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The Relationship between the El Niño Southern Oscillation and the Incidence of Dengue/DHF and Malaria in South America and Southeast Asia

by

Alexandre Sébastien Gagnon ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

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Abstract

Interannual epidemics of dengue and malaria occur in many tropical countries and are thought to be linked with climatic anomalies. The El Niño Southern Oscillation (ENSO) is the strongest interannual signal of climate variability. The two phases of ENSO, i.e., El Niño and La Niña, influence temperature and precipitation in many parts of the world, and are therefore likely to affect the incidence of mosquito-transmitted diseases.

In this thesis annual dengue and malaria incidence data were correlated with ENSO episodes for various South American and Southeast Asian countries. Results show that there is a statistically significant correlation between El Niño and dengue epidemics in Colombia, French Guiana, Suriname, and Indonesia. Similarly, Colombia, Guyana, Peru, Sarawak, and Venezuela are likely to experience malaria epidemics during El Niño years. Public health officials could therefore strongly benefit from the use of El Niño forecasts and they should emphasize control activities such as insecticide sprayings during these years.

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled *The Relationship between the El Niño Southern Oscillation and the Incidence of Dengue/DHF and Malaria in South America and Southeast Asia* submitted by Alexandre Sébastien Gagnon in partial fulfillment of the requirements for the degree of Master of Science.

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Chapter 1: Background and Rationale

1.1 Introduction

A link between climatic anomalies and epidemics of dengue and malaria has previously been proposed. Flooding, for instance, has been associated with malaria epidemics in Ecuador and Peru. The El Niño Southern Oscillation (ENSO) is the strongest inter-annual signal on climate variability. ENSO influences temperature and precipitation in many parts of the world (Stern and Easterling, 1999). For this reason, ENSO is likely to play an important role in the development of dengue and malaria epidemics in countries significantly affected by this atmospheric phenomenon.

ENSO refers to an oscillation between the warm El Niño and the cold La Niña phases. El Niño is a climatic phenomenon that results in a warming of the central and eastern tropical Pacific Ocean. Because of the interaction between the atmosphere and the ocean, this warming of sea surface temperatures, hereafter referred to as SSTs, alters the atmospheric pressure gradient between the western and eastern equatorial Pacific Ocean, thereby affecting the tropical atmospheric circulation. This phenomenon also modifies the global atmospheric circulation through teleconnections in the atmosphere. Teleconnections are the linking of climatic anomalies over large distances (Glantz, 1991). La Niña results in an anomalous cooling of the eastern tropical Pacific Ocean, and generally causes opposite atmospheric perturbations from El Niño years (Nicholls, 1993).

Malaria and dengue fever are two diseases that affect millions of people in tropical and subtropical regions. At present, about 300 million people are infected by malaria each year, causing approximately 2.7 million deaths annually (Liese, 1998). Dengue fever is the most widespread arboviral disease, prevailing in more than 100 countries and territories. Diseases transmitted by viruses that are carried by arthropods (e.g. mosquitoes) are referred to as arboviral. The WHO estimates that every year tens of millions of people contract dengue world-wide, with approximately 500,000 hospitalised cases due to dengue haemorrhagic fever (DHF) (WHO, 1998a).

DHF is the most severe form of dengue; an individual is more at risk of contracting DHF if previously infected by another dengue virus (Frost, 1991).

Currently, there are no vaccines against dengue and malaria, and no drug currently exists to prevent dengue and DHF (Gratz and Knudsen, 1996; WHO, 1998b). Various anti-malaria drugs such as chloroquine exist on the market, but resistance of the malaria parasites against these drugs is increasing and spreading geographically. Only in Central America has resistance to chloroquine of *Plasmodium falciparum,* the most deadly of the four malaria parasites, not yet been reported. In addition, resistance to sulfadoxine/pyrimethine, the main alternative to chloroquine, is widespread in Southeast Asia and South America. Also, resistance to mefloquine, another antimalarial drug, is common in Thailand (WHO, 1997). Moreover, antimalarial drugs are expensive and often unaffordable (WHO, 1998a). Thus, the best method to control malaria, and the only alternative for dengue and DHF, is eradication of the mosquitoes that transmit them.

Since mosquitoes transmit dengue and malaria, their geographical range is primarily delimited by climate, particularly temperature and precipitation. El Niño and La Niña are associated with warmer and cooler air temperatures, respectively, throughout the tropics (Hansen and Lebedeff, 1987). Warmer temperatures favour the spread of dengue and malaria by accelerating the life cycle of the diseases (Poveda and Rojas, 1997; Seghal, 1997). ENSO also produces precipitation anomalies in tropical regions (Ropelewski and Halpert, 1987, 1989). Rainfall has been shown to correlate with the abundance of mosquito breeding sites, and hence, the intensity of diseases transmitted by them (Bouma and Dye, 1997; Hales *et al.*, 1999). Therefore, ENSO-generated climatic variations are likely to be associated with changes in the incidence of dengue and malaria and could even facilitate the development of epidemics.

Some scientists are blaming past ENSO phenomena for outbreaks of dengue (Hales *et al.*, 1996; Hales *et al.*, 1999; Lewis *et al.*, unpublished) and malaria (Bouma *et al.*, 1994; Bouma *et al.*, 1997; Bouma and Dye, 1997; Bouma and van der Kaay, 1994; Bouma and van der Kaay, 1996; Poveda *et al.*, 1999; Poveda and Rojas, 1996;

Poveda and Rojas, 1997). Dengue studies have mainly focused on the Pacific islands, while comprehensive analyses of the ENSO-malaria relationship are limited to Colombia, India, and Venezuela. The relationships in these countries were not similar, because both the climatic impacts of ENSO and the climatic anomalies necessary for the spawning of epidemics vary between countries. In dry regions, flooding increases the number of mosquito breeding sites, whereas in wet regions, drier than normal conditions create pools of stagnant water alongside rivers, providing numerous breeding sites for mosquitoes (Poveda and Rojas, 1997). This thesis extends the analysis to regions that have not yet been studied and provides a global-scale study in the hope of building a predictive tool for improving the control of dengue and malaria.

This thesis identifies statistical relationships between ENSO and epidemics of dengue and malaria in various South American and Southeast Asian countries. The ENSO-disease relationship is analysed in countries located in the following three regions: Southeast Asia (Indonesia, the Philippines, Sarawak, and Thailand), western South America (Ecuador and Peru), and northern South America (Brazil's Amazon, Colombia, French Guiana, Guyana, Suriname, and Venezuela). Sarawak is one of the two Malaysian states located in eastern Malaysia on the island of Borneo (Figure A4.1). These countries were selected because of the identifiable impacts of ENSO on temperature and rainfall variations in those regions (Kiladis and Diaz, 1989; Ropelewski and Halpert, 1987, 1989) as well as the availability of their epidemiological data.

Since ENSO teleconnections are not necessarily consistent over time for all study countries, an initial objective is to determine the temporal consistency of the climatic signals. In countries where a statistically significant relationship exists between El Niño or La Niña and disease outbreaks, the absence of anomalous climatic conditions during an El Niño (La Niña) year suggests an explanation for the lack of disease outbreak during this particular event. Conversely, anomalous climatic conditions in a normal year (i.e., neither an El Niño nor a La Niña year) could explain the occurrence of an epidemic during that year. In addition, this analysis determines whether climatic anomalies are the same throughout the country. Spatial consistency is important in this study, as disease cases are usually reported as a national average. However, if the ENSO signal is different for different regions of the same country, the analysis is necessarily limited if regional disease data are not available.

To study the impact of climatic variations associated with ENSO on the incidence of mosquito–transmitted diseases one needs to understand how climate affects their life cycles. Hence, the remainder of this chapter provides some background on the evidence of the biological relationship between climate and the incidence of dengue and malaria, as well as a literature review of the evidence of ENSO-dengue and -malaria relationships. ENSO teleconnections, with their temporal and spatial climatic fluctuations, are discussed in Chapter 2. The third and fourth chapters present correlations between ENSO and dengue, and ENSO and malaria, respectively. Finally, the last chapter summarises the results and discusses the potential use of El Niño-related climate forecasts to better control mosquito-transmitted diseases in South America and Southeast Asia.

1.2 Biological Evidence of the Climate–Malaria and Dengue Relationship

The life cycles of malaria and dengue are similar; both diseases require hosts, e.g. human beings, and vectors. Mosquitoes are referred to as vectors of these diseases, because they transmit the agent from host to host. An agent is something that produces the disease. It is a parasite for malaria and a virus for dengue. There are four types of malaria parasites, all of the genus *Plasmodium*: *vivax*, *falciparum*, *malariae*, and *ovale*. In the countries selected for this study, *vivax* and *falciparum* malaria are the two most common species. Similarly, four dengue viruses (denoted by DEN-1, DEN-2, DEN-3, and DEN-4) cause dengue disease. Sixty mosquito species of the genus *Anopheles* transmit malaria, whereas only *Aedes aegypti* and *Aedes albopictus* carry dengue viruses. When a female mosquito bites an infected human (who hosts either the malaria parasites or the dengue viruses) to obtain blood, as a part of its own natural life cycle, it becomes infectious and, thus, a vector of the disease.

The life cycle of dengue or malaria is completed if the mosquito carrying the agent bites another person before dying (WHO, 1992a; PAHO, 1994a).

In 1953, the first case of DHF was identified in Manila in the Philippines. DHF is the only fatal form of dengue and it has the same disease cycle as the classical or benign form of dengue (Aiken and Leigh, 1978). In Indonesia, for instance 1,414 out of the 72,133 DHF cases that occurred in 1998 were fatal (R. Kusriastuti, *personal communication*). Although DHF occurs within the geographical range of dengue, it is mainly an urban disease that occurs in poor and crowded areas (Frost, 1991). Accordingly, outbreaks are mainly reported from large urban centres of Southeast Asia where such conditions are common (Cantelar de Francisco, 1983). Thus, DHF is a common disease in Southeast Asia (Frost, 1991), and its incidence is increasing in many Latin American countries (Gubler and Clark, 1995). Colombia, for example, reported 39 DHF cases in 1990, in comparison with 5171 in 1998. The main vector of DHF is *Ae. aegypti* (Aiken and Leigh, 1978), which was associated with almost all epidemics of DHF in Southeast Asia. Nonetheless, *Ae. albopictus* might have contributed to some epidemics, notably in Singapore, but only in secondary importance to *Ae. aegypti* (Meade, 1976).

Temperature, rainfall, and relative humidity are the three primary climatic factors impacting the distribution and intensity of both dengue/DHF and malaria. Warmer temperatures lengthen the longevity of mosquitoes and increase the development rates of both the mosquitoes and malaria parasites as well as hastening the replication of dengue viruses (PAHO, 1994a; Patz *et al.*, 1998; Poveda and Rojas, 1997). For instance, the development of *Plasmodium falciparum* in the mosquito gut takes 27 days at 20°C and only 10 days at 30°C (Thouez *et al.*, 1998). Similarly, the transmission of dengue is four times higher at 30°C than at 17°C (Poveda *et al.*, 1999). Watts *et al.* (1987) calculated that the replication of DEN-2 takes about 12 days at 30°C and only 7 days at 32 to 35°C. Furthermore, warmer temperatures might decrease the size of adult *Aedes* mosquitoes, and these smaller mosquitoes have to feed more frequently in order to produce a batch of eggs (Seghal, 1997).

At extremely high temperatures (i.e., 35°C and higher) the longevity of both *Aedes* and *Anopheles* mosquitoes is shortened and the development of the malaria parasites and dengue viruses is interrupted (Lindsay and Birley, 1996; Patz *et al.*, 1998). Nevertheless, no proof currently exists of the fatal effects of extreme temperatures on transmission of vector-borne diseases, probably because of the ability of mosquitoes to find suitable microclimates (e.g., in houses, drain pipes, or under leafy vegetation) in order to survive (Patz *et al.*, 1998).

Precipitation also influences dengue and malaria transmission, because it affects the relative humidity (50 to 60% relative humidity is optimal for mosquito survival), and is related to the availability of mosquito breeding sites (Martin and Lefebvre, 1995). Malaria mosquitoes prefer to breed in ponds of stagnant water as opposed to flowing water (Bruce-Chwatt, 1985), and hence the number of breeding sites is related to climatic variations. In dry regions, the unavailability of breeding grounds and the short life span of mosquitoes usually limit malaria transmission (Bouma and van der Kaay, 1994). As a result, peaks in malaria incidence are generally associated with the rainy season, for the retreat of water from flooded lands creates ponds of stagnant water, providing adequate breeding grounds for mosquitoes (Dutta and Dutt, 1978; Telleria, 1986). Nevertheless, malaria outbreaks can also be associated with dryness, such as in Sri Lanka, because prolonged droughts can transform rivers into ponds of stagnant water (Bouma *et al.*, 1994).

One would expect seasonal rainfall variations to affect the incidence of dengue and DHF through changes in the availability of mosquito breeding sites (Aiken e*t al.*, 1980). In Indonesia, the number of DHF cases frequently peaks during the rainy season (October through April; Nathin, 1988; Saroso 1978; Sumarmo, 1987), because of high mosquito density (Aiken *et al.*, 1980). The relationship between DHF and rainfall, however, is not always clear-cut, as DHF outbreaks have previously been reported during droughts in Malaysia and Northeast Thailand (Aiken *et al.*, 1980; Eamchan et al., 1989), possibly because of water storage practices.

Ae. aegypti, the primary vector of dengue and DHF, breeds in artificial (i.e., man-made) water containers located in and around houses. As many of those containers are artificially maintained (especially those indoor) the availability of mosquito breeding sites is, in addition to rainfall, affected by human behaviour. For instance, in most cities and villages of Thailand, water is stored year-round (WHO, 1970), because of the deficiency of the water supply and people's preference to drink rainwater (WHO, 1971). Accordingly, researchers found that the larval population diminishes only slightly during the dry season (WHO, 1970). In Bangkok (Thailand) and Jakarta most of the water jars were occupied by larvae during the hot and dry seasons (Tonn, 1970; van Peenen *et al.*, 1972). Furthermore, 73% of larvae of *Ae. aegypti* are found indoor in urban areas of Malaysia (Meade, 1976), whereas in Puerto Rico, most larval habitat are outdoor and are therefore more likely to be influenced by seasonal rainfall patterns (Moore *et al.*, 1978). Consequently, water storage practices and the location of mosquito habitats must be considered when studying the impact of climatic variations on dengue and DHF transmission (Herrera-Basto *et al.*, 1992).

Ae. albopictus is found in rural and suburban areas and is a semi-domestic species, because it breeds in both natural and man-made water containers. This mosquito species transmits dengue in Southeast Asia and the Pacific Islands, but is secondary in importance to *Ae. aegypti*. *Ae. albopictus* is also found in Brazil, but there is no evidence that it acts as a vector of dengue in South America (PAHO, 1994a). *Ae. albopictus* breeds preferably outside in water jars and other breeding sites that result from poor garbage disposal such as tires, tin cans, bottles, etc., as well as in natural water containers (Meade, 1976). Because of *Ae. albopictus*' preference to breed outside, some scientists suggest that a stronger relationship should exist between dengue transmitted by this mosquito species and rainfall (Aiken *et al.*, 1980).

In summary, the transmission of dengue and malaria is highest in areas with high mosquito density. Mosquito density is proportional to the availability of breeding sites and the longevity of mosquitoes. Therefore, precipitation patterns, which multiply the availability of mosquito breeding sites, and warmer and humid weather, which lengthen the longevity of mosquitoes as well as hasten the development of malaria parasites and replication of dengue viruses, are more likely to spawn epidemics. In the case of dengue and DHF, water storage practices and accordingly, the location of mosquito larvae habitat, must also be considered.

1.3 Literature Review

Bouma *et al.* (1994) suspected that ENSO-related climatic variations may be an important factor affecting the transmission of malaria where the disease appears periodically. In those regions, outbreaks are seen to follow a cyclic pattern. Since malaria is not endemic (i.e., it does not constantly occurs), the population lacks protective immunity and when climatic conditions favour transmission of the disease, outbreaks occur. To correlate epidemics of malaria with ENSO events, they first identified those regions that have a history of periodic malaria epidemics; second, they determined the areas where rainfall and temperature are influenced by either phase of ENSO. Comparing the two, they found that there is a correlation between periodic malaria epidemics and ENSO in some regions. In particular, a correlation of El Niño with malaria outbreaks was identified in northern South America.

Bouma and Dye (1997) correlated ENSO with malaria mortality and morbidity (non-fatal contraction of the disease) in Venezuela for the 1910-35 and 1975-95 periods, respectively. They did not find any correlation between negative SST anomalies (i.e., La Niña events) and malaria epidemics. Moreover, rainfall anomalies were not significant during the epidemics that occurred between 1910 and 1935. Hence, they concluded that increased rainfall is not a factor affecting malaria transmission in Venezuela. However, all epidemics were preceded by a year with below average rainfall. The correlation of national malaria cases with SST anomalies reveals that malaria mortality and morbidity increased by about 36.5% in year Niño (+1). Most El Niño events overlay two calendar years. Niño (+1) refers to the year immediately following the peak in SSTs in the equatorial Pacific Ocean, which typically occurs near the end of the calendar year.

Poveda and Rojas (1996) qualitatively compared malaria outbreaks and ENSO years from 1959 to 1994 in Colombia. They found that malaria cases peak during El Niño. Poveda and Rojas (1997) studied this relationship further by correlating malaria cases with SSTs in the eastern tropical Pacific Ocean. They concluded that higher temperature and below average rainfall associated with El Niño increase the incidence of malaria in Colombia, as droughts may increase the density of mosquitoes by forming puddles along rivers as their discharge decreases (Bouma *et al.*, 1994).

Bouma *et al.* (1997) also studied the correlation between malaria and ENSO in Colombia from 1960 to 1992 and provide further details. Results show a statistically significant increase in malaria transmission in El Niño years. On average the number of malaria cases in Colombia increased by 17.3% and 35.1% in Niño (0) and Niño (+1) years, respectively. In addition, they correlated the number of malaria cases with SST anomalies in the eastern equatorial Pacific Ocean, observing a statistically significant positive correlation between SST anomalies and malaria incidence.

Less work has been accomplished on the relationship between ENSO and dengue. Hales *et al.* (1996) correlated the number of dengue outbreaks in the South Pacific between 1970 and 1995 with the Southern Oscillation Index (SOI). The SOI is the standardised difference in sea level atmospheric pressure between Darwin (Australia) and Tahiti (French Polynesia) and is used as an indicator of ENSO activity. During El Niño, the SOI is negative, whereas during La Niña it is positive. They found a positive and statistically significant correlation between the number of dengue outbreaks and the SOI, with a larger number of dengue epidemics during La Niña. Additionally, Lewis *et al.* (unpublished) studied the relationship between ENSO and the incidence of dengue in the South Pacific, and found that more outbreaks occurred during La Niña and normal years than in El Niño years.

Hales *et al.* (1999) further studied the association between the SOI and dengue in 14 island-states of the South Pacific using monthly reports of dengue from 1973 to 1994. They found that the incidence of dengue increased during La Niña in 10 island-states, but in only five of these countries were the correlation coefficients statistically significant. In addition, five of those ten countries show a positive correlation between La Niña and temperature and/or rainfall (i.e., warmer and/or wetter weather). Nevertheless, three of the five countries with a statistically significant correlation between the SOI and dengue cases have negative or weak correlations with temperature and/or rainfall, respectively. The time series, however, were not adjusted for serial correlation (i.e., the correlation of a variable with the previous and following observations), which can lead to the identification of statistically significant correlations when no relationship actually exists.

Also, Poveda *et al.* (1999) noted that the three peaks in the number of dengue cases reported in Colombia between 1980 and 1996 (with missing data for 1993 and 1994) occurred in Niño (+1) years.

Most analyses use morbidity as opposed to mortality data because it is a better representation of disease incidence, particularly for dengue, since this disease is usually not fatal unless haemorrhagic symptoms are observed. Some analyses are qualitative (Bouma *et al.*, 1994; Poveda *et al.*, 1999; Poveda and Rojas, 1996), whereas others use statistical techniques to quantify the relationships (Bouma and Dye, 1997; Bouma *et al.*, 1997; Hales *et al.*, 1996; Hales *et al.*, 1999; Lewis *et al.*, unpublished; Poveda and Rojas, 1997).

Quantitative analysis of the relationship between ENSO and malaria has been limited to Colombia and Venezuela. In this thesis, Colombia and Venezuela will be re-analysed using different statistical techniques and a longer time series in order to verify if previously observed relationships were repeated in more recent El Niño events. In addition, a more refined analysis with epidemiological data at the regional scale is performed for Colombia. Analyses of Brazil's Amazon, French Guiana, Guyana, and Suriname are also performed and represent the first such comprehensive studies of these neighbouring regions. Furthermore, it is necessary to study this association in Ecuador and Peru where ENSO has a direct and immediate impact. Research in this region is limited to the 1982/83 El Niño. In order to capture some of the spatial variability of ENSO's climatic impact, this thesis also analyses some Southeast Asian countries, regions in which no research has yet been accomplished.

Because ENSO teleconnections are not always consistent temporally for all study regions, an investigation of the climatic variations during individual events is necessary in the study of ENSO and epidemics of mosquito-transmitted diseases. For example, the absence of climatic anomalies during some ENSO events due to poor atmospheric teleconnections may explain the lack of dengue and/or malaria epidemic during this particular event. Furthermore, as various countries are analysed, an attempt will be made to identify geographical regions displaying the same relationships between ENSO and disease outbreak. Finally, by determining the climatic variations that spawned past dengue and malaria epidemics, this thesis identifies which countries could benefit from the use of coupled ocean-atmosphere models that predict El Niño to better control the spread of these diseases when favourable climatic conditions are foreseen. Therefore, this research constitutes a basis for the development of a predictive tool that can incorporate climatic indicators in order to help forecast the spread of these diseases.

Chapter 2: Sources of Data and Methodology

The first part of this chapter presents the sources of dengue/DHF and malaria data used to create national disease time series. Because of standardisation of the disease cases by the population and the importance of insecticide sprayings on the incidence of mosquito-transmitted diseases, Section 2.1 also includes information on the sources of annual population estimates and house insecticide sprayings. Section 2.2 classifies the El Niño and La Niña years, while the third section lists the climatic and hydrological data sets utilised in this thesis. The last part of this chapter describes the methods used to provide evidence of ENSO teleconnections and to identify statistically significant correlations between ENSO and epidemics of dengue/DHF and malaria.

2.1 Epidemiological and Non-climatic Data

Epidemiological data for malaria and dengue were acquired from various sources. For the Americas, malaria data were gathered at the headquarters of the Pan American Health Organization (PAHO) (a regional office of the WHO)). Since 1957, PAHO publishes an annual report including information on malaria from most American countries[1]. Each annual report includes national epidemiological data such as the number of malaria cases, and the percentage of malaria cases detected actively and passively (definitions to follow). Moreover, the reports include other relevant data such as annual population estimates and the annual number of house insecticide sprayings.

Malaria cases can be identified through either active or passive case detection. Cases are reported actively when anti-malaria workers look for malaria infection by carrying out home visits and examining the blood of people with fever and those who recently had fever. On the other hand, cases reported by hospitals, health centres, and rural health clinics are characterised as passive cases (Lim, 1992). Active case detection is expensive and, of the total number of malaria cases reported in the Americas, less than 1% originate from active case detection (PAHO, 1998a).

The *Oficina General de Epidemiología del Perú*, the *Oficina de Epidemiología de Colombia*, and Dr. Afonso D.C. Passos of the *Facultade de Medicina* of Brazil's *Universidade de São Paulo* were additional sources of national malaria data. (See Appendix 1 for addresses of data providers.) These additional data lengthened the time series for Peru by 18 years (1941-1958) and allowed for comparison with the data from the PAHO. Furthermore, the above sources also provided regional epidemiological data for Colombia (1995–1998) and Peru (1996 and 1998).

I received epidemiological data as well as annual population estimates for the Philippines from the national health departments of the Philippines, Thailand, and the Sarawak[2]. Malaria data for Indonesia were obtained from the *World Health Statistics Annual*[3] and the *Weekly Epidemiological Record*[4]. These WHO reports also contain malaria cases reported by other countries analysed and therefore allow comparison with data from other sources. Logically, the data from the WHO and from the national departments of health should be the same, as the WHO obtains its data from its regional offices, which obtain them from the malaria surveillance programmes of participating countries.

Additionally, the regional office of the WHO for Southeast Asia and the Communicable Diseases Research Centre of Indonesia's National Institute of Health Research and Development provided supplementary data from 1989 through 1998 for the 27 provinces of Indonesia.

Annual population estimates for Indonesia (prior to 1989) and Thailand were obtained from the *Monthly Bulletin of Statistics*, published by the Statistical Office of the United Nations. Unfortunately, this publication only documents population data for the Federation of Malaysia and not for individual states, except for the 1960s. Hence, the population estimates for Malaysia were multiplied by the percentage of the Malaysian citizens living in Sarawak (about 9.3% in the late 1960s). An estimate of the 1997 population of Sarawak, obtained from a tourist information web-site[5], was 1,954,300 inhabitants, corresponding to 9% of the Malaysian population. Therefore, the percentage of Malaysians living in Sarawak in 1997 is similar to the percentage in the late 1960s so it will be assumed that the population growth of Sarawak is similar to the national average during the study period.

In the Americas, with the exception of French Guiana, cases of dengue and DHF were obtained from a WHO-sponsored publication (Gratz and Knudsen, 1996). More recent annual epidemiological data for Southeast Asia were obtained from various organisations through personal communication[6]. The number of DHF cases reported annually in Indonesia, the Philippines, and Thailand are also published in Halstead (1980, 1993) and Pinheiro and Corber (1997) for a few decades. In addition, Indonesia's *Sub Direktorat Arbovirosis* supplied additional information on the incidence of DHF as well as regional and monthly epidemiological data from 1994 through 1998. As data for the same time periods were supplied by two or more sources, comparisons were possible for quality control.

French Guiana does not report dengue cases to the PAHO. The *Institut Pasteur* in Cayenne documents, however, suspected and diagnosed cases (Reynes *et al.*, 1993). Suspected dengue cases are published in Fouque *et al.* (1995) and Reynes (1996) from 1965 through 1993. The number of dengue cases was estimated from the published graph of each source.

More recent dengue/DHF data in the Americas are limited to Colombia and Venezuela. The annual number of dengue cases reported in Colombia, and for some years DHF, was obtained from Colombia's *Oficina de Epidemiología*. Annual DHF cases for Colombia from 1990 to 1998 are published in the 33rd edition of *Revista Salud Colombia*[7]. Finally, the number of dengue and DHF cases for more recent years in Venezuela were collected through archival searches of the newspaper *El Nacional*[8] published in Caracas.

2.2 ENSO Indices and Classification of El Niño and La Niña Events

Various indices exist to quantify the strength of ENSO events. Data were obtained from the most common ENSO indices: SST anomalies in the tropical Pacific Ocean, the SOI, and the Multivariate ENSO Index (MEI) (Wolter and Timlin, 1998). SST anomalies are typically calculated in four different regions of the Pacific: Niño

1+2, Niño 3, Niño 4, and Niño 3.4 (Figure 2.1). Positive SST anomalies refer to El Niño and negative anomalies to La Niña conditions in all four regions.

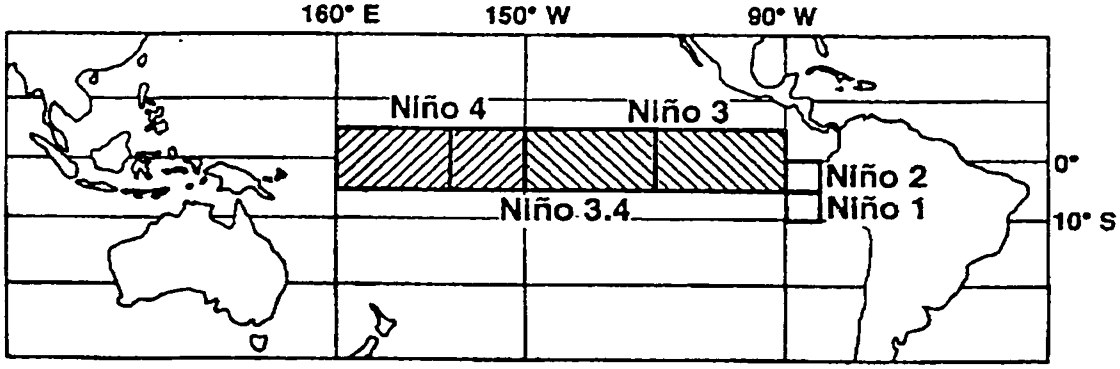

Figure 2.1. Geographical location of the Niño 1+2 (0–10°S, 80°W–90°W), Niño 3 (5°N–5°S, 90°W–150°W), Niño 4 (5°N–5°S, 150°W–160°E), and Niño 3.4 (5°N–5°S, 120°W–170°W) regions. Source: Pielke and Landsea, 1999, p. 2028.

A negative SOI signifies low pressure at Tahiti and high pressure at Darwin with weak easterly trade winds, indicating El Niño conditions. The MEI is a bimonthly index and is considered the most reliable index to monitor ENSO, because it incorporates six climatic variables, as recorded in the Comprehensive Ocean-Atmosphere Data Set (COADS) from the tropical Pacific Ocean. K. Wolter of NOAA provided this data set. The MEI is calculated as the first principal component of the combination of the following six variables: sea level pressure, zonal and meridional components of surface winds, SST, surface air temperature, and cloudiness (Wolter and Timlin, 1993). (Principal component analysis determines the best linear combination of various variables[9].) In contrast to the SOI, positive values of the MEI relate to El Niño conditions and negative values to La Niña conditions. Correlation between the MEI and other ENSO indices varies from ±0.8 to 0.9 (Wolter and Timlin, 1998).

The SST anomalies (calculated as deviations from the mean of the 1950-79 period) and SOI data sets are available on the web site of the Climate Prediction Center of the National Oceanic and Atmospheric Administration (CPC-NOAA)[10]. Of the two SOI data sets, the one with standardised anomalies was selected. The MEI was normalised to produce a time series with a mean of zero and a standard deviation of one as well as to minimise the influence of seasonal changes (Wilks, 1995). Therefore, the SOI, as well as the MEI, are given in terms of variance, and SST anomalies in degrees Celsius. All ENSO indices were smoothed with an 11-month central moving average (i.e., five months on either side) to emphasise inter-annual variations.

At the core of this thesis is the correlation between disease outbreaks and ENSO years. Therefore, it is essential to classify years as El Niño, La Niña, or normal, and to provide tangible explanations for such a classification. The Japanese Meteorological Agency (JMA) (cited in Trenberth, 1997), Kiladis and Diaz (1989), and Trenberth (1997) have suggested some definitions of El Niño (Table 2.1). However, because an ENSO event can considerably differ from another (Leung *et al.*, 1999) and that each definition has its own criteria, no consensus presently exists on the classification of El Niño and La Niña years, because

Table 2.1. Current definitions of El Niño.

Authors	ENSO Index	Criteria
Japanese Meteorological Agency	SSTs (4°N-4°N and 90°-150°W)	Anomalies* > 0.5°C for ≥ 6 months
Kiladis and Diaz (1989)	1. SSTs (4°N to 4°S and 160°W to the American coast) 2. SOI	1. positive for 3 consecutive seasons, with anomalies ≥ 0.5°C for one season 2. SOI <−1 for same duration
Trenberth (1997)	SSTs (Niño 3.4)	Anomalies* > 0.4°C for ≥ 6 months

*Five-month running mean of anomalies

In this thesis, emphasis is given to ENSO events of at least moderate intensity, because weak events are less likely to influence considerably the climate and hence the transmission of vector-borne diseases. All the above definitions include some El Niño events, such as the 1963 and 1979 episodes, that are considered weak and even not significant by other classifications (e.g., Quinn and Neal, 1995; Schneider and

Fleer, 1989). In addition, the JMA classification does not include the 1993 and 1994/95 El Niños, because SST anomalies persisted above the threshold for only five, rather than six months, although the scientific community considers 1994/95 an ENSO event (e.g., Hollis, 1996 and Trenberth, 1997).

A definition that would include the 1994/95 warm event but that would also exclude ENSO episodes of relatively weak intensity is therefore necessary for this study. To classify years as El Niño, La Niña, and non-ENSO, the MEI was used, because it is a composite of different ENSO parameters and thus a better representation of the environmental conditions in the Pacific Ocean. Accordingly, an El Niño (La Niña) event is defined to take place when anomalies are greater than 1.0 (-1.0) for at least 4 consecutive bimonthly values. The latter criterion discards strong anomalies that are not persistent (and hence would not have a lasting climatic impact), but still allows for the inclusion of the 1994/95 El Niño. As a result, only moderate and strong ENSO events are considered.

El Niño and La Niña years, according to the above definition, are, since 1955, summarised in Table 2.2. Some scientists consider the 1990 through 1995 period as one prolonged El Niño, because warm temperatures persisted from 1990 to June 1995 in the central equatorial Pacific (Trenberth and Hoar, 1996). Nevertheless, three peaks are clearly evident in the time series of most ENSO indices (Figure 2.2).

Table 2.2. El Niño and La Niña events included in this thesis.

El Niño years	La Niña year
1957/58	1955/56
1965/66	1964
1972/73	1970/71
1982/83	1973/74
1986/87	1975/76
1991/92	1988/89
1993	
1994/95	
1997/98	

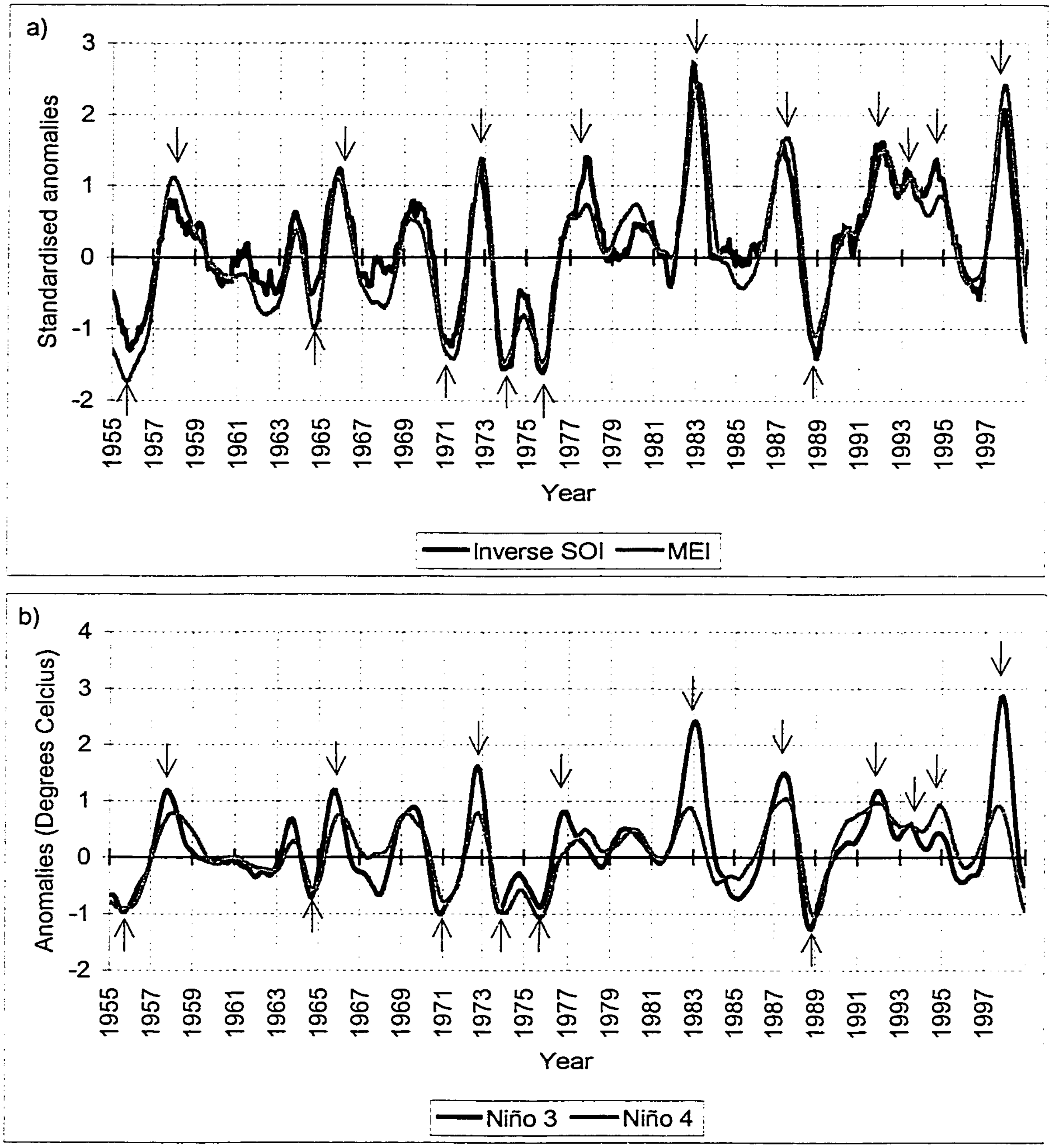

Figure 2.2. Time series of the inverse SOI and MEI (a) and SST anomalies in regions Niño 3 and Niño 4 (b). The arrows pointing downward represent the El Niño episodes and those pointing upward refer to the La Niña episodes analysed in this thesis.

Wolter and Timlin (1998) classified each bimonthly value of the MEI in categories ranging from 1 to 7. Numbers 1, 2, and 3 symbolise strong, moderate, and weak La Niña events, respectively. Number 4 represents a normal year and numbers 5 to 7 are El Niño events of weak, moderate and strong intensity, respectively.

According to that classification, all the selected ENSO events for this study are moderate or strong. Furthermore, the selected El Niños coincide closely with those used by Bouma *et al.* (1997) except for the 1976/77 El Niño.

Quinn and Neal (1995) performed a similar classification as Wolter and Timlin (1998) by categorising El Niño events from weak to very strong according to diverse physical and socio-economic impacts. Some factors used in their classification were: SST anomalies, rainfall and flooding, degree of damage and destruction, sea level variations, mortality of marine organisms and guano birds, impacts on coastal fisheries and fish production. Between 1957 and 1983, only the 1982/83 El Niño is considered very strong. The 1957/58 and 1972/73 episodes are strong; 1965, 1976, and 1987 are moderate; and all other events (except for 1969, which was classified as weakly moderate) were not considered because of their weak magnitude. As this comprehensive classification and Ropelewski and Halpert (1996) consider the 1976/77 El Niño moderate, it is also classified as moderate in this study.

Through 1988, the selected La Niña years correspond to the cold events identified by Kiladis and Diaz (1989) and Ropelewski and Halpert (1996). Except for 1995/96, all other cold events are similar to those used by Poveda and Rojas (1996; 1997). The JMA classification did not consider 1995/96 a La Niña event because SST anomalies were cooler than 0.5°C for only three, rather than six consecutive months. Similarly, Leigh (1996) classified the 1995/96 La Niña as weak.

The El Niño and La Niña events selected in this study are therefore in accordance with those accepted by the scientific community. Although emphasis will be given to ENSO years of moderate and strong intensity, the effect of weaker ENSO events, such as the 1963 and 1969 warm events as well as the 1995/96 cold event, will be discussed when relevant.

2.3 Climatological and Hydrological Databases

Climatological data (mean monthly temperature and total monthly precipitation) were obtained from ground-based meteorological stations. Most data were acquired from the Global Historical Climatology Network (GHCN) of the

National Climatic Data Center (NCDC). (This data file includes monthly temperature and precipitation data for 7,280 temperature and over 20,000 precipitation stations world-wide[11].) The national meteorological services of Colombia, Guyana and Suriname provided additional climatological data for their respective countries[12], because of the scarcity of the NCDC in the region. In Indonesia rainfall data could not be obtained for the 1990s. Hence, areal monthly total precipitation estimates were obtained from National Center for Environmental Protection's Merged Analysis of Precipitation (CMAP) grid-based data set. NCEP computes total monthly precipitation data during this period using gauge observations, satellite estimates, and numerical model outputs (Xie and Arkin, 1997)[13].

Relative humidity is also an important climatic parameter affecting dengue and malaria transmission. Humidity data, however, were not readily available, and were obtained from only a few Colombian weather stations. Nevertheless, all regions analysed in this study (with the exception of southwestern Ecuador and coastal Peru) have equatorial wet climates and their relative humidity is above the necessary threshold for mosquito survival year-round. In French Guiana, for example, the relative humidity is above 80% and 70% during the wet and dry seasons, respectively (Snow, 1976).

Hydrological data were obtained for Colombia, Guyana, and Peru. National meteorological organisations provided monthly river height and river discharge data from five Colombian and four Guyanese rivers. Finally, the Joint Institute for the Study of the Atmosphere and the Oceans (JISAO)[14] supplied monthly rainfall at Piura airport and river discharge of the Piura river in the northern coastal region of Peru were obtained from.

2.4 Methodology

The first objective of this research is to provide temporal and spatial climatological, and at times hydrological, evidence of ENSO teleconnections. Using the current literature and data analysis, this objective verifies temporal and spatial ENSO-climate consistency throughout the country during El Niño and La Niña events.

The nature of this relationship is analysed for individual ENSO events, because lack of temporal correlation of climatic anomalies with ENSO might explain the poor relationship between ENSO and disease incidence. In the case that correlations are not consistent at the national level, regional data (where available) are used to demonstrate that disease epidemics originate from regions in which weather patterns are significantly influenced by ENSO.

The analysis consisted of calculating temperature, rainfall, and hydrological anomalies in terms of variance for all weather and gauging stations. This normalisation procedure is according to the equation:

$$\frac{X_i - M_{ij}}{\sigma_{ij}}, \tag{2.1}$$

in which X_i corresponds to the observed value during month i, and M_{ij} to the long-term mean value for month i during period j (calculated using the entire time series). σ_{ij} refers to the standard deviation of month i for a time series of j months. Missing values, if less than five successive values, were approximated using a cubic-spline interpolation. This FORTRAN programme is available in Press *et al.* (1992). Like the ENSO indices, hydro-climatic time series were smoothed with an 11-month moving average to seasonal variations.

Next, cross-correlation was utilised to identify the greatest correlation coefficient at the best lag time (expressed in months; e.g., Poveda and Rojas, 1997). A lag time is likely to exist between the time of the ENSO event in the tropical Pacific Ocean and the occurrence of climatic and hydrological anomalies in more remote countries that are not directly influenced by ENSO. The Fisher's z-transformation was used to test for the statistical significance of the correlation coefficients using Quenouille's (1952) method to adjust for serial correlation (see Appendix 2 for details).

Since precipitation is highly variable, the national average of standardised anomalies of total annual precipitation was calculated to facilitate the identification of wet and dry years. Moreover, as in Hastenrath (1985), the national average of annual standardised anomalies was computed, because disease data are generally reported as a national average (this method was not possible in countries that do not exhibit spatial coherence of climatic anomalies with ENSO). No form of areal weighting was used in the calculation of national averages.

Although La Niña results in drier conditions in some areas of South America, in the coastal regions of northern Peru and southern Ecuador, which are normally arid, La Niña does not significantly affect precipitation (Tapley and Waylen, 1990). El Niño, however, brings increased rainfall to the region and thus disease epidemics are expected. The northern Ecuadorian coast is very wet with over 2000mm/year and there is no distinct dry season. A little southward a dry season emerges and, at Manta, most precipitation falls during the first four months of the year (Figure A4.2). The relatively warm waters of the Gulf of Guayaquil enhance evaporation and humidity and, thus, a considerable quantity of rain falls in regions located north and east of the city of Guayaquil. In contrast, the cold waters of the Pacific Ocean generate dryness in the southern Ecuador (i.e., from Manta to Guayaquil; hereafter referred to as the Peninsula).

The second objective of this project is the correlation of dengue/DHF and malaria epidemics with ENSO events. To determine the statistical significance of the correlation between ENSO and disease epidemics contingency tables with Fisher's exact test are used (R. Wong, *personal communication*). Fisher's exact test verifies the independence between the rows and columns of a 2×2 contingency table. Bouma and van der Kaay (1996) previously used contingency tables with the Chi-square test for the same purpose.

Fisher's exact test is based on the hypergeometric distribution and is adequate when the total number of observations in the contingency table is less than 200[15]. Given the small number of observations and the frequent lack of expected counts greater than five in all cells of the contingency table (a requirement for the Chi-square test), Fisher's exact test was preferred. This test is adequate for a small number of observations because approximations are not used (R. Wong, *personal communication*; S. Newman, *personal communication*). It calculates the exact probability of obtaining the observed contingency table[16]. Table 2.3 is an example of a contingency table testing for the independence between epidemics during El Niño versus other years.

Table 2.3. Example of a contingency table testing for the independence of epidemics between El Niño years and other years. H_o: the incidence of an epidemic is unrelated to El Niño.

	El Niño years	Other years	Total
Epidemic	a	r-a	r
No Epidemic	m-a	a+n-r	s
Total	m	n	t

Ho: The incidence of an epidemic is unrelated to El Niño

Fisher's exact test calculates the probability of obtaining the observed contingency table using the formula:

$$\Pr(a) = \frac{m!\,n!\,r!\,s!}{a!(r-a)!(m-a)!(a+n-r)!t!}, \tag{2.2}$$

in which r and s (cf., Table 2.3) are the number of years with and without epidemics, respectively. The number of El Niño and non-El Niño years in the time series correspond to m and n, respectively, while t is the total number of observations in the contingency table. Also, a represents the actual number of epidemic years that occurred during El Niño years. (In all contingency tables, the sum of m, n, r, and s equals t). Pr (a), that is the probability of obtaining a in the contingency table, is then calculated for each possible value of a (i.e., $\{0,1, \ldots , r\}$). The value of the statistical test (i.e., the p-value) is calculated by adding the probabilities (Pr) for all values of a greater than or equal to the actual a in the observed contingency table. The two-sided p-value is then calculated by summing the probabilities starting at a = 0 up to the point where the sum does not exceed the one-sided p-value (an example of these calculations is provided in Appendix 3).

Throughout the analysis other factors that may have influenced the incidence of these vector-borne diseases, such as major changes in mosquito control activities, population migration or political turmoil, were considered as reported in the WHO's *Weekly Epidemiological Record* (WER) since 1965. These socio-economic factors might explain the occasional lack of correlation of disease outbreak when the climate was favourable to the spread of those diseases and will be mentioned when they are believed to have occurred.

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[1] Since 1976 the report is titled: *Status of Malaria Programs in the Americas*. But it was previously named *Status of Malaria Eradication in the Americas* (1968-1975), *Report on the Status of Malaria Eradication in the Americas* (1959-1967), and *The Status of Malaria Eradication Programs in the Americas* (1957-1958)

[2] Specifically, Thailand's Department for the Control of Communicable Diseases (malaria division); the Vector Borne Diseases Control Unit of the Sarawak Health Department; and the Office for Public Health Services of the Department of Health of the Philippines.

[3] *World Health Statistics Annual*, 1983, pp. 791-795

[4] Weekly Epidemiological Record, 1999, pp. 265-270

[5] URL: http://www.sarawak-online.com/tourism/population.html

[6] Data were provided by the Sarawak Health Department and the regional offices of the WHO for the Western Pacific and Southeast Asia

[7] *Revista Salud Colombia* is available on-line at http://www.saludcolombia.com

[8] Archival search is available on-line at http://www.el-nacional.com

[9] S-Plus 2000. 1999. *Modern Statistics and Advanced Graphics, User's Guide*. Seattle, Washington.

[10] URL: http://www.cpc.noaa.gov/data/indices/

[11] Data can be downloaded by ftp at the following URL: http://www.ncdc.noaa.gov/ol/climate/climatedata.html.

[12] Specifically, Colombia's *Instituto de Hidrología, Meteorología y Estudios Ambientales* (IDEAM*), Guyana's Hydrometeorological Service, and Suriname's Meteorological Service.*

[13] Data are available on-line at URL: http://tao.atmos.washington.edu/data_sets/cmap_precip/pentad/

[14] Data are available on-line at URL: http://tao.atmos.washington.edu/data_sets/piura/

[15] S-Plus 2000. 1999. Modern Statistics and Advanced Graphics, User's Guide. Seattle, Washington.

[16] Minitab Support (statistical software): http://www.minitab.com/support/

Chapter 3: Climatic and Hydrological Evidence of ENSO Teleconnections

This chapter provides evidence of ENSO teleconnections, which are grouped per geographical region, that is, northern South America, Brazil's Amazon, western South America, and Southeast Asia. Then, Section 3.5 presents the ENSO temperature signal for the same regions, and Section 3.6 summarises the results of this chapter.

3.1 Northern South America

Ropelewski and Halpert (1987, 1989) identified a strong and consistent relationship between both phases of ENSO and rainfall variations in northeastern South America (i.e., north equatorial Brazil, French Guiana, Suriname, Guyana, and eastern Venezuela). They found that there is generally below (above) normal rainfall during El Niño (La Niña) in this region. Moreover, the correlation is stronger from July (0) through March (+1) and from June (0) through March (+1) for El Niño and La Niña years, respectively. (A reminder that Niño (0) and Niño (+1) refer to the development and decay years of an El Niño event, respectively. Niño (+1) follows the peak in SST, which generally occur by the end of the calendar year.) All El Niño events analysed between 1911 and 1982 (except for 1969) had below normal rainfall. Similarly, 76% of the La Niña events examined had above normal rainfall (1964 is the only exception in recent decades).

The Ropelewski and Halpert (1987, 1989) studies demonstrate the spatial consistency of ENSO-generated rainfall anomalies in northeastern South America. However, they also show the absence of rainfall anomalies during some El Niño and La Niña events. As their studies did not extend beyond the 1982/83 El Niño, it is necessary to verify that ENSO teleconnections were temporally consistent in the last two decades. Thus, time series of rainfall and, for Guyana, river discharge, are analysed to confirm the impacts of ENSO on the hydrology of the region.

Since the spatial consistency of the ENSO signal has already been confirmed in the region, only a few weather stations were chosen in each country. The selection process favoured weather stations with a long time range and a small percentage of missing values. It was also desirable to optimise the geographical coverage of the country, yet in some regions the selection was severely limited and the use of weather stations with a shorter temporal record was necessary.

All weather stations in French Guiana, Suriname and Guyana display positive and statistically significant Pearson's correlations (at the 95% confidence level) between the SOI and rainfall, showing the spatial coherence of ENSO-related rainfall anomalies in the region (Table 3.1). To facilitate the identification of wet and dry years (which will be associated with dengue and malaria epidemics in the following two chapters), standardised anomalies of total annual rainfall were calculated to create national rainfall composite indices. In order not to attribute the period of best correlation with ENSO to two different years, and since drier conditions usually appeared in May (0) during El Niño episodes and persist until the following April (Ropelewski and Halpert, 1987), averages were calculated from May through April of the following year. Rainfall anomalies generally appear in May during El Niño episodes, because SSTs are usually 0.2°C above normal between March (0) and June (0) (Wang, 1995). Accordingly, the phase of the SO usually changes around March and rarely between June and January (during most El Niño events, negative rainfall anomalies appear immediately following the reversal of the SOI or lag by 1 to 2 months (Nicholls, 1986).

Table 3.1. Location, elevation, and years of record of weather stations in French Guiana (FG), Suriname (SU), and Guyana (GY) and maximum correlation with the SOI (i.e., when the SOI precedes the rainfall anomalies by 0 to 2 months).

Name (country)	Latitude/longitude	Elevation (m)	Rainfall record	Pearson correlation
Cayenne (FG)	4.8°N/52.4°W	9	1956-1998	0.66
Maripasoula (FG)	3.6°N/54.0°W	104	1960-1985	0.50
St.Georges (FG)	3.9°N/51.8°W	2	1961-1985	0.51
Coeroeni (SU)	3.4°N/57.3°W	148	1961-1986	0.55
Paramaribo (SU)	5.8°N/55.2°W	2	1956-1998	0.43
Nickerie (SU)	6.0°N/57.0°W	4	1956-1998	0.49
Sipaliwini (SU)	2.0°N/56.1°W	243	1961-1986	0.72
Georgetown (GY)	6.8°N/58.2°W	2	1956-1997	0.64
Ebini (GY)	5.6°N/57.8°W	29	1956-1998	0.60

The rainfall composite indices of French Guiana (Figure 3.1), Suriname (Figure 3.2), and Guyana (Figure 3.3) show that all the El Niño events during the 1956-1998 period were associated with below average rainfall in years Niño (0). (In all graphs of this thesis, EN and LN refer to El Niño and La Niña events, respectively.) For some events, notably 1957/58, 1982/83, and 1986/87, anomalies even persisted in years Niño (+1) in the three countries. During the 1991/92 El Niño, however, rainfall was approximately normal in year Niño (0) in Suriname, and negative anomalies occurred only in the following year. Moreover, anomalous rainfall was not recorded in 1993 in Guyana. Although below average rainfall was recorded in 1964, all other La Niña episodes were associated with more abundant rainfall in Niña (0) in the three countries.

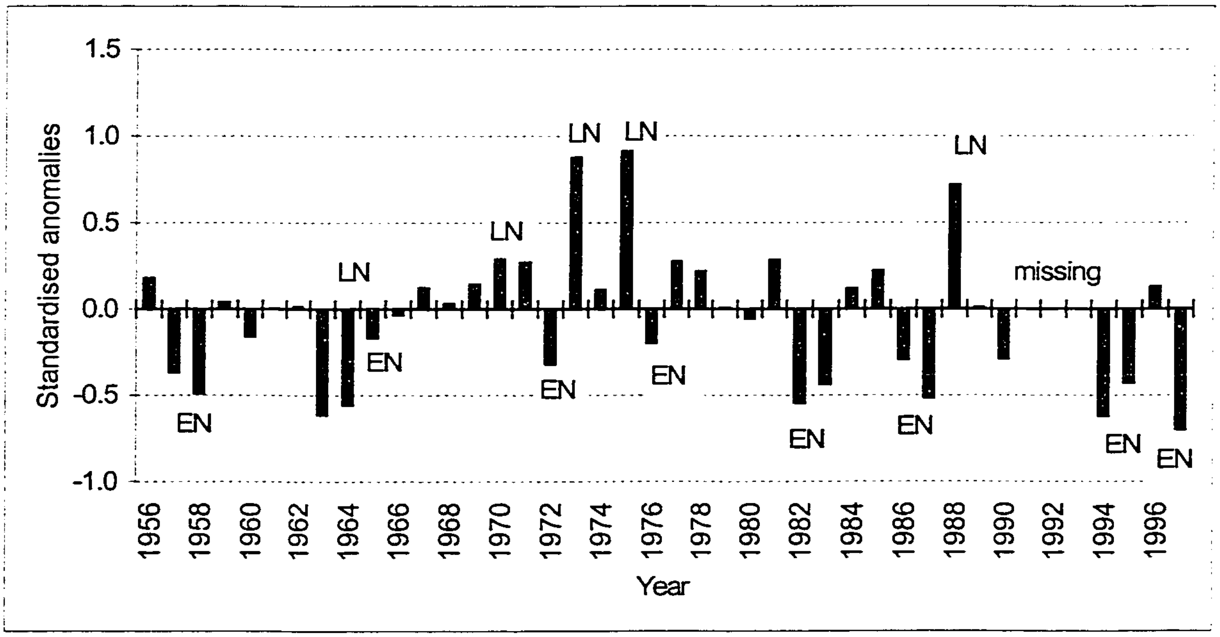

Figure 3.1. Rainfall composite index of French Guiana. Prior to 1961 and after 1985, rainfall data were available from Cayenne only. Also, precipitation data were not available from any weather station between 1990 and 1994.

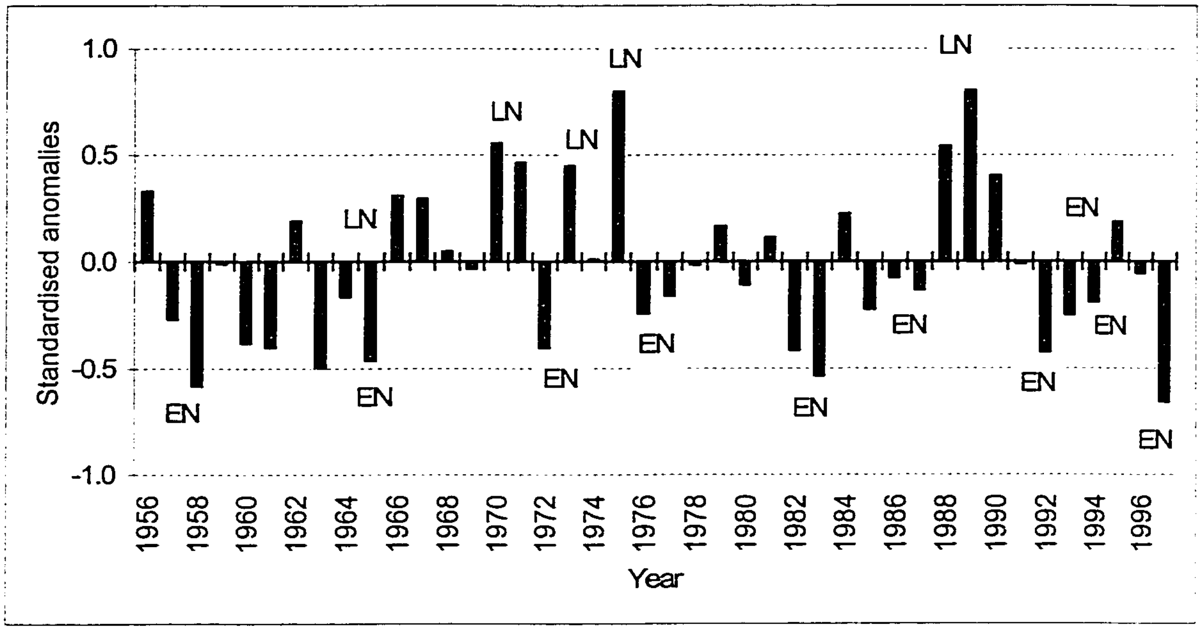

Figure 3.2. Rainfall composite index of Suriname.

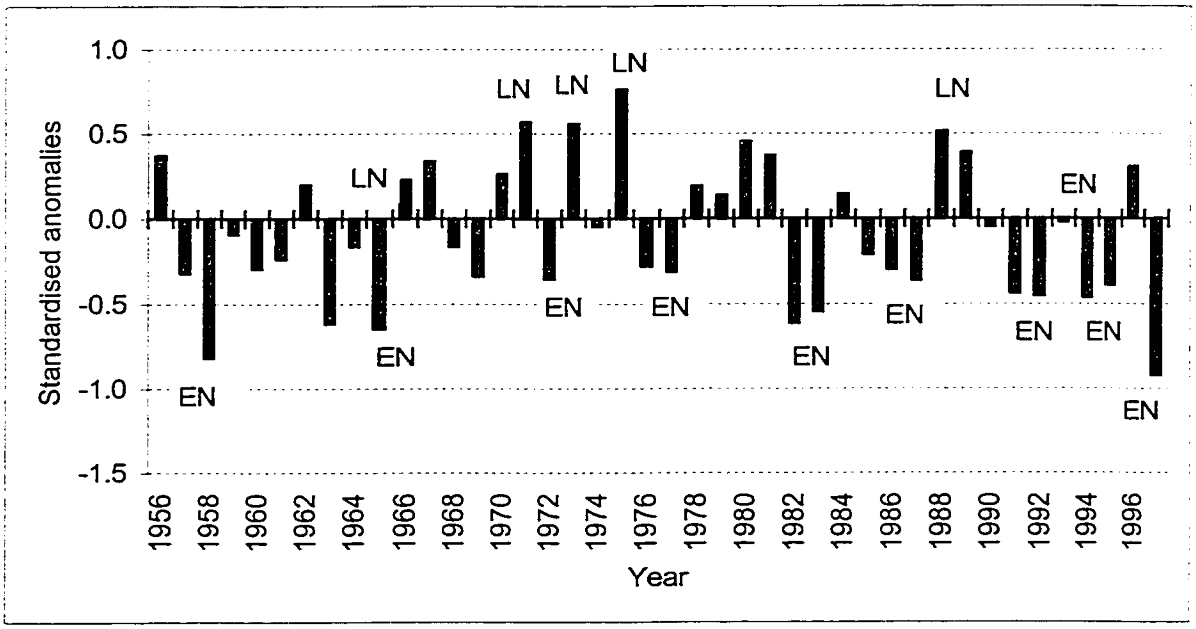

Figure 3.3. Rainfall composite index of Guyana.

The national average of monthly river discharge anomalies in Guyana was calculated from four rivers. River discharge anomalies closely follow rainfall variations with all rivers experiencing lower and higher discharge during El Niño and La Niña events, respectively (Table 3.2). As for rainfall, river discharge was not below average during the 1993 El Niño (Figure 3.4). Rainfall anomalies are often lowest at the end of Niño (0). Because of the lag time between rainfall and peak in river discharge (approximately two months in this country), the lowest river discharge anomalies commonly occur during Niño (+1). In fact, during all El Niño events of the 1956 to 1998 period, the lowest river discharge has always been recorded in years Niño (+1).

Table 3.2. Maximum correlation between the SOI and river discharge anomalies in Guyana (i.e., when the SOI precedes the river discharge anomalies by 4 months).

River	Gauging station	Record length	Pearson correlation
Berbice	Itabru Falls	1961-1988	0.61*
Demerara	Great Falls	1956-1997	0.59*
Essequibo	Plantain Island	1956-1998	0.66*
Mazaruni	Apaikwa	1956-1998	0.47*

*Statistically significant at the 95% confidence level

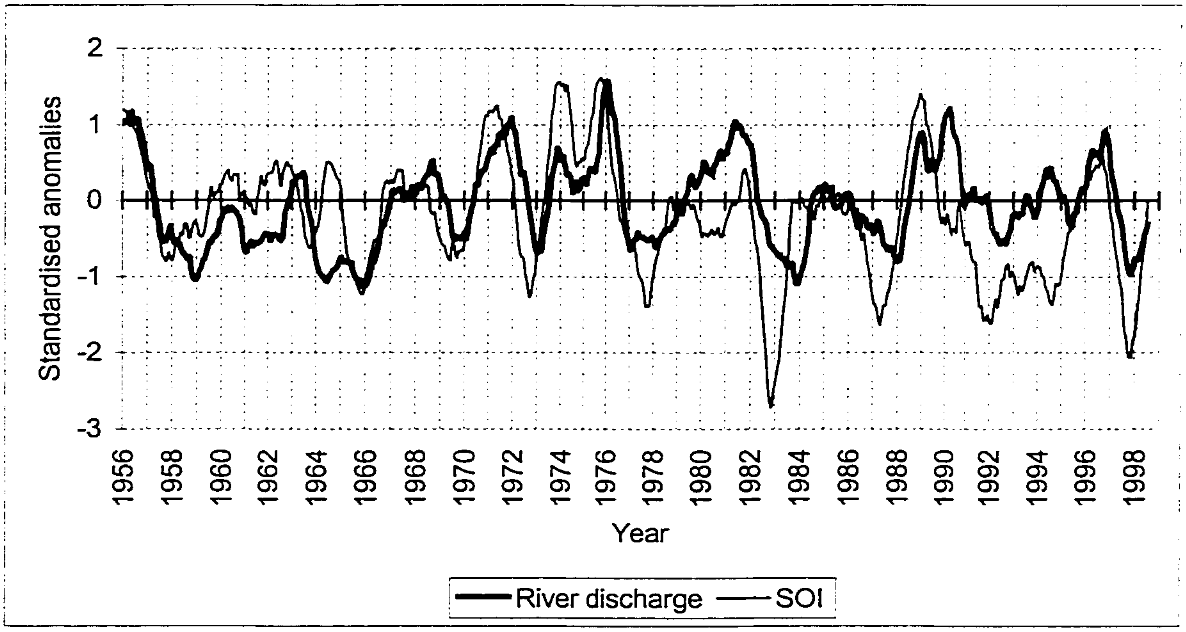

Figure 3.4. Time evolution of the SOI and composite index of river discharge anomalies in Guyana.

Poveda and Mesa (1995) provided evidence of a relationship between ENSO and hydroclimatological variables (i.e., rainfall and river discharge) in Colombia. They found that El Niño is usually associated with below average rainfall and decreased river discharge in most Colombian regions. The Amazon and Llanos regions, situated east of the Andes, were not included in their analysis (Poveda and Rojas, 1997). La Niña, on the other hand, generally engenders opposite climatic effects from El Niño years. Similar research by Quesada and Caviedes (1992) support the above findings. However, no relationship was found for the Fundación river (in the Caribbean region) and Guayuruba river (located east of the Andes).

Correlation between the SOI and monthly total rainfall was calculated for various weather stations in Colombia. Most correlation coefficients are positive, implying drier and wetter conditions in El Niño and La Niña years, respectively (Table 3.3). Only in Barranquilla and Gaviotas is the correlation with ENSO not statistically significant. Barranquilla is located in the same region as the Fundación River, where Quesada and Caviedes (1992) observed no relationship between its discharge and ENSO. The correlation between rainfall anomalies and ENSO at Cartagena, located south-west of Barranquilla, is of magnitude similar to the rest of the country, indicating that the lack of an ENSO signal on precipitation in northern Colombia is limited to the northeastern Caribbean region. The rainfall record of Gaviotas, as well as the river discharge of the Guayuriba river, demonstrates that the hydrology of eastern Colombia is not correlated with ENSO.

Accordingly, river height is inversely related to ENSO and shows an even stronger correlation than with rainfall, as it is considerably less variable than precipitation. Changes in river height are the result of rainfall anomalies over a large area and are therefore less affected by higher-frequency local variability. River height is also influenced by evapotranspiration and soil moisture, which are affected by temperature anomalies generated by ENSO (Table 3.4; Poveda and Mesa, 1995). Only the Guaviare River, situated in eastern Colombia, has no correlation with ENSO, providing further evidence for the lack of an ENSO impact on precipitation in eastern Colombia.

Table 3.3. Location, elevation, and years of record of weather stations in Colombia and their maximum correlation with the SOI (rainfall anomalies occur in the same month).

Name	Latitude/longitude	Elevation (m)	Rainfall record	Pearson correlation
Barranquilla	10.9°N/74.8°W	21	1959-1986	0.24
Bogotá	4.7°N/74.2°W	2548	1951-1998	0.49*
Cartagena	10.5°N/75.5°W	12	1951-1998	0.48*
Cúcuta	7.6°N/72.6°W	1235	1951-1990	0.60*
Gaviotas	4.6°N/70.9°W	167	1969-1998	-0.13
Medellin	6.2°N/75.6°W	1499	1951-1983	0.48*
Neiva	3.0°N/75.3°W	443	1964-1998	0.49*
Quibdo	5.4°N/76.4°W	53	1958-1991	0.48*

*Statistically significant at the 95% confidence level

A national average of standardised anomalies was calculated using all Colombian gauging stations to identify wet and dry years at the national scale. The Guaviare river, in eastern Colombia, was excluded from calculations, because of its lack of correlation with ENSO. All the El Niño and La Niña events selected for this thesis were associated with below and above average river height, respectively, with extreme values occurring by the end of the Niño (0) and Niña (0) or the following year (Figure 3.5). Hence, this figure demonstrates a significant impact of ENSO on the hydrology of Colombia.

Table 3.4. Maximum correlation between the SOI and river height anomalies in Colombia. All correlation coefficients have their maximum value when the SOI precedes the river height anomalies by 1 to 2 months with the exception of the Atrato and San Juan rivers (both located in the Pacific coastal region), which experience their maximum correlation in the same month.

River	Gauging station	Record length	Correlation
Magdalena	Puerto Berrio	1972-1995	0.55*
	El Banco	1976-1998	0.59*
	Calamar	1971-1997	0.65*
Cauca	La Pintada	1977-1997	0.65*
Guaviare	Candilejas	1982-1997	0.13
San Juan	Peñitas	1980-1997	0.67*
Atrato	Bellavista	1971-1998	0.67*

*Statistically significant at the 95% level

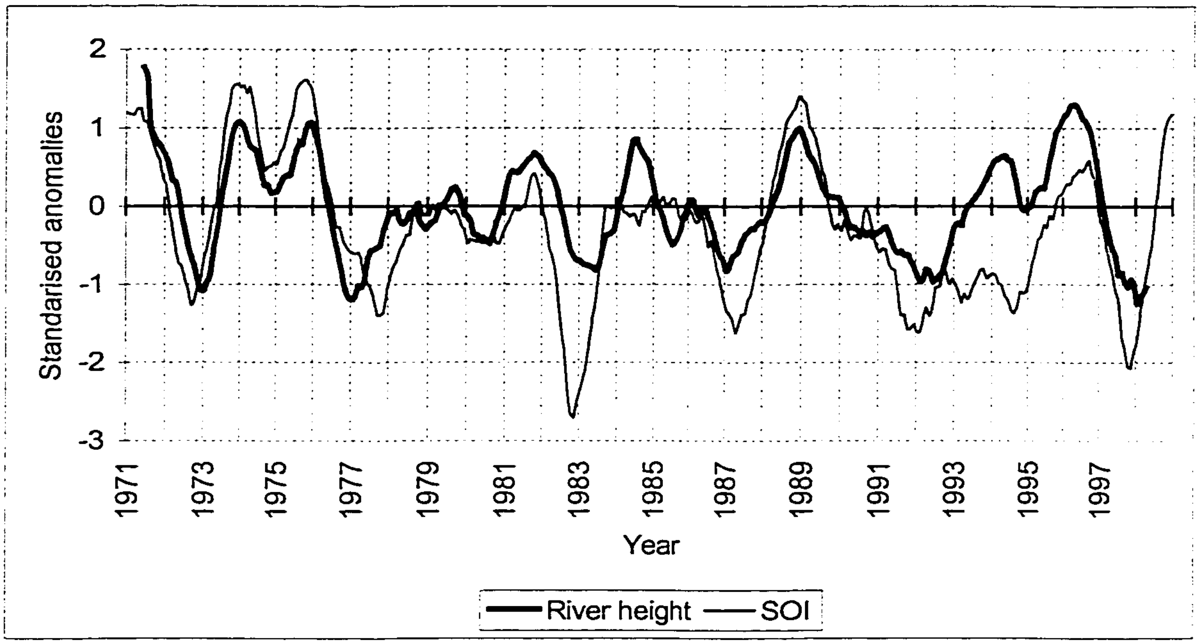

Figure 3.5. Time evolution of the SOI and composite index of river height anomalies in Colombia (maximum correlation is 0.72 when the SOI precedes river height anomalies by 1 month).

Below average rainfall in Colombia, Suriname, and the Guianas during El Niño episodes is explained by a weakening of the South Pacific high pressure cell, which allows the Inter-Tropical Convergence Zone (ITCZ) to move further south. Moreover, El Niño years decreases the SST gradient between the Colombian coast and the normally cold waters off Peru and Ecuador, reducing the winds and moisture advection into western Colombia (Poveda and Mesa, 1995), which is one of the rainiest places in the Americas (Snow, 1976). The climatological mean of total annual precipitation at Quibdo, for example, is more than 7,860 mm, in comparison to 846 mm at Barranquilla in the Caribbean region (Snow, 1976). No statistically significant correlation was found between rainfall and the SOI in Colombia's Amazon or in the Caribbean region of northeastern Colombia. The analysis of the rainfall record of neighbouring Venezuela will identify the spatial extent of this anomalous region along the Caribbean coast.

Venezuela is divided into three climatic regions: the northern and western areas (extending from *Península de P*aria to the Colombian border, and including the Maracaibo basin), the Llanos, and the Guyana highlands (Figure A4.3). The Llanos is a vast plain of low elevation in central Venezuela that extends to northeastern Colombia. The Guyana highlands region is situated in the southeastern portion of the country. The highlands are a rainforest ecosystem that covers more than a third of Venezuela (Snow, 1976). As in other countries of northern South America, the correlation between rainfall anomalies and the SOI was calculated at various weather stations, representing all regions of Venezuela.

No statistically significant correlation was found in the Llanos and the northern and western regions of Venezuela. Moreover, standardised anomalies of total annual rainfall (May through April of the following year) were computed at each weather station and no consistent pattern could be identified. Pulwarty *et al.* (1992) studied the relationship between ENSO and rainfall in Venezuela from 1972 through 1985. Similarly, they did not identify a statistically significant correlation between the SOI and rainfall anomalies in the Llanos and the dry coastal region. They demonstrated, however, a correlation during the December-February season in the Maracaibo basin and the Andes (i.e., west of 70°W).

In the northern Guyana highlands of Venezuela, no statistically significant correlation was found. Pulwarty *et al.* (1992), however, found that rainfall anomalies are weakly correlated with the SOI ($r = 0.34$) in this region but also only during the December-February season. Only in the southern Guyana highlands was a temporally consistent correlation between the SOI and rainfall identified in this thesis ($r = 0.59$ at Santa Elena when the SOI precedes the rainfall anomalies by two months; cf., Figure A4.3). Standardised anomalies of total annual rainfall at Santa Elena (i.e., May through April of the following year) show that all El Niño events during the 1956-1988 period were associated with below average rainfall. Anomalies were weak, however, during the 1986/87 episode. Except for 1970, all Niña (0) years had more abundant rainfall.

Rainfall anomalies are therefore significantly correlated with ENSO in the southern Guyana highlands. Correlations also exist in the Maracaibo basin and in the northern Guyana highlands, but they are significant only during the December-February season. However, the southern Guyana highlands are represented by only one weather station, because of the scarcity of meteorological observations in the region. Analysis of Brazil's Amazon will identify the consistency of ENSO teleconnections in the 1990s and provide a more comprehensive representation of the inter-annual variability of rainfall in the Amazon basin.

3.2 Brazil

There is evidence of below average rainfall and river discharge in Brazil's Amazon region during El Niño. Nobre and de Oliveira (1986) demonstrated that precipitation was below normal during the 1982/83 El Niño. Indeed, reduction in rainfall greater than 0.5 standard deviation was reported in the region during the 1983 hydrological year, which extended from October 1982 through September 1983. The lowest anomalies were found in the central Amazon where only 100 mm of rain fell in January and February compared to the mean total precipitation during this period of 600 mm.

Richey *et al.* (1989) demonstrated that El Niño (La Niña) generally precedes low (high) discharge values of the Amazon River. Amarasekera *et al.* (1997) found a similar relationship with the Negro river at Manaus, and further noted that the correlation between its annual discharge and SST climaxes with the SSTs of the December (-1) through May (0) period (r = -0.31). Similarly, river discharge was very high during the 1975/76 and 1988/89 La Niña events (Molion, 1993).

The correlation between ENSO and rainfall in north equatorial Brazil is weak but statistically significant at most weather stations (Table 3.5). Only at Porto Velho, located in the southern limit of Brazil's Amazon, is the correlation between ENSO and rainfall not statistically significant. As in other countries of northern South America, standardised anomalies of total annual precipitation were calculated from May through April of the following year. The rainfall composite index of Brazil's Amazon (excluding Porto Velho) shows that all Niño (0) years (except for 1986 and 1993) were associated with below average rainfall (Figure 3.6). During the 1986/87 El Niño, rainfall was below average in year Niño (+1) only, and the 1993 warm event did not engender negative rainfall anomalies. In 1994, positive rainfall anomalies were recorded at Manaus; at São Gabriel, however, rainfall was below average and resulted in a regional time series with weak negative rainfall anomalies during that year. Although rainfall anomalies were close to normal conditions in 1964, all other La Niña episodes resulted in more abundant rainfall in the region.

Table 3.5. Location, elevation, and years of record of weather stations in Brazil's Amazon, and maximum correlation with the SOI (i.e., at a 2-month lag maximum).

Name	Latitude/longitude	Elevation (m)	Rainfall record	Pearson correlation
Boa Vista	2.8°N/60.7°W	90	1956-1986	0.48*
Manaus	3.1°N/60.0°W	72	1956-1998	0.38*
Porto Velho	8.8°S/63.9°W	95	1956-1998	0.11
São Gabriel	0.1°S/67.1°W	90	1956-1985; 1993-1998	0.39*

*Statistically significant at the 95% confidence level

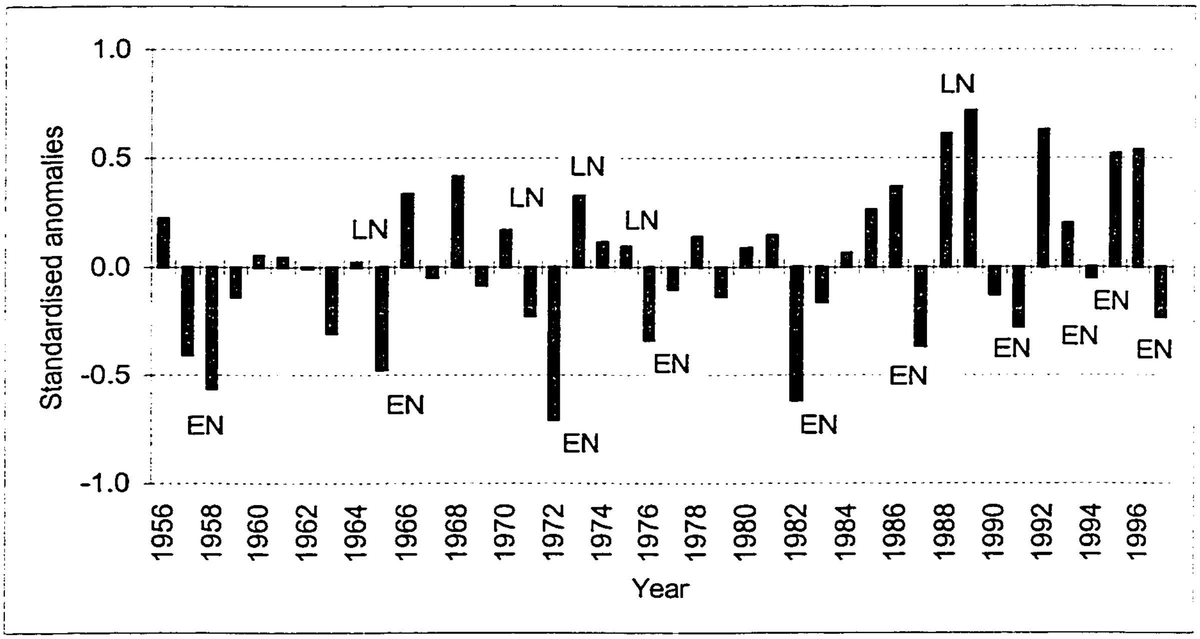

Figure 3.6. Rainfall composite index of Brazil's Amazon.

3.3 Western South America

El Niño is known to generate abundant rainfall in southern Ecuador and northern Peru (Evans *et al.*, 1999). In addition to causing a southward displacement of the ITCZ, El Niño engenders an increase of SSTs along the coast. These atmospheric perturbations result in an average 88% increase in total annual rainfall in the northern coastal region of Peru (Tapley and Waylen, 1990). However, annual total precipitation in El Niño years is not statistically different from other years in Peru's coastal region south of approximately latitude 10°S to the Bolivian border (Tapley and Waylen, 1990).

As explained in Section 2.4, the method used to identify years with statistically significant rainfall anomalies in Ecuador and Peru is different from the other two geographical regions, because we are interested on the impacts of El Niño only in this region. Annual total rainfall at Piura airport was calculated from September through August in order not to attribute the rainy season (i.e., from October to June) to two calendar years (Tapley and Waylen, 1990). For example, the hydrological year 1983 extends from September 1982 through August 1983. In this section, the statistical significance of the annual anomalies was calculated using Rossel's (1999) method, that is an anomaly has to be at least one half a standard deviation above the mean to be statistically significant. This method is not necessary in northern South America and Southeast Asia, as the statistical significance of the correlation between ENSO and rainfall have been determined in previous research. The year 1983 was excluded in the calculation of the long-term mean because the extreme hydrological anomalies during this event would considerably minimise the statistical significance of other warm events (it would importantly increase the standard deviation, which is the criterion used to determine the threshold value).

All El Niño years were associated with above average rainfall in northern coastal Peru, with extreme rainfall during the very strong 1982/83 El Niño (Figure 3.7). In 1993 and 1994, rainfall anomalies were not above the threshold value (i.e., one half a standard deviation above the mean). The 1997/98 El Niño, which was of magnitude similar to the 1982/83 El Niño, also had extreme rainfall, even though data were obtained for the first four months of the 1998 hydrological year only. Similarly, discharge of the Piura river in the same region was above the threshold value during all El Niño events, including the 1993 and 1994/95 episodes (Figure 3.8).

The Altiplano (i.e., the plateau between the two cordilleras of southern Peru) experiences an average 18% decrease in total annual precipitation during El Niño events (Tapley and Waylen, 1990). Similarly, water levels of Lake Titicaca, bordering Bolivia, are substantially low in El Niño years (Caviedes, 1984; Figure A4.4).

Tapley and Waylen (1990) did not extend their study to Peru's Amazon, located east of the Andes. Rainfall data were obtained from Iquitos and Yurimaguas, two weather stations located in the department of Loreto, and from the weather station of Pucallpa, in the department of Ucayali (cf., Figure A4.3). The lag zero correlation coefficients between standardised rainfall anomalies and the SOI are 0.04, 0.09, and 0.31 at Iquitos, Yurimaguas, and Pucallpa, respectively. Only the correlation at Pucallpa is statistically significant, peaking at a two-month lag. However, it is temporally weak, explaining only 11% of the variance in rainfall variations.

Ecuador displays spatial variations in climate variability related to El Niño. El Niño is associated with abundant rainfall in the coastal region from Esmeraldas (in the northern part of the country) to the Peruvian border (cf., Figure A4.2). Most El Niño events between 1964 and 1993 were associated with above average rainfall in the region. The only exceptions are the 1965 and 1969 El Niños. In 1965, rainfall anomalies were not spatially consistent; and in 1969, the entire coastal region had below average rainfall. No relationship was found, however, between El Niño and annual rainfall in the inter-Andean valleys and the Amazonian slope. The region along the northern coast (mid-way between Esmeraldas and San Lorenzo to the Colombian border; cf., Figure A4.2) and the western slopes of the Andes is affected by ENSO, but the relationship is not as temporally consistent as in southern Ecuador (Rossel *et al.*, 1999).

Rossel *et al.*'s (1999) method was used to identify rainfall anomalies in more recent years in Ecuador's coastal region. Anomalies were calculated for Portoviejo (cf., Figure A4.2) by subtracting total annual rainfall from the long-term mean. As in coastal Peru, the 1983 and 1998 El Niño years were excluded from the statistical calculations, because their extreme values would have considerably minimise the influence of other El Niño episodes. In more recent years, only the strong 1997/98 El

Niño generated extreme rainfall at Portoviejo. Total annual rainfall during the 1993 and 1994/95 El Niño events was below normal (Figure 3.9).

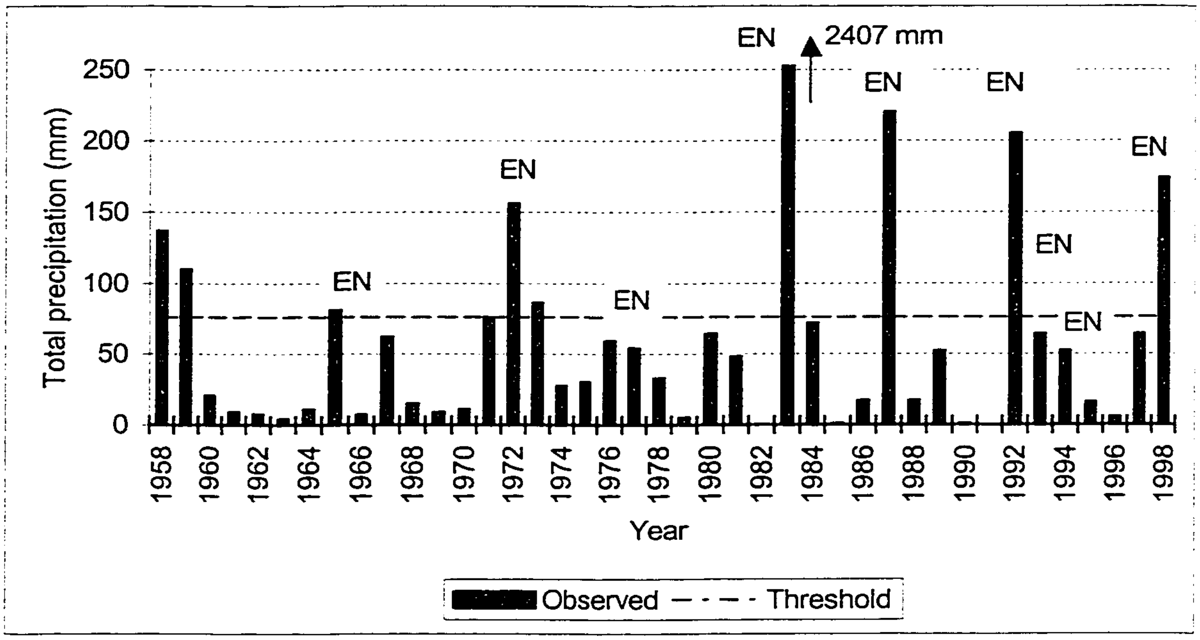

Figure 3.7. Total annual precipitation at Piura airport (data for 1998 were available for the first four months only).

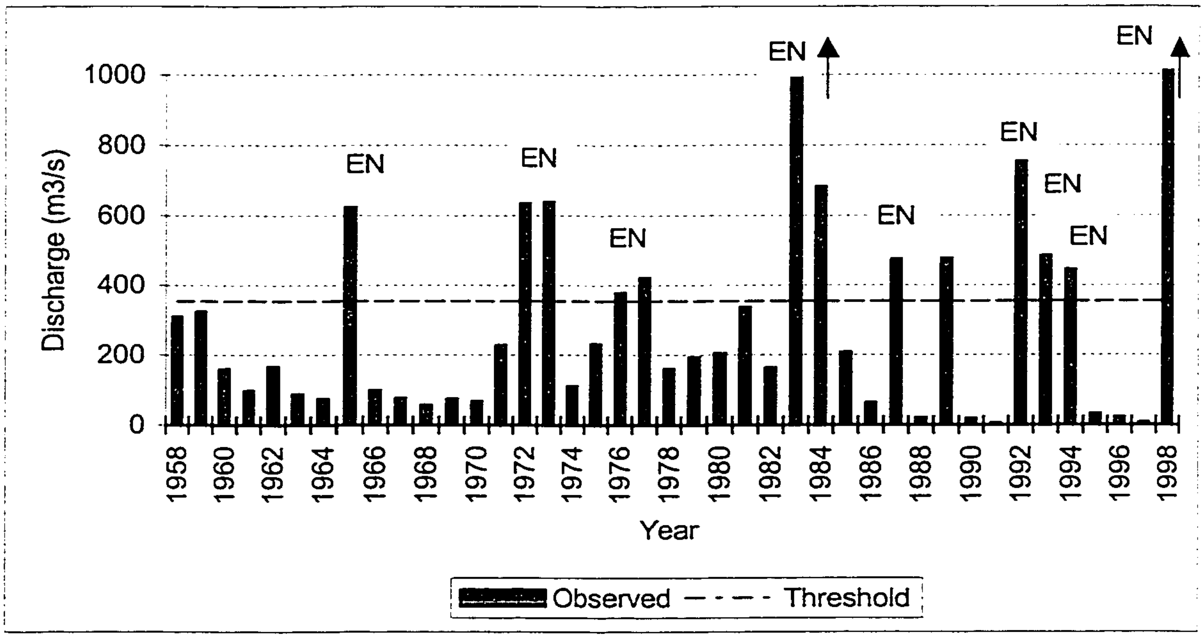

Figure 3.8. Discharge of the Piura river (data for 1998 were available for the first nine months only).

El Niño has a significant impact on rainfall anomalies in coastal Ecuador and northern Peru due to the proximity of the region to the Pacific Ocean. The Andes, however, limit the impact of El Niño in both the inter-Andean valleys and the Amazon region of those two countries.

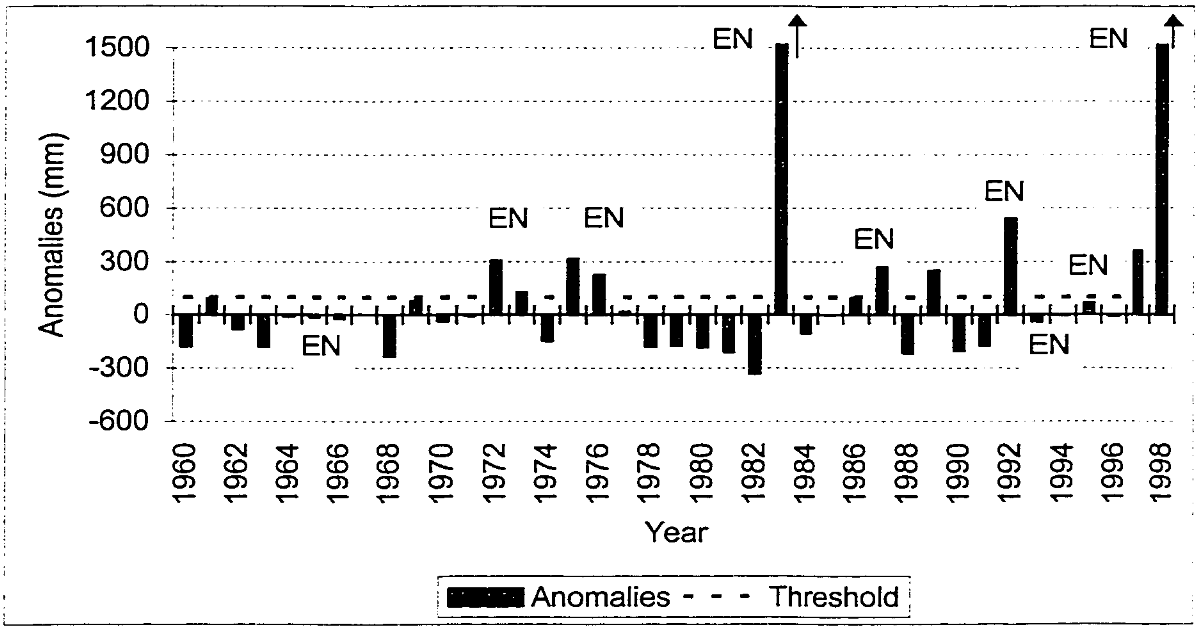

Figure 3.9. Precipitation anomalies at Portoviejo.

3.4 Southeast Asia

During El Niño, the weakening of the trade winds displaces the centre of deep convection to the central equatorial Pacific, causing dryness in Indonesia and Sarawak. Conversely, convection is enhanced during La Niña episodes (Roswintiarti, 1994). Drought during the dry season (i.e., May to November) in Indonesia coincides with El Niño events (Quinn *et al.,* 1978). The recent 1997/98 El Niño, for example, engendered a severe drought that caused hundreds of forest fires throughout the archipelago. A drought was also reported from 1990 through 1994, and was associated with the extended El Niño of the early 1990s (Evans *et al.*, 1999). Accordingly, 80% of the El Niño events that occurred between 1879 and 1982 were associated with below normal rainfall between June (0) and November (0). Although rainfall was not anomalous in 1964, above average rainfall was recorded from July (0) through December (0) during all other La Niña events since 1955 (Ropelewski and Halpert, 1987, 1989).

Roswintiarti (1994) performed a more detailed analysis of the relationship between ENSO (as indicated by the sea level pressure at Darwin) and rainfall at 10 Indonesian weather stations. She found that the impact of ENSO on precipitation is stronger in central and eastern Indonesia. Rainfall variations at the westernmost weather stations, all located on the island of Sumatra (i.e., Banda Aceh, Medan, and Padang), were not correlated with ENSO. On the island of Java, a statistically significant correlation exists, but only between September (0) and November (0). Farther east, the relationship is statistically significant from June (0) through November (0).

The correlation between ENSO and rainfall is therefore statistically significant for only a short time period, particularly on the island of Java. Consequently, the calculation of a correlation coefficient between the SOI and total annual rainfall (as done for northern South America) would be unrevealing. As a result, the analysis in this region consists of identifying the wet and dry years only, using a few weather stations situated in areas where a statistically significant correlation between ENSO and rainfall has previously been identified. These areas are listed in Table 3.6. Since the impacts of ENSO on rainfall are stronger during the dry season, and since drier conditions in El Niño years usually appear in January (0), standardised anomalies of total annual rainfall were calculated from January through December (Ropelewski and Halpert, 1987).

Most El Niño episodes (the 1986/87 and 1993 events were exceptions) produced dryness in central and eastern Indonesia (Figure 3.10). During the latter two events, the national rainfall composite index should be viewed with caution, because rainfall anomalies varied within the islands of Indonesia during the 1986/87 El Niño and rainfall data were available for Jakarta only in 1993. Rainfall was abundant during all Niña (0) years, although anomalies were small during the 1964 event.

In Sarawak, Malaysia, all the major El Niño episodes engendered dryness between 1960 and 1991. Conversely, above average rainfall was recorded during all the La Niña events between 1960 and 1991 (Cheang, 1993). Although above average rainfall was recorded in 1994, all other Niño (0) years in more recent years were associated with less abundant rainfall (Figure 3.11). All La Niña episodes, on the other hand, led to more abundant rainfall.

Table 3.6. Location, elevation and years of record of weather stations in Indonesia (IN), Sarawak (SK), and the Philippines (PH).

Name	Latitude/longitude	Elevation (m)	Years of record
Banjarmasin (IN)	3.4°S/114.8°E	20	1961-1988
Denpasar (IN)	8.8°S/115.2°E	1	1961-1984
Jakarta (IN)	6.2°S/106.8°E	8	1961-1995
Menado (IN)	1.5°S/124.9°E	80	1961-1984
Palembang (IN)	2.9°S/104.7°E	10	1961-1983
Pontianak (IN)	0.2°S/109.4°E	3	1961-1991
Surabaya (IN)	7.2°S/112.7°E	3	1961-1990
Yogyakarta (IN)	7.8°S/110.4°E	107	1961-1984
Bintulu (SK)	3.2°N/113.0°E	9	1961-1980 and 1988-1998
Kuching (SK)	1.5°N/110.3°E	26	1961-1998
Miri (SK)	4.4°N/114.0°E	51	1961-1980 and 1991-1998
Dagupan (PH)	16.1°N/120.3°E	2	1961-1997
Iloilo (PH)	10.7°N/122.6°E	8	1961-1995
Legaspi (PH)	13.1°N/123.7°E	17	1961-1997
Tacloban (PH)	11.3°N/125.0°E	3	1961-1997
Zamboanga (PH)	6.9°N/122.1°E	6	1961-1996

A strong relationship also exists between El Niño and dryness in the Philippines. Drier conditions generally appear in September (0), but the relationship is stronger from October (0) through May (+1). Similarly, the best correlation with La Niña extends from September (0) through May (+1). Between 1957 and 1982, all El Niño events were associated with below average rainfall during this period. Many La Niña years were associated with above normal rainfall, but the relationship is not statistically significant (at the 90% confidence level). Nevertheless, since 1954, all the La Niña events (except for 1964) had above normal rainfall from September (0) through May (+1) (Ropelewski and Halpert, 1987, 1989).

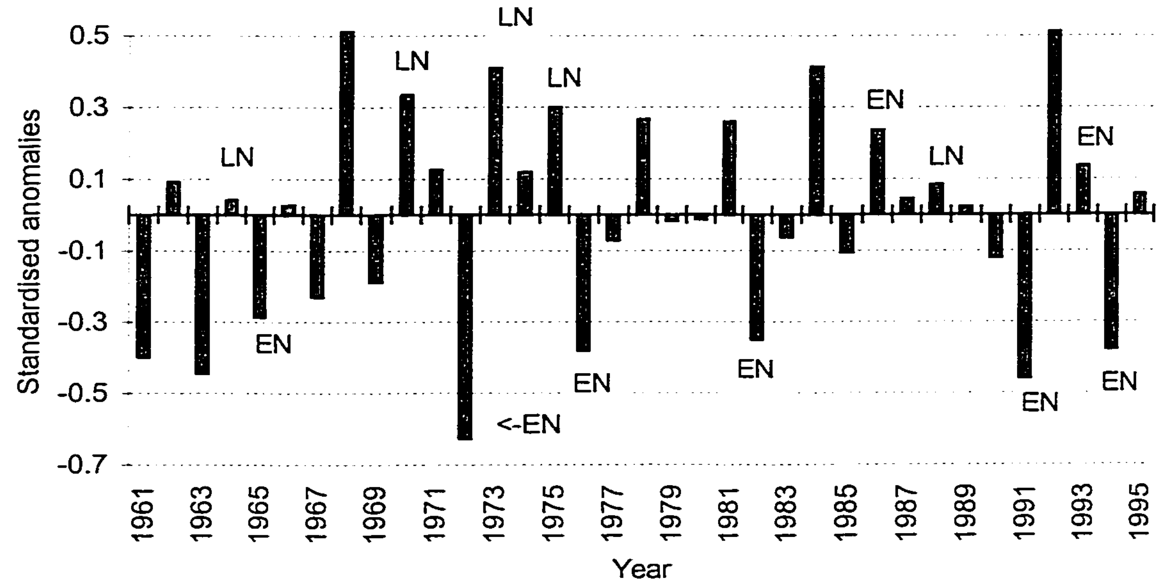

Figure 3.10. Rainfall composite index of Indonesia.

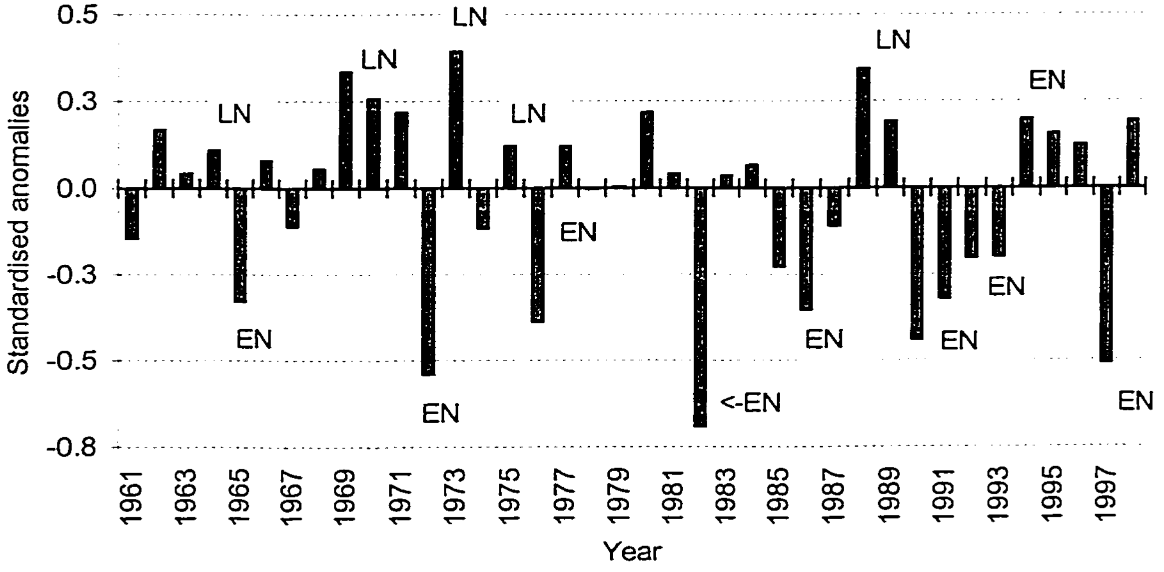

Figure 3.11. Rainfall composite index of Sarawak (Malaysia).

In addition to drier and wetter conditions from October (0) through May (+1) in the Philippines, rainfall anomalies opposite to those during the above period generally occur between June (0) and August (0) (Kiladis and Diaz, 1989;

Ropelewski and Halpert, 1987). Because the opposite climatic signals during different time periods of the same ENSO event would decrease the magnitude of the annual correlation coefficient, a correlation coefficient between rainfall and the SOI would be inappropriate in this country. Therefore, the analysis consists of identifying wet and dry years only using five weather stations scattered across the archipelago (cf., Table 3.6). Standardised rainfall anomalies were calculated from September (month of the appearance of both El Niño and La Niña conditions) through May of the following year. Wetter conditions during La Niña do not persist beyond this month. Most El Niño episodes (except for 1965 and 1993) engendered below average rainfall in the Philippines (Figure 3.12). In 1965, rainfall anomalies were not spatially consistent throughout the archipelago; and in 1993, more abundant rainfall was recorded at all weather stations. Similarly, all Niña (0) years were associated with above average rainfall.

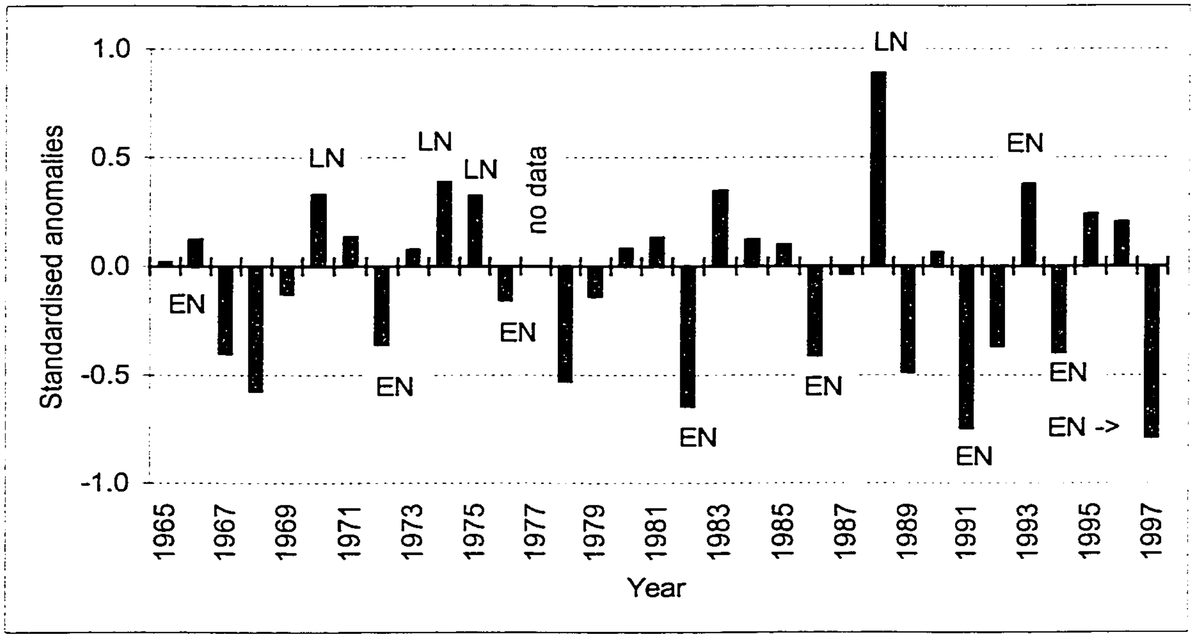

Figure 3.12. Rainfall composite index of the Philippines. (No data available for 1977.)

Kiladis and Diaz (1989) found that in Thailand drier conditions usually occur from June (0) through August (0). In contrast, wetter conditions were found from September (0) through November (0) in some regions. Because of the large spatial extent of the study, specific delimitation of this area is unworkable. No correlation was found from December (0) through February (+1), and dry conditions prevail in central and southern Thailand from March (+1) through May (+1).

Rainfall time series of six Thai weather stations were analysed to delimit the spatial extent of the relationships mentioned above (Table 3.7). The analysis consists of identifying wet and dry seasons during El Niño and La Niña events for the same quarterlies as Kiladis and Diaz (1989). The average standardised anomaly of each quarterly period was calculated at each weather station.

Table 3.7. Location, elevation, and years of record of weather stations in Thailand.

Name	Latitude/longitude	Elevation (m)	Years of record
Bangkok	13.7°N/102.6°E	20	1961-1998
Chiang Mai	18.8°N/100.0°E	314	1961-1998
Nakhon Sawan	15.8°N/100.2°E	35	1961-1998
Prachuap	11.8°N/99.8°E	5	1961-1998
Songkhla	7.2°N/100.6°E	5	1961-1998
Udon Thani	17.4°N/102.8°E	182	1961-1998

El Niño usually generates drier conditions from June (0) through August (0) in northern Thailand (i.e. Chiang Mai, Nakhon Sawan, and Udon Thani), but the relationship is less clear during the last two El Niños (Table 3.8a). Similarly, wetter conditions were observed during all La Niña events (except for 1964) in the same region. In Bangkok, and particularly in southern Thailand (i.e., Prachuap and Songkhla), the relationship is not temporally consistent. Some El Niño events, for instance, were associated with more abundant rainfall, while others engendered below normal rainfall. During the September (0) through November (0) quarterly, wetter conditions occurred during three warm events in Bangkok, and one warm episode generated drier conditions. The relationship is neither temporally nor spatially consistent throughout the country for either El Niño or La Niña events (Table 3.8b).

Table 3.8. Identification of dry and wet ENSO episodes for the June (0) through August (0) (a) and September (0) through November (0) (b) quarterlies. D and W refer to dry and wet ENSO events, respectively (the absence of a letter signifies normal conditions). Anomalies greater than one half a standard deviation are considered statistically different from normal conditions.

a) June (0) through August (0)

		[-----------Northern cities	---------][		-----------Southern cities	--------]	
		Chiang Mai	Nakhon Sawan	Udon Thani	Bangkok	Prachuap	Songkhla
Niño (0)	1965	D			D		W
	1972	D		D	D	W	
	1976	D					
	1982	D		D		W	
	1986	D				D	D
	1991		D				W
	1993	D	D	D	W	D	D
	1994	W				W	
	1997	W	D	W	D	W	W
Niña (0)	1964			D		D	
	1970	W	W	W	W		W
	1973	W	W		D	W	
	1975	W					
	1988		W				W

b) September (0) through November (0)

		[---------Northern cities	----------][		----------Southern cities	---------]	
		Chiang Mai	Nakhon Sawan	Udon Thani	Bangkok	Prachuap	Songkhla
Niño (0)	1965				W		
	1972				W		W
	1976					W	
	1982					D	
	1986		D		W		
	1991	D	D				
	1993	D		D	D	D	W
	1994		D	W		D	D
	1997			D		D	
Niña (0)	1964		W		D		D
	1970	D		W			
	1973		D			W	
	1975			W			
	1988		W				

Drier conditions generally prevail in northern Thailand from June (0) through August (0). In other regions and for other time periods, the relationships are neither temporally nor spatially consistent throughout the country. In summary, we illustrated in this chapter that El Niño generates more abundant rainfall in the coastal regions of

Ecuador and Peru, while drier and wetter conditions generally occur during El Niño and La Niña events respectively in almost all of northern South America and Southeast Asia. The magnitudes of those anomalies are summarised in Table 3.9. In addition to rainfall anomalies, the following section will demonstrate that all the regions studied experience temperature anomalies related to ENSO.

Table 3.9. Percentage change in median precipitation during El Niño and La Niña events in northeastern South America, the Philippines, and Indonesia-Sarawak (based on Ropelewski and Halpert, 1996, p. 1045).

Region	Period	Median precipitation (mm)	El Niño (decrease)	La Niña (increase)
N.A. S.America[1]	Jul (0)-Mar (+1)	1100	15%	8%
the Philippines	Oct (0)-May (+1)	1705	20%	16%
Indonesia-Sarawak	Jul (0)-Nov (0)	760	18%	20%

[1] Northeastern South America refers to eastern Venezuela, Suriname, the Guianas, and north equatorial Brazil

3.5 Temperature

In general, El Niño generates warmer temperatures throughout the tropics, and La Niña produces cooler temperatures. In this section, the impact of ENSO on temperature is analysed for all El Niño and La Niña events that occurred between 1956 and 1998 in the three study regions. The number of weather stations selected is small because ENSO-related temperature anomalies have a tendency to be of broad spatial extent, and previous research has already delimited the spatial extent of those anomalies (Kiladis and Diaz, 1989). Temperature data were obtained from airports to minimise the urban heat island effect (which is likely to exist in cities of developing countries, because of rapid urbanisation).

Because of the proximity of the Peruvian coastal stations to the Pacific Ocean, all weather stations along the Peruvian coast have a strong and immediate correlation with ENSO (Kiladis and Diaz, 1989). During all El Niño episodes since 1956, air temperatures rose as soon as the SSTs became positive in the eastern Pacific Ocean. Likewise, cooler temperatures were recorded during all La Niña events. A similar correlation is observed along the Ecuadorian coast, though data were not available after 1991.

In the Andes (e.g. Quito), where El Niño generates warmer temperatures and La Niña cooler temperatures, the relationship with ENSO is also strong, with the SOI leading the temperature anomalies by one month (data in this region were limited to the 1951-1980 period). Given the proximity of the region to the Pacific Ocean and the fact that all ENSO events prior to 1981 engendered temperature anomalies in the region, we will assume that the relationship was also temporally consistent in more recent years. East of the Andes, the temperature record is scarce and the presence of inhomogeneities in the time series of both Iquitos and Pucallpa (in Peru's Amazon) impede adequate analysis (a constant increase in temperature until the early 1960s and a step-like decrease in mean temperature in 1973). The presence of the Andes isolates this region from the direct impact of the Pacific Ocean; analysis of the temperature record of Brazil and northern South America will reveal the impact of ENSO east of this orographic barrier.

Since the temperature anomalies during ENSO events are spatially coherent throughout northern South America, i.e., warmer temperatures during El Niño and cooler temperatures during La Niña (Kiladis and Diaz, 1989), analysis for this region consisted of calculating a regional temperature composite index. This index is comprised of 11 weather stations that all have a strong and statistically significant correlation with the SOI (Table 3.10). The SOI leads the temperature anomalies by approximately three months (r = -0.75). As during the development of an El Niño event, the SOI generally reverses sign in March (0) and warmer conditions generally appear in June (0) in this region (Kiladis and Diaz, 1989).

All La Niña events engendered cooler temperatures, while all El Niño episodes (except for 1993) were associated with warmer temperatures, often peaking by the end of Niño (0) (Figure 3.13). The magnitude of the anomalies was minimal, however, in 1976 and 1977. In fact, during the 1976/77 episode, most weather stations in the region reported normal conditions. The following section examines the consistency of ENSO-related temperature anomalies in Southeast Asia.

Table 3.10. List of weather station used in the calculation of the temperature composite index of northern South America and their maximum correlation with the SOI. All correlation coefficients peak when the SOI precedes the temperature anomalies by 2 to 4 months. (Location and elevation of all selected weather stations are reported in previous sections.)

Name (Country)	Years of record	Correlation
Caracas (Venezuela)	1956-1989	-0.63*
Cartagena (Colombia)	1956-1991	-0.63*
Cayenne (French Guiana)	1956-1991 and 1995-1998	-0.63*
Cúcuta (Colombia)	1971-1998	-0.79*
Georgetown (Guyana)	1956-1998	-0.63*
Manaus (Brazil)	1956-1991	-0.58*
Maracaibo (Venezuela)	1956-1986 and 1994-1998	-0.65*
Neiva (Colombia)	1964-1993	-0.72*
Nickerie (Suriname)	1956-1980	-0.73*
São Gabriel (Brazil)	1956-1984	-0.72*
Sipaliwini (Suriname)	1961-1980	-0.87*

*Statistically significant at the 95% confidence level

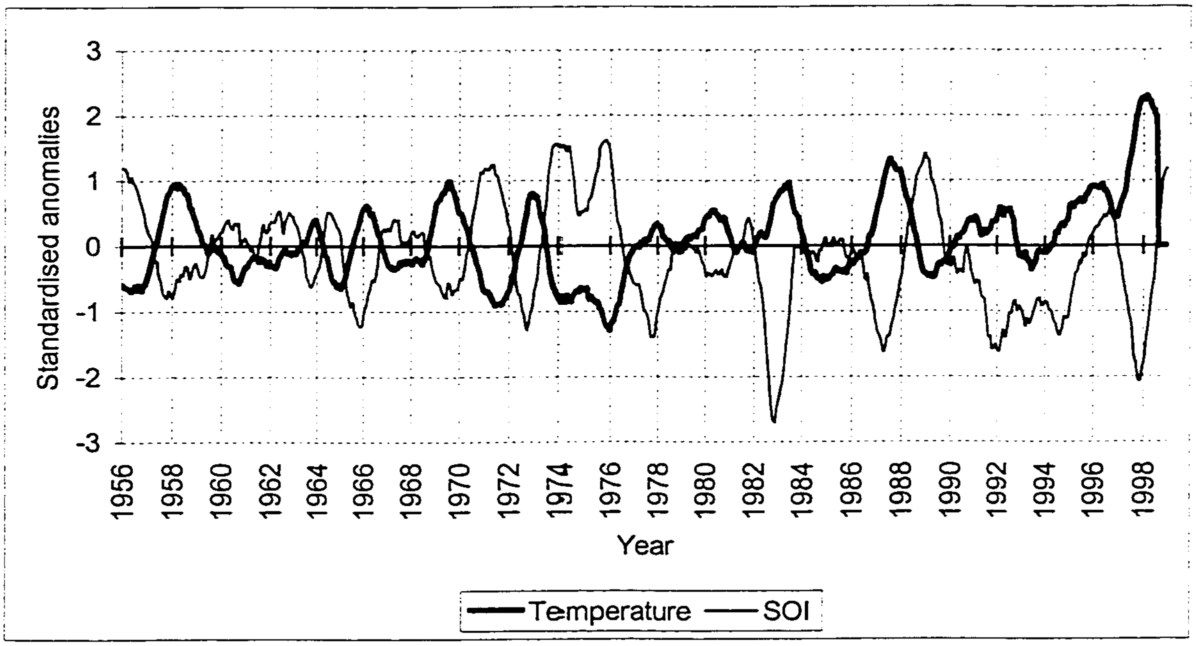

Figure 3.13. Time evolution of the SOI and temperature anomalies in northern South America.

In Southeast Asia, temperatures in El Niño years are warmer than average and spatially consistent throughout the region with the exception of the easternmost part of Indonesia (Kiladis and Diaz, 1989; NOAA, 2000). Analysis of six weather stations shows that at all stations, the correlation between temperature anomalies and the SOI is positive and statistically significant (Table 3.11). Moreover, temperature anomalies generally become positive six months following the onset of El Niño.

Warmer than average temperatures generally occur during El Niño events in Indonesia (Harger, 1995). In fact, all El Niño episodes from 1971 through 1989 produced warmer temperatures at Surabaya (Figure 3.14). Temperatures were also warmer than normal during the 1994/95 and 1997/98 El Niños on the island of Borneo, but not in 1993 (as observed at Kuching in Sarawak). Moreover, the temperature record at Kuching and Surabaya demonstrates that all La Niña events (except for the 1988/89 episode) generated cooler temperatures in the region (cf., Figure 3.14). In comparison to previous years, temperature was decreasing during the 1988/89 cold event, but, because of the increasing trend in temperature in the time series, temperatures were not significantly below the long-term mean during this event.

Table 3.11. List of weather stations analysed for evidence of ENSO-related temperature anomalies in Southeast Asia, and their correlation with the SOI when it precedes the temperature anomalies by six months. (Location and elevation of all selected weather stations was reported in previous sections.)

Name (Country)	Years of record	Correlation
Bangkok (Thailand)	1956-1990	-0.52*
Dagupan (Philippines)	1956-1998	-0.47*
Kuching (Sarawak)	1956-1998	-0.55*
Legaspi (Philippines)	1956-1998	-0.53*
Surabaya[1] (Indonesia)	1971-1990	-0.64*
Udon Thani (Thailand)	1956-1998	-0.60*

[1] Latitude/longitude: 7.2°S/112.7°E; elevation: 3 m
*Statistically significant at the 95% confidence level

An increasing trend is present in the temperature time series of most weather stations. At Surabaya, for example, warming has been particularly pronounced in recent decades, as mean monthly temperature has increased by approximately 1.4 standard deviations from 1971 through 1989 (which roughly corresponds to 0.7°C) (cf., Figure 3.14). This trend is probably the result of more intense and frequent El Niños in the last two decades as well as global warming. Temperature data were obtained from airport weather stations to minimise the impact of rapid urbanisation.

Harger (1995) also reported an increasing trend in mean monthly temperatures of 1.64°C from 1866 to 1993 at Jakarta and Semarang (Indonesia).

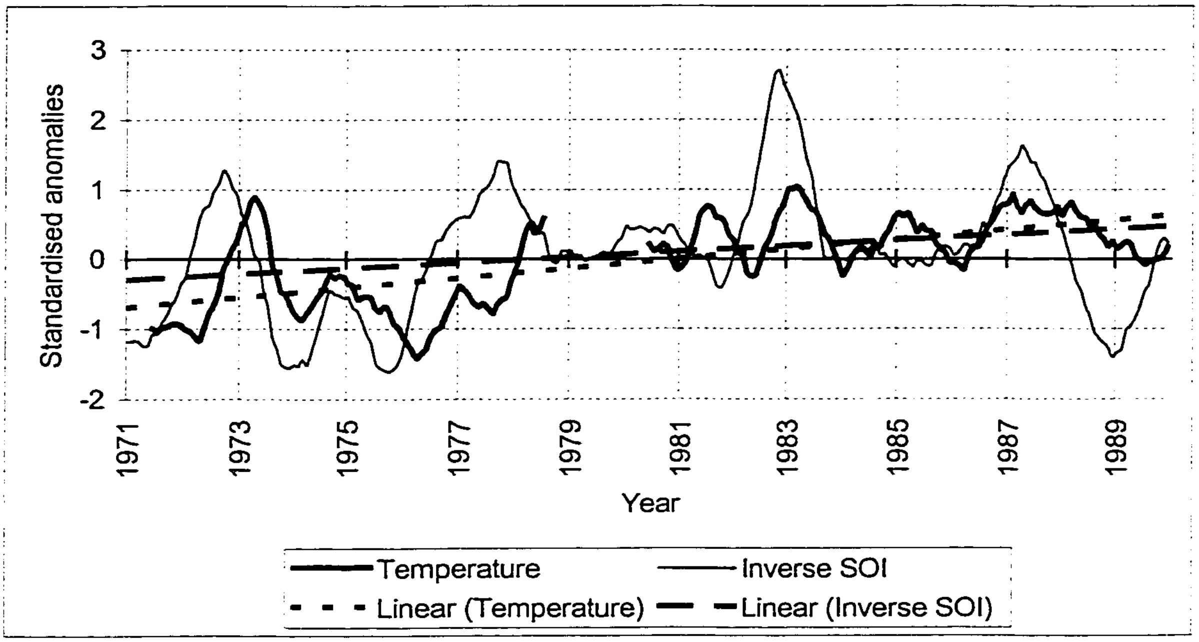

Figure 3.14. Time evolution of the SOI and temperature anomalies at Surabaya (Indonesia). Also illustrated are the linear trend-lines of the SOI and temperature anomalies.

In the Philippines, the correlation between ENSO years and temperature anomalies is not as temporally consistent as in other countries. Some El Niño events were associated with warmer temperatures, and the opposite for La Niña episodes, but there were a few exceptions to the general pattern.

In Thailand, the relationship between ENSO and temperature anomalies is temporally coherent, as all El Niño events, including the 1976/77 episode, engendered warmer temperatures. Likewise, all cold episodes were associated with cooler temperature (except for the 1988/89 event).

Temperature anomalies during ENSO events occurred throughout most of the tropics, with a spatially coherent signal from December (0) through May (+1), corresponding to the mature and decay stages of El Niño. The relationship is especially temporally and spatially consistent in South America. The relationship is also strong in Southeast Asia, but less temporally consistent than in South America.

Annual mean temperature is on average only half a degree Celsius warmer or cooler during ENSO events, because of the small variability of tropical temperature. At Manaus, for instance, the maximum increase (decrease) in mean temperature during El Niño (La Niña) episodes is 0.6°C (-0.4°C) during the December (0)-February (+1) season (Kiladis and Diaz, 1989). Also of particular interest is the increasing trend in mean monthly temperatures present in most time series, as demonstrated for Surabaya, suggesting global warming.

3.6. Summary of temperature and hydrological anomalies during ENSO events

Summarised below are the climatic anomalies associated with El Niño in northern and western South America and Southeast Asia.

- Below average rainfall and warmer temperatures in French Guiana, Guyana, Suriname, southern Venezuela and most of Colombia (the region east of the Andes is an exception).
- Warmer temperatures and torrential rains in northern Peru and southern Ecuador
- Below average rainfall and warmer temperatures in Southeast Asia

Opposite climatic perturbations are generally observed during La Niña in northern South America and Southeast Asia. In the following two chapters, these climatic anomalies are correlated with dengue/DHF and malaria epidemics.

Chapter 4: ENSO and Dengue/DHF

Following a short review of the history of dengue and DHF, this chapter presents the results of an analysis correlating dengue/DHF epidemics with ENSO episodes in various South American and Southeast Asian countries. Because of the geographical spread of DHF in Southeast Asia and its recent emergence in South America, the possibility of including El Niño forecasts would be very useful for improving the current control of this disease.

4.1 History of Dengue/DHF in South America and Southeast Asia

In 1947 the PAHO launched a campaign to eradicate the mosquito vector carrying dengue fever, *Ae. aegypti* (Gubler and Clark, 1995; Reiter, 1996), because it also carries the potentially fatal disease yellow fever. Accordingly, dengue was successfully eradicated from most countries (Gómez-Dantés, 1991; Gubler and Clark, 1995) with the exception of Venezuela, which is the only country in the Americas that reported cases of dengue to the WHO during the eradication period. The eradication, however, did not last for long.

The end of the eradication programme resulted in re-infestation of the South American by *Ae. aegypti* slowly began in the 1960 (Gratz and Knudsen, 1996). By 1971 the entire Caribbean coast of Colombia was re-infested (WHO, 1976) and there is evidence that a dengue epidemic occurred in late 1971 and early 1972 in that region (Groot *et al.*, 1979). However, no dengue cases were officially reported prior to 1980 (Pinheiro and Corber, 1997).

In Suriname the first case of dengue was identified in 1978 but the incidence of the disease was very low in comparison to Colombia (Gratz and Knudsen, 1995). Nevertheless, outbreaks have occurred about every five years, more or less following the cyclical pattern of ENSO.

French Guiana was re-infested by *Ae. aegypti* in 1963 (Reynes, 1996). This territory documented its first confirmed case of dengue in 1965, and hence, has the longest dengue time series in South America (Fouque *et al.*, 1995). As opposed to the other South American countries where only those dengue cases confirmed through blood examination are counted in the annual total, in French Guiana, the incidence of dengue represents the total number of suspected dengue cases.

In Guyana, the first case of dengue was documented in 1978. However, the disease was sporadic and many years have missing values. Moreover, no information could be obtained about the situation of the disease after 1992.

Brazil was re-infested *by Ae. aegypti* in 1976, but no dengue cases were reported prior to 1982. Moreover, Brazil was free from the disease from 1983 through 1985, and the disease reappeared between 1986 and 1987. In two states of the Nordeste region, dengue cases have consistently been reported since 1986 (Silveira, 1998), but they are located outside of the study area of this thesis (Silveira, 1998). Similarly, Ecuador and Peru reported their first cases of dengue in 1988 (MMWR, 1989) and 1990, respectively (MMWR, 1991).

Since El Niño events usually occur every two to seven years (Trenberth and Hoar, 1996), only countries with disease time series of at least 15 years are analysed in this thesis in order to study the influence of at least three major El Niño events on disease epidemics. Thus, Brazil, Guyana, Ecuador and Peru are not included in the present study. Colombia, French Guiana, Suriname and Venezuela are therefore the only countries in South America that have dengue time series of substantial length for further analysis.

As the eradication programme was limited to the Americas, Southeast Asian countries have longer dengue time series. Moreover, DHF is a common disease in most countries of the region. Following its first identification in 1953 in the Philippines, DHF spread to neighbouring countries and was first noticed in Thailand in 1958 and 10 years later in Indonesia. Today, DHF is endemic in most Southeast Asian countries and the national public health services limit their dengue reporting system to this form of the disease, as it has a high incidence and is the only fatal form of dengue. In Sarawak, the first case of dengue was reported in 1973, but its incidence was sporadic prior to 1981 (Chang *et al.*, 1981). Sarawak is therefore the only region in

Southeast Asia where the time series is sufficiently long for the analysis of the relationship between the classical form of dengue and ENSO.

4.2 Country-Specific Temporal Correlations

An outbreak is defined as a rapid increase in the incidence of a disease. The words "outbreak" and "epidemic" are used interchangeably in the health literature and thus refer to the same phenomenon. Most of the analysis in this thesis is done at the inter-annual time scale and an outbreak will therefore be defined as an anomalous increase in disease incidence from one year to the next. In this thesis, we consider an increase in dengue transmission as an outbreak when it is greater than one half a standard deviation above the mean (the mean value refers to the average change in the number of dengue cases reported between years over the time series). This method is commonly used to identify anomalies that are significantly higher than the mean (e.g., Rossel *et al.*, 1999).

To better visualise changes in disease incidence between years, the rate of change was calculated for each time series. The rate of change corresponds to the first order derivative with respect to time of annual dengue incidence. In other words, it signifies the change in the number of dengue cases standardised to the population reported from one year to the next. Depiction of the rate of change facilitates the identification of outbreaks because (1) it gives a mean close to zero, (2) it substantially reduces the increasing trend in disease incidence that is present in most time series, and (3) it clearly illustrates the variability in dengue transmission between years. (Reasons for the increasing trends in dengue and DHF incidence are discussed in Chapter 6.)

The time series of dengue in Colombia extends from 1981 through 1998 (Figure 4.1). All El Niño events (except for 1993) were associated with a peak in dengue transmission in Niño (+1) years. The 1983 and 1987 peaks, however, are slightly below the outbreak threshold value. All those peaks in dengue incidence occurred during years with warmer temperatures, less abundant rainfall, and lowered river height. Though the number of dengue cases increased in almost all Colombian departments, the majority of cases originate from regions where ENSO significantly affects rainfall variations, as it is where most of the population lives (based on regional data from 1996 through 1998). In contrast to the other El Niño episodes, river height was increasing during the 1993 El Niño, possibly explaining the lack of outbreak during this year (cf., Figure 3.5).

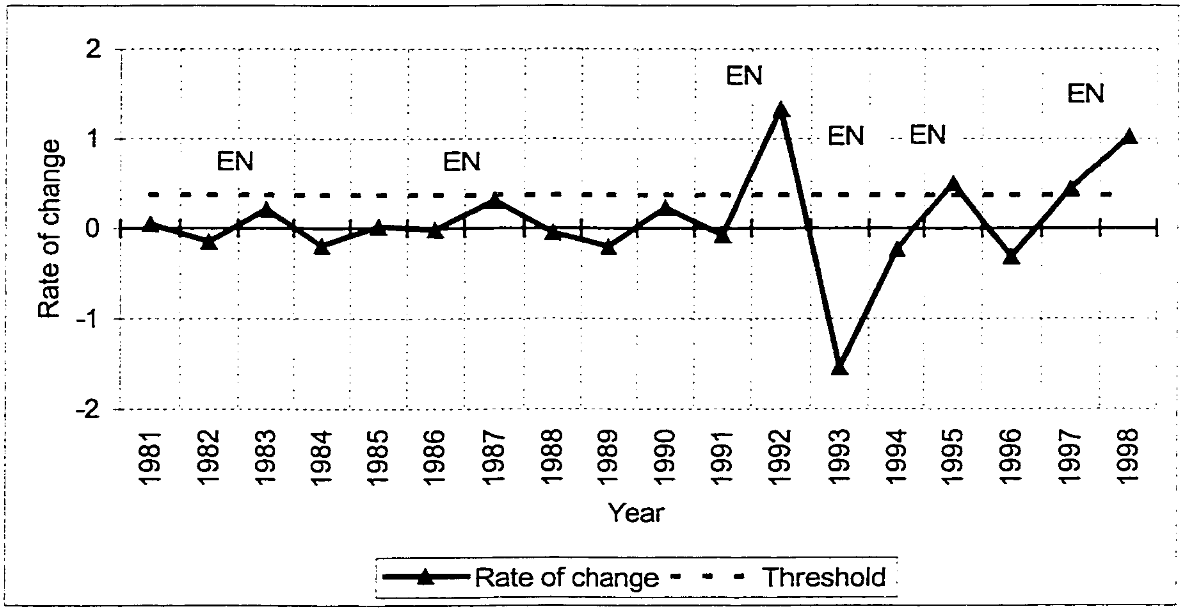

Figure 4.1. Dengue in Colombia.

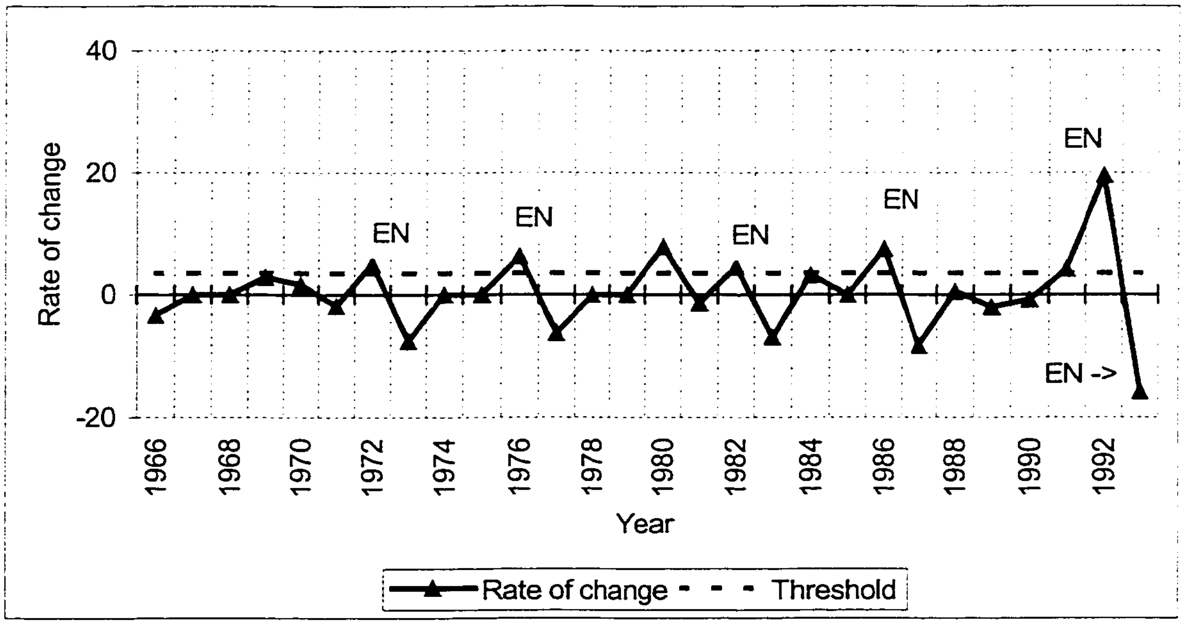

Figure 4.2. Dengue in French Guiana.

In French Guiana, five of the six El Niños during the 1965-1993 period were associated with an epidemics of dengue (the 1993 El Niño is the only exception) (Figure 4.2). In contrast to those in Colombia, dengue outbreaks in French Guiana generally occur in Niño (0) years. During the 1991/92 warm event, however, an epidemic started in July 1991, a Niño (0) year, and continued to peak in the following Niño (+1) year. As in Colombia, all those outbreaks were associated with less abundant rainfall and warmer temperatures (cf., Figures 3.1 and 3.13).

In Suriname, the analysis is limited to the 1978 through 1992 period, because dengue data were obtained for only two years after 1992. The number of dengue cases reported during those two years was very large in comparison to the rest of the time series, showing the increasing importance of dengue in the country. Dengue outbreaks occurred in 1986 and 1991, which are Niño (0) years (Figure 4.3). As in neighbouring French Guiana, these two epidemics were associated with warmer temperatures and less abundant rainfall (cf., Figure 3.2).

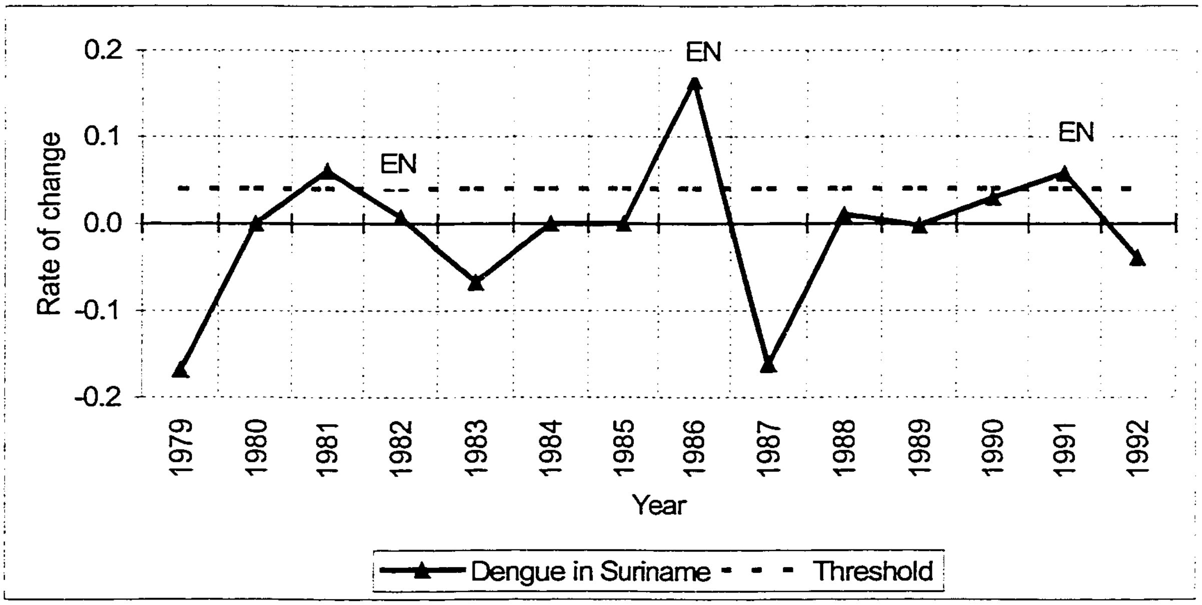

Figure 4.3. Dengue in Suriname.

Another outbreak affected Suriname in 1981. To avoid deterioration of the situation, emergency control measures soon followed (Hudson, 1986). Accordingly, the number of houses per 1000 persons that were sprayed annually from 1956 through

1991 (Figure 4.4), clearly depicts the intensification of insecticide sprayings during the 1982/83 El Niño, probably explaining further deterioration of the epidemic during the 1982/83 El Niño. After 1992, Suriname experienced dengue epidemics in 1993 and 1994, but the number of cases during those two years was not reported (PAHO, 1998b). These two years were Niño (0) and were also associated with below average rainfall (cf., Figure 3.2).

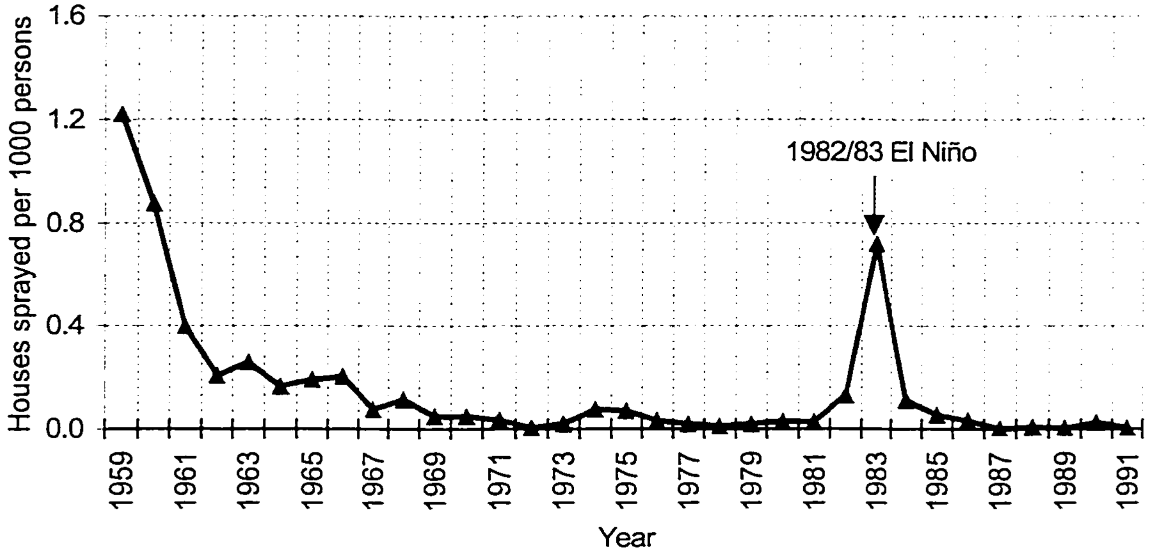

Figure 4.4. House insecticide sprayings in Suriname.

Dengue cases were reported during the 1942 to 1963 period in Venezuela (see Llopis *et al.*, 1979), but the disease was infrequent and this time interval was therefore discarded from the present study. After a period of higher incidence from 1964 to 1970 (Figure 4.5a), dengue was nearly eradicated from 1970 through 1988, with the exception of 1978, which was the year of a large epidemic with more than 100,000 classical dengue cases. Gratz and Knudsen (1996) attributed the 1978 epidemic to the insufficient control of *Aedes* population in the centre of the country. After nearly two decades of low incidence, Venezuelan health officials reported a dengue epidemic from December 1989 through April 1990. The first cases of DHF were identified during this outbreak, which affected 22 of the 23 states and territories of Venezuela (Gratz and Knudsen, 1996).

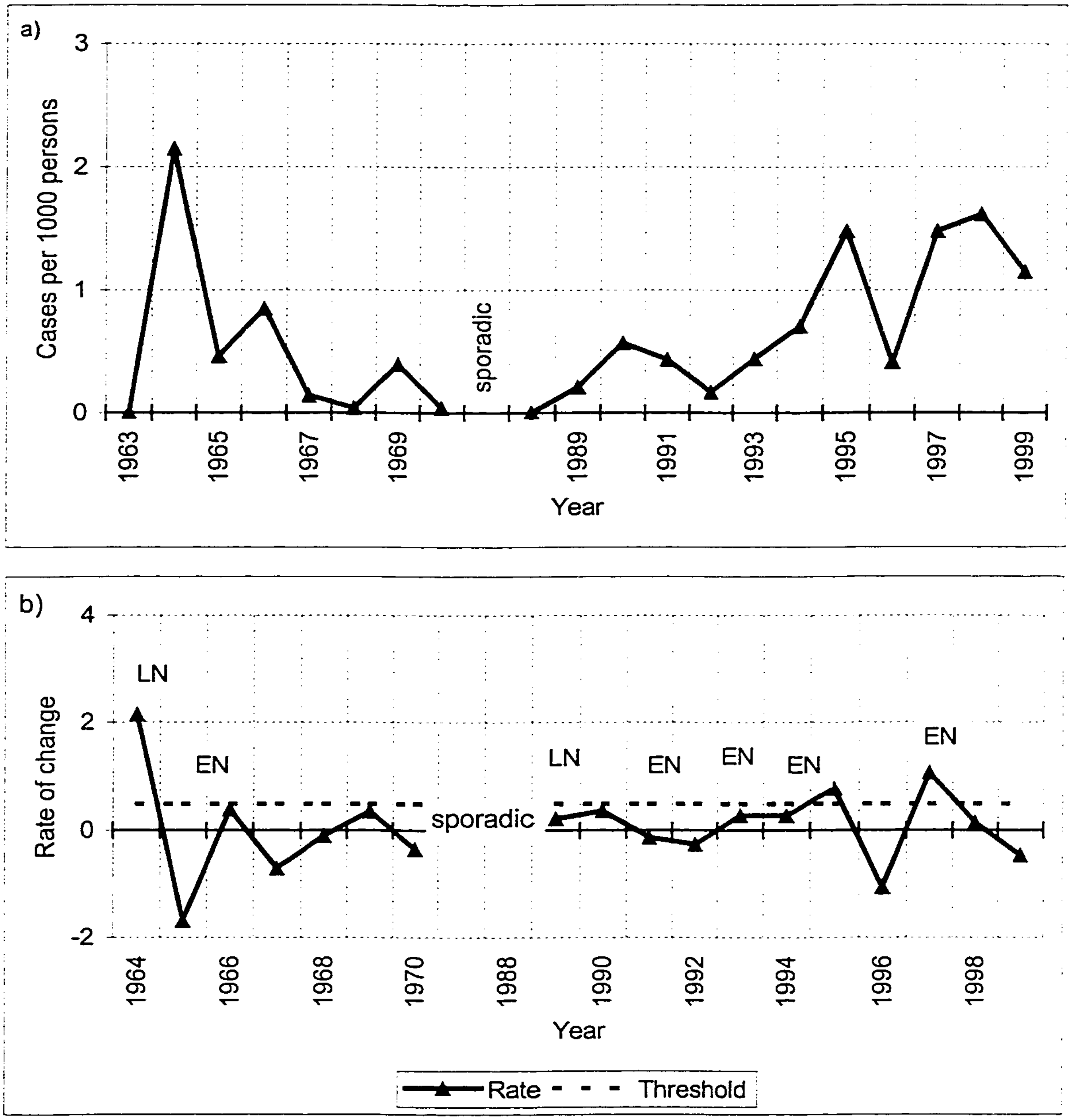

Figure 4.5. Dengue and DHF in Venezuela. Number of cases per 1000 persons (a) and rate of change (b). The disease was sporadic from 1970 through 1988.

Interestingly, dengue reappeared in Venezuela after a period of near eradication during the 1964 and 1988/89 La Niña episodes (cf., Figure 4.5a), but only in 1964 was an epidemic detected (Figure 4.5b). As in Colombia, the 1994/95 and

1997/98 El Niños were also associated with dengue epidemics. The lack of an uninterrupted time series of considerable length does not allow adequate conclusions to be made for Venezuela, especially because most years in the second part of the time series were El Niño years.

Unlike in South America where DHF is a recent disease, DHF has occurred in Southeast Asia since the 1950s. Because of the lower incidence of DHF, the number of DHF cases is standardised to 100,000 persons (as opposed to 1000 persons as was the case for dengue). Most El Niño events, with the exception of the 1976/77, 1991/92 and 1993 events, were associated with DHF epidemics in Indonesia (Figure 4.6). Furthermore, the *Sub Direktorat Arbovirosis* in Jakarta (an agency reporting DHF cases in Indonesia) identified 1973, 1983, 1988 and 1998 as the most important DHF epidemic years (R. Kusriastuti, *personal communication*). All these years, in addition to 1995, are Niño (+1) years (with the exception of 1988).

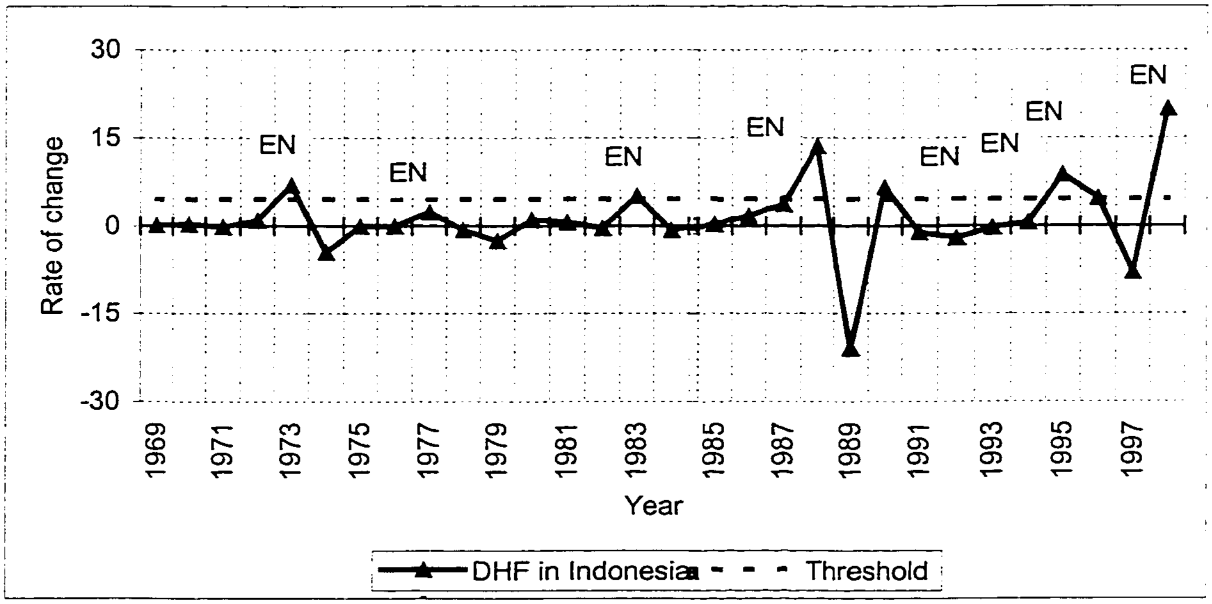

Figure 4.6. DHF in Indonesia.

With the exception of 1988, rainfall was below average in Indonesia during all years that preceded the epidemics of DHF (cf., Figure 3.10). From 1991 through 1998, only 5.3% of the total number of DHF cases reported in Indonesia originated from the western provinces situated on the island of Sumatra (i.e., Di Aceh, Sumatra

Utara, Sumatra Barat, Riau, and Jambi), where the relationship between ENSO and rainfall variations is not statistically significant.

In contrast to the other El Niños, the 1986/87 warm event produced two peaks in SSTs. The first peak occurred at the average time as most El Niños (December to January). However, SSTs also peaked in July and August of 1987 (Wang, 1995). As during most Niño (0) years, rainfall was below average in 1986 on the island of Borneo (cf., Figure 3.11), but excessive rainfall fell at the same time at Surabaya (on the island of Java), resulting in more abundant precipitation at the national scale in 1986. In 1987, a drought was reported at Jakarta (located at the other extreme of Java) as well as in southern Borneo. Hence, depending on the geographical origin of the 1988 epidemic, the epidemic could also have been preceded by a year with below average rainfall (regional epidemiological data are only available since 1991, however).

Data for the Philippines were obtained from three sources: A publication by Gratz and Knudsen (1996) (which is distributed by the WHO), the Regional Office of the WHO for the Western Pacific, and Pinheiro and Corber (1997). Most sources publish the number of DHF cases reported annually in the country. Data from the WHO's regional office, however, also include dengue cases. Pinheiro and Corber (1997) display similar data, although some values are missing. Contrary to the WHO publication, they mention that all dengue cases are of the haemorrhagic form (Table 4.1). This disagreement between the data published by public health scientists and those reported by the WHO was previously noted in Gratz and Knudsen (1996).

Analysis of the correlation between ENSO and dengue is ill advised in the Philippines, as there is no agreement in the annual number of dengue cases between the three sources of data. The Philippines will therefore be discarded from the dengue analysis, because the Philippine's department of health could not explain this disagreement. Nevertheless, they kindly provided the number of dengue admissions to sentinel hospitals from 1990 through 1998, but the time series (i.e., nine years) is too short for adequate analysis. (Sentinel hospitals, which can be either public or private, report cases of all the notifiable diseases included in the surveillance network of the Philippines (N. Dominguez, *personal communication*)).

Table 4.1. Annual dengue and DHF cases in the Philippines according to various sources.

Year	Gratz and Knudsen (1996)	WHO-Regional Office	Pinheiro and Corber (1997)
1954-1978	26120		
1980	627	968	
1981	324	123	123
1982	816	305	305
1983	1684	1684	1684
1984	2514	2545	2545
1985	2096	1520	
1986	1623	839	839
1987	1696	857	859
1988	2321	2922	2922
1989	2240	305	305
1990	1042	588	588
1991	1865	11317	
1992		918	
1993		21146	5715
1994		5603	5603
1995		5166	7413
1996		13614	13613
1997		12811	
1998		*31829	

* As of December 22

Annual cases of DHF in Thailand were also obtained from different sources: Gratz and Knudsen (1996), the WHO Documentation Centre in Thailand, Pinheiro and Corber (1997), and the Regional Office of the WHO for Southeast Asia. As opposed to the Philippines, the data from all sources coincide well with only minimal differences (the average of all sources was taken for the calculation of the rate of change). The 1986/87 El Niño was associated with the largest epidemic that ever occurred in this country (Figure 4.7). Nevertheless, no clear pattern is observed between DHF transmission and either phase of the SO, as only 3 out of 8 El Niño episodes ($p = 0.38$) and 1 out of 5 La Niña events ($p = 0.20$) were associated with DHF epidemics.

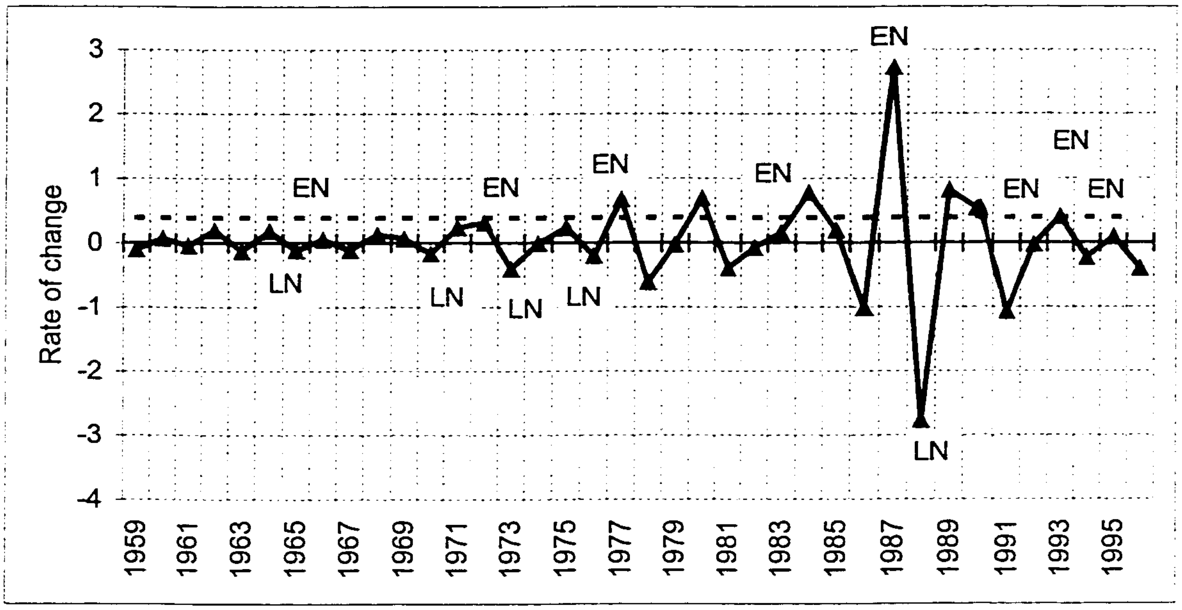

Figure 4.7. DHF in Thailand.

As previously mentioned the State of Sarawak is the only region in Southeast Asia where the relationship between ENSO and classical dengue was analysed. The time series, however, is short and includes only one La Niña event of moderate to strong intensity. The incidence of dengue closely follows that of DHF, except that the 1989 peak in DHF transmission preceded by one year the peak in dengue (Figure 4.8a).

The 1982/83 and 1986/87 El Niños coincided with DHF epidemics in Sarawak (Figure 4.8b). An outbreak of dengue also occurred in 1983 as well as during the 1997/98 El Niño, but not during the 1986/87 event (Figure 4.8c). Nevertheless, only 2 out of 6 El Niño events coincided with a dengue epidemic, and the same probability is observed for the occurrence of a DHF epidemic. In addition, a large epidemic of dengue and DHF occurred during the 1988/89 La Niña, which is the only cold event in the time series.

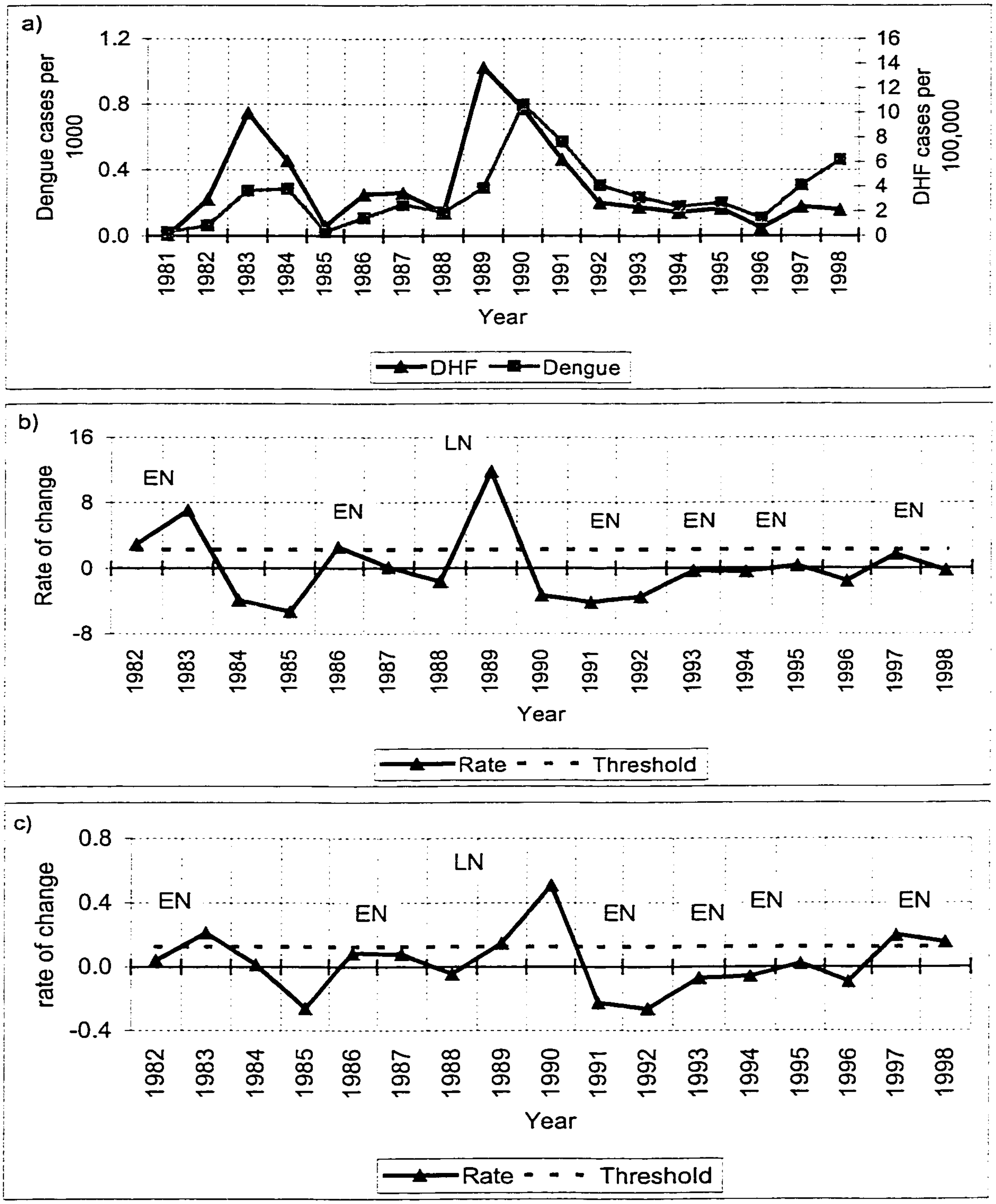

Figure 4.8. Dengue and DHF in Sarawak (Malaysia). Number of cases per 1000 persons (a), the rate of change of DHF (b), and the rate of change of dengue fever (c). (The magnitude of the rate of change of DHF is higher than the one of dengue, because DHF cases were standardised to 100,000 persons as opposed to 1000 for dengue.)

Contingency tables with Fisher's exact test were used to test for the statistical significance of the observed relationships. The four statistical hypotheses tested were that outbreaks of dengue and DHF are not more likely to occur during (a) Niño (0) than in other years, (b) Niño (+1) versus other years, (c) La Niña years versus other years.

A problem arises with the 1993 El Niño, since it is the only warm event that did not extend over two years. This episode could be considered an extension of the 1991/92 El Niño, because SSTs as well as the SOI and MEI did not reverse sign from 1990 through 1995. Nevertheless, three peaks are clearly evident in the time series of most ENSO indices, indicating the presence of three different warm events (cf., Figure 2.2). Most El Niño events are associated with increasing SSTs and strengthening SOI in Niño (0) and a weakening of El Niño conditions in Niño (+1). In 1993, the development and decay of El Niño occurred within the same year. Therefore, 1993 is an exception to the classification used in this thesis and is considered both a Niño (0) and Niño (+1) year in the statistical analyses.

Only in French Guiana and Indonesia is the relationship between El Niño and dengue transmission statistically significant at the 95% level. In Colombia and Suriname, it is also statistically significant, but at the 90% confidence level. Moreover, the risk of a dengue epidemic is high in Niño (0) years in French Guiana and Suriname versus Niño (+1) years in Colombia and Indonesia (Table 4.2).

In Colombia, the 1983 and 1987 peaks in dengue cases are slightly lower than the outbreak threshold value, explaining the statistical significance of the relationship at the 90% rather than the 95% confidence level. The high variability of the rate of change in the 1990s in comparison with the previous decade increases the standard deviation, resulting in peaks below one half the standard deviation in the 1980s. Calculation of two mean values and two standard deviations (i.e., prior to and after 1991) results in the consideration of the 1983 and 1987 peaks as outbreaks. However, due to the resulting high standard deviation in the 1990s, the 1994/95 peak becomes below the outbreak threshold value. The results are not influenced by these changes, however, so we conclude that the correlation between El Niño and dengue transmission is robust in Colombia.

Table 4.2. Results of Fisher's exact test for dengue fever[†]

Country	Niño (0)	Niño (+1)	La Niña years
Colombia	0.00	*0.92	—
French Guiana	*0.99	0.00	0.00
Indonesia	—	**0.97	0.78
Sarawak (dengue)	0.40	0.00	0.69
Sarawak (DHF)	0.42	0.00	0.75
Suriname	*0.91	—	—
Thailand	0.00	0.38	0.00
Venezuela	0.00	0.00	0.56

[†] Results refer to one minus the p-value

** Statistically significant at the 95% level

* Statistically significant at the 90% level

(—) Not calculated since no epidemic occurred during this period.

[1] Computations started in 1967, because of the absence of year Niño (0) of the 1965/66 episode.

In Colombia and Suriname, where the relationship with El Niño is statistically significant, La Niña has no effect on the occurrence of dengue epidemics, as demonstrated by the lack of outbreak during all La Niña events. In French Guiana, only one of the four La Niña episodes were associated with a dengue epidemic, resulting in a probability of an epidemic during a La Niña event of only 0.25, which is not statistically significant. In Indonesia, the result of the statistical test is higher, i.e., 0.78, because of the 1973 and 1988 outbreaks (cf., Table 4.2). El Niño precedes the majority of La Niña events; the 1975/76 cold event is the only exception. Hence, Niño (+1) is occasionally the first year of a La Niña event (i.e., Niña (0)), as was the case in 1973. The 1988 outbreak is unlikely to have been caused by La Niña, because dengue cases started to increase during Niño (0). We therefore conclude that La Niña does not significantly affect the incidence of dengue and DHF in any of the countries studied.

In summary, El Niño and its associated warmer and drier climatic conditions generally precede dengue/DHF epidemics in Colombia, French Guiana, Indonesia, and Suriname. Physical explanations for these relationships are suggested in the discussion. In the following chapter, malaria epidemics are associated with ENSO events in order to determine if relationships similar to dengue and DHF are observed for this vector-borne disease.

Chapter 5: ENSO and Malaria

This chapter presents the results of an analysis correlating ENSO with malaria epidemics. National analyses are grouped per geographical region, i.e., northern South America, Ecuador and Peru, and Southeast Asia. Physical explanations for the observed relationships are suggested in the following chapter.

5.1 Temporal Correlations in Northern South America

Prior the beginning of malaria control activities in 1949, malaria was endemic throughout French Guiana. The use of DDT and distribution of anti-malaria drugs such as chloroquine resulted in the near eradication of malaria in the region (Lepelletier *et al.*, 1989). From 1956 through 1971 only 12 to 117 malaria cases were reported annually, most originating from along the Maroni and Oyapock rivers, bordering Suriname and Brazil, respectively (Cochet *et al.*, 1996).

Although control activities continued, malaria incidence started to increase in the 1970s (Figure 5.1a). Population migration and immigration, which provide a new source of malaria parasites, are two suggested reasons for the increase in malaria transmission in the last two decades (Lepelletier *et al.*, 1989). Illegal Brazilian migrants looking for gold in the Oyapock river basin (i.e., garimperos) also explain part of the national increase, especially since 1985 (Esterre *et al.*, 1990).

A drastic increase in malaria transmission occurred in 1987, and the incidence of malaria remained high until 1990. Health authorities associated the 1987 outbreak with the political problems in Suriname, which forced many Surinamers to seek health treatment in French Guiana (Esterre *et al.*, 1990). Furthermore, the creation of health centres in remote areas tripled the number of blood slides examined (Cochet *et al.*, 1996; Lepelletier *et al.*, 1989). Thus, the high malaria incidence in the late 1980s and early 1990s could be explained by a more comprehensive malaria screening. Accordingly, early case detection is probably the cause for the decreasing trend in malaria transmission since 1990, as infected people are treated promptly, reducing the number of subsequent infections and thus epidemic risk.

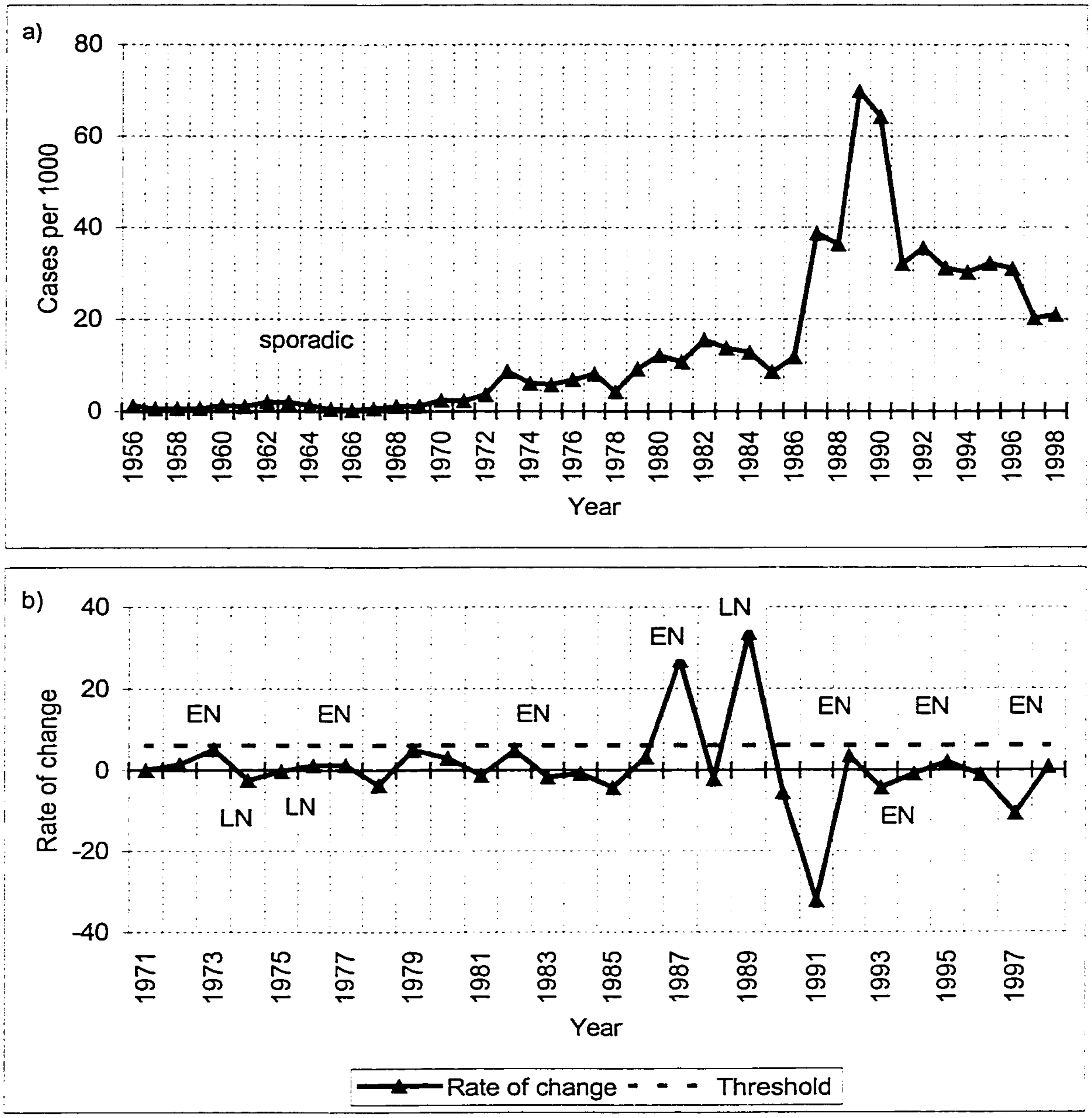

Figure 5.1. Malaria in French Guiana. Cases per 1000 persons (a), and the corresponding rate of change (b). Because of the near eradication of malaria prior to 1971, early years were removed from the calculation of the rate of change.

Since malaria was nearly eradicated prior to the 1970s, the analysis for French Guiana only includes the 1971 through 1998 period. As non-climatic factors contributed to the 1987 epidemic (political problems in Suriname and improvement of the reporting system) and since no other warm event was associated with a malaria epidemic, there is no evidence of the influence of El Niño on malaria transmission in this territory. The 1989 epidemic, however, had over 6200 cases and occurred during a La Niña event.

Until the mid-1940s, malaria was the most important cause of death in Guyana (Mandle, 1970). Many of Guyana's coastal plains lie below sea level and are ideal breeding grounds for *Anopheles* mosquitoes. As in French Guiana, the use of DDT and chloroquine-containing salt resulted in the eradication of malaria from the coastal and near-interior regions of the country between 1945 and 1951 (Giglioli *et al.*, 1967; Mandle, 1970). Accordingly, the number of deaths due to malaria and other undefined fever decreased from 47.6 per 100,000 persons in 1950 to less than one per 100,000 persons in 1960. However, malaria was still endemic in the deep interior of the country, although only 10% of the population live in that region (*Giglioli et al.*, 1967). Thus, few malaria cases were reported from 1956 to 1972 (Figure 5.2a).

Reported malaria cases began to increase in Guyana in 1972, when imported and introduced cases from Brazil caused an 885% increase compared to 1971 (a malaria case is classified as introduced when secondary infection results from an imported case). In addition, the energy crisis of 1973-74 and global inflation severely affected the economy of Guyana, causing a reduction of anti-malaria measures (Giglioli *et al.*, 1976). As a result, malaria cases were reported once again from the entire Guyanese hinterland in 1975 (WHO, 1983). Another factor contributing to the increase in malaria after 1985 is the increase in exposure to *Anopheles* mosquitoes with expansion of gold and diamond mining. In the northwestern region of Guyana, for example, 97% of the cases of *falciparum* malaria were reported from mining areas in 1986 (Rambajan, 1994).

Malaria epidemics were observed during the 1986/87, 1991/92, 1994/95 and 1997/98 El Niños (Figure 5.2b). Guyana experienced below average rainfall during all those epidemics (cf., Figure 3.3). Although, the 1976/77 and 1982/83 El Niños limited the amount of rainfall in the country, no epidemics were reported. Emergency control measures in 1977 possibly explain the lack of outbreak during this year (WHO, 1979). No explanation is provided for the absence of epidemic during the 1982/83 El Niño.

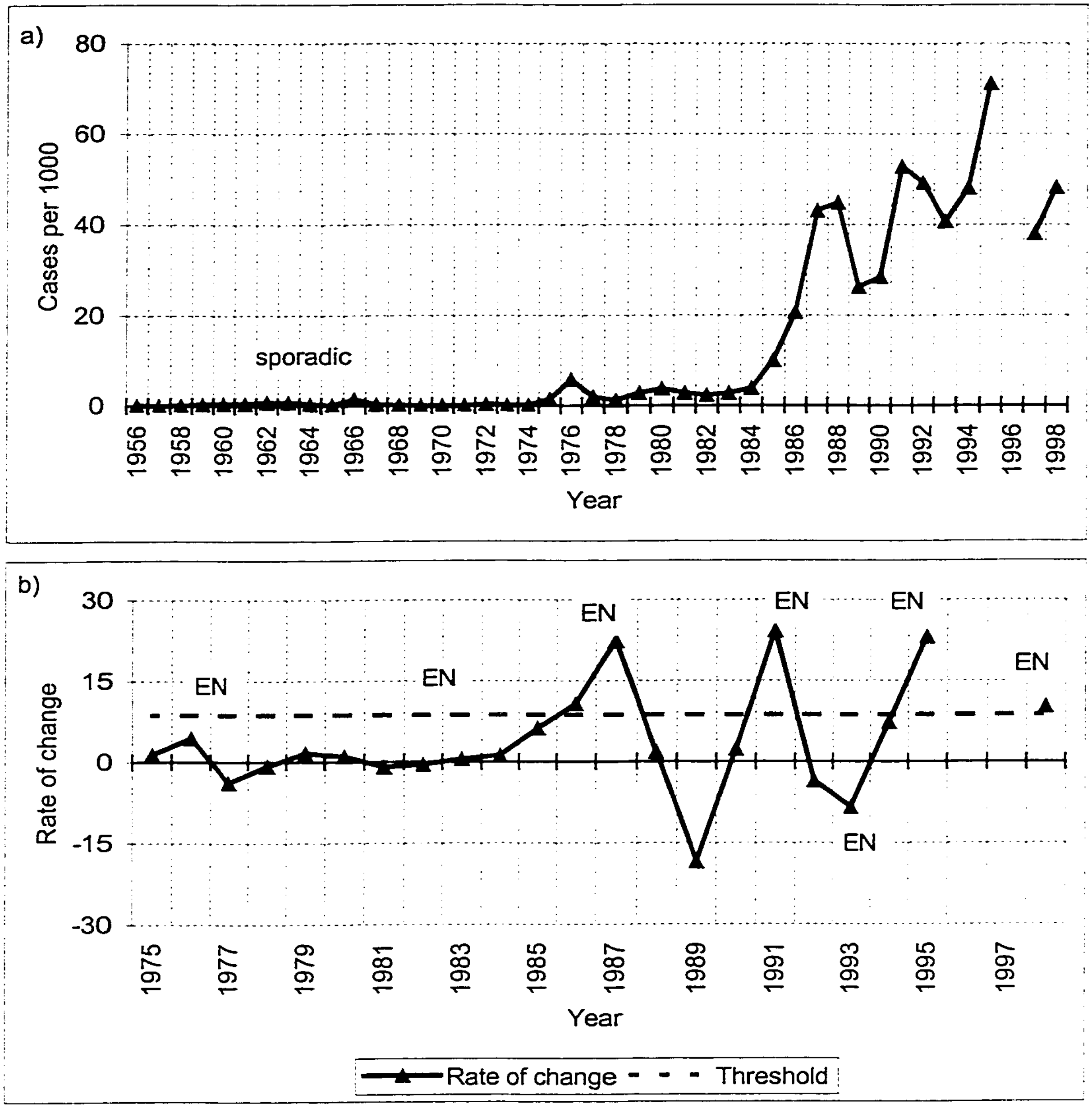

Figure 5.2. Malaria in Guyana. Cases per 1000 persons (a), and rate of change (b). Because of the near eradication of malaria prior to 1975, early years were removed from the calculation of the rate of change. (No data available for 1996.)

Although malaria was eradicated from the coastal region of Suriname between 1950 and 1960 (Rozendaal, 1991), it was still considerable in other regions. Data are not available for 1993, but beginning in 1994, the number of malaria cases increased dramatically (Figure 5.3a). Malaria epidemics occurred during the 1957/58, 1965/66, and 1994/95 El Niños. All those epidemics took place during years with warmer and drier climatic conditions (cf., Figures 3.2 and 3.13). No outbreak was reported during the 1976/77, 1982/83, 1986/87, and 1991/92 El Niños, even though warmer and drier conditions prevailed in most of those years.

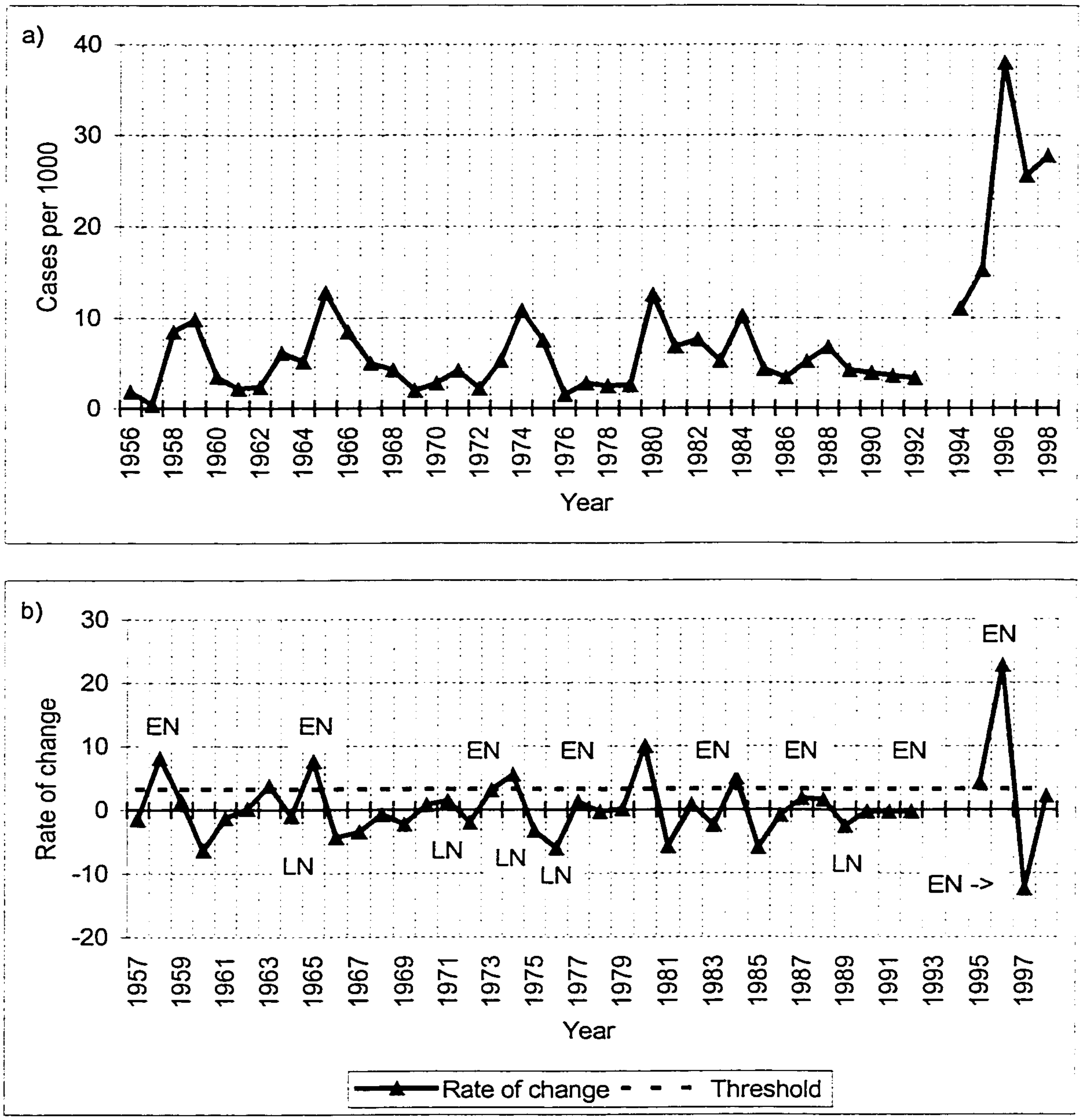

Figure 5.3. Malaria in Suriname. Cases per 1000 persons (a), and rate of change (b).

The number of malaria cases increased in Suriname in 1973, a Niño (+1) year, but the peak was slightly below the outbreak threshold value (Figure 5.3b). This increase, however, also coincided with the 1973/74 La Niña, because the number of malaria cases increased and peaked in 1974, the decay year of the La Niña episode. Similarly, an epidemic occurred started during the weak 1995 Niña (0) year, and peaked in the following Niña (+1) year. Nevertheless, malaria incidence was low during the 1964 and 1975/76 La Niña events.

In Venezuela two prominent peaks are evident in the malaria time series (Figure 5.4a). These two epidemics occurred during La Niña episodes (i.e., 1970/71, and 1988/89) and were preceded by an El Niño event (i.e., 1969 and 1986/87) (Figure 5.4b). Also, an outbreak occurred during the 1964 La Niña and was preceded by the weak 1963 El Niño. The 1983 epidemic occurred during an El Niño event and was not associated with a La Niña year. The rise in malaria cases in 1983 was the result of increased internal and international migratory movements (WHO, 1985). Other El Niño episodes not followed by a La Niña event did not engender malaria epidemics.

Malaria was previously eradicated from the northern region of Venezuela (WHO, 1975). In the southern region, however, malaria is still a common disease today, with, on average, 24,170 malaria cases reported annually from 1990 through 1998. The areas with high risk of malaria transmission in Venezuela are the states of Amazonas and Bolivar (WHO, 1996), as well as the eastern part of the states of Apure and Delta Amacuro (PAHO, 1994b) (cf., Figure A4.3). The state of Delta Amacuro is located at the mouth of the Orinoco river, while the other states correspond to the region previously classified as the Guyana highlands. Another region with problems for malaria control is along the Colombian border, particularly in the state of Táchira near Cúcuta (Colombia; PAHO, 1994b). In addition to suitable climatic conditions, malaria control in those regions is difficult because of migration across the border and unauthorised mining in the jungle (WHO, 1984; WHO, 1997), notably by Brazilian's *garimperos* (G. Orlandoni, *personal communication*).

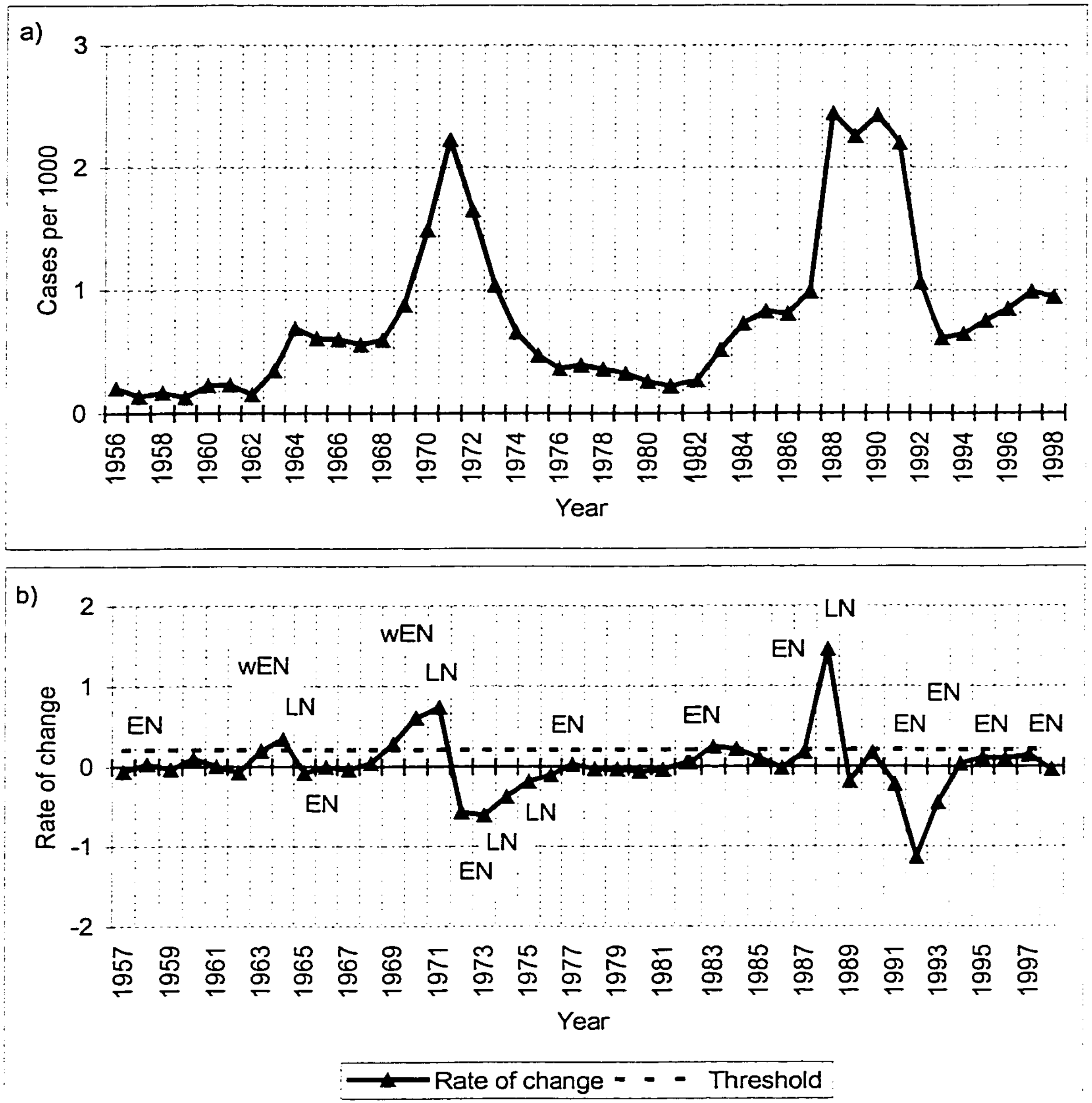

Figure 5.4. Malaria in Venezuela. Cases per 1000 (a), and rate of change (b). (wEN refers to El Niño events of weak intensity).

Only in the southern Guyana highlands (i.e., the southern part of Venezuela's Amazon region) was a temporally consistent correlation between ENSO and rainfall variations identified. Meteorological observations were obtained from only one weather station in the southern highlands (i.e., Santa Elena, cf., Figure A4.3). Nevertheless, analysis of the rainfall record of Boa Vista in northern Brazil also reveals a warmer and drier climate during El Niño events and a cooler and wetter climate in La Niña years. Pulwarty *et al.* (1992) found a similar correlation between ENSO and rainfall anomalies in the northern Guyana highlands, but the correlation is weak and statistically significant during the December-February season only. The correlation of rainfall anomalies with ENSO is not statistically significant at San Cristóbal (i.e., where malaria occurs along the Colombian border; contradicting Pulwarty *et al.*'s (1992) results. The complex orography of the region can explain the difference, because a strong and statistically significant correlation exists for Cúcuta in neighbouring Colombia (cf., Table 3.3 and Figure A4.3).

Although rainfall variations in the northern Guyana highlands of Venezuela are weakly correlated with ENSO, most rivers in southern Venezuela have their source in the southern highlands and flow northward and westward to the Orinoco river. The Orinoco river is the most important river in Venezuela; it more or less forms the border between the Guyana highlands and the Llanos as well as the international border between Colombia and southern Venezuela. It flows north-eastward to discharge its waters into the Atlantic Ocean in the state of Delta Amacuro (cf., Figure A4.3). Therefore, the hydrology of all of southern Venezuela is likely to be impacted by ENSO-related rainfall variation since the catchment area of most rivers is under the influence of ENSO.

Epidemics of malaria in Venezuela were correlated with rainfall anomalies at Santa Elena. During all the El Niño events that preceded the malaria epidemics, rainfall was approximately 0.5 standard deviation below the long-term mean (Figure 5.5). Although rainfall was more abundant during the 1964 and 1988/89 La Niñas, no positive rainfall anomalies were observed during the 1970/71 epidemic. As temperature was also above average during the epidemics, the data indicate that malaria epidemics tend to occur after droughts in Venezuela.

The number of malaria cases reported annually in Colombia has been increasing dramatically since 1959 (Figure 5.6a). A step increase in malaria transmission occurred from 1990 to 1991, because of modernisation of the malaria control programme. Before 1991, the national malaria control programme did not recognise the malaria cases detected by some regional health services, such as

Antioquia. Decentralisation of malaria control activities resulted in the inclusion of those data in the national average (WHO, 1993).

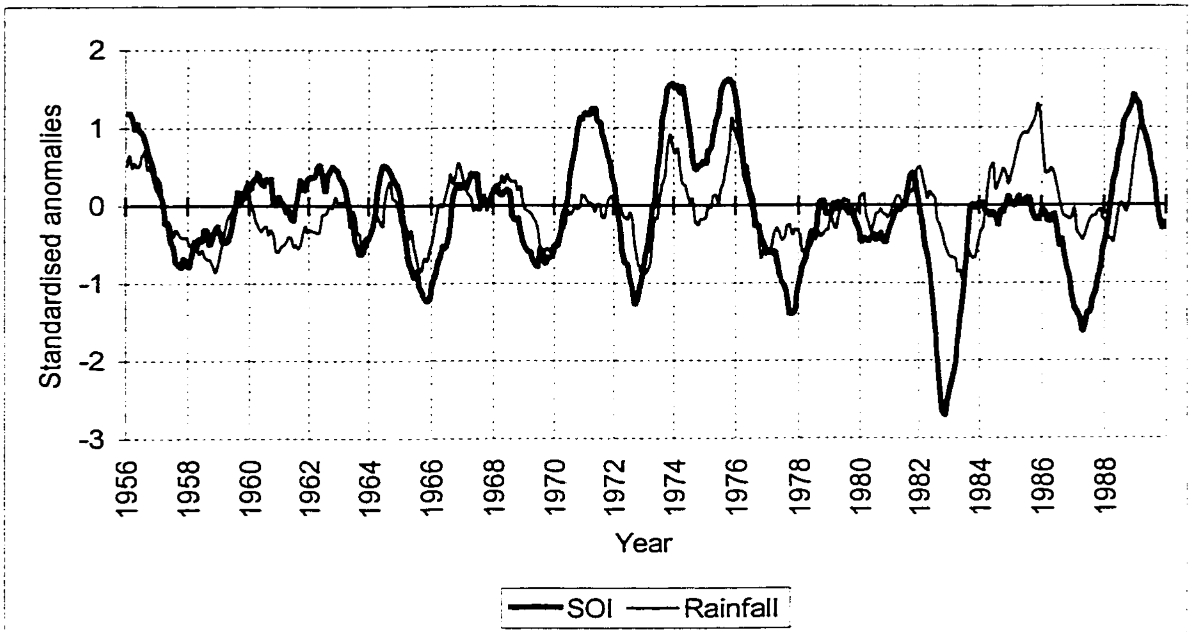

Figure 5.5. Time evolution of the SOI and rainfall anomalies at Santa Elena (Venezuela).

Except for the 1965/66 and 1993 episodes, all other El Niño events during the 1959-1998 period were associated with a malaria epidemic (Figure 5.6b). Moreover, an epidemic was reported during the weak 1969 El Niño. All those epidemics were associated with warmer temperatures and lowered river height in northern, western, and central Colombia (cf., Figures 3.5 and 3.13). River height was increasing during the 1993 El Niño, possibly explaining the lack of outbreak during this year. Therefore, we conclude that there is a clear positive correlation between El Niño and malaria transmission in Colombia as Poveda and Rojas (1996; 1997) and Bouma *et al.* (1997) previously suggested using different statistical techniques for shorter time series.

Colombia experiences warmer temperature during El Niño, but rainfall anomalies are not spatially consistent throughout the country. Consequently, it is necessary to identify the region of origin of malaria cases to confirm the relationship between ENSO-related rainfall anomalies and malaria epidemics.

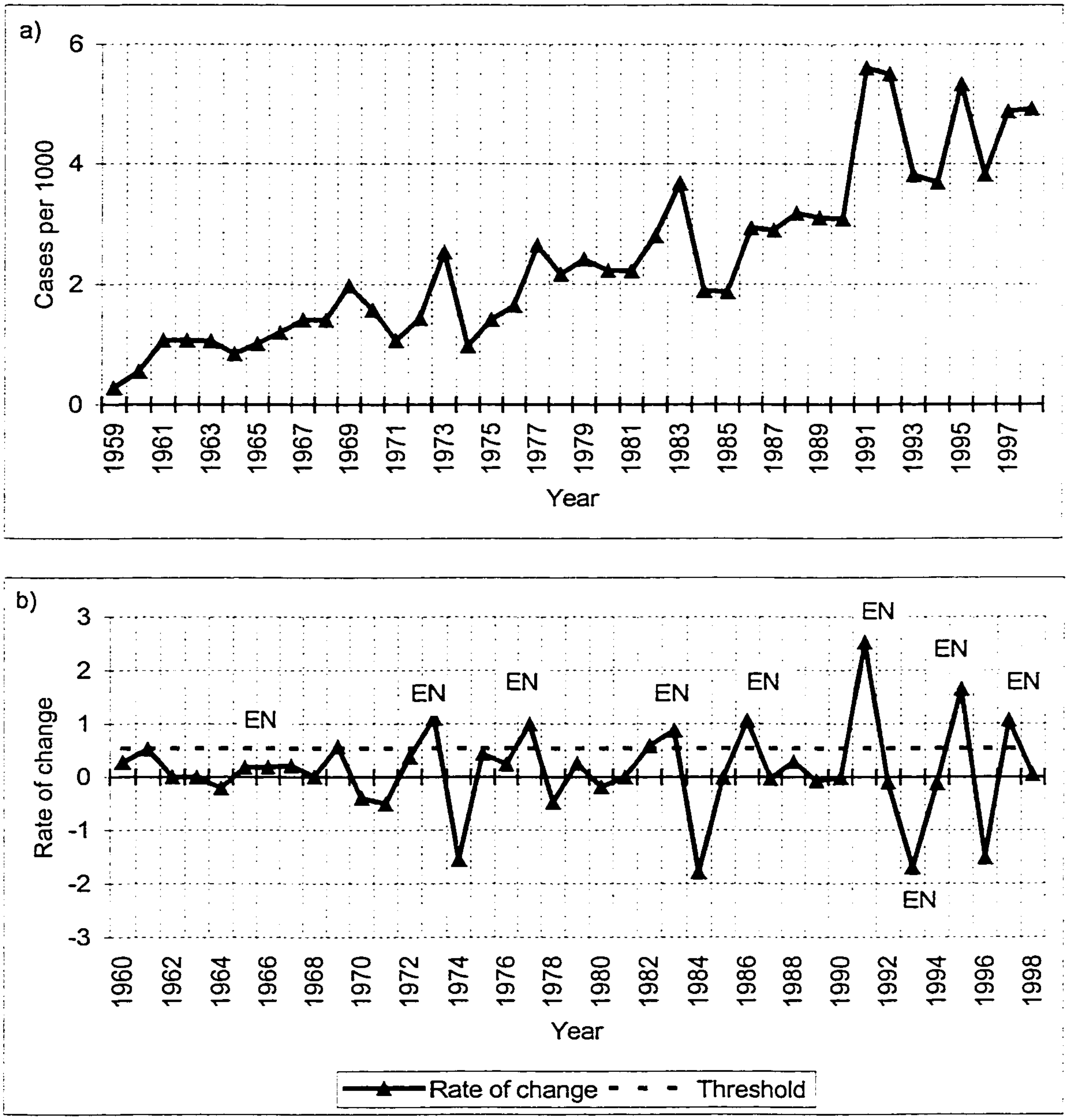

Figure 5.6. Malaria in Colombia. Cases per 1000 (a), and rate of change (b).

In Orinoquia and Amazonia, which form the northern and southern portions respectively of the two Colombian regions east of the Andes, the number of malaria cases as a percentage of the national total was lower during El Niño than for the weak

La Niña of 1996 (Table 5.1; Figure A4.5). In contrast, 38.4% of the malaria cases originated from western Colombia (i.e., Occidente region) in 1996 in comparison with more than 62% during the 1997/98 El Niño. Changes were small in central Colombia (Centro Occidente), where malaria incidence is generally very low, as well as in the Caribbean region (Costa Atlantica; cf., Figure A4.5).

Table 5.1. Malaria cases originating from different Colombian regions as a percentage of total cases.

Region	Weak La Niña (1996)	Strong El Niño (1997/98)
Amazonia	13.2%	5.0%
Orinoquia	27.4%	12.5%
Centro Occidente	3.3%	2.0%
Occidente	38.4%	62.7%
Costa Atlantica	17.6%	17.8%

The climate of northern, central, and western Colombia is warmer and drier during El Niño and cooler and wetter during La Niña. In eastern Colombia (i.e., east of the Andes) temperature anomalies are positive during warm events, but rainfall anomalies are not significantly impacted by ENSO (although availability of hydrological data in this region is limited). Likewise, in the eastern Caribbean region, neither rainfall nor river discharge is correlated with ENSO, explaining the lack of El Niño-related changes in malaria transmission in this region. The percentage of malaria cases originating from western Colombia (i.e., Occidente region) considerably increases during El Niño, when drier conditions prevail. As previously noted, the Pacific coast of Colombia is normally one of the rainiest places in the Americas.

The WHO divides Brazil into three regions: the Amazon region, the northeastern states, and the southern states (WHO, 1991; Figure A4.6 depicts the geographical location of the nine states and territories of the Amazon region). In recent decades, malaria has not been a problem in Brazil, except for the Amazon region (A. Passos, *personal communication*), as climatic conditions generally do not favour malaria transmission outside of the Amazon (WHO, 1991). Passos and Fialho (1998) noted that since 1980, more than 95% of malaria cases reported in the country originated from the Amazon basin. Malaria cases that are reported in non-endemic regions outside the Amazon are usually caused by migrants who return to their place of origin after their journey into the Amazon jungle (PAHO, 1980; A. Passos, *personal communication*; WHO, 1994).

In addition to favourable climatic conditions, the migration of people from non-malarial areas is one of the most important causes of high malaria endemicity in the Amazon region (PAHO, 1980). Brazil's gold rush as well as agricultural settlements at the margins of the forest (which resulted from new development policies aimed at increasing the population density in Brazil's less inhabited regions (PAHO, 1980)) brought many people to the Amazon basin (Liese, 1998; WHO, 1993). Most of these workers lack immunity against malaria (Liese, 1998), rarely use anti-malaria drugs (de Andrade, 1995), and live in houses without complete vertical walls on all sides (allowing mosquitoes to enter into the house), making them at high risk to malaria infection (Liese, 1998).

The rapid population increase in the Amazon basin that resulted from rapid economic development explains the large increase in the number of malaria cases that started in the mid-1970s (PAHO, 1980; Figure 5.7a). Development activities include agricultural settlement, hydrological projects, mining, and highway construction (PAHO, 1980). These development projects contribute to high malaria incidence, particularly because of irrigation for agriculture as well as pits from mining activities and road construction, which fill with rainwater, creating breeding grounds for mosquitoes.

Within the Amazon region, the states of Rondônia and Pará account for the majority of the malaria cases reported in Brazil (cf., Figure A4.6). In 1987, for instance, 68% of the malaria cases reported in the country originated from the states of Rondônia and Pará (WHO, 1989). The percentage increases to 79% with the inclusion of the state of Mato Groso (WHO, 1993). A temporally and spatially consistent ENSO-related precipitation signal was identified in northern equatorial Brazil. However, the correlation of rainfall with ENSO in the southern part of the Amazon basin (as demonstrated by Porto Velho in the state of Rondônia) is not temporally consistent (Figure 5.8). Since the states of Rondônia and Mato Groso are located in a region with poor ENSO-related rainfall anomalies, a strong and statistically significant correlation of malaria epidemics with ENSO is unlikely for Brazil.

The malaria epidemics of 1983, 1986-88, 1994, and 1998 coincided with EL Niño years (Figure 5.7b). With the exception of 1994, These epidemics were associated with less abundant rainfall in northern equatorial Brazil (cf. Figure 3.6). In addition, rainfall was also below average at Porto Velho, in the southern part of the Amazon basin, during those outbreaks (except for 1994) (Figure 5.8). Epidemics have also occurred in 1962/63, 1971, 1979, and 1984 (cf., Figure 5.7b). During the 1962/63 (non-ENSO), 1971 (Niña (+1)), and 1984 (non-ENSO) epidemics, negative rainfall anomalies were recorded at Porto Velho. The 1979 epidemic (a non-ENSO year) was caused by outbreaks in newly settled areas of Rondônia and Pará (WHO, 1981). Therefore, a warmer and drier climate generally engenders malaria epidemics in Brazil, but non-climatic factors also influence the incidence of the disease in the region.

Contingency tables with Fisher's exact test were used to test for the statistical significance of the observed relationships. In northern South America, only in Colombia and Guyana is the relationship between El Niño and malaria epidemics statistically significant at the 95% level (Table 5.2). In Colombia, some malaria epidemics have occurred in Niño (+1) years (i.e., 1973, 1977, and 1995), whereas others took place in Niño (0) years (i.e., 1986, 1991, and 1997) (cf. Figure 5.5). For the strong 1982/83 El Niño, the epidemic started in 1982 and peaked in 1983. Similarly, the 1987, 1995, and 1998 malaria epidemics in Guyana occurred during Niño (+1) years, but outbreaks were also reported in 1986 and 1991, two Niño (0) years. The peak in rainfall anomalies generally occurs by the end of Niño (0) and hence drier conditions are strongest from the end of the calendar year through Niño (+1). Therefore, in Colombia and Guyana the risk of a malaria epidemic is higher during warmer and drier conditions.

The Fisher's exact test also reveals a statistically significant relationship between La Niña and malaria epidemics in Venezuela (cf., Table 5.2). Only La Niña events preceded by El Niño episodes, however, engendered malaria epidemics.

Moreover, not all La Niña episodes led to more abundant rainfall, while all warm events (including the 1963 and 1969 weak episodes) that preceded the epidemics led to less abundant rainfall. Therefore, when Venezuela experiences a drought such as during El Niño events, the risk of an epidemic is high in the following year.

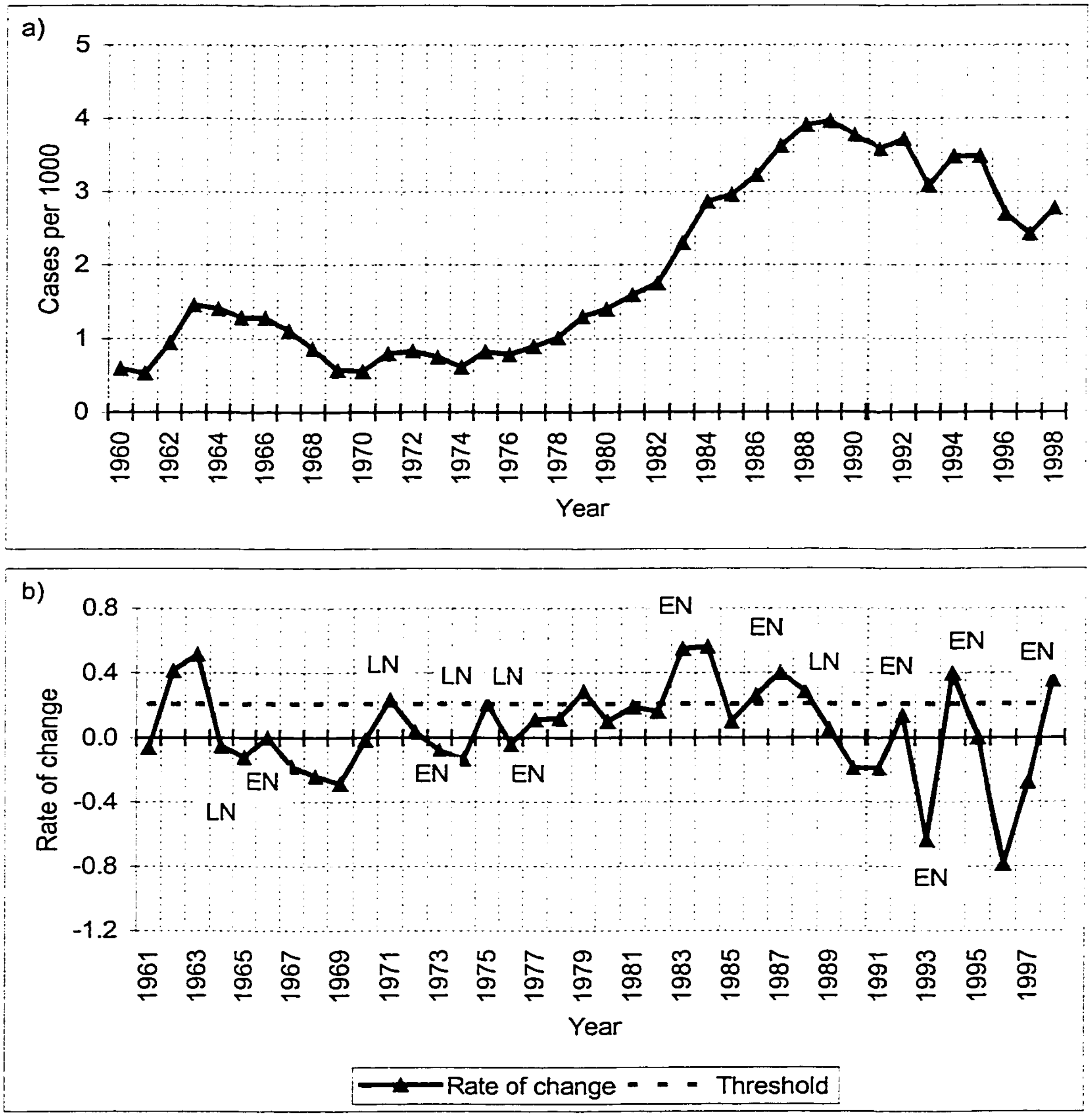

Figure 5.7. Malaria in Brazil. Cases per 1000 (a), and rate of change (b).

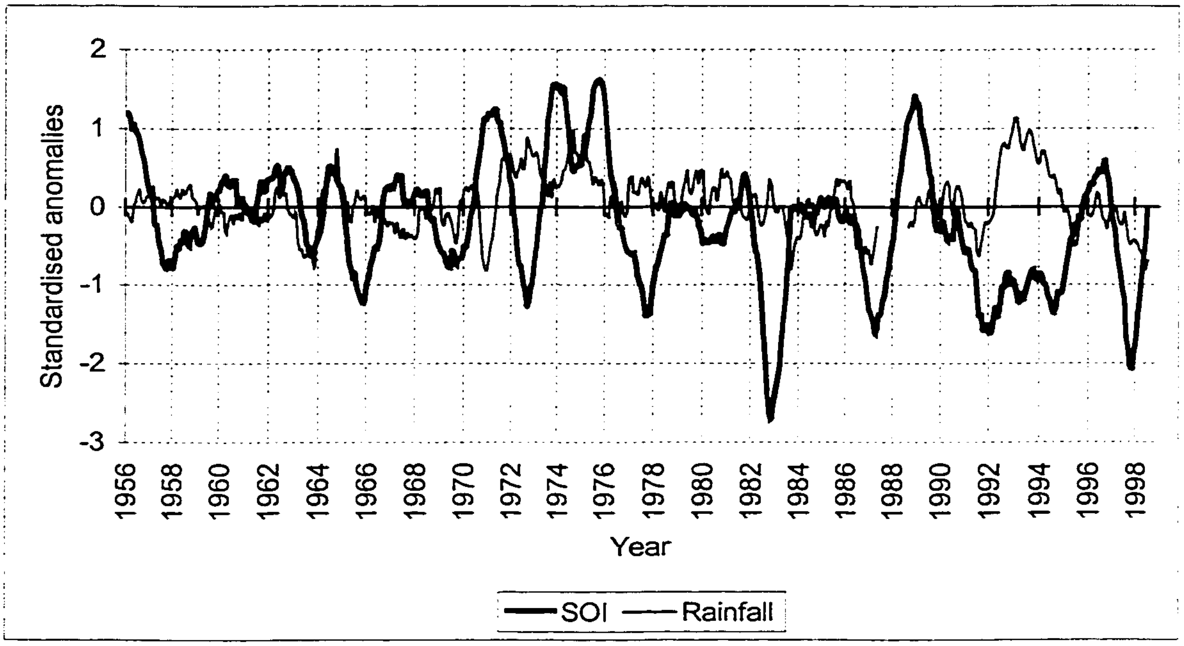

Figure 5.8. Time evolution of the SOI and rainfall anomalies at Porto Velho (Brazil).

Table 5.2. Results of the Fisher's exact test for malaria in countries of northern South America†.

Country	Niño (0)	Niño (+1)	Niño (0) or Niño (+1)	La Niña years[2]
Brazil	0.00	0.35	0.57	0.36
Colombia	0.83	0.83	*0.99	0.00
French Guiana	—	0.50	0.00	[1]0.76
Guyana	0.41	0.73	*0.99	—
Suriname	0.00	0.00	0.35	0.00
Venezuela	—	0.00	0.36	*0.99

† Results refer to one minus the p-value

* Statistically significant at the 95% level

(—) Not calculated since no epidemic occurred during this period.

[1] Computations started in 1972, because of the absence of year Niña (0) of the 1970/71 episode.

[2] Niña (0) or Niña (+1)

In all northern South American countries, including most of Brazil's Amazon, the climate is generally warmer and drier during El Niño and cooler and wetter during La Niña. Warmer temperatures and below average rainfall, and hence lower river height and discharge, were found to spawn malaria epidemics in Colombia and Guyana; while in Venezuela the epidemics lag a drought period by one year. In

Brazil's Amazon, the risk of a malaria epidemic is also high under drier conditions, but years with below average rainfall are not always associated with El Niño, particularly in the southern part of the Amazon region. The tropical Atlantic Ocean might also influence the climate of the region, as it is known to modulate the impact of El Niño in South America (Mason *et al.*, 1999). Physical explanations for the relationships observed in this chapter are suggested in the discussion. The following section analyses the correlation between malaria outbreaks and ENSO in western South America, where in the coastal zone of this region the climate is both warmer and wetter during El Niño.

5.2 Temporal Correlations in Western South America

Risk of malaria transmission exists in most of Ecuador's coastal region, where the relationship between El Niño and rainfall anomalies is consistent. In 1990, for example, 91.5% of the total malaria cases reported in the country originated from the coastal provinces of Esmeraldas, Manabí, Guayas, and Los Ríos (PAHO, 1991). Esmeraldas is the main centre of malaria transmission (WHO, 1984), as it accounted for 40% and 47% of the total cases reported nationally in 1983 and 1996, respectively (WHO, 1985; 1996 percentage was calculated using regional data collected at PAHO headquarters). Similarly, approximately 90% of the total malaria cases reported in 1984 originated from the same provinces as well as Napo. The latter province is situated east of the Andes, where no relationship of rainfall variations with ENSO was identified (cf., Figure A4.2; WHO, 1986). More recently, the risk of malaria transmission has increased in the province of Sucumbíos (which is also located east of the Andes), because of oil exploration in the region (WHO, 1993).

Rainfall is generally abundant in most of the provinces where malaria transmission commonly occurs, particularly in the province of Esmeraldas (Johnson, 1976). As previously mentioned, only the northern and eastern parts of the provinces of Manabí (i.e., north of Manta) and Guayas, respectively, normally experience a wet climate (cf., Figure A4.2). In the southwestern part of the country (i.e., the region previously referred to as the Peninsula), semi-arid conditions usually prevail, because of the cold SSTs in the Pacific Ocean in normal years (cf., Figure A4.2; Johnson, 1976). The city of Guayaquil forms the climatic boundary between the semi-arid region to the west and the swampy areas to the north and east (Johnson, 1976). Thus, the majority of the malaria cases reported in the provinces of Manabí and Guayas in non-El Niño years are likely to originate from the wet sections of those provinces, as dryness might restrict mosquito habitats in the Peninsula.

The warming of SSTs in the Pacific Ocean enhances evaporation and humidity, producing abundant rainfall in the coastal region (cf., Figure 3.9). Cedeño (1986) associated the 1983 malaria epidemic to the flooding caused by the 1982/83 El Niño in the Guayas river basin. The Guayas river flows through the city of Guayaquil and discharges its water in the Gulf of Guayaquil (cf., Figure A4.2). Because of its low elevation and slow discharge, the torrential rains produced by the 1982/83 El Niño resulted in overflowing of the river, increasing the number of mosquito breeding sites. Moreover, the increase in malaria transmission was not only observed in the flooded region, but also in other provinces, as a result of the migration of the inundated population (Cedeño, 1986). Furthermore, abundant rainfall increased malaria transmission in the Peninsula (Cedeño, 1986). Total annual precipitation increases, on average, by 177% in this region in El Niño years (Rossel *et al.*, 1999). The 1983 epidemic persisted in 1984, probably because of continued disorder in the country following one of the strongest El Niño events of the century (Figure 5.9).

Likewise, the 1997/98 El Niño generated extreme precipitation in coastal Ecuador, spawning a large malaria epidemic (cf., Figures 3.9 and 5.9). Abundant rainfall during the 1987 El Niño also engendered an epidemic. Its magnitude, however, was not as large as the 1983 and 1998 epidemics, possibly because of the smaller rainfall anomalies during this year (cf., Figure 3.9). Above average rainfall probably increased the number of mosquito habitats in the Peninsula, because the arid climate restricts their abundance in normal years. Nevertheless, rainfall anomalies were unlikely to be severe enough to cause large population migrations and, hence, a sizeable malaria epidemic.

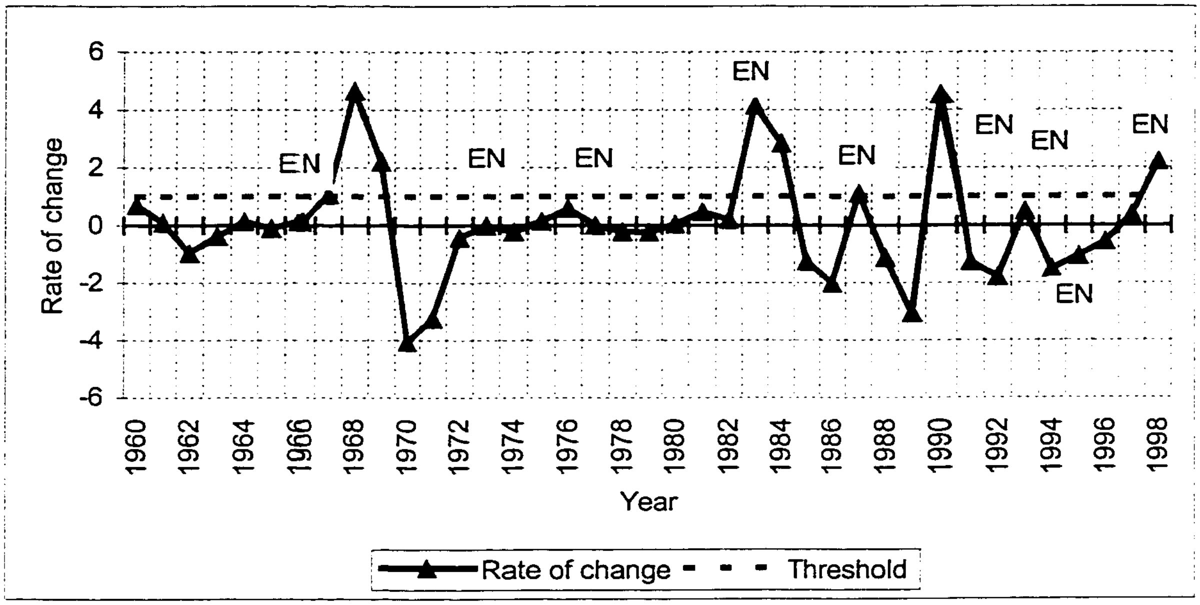

Figure 5.9. Malaria in Ecuador.

The 1965/66, 1972/73, 1976/77, 1991/92, 1993, and 1994/95 El Niños did not spawn malaria epidemics. Malaria transmission rose in 1976, but the peak is below the outbreak threshold value. As previously mentioned, rainfall anomalies were not spatially consistent in coastal Ecuador during the 1965/66 El Niño, and normal rainfall conditions prevailed in most of the coastal zone during the 1993 and 1994/95 El Niños (cf., Figure 3.9), explaining the lack of epidemics there. Therefore, 1972/73 and 1991/92 are the only two El Niño episodes that generated abundant rainfall that did not result in malaria epidemics.

Ecuador experienced a prolonged malaria epidemic from 1967 through 1969 as a result of a drastic reduction of control measures using DDT in 1966 and 1967 (cf., Figure 5.9; Cedeño, 1986). Accordingly, the number of house insecticide sprayings per 1000 inhabitants was extremely low in 1967 (Figure 5.10). The 1990 epidemic, which also occurred during a non-ENSO year, has been attributed to increased population migration in some coastal provinces because of agricultural colonisation and mining activities in those regions (WHO, 1992b).

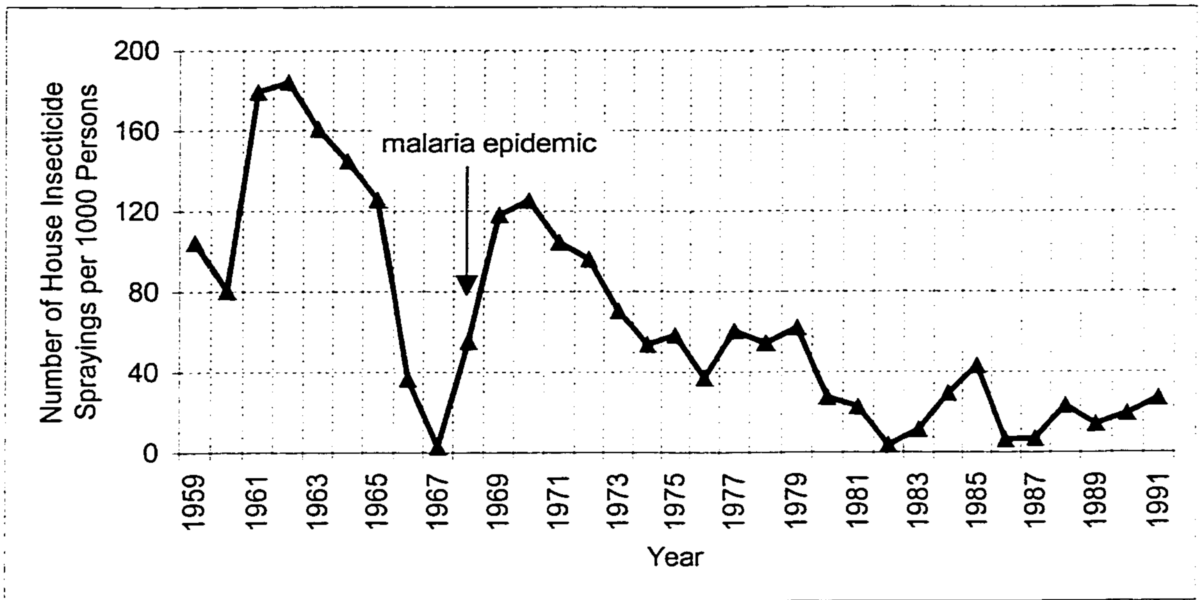

Figure 5.10. House insecticide sprayings in Ecuador.

The relationship between El Niño and malaria epidemics is more temporally consistent in Peru than in Ecuador. In 1941, the Peruvian government created a national service to combat malaria and five years later, DDT was used to eradicate malarial mosquitoes (P. Valencia, *personal communication*). Accordingly, the national incidence of malaria began to decrease drastically in 1946 and remained low for the next two decades (Figure 5.11a). Following a decade of reduced insecticide sprayings, malaria began to resurface in 1972 when the number of malaria cases more than doubled in comparison with 1971. The present analysis is limited to the 1972-1999 period, because malaria eradication was successful in prior decades, hiding any signal that ENSO might have had.

El Niño engendered warmer temperatures and abundant rainfall, and consequently elevated river discharge, during the 1973, 1977, 1983, 1987, 1992-1994, and 1998 hydrological years in northern Peru (cf. Figure 3.8). Accordingly, malaria epidemics were reported during most of those years with the exception of 1973, 1983 and 1987 (Figure 5.11b). A continuous epidemic state was reported from 1992 through 1995, corresponding to a prolonged period (1991-1995) of elevated SSTs (cf.,

Figure 2.2). Though the WHO reported that widespread flooding in northern Peru was the cause for elevated malaria transmission in 1983 (WHO, 1985), the number of malaria cases during this year was below the outbreak threshold value. Nevertheless, the incidence of malaria increased by 40% in 1983 in comparison with 1982. The high variability of malaria in the 1990s reduces the significance of the epidemics that occurred in the 1980s.

There is evidence of increased malaria transmission in northern Peru during El Niño events. For instance, a 225% and 7360% increase in malaria cases were reported in the departments of Piura and Tumbes, respectively, between 1982 and 1983 (Russac, 1986). Less than 7% of the malaria cases reported nationally in 1996 originated from the northern coastal departments of Tumbes, Lambayeque, and Piura, in comparison with 48% during the 1998 Niño (+1) year (calculations were performed using regional data from Peru's *Oficina General de Epidemiología*; cf., Figure A4.4). Therefore, in addition to warm and humid weather, widespread flooding engendered by El Niño in northern Peru is likely to be the reason for malaria epidemics in Niño (+1) years in this country.

No statistically significant correlation (at the 95% confidence level) was found between El Niño and malaria epidemics in Ecuador (Table 5.3). Even by limiting the analysis to the 1972-98 period, in order to remove the epidemic of the late 1960s, which resulted from a drastic reduction of vector control measures, the relationship is still below the significance level (i.e., 0.86). The absence of negative rainfall anomalies during a few El Niño events is likely to explain the lack of statistical significance, because 60% of the El Niño events that engendered positive rainfall anomalies during Niño (+1) spawned malaria epidemics in Ecuador.

A statistically significant correlation exists between malaria epidemics and Niño (+1) years in Peru (cf., Table 5.3). As previously mentioned, the aridity of the climate during non-El Niño years restricts mosquito breeding sites and, hence, malaria transmission in the coastal departments of northern Peru. The retreat of water from flooded lands during El Niño events in this region causes an increase in mosquito breeding grounds, spawning malaria epidemics.

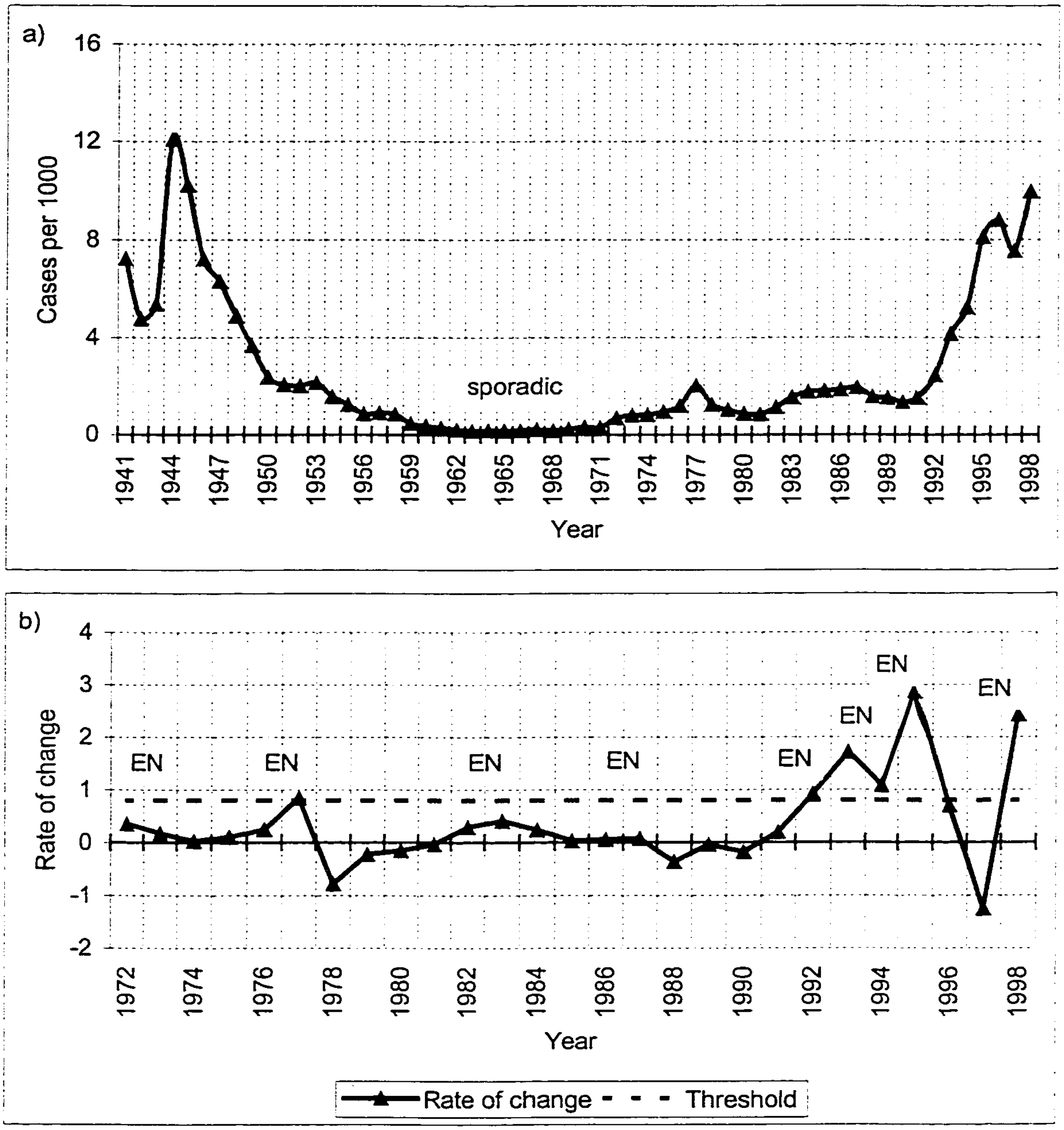

Figure 5.11. Malaria in Peru. Cases per 1000 persons (a), and rate of change (b). Because of the eradication period and the following low incidence of the disease, the rate of change was illustrated as of 1972 only.

Table 5.3. Results of the Fisher's exact test for malaria in countries of western South America[†].

Country	Niño (0)	Niño (+1)	Niño (0) or Niño (+1)	La Niña years
Ecuador	—	0.65	0.34	—
Peru	0.0	*0.99	*0.99	—

[†] Results refer to one minus the p-value

* Statistically significant at the 95% level

(—) Not calculated since no epidemic occurred during an El Niño event.

5.3 Temporal Correlations in Southeast Asia

The use of chloroquine and DDT during the worldwide malaria eradication campaign between 1955 and 1969 resulted in less than 0.18 malaria cases per 1000 persons reported annually in Indonesia during the 1960s (Trigg and Kondrachine, 1998). Since 1970, more than 100,000 cases have been reported annually (Figure 5.12a). The 1960s will therefore be omitted from the present analysis, because of low malaria incidence during this decade. Although the temporal consistency of ENSO-related rainfall variations is strong in most of Indonesia, only the 1972/73 and 1982/83 El Niños were associated with malaria epidemics (Figure 5.12b). No outbreaks were reported during other warm events.

Epidemiological data for the Philippines were obtained from both the WHO and the national Department of Health. Although the Department of Health provides the malaria data to the WHO, it is interesting to note the large difference in the number of reported cases between the two sources (Figure 5.13a). (The same problem was noticed for DHF.) The data from the government of the Philippines are selected for further analysis, because it manages the malaria control programme and is therefore the primary reporter of the malaria cases in the country.

The malaria control activities were resumed in the Philippines in 1946 following the Second World War and they continued until 1958, when the malaria control programme was changed to a malaria eradication programme, which ended in 1970 (Cabrera and Arambulo, 1977). Both the malaria control and eradication programmes were successful, as the incidence of malaria decreased from 10 cases per

1000 persons in 1946 to less than one case per 1000 persons in the 1970s. Malaria cases are reported from 72 of the 75 provinces of the country (Salazar *et al.*, 1988).

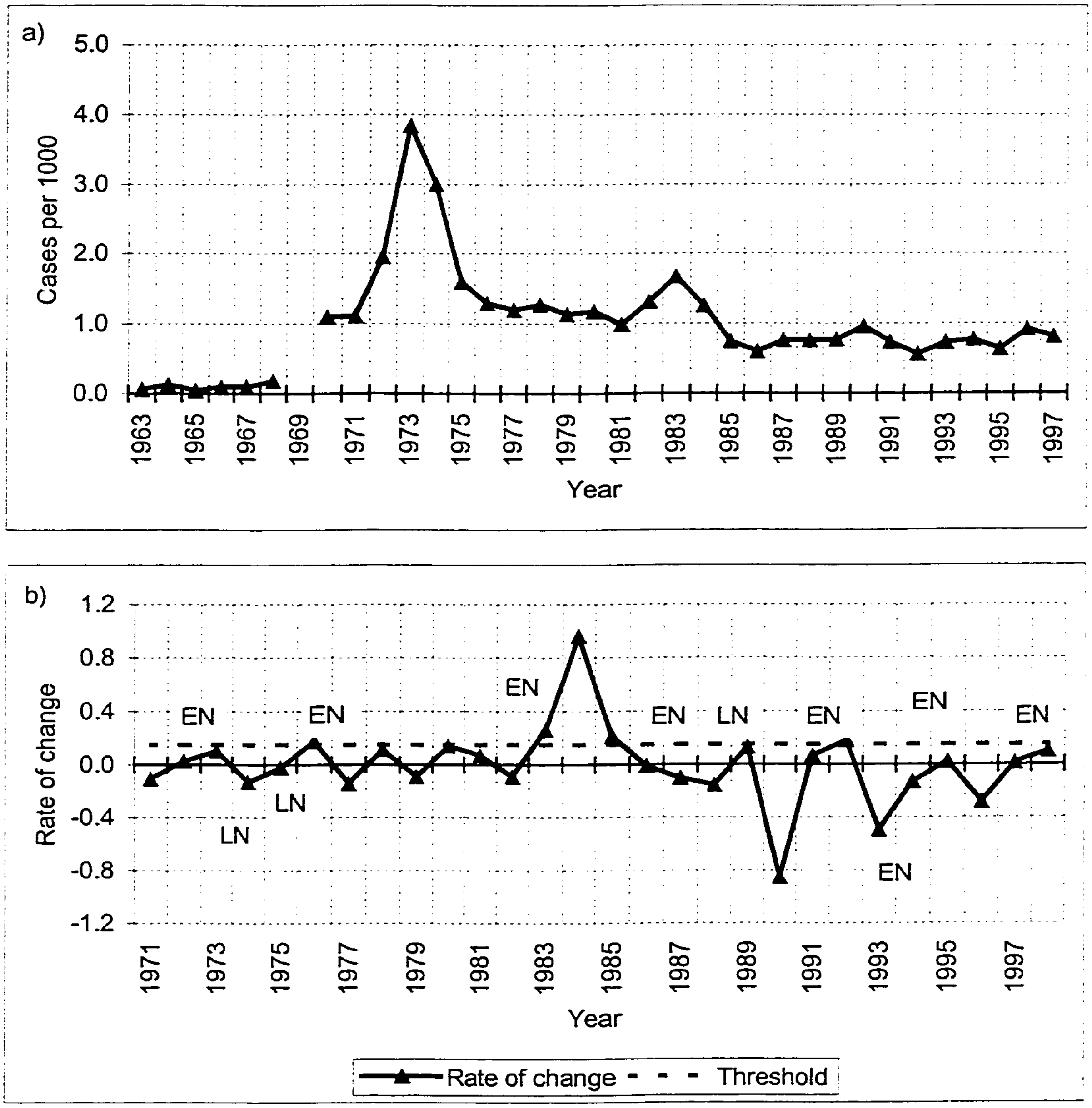

Figure 5.12. Malaria in Indonesia. Cases per 1000 (a), and rate of change (b). Because of the low incidence of malaria prior to 1971, the 1960s were excluded from the calculation of the rate of change.

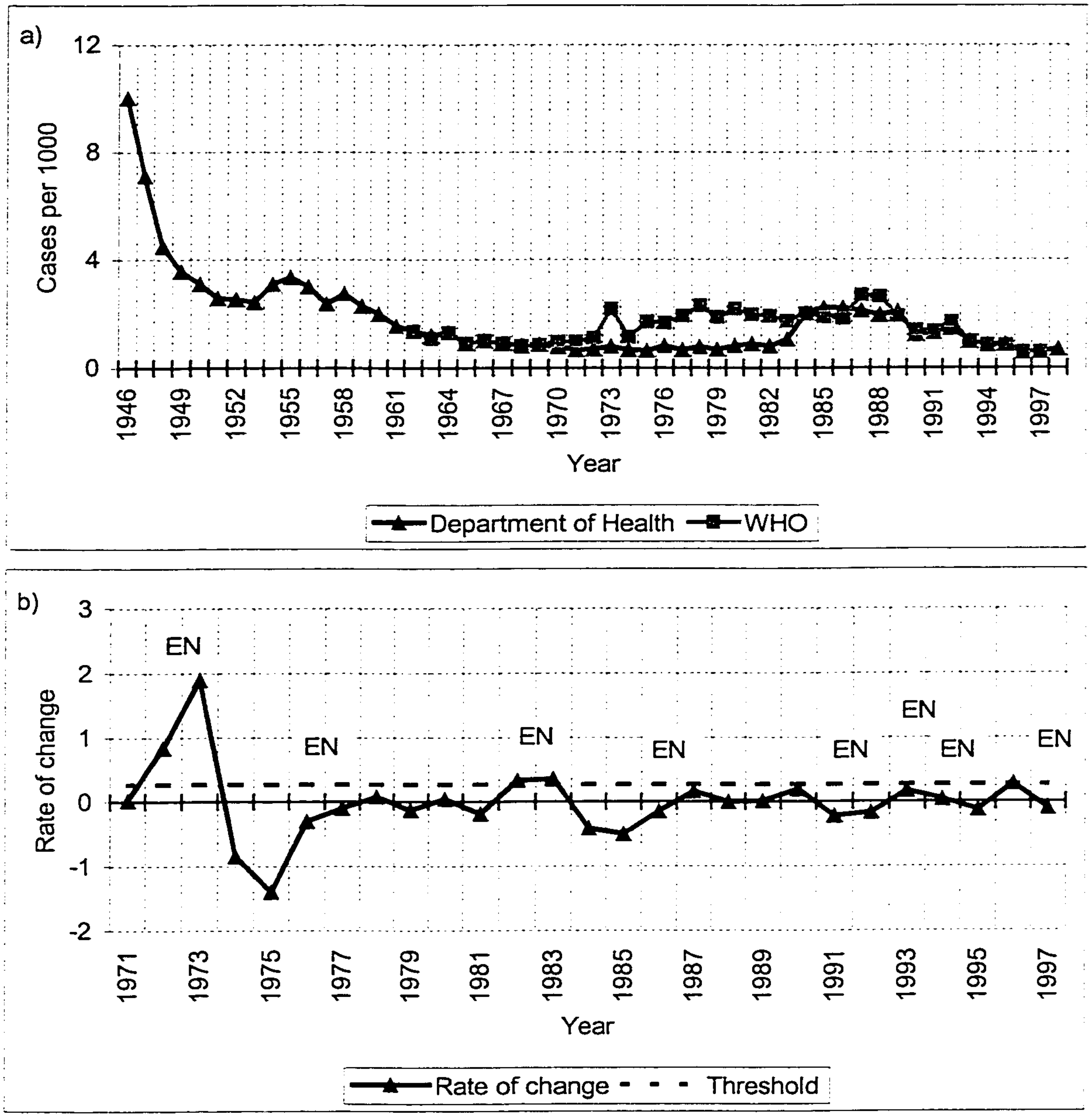

Figure 5.13. Malaria in the Philippines. Cases per 1000 persons (a), and rate of change (b). The rate of change was calculated since the end of the malaria eradication programme.

The analysis of the correlation between ENSO and malaria transmission extends from 1971, one year after the end of the malaria eradication programme, to 1998. Some El Niño events (which engendered below average rainfall from September (0) through May (+1) (cf., Figure 3.12)) were associated with malaria epidemics (i.e., 1976/77, 1982/83, and 1991/92) (Figure 5.13b). But, the relationship is not temporally consistent, as many other warm episodes, which engendered rainfall anomalies, were not associated with malaria epidemics, particularly the very strong 1997/98 El Niño (cf., Figures 5.13b). On the other hand, no La Niña episodes were associated with a malaria epidemic.

Unlike in the Philippines, the ENSO-malaria epidemic relationship in the Sarawak is more clear-cut. Annual malaria cases are available for Sarawak since 1961, the year of initiation of the malaria eradication programme in eastern Malaysia (Rahman, 1982). There are slight differences between the data from the WHO and those from the Sarawak Health Department, especially from 1963 to 1973, but the disagreement is not as large as in the Philippines (Figure 5.14a). The data from the Sarawak Health Department were selected for further analysis for the same reason as in the Philippines.

A step decrease in the mean value of the annual number of malaria cases is clearly evident before 1974 and after 1980 in Sarawak, probably because of successful malaria control efforts (cf., Figure 5.14a). Thus, the 1975 through 1979 period is omitted from the statistical analysis and we used two time periods and thus two standard deviations for the calculation of the outbreak threshold value, i.e., from 1962 through 1974 and 1980 through 1998 (Figure 5.14b).

The 1965, 1972, 1982, 1991, 1994, and 1997 Niño (0) years, which were all associated with warmer temperatures and below average rainfall (cf., Figure 3.11), engendered malaria epidemics (cf., Figure 5.14b). The El Niño-precipitation signal was not consistent, however, during the 1994 El Niño. Below average rainfall was recorded at Bintulu and Miri in 1994, but not at Kuching (cf., Figure A4.1). Most epidemics occurred during Niño (0), although the 1973 outbreak occurred during Niño (+1). An epidemic was also reported in 1990 and, accordingly, rainfall was below normal during that year (cf., Figure 3.11). Nevertheless, Sarawak experienced epidemics in 1968, 1970, and 1996 when normal or more abundant rainfall prevailed.

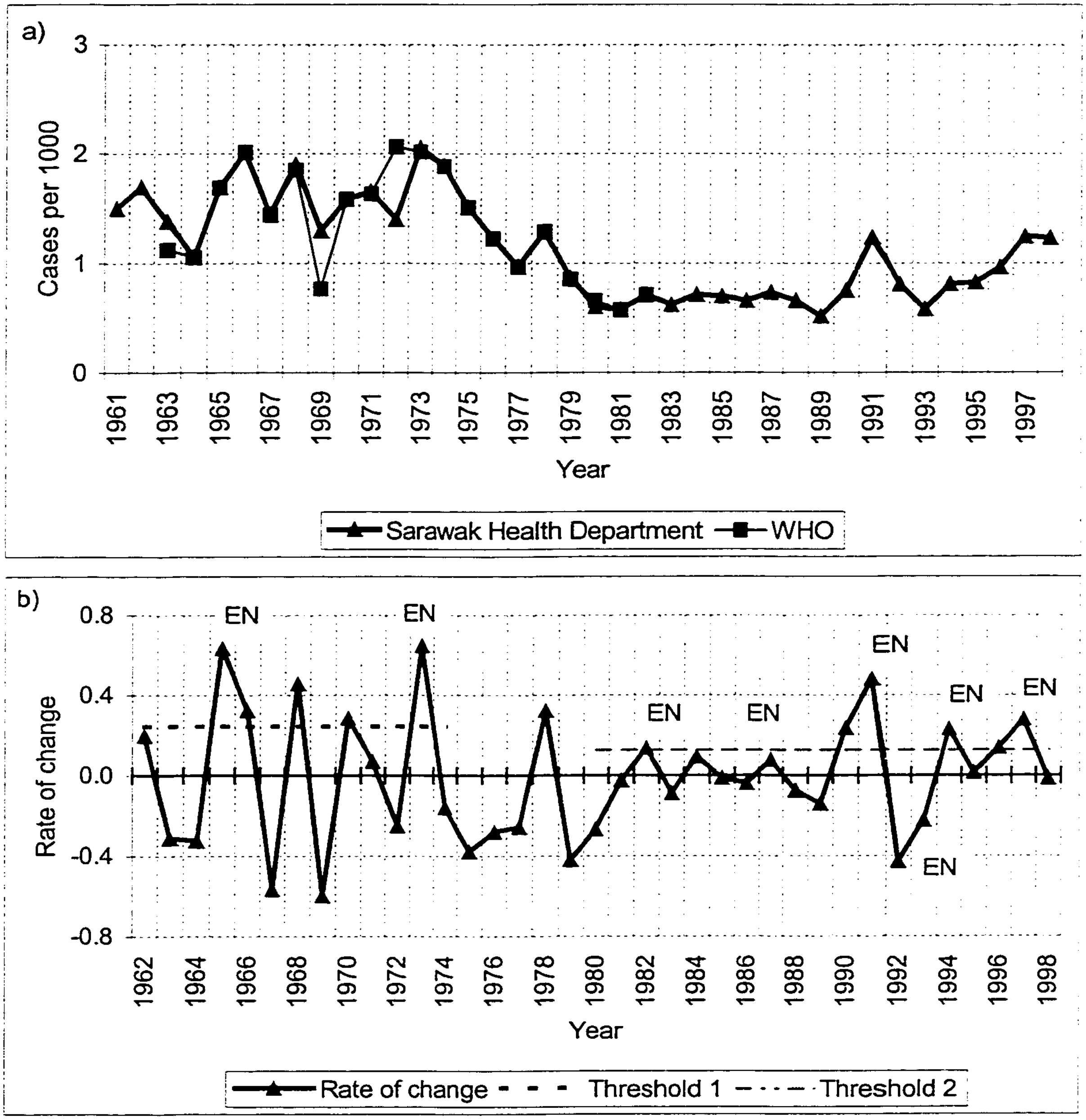

Figure 5.14. Malaria in Sarawak. Cases per 1000 (a), and rate of change (b).

The only El Niño that was associated with warmer and drier conditions and that did not generate a malaria epidemic in Sarawak is the 1986/87 episode. Also, the 1978 peak in malaria cases was not associated with ENSO. Resistance of *falciparum* malaria to chloroquine and a high number of imported cases that led to secondary infections among the native Punans are two explanations for this peak in malaria transmission (WHO, 1980).

In Thailand, there is also a major contrast between the two sources of data prior to 1972 (Figure 5.15a). As in the Philippines and Sarawak, data from the national department of public health were selected for further analysis. The incidence of malaria constantly increased from 1972 through 1982 in this country. After a period of more or less stable incidence, malaria transmission further decreased from 1989 until the 1997/98 El Niño.

Malaria epidemics occurred during 1973 and 1986, two Niño (+1) years (Figure 5.14b). However, the 1973 outbreak could also have been caused by the 1973/74 La Niña, as the rate of change further increased and peaked in 1974. Furthermore, the 1970/71 and 1988/89 La Niñas were also associated with a malaria outbreak. The increase in malaria cases from 1986 through 1988 was partly caused by higher malaria transmission in southern Thailand, because of increased population movement across the border (WHO, 1990). Some epidemics also occurred during non-ENSO years, notably 1980 and 1981.

Only in Sarawak is the relationship between El Niño and malaria epidemics statistically significant (at the 95% confidence level) in Southeast Asia (Table 5.4). Moreover, malaria epidemics in this state are more likely to occur in year Niño (0), i.e., when warmer and drier conditions prevail. The 1972/73 El Niño is the only exception to this pattern, as the epidemic was reported during Niño (+1).

The relationship between La Niña and malaria outbreaks is statistically significant in Thailand (cf., Table 5.4). Regional and monthly epidemiological data would be necessary to draw conclusions for this country, since the relationship between ENSO and rainfall variations in Thailand is not spatially consistent and also varies seasonally. Unfortunately, these data are not collected at this time (P. Ngamtao, *personal communication*).

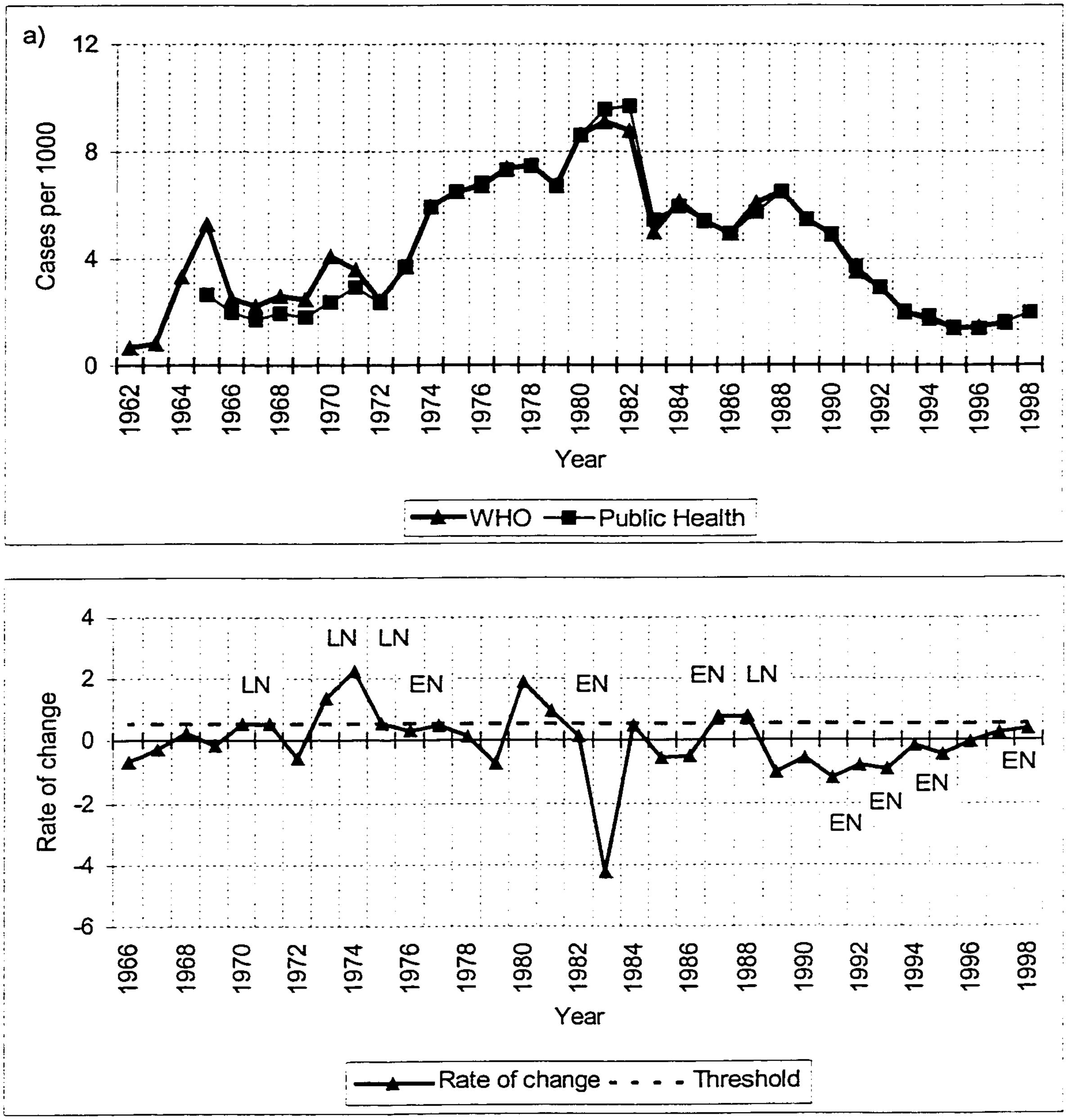

Figure 5.15. Malaria in Thailand. Cases per 1000 (a), and rate of change (b). Because the data from the national department of public health were selected for further analysis, the time series of the rate of change begins in 1966.

Table 5.4. Results of the Fisher's exact test for malaria in countries of Southeast Asia[†].

Country	Niño (0)	Niño (+1)	Niño (0) or Niño (+1)	La Niña years
Indonesia	0.38	0.42	0.47	[1]0.46
Philippines	0.00	0.39	0.67	—
Sarawak	*0.91	0.32	**0.97	0.38
Thailand	—	[2]0.00	[2]0.34	**0.99

[†] Results refer to one minus the p-value

*Statistically significant at the 90% level

** Statistically significant at the 95% level

(—) Not calculated since no epidemic occurred during an El Niño event.

[1] Computations started in 1972, because of the absence of year Niña (0) of the 1970/71 episode.

[2] Computations started in 1967, because of the absence of year Niño (0) of the 1965/66 episode.

Chapter 6: Discussion and Conclusion

In addition to summarise the results of this thesis, the first and second sections of this chapter include some suggestions that explain the relationships identified between ENSO and dengue/DHF epidemics and ENSO and malaria epidemics, respectively. Also included are explanations for the lack of a relationship between ENSO and disease epidemics in a few countries. Finally, we mention the practical use of those correlations for a better control of dengue/DHF and malaria in the tropics.

6.1 Dengue/DHF

This thesis reveals a statistically significant relationship between El Niño and epidemics of dengue and DHF in Colombia, French Guiana, Indonesia, and Suriname. Moreover, epidemics tend to occur in Niño (+1) in Colombia and Indonesia, and in Niño (0) in French Guiana and Suriname. It was demonstrated that during El Niño episodes, French Guiana, Suriname, and Colombia normally experience below average rainfall from May (0) through April (+1), and warmer temperatures. Further, hydrological analysis showed that the height of most Colombian rivers was decreasing during El Niño episodes, with the lowest river height generally reported by the end of Niño (0). Though river height slowly returns to normal conditions during Niño (+1), it was still considerably below average during most epidemics (e.g. 1983, 1987, and 1992) (cf., Table 3.5). Therefore, it is concluded that dengue epidemics in northern South America are more likely to occur during droughts.

In Indonesia, warmer temperatures prevail in most of the country from September (0) through May (+1). In contrast, the negative rainfall anomalies engendered by El Niño generally appear as early as January (0) and persist for at least one year. Nevertheless, they are strongest and statistically significant from June (0) through November (0), when most of Indonesia experiences its dry season. These patterns are particularly evident on the island of Java, where the majority of DHF cases originate.

Monthly epidemiological data and estimates of rainfall for the 1994 through 1998 period were analysed to determine the climatic variations associated with DHF epidemics in Indonesia. Using the CMAP grid-based data set, total monthly precipitation was estimated by averaging all grid cells over the island of Java. These rainfall estimates were then compared with the monthly incidence of DHF.

Results show that the 1995 and 1998 epidemics occurred following the onset of rainfall and not during the drought (Figure 6.1). Nevertheless, the magnitude of the epidemics does not appear to be related to rainfall amplitude. A minimal quantity of rain fell for approximately five months during the two Niño (0) years that preceded the epidemics, suggesting that prolonged droughts seem to spawn DHF epidemics (cf., Figure 6.1). Therefore, the likelihood of a DHF epidemic increases during Niño (+1) years in Indonesia, following a prolonged drought. Table 6.1 lists the countries with a statistically significant correlation between ENSO and dengue/DHF epidemics, together with the ENSO year with high epidemic risk and the climatic anomalies associated with the spawning of those epidemics.

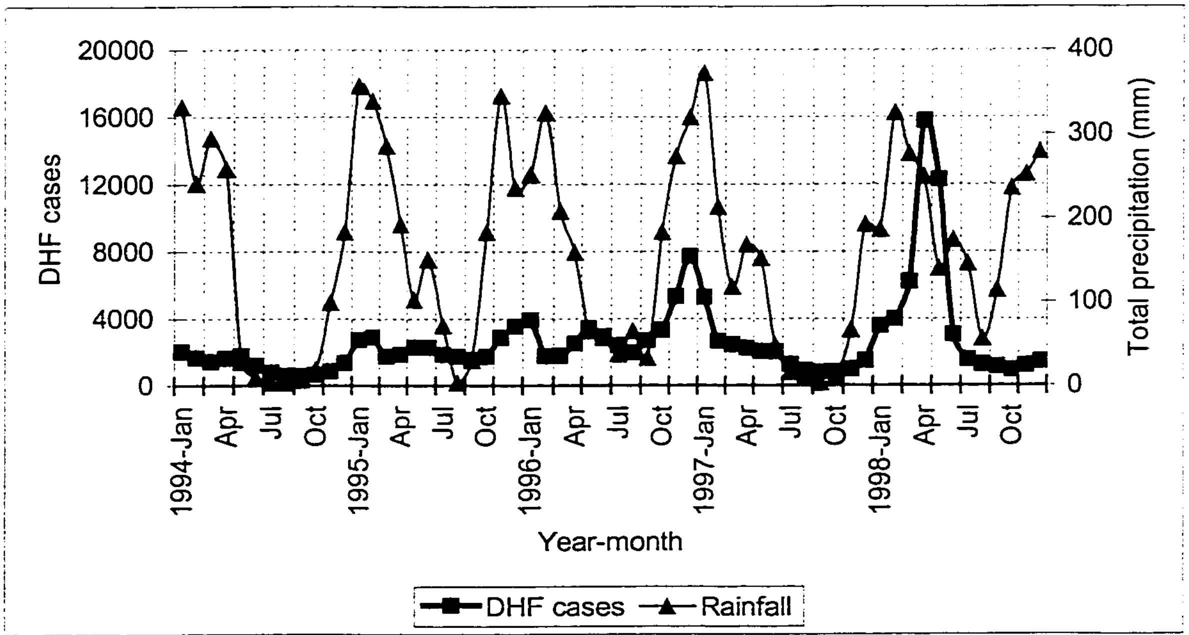

Figure 6.1. The relationship between monthly DHF cases and total monthly precipitation on the island of Java (Indonesia).

Table 6.1. ENSO year with high dengue/DHF epidemic risk and the climatic anomalies associated with the spawning of those epidemics.

Country or territory*	Year with epidemic risk	Climatic conditions
Colombia	Niño (+1)	Dry and warm
French Guiana	Niño (0)	Dry and warm
Indonesia	Niño (+1)	Dry and warm
Suriname	Niño (0)	Dry and warm

*Only countries with a statistically significant correlation between ENSO and dengue/DHF epidemics are included.

Warmer temperatures are likely to increase the incidence of dengue and DHF by lengthening the life span of mosquitoes and by increasing the replication rate of dengue viruses. The magnitude of the temperature anomalies during El Niño, however, is significant, but seems too small to spawn dengue epidemics in northern South America without the contribution of rainfall variations.

In some regions, such as in southwestern Puerto Rico, the incidence of dengue is related to rainfall variations, because it is associated with the availability of mosquito breeding sites. In other regions, however, such a relationship is not clear-cut. The vector of dengue and DHF in South America and Southeast Asia, respectively, is *Ae. aegypti*. As previously mentioned, it is a domestic species that breeds in artificial water containers such water storage containers, plant pots and discarded car tires (Frost, 1991). Thus, in some regions, non-climatic factors such as the collection of rainwater due to the non-accessibility of piped water and poor garbage disposal also influence the availability of mosquito breeding sites, and hence the incidence of dengue and DHF (PAHO, 1994b).

During prolonged droughts, such as in El Niño years, water supply is a problem in Colombia and storage of water increases, increasing the number of breeding sites for *Ae. aegypti* (Poveda *et al.*, 1999). Likewise, Ungchusak and Kunasol (1988) associated the large 1987 DHF epidemic in Thailand to the dry conditions that existed during the summer season, because the drought forced people to store water. The incidence of DHF is generally highest in the driest areas of Northeast Thailand and DHF outbreaks in this region generally precede the rainy season (Eamchan *et al.*, 1989). A similar explanation is possible in French Guiana and Suriname.

In addition to less abundant rainfall, warmer temperatures also contribute to drought conditions, as they increase potential evapotranspiration. Potential evapotranspiration is the quantity of moisture that would evaporate and transpire if it were available (Christopherson, 1994). The combination of both warmer temperature and less abundant rainfall is therefore suggested for the spawning of dengue and DHF epidemics in Colombia, French Guiana, and Suriname.

As opposed to dengue epidemics in South America, DHF epidemics in Indonesia tend to occur following a drought and not during the drought. Two suggestions are provided to explain this correlation. First, the intensity of the drought (particularly on the island of Java), might result in empty water containers in most houses after a few weeks, especially if piped water has been interrupted. Thus, to take the maximum benefit of the infrequent rainwater, people might place numerous buckets and others receptacles outside the house. If those receptacles are not removed after the beginning of the rainy season (and they are likely not to be if piped water is irregular) they would provide ideal breeding grounds for mosquitoes.

Second, the drought may reduce the population of mosquitoes and their predators. Since the increase in the population of mosquitoes is substantially faster than that of their predators, the mosquito population is high for a certain time period at the beginning of the rainy season (Bouma and Dye, 1997). Analogously, the 1993 outbreak of hantavirus in the Southwest of the United States occurred following intense rains generated by the 1992/93 El Niño, but it was also preceded by a prolonged drought. The drought reduced the population of predators such as owls, coyotes, and snakes that prey on rodents that transmit the disease. The intense rains associated with El Niño increased the population of insects on which rodents feed. Since the increase in the population of rodents lagged behind that of mosquitoes, mosquito density was high for a certain time period, spawning a hantavirus outbreak (Stern and Easterling, 1999).

Dengue fever has been endemic in the rural areas of Southeast Asia for many years. In those regions, notably in Sarawak, the vector of dengue is *Ae. albopictus* (Aiken and Leigh, 1978; Chang *et al.*, 1981). *Ae. albopictus* breeds mainly outdoors in broken bottles and domestic containers, as well as in natural habitats such as in the axils of the leaves of banana and pineapple trees (Chang and Jute, 1986). Thus, the population of *Ae. albopictus* is likely to be affected by rainfall patterns. In the Philippines, for example, Schultz (1993) found that the incidence of dengue increases 2 months following the onset of the rainy season. Foo *et al.* (1985) identified a similar relationship in Peninsular Malaysia. Only in Sarawak was the correlation between ENSO and dengue analysed in Southeast Asia. No statistically significant relationship was found, however. Different results might have been obtained had it been possible to do the analysis in rural areas only. Such an analysis was not possible, because of aggregation of the data at the state scale.

An increasing trend-line is present in the dengue and DHF time series of most South American and Southeast Asian countries. Population growth is not an explanation, however, as the disease cases were normalised by the population. Rapid urbanisation may explain part of the increase, because water supply and other basic public services such as sewage and waste management do not keep pace with rapid urban growth in many developing countries, increasing the availability of mosquito breeding sites (Carrada-Bravo, 1987; Gómez-Dantés, 1991; Gubler and Clark, 1995). Moreover, rapid urbanisation is also associated with squatter settlement, such as in Kuala Lumpur (Malaysia). Mosquito breeding abounds in squatter settlements, because the unavailability of piped water makes the storage of water a necessity (Aiken and Leigh 1975).

Furthermore, Gubler and Clark (1995) mentioned the deterioration of the public health services in Latin America and increased air travel, which allows for the introduction of new dengue viruses, as other explanations. In addition, the improvement of the reporting system was suggested by Eamchan *et al.* (1989) to explain the rising trend of DHF in Thailand, which might also be a factor in other countries. Finally the expansion of the geographical range of dengue and DHF might be one of the most important factors.

In Thailand, for instance, DHF was first identified as an urban disease, but it is now spreading to rural areas (Eamchan *et al.*, 1989). Also, the number of regencies (i.e., municipalities) reporting DHF cases has been increasing in Indonesia since the identification of the first case of DHF in 1968 (Figure 6.2). The increase continued in 1997 and 1998 though the exact number of regencies affected was not provided (R. Kusriastuti, *personal communication*).

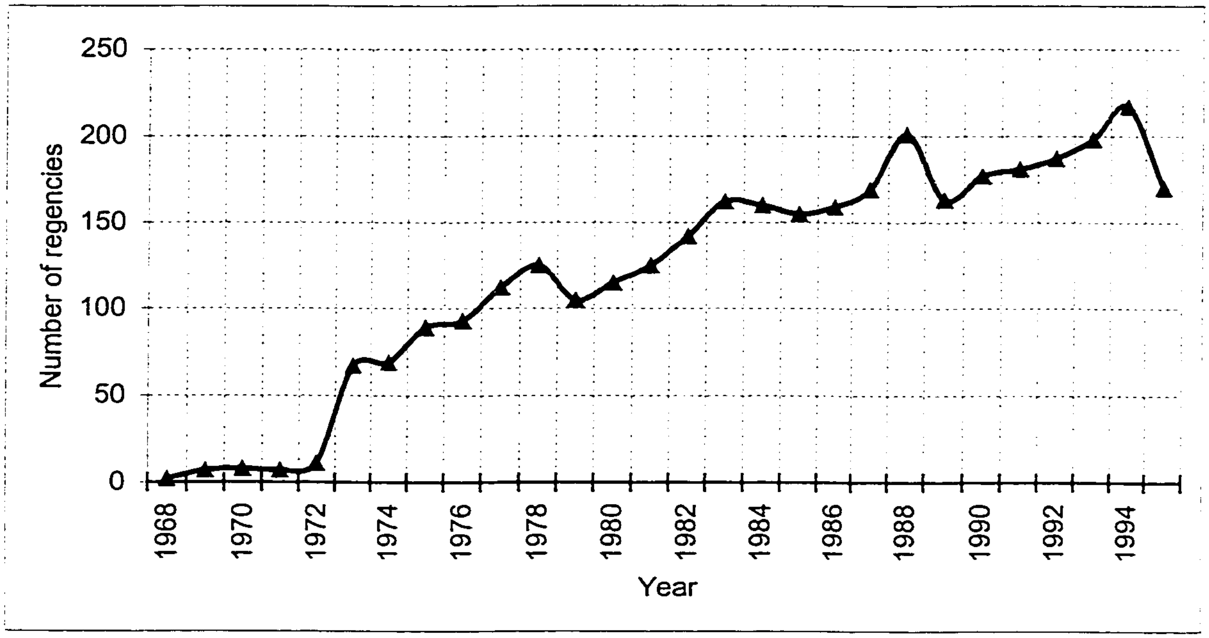

Figure 6.2. Number of regencies reporting DHF cases in Indonesia. (Data were provided by the WHO-regional Office for Southeast Asia.)

Patz *et al.* (1998) found that the potential of dengue epidemics would increase world-wide with a temperature rise of only 1°C or so, as predicted for the year 2050 by many General Circulation Models (GCMs). Their epidemiological model, however, did not consider precipitation changes that might occur under climate change and the cultural factors affecting the availability of *Ae. aegypti* breeding sites. The increasing temperature trend present at most weather stations could therefore explain part of the increase in dengue and DHF transmission or even provide an explanation for their geographical spread. It was suggested that more frequent and intense El Niños and global warming might have caused this temperature trend.

6.2 Malaria

A statistically significant correlation between malaria outbreaks and El Niño was demonstrated in Peru, Colombia, Guyana, and Sarawak. In Peru, warm and humid air condenses as it rises on the eastern slopes of the Andes, generating abundant rainfall on the Amazonian slope. On the lee side, air subsidence as well as cold SSTs produce dryness in coastal Peru (Martyn, 1992). During El Niño the warming of SSTs off the coast of northern Peru engenders torrential rain, particularly in the departments of Piura, Tumbes, and Lambayeque (A. Martinez, *personal communication*; cf., Figure A4.4). Hence, malaria transmission is low in non-El Niño years in northern Peru, because the dry climate restricts mosquito habitats. Because of the low incidence of malaria in the region, the population lacks protective immunity and when environmental conditions favour the spread of malaria, such as during El Niño episodes, epidemics occur following the retreat of water from flooded lands (Bouma and van der Kaay, 1994).

Colombia, Guyana and Sarawak also experience malaria epidemics during El Niño episodes. Although epidemics generally occur during Niño (0) years in Sarawak, there is no consistency in whether epidemics occur in Niño (0) or Niño (+1) in Colombia and Guyana. In Sarawak, dryness is limited to Niño (0), whereas in Colombia and Guyana, it extends over both Niño (0) and Niño (+1), because of the tendency of negative hydrological anomalies to peak by the end of Niño (0). Thus, in the three countries malaria epidemics occurred during periods with warmer temperatures, less abundant rainfall, and low river height and river discharge. Moreover, the largest increase in malaria transmission in Colombia during the 1997/98 El Niño was observed in the Pacific region, where total annual precipitation is extreme in normal and La Niña years.

There is evidence of seasonal variation in malaria transmission in Brazil's Amazon. Camargo *et al.* (1996) found that in Candeias do Jamary, a village in

Rondônia, malaria transmission occurs year-round with a higher incidence in the dry season. However, in addition to El Niño, other climatic phenomena generate droughts in southern Amazon, and dryness has also occurred in normal and La Niña years. These dry, non-El Niño years also spawned malaria epidemics.

It is unlikely that the small temperature anomalies during El Niño episodes can spawn malaria epidemics without an increase in the population of mosquitoes (refer to Section 1.2 for examples of temperature variations on malaria transmission). It is therefore suggested that numerous mosquito habitats become available under dry conditions. A large percentage of mosquito habitats are probably washed away in normal and La Niña years, because of heavy rainfall and high water level. Lowered river height and slower river discharge in El Niño years might create new breeding grounds, as many *Anopheles* species breed in ponds of stagnant water alongside rivers, as previously observed in Sri Lanka by Bouma *et al.* (1994). Figure 6.3 illustrates examples of breeding sites that become available under dry hydrological conditions. Moreover, malarial mosquitoes can also breed in open water tanks that are used to store water as observed in Guayaquil (Ecuador; Cedeño, 1986). Also, Colombia, Guyana, and Sarawak enjoy equatorial wet climates, and in drier El Niño years, the relative humidity is still likely to be favourable to mosquito survival. Therefore, a warmer and drier climate, i.e., drought conditions, associated with El Niño generally increases the risk of malaria epidemics in Colombia, Guyana, and Sarawak.

In Venezuela, the risk of a malaria epidemic generally increases in the year following a drought. Bouma and Dye (1997) previously explained this relationship by an increase in mosquito population, as the increase in the population of mosquitoes is substantially faster than their predators' following a drought. We previously suggested a similar explanation for DHF epidemics in Indonesia.

In contrast to Guyana, no relationship was found between El Niño and malaria epidemics in neighbouring Suriname. In the coastal region of Suriname, malaria transmission is limited to the submerged and forested areas during the rainy season, because the tidal action of the sea washes out mosquito breeding sites alongside rivers (Rozendaal, 1991). Nevertheless, at the national scale, peaks in biting densities are correlated with high water level in the long rainy season, low water level in the long dry season and abundant rainfall in the short rainy season. Similarly, data collected by the Anti-Malaria Campaign show that peaks in malaria transmission are common during the long dry season, and smaller peaks are also observed during the long rainy season (Rozendaal, 1992). As a result of the availability of mosquito breeding sites under a variety of hydrological conditions, malaria epidemics cannot be predicted from ENSO-generated rainfall patterns in Suriname.

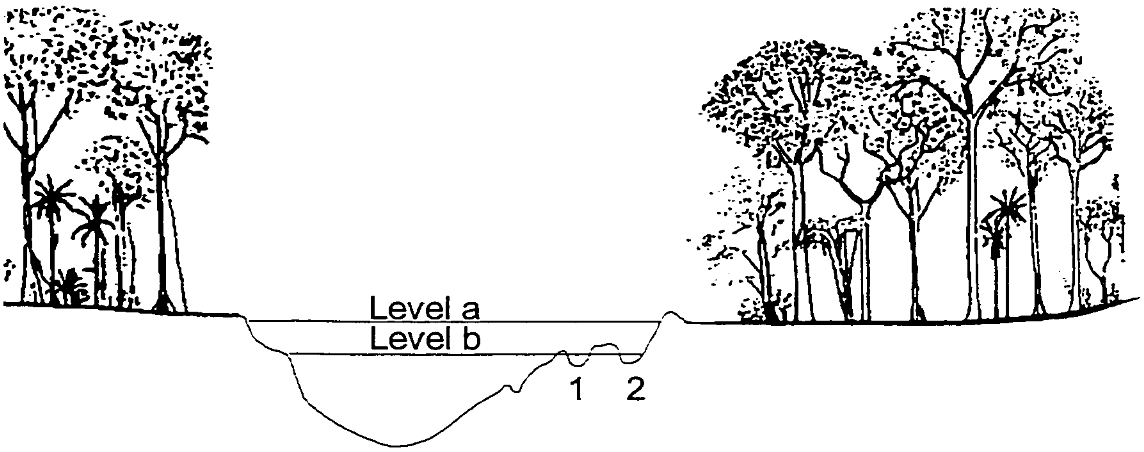

Figure 6.3. Example of mosquito habitats (as represented by numbers 1 and 2) appearing in dry periods. Level "a" refers to the river height in normal years, and level "b" to that of El Niño years. (Figure modified from Rozendaal, 1992, p.19).

French Guiana is divided into three epidemiological regions: the coast; the Amazon, located in the southernmost portion of the territory; and the transition zone in-between. In the coastal region, outbreaks occur when new hosts of the malaria parasites move into a region with high mosquito density. In the Amazon, malaria is endemic and cases are more or less constantly reported throughout the year, mostly from children since the majority of adults have acquired immunity. In the transition zone between the coast and the Amazon, malaria transmission is periodical and, hence, immunity is not acquired by the population (Cochet *et al.*, 1996). In this region, the incidence of malaria generally peaks during the driest months of the year, when the mosquito population is highest. In other months, excessive rainfall washes away mosquito breeding sites (Esterre *et al.*, 1990; Juminer *et al.*, 1981).

No relationship was identified between the drier conditions engendered by El Niño and malaria epidemics in French Guiana. With the exception of a drastic increase in malaria transmission in the late 1980s, which was associated with the non-climatic factors described in the previous chapter, malaria is considerably well controlled in French Guiana (Cochet *et al.*, 1996). For instance, malaria transmission has been gradually decreasing since 1990, as opposed to a drastic increase in most other Latin American countries. Since French Guiana is officially part of France (like Guadeloupe and Martinique, it is known as a French *department d'Outre-mer*), it benefits from the financial and technical help from the latter country, possibly explaining the relatively good control of malaria in the region.

Cabrera and Arambulo (1977) found that in regions with a distinct dry and wet season in the Philippines, the incidence of malaria is seasonal, because the density of mosquitoes varies with rainfall. Malaria transmission is usually interrupted during the dry season because small streams dry up. Conversely, mosquito breeding sites are often washed away by torrential rains during the rainy season. Consequently, the incidence of malaria is generally highest at the beginning and towards the end of the dry season, when rainfall increases again. No relationship with ENSO-generated rainfall anomalies was found, however. This lack of relationship might be the result of successful control measures, as the incidence of malaria has been fairly low and constant since the end of the malaria eradication programme in 1970. Table 6.2 lists the countries with a statistically significant correlation between ENSO and malaria epidemics, together with the ENSO year with high epidemic risk and the climatic anomalies associated with the spawning of those epidemics.

In all the Latin American countries analysed in this study a gradual increase in malaria transmission is observed. For some countries, explanations have previously been suggested. Interestingly, none of the Southeast Asian countries show this increasing trend in malaria transmission, suggesting that global warming might not be an explanation for higher malaria incidence in recent decades in South America, since increasing temperatures are also observed in Southeast Asia.

Table 6.2. ENSO year with high malaria epidemic risk and the climatic anomalies associated with the spawning of those epidemics.

Country or state*[1]	Year with epidemic risk	Climatic anomalies
Colombia	Niño (0) and Niño (+1)	Dry and warm
Guyana	Niño (0) and Niño (+1)	Dry and warm
Peru	Niño (+1)	Wet and warm
Sarawak	Niño (0)	Dry and warm
Venezuela	Niña (0)[2]	Dry and warm

*Only countries with a statistically significant correlation between ENSO and malaria epidemics are included.

[1] Thailand is excluded because of the lack of data to explain the relationship.

[2] Epidemics generally occur following an El Niño-induced drought and seem unrelated to La Niña-related rainfall anomalies.

In Latin America, we noted that there has been a gradual decrease in the annual number of houses sprayed with insecticides (e.g. Suriname, cf., Figure 4.4). This reduction in the use of insecticides has previously been suggested for the rising trend in malaria transmission in recent decades in Colombia (Bouma *et al.*, 1997). Ecuador is the only country in South America that still uses DDT to eradicate malaria mosquitoes and with the exception of French Guiana, it is also the only country that reported a decline in malaria transmission in the 1990s (Roberts *et al.*, 1997). Although insecticide data were not available from French Guiana in recent years, the number of house insecticide sprayings was 68,000 in 1989, more than any other year in prior decades. Insecticide data have yet to be collected for Southeast Asian countries to see if the lack of a rising trend in malaria transmission is explained by a more or less constant use of insecticides during the study period.

Other explanations have been suggested to explain the increasing trend in malaria incidence in Latin America, including resistance to insecticides and anti-malaria drugs, and new development policies in regions where malaria transmission is a problem such as the Amazon basin. Development activities such as agricultural expansion, road building, and irrigation often lead to higher malaria incidence because of the migratory movements they cause as well as the numerous mosquito breeding sites they create (Liese, 1998).

6.3 Conclusion

In a report recently published, the PAHO (1998c) noted that flooding is likely to have an impact, though small, on the incidence of dengue and malaria in Latin America. In addition, they mentioned that drought does not have any impact on malaria and its impact on dengue is unknown. Furthermore, no mention of the effect of temperature variations was noted for dengue, though the report includes the possibility of temperature variations on malaria incidence. This thesis has demonstrated that flooding engenders malaria epidemics in the dry region of northern Peru. Contrary to PAHO's report, this thesis found that droughts were associated with malaria epidemics in Guyana, Colombia, Sarawak, and Venezuela. Moreover, droughts are also associated with dengue/DHF epidemics in Colombia, French Guiana, Suriname, and Indonesia. Figures 6.4 and 6.5 summarise the results of this thesis for dengue (including DHF) and malaria, respectively. These new results will aid in updating the PAHO report.

This information, when coupled with El Niño and climate forecasts can be useful in identifying high risk years for the spawning of dengue/DHF and malaria epidemics. The International Research Institute for Climate Prediction (IRI) provides seasonal (i.e., 3 months) climate forecasts for different regions around the world. Climate forecasts are created according to two main procedures. First, SSTs in the tropical Pacific Ocean are predicted using coupled ocean-atmosphere models such as the coupled model from the climate modelling branch of the NOAA NCEP. Second, dynamic models of the atmosphere and statistical analyses of historical data relating climatic variability to SST in the tropical Pacific Ocean provide probabilities of above average, normal, or below average temperature and precipitation over specific regions.

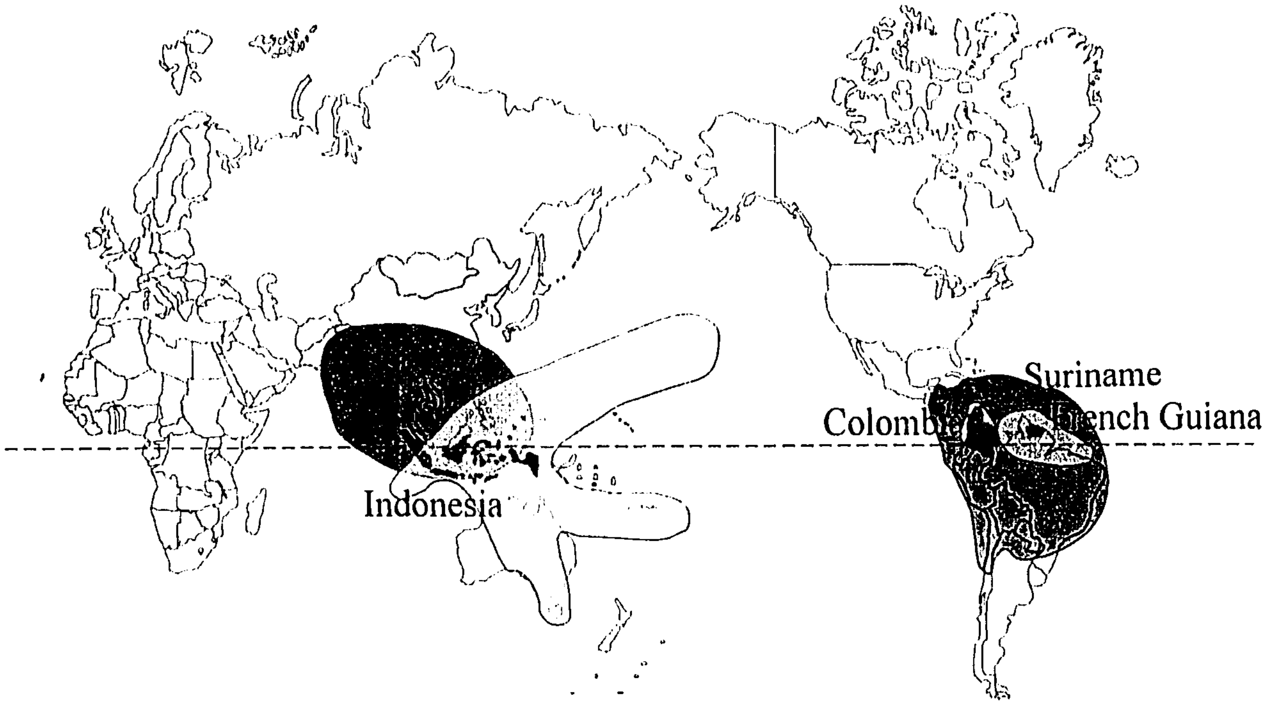

Figure 6.1. Countries with a statistically significant correlation between El Niño and dengue/DHF epidemics. Dark grey shading indicates warmer climatic conditions and light grey shading indicates drier conditions during El Niño. (Temperature anomalies are only plotted for the landmasses.)

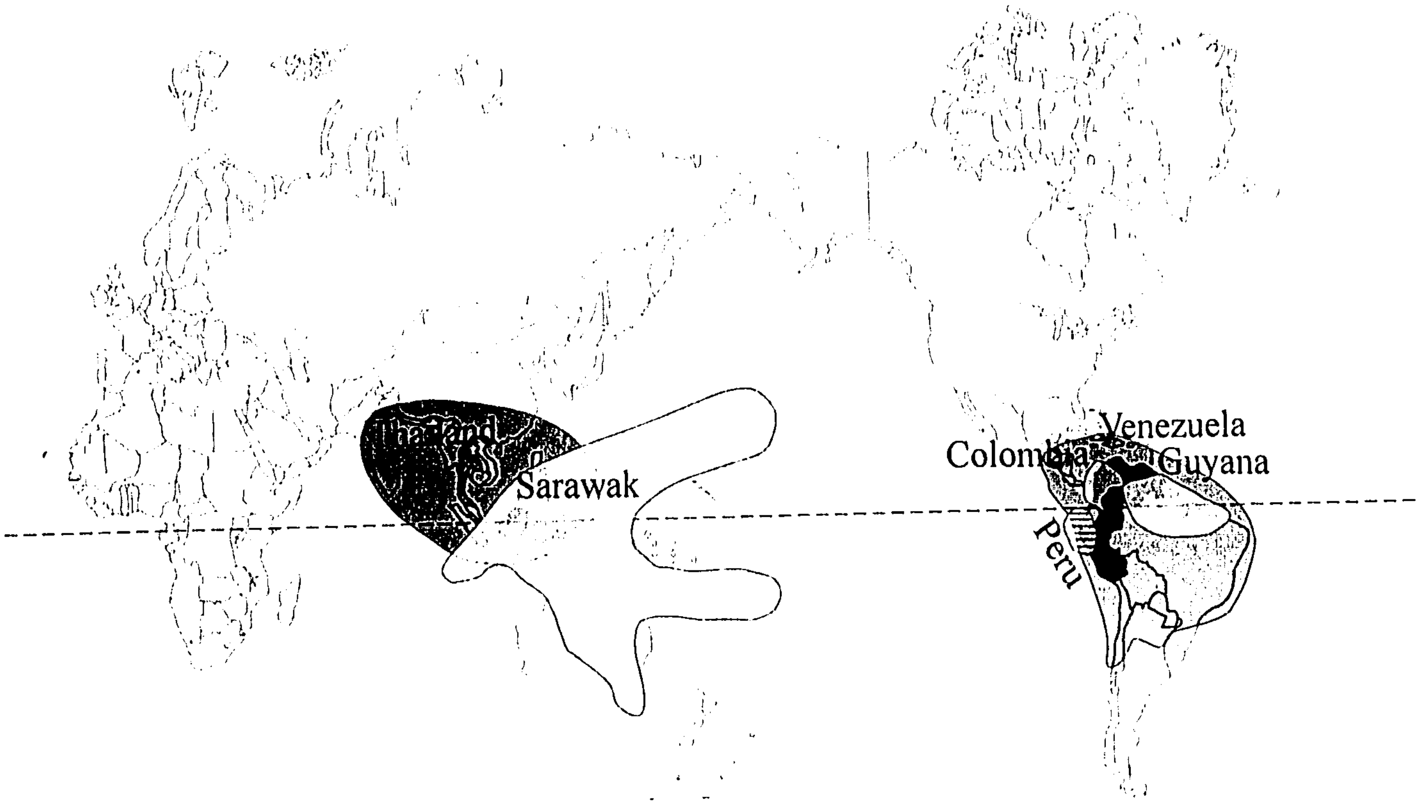

Figure 6.2. Countries with a statistically significant correlation between El Niño and malaria epidemics (black), and La Niña and malaria epidemics (dotted). Dark grey shading indicates warmer climatic conditions and light grey shading indicates drier conditions during El Niño. El Niño usually generates abundant rainfall in western South America (striped area). (Temperature anomalies are only plotted for the landmasses.)

This research shows that in certain regions, public health officials could potentially take advantage of El Niño and the associated climate forecasts to take measures that could prevent epidemics of malaria, dengue, DHF, and possibly other mosquito-transmitted diseases. These models are presently reliable for large geographical areas. As considerably good relationships between ENSO and epidemics of dengue, DHF, and malaria were identified at the national scale in this thesis, the current spatial scale of climate forecasts seems presently adequate for helping in the control of vector-borne diseases.

Therefore, the public health sector is a potential user of El Niño-related climate forecasts, as they could facilitate early interventions when climatic anomalies favour the spawning of epidemics. Examples of early interventions to avoid dengue/DHF epidemics are media campaigns concerning the breeding sites of *Ae. aegypti,* which might lead people to cover their household water containers; neighbourhood clean-ups (i.e., removing tires and other garbage that create adequate breeding grounds for mosquitoes); as well as insecticide sprayings. In the case of malaria, the distribution of anti-malarial drugs should be facilitated in times when epidemics are forecast, including distribution programmes to those who need but cannot afford the drugs. Coupled with remote sensing techniques, El Niño forecasts could be used to spread larvicides in areas that are likely to become potential breeding sites for Anopheles *mosquitoes*. Remote sensing techniques can be used to localise areas where pools of stagnant water generally form during climatic anomalies (Stern and Easterling, 1999). However, in regions where the relationship between ENSO and climate variability is weak, such as in Brazil's Amazon, the use of El Niño forecast for better control of mosquito-transmitted diseases is limited.

Research needs to be pursued in Thailand, because of the unexplained relationship between La Niña and malaria epidemics identified in this thesis. Hydrological analyses coupled with monthly and regional epidemiological data are necessary, because the impacts of ENSO on rainfall anomalies vary seasonally and are not spatially consistent throughout the country. Also, field research needs to be done in French Guiana and Suriname in order to provide evidence of the hypothesised storage of water during droughts in both countries. Finally, ecological analyses providing evidence of higher density of *Anopheles* and *Aedes* mosquitoes in the year following a drought in Venezuela and Indonesia have yet to be performed.

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Appendix 1: Name and Addresses of Individuals who Provided Climatic, Hydrological and Epidemiological Data (by alphabetical order).

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Appendix 2: Problem of Serial Correlation

To test for the statistical significance of a correlation coefficient between two time series, Fisher's z-transformation is used according to:

$$z = \frac{1}{2}\ln\frac{(1+r)}{(1-r)}, \tag{A2.1}$$

in which z is the normalised value of the correlation coefficient r (Pearson's correlation) between the two time series. This equation transforms the correlation coefficients so that they become approximately normally distributed, with a standard deviation (σ_z) equal to:

$$\sigma_z = \sqrt{\frac{1}{n-3}}, \tag{A2.2}$$

where n is the number of observations in the time series[1] (Quenouille, 1952).

Climatological, hydrological and oceanic data (hereafter referred to as atmospheric/oceanic data) display serial correlation, because of the time-scales involved in their evolution and the relatively rapid frequency with which the data are collected. Atmospheric/oceanic time series are often smoothed using moving averages, further increasing serial correlation (Wohlleben, 1994; Figure A2.1). For that reason, atmospheric/oceanic time series do not meet the assumption of random or independent observations required by standard statistical tests, because the number of independent observations is substantially less than the actual number of observations (Wilks, 1995).

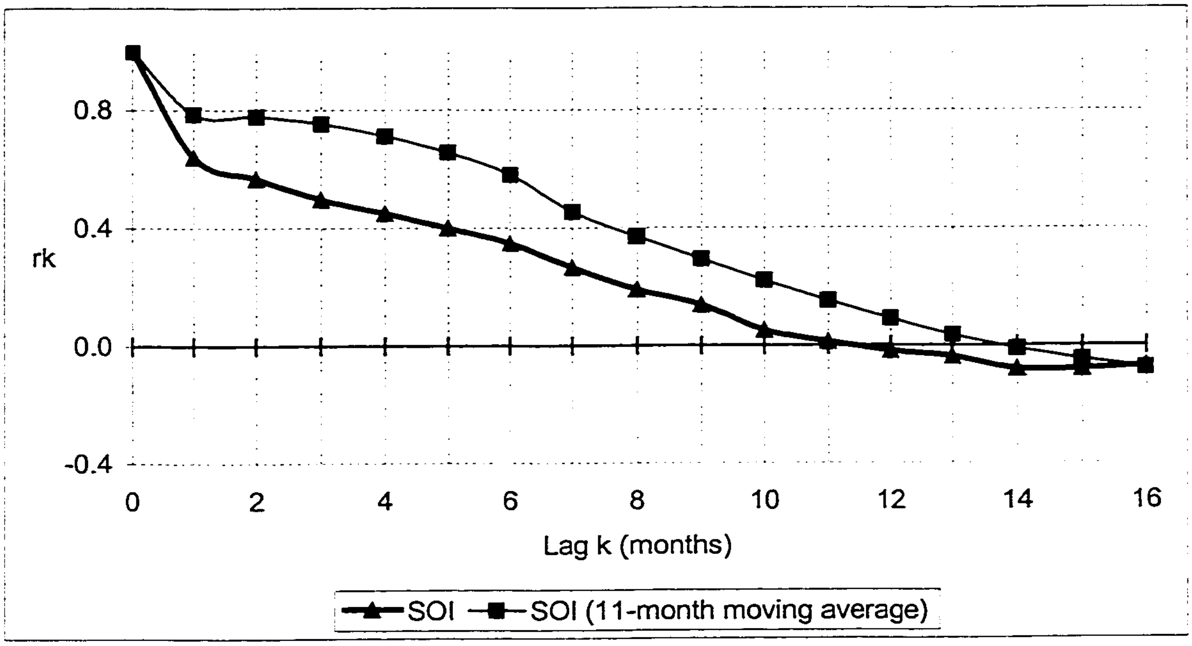

Figure A2.1. Autocorrelation function of the SOI (autocorrelation function refers to the compilation of autocorrelations at various lags).

Serial correlation decreases the sample variance and hence the standard deviation (Wilks, 1995). As the standard deviation is the criterion used to test for statistical significance, a relationship can be determined as statistically significant when no correlation actually exists if serial correlation is not accounted for. Therefore, Quenouille's (1952) method, which is commonly used by the meteorological community (e.g., Hastenrath, 1990; Alexander *et al.*, 1999), is utilised to adjust for serial correlation by identifying the effective number of independent observations in the time series, which can be estimated by the following equation:

$$n' \cong \frac{n}{(1+2r_1r'_1+2r_2r'_2+2r_3r'_3+...)}, \qquad \text{(A2.3)}$$

in which n corresponds to the total number of observations in the time series and n' to the number of independent observations. The autocorrelation coefficients of two time series at k lags (k = 1, 2, 3, 4, ...) are denoted by r_k and r'_k. The lag-k autocorrelation coefficient is obtained by correlating a time series with the same time series shifted by a k-month lag. This equation refers to the degrees of freedom, which are equal to n-2.

Since the time series analysed in this project contain large number of observations, the correction for the degrees of freedom is necessary but relatively minimal (Quenouille, 1952).

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[1] The value of z must equal or exceed two standard deviations for 95% significance

Appendix 3: Example of Contingency Table with Fisher's Exact Test, Testing Independence of Dengue Epidemics between Niño (0) versus Non-Niño (0) years in French Guiana.

In this example, we are testing the hypothesis that the probability of a dengue epidemic during Niño (0) years ($p_1 = 5/7 = 0.71$) is not statistically different from the probability of an epidemic during non-Niño (0) years ($p_2 = 1/21 = 0.048$) (Table A3.1).

Table A3.1. Example of contingency table with Fisher's exact test, testing independence of dengue epidemics between Niño (0) and non-Niño (0) years in French Guiana.

	Niño (0)	non-Niño (0)	
Epidemic	5	1	6
No epidemic	2	20	22
	7	21	28

H_o: Dengue epidemics in French Guiana are not more likely to occur in Niño (0) years than in other years

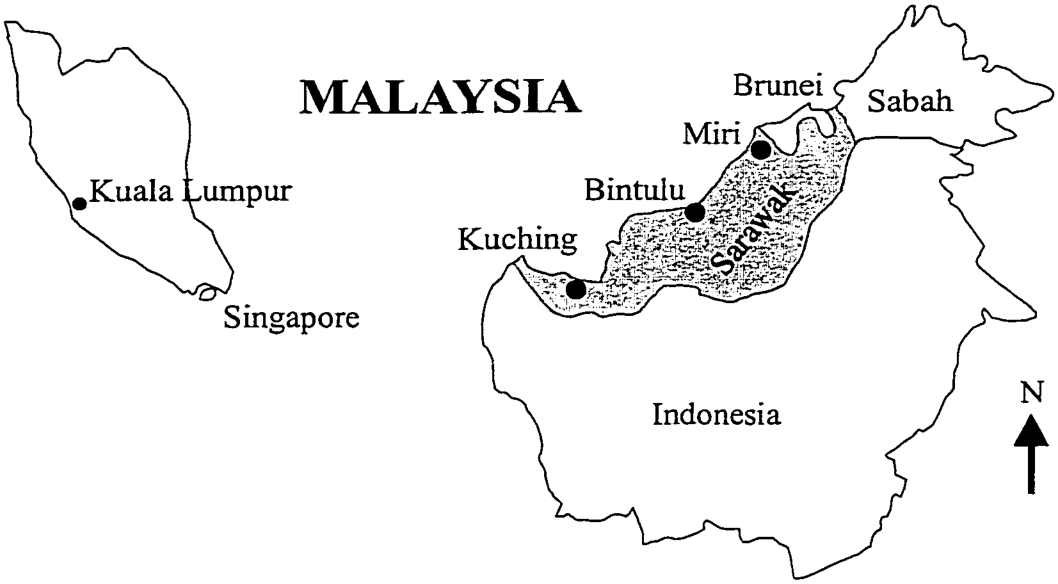
After rearranging the contingency table so that the smallest row total is the first row and the smallest column total is the first column (in this case rearranging is already accomplished), Pr (*a*) is calculated for each possible value of *a* in the above contingency table (i.e., 0,1, ..., 6) (Pr (*a*) is the probability of obtaining *a* in the contingency table; Table A3.2). (Calculation of Pr (*a*) is according to equation 2.2.) Note that *m*, *n*, *r*, and *s* in Table 2.3 are fixed and the other numbers are adjusted according to the new *a* value (Rosner, 1982).

Table A3.2. Probability of obtaining each possible value of *a* (i.e., Pr (*a*)) in the contingency table.

a	Pr (*a*)
0	0.144
1	0.378
2	0.334
3	0.124
4	0.0196
5	0.00118
6	0.0000187

The one-sided p-value is obtained by adding the probabilities greater than or equal to the actual a value (i.e., 5), which give 0.00118 + 0.0000187 = 0.0012. For a two-sided p-value the sum of the probabilities starting at $a = 0$ is calculated up to the point where the sum does not exceed the one-sided p-value. In this case, Pr (0) is already greater than the one-sided p-value (cf., Table A3.2). Hence, the two-sided p-value is 0.0012, meaning a significance level of more than 99%. The two proportions are significantly different, therefore we can say that the risk of a dengue epidemic in French Guiana is greater during Niño (0) years than in non-Niño (0) years (S. Newman, *personal communication*; Rosner, 1982).

Appendix 4. Maps



Scale:
1: 20,000,000

Figure A4.1. Geographical location of the Malaysian State of Sarawak.

Figure A4.2. Map of Ecuador.

Scale:
1: 12,600,000

Figure A4.3. Geographical regions of Venezuela.

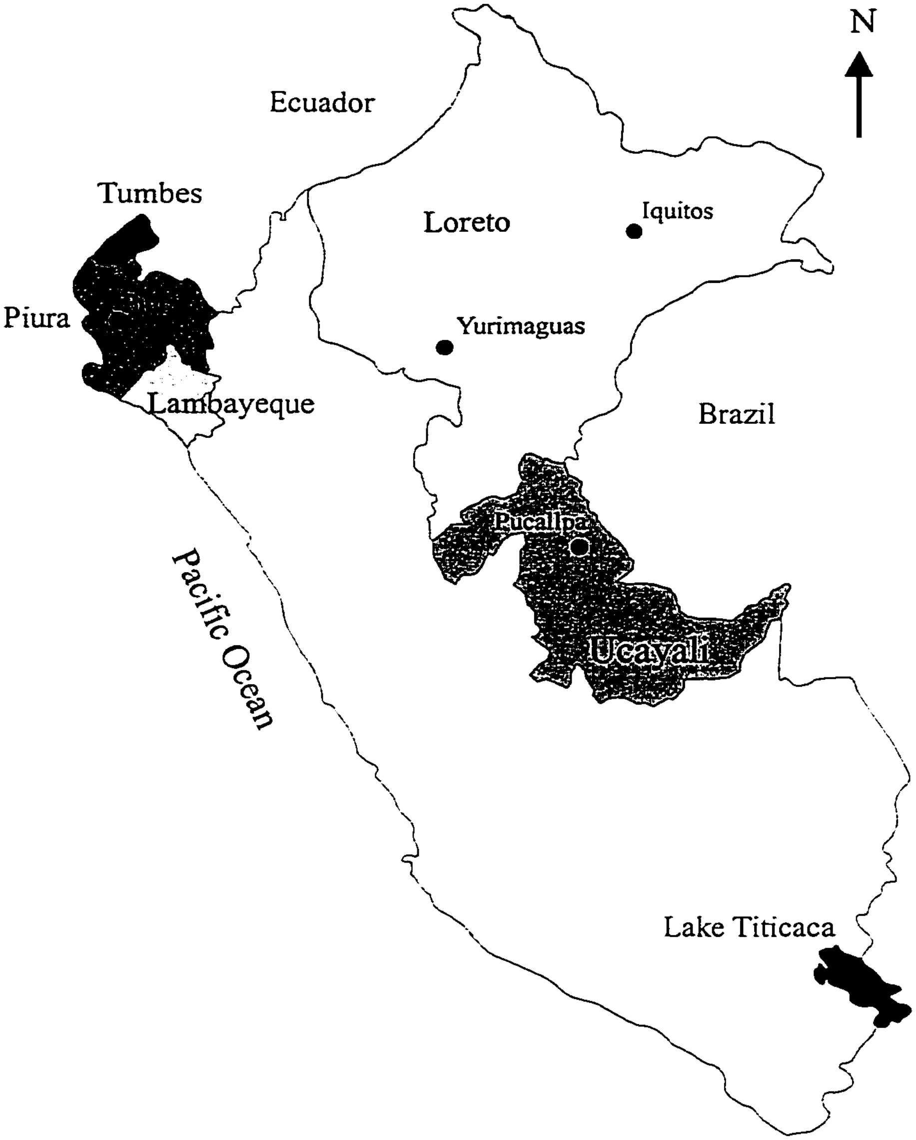


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Figure A4.4. Map of Peru.

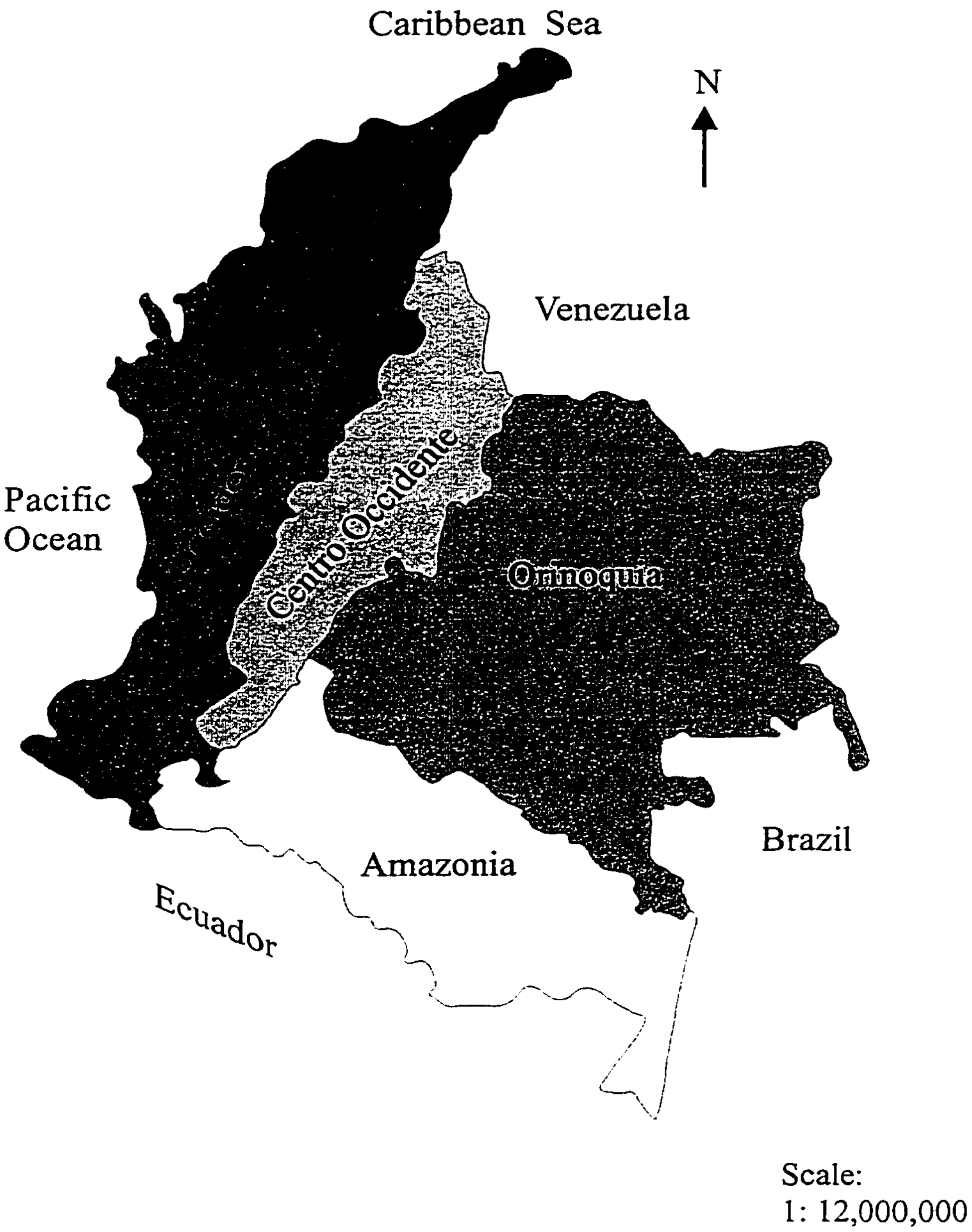

Figure A4.5. The geographical regions of Colombia.

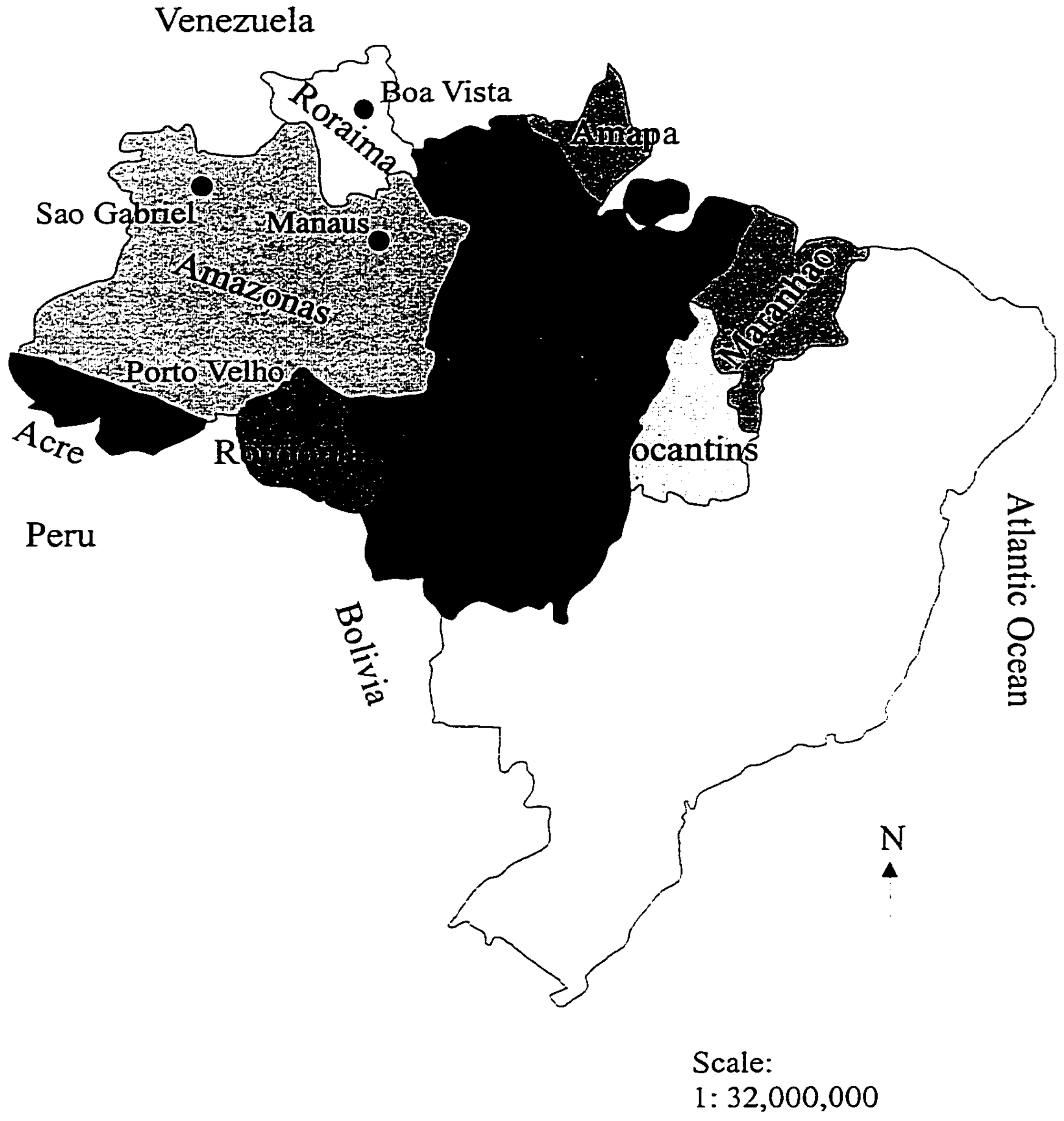

Figure A4.6. States and territories of Brazil's Amazon region.