price of staple foods and malaria mortality.

Sri Lanka

Sri Lanka, with its close proximity to the equator, is warm and humid throughout the year. The diurnal temperature variation is very small and only in the highlands can lower temperatures be expected to restrict the development of the parasite in the vector. The humidity is high throughout the year and rarely drops below levels that restrict the longevity of vectors, and thus the capacity to transmit malaria.

Rainfall in Sri Lanka is abundant compared to the Punjab (Figure 1a). The north-east monsoon (September–December) is mainly responsible for an annual figure of over 100 cm for the island. Only the south-western quarter of the island benefits from a second (south-western) monsoon season (March–July). This second monsoon is the same monsoon that the Punjab, due to the geographical position, experiences after a delay of a few months. The rainfall of this extra monsoon makes the rest of the island appear dry by comparison. Thus the island is divided into a 'dry' (100–200 cm of annual rainfall) and an 'inter-mediate' and 'wet' zone (200–500 cm). Before the introduction of residual insecticides the dry zone malaria was endemic with a seasonal increase in morbidity and mortality following the rains, peaking in January–February (Gill 1935). Malaria in the wet and intermediate zone was less common as a result of fast flowing rivers, providing less suitable conditions for breeding. Although the annual incidence pattern followed the rainy periods with peaks in July and January (Gill 1935), serious epidemics were observed after failures of the south-west monsoon that occurred with regular intervals (Carter 1927; Briercliffe 1935; Gill 1935; Sivagnanasundram 1971). Reduced rainfall caused rivers to pool, creating abundant breeding sites, the opposite condition to that associated with the Punjab epidemics.

Mortality data and definition of epidemics

In the Punjab previous investigators used the 'epidemic figure' suggested by Christophers (Yacob & Swaroop 1946) as a measure of the yearly fluctuation of malaria mortality. This is the ratio of the average monthly 'fever deaths' (standardized in the administrative records) in October–December, when most malaria mortality occurs, to April–July. This allows a long-term comparison, less likely to be confounded by changes in the size of the population, method of diagnosis, and mortality from 'fever deaths' due to other causes. The merits of this parameter have been discussed by Yacob and Swaroop (1945). The epidemic figures between 1867 and 1943, as calculated by Yacob and Swaroop (1946), were used for analysis. This almost covers the period until the introduction of residual insecticides (DDT) in 1949 in Pakistan. To analyse features of epidemic years, we arbitrarily defined years with an epidemic figure over 2 as epidemic years, which compares well with Christophers' (1911) records. Where epidemics lasted for more than one year, only the first year was used. The epidemic years thus identified are 1869, 1872, 1875, 1878, 1881, 1884, 1887, 1889, 1892, 1897, 1900, 1906, 1908, 1917, 1933 and 1942.

In Sri Lanka the period under study was chosen from the first documented epidemics in the late 19th century until the commencement of residual insecticides in 1946. The Civil Medical Department's reports, available since 1867, provided years with a high prevalence of fever cases. From these data, Briercliffe (1935) identified the epidemic years before 1900. Mortality figures after 1900 have been used by Briercliffe (1935), Gill (1935) and Sivagnanasundram (1971) to calculate malaria related mortality and define epidemic years. The high fever mortality reported in 1867, in the first available report, was excluded from analysis because it is uncertain whether the epidemic started in that year. Between 1870 and 1945, the following (first) epidemic years were used: 1877, 1880, 1884, 1891, 1906, 1911, 1914, 1919, 1923, 1928, 1934, 1939, 1943 and 1945.

El Niño Southern oscillation and sea surface temperatures

Anomalies of the sea surface temperatures (SST) in the eastern equatorial Pacific (EEP) and air pressure deviations between the eastern and western Pacific, e.g. the Tahiti–Darwin southern oscillation index (SOI), are two parameters of the El Niño Southern Oscillation (ENSO). One of its extremes, the El Niño or 'warm' event, refers to a positive deviation of the SST, and the La Niña or 'cold' event to the opposite phase with negative deviations of the SST. Negative deviations of the Tahiti–Darwin SOI are associated with a Niño event, and positive deviations with La Niña. The SST anomalies data set prepared by Parker *et al.* (1994) from 1868 onwards for the eastern equatorial Pacific (20°N–20°S, 170°E–American coast) was used for correlation with monsoon rainfall and the 'epidemic figure' for malaria between 1867 and 1943.

The definition of El Niño years depends on the criteria used, and the list of El Niño years may show minor variations between authors. We used the El Niño years (1875–1979) identified by Rasmusson and Carpenter (1983) for the study of rainfall in the Indian subcontinent. Their selection includes only first El Niño years where these events lasted more than one year, as the rainfall anomaly in the first year during protracted El Niños is more pronounced. We extended the range (1861–1985) with El Niño described by Quinn *et al.* (1987). The following years were thus obtained: 1864, 1866, 1871, 1874, 1877, 1880, 1884, 1887, 1891, 1896, 1899, 1902, 1905, 1911, 1914, 1918, 1923, 1925, 1930, 1932, 1939, 1941, 1951, 1953, 1957, 1965, 1969, 1972, 1976 and 1982.

For the opposite phase (associated with La Niña, or 'cold event'), years identified by Ropelewski and Halpert (1989) between 1885 and 1983 were used, and again only the first year where these events lasted more than one year: 1886, 1889, 1892, 1904, 1909, 1916, 1924, 1928, 1938, 1950, 1955, 1964, 1970, 1973 and 1975. These were years in which the Tahiti–Darwin southern oscillation index remained in the upper 25% of the distribution for 5 months or longer.

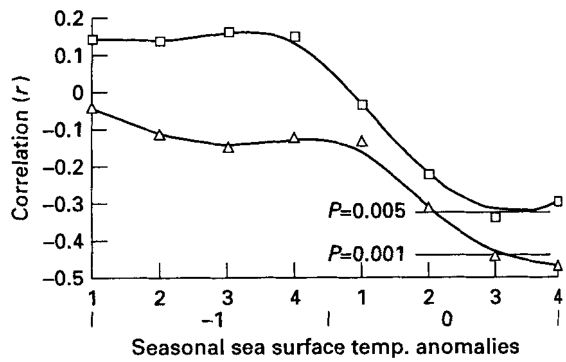

Figure 2 Correlation coefficients (r) of 'the epidemic figure' for □, malaria mortality in the Punjab (1868–1943) and △, monsoon rainfall (present-day Punjab and Haryana, 1871–1943), with the seasonal sea surface temperature anomalies in the eastern equatorial Pacific (1: January–March, 2: April–June, 3: July–September, 4: October–December) in the same year (0), and lag correlations with seasonal sea surface temperatures in the previous year (-1).

Rainfall data

Reliable monsoon (June–September) rainfall data were obtained from a published source (Parthasarathy *et al.* 1987), used in many subsequent meterological studies. For the subdivisions Punjab (10 stations) and Haryana (12 stations), the main part of the previous eastern Punjab, monsoon rainfall was calculated as the sum of all values of the meteorological stations (weighted for the area of the district) divided by the area of the subdivision for every year between 1871 and 1985. A second source of rainfall data was obtained for the old Punjab (Normand 1928), covering the period 1875–1924. This data covers a shorter period but includes more stations, including the western part of the Punjab, which are not represented in the first data set. Deviations (between normals 1875–1910 and the average monthly rainfall for all stations below 1067 m) for the 'Punjab East and North' (121 stations in 1924) and 'Punjab Southwest' (39 stations in 1924) are given. These two areas of the old Punjab are shown in Figure 1c. Monthly rainfall data (World Weather Records 1920–1980) for Lahore (1862–1980) and Colombo (1870–1980) were used to investigate monthly rainfall patterns in relation to the ENSO.

Results

Between 1860 and 1943 the 'epidemic malaria figure' for the Punjab shows significant negative correlations with sea surface temperature anomalies between April and December in the same year (Figure 2). During this period, similar significant negative correlations are apparent between monsoon rainfall, the variable earlier identified as most important for these epidemics, and SST anomalies (Figure 2). This relation between the ENSO and rainfall in the same year supports findings of previous studies (Pant & Parthasarathy 1981; Rasmusson & Carpenter 1983). Between 1944 and 1985, similar correlations are found ($r = -0.42$ and -0.44 in the 3rd and 4th season), which supports observations (Elliott & Angel 1987) that the relation between the oscillation and rainfall on the subcontinent has remained unchanged over time. The

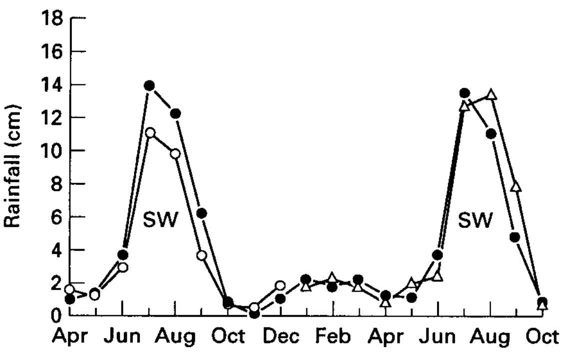

Figure 3 Average monthly rainfall in Lahore (Punjab) from 1862 to 1980 for ○, El Niño years; △, post El Niño years compared to ●, other years (non-El Niño and non-post El Niño years respectively). South-west monsoon season (SW).

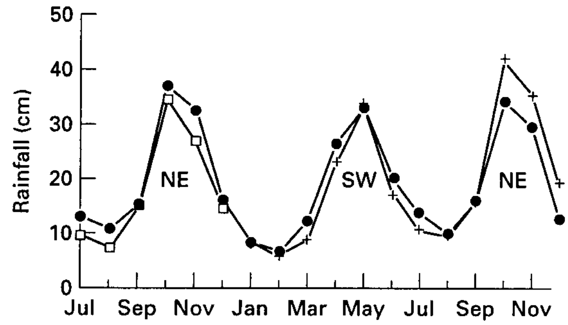

Figure 4 Average monthly rainfall in Colombo, SW Sri Lanka between 1870–1980, during □ pre-El Niño years and +, El Niño years, as compared to ●, other years (non-pre-El Niño and non-El Niño years respectively). North-east winter monsoon (NE), and south-west summer (SW) monsoon.

1875–1924 data set for the eastern and western section of the old Punjab reveals higher negative correlations (4th season) for the eastern ($r = -0.60$) than for the western ($r = -0.41$) part (not shown).

Malaria mortality and rainfall appear similar in their correlations with SST anomalies in the eastern Pacific in the same year. However, lag correlations with these variables and SST anomalies in the previous year show positive correlations for the epidemic figure and negative correlations for rainfall.

Precipitation anomalies in the Punjab exist for both extremes of the oscillation (Table 1). Average monsoon rainfall during El Niño years is significantly lower than during non-El Niño years, and higher during the opposite (La Niña) extreme of the oscillation. However, the year immediately following an El Niño year (Niño^{+1}) also has above average monsoon rainfall. The average rainfall in both types of 'wet' years is significantly more than in other (non-Niño^{+1} or La Niña years) years. Only in the Haryana province (Table 1) are the La Niña years not significantly wetter. Of these two types of 'wet' years, only the post El Niño years are preceded by a year (El Niño year) that tends to be dry.

Malaria epidemics in the Punjab occurred particularly in the years following an El Niño. In the period for which Yacob and Swaroop (1946) calculated the 'epidemic figure' (1867–1943), 10 out of 16 epidemics (epidemic figure >2) were recorded in post El Niño years (Table 2), and the probability of an epidemic in a post El Niño year was 47.6% compared to only 10.7% in other years (significant, $\chi^2 = 12.6$, d.f. = 1, $P < 0.001$). In the last half of the time series (1905–1943) the association appears less striking and the χ^2 test is not significant. However, the more sensitive parametric correlation coefficient during 1905–1943 between the epidemic figure and the SST anomalies is only 0.02, 0.04 and 0.03 lower respectively in the first 3 seasons. The correlation in the fourth season ($r = -0.38$, significant, $P < 0.02$) is

Table 1 Average monsoon (June–September) rainfall, rounded to the nearest cm, and (SD) for Punjab and Haryana during El Niño and post El Niño (Niño^{+1}) years (1871–1985), and La Niña years (1884–1983)

	All years 1871–1980	Niño years	Non-Niño years	Niño^{+1} years	La Niña years	Non-Niño^{+1}/ La Niña years
Punjab	49.5	40.4**	52.4	55.4†	57.6†	47.0
	(16.7)	(12.8)	(16.8)	(16.0)	(18.2)	(16.4)
n	115	28	87	28	15	65
Haryana	46.0	40.5‡	47.7	51.9*	49.1	44.0
	(13.6)	(13.6)	(13.2)	(13.5)	(14.8)	(12.5)
n	115	28	87	28	15	65

*$P < 0.01$; **$P < 0.001$, †$P < 0.05$, ‡$P < 0.02$.

higher (negative) than in the 1867–1943 period ($r = -0.30$) (Figure 2).

During the 9 La Niña events between 1885 and 1943, only 2 epidemics occurred (1889 and 1892), of which 1892 was also a post El Niño year. The average 'epidemic figure' in the wet La Niña years between 1883 and 1943 is only 1.6, even below the 77-year average of 1.76, and considerably below the 2.1 average for the post El Niño years. It appears that a failing monsoon in the previous year plays an important role in the epidemics in the Punjab.

An analysis of monthly rainfall data in Lahore shows that during El Niño events, rainfall in all months of the SW monsoon is deficient (Figure 3). The average monsoon rainfall deficit in El Niño years is 9.4 cm (significant, $P<0.01$). The post El Niño (often epidemic) years show more rainfall in May (average excess 1.0 cm, significant, $P<0.02$) and August and September combined (average excess 6.1 cm, significant, $P<0.05$) in comparison with other years. In Normand's (1928) data set for the east and west Punjab (1874–1925), this pattern with above average rainfall in May, August and September is also found (not shown). It is precisely these months that show the highest correlations (May: 0.56, August: 0.80 and September: 0.56) with the 'epidemic figure' in the study of Yacob and Swaroop (1946).

Monsoon rainfall in the present-day Indian provinces Punjab and Haryana showed a moderate increase between 1871 and 1985 (Figure 5). Based on the trend, monsoon rainfall (approximately 80% of the total annual rainfall) has exceeded the 50 cm isohyet in the present Punjab in the 1930s, and this mark was recently reached for Haryana. The average annual rainfall in both provinces has been between 50 and 100 cm since the last century, thus outside the 25–50 cm belt identified in Pakistan (Najera 1970).

In Sri Lanka, 9 out of 16 epidemics (Table 2) in the SW part of the island were recorded between 1870 and 1945 during El Niño years. The epidemic probability in these years is 45.0% compared to 12.5% in other years (significant, $\chi^2=9.43$, d.f.$=1$, $P<0.005$). Of the 7 epidemics that apparently do not coincide with El Niño events, the 1906 epidemic showed its first peak in the 1905 El Niño year (Gill 1935). The excessive mortality in 1919 is likely to have been caused by the influenza pandemic and not by a malaria epidemic (Briercliffe 1935; Sivagnanasundram 1971), and the epidemics that started in 1934 and 1945 were seen in years with air pressure deviations consistent with a starting El Niño which did not develop into a mature event. An analysis of monthly data for Colombo in the wet zone (Figure 4) shows that during El Niño years the SW monsoon (March–July), previously associated with epidemic malaria, is deficient (average deficit 16.8 cm, significant, $P<0.01$). The NE monsoon in the pre El Niño year also shows a deficit (15.1 cm, significant, $P<0.05$). In the period between 1870 and 1945, the average SW monsoon rainfall during actual epidemic years and non-epidemic years does not differ significantly. Only when the preceding NE monsoon (pre El Niño year) is included does the combined rainfall deficit become significant ($T=2.57$, $P<0.02$). In an El Niño year, the NE monsoon (October–December) shows on average an excess of 18.8 cm (significant, $P<0.002$). This is consistent with findings of other studies (Rasmusson & Carpenter 1983; Ropelewski & Halpert 1987), which include Sri Lanka and southern India.

Table 2 Epidemic years in the Punjab in relation to post El Niño (Niño^{+1}) years between 1867 and 1943, and epidemic years in Sri Lanka in relation to El Niño years between 1870 and 1945

	Punjab				Sri Lanka		
	Epidemic years	Non-epidemic years	Total		Epidemic years	Non-epidemic years	Total
Niño^{+1} years	10	11	21	Niño years	9	11	20
Non-Niño^{+1} years	6	50	56	Non-Niño years	7	49	56
Total	16	61	77		16	60	76

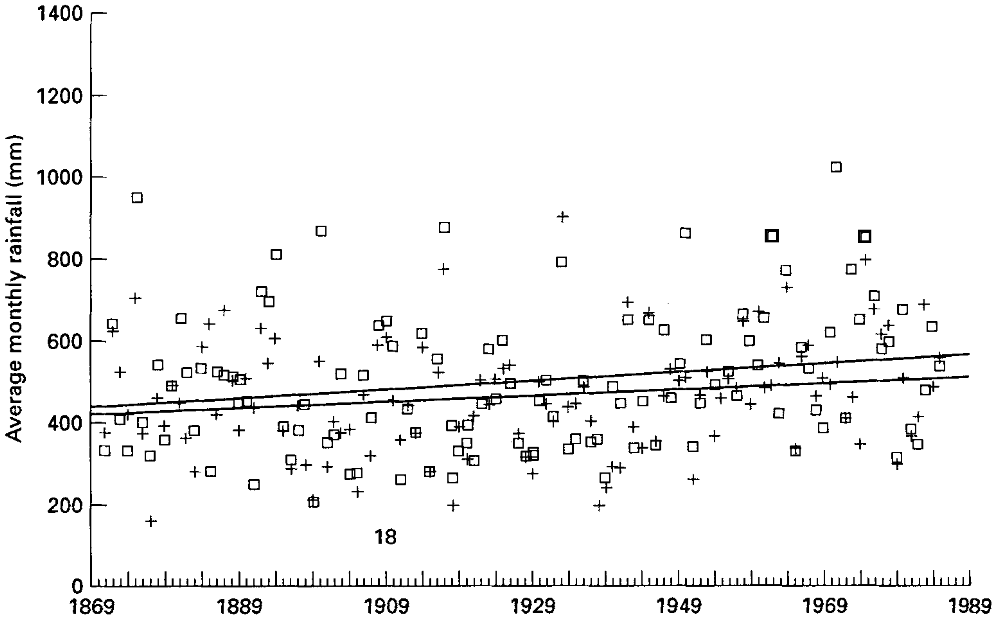

Figure 5 Monsoon rainfall (June–September) in cm, between 1871 and 1984 (Parthasarathy *et al.* 1987) for □, the Indian Punjab, and +, Haryana, with trends (regression lines).

Discussion

The El Niño southern oscillation has here been shown to relate to the historic malaria epidemics in the Punjab and Sri Lanka, and to periodic fluctuations in monsoon rainfall previously associated with these epidemics. In the Punjab, malaria mortality and monsoon rainfall correlate significantly with sea surface temperature anomalies in the eastern equatorial Pacific, one of the parameters of the ENSO. The year immediately following El Niño events was particularly at risk of epidemics. These years usually have above average monsoon rainfall in critical months, and follow an El Niño year in which the monsoon tends to fail. The monsoon during La Niña years is on average also wetter. However, these La Niña years appear not to give rise to epidemics. The sequence of a dry year followed by a wet one appears of significance for the genesis of epidemics. That 'fever years follow famine years' was noticed in the Punjab long before the origins of malaria were discovered, and Christophers (1911) also found that wet years without 'economic stress' (reflecting previous monsoon failure) were not likely to result in malaria epidemics. The positive correlation between food prices and malaria mortality found by Christophers (1911) and Gill (1923), nurtured the hypothesis that famine conditions were, by lowering resistance, responsible for increased malaria mortality. It now appears more likely that reduced exposure to *Plasmodium falciparum* during dry years with low transmission resulted in a lower population immunity, which rendered the population more susceptible in the following year. The conclusion by Swaroop (1949), that an immune phenomenon was not a likely explanation because of the absence of a correlation between spleen rates and malaria mortality, appears premature. The spleen rate is not a reliable measure of protective immunity, and in the Punjab where *P. vivax* prevails, not specific for potentially lethal *P. falciparum* infections.

In the period 1905–1943, epidemics defined in terms of mortality appear less frequent in post El Niño years, which suggests a weakening relation between epidemics and the ENSO. However, the correlation coefficients between the annual epidemic figure (which also includes years without epidemics) and the SST anomalies in this period have hardly changed. The reduction of serious mortality during epidemics this century may be explained by the improved diagnosis, chemotherapy, and the successful early warning system for epidemics employed in the Punjab since 1921. Interannual variation in ambient temperature has not been identified in the Punjab as an important factor in malaria transmission. During El Niño years, late season temperatures that may affect *P. falciparum* transmission are higher on the sub-continent (Kilades & van Loon 1988). This has indeed been shown to affect transmission of this species in Pakistan's cooler North-West Frontier Province, most of which is at a higher latitude and altitude (Bouma *et al.* 1994b) than the Punjab.

In Sri Lanka, the historic epidemics are especially conspicuous during El Niño years. The ENSO places the historical epidemics, particularly where these extended into the more endemic 'dry' zone, in a new perspective. It appears that the failure of the SW monsoon (El Niño), earlier associated with the epidemics in the wet part of the island, combined with the frequent failure of the NE monsoon in the preceding (pre-Niño) year, contributes significantly to the likelihood of an epidemic. Failure of the NE monsoon in the pre-Niño years will lower the water tables in the rivers of the epidemic wet zone and reduce malaria transmission in the 'dry' endemic zone. A below average SW monsoon rainfall in the wet zone followed by an above average NE monsoon in all zones, conditions often seen during El Niño years, results therefore in conditions favourable for transmission over the whole island.

Since the introduction of residual insecticides on the subcontinent and Sri Lanka, several resurgences of malaria have occurred. It is difficult to interpret these fluctuations due to changes in spraying strategy, type of insecticide and level of vector resistance over the years. Population movement, particularly in Sri Lanka, has also been identified as a contributing factor in these resurgences (Sivagnansundram 1971; Wijesundera 1988). Extensive irrigation and related waterlogging have changed the ecology of the old Punjab. Moreover, changes in the climate, as suggested by the trend towards higher monsoon rainfall in Indian Punjab and Haryana provinces, are likely to have changed the epidemic potential in areas at risk earlier this century. However, recent epidemics in drier neighbouring west Rajasthan (Mathur *et al.* 1992) show that the epidemic potential in relation to excessive monsoon rainfall still exists. The monsoon rainfall in this area is only 26 cm (below 35 cm on an annual basis) and shows a strong correlation with the ENSO (Bouma & van der Kaay 1994). In Sri Lanka, after the reappearance of *P. falciparum* in 1964–65, several epidemics have been associated with failing monsoons, which indeed started during El Niño events. The diversion of water for irrigation and hydroelectric schemes, compounding the water shortage in 1987 (an El Niño year), has been associated with focal malaria outbreaks in the wet zone of Sri Lanka (Wijesundera 1988).

Although Niño events can now be forecast, the actual occurrence of an El Niño event is usually apparent in December (hence the name El Niño; Christmas child) or the first months of the year, and is reported in the monthly issues of the *Climate System Monitoring* (CMS) bulletin of the World Climate Programme in Geneva. In Sri Lanka where areas might be more at risk during El Niño years, this is a few months ahead of the SW monsoon in the wet part of the island, and 9 months ahead of the NE monsoon. A failing NE monsoon in the pre-Niño year may already put a malaria programme on alert. This offers sufficient time to secure sufficient drug and, where appropriate, insecticide supply if demand increases and to improve the vigilance of the reporting system.

Historically, in Ceylon and British India there was considerable geographical variation in precipitation anomalies and epidemic foci, even within an epidemic prone province in a single year. Whereas the El Niño may be used as atemporal indicator of epidemic risk, the use of meteorological data may be of great importance in supplying spacial indicators. Remote sensing, using available satellite data, may facilitate this activity and appears more suitable to define geographical areas at risk. Further refinement of early warning systems may include monitoring of entomological parameters as suggested by Onori and Grab (1980). To anticipate malaria epidemics, these possible tools deserve further exploration. The significance of the changing pattern of El Niño in frequency and duration in the last decades, which may limit its value as a forecasting tool, requires further investigation. It is to be hoped that the implementation of control activities based on early warning systems will permit a more discriminating and cost effective use of scarce resources, needs identified in the new global strategy for malaria control (WHO 1993).

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