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CHANGES IN THE MAGNITUDE-FREQUENCY OF LARGE RAINSTORMS AND THE YEAR-TO-YEAR VARIABILITY OF RAINFALL IN MALAYSIA

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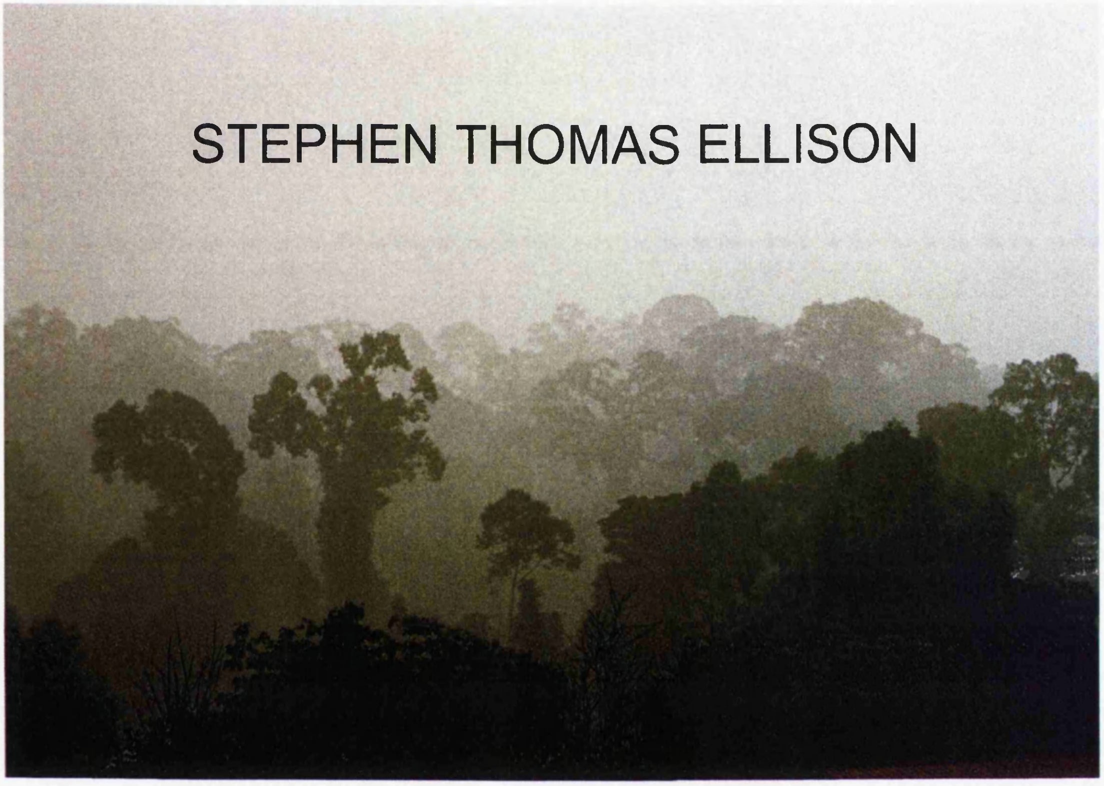

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SUMMARY

Changes in the magnitude-frequency of large rainstorms and the year-to-year variability of rainfall in Malaysia

The aims of the thesis were to investigate changes in:

1. the magnitude-frequency of large rainstorms in Malaysia over a longer timescale than previously examined,
2. seasonal and annual rainfall for the region,
3. year-to-year variability in annual totals and high magnitude rainfall events

Data were collected from a variety of archival sources including rainfall statistics from the British North Borneo Herald and the Sarawak Gazette from the early 20th century. Rainfall records from the post-war period were gathered from a store at the Malaysian Meteorological Service in Kota Kinabalu, Sabah. Monthly and annual totals to complete rainfall series at stations across Malaysia were obtained from ASEAN publications in 1982 and 2004. Recent data were provided by the Malaysian Meteorological Service both in Kuala Lumpur and Kota Kinabalu.

Results suggest that there has been no region-wide change in the magnitude or frequency of extreme rainfall events. Only at Kota Kinabalu was a rainfall decrease found to be statistically significant. Decreases in annual rainfall and an increase in years with low rainfall totals occurred in the northern regions in Peninsular Malaysia and the northwest coast of Borneo. Only the major ENSO events produce negative anomalies across the whole region. Weak and moderate ENSO events caused both high and low annual totals. Sea surface temperatures along with other factors such as wind speed, wind direction, the ITCZ and upper air circulation may have been responsible for the weak correlations found between ENSO events and rainfall events and totals throughout Malaysia.

DECLARATIONS AND STATEMENTS

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed .... (candidate)

Date ......30/01/2007...

This thesis is the result of my own investigations, except where otherwise stated. Where correction services have been used, the extent and nature of the correction is clearly marked in a footnote(s).

Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

Signed .... (candidate)

Date ....30/01/2007............................

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed .... (candidate)

Date ....30/01/2007............................

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Finally, I would like to thank my parents for encouragement and financial backing which allowed me to continue my studies.

CHAPTER 1: INTRODUCTION

1.1 OPENING STATEMENT

This thesis assesses changes in rainfall in Malaysia compared with the other parts of the tropics. It focuses on changes not only in annual and seasonal rainfall but also in the magnitude-frequency of large daily rainstorms. Links to changes in the Southern Oscillation Index are explored and comparisons are made with changes predicted by recent climate models with global warming.

This chapter first examines rainfall and its influences in the study area. It then reviews previous work on rainfall both in SE Asia and the humid tropics in general before identifying the research gaps explored in the thesis. It ends with statements of the aims and hypotheses of the thesis and the structure of the thesis.

1.2 RAINFALL CHARACTERISTICS OF THE STUDY AREA

"Most tropical rainfall is characterized by irregularity and high intensity" (Nieuwolt, 1989). This variability is a threat to agriculture and tropical ecosystems particularly via unusually long droughts and spells of heavy rainfall. Both, however, are often concealed by monthly rainfall averages. In some tropical regions rainfall is so variable that it is close to the mean only in a minority of years. Rainfall deviations are more frequently negative than positive showing the effects on the mean of a few years of excessive rainfall, perhaps linked to the La Niña events in the tropics (Riehl, 1954). Jackson (2003) illustrated that for periods of time over one month the variability in rainfall can differ considerably from one location to another within close proximity to each other (1-20km), even when they contain similar relief, and possess similar long-term averages. This "localness" in rainfall variability is a common feature of tropical latitudes and is important when considering the analysis of changes in rainfall in the tropics.

Figure 1.1. *Map of Malaysia and the stations covered in the thesis.*

Southeast Asia experiences a large variety of tropical climates from perennially very wet to strongly seasonal monsoon climates. The area experiences a range in year-to-year rainfall variability with some areas being more drought-prone than others. The whole region's climate is subject, to differing degrees, to the influence of monsoon winds and the migration of the ITCZ. Coastal and mountain range configurations modify this influence of the monsoonal changes.

The monsoon winds that affect Southeast Asia are a result of the dominance of either the Siberian high-pressure cell during winter, or the Indian summer low pressure centre during the summer and pressure changes over Australia and the Southern Hemisphere. This is known as the Indo-Australian Monsoonal system.

The Siberian high-pressure cell begins its formation in September as the days become shorter and continental Asia cools. The Siberian Anticyclone creates the Northeast monsoon that flows out from the anticyclone across Southeast Asia. Its presence is evident often into May. The source region is dry and cold, but once moving southwards it changes significantly in its characteristics, especially after crossing the China Sea. The other air mass affecting this area in winter is brought by the NE trade winds from the Pacific Ocean north of the equator (Nieuwolt, 1981).

The Indian summer low pressure is the dominant cause of the Southwest monsoon across most of South Asia in summer months. Appearing in March and reaching its greatest development by July, its influence extends eastwards as it strengthens and continues as a dominant feature until October (Air Ministry Meteorological Office, 1945b). South of the Equator a dry season occurs over many parts of Indonesia due to dry air of the Southeast Trades deriving from the high pressure over the Australian continent. Relatively stable air associated with a low-level inversion conditions prevent the vertical development of convectional cells during this period.

During the transition period between the monsoons, winds are typically lighter and more variable. It is at this time at the equinoxes that the ITCZ migrates to become dominant over the equator.

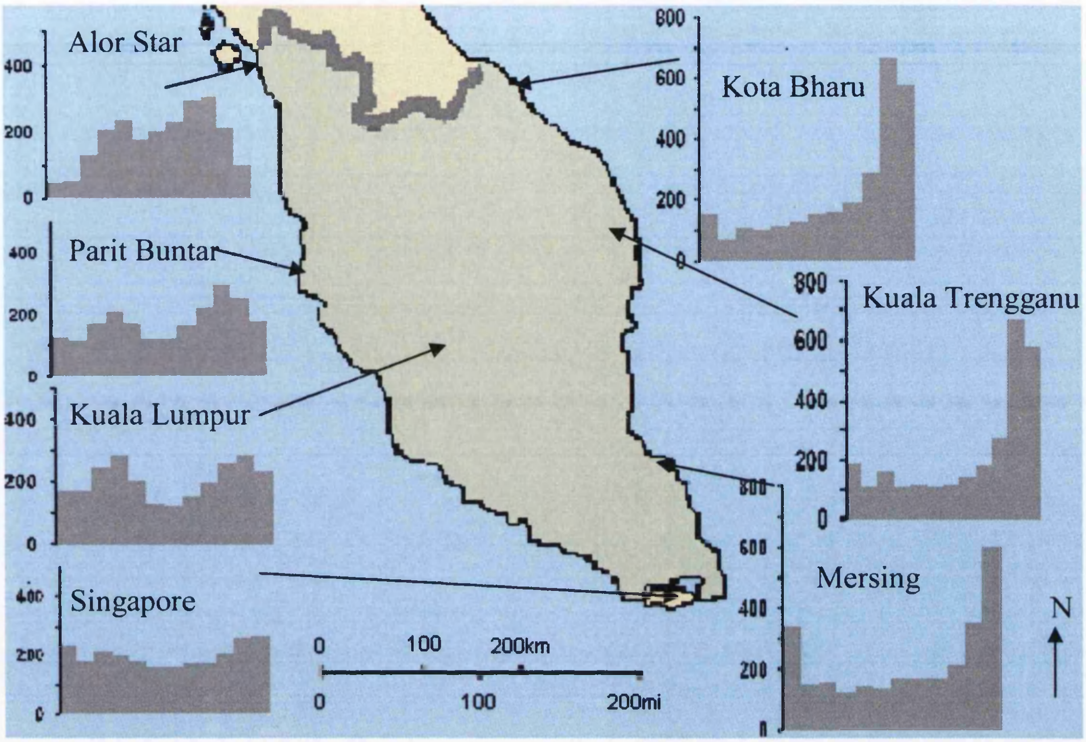
In Malaysia the importance of orographic, convectional or cyclonic rainfall cannot be overemphasised. In most cases it is a combination of all three. Cyclonic rainfall is associated with mid-tropospheric lows (not surface lows). Convectional rainfall is most common in Malaysia, but cyclonic processes produce the heaviest rainfalls (Subramaniam, 1997). Tropical cyclones do not affect Malaysia. Thunderstorms are very common in Malaysia, occurring in the late afternoon as a result of the heating of moist air at the Earth's surface; these clouds can grow to heights in excess of 15km.

In maritime Southeast Asia, the air contains more water vapour than any other equatorial area due to the warm sea surface temperatures surrounding the maritime continent (Lockwood 1974, as cited in Nieuwolt 1977).

1.2.1 THE MALAY PENINSULA

Down the length of the Malay Peninsula the impact of the monsoon systems are dependent on the geographical location, as this determines whether the airflow is onshore or offshore. Distribution of rainfall reflects, to a large extent, the configuration of major topographic features. The diurnal pattern of rainfall is also dependent on geographical location. Inland areas often receive rain from the late afternoon/early evening to the early part of the night. Islands and coastal areas with an onshore prevailing wind generally receive rain during the night or early morning and over the hilly areas rain starts in the early afternoon (Subramaniam, 1997).
On the east coast there is a single seasonal peak in rainfall in the northeast monsoon season, whereas the west coast has two rainfall peaks around the transition months (Figure 2).

Figure 1.2. *Rainfall Regimes in Peninsular Malaysia.*



Average conditions across Malaysia throughout the year are described below, (adapted from Nieuwolt, 1966):

1.2.1.1 <u>The Northeast Monsoon November-March</u>

The northeast monsoon spreads from the north from November. Its progression at the start is slow and occasionally reversed until it peaks during January when the east coast of the peninsula receives particularly bad weather with high intensity rainfalls and strong winds. The west coast and especially the North West is in the rain shadow created by the central highlands and experiences a dry season during the Northeast monsoon (Hsueh, 1972).

Large daily rainfalls occur frequently on the east coast of the peninsula during the northeast monsoon, often as a result of cold surges of air that push down from the north. These outbreaks are associated with temporary breakdowns of the Siberia–Mongolia high (Wu and Chan, 1997). On average 13 cold surges occur in the region between November and March (Zang et al, 1996). It is the remnants of these cold surges that often progress southward to affect Malaysia. Farther south, away from the large influence of the Siberian High, it is the effects of the cold surges that result in a wind maximum in the South China Sea. Intense evaporation and humidification occur as the airmass moves over the warm China Sea and the NW-SE alignment of the topography intensifies the precipitation (Air Ministry Meteorological Office, 1945b).

Apart from isolated areas of high rainfall in the Larut Hills and Kedah Peak in the west of Malaya the wettest part of the country in the north-easterly monsoon months is the east roughly 25-100 miles inland from the coast, in the foothills (Dale, 1959). Year-to-year variability in rainfall is greatest in this season on the east coast with Kuala Trengganu for example, having a coefficient of variability of 113% (Dale, 1960).

1.2.1.2 Transition, April

During March winds become much lighter and more variable, resulting in more uniform rainfall totals across the region except where orographic uplift is significant. April is usually the transition month as the northeast monsoon has ended by this time. Drier conditions occur across Malaysia, partly because of the surface low that forms over Thailand as a result of surface heating there, creating stabilizing divergence within the north-eastern air-stream (Dale, 1956, as cited in Nieuwolt, 1968). The west coast is no longer in a rain shadow and so is wetter than previous months (Air Ministry Meteorological Office 1945a). The ITCZ at this time has moved north and is situated somewhere around the Equator and thus still influences the south of the peninsula.

1.2.1.3 The Southwest Monsoon, May – September

The monsoon from the southwest is much weaker than the northeast monsoon. Winds are more variable and are often dominated by land and sea breezes. In the east of the Malay Peninsula, it is a relatively dry season due to the creation of a rainshadow as air passes over the central highlands, although convectional rainfall is still significant. On the west coast it is the main wet season. However, the influence of the monsoon wind is not as strong as the northeast winds are on the east coast due to the partial rainshadow created by Sumatra. In the west the variability of rainfall is greatest in this period in June and July (Dale, 1960). High magnitude daily rainfall events are also at their most frequent during the southwest monsoon season.

During this season the west coast experiences a climatic phenomenon called "Sumatras". These are squalls that affect the Straits of Malacca between April and November mostly between 2100hrs and 0300hrs. They appear when katabatic winds from the mountains of Sumatra and the Malay Peninsula meet and then the showers drift across the west coast of the Peninsula. They are often very strong with winds as high as force 8 and can continue for up to 8 hours (Air Ministry Meteorological Office, 1945b).

1.2.1.4 Transition, October

In the October transition, all regions experience high rainfall totals as a result of light winds enhancing convective activity (Nieuwolt 1968).

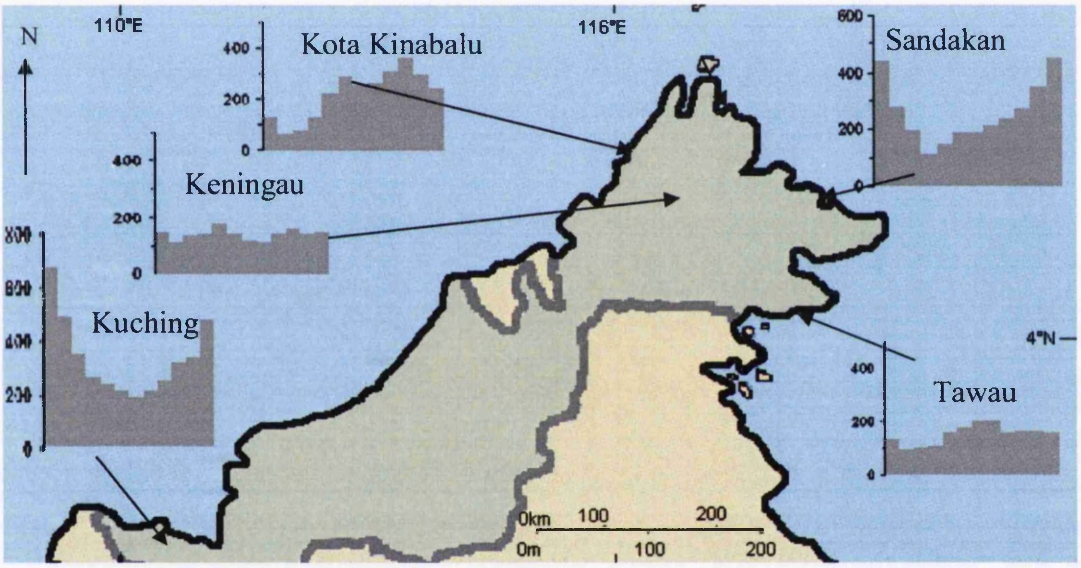
1.2.2 SINGAPORE

Singapore lies at the foot of the Peninsula at just 3°N and experiences a climate containing no dry season. Heavy convectional showers and storms occur year round, though slightly more rain falls between November and January. Rainfall variability in southern regions of the Malay Peninsula including Singapore is much lower than further north (Dale, 1960).

1.2.3 SABAH, SARAWAK AND THE CELEBES SEA

The primary influence on the climate across Borneo is the Monsoon winds of the Indo-Australian monsoon system. Johnson and Priegnitz (1981) suggested that the diurnal wind cycle also exerts a major influence. Figure 3 shows the rainfall regime for stations in Sabah and Sarawak.

Figure 1.3. *Rainfall Regimes at locations in Sabah and Sarawak. (Monthly Rainfall in mm)*



1.2.3.1 North and Northeast facing coasts

In NE Sabah and the coastal regions of Sarawak maximum rainfall occurs in January as a result of onshore northerly monsoon winds. The minimum occurs in June or July in coastal Sarawak (due to its protection from the Southwest monsoon as it blows across Borneo) and in April in the northeast of Sabah. This minimum in April results mainly from very low rainfall totals in El Niño years (Malaysian Meteorological Service). The January peak on coasts exposed to the NE monsoon is due to low-level convergence of the northeast wind and the land breeze along the north coast. This convection creates high rainfall totals at this time of year in areas facing the NE monsoon; therefore rainfall off the north coast was suggested to be associated with the passage of a “monsoon surge”. When monsoon winds increased from the northeast convection increased. In monsoon lulls, convective activity would therefore decrease due to less convergence between the land breeze and monsoon wind (Houze *et al.* 1981:1595). These are also known as cold surges, which also affect the east coast of Peninsular Malaysia. A cycle of convection just off the coast off northern Borneo is created in the Northeast Monsoon season as just after midnight an offshore land breeze meets the monsoon flow just off the coast forming convection cells. Other heavy rains over north Borneo are due to westward moving disturbances (waves), moving across the South China Seas from the equatorial Pacific Ocean (Chang *et al.* 1979).

1.2.3.2 Inland Borneo

Inland areas exhibit a more evenly distributed rainfall regime, but there is still a slight minimum in June and July in the southwest monsoon. On exposed hill slopes facing the northern monsoon winds the highest annual totals may occur with over 5000mm annually. Some inland stations in Sabah, such as Keningau, are sheltered by the Crocker Range and are therefore drier (1716mm annually). Heavy daily rainfall events can occur at almost any time of year as the influence of the monsoon winds is less significant and rainstorms are often a result of convective showers and the passage of westerly-moving regional waves.

1.2.3.3 Northwest and Western Coasts of Sabah and Sarawak

The northwest coast of Sabah experiences a rainfall regime with two maxima (June and October), and two minima (February and August). The dry season at Kota Kinabalu is particularly significant from January to April as the coastal configuration is parallel to the NE monsoon winds creating low level divergence, subsiding air and therefore dampened convection. Annual rainfall totals are high, ranging from 2500 to over 4000mm.

High-magnitude rainfall events are most common here during the northern hemisphere summer months when the southwest monsoon brings warm moist air from the South China Sea.

1.2.3.4 The East Coast

Rainfall along the east coast of Sabah varies with the aspect of the coastline but is generally drier and sees a more uniform rainfall pattern spread out throughout the year. Monthly rainfall can be below 100mm for 2-3 of months of the year and large areas have perhumidity values of less than 15 (Walsh, 1996). The drier climate is reflected in fewer and smaller heavy daily rainfall events than in other areas in Borneo.

Local characteristics can create great variations in the rainfall. Tawau and Tarakan lie roughly 60 miles apart (100km), yet the maximum rainfall at Tawau is from May to August (a result of the aspect) and minimum in February, whereas at Tarakan maxima occur in November and March and minimum in July (Air Ministry Meteorological Office, 1945b:637). This is due to the aspect of the coastline.

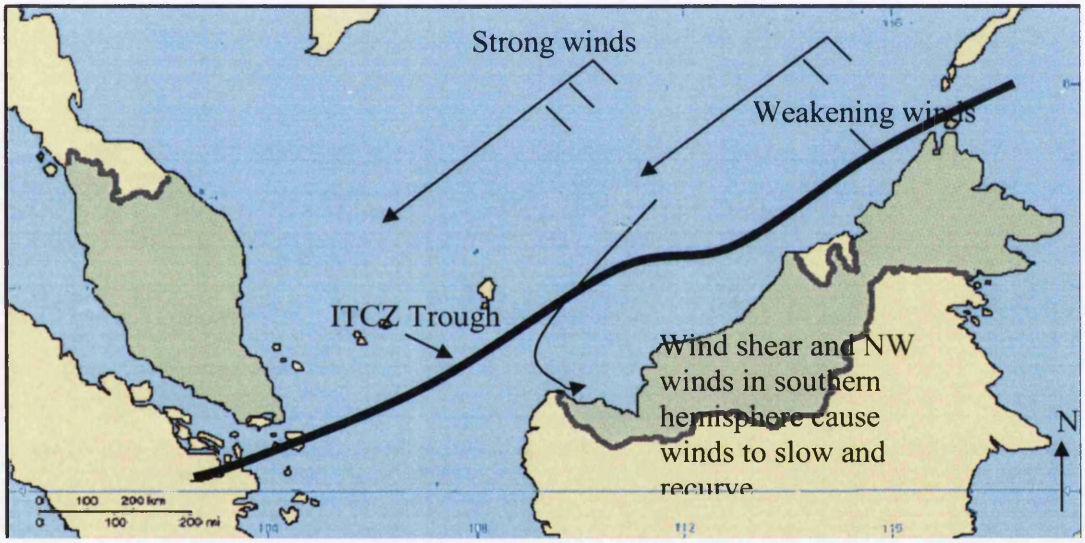
On the east coast of Borneo the northeast monsoon flow, which affects Southeast Asia, is more northerly, thus the north-facing coasts and mountains have high cloud and rainfall in December and January. At times not dominated by the northerly monsoon drier months can occur in any month from February to September.

1.2.4 THE SEASONALITY OF HIGH MAGNITUDE RAINFALL EVENTS IN MALAYSIAN BORNEO.

Across Borneo and the whole of Malaysia the frequency of high-magnitude rainfall events is dominated by the direction of the monsoon flow and the coastal configuration in relation to the monsoonal winds. High-magnitude rainstorms occur as a result of either one or a combination of convective thunderstorms, orographic uplift and low-level convergence of local winds (notably sea and land breezes) with the monsoonal wind. The largest falls often occur due to cold surges interacting with low-pressure atmospheric systems and cyclonic vortices. The cyclonic vortices are formed near the equator resulting in strong winds and high seas in the South China Sea and heavy rainfall occur on the east coast states of Peninsular Malaysia as well as the west coast of Sarawak in East Malaysia (Malaysian Meteorological Service).

Heavy rainfall events on the west coast of Sarawak occur during the northeast monsoon because of the effect of cyclonic shear when winds from the northeast re-curve slightly under slower wind conditions near the west coast and also the effect of the northwest winds in the southern hemisphere when this occurs winds slow creating more convergence. This is especially true in the south of Sarawak in locations exposed to the northeast monsoon such as Kuching. This does not affect areas that are protected from the northeast monsoon winds by the mountains such as Kota Kinabalu (Figure 1.4 below).

Figure 1.4. *Winds during the northeast monsoon season creating heavy rainfall events in Coastal Sarawak.*



In Sabah the frequency of high magnitude falls are associated with on-shore winds.

1.3 THE CLIMATE OF DANUM VALLEY

Danum Valley Conservation Area (DVCA) lies in the interior of eastern Sabah (Figure 1.1), and consists mainly of lowland, evergreen dipterocarp forest. Situated just outside the DVCA lies the Danum Valley Field Centre (DVFC) which, established in 1985, has become one of the world's leading rainforest research stations (Brown, 1990:154). As climatic change at Danum is of considerable scientific interest due to the extensive research based at the station, it formed a secondary focus of the present study. The climate of the field station is therefore described here.

Monthly mean temperatures vary little around the annual mean of 26.7°C, with the mean daily range being 8.4°C. In the period 1985-2004 mean annual rainfall at DVFC was 2825.3mm with an average 220 rain days per annum. The study area experiences highest rainfall during the transition months following the equinoxes (May-June and October-November) and at the height of the northerly monsoon in December and January. August and September are drier as the south-westerly monsoon reaches its height, and rainfall is also sometimes lower in March and April, which are the months most prone to low rainfall in ENSO atmospheric conditions (Walsh & Newbery 1999). Daily falls exceeding 50 mm occur on average 9.3 times per year and those exceeding 100 mm occur 0.9 times per year. The highest recorded daily fall to date was 182 mm on February 9th 2006.

In terms of drought and dry periods the record at Danum indicates an intermediate magnitude-frequency between the drought-prone east coast and the reliably wet west coast of Borneo. Danum appears to have a drought duration profile similar to that of Kilanas in Brunei with frequent dry periods of up to 3-4 months, but none of longer duration (Walsh and Newbery, 1999).

More recently Danum has had a very wet spell, with the wettest series of years on record at Danum from 1999 to 2003. In four of the five years annual rainfall has exceeded 3000 mm and in three years has exceeded all previous annual totals from 1986 to 1998 (Walsh, 2004).

1.4 **LITERATURE REVIEW**

1.4.1. INTRODUCTION

The future climate in the tropics is of utmost importance to society and the environment, especially as 50% of the global land surface lies between the latitudes 30°N and 30°S, and over 75% of the world's population inhabits these tropical regions (Barry and Chorley, 1998). Many recent studies have indicated that changes occurring in tropical climates are threatening the livelihoods of those living there. It is for these reasons that studies into changes of the tropical climate are so important. The aims of this literature review are (1) to examine current understanding of the tropical climate system, including the monsoons, the ITCZ, and events such as El Niño; (2) Assess recent changes in tropical climate, especially in rainfall and ENSO (El Niño Southern Oscillation) events; (3) outlines the latest modelling projections of future tropical climate that could occur as a result of global warming; and (4) examines the extreme rainfall events and changing annual and seasonal totals. Throughout particular attention will be given to the study area of Malaysia.

1.4.2. THE TROPICAL CLIMATE

The tropics can be defined simply using the Tropics of Cancer and Capricorn at 23.5° N and 23.5°S latitude. This is rather simplified as many regions experience tropical weather when located outside of the tropics of Cancer and Capricorn. Instead the 18°C monthly mean is often used (Nieuwolt, 1977; Walsh, 1998a) where all monthly means should be above 18°C.

Rainfall averages are often used in order to define what is a "tropical" climate, but this causes problems when segregating tropical climates into classes as the use of rainfall averages often underestimates the actual frequency of dry periods (Walsh 1996). Also the climatic averages used may be unrepresentative of the longer term due to short and fragmented records often found at tropical stations (Brünig 1969).

1.4.2.1 Influences on Rainfall Generation in the Tropics

In the Tropics, circulation is generally in an easterly direction (northern hemisphere), under the influence of the upper airflow. When air moves over the Earth, the rotation causes it to be deflected to the right in the northern hemisphere and left in southern. The movement is from high to low pressure (sub-tropical high pressure to the equatorial low), but deflected to the right in the northern hemisphere and left in the southern hemisphere to produce north-east and southeast trades respectively (Watts, 1955).

All across the tropics surface heating and low-level convection occur daily even in the arid regions. For rain to occur, however, conditions must include at least one of the following: a deep moist layer, low level convergence of air to sustain the up-draughts and upper air conditions that allow high level divergence (Walsh, 1998a).

Much of the rainfall in the tropics is known to be associated with the passage of weather systems in waves of a variety of types, with westward moving waves in the upper easterlies leading to low level divergence in front of the wave. Low-level convergence and high-level divergence behind it last for a few days creating heavy convectional showers (Nieuwolt, 1977). Orographic uplift or local wind systems can also play a significant role in rainfall formation (Walsh, 1998a).

In the tropics, the very high intensity rainfall that is experienced is a result of the convectional nature of the rainfall and the high water-holding capacity of the warm air (Nieuwolt, 1968).

1.4.2.2 The Intertropical Convergence Zone and Monsoonal Wind Criculations

Between the two subtropical high-pressure zones there is a low-pressure area known as the "Doldrums", or "equatorial trough" and also known as the intertropical convergence zone (ITCZ). Located roughly at 5°S in January and 12-15°N in July, it migrates seasonally during the year. This migration is accompanied by seasonal changes in cloudiness, rainfall and the formation of tropical storms.

Clouds in the ITCZ appear in clusters separated by clear areas. Clusters develop and decay *in situ* for periods of days, with repositioning and migration occurring irregularly with each redevelopment (Walsh, 1998a: 179). Satellites show the ITCZ to be primarily an oceanic feature. Variation can occur from day-to-day with small temperature changes. The ITCZ is a very well defined feature in terms of the spatial pattern of rainfall beneath. For example along the West African coast moving into the ITCZ the precipitation increases by 440% in a distance of only 330km (Barry and Chorley, 1998:236). The ITCZ affects rainfall regimes, tending to create double or single peaks depending on the distance from the equator. Locations away from the Equator at equatorial margins tend to show a single rainfall maximum whereas nearer the equator many experience double rainfall maxima. In reality however, very few stations within the equatorial belt experience the theoretical type of 'zenithal rainfall' (Nieuwolt, 1968:24), due to the variability of the ITCZ and interference from other climatic factors such as orographic uplift, coast and mountain range alignments and the more dominant monsoon flows. This is very true of the study region.

More recently evidence has been gathered from satellite observations of a double ITZC one to the north and one to the south. This double ITZC is most notable in the Eastern Pacific in the months of March and April (Hung and Yanai, 2001). Rainfall rates from the southern ITCZ have been found to be higher in the El Niño years of 1983 and 1998 as well as in weaker El Niño years 1987, 1992, and 1993. Rainfall was also higher in La Niña years (1984, 1985, 1986 and 1989). Therefore the heavy March-April rainfall in the Southern ITCZ region in 1983, 1987, 1992, 1993 and 1998 was associated with El Niño, and that in 1984, 1985, 1986 and 1989 was related to La Niña.

Migrations of the ITCZ can also lead to monsoonal changes in winds in the equatorial areas between the northern and southern ITCZ migration limits. Ramage (1971:6) defines monsoonal areas, as regions with January and July surface circulations in which:

1) The prevailing wind direction shifts by at least 120° between January and July.
2) The average frequency of prevailing wind directions in January and July exceeds 40%.
3) The mean resultant wind in at least one of the months exceeds 3 m s^{-1}, and
4) Less than one cyclone-anticyclone alternation occurs every two years in either month in a 5° latitude-longitude rectangle.

1.4.2.3 El Niño -Southern Oscillation (ENSO)

The IPCC 2001 report suggests that El Niño -Southern Oscillation (ENSO) is the primary global mode of climate variability in the 2-to 7-year time band. Research has increasingly shown El Niño-Southern Oscillation as being primarily responsible for abnormally dry or wet years in many parts of the tropics (Dai *et al.*,1998, Hulme and Viner, 1998). Glynn (1990) describes ENSO as a large-scale dynamic interaction between the world's major low-latitude atmospheric pressure centres and basin-wide thermocline/nutricline depths across the Pacific and Indian oceans.

The southern oscillation index (SOI) is defined as the anomaly (difference from average) of Tahiti sea level pressure minus Darwin sea level pressure for a particular month. Normally it is strongly positive with high pressure over Tahiti and low pressure over Darwin (Indonesia and northern Australia). Strong south-easterly trade winds in the eastern and central Pacific lead to upwelling of cold water off the South American Coast and an area of cold water, stable atmosphere and low rainfall extending westward to the dateline in the central Pacific. In contrast, rainfall is very high in the unstable low-pressure zone over Indonesia, New Guinea and Malaysia. In ENSO years the high pressure breaks down and the pressure difference is much lower than normal, with negative SOI values (Walsh and Newbery, 1999:1870). Many studies and institutions such as the Australian Bureau of Meteorology multiply the SOI value by 10. Using this convention, the SOI ranges from about –35 to about +35, and the value of the SOI can be quoted as a whole number.

Every year a weak southward flow of warm water replaces the northward-flowing Humbolt Current and its upwelling to about 6°S beside Ecuador. El Niño events occur when this occurrence strengthens every two to ten years (average 4) as a result of a reorganisation of the Walker circulation, when 1) pressure declines and the trade winds weaken over the eastern equatorial Pacific, leading to a reduction in wind-driven upwelling, a sharp increase in sea surface temperatures and a more southerly than normal migration of the ITCZ towards Peru; and 2) in response to a weakening of the Walker circulation the warm sea surface temperatures of the western tropical Pacific move eastwards towards the central Pacific (Barry and Chorley, 1998). El Niño is far from a regular occurrence. Between 1943 and 1951 no events were observed, but 3 events including 1 strong event were recorded during the 5 years between 1939 and 1943 (Hansen, 1989:2).

At the other end of the cycle, La Niña events occur when abnormally warm waters are pushed farther west, creating unusually high rainfalls in the western equatorial Pacific. La Niña events occur when the SOI is strongly positive.

Any net shift in El Niño frequency or intensity could have a greater impact on tropical rainforests than a gradual long-term trend in climate; this is due to the large deviations from the mean rainfall and drought periods that are often experienced during ENSO events.

1.4.3. NATURAL OR ANTHROPOGENIC TROPICAL CLIMATE CHANGE?

Recently the changing global climate as a result of human activity has been at the forefront of concerns over the future of the planet both environmentally and economically. Extreme weather events have been reported more frequently, with losses of life and damage to economies. In light of this, extensive research has been carried out trying to predict changing climates. The establishment of the IPCC (Intergovernmental Panel on Climate Change) originated from proposals put forward during debate at the Tenth Congress of the World Meteorological Organization

(WMO) in Geneva in May 1987. Directors of National Meteorological Services called on WMO to establish a mechanism that would enable them to brief their Governments and national communities on the reality or otherwise of the threat of global warming as a result of increasing atmospheric concentrations of greenhouse gases. Since its first assessment report in 1990 (IPCC, 1990) they have been producing reports of changes that have been experienced, and estimates of future changes to the global climate using increasingly high-resolution computer models.

1.4.3.1 Natural Rainfall Changes in the Tropics

The world's climate has always changed throughout the course of Earth's existence, and these changes have occurred in response to a number of different forcing factors and feedback mechanisms operating on different timescales. Some of the factors affecting the climate that occur naturally (in order of longest duration changes first), are: Galactic Dust, Evolution of the sun, continental drift/polar wandering, orogeny/isostacy, orbital parameters, ocean circulation, evolution of the atmosphere, volcanic activity, air-sea-ice-land feedbacks, solar variability, atmosphere-ocean feedbacks and atmospheric auto-variation (Goodess *et al.* 1992). In the last million years a pattern of climate change can be identified in Pleistocene glacial-interglacial cycles. The most likely cause over timescales of 20,000-100,000 years is orbital forcing. The future is likely to be different to the past million years because of anthropogenic forcing mechanisms, with the principal climatic influence of the next thousand years or so being the enhanced greenhouse effect (Goodess *et al.* 1992).

Changes that have occurred in the past (prior to large scale industrialization pre-1900) have been unaffected by anthropogenic influences and thus natural climate change could be part of the trend of what is occurring in the tropical regions of the world. Drying or wetting trends with increases or decreases in both annual and extreme rainfall events in the past or currently may just be part of the natural cycle of climate change and not associated with the anthropogenic increase in greenhouse gases.

Prior to the 1960s it was believed that the tropics had escaped most of the climate changes that affected higher latitudes throughout the Pleistocene. More recently, however, there is much more evidence that the tropics as a region experienced very different climates to those experienced today, with much drier, cooler conditions during the last glacial. A much wetter climate is also believed to have been present throughout the early part of the Holocene between 10 000 and 5 000 years BP. Evidence for such changes has come from many sources such as lake deposits and levels (Street-Perrott *et al.* 1985), tree rings, relict sand dunes and river terrace and delta sediment characteristics (Walsh, 1998a). Evidence from fossil dune deposits suggests that periods of significant dune building occurred 20-26000 years ago and 9-16000 years ago over large parts of the tropics. Much of this evidence on climatic change in the tropics originates from the seasonal tropics and high mountain areas of Africa, primarily due to the abundance of lakes that are scarce in much of tropical South America and SE Asia.

Street-Perrott *et al.* (1985) identified several climatic epochs for tropical Africa and the Middle East based on fluctuations in lake levels during and since the last glacial. Pollen analysis has also been used in order to ascertain the temperatures of previous climatic epochs in the tropics from mountain sites using the changing tree line as evidence, though more recently such vegetation changes have also been shown to be a response to CO_2 changes rather than temperature and precipitation changes (Street-Perrott *et al.* 2004).

In order to suggest that the climate is undergoing an unnatural climate change scientific detection requires demonstration that the observed change is significantly different from the natural pattern of variation (Hardy, 2003).

1.4.3.2 The Impact of Rainforest Removal on Tropical Climate Change

Recent climatic changes, especially rainfall changes in the tropics, have been partly attributed to the removal of tropical rainforests (Henderson-Sellers, 1987). Rainforests present unique characteristics, such as low albedo (%), high rates of evapotranspiration, large roughness to the surface airflow, and large water-holding capacity of soils. It has been argued that these characteristics together help to maintain a higher level of precipitation than would exist without the forest (Nobre, 1998). It is also argued that deforestation causes larger amounts of water to be lost out of the system through streamflow as less is lost through evapotranspiration, especially where the existing rainfall regime is greatly dependent on recycling (Salati *et al.* 1984). A reduction in this recycling process is likely also to result in a different rainfall regime.

A number of models have been formulated with different resolutions and parameters in an attempt to simulate the effects of deforestation on climate. Table 1 shows some of the many studies and their estimates of precipitation change in tropical areas.

Table 1.1. *Results of predicted precipitation changes as a result of deforestation.*

Study	Predicted precipitation change	Scale – Where
Shukla *et al.* (1990)	-657mm per year	Regional – Amazon
Lean and Warrilow (1989)	-474.5mm per year	Local – Amazon
Lean and Rowntree (1993)	-292mm per year	Local and Regional – South America.
Dickenson *et al.* (1992)	-511mm per year	Regional – Amazon
Henderson-Sellers (1987)	-182.5 to -255.5 mm per year	Regional – Amazon
Potter *et al.* (1975)	- 233.6 mm per year	5°N and 5°S. Global
Zhang *et al.* (2001)	-310.3mm per year -171.6mm per day +25.6mm per day	Amazon Southeast Asia Tropical Africa

All studies predicted an overall decrease in rainfall as a result of deforestation, although Zhang et al. (2001) showed regional differences. Changes to annual rainfall would occur as a result of changes in the large-scale atmospheric circulation, not directly due to changes in forest cover. Criticisms of models and between models are that substantial differences exist between the schemes for representing physical processes and the methods used to simulate the GCMs (General Circulation Models) (different parameters and resolutions) therefore they have not presented a uniform picture of the possible effects of deforestation on the climate (Lean and Warrilow, 1992). Many of the parameters used also come from only a few direct observations and empirical calculations. It is acknowledged that many of the projections are based on results that are constrained by a lack of observations in forested and deforested areas. Currently with the small percentage of total deforestation scattered over a large area, large changes in the basin-scale hydrological cycle are difficult to isolate and unlikely to have been already detected.

1.4.4 RECENT ANNUAL AND SEASONAL RAINFALL CHANGES IN THE INSTRUMENTAL PERIOD IN THE TROPICS AND GCM PROJECTIONS

In recent decades the increase in precipitation in the higher latitudes has been balanced by a decrease in the tropics and sub-tropics (IPCC 2001).

1.4.4.1 Tropics in General

In early studies Kraus (1955) highlights the abrupt reduction of rainfall in many eastern areas of sub-tropical areas such as Eastern Australia, Eastern North America, East South Africa, East Asia, and East South America at the end of the 19th Century. These reductions were simultaneous with reductions in rainfall in semi-arid western parts of New South Wales and other dry regions such as Arabia. Declines were attributed to decreases in the trade-wind circulation and a corresponding decrease of evaporation. Changing patterns in the climate at the end of the last century were characterized not only by a weakening of the ITCZ, and hence drier conditions in the tropics, but also with expansion of the sub-tropical high pressure belts (Kraus, 1955).

Walsh (1998b) investigated changes in the pattern and variability of annual rainfall, rainfall regimes and heavy rainstorm frequency in the Caribbean using archival colonial rainfall records. Findings showed that rainfall in the region occurred in epochs of high and low totals. A pattern of very high rainfall in the late 19th century, low rainfall in 1899-1928, higher in 1929-58 and very low rainfall since 1959 characterized most stations studied. There is also the suggestion from very early records in St Vincent that the early 19th century was very dry. Rainfall cycles were identified such as the 44-year cycle at Codrington, Roseau (Dominica) and St Clair (Trinidad), and the shorter 5.5-year cycle that was important at St Clair.
The seasonal cycles also change in time with the changing epochs. A clear trend is that there has been a recent increase in drought frequency in the early wet season months of June and July throughout the Caribbean region.

Stoddart and Walsh (1992) found in Suva, Fiji, that the annual precipitation in the 1906-1941 period was 711mm greater than the period from 1883-1905, nearly a 30% change that is in contrast to other tropical locations at this time. Similarly in opposition to many global records Morrissey and Graham (1996) found a significant increase in rainfall in the tropical Pacific between the years 1971 and 1990. Using data from 44 island stations, they suggested that the increase in rainfall near the Equator and decrease poleward might be the result of an intensified Hadley circulation.

Other recent reductions include those from Sudan where there were significant deficiencies since the 1980s. Annual rainfall totals from 1980-1987 were all well below the long term mean. Reductions in annual rainfall of up to 40% were found between the two epochs of 1920-39 and 1965-84 (Walsh *et al.* 1988, Lamb, 1982 and Quan *et al.* 2003). Hulme (1990) in the semi-arid centre of Sudan, identified that the annual wet season had contracted by three weeks and rainfall zones retreated by 50-100km southwards between the periods 1921-50 and 1956-85. Nicholson *et al.* (2000) demonstrated using 1400 stations across Africa that the strong drying trend in northern sub-Saharan Africa extended into the tropical rainforest belt of West Africa and north Congo peaking in the 1980s.

Malhi and Wright (2004) have looked at recent changes in the climate of tropical rainforest regions over the period between 1960 and 1998 using 19295 stations across central and southern America, Asia and Australasia. They concluded that over the study period rainfall in rainforest regions declined by 1.0% (+ or - 0.8%) per decade (p< 5%), or 22mm (+ or - 17 mm) per decade. Reductions were not statistically significant between 1960 and 1970, but declined steeply after that. This reduction was more significant in northern tropical Africa at 2.4% (+ or - 1.3%) per decade (p< 0.01%). Giannini *et al.* (2003) suggest that the drying in the Sahel (and hence probably the entire northern African subtropics) is a direct response to the general warming trend in the Indian Ocean and tropical Atlantic Ocean, which has weakened the African monsoon. Malhi and Wright (2004) found only a slight reduction is in Asia of 1.0% (+ or - 1.1%) per decade p< 5%, and no significant changes in the American rainforest area with 0.6% (+ or - 1.1%) per decade. Studies acknowledge that the trend over these four decades may not necessarily be indicative of a longer-term trend, as they could be just part of a longer multi-decadal time-scales oscillation.

1.4.4.2 Southeast Asia and Malaysia

Time series analysis carried out by the Malaysian Meteorological Service (Subramaniam, 1997) show large year-to-year variation in annual rainfall over Malaysia, but no clear longer-term periodicities or trends in the rainfall, although signals corresponding to the sun-spot cycle, the quasi-biennial oscillation (QBO) and most notably ENSO were detected. Fluctuations with an 18.5-year cycle were also identified using a small sample of stations; this was thought to be linked to solar-lunar tidal forcing (Subramaniam, 1993).

Manton *el al.* (2001) reported that annual totals overall in Southeast Asia decreased between 1961 and 1998. Trenberth and Hoar (1997), as cited in Manton *el al.*

(2001:273), attribute the decline to more frequent and stronger El Niño events since the mid-1970s.

1.4.4.3 Seasonal Changes, Past, Present and Predicted

Multi-decadal and decadal variations of Indian monsoon rainfall have been widely noted, but Pant and Kumar, (1997) as cited in Slingo *et al.* (1999), suggested that links with El Niño are not straightforward. In the South China Sea significant inter-annual variations in the onset of the summer monsoon seem to be closely related with ENSO events. Thus in years when the onset is delayed, the Walker circulation is weaker and the sea surface temperature anomalies in the western Pacific are negative (Xie *et al.*1998). In Africa and especially the Sahel, the increased dry conditions since 1965 were associated with the increased frequency of ENSO warm events (Moron, 1997 as cited in the IPCC 2001 report). Since the late 1980s however, the Sahel has become moderately wetter despite the increased drying influence of ENSO events, with the trend continuing to 1999 (Oarker and Horton, 2000 as cited in the IPCC 2001 report). This breakdown in the relationship between stronger El Niño events and weaker summer monsoon in both India and Africa has occurred in the most recent two decades (Kumar et al., 1999) suggesting that the link may be operating on multi-decadal time-scales. Changes in monsoon variability appear to be occurring globally with rainfall becoming more erratic. For example the western coast of Mexico has experienced a more erratic pattern of monsoonal rainfall (Douglas and Englehart 1999, as cited in the IPCC 2001 report).

Sea surface temperatures in the region affect monsoon rainfall. Zveryaev and Aleksandrova (2004) suggest that high sea surface temperatures in the northern Indian Ocean and South China Sea (in January or February) precede higher rainfall from the Southeast Asian summer monsoon.

Anderson *et al.* (2002) suggested that even subtle small interglacial changes in the North Atlantic may have a significant effect on the strength of the Asian monsoon system. This was supported by the proxy record of the planktonic foraminifer *Globigerina bulloides* from the floor of the Arabian Sea. Millennial scale abrupt changes in the monsoon were attributed to changes in the North Atlantic and over Europe and Eurasia (Gupta *el al.,* 2003). Both studies suggest that there will be a strengthening in the southwest monsoon system in the future as the globe warms and levels of greenhouse gases increase.

It has been suggested that increased snow cover and generally cooler conditions over Eurasia has weakened the southwest monsoon in the following summer (Kumar *et al.*1999, Anderson *et al*., 2002 and Gupta *et al.,* 2003). Meehl (1994) showed this in his results with suprising consistency using a GCM to examine the link between southwest monsoon strength and surface variables (land-sea temperature contrast, sea level pressure over land, snow cover, and soil moisture).

The Asian Development Bank (1994) examined various climate scenarios for 2010 and 2070 based on a doubling of atmospheric CO_2 generated by the GCM-GISS model used in an earlier UNEP study. Results for Malaysia suggested that there would be no significant change in temporal rainfall pattern, with wet and dry periods occurring at the same time of year; however, a significant increase in rainfall would be expected during January and February in Sarawak. There would also be a significant increase in the inter-monsoon rainfall in the Southwest Peninsula Malaysia during March, April and May. This model however does not take into account topographic features due to its low resolution, and does not simulate the behaviour of the ENSO phenomenon and since this is a major source of year-year variability in this region, this is a serious limitation.

The Malaysian Meteorological Service also conducted an unpublished study looking at the future climate of Malaysia with a doubling of CO_2 using 14 GCM simulations, with changes in temperature and precipitation as the focus of the study. Malaysia was split up into 4 regions: North Peninsular Malaysia, South Peninsular Malaysia, Sabah and Sarawak. Projections of changes in 30-year mean rainfall centred on the year

2070 varied from +30% to -30% of current levels, with an increase in SW monsoon rain thought most likely. Changes in ocean dynamics associated with a sharper thermocline were predicted to lead to an enhanced interannual variability.

The New Scientist (Feb 2005:10) was concerned with the effects on the climate system if the Ocean Conveyor Belt (including the Gulf Stream) shuts down. This would be a result of a reduction in ice formation in the North Atlantic, which drives the Conveyor, or an increase in melt water from the Greenland ice cap diluting the dense salty water. It was suggested that one possible impact would be the failure of the Asian Monsoon system. This would greatly reduce the rainfall throughout the region, leading to droughts and destruction of large areas of rainforest as a result of forest fires.

1.4.5 THE EFFECTS OF ENSO AND CHANGES IN ENSO FREQUENCY AND INTENSITY

1.4.5.1 Global Changes

During the 1970s basin-wide warming of the Pacific was noted. During the period from the 1970s onwards ENSO events were more frequent, intense and persistent (Wang, 1995). A period of low Southern Oscillation Index dominated from 1990-1995, resulting in continued weak to moderate El Niño events with no intervening La Niña events. This dominance of El Niño conditions is statistically very rare (IPCC 2001). It was suggested that changes in the condition of the Pacific were partly due to the situation of abnormally large cyclones in the Pacific, as positions of cyclones during ENSO events changed after the late 1970s (Wang, 1995).

Another feature of the global circulation during the period post-1968 was that the strength of the Siberian high pressure weakened towards a minimum around 1990 (Gong and Wang, 1999b as cited in the IPCC 2001), again in phase with the positive phase in the North Atlantic Oscillation.

ENSO events affect the whole of the tropics with repercussions felt globally. Giannini *et al.* (2001) found Caribbean rainfall to be affected by the El Niño events. Likewise in northern Amazonia deficient rainy seasons from 1976, associated with stronger westerlies over the equatorial Pacific and weakened Atlantic northeast trades over the region, were due to more frequent and intense El Niño events during the relatively dry period 1975–98. In 1950-75 there were enhanced Northeast Trades into the basin and fewer weaker ENSO events (Marengo, 2004:92).

ENSO events are difficult to simulate in climate models and thus predicting the effects of anthropogenic climate change on ENSO produces disagreements between models (Malhi and Wright, 2004). Most, though not all, climate models indicate a net shift of the equatorial Pacific towards an El Niño -like mean state (Cubasch *et al.* 2002 as cited in Malhi and Wright, 2004), but there is little consistency between models. It was also suggested that along with the change in state towards mean El Niño conditions, the ENSO phenomenon becomes more energetic relative to the present so that variations from year to year become more extreme (Timmermann *et al.* 1998).

Timmermann (1999) tested a null hypothesis to find out whether changes since the 1970s were outside the range of natural variability of the ENSO cycle. This was done by taking into account ENSO statistics that were simulated in realistic GCMs, using changes in greenhouse warming. The results suggested that most of the changes in the frequency and intensity of ENSO events may not be due to greenhouse warming, but more likely just a part of a natural cycle.

1.4.5.2 ENSO Cycles and Changes in Drought Magnitude-Frequency in Southeast Asia

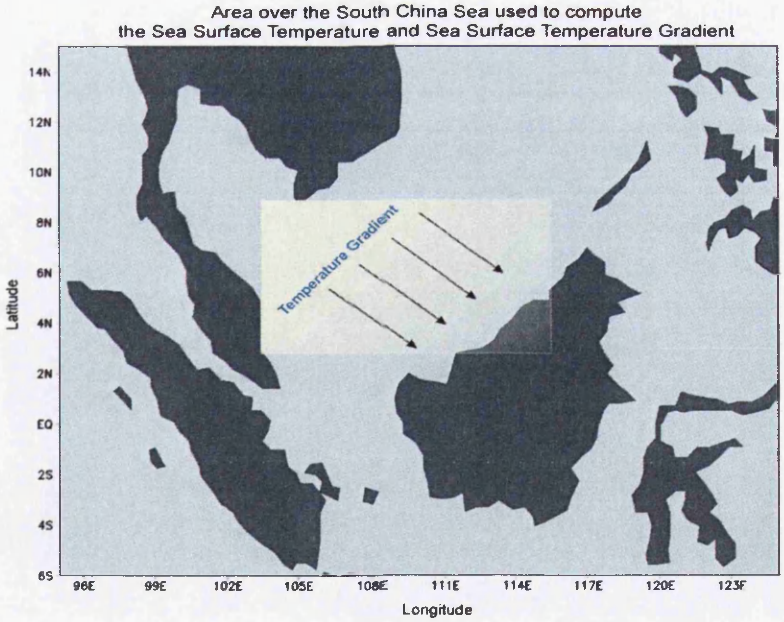
For 125 stations in Southeast Asia, Kripalani and Kulkarni (1997) investigated inter-annual and decadal changes in seasonal and annual rainfall over timescales varying from 25-125 years. Using the instrumental data available, regional rainfall anomaly time series were constructed for regions over Thailand, Malaysia, Singapore, Brunei, Indonesia and Philippines. Results revealed that as well as random fluctuations, there were certain epochs of above and below normal rainfall over each region, that were unrelated to El Niño /La Niña frequency. It was found, however, that there was no overall systematic climatic change or trend in any of the series. Summer monsoon (June-September) rainfall varied in two opposite phases. Central India, north China, northern parts of Thailand, Brunei and central parts of Borneo and the Indonesian region east of 120°E vary in phase to each other, whereas regions surrounding the South China Sea, in particular the north-west Philippines, vary in the opposite phase. Near the equator regions the epochs tend to last for about a decade, whereas over the tropical regions, away from the Equator, epochs were found to last for about three decades. Extreme drought/flood situations tend to occur when the epochal behaviour and the El Niño/La Niña events are in phase (Kripalani and Kulkarni, 1997:1155). Quah (1988) suggested a similar pattern of ENSO with a strong response to ENSO forcing over Indonesia, Borneo and the Philippines, a moderate to weak response over west Malaysia and Sumatra, but that over Thailand and the east coast of Peninsula Malaysia rainfall anomalies seem to be unrelated to ENSO forcing.

Harger (1995) has argued that each ENSO event leaves a different signature on different regions and that no two are the same. This is why across the region of South East Asia and even on the smaller scale of Malaysia (Walsh and Newbery, 1999), ENSO events vary in strength with location. A strong ENSO event may be felt less in one area than a weaker one in another year. It is also thought that there is a strong underlying link between climates of previous years and the effect the ENSO event will have on a region, to the extent of being able to predict the effect of the event based on the climate of previous years (Harger, 1995).

As already established in previous studies, the effect of ENSO events across Malaysia is markedly different dependent on location. These differences have been attributed to the temperature of the South China Sea during ENSO events (Subramaniam, 2004). The typical conditions during the northeast monsoon season in the South China Sea are shown in Figure 1.5. The South China Sea acts independently of the Pacific during ENSO events. In ENSO events there is a strong negative correlation between the SOI and sea surface temperatures of the South China Sea (Subramaniam, 2004). With the warmer seas (a result of reduced NE winds pushing cold water from the north) in moderate/weak ENSO events, northeast monsoon rain is increased above the mean as the warm moist air rises over the land. Reduced wind occurs because of a smaller contrast in sea surface temperatures in the South China Seas between Malaysia and Indo-China. The suppressed winds mean that warm waters remain in the South China seas, as they are not pushed south by colder waters farther north (Figure 1.6a).

Figure 1.5 *(a)Thermal gradient creating the strong winds of the Northeast monsoon and (b) the progression south of cooler waters in an average year (Subramaniam, 2004)*

(a)



Area over the South China Sea used to compute the Sea Surface Temperature and Sea Surface Temperature Gradient

(b)

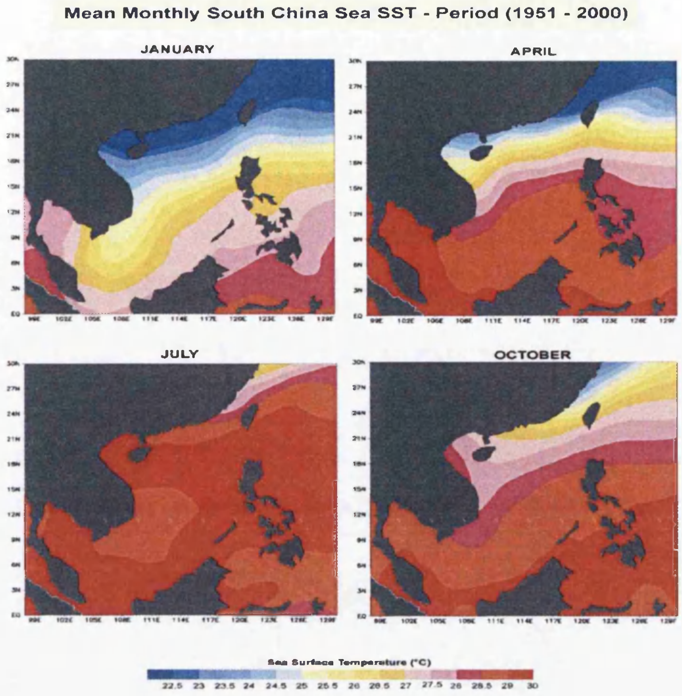
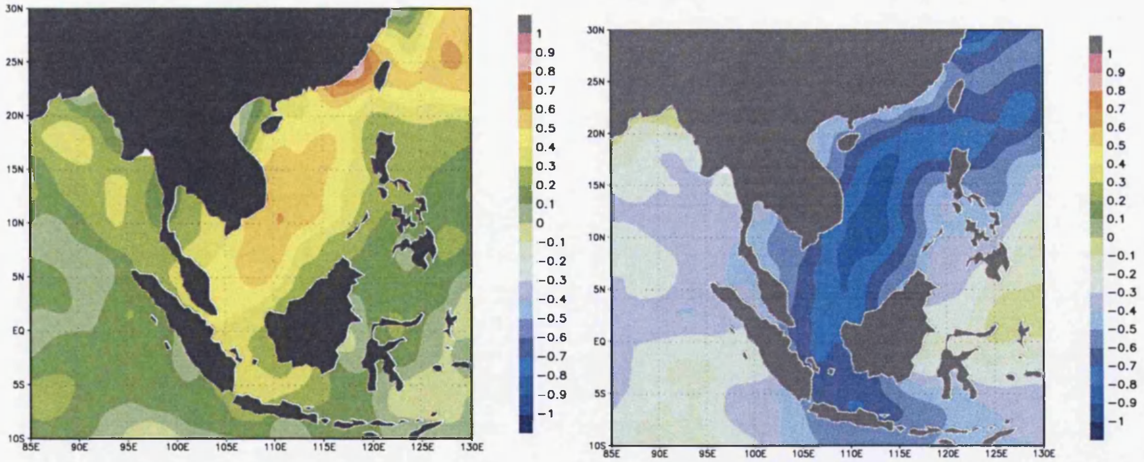


Figure 1.6. *Composite sea surface temperature during January in (a) El Niño and (b) La Niña. After Subramaniam (2004).*



(a) El Niño (b) La Niña

Thus in weak and moderate ENSO events the effect in Peninsular Malaysia may be opposite to the expected outcome, with high rather than low rainfall totals. Thus in contrast Northern and Eastern Borneo are more likely to be affected by the drought conditions during the winter monsoon months as the dominant winds are coming off the colder Pacific Region. This is why many ENSO events are often shown in the rainfall record as being below average rainfall in northern Borneo, but above average in Peninsular Malaysia. La Niña events often cause a reduction in temperatures in the South China Sea with more cold water pushed from the north (Figure 6b) (Subramaniam, 2004). The correspondence in Kalimantan supports Subramaniam as Leighton (1984) showed that in the 44 years of record ten droughts occurred, nine of which corresponded to one of the ten El Niño events that occurred over the period.

Some studies, such as Webster and Yang (1992), have suggested that ENSO events influence the inter-annual variability of the Southeast Asian summer monsoon. However it is stressed that many monsoon-related droughts and floods have been unrelated to ENSO events (Webster *et al.,* 1998). The monsoon-ENSO relationship has also been demonstrated to be unstable with inter-decadal changes.

El Niño-induced climate variability in the Philippines usually results in: (a) late onset of the rainy season, (b) early termination of the rainy season, (c) weak monsoon events characterized by isolated heavy rainfall events of short-duration, and (d) weak tropical cyclone activity characterized by less intense cyclones and a smaller number of tropical cyclones occurring within Philippine territory (PAGASA, 1997 as cited in Lansigan *et al.,* 2001).

1.4.6 EXTREME CLIMATIC EVENTS

The variability of extremes in climate within the tropics is the most pressing concern to society, with projections of increases in the frequency of extreme drought and the frequency, strength and spatial coverage of tropical cyclones. Many of the deleterious impacts of global climate change may result from changes in frequency or intensity of extreme weather events than from changes in mean values of atmospheric variables such as temperature (Nicholls, 1995). Thus it has been argued that:

"Extremes are a key aspect of climate change. Increases and decreases in the frequency of many extremes can be surprisingly large for seemingly modest mean changes in climate, and are often the most sensitive aspects of climate change for ecosystem and societal responses" (Katz, 1999 as cited in the IPCC 2001 scientific basis, section 2.7.2).

1.4.6.1 Drought in the Tropics

At Barro Colorado Island (Panama) a sharp increase in the length and intensity of the dry season between mid-December and mid-April in recent decades has been noted (Condit, 1998; Condit *et al.,* 1996). In the period before 1965, 1 in 6.2 of years experienced less than 100mm rain in the dry season, but since 1966 1 in 3.5 years have experienced such intense dry seasons (Windsor, 1990 as cited in Condit *et al.,* 1996). These changes parallel a downward trend in annual rainfall. Similarly at Roseau (Dominica) and other stations in the Eastern Caribbean, there has been a large increase in the magnitude and frequency of drought duration since 1959 (Stoddart and Walsh, 1992). In the Caribbean these drought periods appear to be in epochs, with the climate since 1959 being characterised by annual rainfall totals 10-20% lower than in 1929-58, with longer dry seasons and more frequent and extreme drought events (Walsh, 1998b).

Not all tropical locations follow the same pattern. Manaus in Amazonia had its most intense period of droughts early in the 20th century with 6 out of 7 Cumulative Rainfall Deficiencies exceeding 300mm occur in the period from 1901-1923 (Walsh and Newbery, 1999).

Hulme and Viner (1998), using a GCM for analysis of rainfall changes in the tropics, accepted the difficulties in simulating rainfall changes, due to sub-grid scale processes. However, they identified drying trends since the 1960s over the Amazon basin, southern and western Africa, an increase in seasonality in Indonesia, and an overall trend in the tropics towards increased dry season length, especially in South

America, South Africa, S.E. Asia and Australia. These changes have been attributed to increases in ENSO magnitude-frequency in the Pacific.

1.4.6.2 Drought in Sabah/Borneo

In Sabah the main period of drought in ENSO years occurs from January to May in the second year of the cycle. The stronger ENSO events lead to particularly significant droughts throughout Malaysia (Walsh, 1996), unlike the less intense events that affect north Borneo more than the Peninsula.

Droughts in Sabah (particularly major and widespread ones) seem to be mainly related to warm phases of the ENSO cycle as shown by drought events in 1878, 1885, 1905, 1912, 1914-15, 1930-31, 1957-8, 1969, 1972-3, 1982-3, 1987 and 1997-98. Some El Niño events, however, produce little evidence of drought in Sabah, or drought only at a few stations. Also some droughts that the area experiences are not linked to ENSO events (Walsh, 1996).

Walsh (1996) examined the changes in drought frequency in Borneo using the extensive monthly rainfall series from the stations in the region. In the rainfall record at stations in Sabah the pattern of drought magnitude- frequency is high for the late 19th century with a relatively drought-free period from 1916-67, and with increasing drought magnitude/frequency in more recent decades (Walsh 1996, Walsh and Newbery 1999). This pattern is similar to the pattern of ENSO magnitude-frequency as indicated by sea surface temperature anomalies in the equatorial Pacific since 1860 (McPhaden, 1999).

In Borneo a particularly important finding of Walsh (1996) was the regional impact of drought events. Individual stations across Borneo were affected differently by the intensity of drought events. This has been partly attributed to the random nature of convectional rainfall in the tropics. Individual droughts in Sabah affected some stations significantly more than others. For example the drought of 1987 was severe at Sandakan, Kota Kinabalu and Kilanas, but not at Labuan and Tawau; and the drought of 1959 was significant at Kota Kinabalu, Tawau and Keningau, but not at Sandakan. Many other years show the effect of ENSO varies dependent on location. The correspondence between droughts in Sabah and stations in the southwest of Borneo is inconsistent. Dry periods at Kuching and Pontianak do not consistently coincide with those in Sabah (Walsh, 1996).

From January to mid-April/early May 1998 Sabah was hit particularly hard by drought with most areas receiving less than 25 % of the long-term mean rainfall (Shaaban and Sing, 2003). Miri in the northeast of Sarawak recorded 102 days without rain from the end of December 1997, the longest number of days without rain ever recorded in Sarawak. Between July and September 1997, a long dry spell was experienced in western Sarawak where a number of stations recorded more than 30 days without rain.

The 1997-98 event caused large fires across the whole region of Malaysia in response to both the heightened fuel source from dead leaf litter and logging debris, and the dry ground as a result of the drought, with ecological consequences for the rainforests. The 1997-98 ENSO event also created water shortages for much of Malaysia especially areas such as Selangor, Kuala Lumpur Federal Territory, Penang, Kedah, Kelantan, Sarawak, and Sabah. Domestic water supply was disrupted in Kuala Lumpur from April-September 1998 (Shaaban and Sing, 2003).

1.4.6.3 Magnitude-Frequency of Rainstorms

Extreme rainfalls are of interest because they generate damaging floods in rivers and streams (Lockwood, 1968), and so are of great importance to ecology, erosion, river hydrology and planning within the tropics. The analysis of such falls can be assessed using the daily rainfall records. Within the tropics extremely high 24-hour totals have been recorded such as in 1952 at a station on Réunion, Mascarenes, which recorded a 24-hour rainfall of 1870mm (6.14ft) (Walsh and Stoddart, 1992).

The IPCC (2001) report predicts an increase in intense rainfall events throughout the tropics; the same report also noted a worldwide tendency for increased variability of years with high and low numbers of anomalously large rainstorms. However, objective assessments of this have been difficult and the issue of the magnitude-frequency of large rainstorms has rarely been tackled because of the lack of easily accessible and reliable long-term daily rainfall series (Walsh, 2000).

Using rainfall data from the Caribbean, Walsh (1998b) investigated changes in the magnitude and frequency of extreme precipitation events. Evidence from relatively long records at Barbados and Roseau (Dominica) showed epochs of high rainstorm magnitude-frequency within the epochs of high annual rainfall. At Barbados, the frequency of daily falls over 76.4mm was more than three times greater in the wet period from 1889-1906 as in 1907-1925 and 1962-1972; the same was true for falls over 127mm. At Roseau, Dominica, falls greater than 76.4mm were twice as frequent in the very wet period from 1929-1958 as 1959-76. The more recent trend towards a reduction in the high intensity rainfall events is associated with the current dry epoch, in which rainfall was 10-20% lower than in the 1929-58 period. This study, however, does not include data from the 1990s and therefore may not be affected by the onset of global warming changes. In a more recent Caribbean study, Peterson *et al.* (2002) suggest that since the 1950s one measure of extreme precipitation shows an increase.

Table 1.2. *Changes in the frequency of Heavy Daily Rainfalls at (a) St Thomas Police Station Barbados and (b) Botanic Gardens Roseau, Dominica. From Walsh (1998b)*

(a)

Period	Annual Rainfall (mm)	Falls greater than 25.4mm	Falls greater than 76.2mm	Falls greater than 127mm	Mean Max Rainfall (mm)
1889-1906	2166	22.0	2.3	0.56	127.8
1907-1925	1574	11.7	0.6	0.16	89.4
1926-1958	1776	14.5	1.1	0.13	89.9
1962-1972	1570	11.6	0.7	0.20	96.5

(b)

Period	Annual Rainfall (mm)	Falls greater than 25.4mm	Falls greater than 76.2mm	Falls greater than 127mm	Mean Max Rainfall (mm)
1921-1928	1749	11.7	0.8	0.25	99.6
1929-1958	2039	18.9	1.7	0.37	111.3
1959-1976	1781	16.5	0.8	0.22	96.3

A reduction in heavy rainfall events (>30mm/day) during dry epochs in the 1970s and 80s in Niger was shown by Shinoda *et al.* (1999) when analysing hourly rainfall data.

Groisman *et al.* (1999) and Kharin and Zwiers (2000) both using a GCM suggest that globally in the future, due to increases in atmospheric water content and temperature, predicted by many GCMs, increases in extreme precipitation events will be disproportionately large in comparison to any changes in total precipitation. Thus return periods of extreme precipitation events are shortened almost everywhere (Zwiers and Kharin, 1998; and Groisman *et al.,* 1999). In any areas with an increase in precipitation, with no change in the frequency of days with rain, the precipitation that fell would be in larger events.

Fowler and Hennessy (1995) suggest that as global warming enhances the global hydrologic cycle, global precipitation will increase by about 10%. The consider that this increase is most likely to come in the form of heavier rainfall, rather than as more frequent falls or longer rainfall duration. However this study is very large scale with less emphasis on the tropical regions and is not necessarily reliable.

Walsh and Pittock (1998) suggested that at present, models could not show 100% accuracy due to the poor representation of sub-grid scale processes, but they do suggest that an increase in heavy rainfall is likely. All the GCM results are only a guide to possible outcomes, they are not necessarily accurate as they are not from "real world" scenarios. The issue of comparing GCM simulations to global rainfall gauge data has also been criticized by Hegerl *et al.* (2004) suggesting that the two are not comparable because model data represent area averages while station data are points, yielding quite different extremes, particularly for precipitation because of its variability from one place to another.

The most recent study into changes in daily extremes in precipitation by Alexander *et al.* (2006) suggests that precipitation changes showed a widespread and significant increase, but that changes were much less spatially coherent when comparing them to temperature change. This was derived from 600 glabal precipitation stations with near-complete data for 1901-2003 (Alexander *et al.,*2006:1).Evidence from the paper suggests that precipitation changes are complex but they generally suggest a wetter world.

1.4.6.4 Heavy Rainfall Changes in Malaysia and Southeast Asia

Malaysia (comprising Peninsular Malaysia, Sabah and Sarawak) has been blessed with an extensive network of well-run rain gauges prior to and after political independence (Walsh and Leong, 2003). Walsh and Leong (2003) in their study concluded that at the majority of stations there had been no statistically consistent increase since 1980 in extreme rainfall events in comparison to the pre-1980 period. Daily falls of at least 50mm increased at Tawau, Kuching and Sitiawan by one fall per year in the 1980 to 2001 period. Four stations recorded a decline by 1.0-1.5 falls per year since 1980 (Kota Kinabalu, Miri, Alor Star and Kota Bharu). 100mm falls showed little change in average frequency between pre- and post-1980, but the 5-year running mean suggested a strong upswing since the later 1990s at Bintulu in Sarawak.

Despite little change in the overall frequency of such extreme rainfall events, Walsh and Leong (2003) demonstrated an increase in year-to-year variability in Borneo as years with very high and very low frequencies of 50mm rainfalls increased (with the exception of Kuching). Only at the two most northern stations Kota Bharu and Alor Start did the standard deviation increase on Peninsular Malaysia. The most convincing evidence came from Sandakan (Sabah) where 5 or more heavy falls occurred in seven years since 1980, compared with a maximum annual frequency of 4 in the period 1960-79. The increase in high frequency years was offset by a parallel increase in frequency of years with no or only one 100mm fall. There were seven such years in the 1980-2001 period compared with just two years in 1960-79. Analysis of whether extreme events had increased in size gave inconclusive results.

Manton *et al.* (2001) examined temperature and rainfall trends in Southeast Asia and the South Pacific using data from 91 stations in 15 countries from 1961-1998. They used this period of time in order to optimize data availability across the region, using high-quality data from 91 stations in 15 countries. Stations with long, continuous and homogeneous records and minimal influence from urbanization were chosen. Owing to the broad region of study extreme climatic indices were based on the 1st and 99th percentiles. The indices they used to define the extreme events were:

1) Frequency of daily rainfall exceeding the 1961–1990 mean 99th percentile (extreme frequency).
2) Average intensity of events greater than or equal to the 99th percentile each year, i.e. in the four wettest events (extreme intensity).
3) Percentage of annual total rainfall from events greater than or equal to the 99th percentile, i.e. received in the four wettest events (extreme proportion).
4) Frequency of days with at least 2 mm of rain (rain-days).

Only the number of rain days showed any statistically significant trends. The general consistency, and the similarity of trends in neighbouring countries, lends credibility to the overall trends. Their results suggested that the number of rain-days >2 mm had decreased significantly throughout Southeast Asia, but had increased in the north of French Polynesia, in Fiji and at some stations in Australia. Most of SE Asia appears to be experiencing a lower frequency of extreme events. The main exception was French Polynesia where an increase was detected.

In Malaysia Manton *et al.* (2001) found that there had been a significant decrease in rain days at all stations, except Kuching. There were no other significant trends in extreme rainfall indices in Malaysia.The main problem with this study is the short period of the record, only 38 years. The results therefore may produce trends that are sensitive to the sampling period, thus not showing the overall trend in climate change.

1.5 RESEARCH GAPS

Relatively few studies on recent climatic change in the tropics have used long-term monthly and daily rainfall data from weather stations. This has been due to the small number of stations in the tropics with unbroken records of sufficient duration and reliability to enable analysis. Many studies have only used short series (e.g. Manton *et al.* 2001). This constrains assessments of long-term change. Any changes observed could just be part of cycles that occur naturally in the tropics. Also most research has focused on annual and monthly rainfall changes, with very few studies (e.g. Manton *et al.,* 2001; Walsh, 1998 and Walsh and Leong 2003) on daily rainfall and thus the magnitude-frequency of daily rainstorms.

The original idea for this research project came from a paper by Walsh and Leong (2003) “Recent changes in the magnitude-frequency of large rainstorms in Malaysia”. Within this article it was suggested that “more detailed analyses incorporating more rigorous extreme value analysis should be possible if longer comprehensive daily series are assembled in the future” (Walsh and Leong, 2003:29). The search to increase the duration of the record of daily rainfall data is one of the foci of this thesis.

Not just in Malaysia, but also globally, there have been very few studies that have used daily rainfall records to assess changes in the magnitude and frequency of daily rainfall events in the tropics. The future of heavy rainfall events is also of significant relevance to societies and the natural environment as projections of global warming suggest a change in their frequency and intensity. A study looking at the frequency and intensity of such rainfall events could offer an insight into whether global warming has begun to affect them.

1.6 AIMS AND HYPOTHESES

In the light of the above research gaps, the thesis aims to examine the extent to which annual totals, seasonal totals and high magnitude-frequency rainfall events and their year-to-year variability have changed over the archival rainfall period in Malaysia. The thesis also aims to explore possible relationships between these changes and changes to the ENSO cycle. A separate, but subsidiary aim is to reconstruct the rainfall at Danum using a longer-term station with a strong correlation, enabling one to stretch the rainfall record beyond the current record.

A series of hypotheses were constructed to be tested by this study, namely that:

1. there have been recent reductions in annual and seasonal rainfall in Malaysia;
2. the reductions are related to the ENSO cycle;
3. there has been a recent increase in annual and seasonal rainfall variability linked to an increase in intensity of the ENSO cycle in Malaysia, and
4. there has been a recent increase in the frequency and year-to-year variability of large rainstorm events in Malaysia.

Justification for the research hypotheses relating to ENSO events comes from the many studies which have found changes in annual rainfall in association with El Niño events. The IPCC (2001) report suggested that there would be an increase in erratic monsoonal rainfall, creating more variability between years. Justification for the third hypothesis comes from past research such as that of Groisman *et al.* (1999) who predicted an increase in extreme events using General Circulation Models (GCMs), which expect increases in extreme precipitation events to be disproportionately large in comparison to any changes in total rainfall. The increase in variability of extreme events between years has also been suggested in the IPCC (2001) report and this was one of the findings in Malaysia in Walsh and Leong (2003). Possible contrary arguments to these hypotheses include the short duration study of Manton *et al.* (2001), which suggested a recent decrease in extreme events over Southeast Asia. Seasonal rainfall changes must be examined because they may help to explain changes in annual totals.

1.7 STRUCTURE OF THESIS

In Chapter 2 the research design and its rationale are described. Practical considerations influencing the study such as data needs, availability and locations are examined. Data sources used are outlined and the different data analysis techniques used are described.

Chapters 3, 4 and 5 give a detailed account of the changes in annual, seasonal and daily rainfall events at each station covered by the study. The final part of the results and analysis, Chapter 6, examine the record at Danum Valley Field Centre (which has a relatively short (20 years) record of rainfall for an interior station in Sabah) and attempts to extend this record via cross-correlation with stations with longer-term records.

Chapter 7 discusses the main points from the study highlighting differences and similarities in trends across Malaysia. Comparisons are made with other studies in the tropics and suggestions are made to why changes are occurring with reference to past literature and research. Comparisons with projections of modelling studies regarding likely future climate change in the tropics and the region are made. Finally implications of the findings will be described with reference to both the human and natural environment. Chapter 8 presents the conclusions.

CHAPTER 2: METHODOLOGY

2.1 RESEARCH DESIGN

Figure 2.1 describes the research design of the thesis and reflects also the stages of thought involved in its formulation. In order to investigate the aims and hypotheses of the thesis a choice had to be made regarding which stations to include in the study. Section 2.2 describes the rationale for choosing the stations and their locations, including the duration of the record at each station. In section 2.4 the data sources are explained using data from a variety of sources for both seasonal and daily values. Other data collected is also considered in this section such as the data on ENSO events. Section 2.5 outlines the data analysis techniques, using different techniques for monthly seasonal and annual rainfall values (times series analysis and epoch analysis) and also different techniques when analyzing the daily data record (time series and extreme value analysis). The role of ENSO events and sea surface temperatures are investigated to assess whether they are making any significant impact on the rainfall patterns of the region. Finally in chapter 6 the Danum rainfall record is cross-correlated with a longer record in Sabah in an attempt to extend the rainfall record at Danum Valley.

2.2 STATION LOCATION AND RECORD DURATION

Figures 2.2 and 2.3 show the location of the monthly and daily data sets used within Malaysia. The stations included in the study and the duration of monthly records are shown in Table 2.1 and stations where daily rainfall data were used are listed in Table 2.2.

Figure 2.1 *Research Design.*

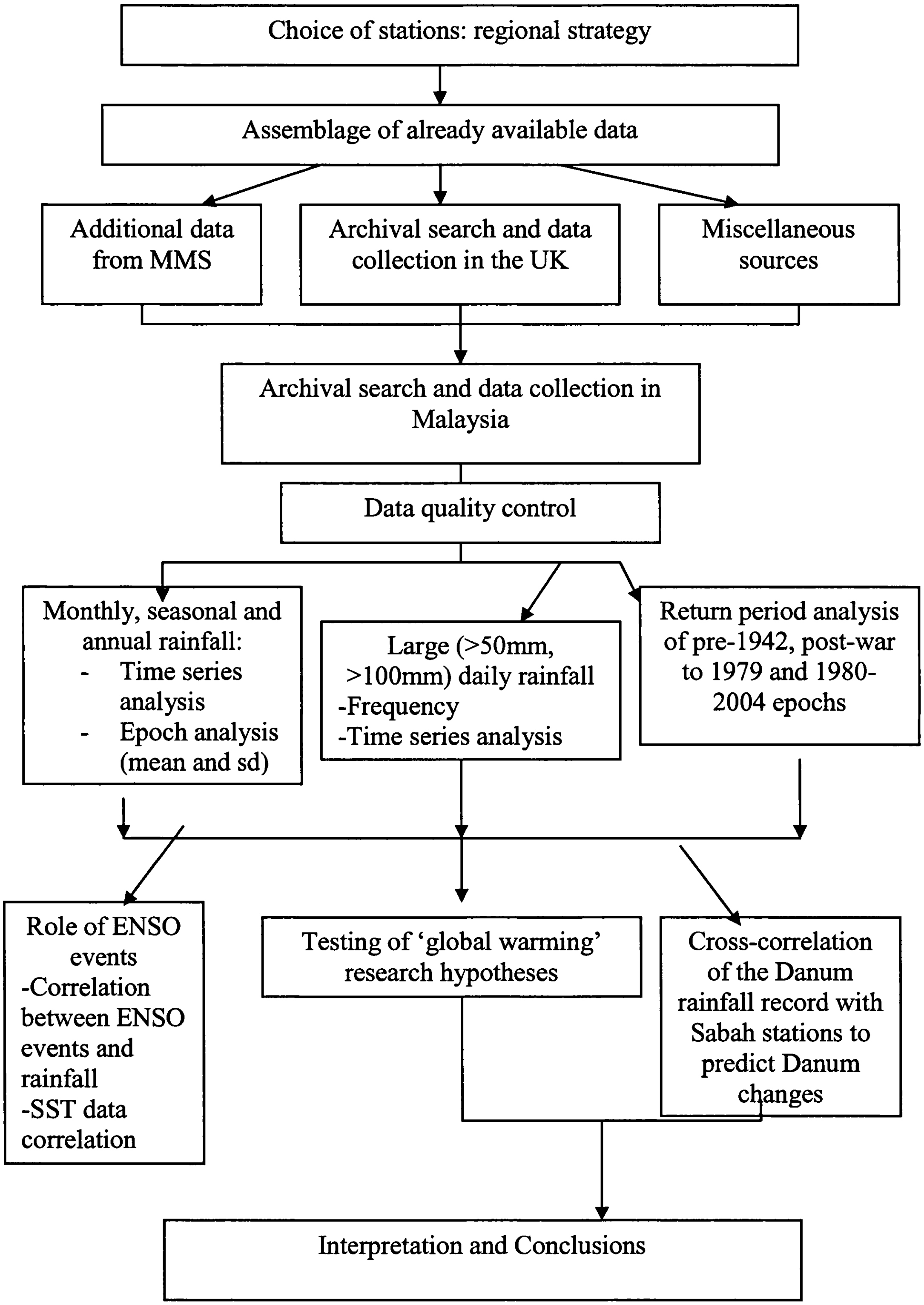


Figure 2.2. *Distribution of stations with long-term monthly data used in the thesis.*

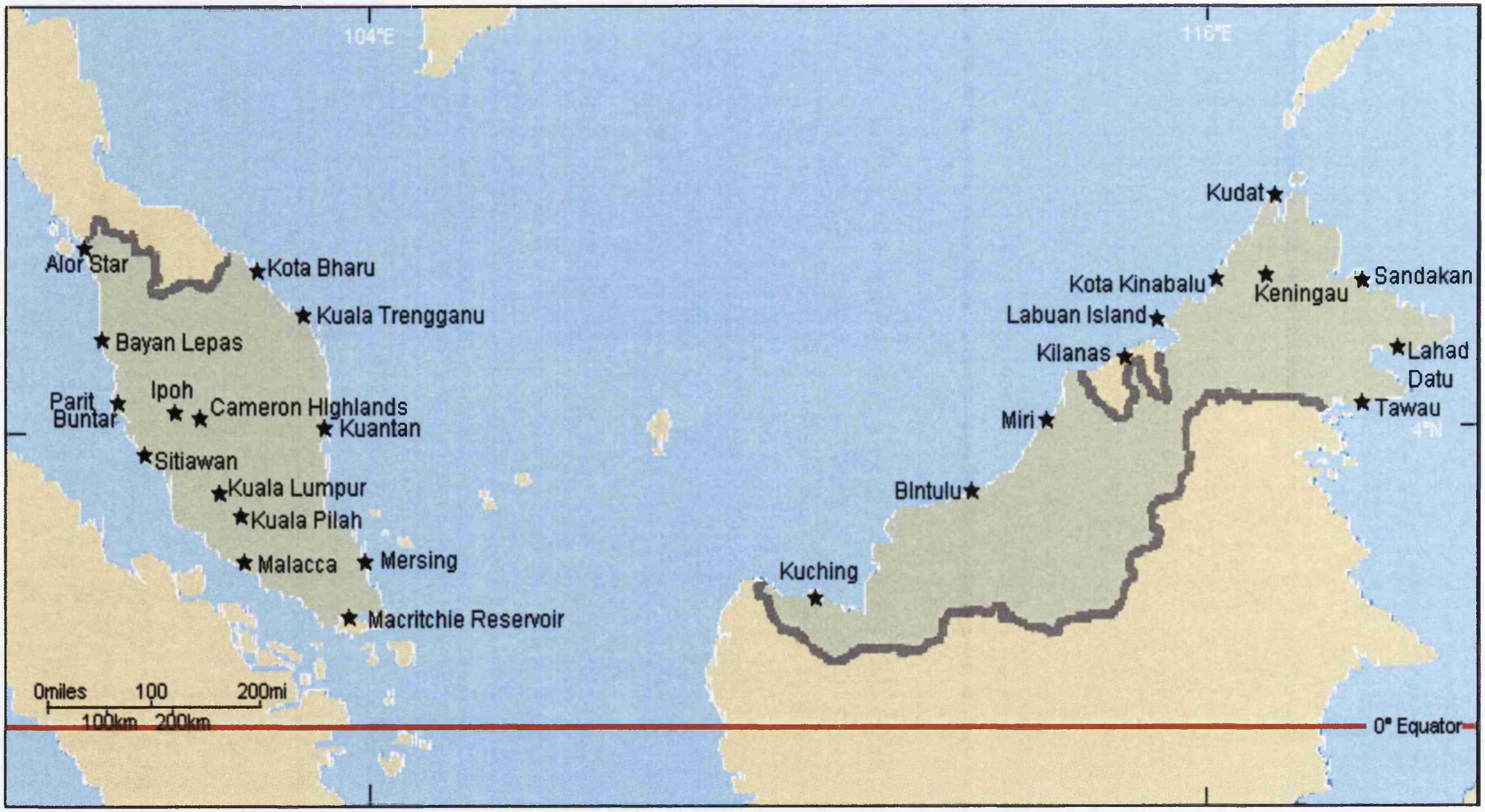


Figure 2.3 *Locations of stations with long-term daily records compiled and analyzed in the thesis in Sabah and Sarawak.*

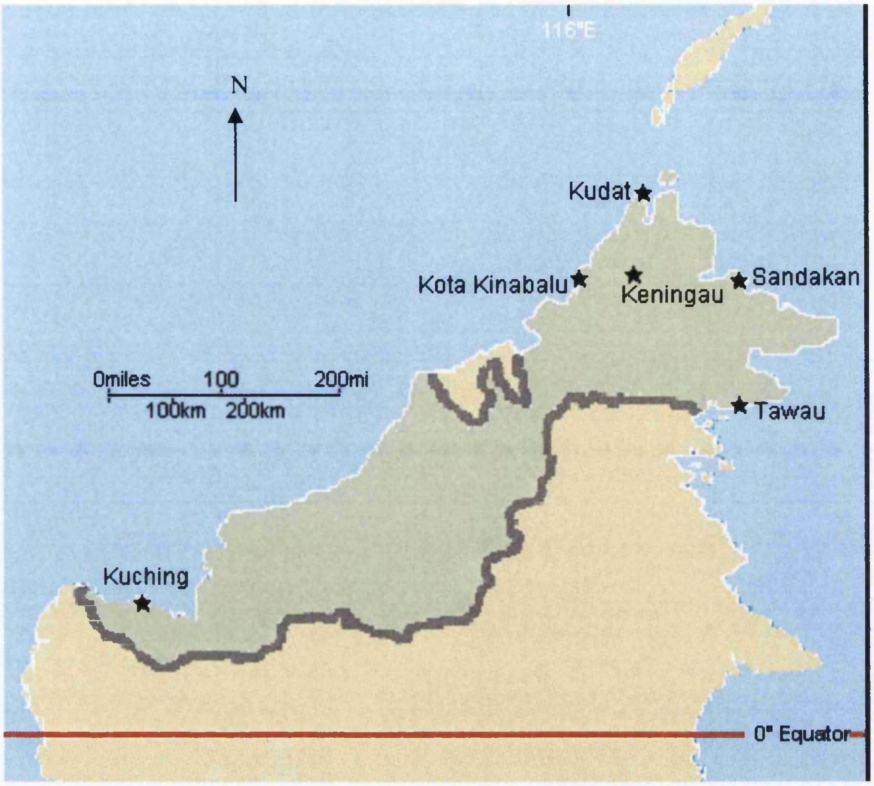


Table 2.1. *Stations with long-term monthly records used in the thesis.*

Location	Station Name	Record Duration	Co-ordinates	Height Above sea level (m)
West Coast Peninsula	Sitiawan	1930-2004	4°13N 100°42E	7
	Parit Buntar	1888-2004	5°09N 100°50E	3
	Malacca	1930-2004	2°16N 102°15E	8.5
	Bayan Lepas	1933-2004	5°18N 100°16E	2.8
	Alor Star	1930-2004	6°12N 100°24E	3.9
Central Peninsula	Ipoh	1938-2004	4°57N 101°10E	39
	Tapah	1889-2004	4°09N 101°30E	42
	Cameron Highlands	1925-2004	4°50N 101°40E	1472

	Kuala Lumpur	1928-2004	3°12N 101°50E	27
East Coast Peninsula	Mersing	1928-2004	2°45N 103°80E	44
	Kuantan	1898-2004	3°80N 103°30E	9
	Kuala Trengganu	1930-2004	5°20N 103°8E	35.1
	Kota Bharu	1930-2004	6°10N 102°17E	4.6
Singapore Island	Macritchie Reservoir	1875-2000	1°40N 103°80E	8
Sabah, Borneo	Sandakan	1879-2004	5°54N 118°04E	9
	Lahad Datu	1890-2004		
	Kudat	1884-2004	6°53N 116°52E	3
	Kota Kinabalu	1889-2004	5°56N 116°03E	2
	Labuan Island	1855-2004	5°17N 115°16E	30
	Keningau	1918-2004	5°21N 116°52E	305
	Tawau	1906-2004	4°15N 117°53E	6
Sarawak, Borneo	Miri	1917-2003	4°20N 113°59E	5
	Kuching	1876-2004	1°29N 110°20E	7
	Bintulu	1915-2003	3°12N 113°2E	1
Brunei	Kilanas	1936-88	4°54N 114°51E	14

Table 2.2. *Stations with long-term daily records used in the thesis.*

Location	**Station Name**	**Record Duration**
Sabah	Kota Kinabalu	1908-40 and 1949-2004
	Keningau	1933-40 and 1953-2004
	Kudat	1906-40, 57-69 and 82-2004
	Tawau	1906-40 and 1951-2004
	Sandakan	1906-40 and 1952-2004
Sarawak	Kuching	1900-1926 and 1951-2004

2.3 STATION LOCATION CHANGES

Some of the stations used have undergone site changes at some point in the record. The station at Alor Star, for example, moved from the hospital to the airport in 1941. The station at Kota Kinabalu moved after World War II from Kapayan to the meteorological station at the airport. Sandakan also moved from the Old Hospital to the airport after the Second World War. Many other stations have seen a similar move in the location of the climate stations often from town locations to airport locations once airports became established (usually shortly after the Second World War).

Changes of location may have an effect on the rainfall trend of the record, due to differences in altitude, relief and proximity to the sea. In order to avoid a misinterpretation of changes in the rainfall records with climate change instead of the explanation that the station just changed location, rainfall totals at both stations during times of overlapping data collection were analyzed. Analysis was done by comparing the annual and monthly totals and the annual and monthly means between the two stations. Also cross correlation was used to establish the strength of the correlation between the two stations. If r-values were statistically significant between the two stations then it was considered that the records could be joined to form longer records. The critical levels of significance was dependent on the duration of the overlapping period between the stations, the higher the number of years the lower the r value between the stations could be to achieve significance. This analysis avoided the possibility of changes in location and gauge equipment from causing a step change in the rainfall record at the stations studied.

As a result of this cross-correlation analysis, some stations were not included in the study due to a significant change in the rainfall totals between the old and new stations; this was the case, for example, at Kulim on the Peninsula.

2.4 DATA SOURCES AND COLLECTION

Southeast Asia and especially Malaysia have, in comparison to many other tropical locations, a good coverage of climatic stations, many of which have recorded temperature and rainfall since the beginning of the 20th century and in some cases as far back as the mid-19th century. Records from most of Malaysia tend to be complete with the exception of the Japanese Occupation in the Second World War from the end of 1941 when the majority of stations have a gap of 5-8 years.

Although the records exist for many locations throughout Malaysia Page *et al.* (2004) found a lack of digital rainfall data before the 1950s, meaning rainfall data pre-1950s was documents that had to be digitized for this work.

In Malaysian Borneo there are very few continuous records from inland stations. Many stations that started recording climatic variables stopped in the 1990s, such as Kalabakan in Sabah. This is also the case throughout much of Kalimatan in southern Borneo and the rest of Indonesia where data into the 1990s becomes fragmented and unreliable. The original data used in the analysis of daily rainfall by Walsh and Leong (2003) mainly came from the archival rainfall records provided by the Malaysian Meteorological Service (MMS) HQ in Kuala Lumpur, the Sabah Office in Kota Kinabalu, from ASEAN (1982) (a climatic compendium) of data and from early sources assembled by Walsh (1996).

2.4.1 DAILY RAINFALL DATA COLLECTION

For the analysis of changes in the magnitude-frequency of rainstorms, daily rainfall data are needed (24 hour rainfall totals usually from 0800 to 0800). The principal sources used in compiling daily data series are summarized below:

a) Data since 1960 in Sabah and 1968 in Peninsular Malaysia and Sarawak.
The source of these data were computerized manuscript data of the MMS in Kuala Lumpur and Kota Kinabalu.

b) Early data up to 1941.

To enlarge the time-span of daily rainfall, archival sources in London that were used were The British Newspapers Library (Collindale) and The National Archives (Kew), which provided the majority of the data. The Meteorological Office Library at Exeter was also visited and provided a little information. The sources at the British Newspapers Library at Collindale and the National Archives at Kew helped extend the daily data series mainly for stations in Sabah, and Kuching in Sarawak. For stations in Sabah, copies of the British North Borneo Herald were consulted at Collindale and Kew, with the majority of data coming from Kew. The data for Kuching were gathered mostly from Collindale and were from the published Sarawak Gazette. The Sarawak Gazette and the British North Borneo Herald were published from the 1880s and continued without a break until the Japanese occupation at the end of 1941 during the Second World War. Although daily rainfall data were only printed sparsely in the British North Borneo Herald in the early years, occasional months with daily rainfall data were printed for a variety of stations. Consistency in the meteorological reports started after 1905 and daily data for the four stations of Kota Kinabalu (then Jesselton), Sandakan, Kudat and Tawau were consistently printed in the British North Borneo Herald from 1905 to 1941. Data for Keningau was incorporated into the reports consistently from 1933. The meteorological data stopped during the Second World War and the British North Borneo Herald changed to become first the North Borneo News and then the Sabah Times in the 1950s, but from then on meteorological reports were no longer printed. Daily data for Kuching were printed in the Sarawak Gazette from the 1880s to 1941. After the war the Sarawak Gazette also changed format, becoming a daily print and the collection of data in this format became impractical.

Stations used for daily data analysis were selected by the completeness and reliability of the record found in the archival sources. Those stations included that had the most complete records in the colonial archives at Kew and Colindale were: Sandakan, Kota Kinabalu, Kudat, Tawau, Keningau and Kuching. Although data from other stations were published, none was sufficiently complete to be used for analysis.

Quality control on all documented data that was not in digital format was by visual analysis of the documents; if figures were illegible then they were discarded. Also checks were conducted to see if sums of daily totals were equal to the monthly totals.

c) Data from the 1940s to 1960s.

After the collection of the daily rainfall data before the Second World War from the sources in London, there was still the question of the large gap, between 1940 and when the records were available in computer or manuscript form from the MMS in 1960. A trip to Malaysia was necessary to attempt to locate the missing data especially for the 1950s. The daily data for stations in Sabah were found in an archive store room of the MMS, Sabah at Kota Kinabalu airport. From these daily rainfall data the records could be extended at many of the stations much further back into the 1950s. Monthly meteorological summaries which included the number of falls over 50mm and 100mm were used in some cases to fill in gaps and also to extend the record back to 1949 at some stations. The record for Kuching was also extended back to 1951 using these meteorological summaries.

2.4.2 MONTHLY RAINFALL DATA COLLECTION

Data for the early years to 1975 were derived from the ASEAN 1982 publication and from data compiled by Walsh (1996). The MMS provided a CD containing ASEAN compendium of climatic statistics that contains updated records for many stations throughout Asia since the 1982 publication. The Global Climatic Dataset at the University of East Anglia was also consulted and provided gaps which were filled in prior to the arrival of the CD. The data gathered from ASEAN aided the development of the monthly and annual rainfall series throughout Malaysia. The most recent years of monthly rainfall data, which were not on the ASEAN disk, were sent by the MMS after the visit to the headquarters in Kuala Lumpur. The Meteorological Office Library in Exeter also provided some useful monthly data to fill in some gaps in the series. Also used were records already compiled from MMS records at Kota Kinabalu and other documentary sources obtained by Walsh.

For the monthly data sets the locations were chosen for their longevity, completeness and reliability, and geographical spread throughout Malaysia (listed in table 1). This was an attempt to get an example of the climate record from as many regions as possible from peninsular Malaysia and from Sabah and Sarawak.

2.4.3 ENSO EVENTS DATA COLLECTION

Data for the intensity of each ENSO event were gathered from the Australian Government Bureau of Meteorology using the web site link http://www.bom.gov.au/climate/current/soihtm1.shtml which gave data for the Southern Oscillation Index (SOI), calculated from monthly air pressure difference between Tahiti and Darwin. Sustained negative values of the SOI often indicate El Niño episodes and these can be correlated with rainfall totals. There are a few different methods of how to calculate the SOI. The method used by the Australian Bureau of Meteorology is the Troup SOI which is the standardized anomaly of the Mean Sea Level Pressure difference between Tahiti and Darwin. It is calculated as follows:

$$\mathrm{SOI} = 10 \; \frac{[\, \mathrm{Pdiff} - \mathrm{Pdiffav} \,]}{\mathrm{SD}\,(\mathrm{Pdiff})}$$

Where:

Pdiff = (average Tahiti MSLP for the month) - (average Darwin MSLP for the month),

Pdiffav = long term average of Pdiff for the month in question, and

SD(Pdiff) = long term standard deviation of Pdiff for the month in question.

Units of pressure = mb

The multiplication by 10 is a convention. Using this convention, the SOI ranges from about –35 to about +35, and the value of the SOI can be quoted as a whole number. The SOI is usually computed on a monthly basis. Because of fluctuations in weather, daily or weekly values of the SOI do not convey much in the way of useful information about the current state of the climate, and accordingly the Bureau of Meteorology does not issue them.

2.4.4 SEA SURFACE TEMPERATURE DATA

Sea Surface Temperature data for two locations in the South China Sea and one in the Straits of Malacca were obtained from the internet using Reynolds SST data set, (http://www.cdc.noaa.gov/cdc/data.noaa.ersst.html). The data are reconstructed historical data with monthly values from the beginning of 1854 through to present. The three sites that were chosen were all at 6°N. The first was in the Straits of Malacca at 98°E, which was chosen to represent effects of winds from this direction during the SW monsoon season. The second site at 104°E just off the east coast of the Peninsula was selected to show possible effects of SST on rainfall during the NE monsoon season. The third site was at 114°E off the west coast of Sabah. These data were used to try to represent the different SST conditions that occur in the South China Sea during ENSO events as the might help to explain rainfall changes.

2.5 DATA ANALYSIS TECHINIQUES

2.5.1 ANNUAL CHANGES

To test whether there have been any changes in the annual totals, graphs of annual rainfall with a 5-year running mean were developed along with annual deviation from mean charts. Five-year running means were preferred to those of ten or other duration because they are short enough to pick up changes which occur over the smaller timescales as a result of ENSO events (such as the increased El Niño frequency from the mid 1970s to mid 1990s). These may not be picked up if using ten-year running means. The annual totals represented as bars show the year-to-year variation in rainfall enabling years or groups of years of higher or lower rainfall to be picked out. If appropriate a linear regression line was applied to any graph that shows a consistent decline or rise in rainfall since the start of the record.

If the change looked large then it was tested for significance. The r-value of the trend line was used to assess whether the change over the record was significant (If the r value was greater than the critical value of the trend line). This was applied to the seasonal changes also.

The mean annual rainfall for the whole series for each station was used to construct graphs showing annual deviations from long-term means. These graphs permit years or periods of above or below average rainfall to be identified.

2.5.2 SEASONAL CHANGES

Seasonal changes were analyzed by constructing running means of either different months or groups of months. This would show whether changes in the rainfall totals in particular seasons account for any changes in annual rainfall. The NE monsoon was defined as November to March. The period from May to September was defined as the season dominated by the Southwest monsoon. October and April are typically the transition months when at some time the wind direction swings round from one monsoon direction to the other and the resulting climate is different. Consequently these months are analyzed separately as transition months. The monthly segregations may not accurately reflect the changing climate every year, but they were the best approximation available.

2.5.3 CORRELATION OF RAINFALL TOTALS WITH THE ENSO INDEX

In order to answer the question of the effect that changes in ENSO magnitude and frequency have on annual rainfall, relationships between the SOI and annual rainfall were analysed. As the SOI index is published as monthly values, they can then be used to correlate with annual rainfall experienced at each station throughout the region. An annual Southern Oscillation Index (calculated by summing and averaging individual monthly SOI values) was used to correlate with the annual rainfall at a station to find out the strength and statistical significance of the relationship between the two. Scatter graphs of the SOI versus annual rainfall at each permit the type of relationship to be discerned (e.g. whether it is linear, or whether a threshold relationship is involved). The statistical significance, when mentioned, was tested using the r-value of the correlation and testing it at 5% significance level or 1% significance level. If significant then the correlation was stronger than the critical values of the correlation coefficient.

Tables were constructed to assess whether, and to what degree, annual rainfall in ENSO years are below (or above) the annual mean. These were achieved using the annual strength of the ENSO events and categorizing them as either strong to very strong, moderate or weak and then using a simple tally of the number of years with different sized deviation from the mean annual rainfall in relation to the strength of the ENSO event. Using SOI values three categories of ENSO event were established: moderate to weak (4 months below -5 SOI or annual average SOI below -5), strong (4 months below -10 SOI) and very strong (4 months below -15 SOI). These divisions were based both on previous work by Quinn (1992), which was based on manifestations of climate not the SOI, the modern SOI. Correlations were also assessed between the average SOI in each monsoon season and rainfall in that season.

Another task was to examine similar strength ENSO events throughout the record and to judge whether dry periods stemming from ENSO events have intensified in more recent times. This was achieved by splitting the record into three different time periods and simply plotting the annual SOI against annual rainfall and representing each period as a different symbol on the graph. Looking at the spread of each period it may be that in one period rainfall correlates better with SOI or that the high strength ENSO years in the recent period have significantly more years with negative annual rainfall anomalies. A trend line and R^2 value were added for each period where the strength of the relationship warranted it.

2.5.4 CHANGES IN THE MAGNITUDE-FREQUENCY OF EXTREME EVENTS

Two approaches were used: (a) changes in frequencies of rainstorms exceeding threshold values and (b) extreme value analysis of selected periods.

Two threshold values were used to define large daily rainstorms: 50mm and 100mm. These were used to test whether there is any evidence of a change in the frequency of large rainfall events. Annual frequencies of days with rainfall above these values were calculated for each station. Despite the use of 50 and 100mm boundaries being somewhat arbitrary, there are a number of reasons why these values have been used. First, these figures have been used in past studies in tropical locations to indicate large daily rainfalls. Second, it can be argued that falls of 50mm have a significant impact on river hydrographs, creating a sharp peak. Third, 100mm falls are likely to cause a major rise in river levels and the possibility of flood events (Walsh, Pers.comm). Another reason for the use in of the 50mm value is that data on the frequency of daily falls over 50mm in Malaysia were assembled and published in the ASEAN (1982) publication. Also in the weather summaries for stations in Borneo frequencies of different magnitude falls were included with boundaries at 50mm and 100mm.

The rainfall series of Walsh and Leong (2003) for Borneo stations were updated and extended back in time. To analyze the data, graphs similar to those for annual rainfall were constructed, with the annual number of falls per year and a 5-year running mean plotted on the same graph. For years which have one month short in the record, a plus sign was positioned above the bar representing that year to indicate that the number of falls in that year is not complete in the record. Years with more months missing were not included. This format was used for both 50 and 100mm falls at all stations. Question marks were inserted along the x-axis where years of data are missing.

In order to test whether there had been recent changes compared with earlier periods means and standard deviations were calculated for the following periods:

- from the start of the record to 1941,
- from 1946 to 1979, and
- from 1980 to 2004.

These periods were used partly because the periods up to 1979 and post-1980 were used in Walsh and Leong (2003) and also because it involved using periods of substantial and roughly equal length. The 25-year period from 1980 onwards was considered long enough to be used as a test to see if there have been any recent changes. These periods, however, were decided upon before looking at the data series and clearly different periods might have been in some cases be more appropriate, but on the other hand they would be different at each station and of differing lengths, and so would be difficult to compare between stations. The same reasons are considered valid when analyzing changes in annual rainfall between periods in section 2.5.2.

Secondly, extreme value analysis was also used to estimate the recurrence interval for extreme events for these different periods. The probability of occurrence of a large rainfall event is reflected in the length of 'return period' of the fall size considered. The return period of an event is the average number of years that pass before the same event magnitude is equalled or exceeded (Lockwood, 1968). Using all complete years in the record, the data were split into the three periods shown above.

In each period, a complete list of the x largest daily falls, where $x = n + 5$ and n = the number of years of the record in the period, was compiled. Rank 1 represents the largest fall in each period. The extreme value analysis calculates the likely return period of different sizes of events by using the formula:

$$\text{Return Period (RP)} = \frac{n+1}{m}$$

n = Number of years of record
m = Rank of daily rainfall (1 = highest)

The results of return period for each period were plotted on a logarithmic scale with the size of the fall (y-axis) against the return period (x-axis), with all three periods plotted on the same graph. Logarithmic regression lines were calculated and fitted for each period. The above procedure was used for each station separately.

2.5.5 TECHNIQUES FOR ASSESSING CLIMATE CHANGE AT DANUM VALLEY

In Chapter 7 attempts are made to find a surrogate station for the short-term climate record at Danum Valley by comparing the record at Danum Valley Field Centre with the longer series from stations in the coastal regions of Sabah, namely at Sandakan, Lahad Datu, Kudat, Tawau and Kota Kinabalu. In order to compare stations to Danum, cross-correlation is used. However there is a problem when using the regression equation of y on x (or x on y) when no causal relationship between the two is involved. The slope is biased so that the regression line either over-estimates or underestimates values. Instead the "Reduced Major Axis" (RMA) was used which is the bisector of the regression lines of y on x and x on y. This line is "the geometric mean of the linear regression coefficient of Y on X, and of the reciprocal of the regression coefficient of X on Y" (Sokal and Rohlf ,1981)

The equation for the RMA is $y = a + bx$

The equations for a and b for RMA line are:

$$a = \breve{y} - b\,\bar{x}$$

$$b = \sqrt{\frac{\sum y^2 - \frac{(\sum y)^2}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}}}$$

Once the RMA equation is established then this can be used as a predictor of the values of rainfall at Danum Valley for the years which are complete at the other station.

Correlation was used for both annual totals and monthly totals. The annual correlation simply illustrates which station has the best overall correlation with the data at Danum. The monthly totals may show that at one station there is a good correlation for one month, but another station shows better correlation than that station for another month. Therefore a more accurate picture of the past climate at Danum can be built up by using the best correlation for each individual month.

2.5.6 ADDITIONAL ANALYSIS

Following the original analysis it was decided that additional analysis would provide a better or more complete explanation of some of the original analysis. Firstly it was decided that in Malaysia the ENSO events do not follow calendar years and often the strongest periods of an ENSO event occur in the early months of the year and the latter months of the year can have much higher rainfall values, masking the effect of ENSO. A July to June year was used for extra correlation, in the same way as the original data.

Coefficients of variation were also added to the analysis to highlight variation in rainfall totals between periods. The coefficient of variation is the variation in relation to annual totals. The standard deviation may be the same at a station with very high rainfall and very low annual rainfall averages, however the impact of the variation would be different, it would be much more significant at the station with a lower annual average.

The coefficient of variation was calculated using:
(Standard deviation / Mean annual rainfall) *100

Changes in rainfall between the periods, already analysed using changes in the mean were analysed in relation to changes in mm per year. Using this analysis the magnitude of the change was clearer, although stations with only a small number of years record in the early (pre-World War II) period couldn't be included in analysis as the small number of years produced unrepresentative changes in the rainfall in mm per year.

CHAPTER 3:

RESULTS AND ANALYSIS: CHANGES IN ANNUAL AND SEASONAL RAINFALL IN PENINSULAR MALAYSIA

3.1 INTRODUCTION

In this chapter inter-annual variability and longer-term changes in annual and seasonal rainfall in Peninsular Malaysia are analysed. Firstly patterns in the annual and seasonal rainfall data and relationships with variations in the Southern Oscillation Index are explored. The analysis divides Peninsular Malaysia into three areas: West Coast, East Coast and the Interior. The division of the stations on the coasts was made both by geographical location and the use of correlating the values for the 5-year running means between stations. Reference is also made throughout the chapter to Table 3.1, which gives means and standard deviations of annual rainfall for sub-periods for all peninsula stations studied.

3.2 WEST COAST PENINSULAR MALAYSIA: ANNUAL AND SEASONAL RAINFALL TRENDS AND CORRELATION WITH ENSO EVENTS.

3.2.1 THE NORTHWEST: Alor Star (1907-2004), Bayan Lepas (1934-2004) and Parit Buntar (1888-2004)

These three stations in the northwest of the Peninsula show close similarities in rainfall trends with periods of high and low rainfall occurring in phase with each other (Figures 3.1 – 3.3). Correlations between the stations' annual rainfall for the period were high and statistically significant at the 95 % confidence level: Alor Star and Bayan Lepas r =+ 0.23, Alor Star and Parit Buntar r =+0.37 (1% confidence level) and between Bayan Lepas and Parit Buntar r = + 0.55 (1% confidence interval).

Some wet periods occur between the early/mid 1950s and mid 1960s more especially at Bayan Lepas, and a slightly wetter period from the late 1960s to early 1970s. Alor Star's record shows a low period around 1918/19 and then a high peak in the early 1920s. This peak is also shown at Parit Buntar along with low totals in 1902-07, 1916-19 and the early 1930s.

Figures 3.1 to 3.3 show the station data of Alor Star, Parit Buntar and Bayan Lepas with a decline in annual precipitation over the course of the 20th century. The minimum occurs in 1992 for Alor Star and Parit Buntar at 1789 and 1693mm respectively and a minimum at Bayan Lepas of 2106mm in 1995. At both Alor Star and Bayan Lepas peaks in the 5-year mean were followed by troughs lower than the previous one. The magnitude of the overall decline in the 5-year running mean was from 2434.4mm in 1909 to 2147.2mm in 2002 at Alor Star and from 2796mm in 1936 to 2360.7mm in 2002 at Bayan Lepas. The largest reductions in rainfall occur towards the end of the records throughout the 1980s and into the 1990s.

The annual deviation charts (Figures 3.4, 3.5 and 3.6) demonstrate the recent drying trends particularly well, since the mid 1970s rain in most years has been well below the long-term mean. Table 3.1 shows this decrease in annual totals over the three periods (first period from beginning of the record to 1940, second from 1946 to 1979 and third from 1980 to 2004). A gradual decrease from one period to the next results in a reduction in the mean annual rainfall of just under 400mm at Alor Star and just over 400mm at Bayan Lepas and over 200mm at Parit Buntar. Standard deviation at both Alor Star and Bayan Lepas has decreased as the annual rainfall decreased, but increased slightly at Parit Buntar.

Table 3.1. *Means, Standard Deviations and Differences Between Three Periods (Pre-1942, 1942-79 and 1980-2004) at Stations in Peninsular Malaysia.* * *= Statistically significant reduction or increase (95% level). Periods with less than 10 years of record are placed in brackets.*

			PRE 1942		1942-79 (1942-79 at Macritchie)				1980-2004			
STATION	REGION	PRE 1942 Years	MEAN	SD	MEAN	Difference (mean)	SD	Difference (s.d.)	MEAN	Difference (mean)	SD	Difference (s.d.)
Alor Star	West Coast Pen.	1907-1941	2354.5	342.2	2174.4	-180.1 *	262.4	79.7	1978.8	-195.6 *	287.7	25.2
Bayan Lepas	West Coast Pen.	1934-1941	(2845.0)	(434.9)	2511.7	(-333.3 *)	364.0	(-70.9)	2373.4	-138.3	391.4	27.4
Parit Buntar	West Coast Pen.	1888-1940	2231.0	343.8	2163.1	-67.9	275.3	-68.5	2011.0	-152.1	384.9	109.6
Sitiawan	West Coast Pen.	1931-40	1885.4	275.3	1798.9	-86.5	257.5	-17.8	1791.3	-7.6	225.7	-31.8
Malacca	West Coast Pen.	1930-	2262.5	282.9	2061.5	-200.9 *	272.9	-10.0	2003.8	-57.8	285.7	12.8
Kota Bharu	East Coast Pen.	1931-40	3043.7	591.0	2756.1	-287.6	520.9	-70.1	2518.8	-237.3	626.8	106.0
Kuala Trengganu	East Coast Pen.	1930-	3013.8	670.6	2708.2	-305.6	630.0	-40.6	2588.2	-120.0	503.1	-126.8
Kuantan	East Coast Pen.	1898-	2920.6	632.1	2789.9	-130.6	558.5	-73.6	2934.7	144.7	549.5	-9.0
Mersing	East Coast Pen.	1930-	2702.8	453.2	2749.9	47.1	447.1	-6.1	2663.4	-86.5	528.1	81.0
Ipoh	Central Pen	1938-	(2344.6)	(151.6)	2442.8	(98.1)	315.8	(164.2)	2527.1	84.3	401.0	85.2
Cameron Highlands	Central Pen	1925-	2667.1	385.9	2568.6	-98.5	312.2	-73.7	2724.2	155.6	364.1	51.9
Tapah	Central Pen	1889-	3693.1	480.1	3458.5	-234.6 *	500.4	20.3	3132.7	-325.7 *	401.3	-99.1
Kuala Lumpur	Central Pen	1928-40	(2363.7)	(380.9)	2420.3	(56.5)	311.7	(-69.2)	2552.7	132.4	326.0	14.3
Macritchie Reservoir	Singapore	1875-41	2432.0	371.0	2291.5	-140.5	400.6	29.6	2515.2	223.7 *	359.5	-41.1

Figure 3.1. *Annual Rainfall at Alor Star*

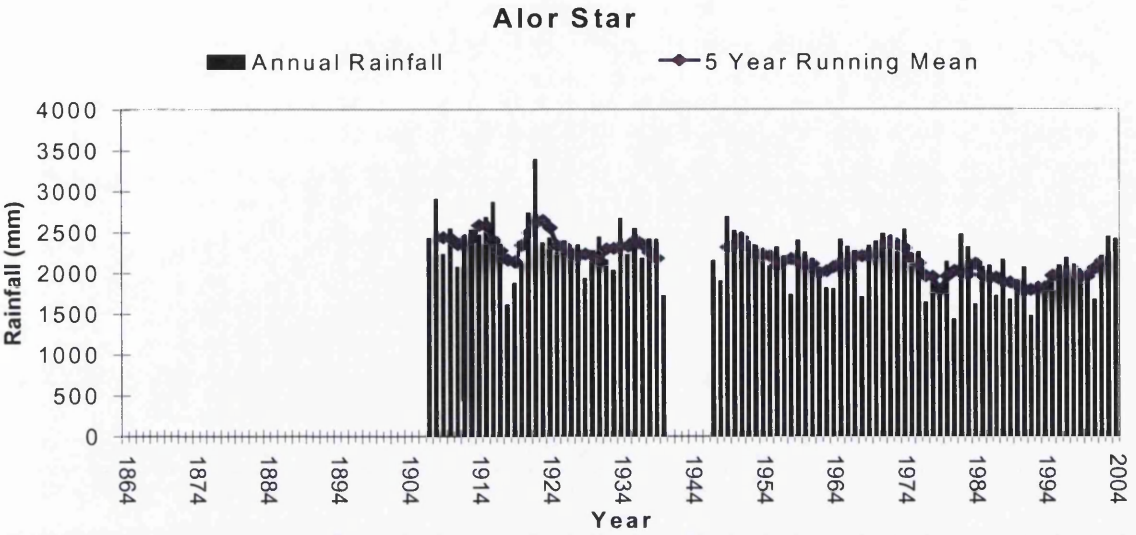


Figure 3.2. *Annual Rainfall at Bayan Lepas*

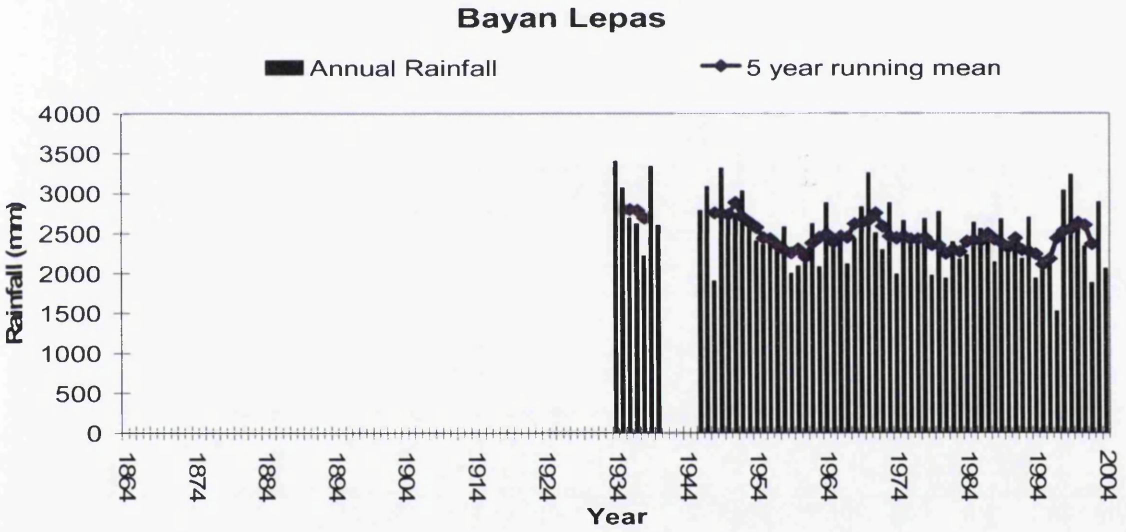


Figure3.3. *Annual Rainfall at Parit Buntar*

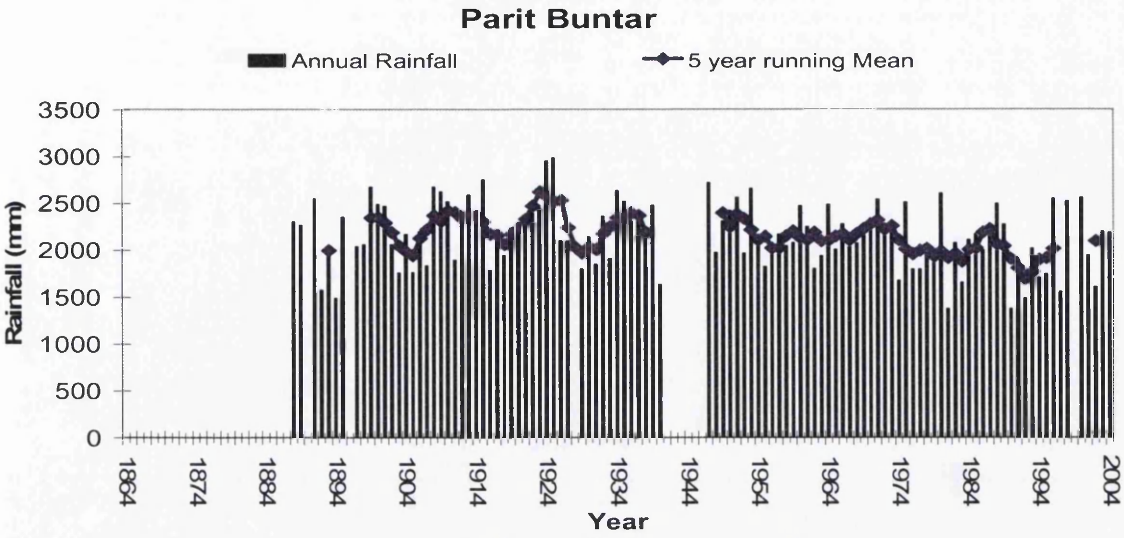


Figure 3.4. *Annual Deviation from the Long-term Mean Annual Rainfall at Alor Star*

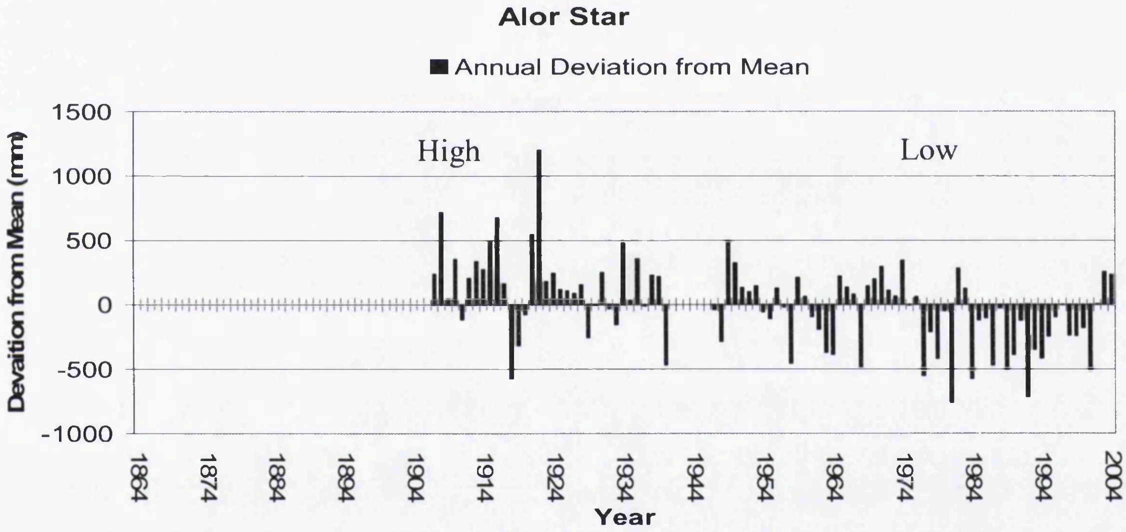


Figure 3.5. *Annual Deviation from the Long-term Mean Annual Rainfall at Bayan Lepas*

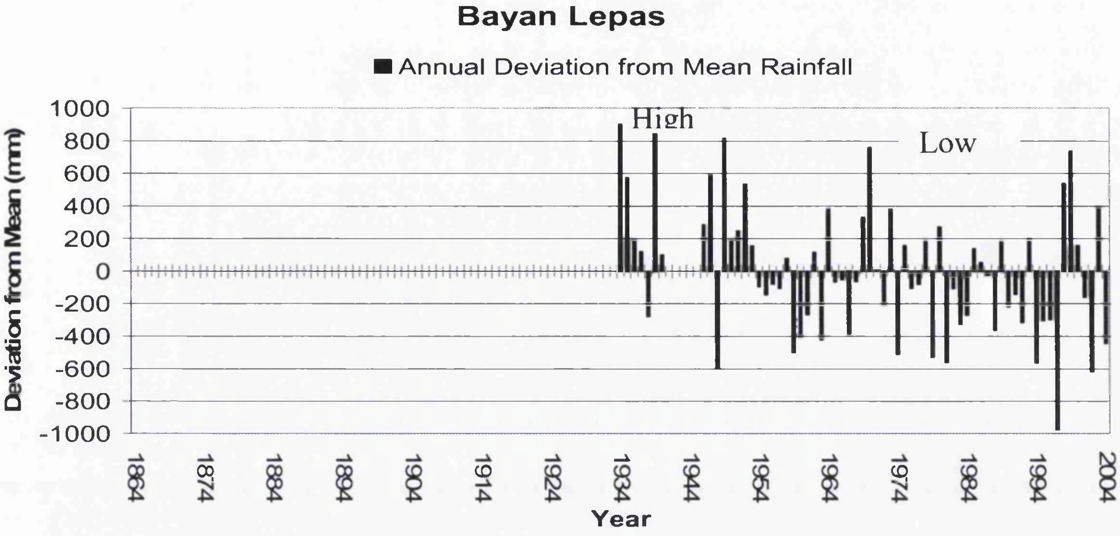
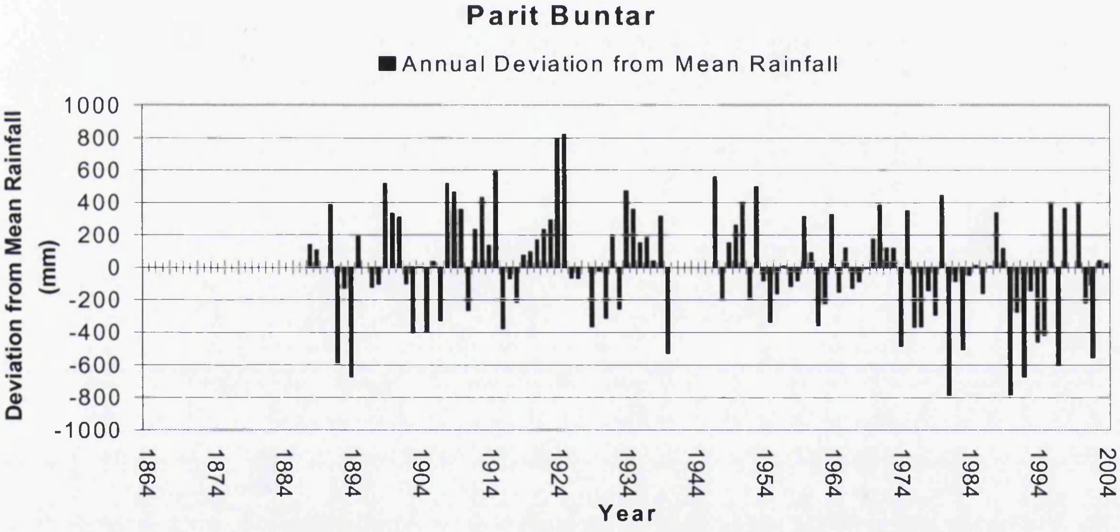


Figure 3.6. *Annual Deviation from the Long-term Mean Annual Rainfall at Parit Buntar*



Figures 3.7-3.9 explore whether the decline in rainfall occurs throughout the year or is limited to a particular part of the season. At Alor Star and Bayan Lepas the southwest monsoon season brings the majority of the rainfall in the year, whereas at Parit Buntar rainfall comes more evenly in both monsoon seasons (Figures 3.7 to 3.9). The reduction in rainfall at Alor Star and Bayan Lepas appears to be a result of a long-term decline in the southwest monsoon rainfall totals (steady reduction of

over 300mm at Alor Star), but at Parit Buntar the decline is linked to reductions in both monsoon seasons. At Alor Star the reduction in southwest monsoon rainfall is statistically significant at the 5% significance level (The significance was tested by using the strength of the r value from the trend line. Refer to methodology chapter for clarification).

Figure 3.7. *Five-year running means of the rainfall for monsoonal and transition months at Alor Star*

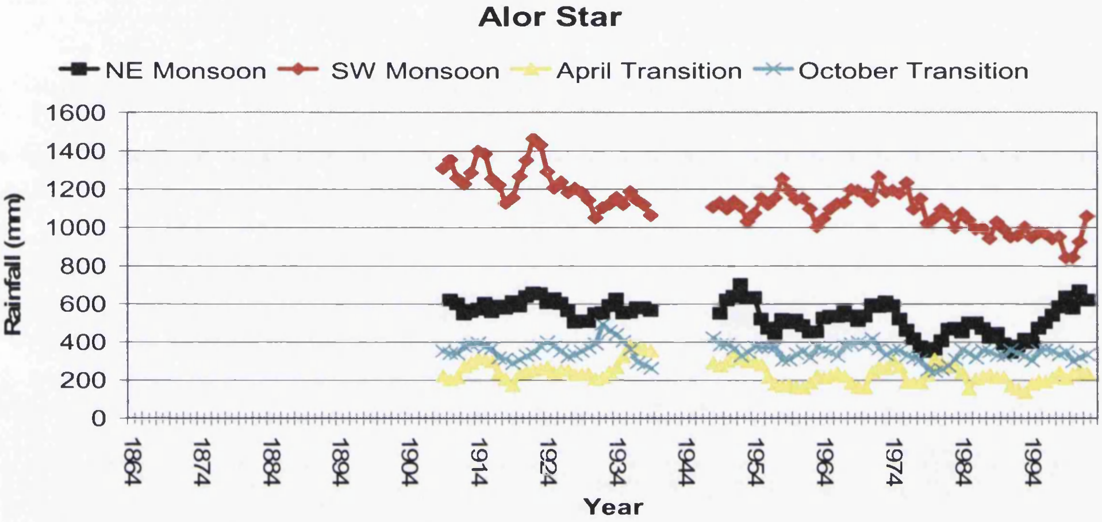


Figure 3.8. *Five-year running means of the rainfall for monsoonal and transition months at Bayan Lepas*

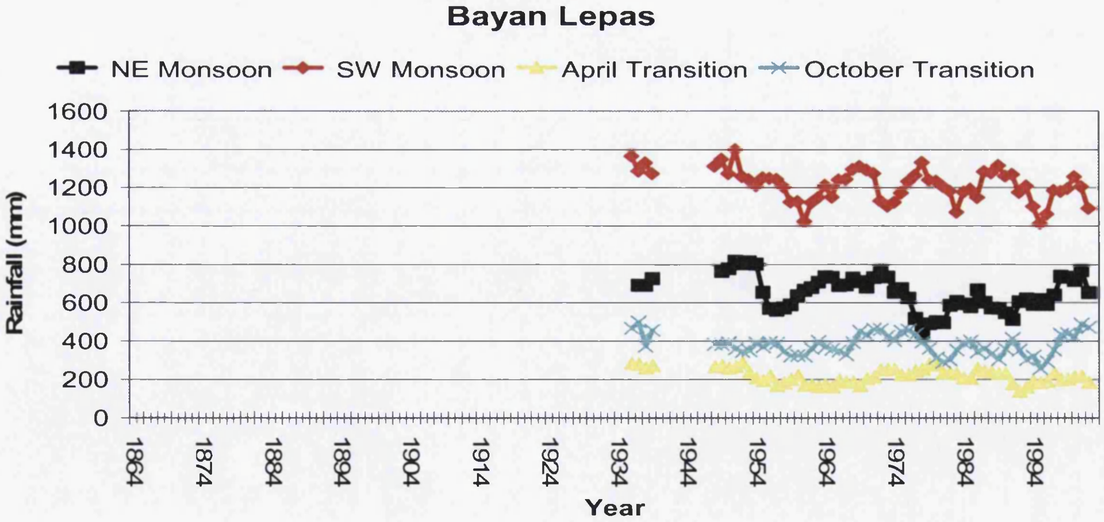
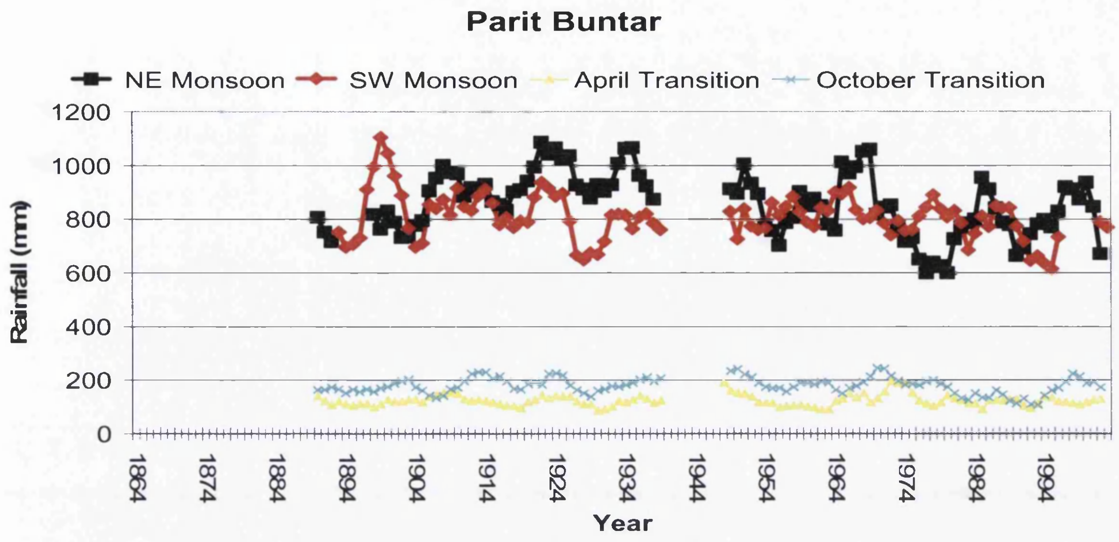


Figure 3.9. *Five-year running means of the rainfall for monsoonal and transition months at Parit Buntar*



Correlation coefficients between annual rainfall totals and the Southern Oscillation Index (SOI) were low at all stations (r=+0.25 at Alor Star, r=+0.18 at Bayan Lepas and r=+0.20 at Parit Buntar), but at Alor Star and Parit Buntar these correlations were significant at 5% level due to large datasets. Some of the very low annual rainfall totals, however, did occur in El Niño years such as in 1918-1919 and 1940 at Alor Star and especially 1997 at Bayan Lepas. Also the dry epoch since the mid-1970s coincides with a well-documented increase in frequency and intensity of ENSO events regionally and worldwide. At all stations covered correlations should be expected to be low due to the ENSO events not falling directly within calendar years.Thus the average SOI of a year may hide large El Niño or La Niña events. This caution is applied to all correlations between SOI and rainfall throughout the results and analysis.

Tables 3.2, 3.3 and 3.4 showing the anomaly from mean annual rainfall demonstrate that ENSO events do not necessarily mean a reduction in annual rainfall, as there are many ENSO events that had higher than average rainfall in the year. Again this can in part be attributed to ENSO events not covering a complete calendar year, as mentioned above. Bayan Lepas and Parit Buntar showed that in the period since 1980, when the SOI was less than -5, all but one and two years respectively had low rainfall totals.

Table 3.2. *ENSO severity and annual rainfall anomalies at Alor Star in thirty-one ENSO events.*

Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	0	3	0	1	9	0	0
Moderate to Strong	1	3	2	0	5	0	1
Very Stong	1	2	1	1	2	0	0
All	2	8	3	2	15	0	1

Table 3.3. *ENSO severity and annual rainfall anomalies at Bayan Lepas in twenty-six ENSO events.*

Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	1	1	1	4	1	2	2
Moderate to Strong	1	0	2	2	1	0	0
Very Strong	1	2	1	2	1	0	1
All	3	3	4	8	3	2	3

Table 3.4. *ENSO severity and annual rainfall anomalies at Parit Buntar in thirty-six ENSO events.*

Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	2	0	4	4	1	3	2
Moderate to Strong	0	2	5	1	5	0	1
Very Stong	4	1	0	2	0	2	0
All	5	3	9	5	6	5	3

3.2.2 THE WEST COAST: Sitiawan (1930-2004) and Malacca (1930-2004).

Malacca (Figures 3.10 and 3.12) shows a period of high rainfall from 1930 to 1960 and then from 1960 onwards the totals were lower (as shown by the 5-year running mean). Figure 3.12 shows that between 1959 and 2003 only three years had annual totals more than 200mm above the annual mean (two of which were greater than 400mm). A fitted regression line applied to the data at Malacca showed a statistically significant decline in annual rainfall at 1% significance level despite the peaks and troughs contained within the record. Sitiawan (Figures 3.11 and 3.13) shows a different pattern to the stations farther north, with no real evidence of a decline in annual rainfall, experiencing a wetter period from the late 1980s to mid 1990s.

Figure 3.10. *Annual Rainfall at Malacca*

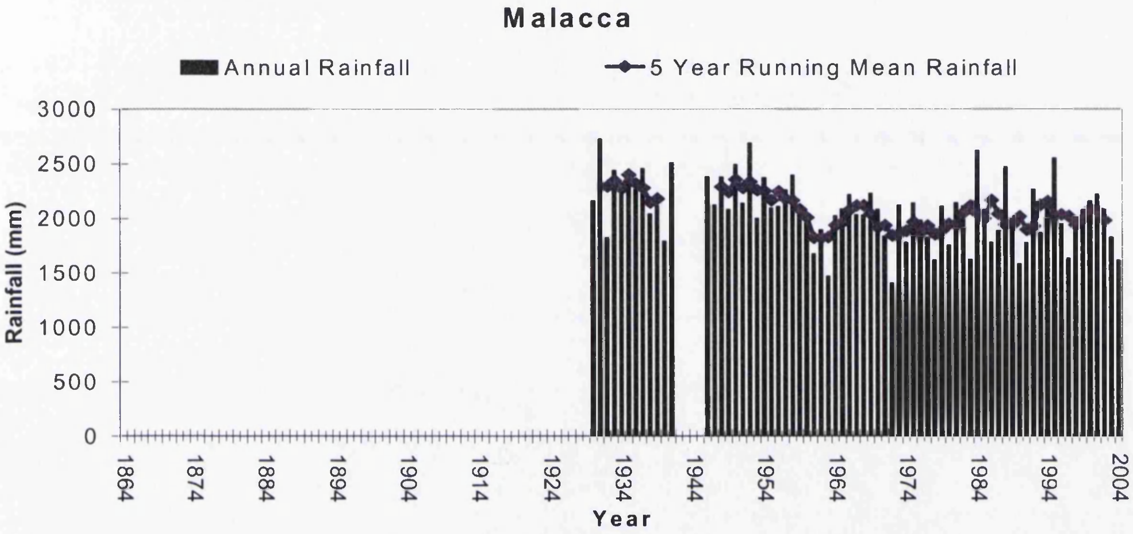


Figure 3.11. *Annual Rainfall at Sitiawan*

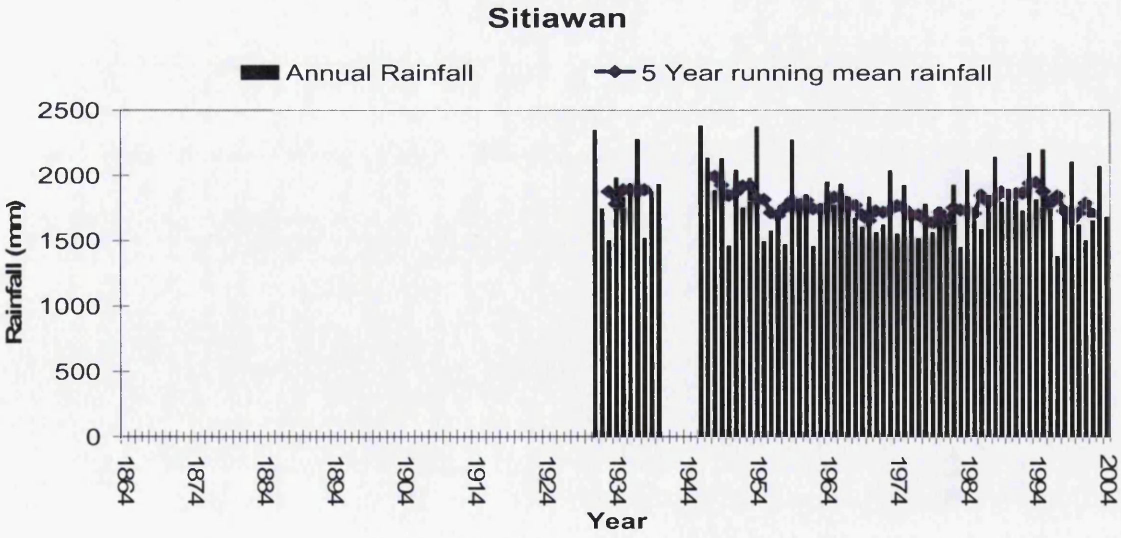


Figure 3.12 *Annual Deviation from the Long-term Mean Annual Rainfall at Malacca*

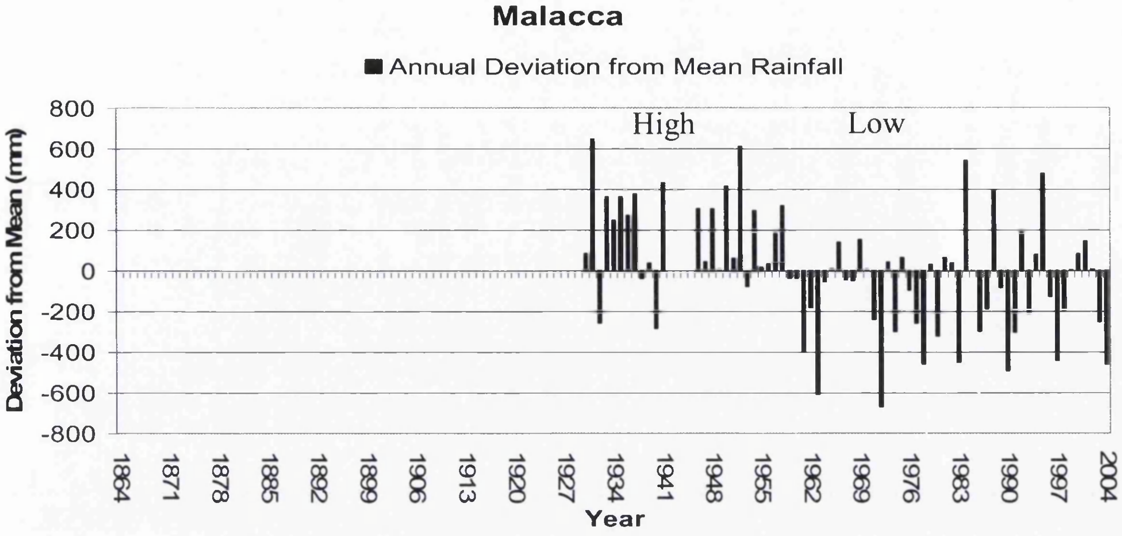
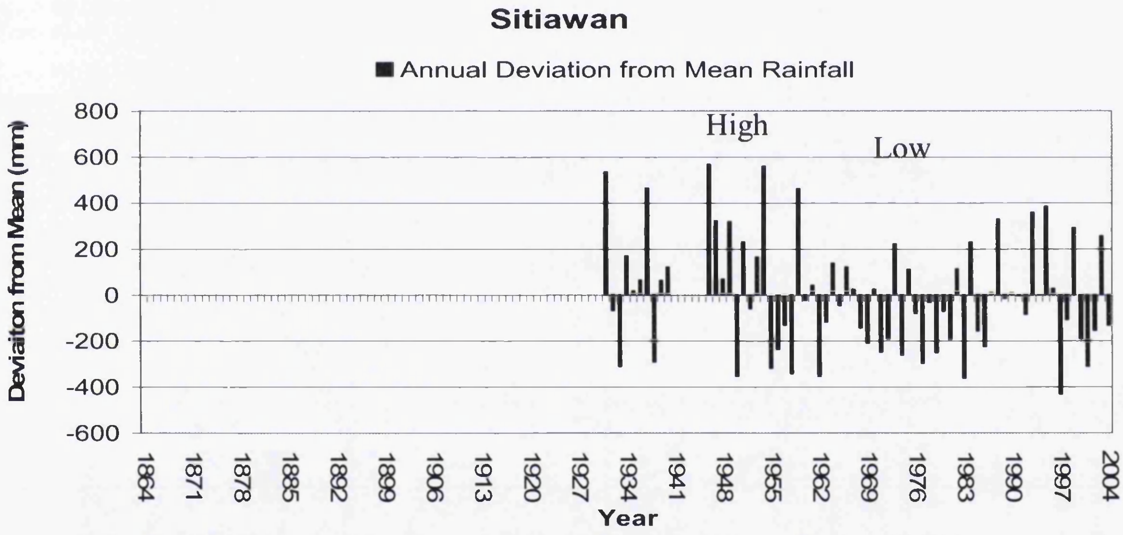


Figure 3.13. *Annual Deviation from the Long-term Mean Annual Rainfall at Sitiawan*



At both stations the particularly low annual rainfall of the late 1960s and early 1970s (Figures 3.12 and 3.13) are a result of significantly reduced northeast monsoon totals (Figures 3.14 and 3.15) and also SW monsoon rain at Malacca (Figure 3.14) The drier 10 years at Sitiawan from 1968 are due to low NE monsoon rainfall totals (Figure 3.15).

At Sitiawan the decade 1987-1996, unlike many other west coast stations, but similar to other stations inland, was particularly wet, mainly due to the large rise in the northeast monsoon rainfalls (as seen on the east coast (see Figures 3.20 and 3.21)).

After this short period the rainfall in 1997-2002 was below the annual mean with the largest negative deviation in 1997 of 432.2mm. In this period both monsoons were drier.

Figure 3.14. *Five-Year Running Means of Rainfall for Monsoonal and Transition Months at Malacca*

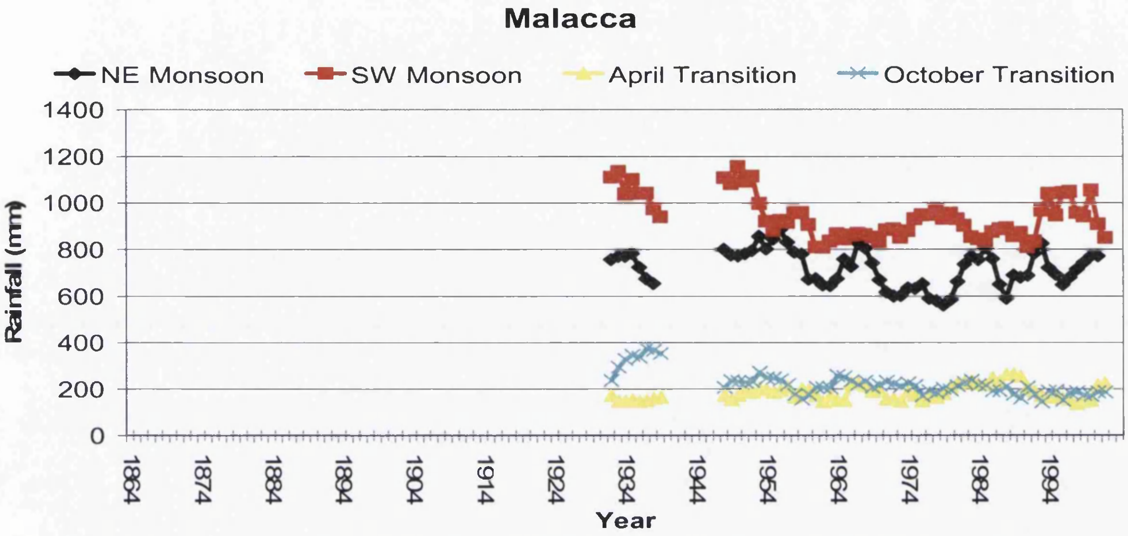
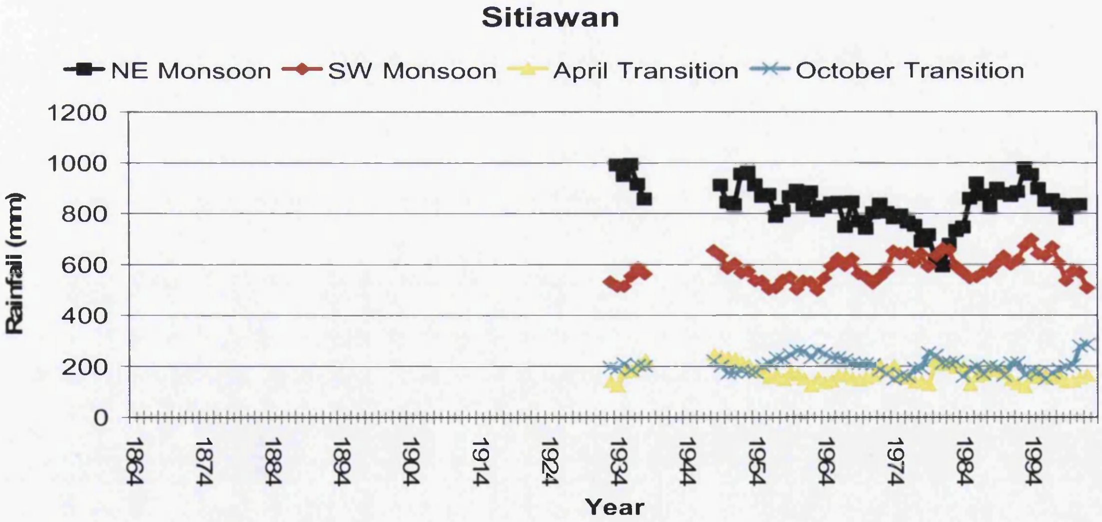


Figure 3.15 *Five-year Running Means of Rainfall for Monsoonal and Transition Months at Sitiawan.*



No significant relationship between SOI and annual precipitation was found for Malacca (r=+0.19) or Sitiawan (r=-0.04) and likewise no significant relationship was found for the monsoon seasons. Tables 3.5 and 3.6 reinforce the poor relationship between ENSO events and annual rainfall deviations from mean at both stations.

Table 3.5. *ENSO severity and annual rainfall anomalies at Malacca.*

Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	1	2	2	3	1	1	1
Moderate to Strong	1	1	2	2	1	0	0
Very Stong	0	2	3	1	1	1	0
All	2	5	7	6	3	2	1

Table 3.6. *ENSO severity and annual rainfall anomalies at Sitiawan*

Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	0	1	4	3	3	0	0
Moderate to Strong	0	0	2	3	0	1	1
Very Stong	0	2	1	2	2	0	0
All	0	3	7	8	5	1	0

3.3 EAST COAST PENINSULAR MALAYSIA: ANNUAL AND SEASONAL RAINFALL TRENDS AND CORRELATION WITH ENSO EVENTS.

3.3.1 THE NORTHEAST: Kota Bharu (1930-2004) and Kuala Trengganu (1930-2004)

The five-year running means of annual rainfall decline from 1975 steadily to a minimum between 1987 and 1992 at Kota Bharu (Figure 3.16) and a less defined but longer minimum from the late 1970s to early 1990s at Kuala Trengganu (Figure 3.17). During these troughs, many years had annual totals more than 500mm below the annual mean (Figures 3.18 and 3.19). At both stations annual rainfall recovered strongly in the late 1990s onwards. The decrease in annual rainfall appears at the same time as declines on the west coast, but the large increase at the end of the records is not evident at stations on the west coast. There has been a reduction in the annual mean of 525mm at Kota Bharu and 426mm at Trengganu, a similar magnitude of reduction to the more northerly stations on the west coast.

In terms of period means (Table 3.1), at both stations mean annual rainfall fell substantially (288-306mm) from the pre-1942 period to the 1943-1979 period and substantially again (120-237mm) in the 1980-2004 period compared with 1943-1979.

Figure 3.16. *Annual Rainfall at Kota Bharu.*

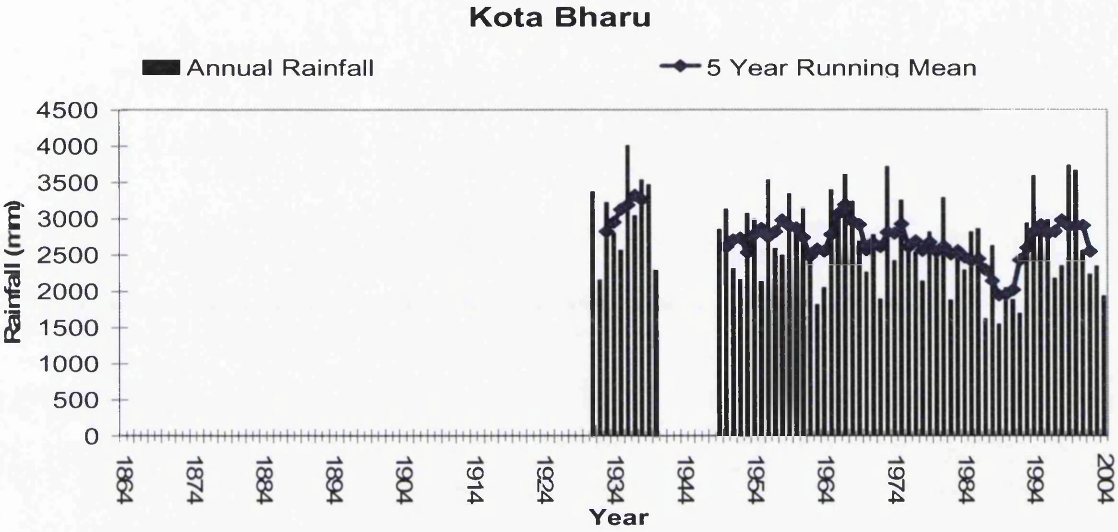


Figure 3.17. *Annual Rainfall at Kuala Trengganu*

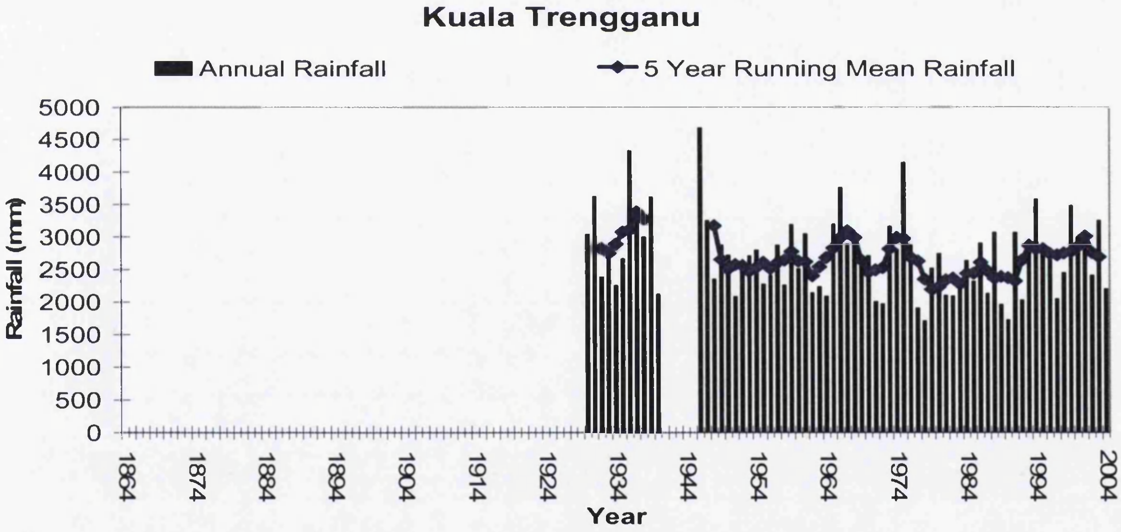


Figure 3.18. *Annual Deviation From the Long-term Mean Annual Rainfall at Kota Bharu*

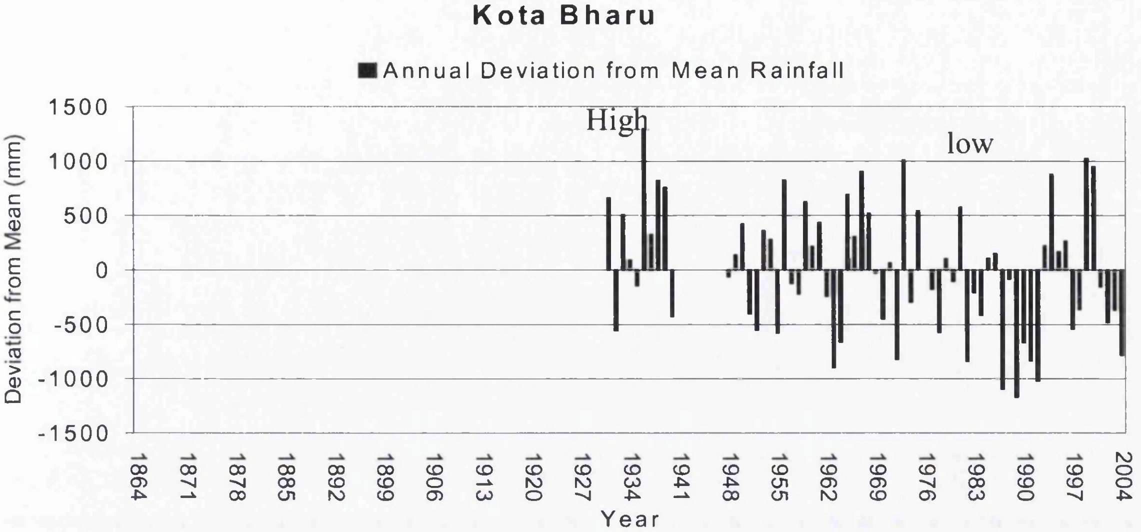
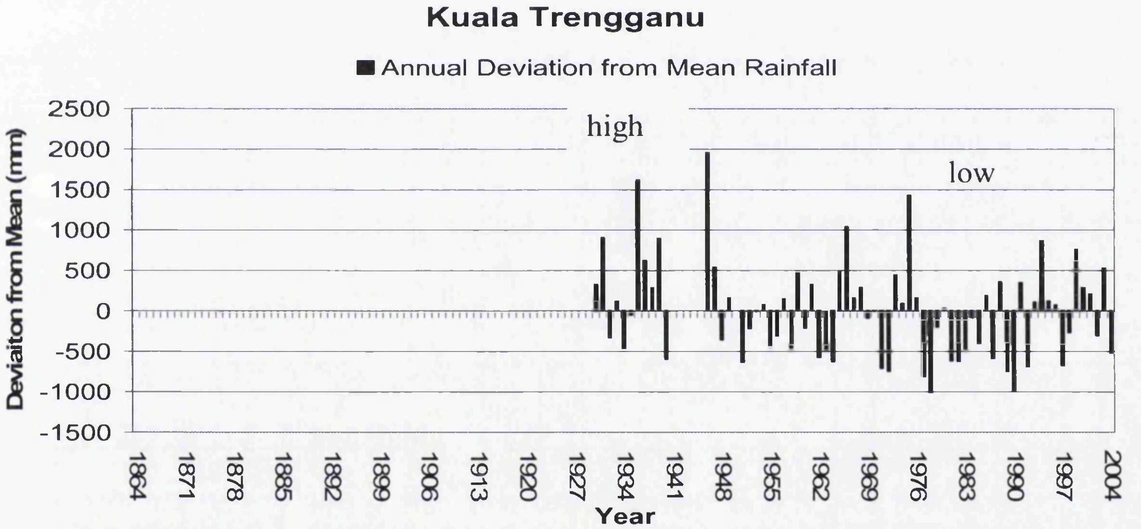


Figure 3.19. *Annual Deviation From the Long-term Mean Annual Rainfall at Kuala Trengganu*



The dry periods and the recent rise in annual rainfall at both stations are produced by fluctuations in northeast monsoon rainfall totals. Thus NE monsoon rain fell by over 600mm in less than 10 years, from the early 1980s to early 1990s (Figure 3.20) before rising sharply at the end of the record.

The 1975-1992 decrease in rainfall at Kota Bharu occurs partly as a result of a continuous decline in the southwest monsoon (Figure 3.20, r-value of -0.58 for the SW monsoon, which is statistically significant at the 1% level). There is only a small decrease in the southwest monsoon rainfall totals further south at Kuala Trengganu (Figure 3.21).

Annual rainfall is greatest at the beginning of both records in the 1930s when the 5-year mean greatly exceeded the long-term mean. This period of high rainfall was a result not only of both monsoons having high totals, but also the October transition month experienced higher rainfall at this time.

The increase in the standard deviation at Kota Bharu in recent times (Table 3.1) seems to suggest that the northeast corner of Malaysia is experiencing a more variable climate with an increasing dependence on the variable rainfall in the northeast monsoon.

Figure 3.20. *Five-Year Running Means of Rainfall for Monsoonal and Transition Months at Kota Bharu*

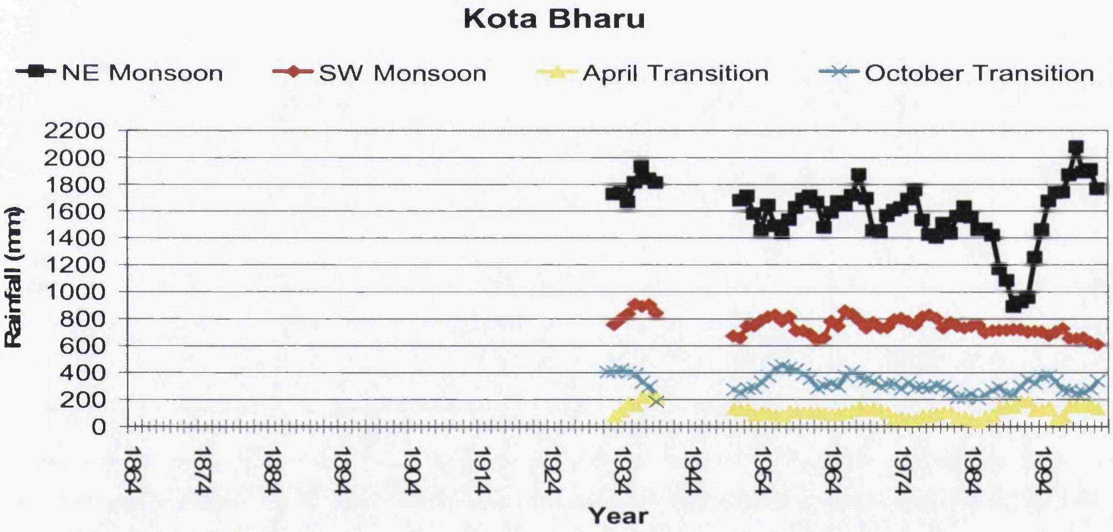
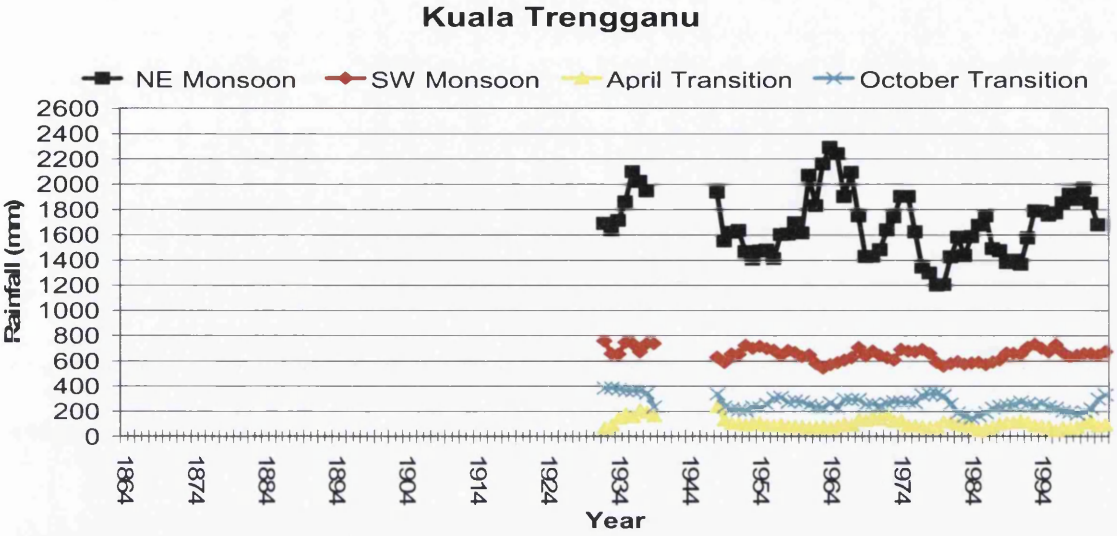


Figure 3.21. *Five-Year Running Means of Rainfall for Monsoonal and Transition Months at Kuala Trengganu*



Unlike at the other stations discussed above, annual precipitation in Kota Bharu shows a statistically significant correlation (r =+0.38) with the SOI. It is still a weak correlation (R^2= 0.145). Kuala Trengganu also shows a very weak relationship and non-significant correlation (r=+0.16). Since the mid-1970s ENSO events became more frequent and annual rainfall decreased, and during the 1930s, a period with few ENSO events annual rainfall was above normal. However, the driest year at Kota Bharu (1989) was not an El Niño year. Tables 3.7 and 3.8 indicate that during very strong ENSO events anomalies are invariably negative, but many weak or moderate El Niño events have annual rainfall totals above the long-term mean.

Figure 3.22. *Correlation between SOI and rainfall at Kota Bharu.*

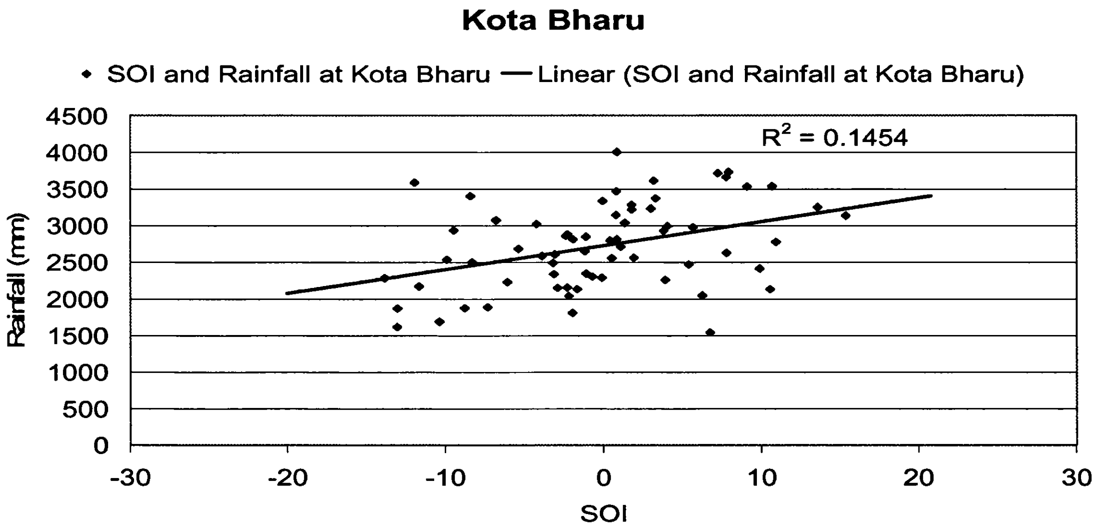


Table 3.7. *ENSO severity and annual rainfall anomalies at Kota Bharu in twenty-four ENSO events.*

	Anomaly (mm) compared to annual average						
	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	4	3	1	1	1	1	1
Moderate to Strong	2	0	1	0	1	0	2
Very Stong	3	3	1	0	0	0	0
All	8	6	3	1	2	1	3

Table 3.8. *ENSO severity and annual rainfall anomalies at Kuala Trengganu in twenty-five ENSO events.*

	Anomaly (mm) compared to annual average						
	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	4	3	1	1	1	0	3
Moderate to Strong	2	0	0	1	0	2	2
Very Stong	4	1	1	0	0	0	0
All	9	4	2	2	1	2	5

3.3.2 THE SOUTH-EAST: Kuantan (1898-2004) and Mersing (1930-2004)

The significantly longer record at Kuantan shows more oscillations between periods of dry and wet years but with no significant long-term patterns or trends (Figure 3.22, Table 3.1). The dry period evident at all the stations covered so far usually from the 1960s onwards, starts at Kuantan (Figure 3.23) in the 1960s finishing in the mid-1980s (with the exceptions of the years 1996 and 1997 which were also very dry), earlier than at many other stations in the peninsula. The 1920s was a period of mostly wetter than average years.

Figure 3.23. *Annual Rainfall at Kuantan.*

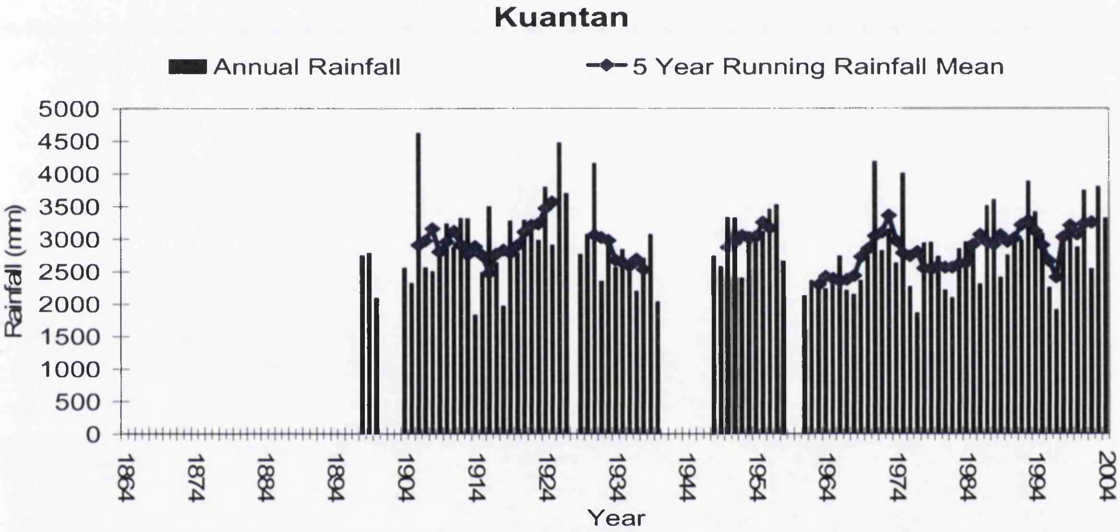
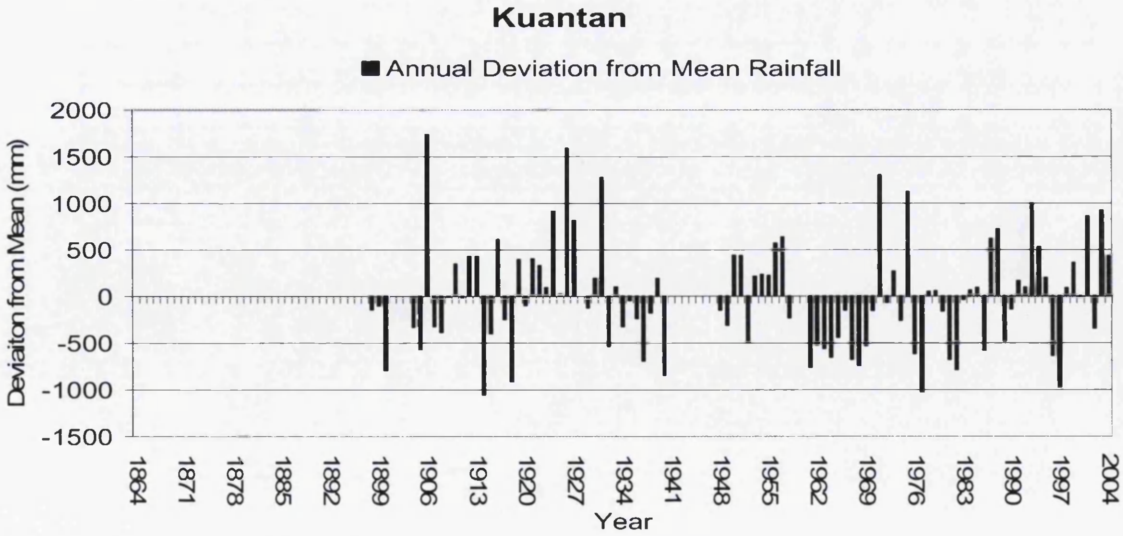
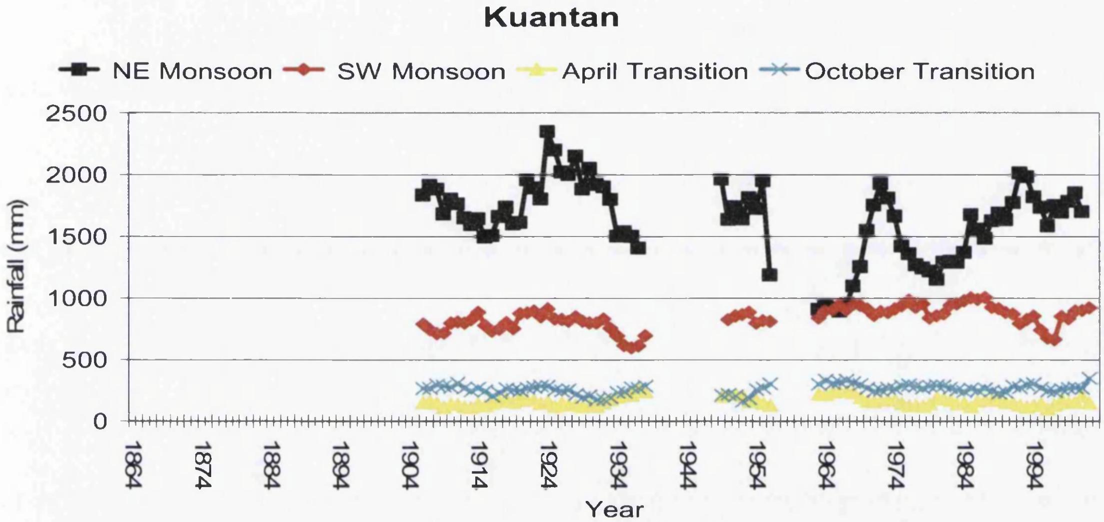


Figure 3.24. *Annual Deviation from the Long-term Mean Annual Rainfall at Kuantan*



Rainfall variation here is similar to the stations further north with large fluctuations between years, a result of the erratic northeast monsoon (the main source of rainfall). Low northeast monsoon totals were common in the mid-1970s to 1980s, but have risen since (Figure 3.25)

Figure 3.25 *Five-Year Running Mean of Rainfall for Monsoonal and Transition Months at Kuantan*



Mersing, like Kuantan, shows little change in annual rainfall over the three periods studied (Figure 3.26, Table 3.1) despite high year-to-year variability (Table3.1, Figure 3.27). Again the Northeast monsoon rain dominates annual totals (Figure 3.27).

Figure 3.26. *Annual Rainfall at Mersing*

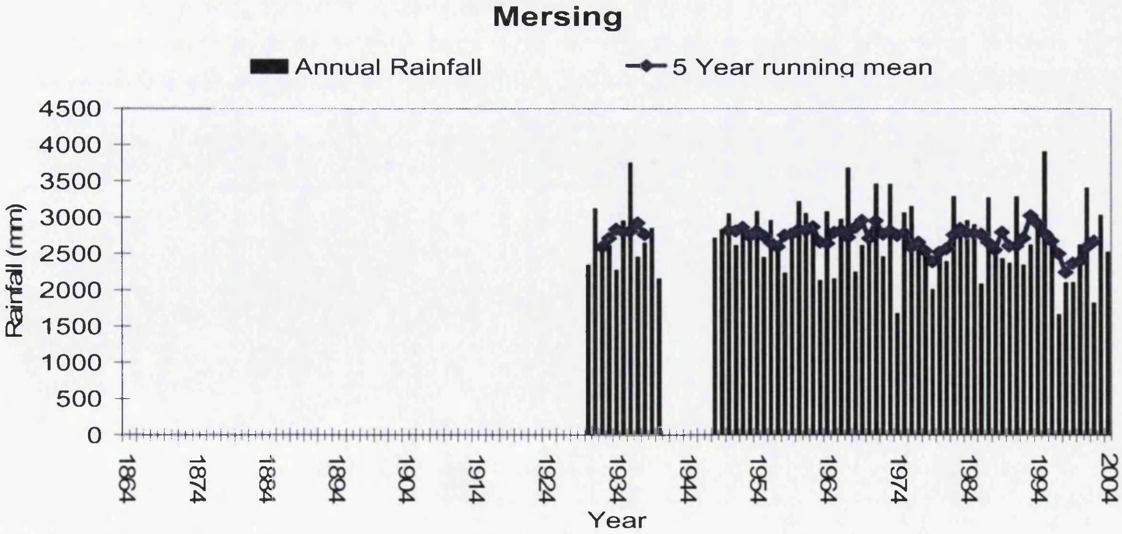


Figure 3.27. *Annual Deviation from the Long-term Mean Annual Rainfall at Mersing.*

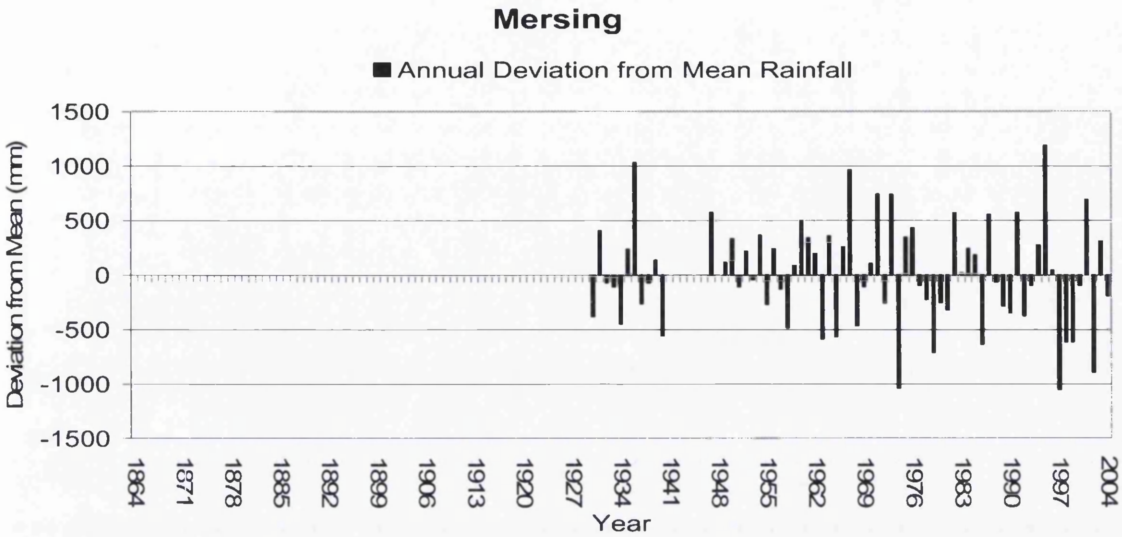
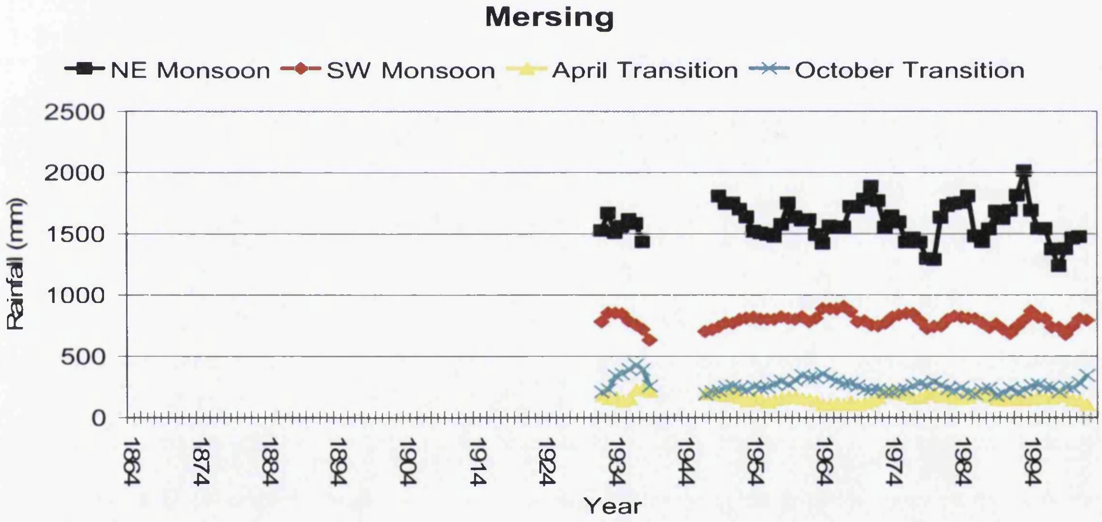


Figure 3.28. *Five-Year Running Mean of Rainfall for Monsoonal and Transition Months at Mersing*



Correlation coefficients of annual rainfall with the SOI index are positive, but very weak and only just statistically significant at Kuantan (r= +0.22). The driest years of 1914, 1977, and 1997 all occurred during very strong El Niño events. Tables 3.9 and 3.10 show that during ENSO events (especially very strong events) there is more chance of large negative anomalies of annual rainfall but not invariably so. Likewise although many of the years with highest rainfall occur at times of positive SOI indicating La Niña events, there are contrary examples against this such as the large rainfall deficit in 1974 that occurred with La Niña conditions. Again this could be a result of the fact that ENSO events do not necessarily stop and start at the beginning of calendar years.

Table 3.9. *ENSO severity and annual rainfall anomalies at Kuantan in thirty-five ENSO events.*

Kuantan	Anomaly (mm) compared to annual average								
		Negative			Average			Positive	
El Niño Severity/rainfall anomaly (mm)	>500	300-499	100-299		-99 to +99		100-299	300-499	>500
Weak	3	2	3		2		1	1	2
Moderate to Strong	2	2	0		2		2	2	2
Very Strong	5	0	0		1		2	0	1
All	10	4	3		5		5	3	5

Table 3.10. *ENSO severity and annual rainfall anomalies at at Mersing in twenty-seven ENSO events.*

Mersing	Anomaly (mm) compared to annual average								
		Negative			Average		Positive		
El Niño Severity/rainfall anomaly (mm)	>500	300-499	100-299		-99 to +99		100-299	300-499	>500
Weak	3	2	2		0		3	1	0
Moderate to Strong	1	0	1		2		1	0	1
Very Stong	3	1	0		1		0	0	2
All	7	3	3		3		4	4	3

3.4 CENTRAL PENINSULAR MALAYSIA: ANNUAL AND SEASONAL RAINFALL TRENDS AND CORRELATION WITH ENSO EVENTS

The rainfall record at Ipoh (1938-2004) differs from those at stations on the east and west coasts. The 5-year running mean indicates a period of somewhat lower rainfall from 1960 to 1992 during a time when the northeast monsoon rainfall was generally low (Figure 3.30) and roughly similar to SW monsoon rainfall. 1992 had the lowest annual total in the record with 1827.7mm again mostly as a result of low northeast monsoon rainfall. The years 1995 and 2003 (the highest on record) were well above the mean, whereas 1997/98 and 2002 were anomalously dry.

Since 1994 the variability from year to year seems to have increased with some totals well above the mean and others well below. Thus standard deviation rose from 315mm in 1942-1979 to 400mm in 1980-2004 (Table 3.1).

Figure 3.29. *Annual Rainfall at Ipoh*

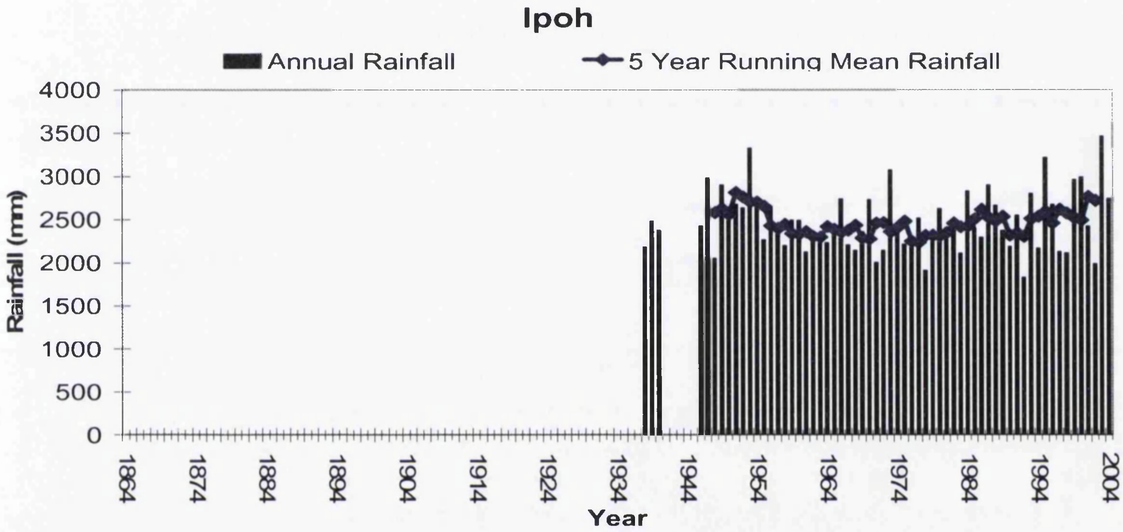


Figure 3.30. *Annual Deviation from the Long-term Mean Annual Rainfall at Ipoh*

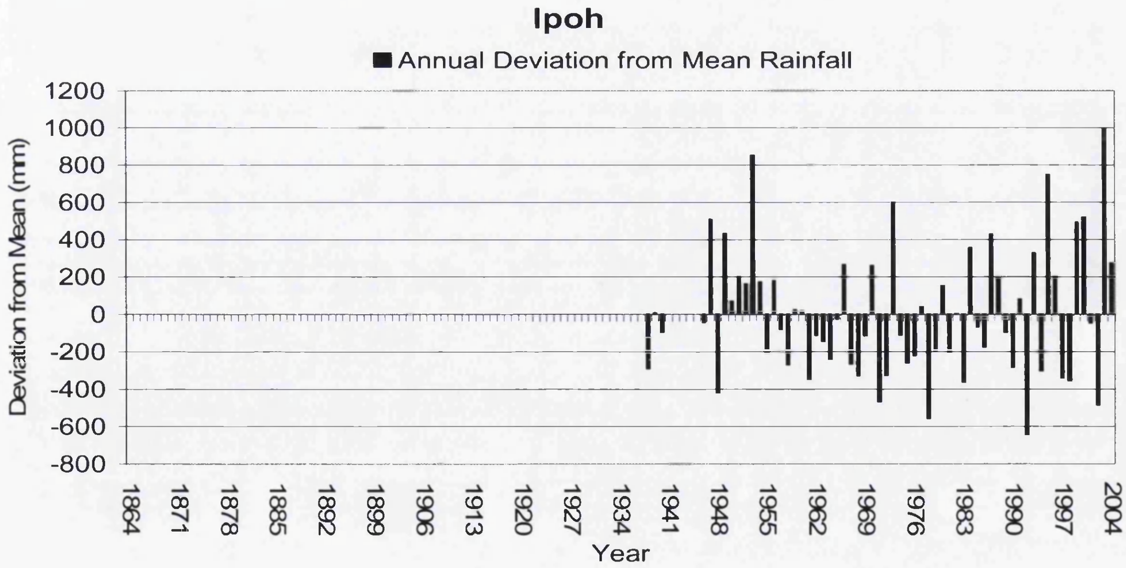
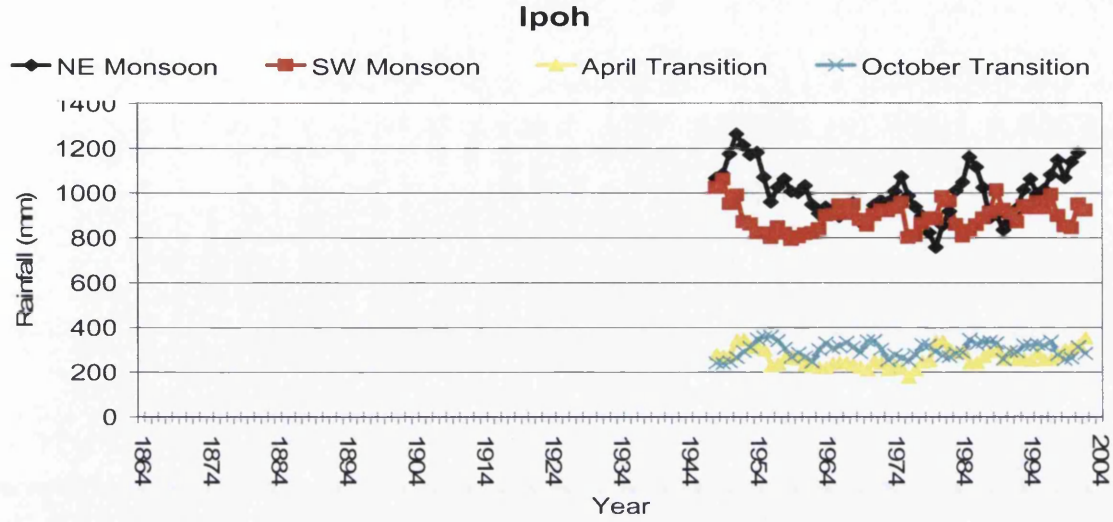


Figure 3.31. *Five-Year Running Means of Rainfall for Monsoonal and Transition Months at Ipoh.*



At the Cameron Highlands station (1930-2004) there is little variation in the five-year mean during most of the record apart from a dip from 1976-1982 and a recent rise (as at Ipoh) from 1993 onwards (Figures 3.32 and 3.33), this leading to a rise of 155mm in the 1980-2004 mean compared with 1946-19 (Table 3.1)

Figure 3.32. *Annual Rainfall at Cameron Highlands Station*

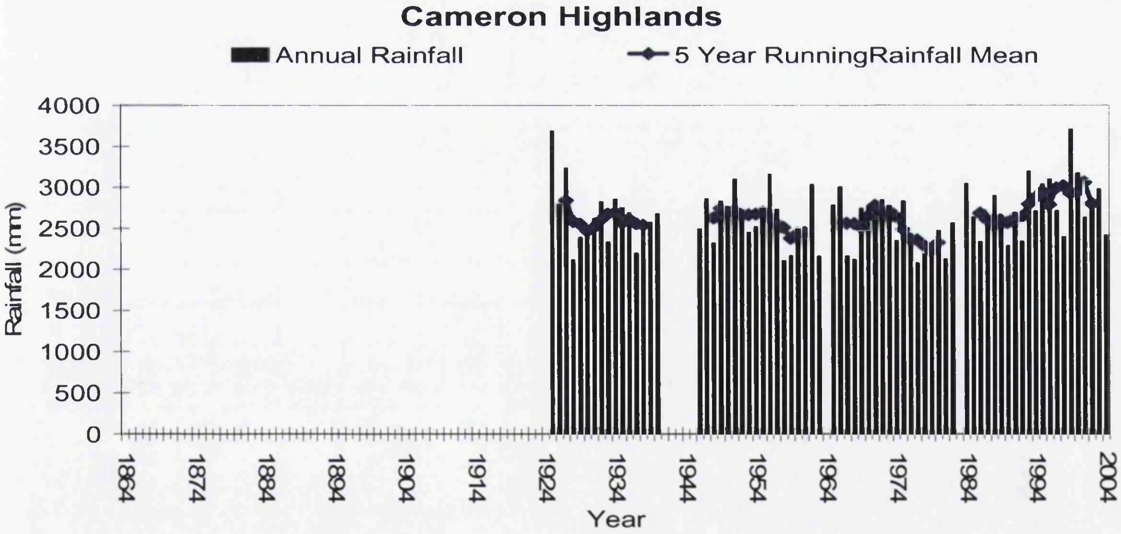


Figure 3.33. *Annual Deviation from the Long-term Mean Annual Rainfall at Cameron Highlands Station.*

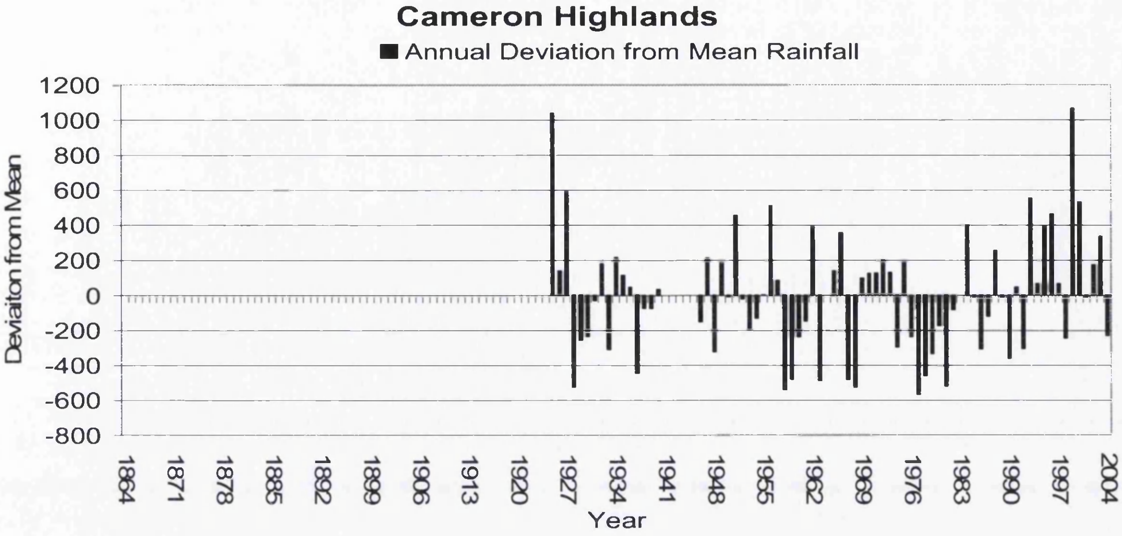
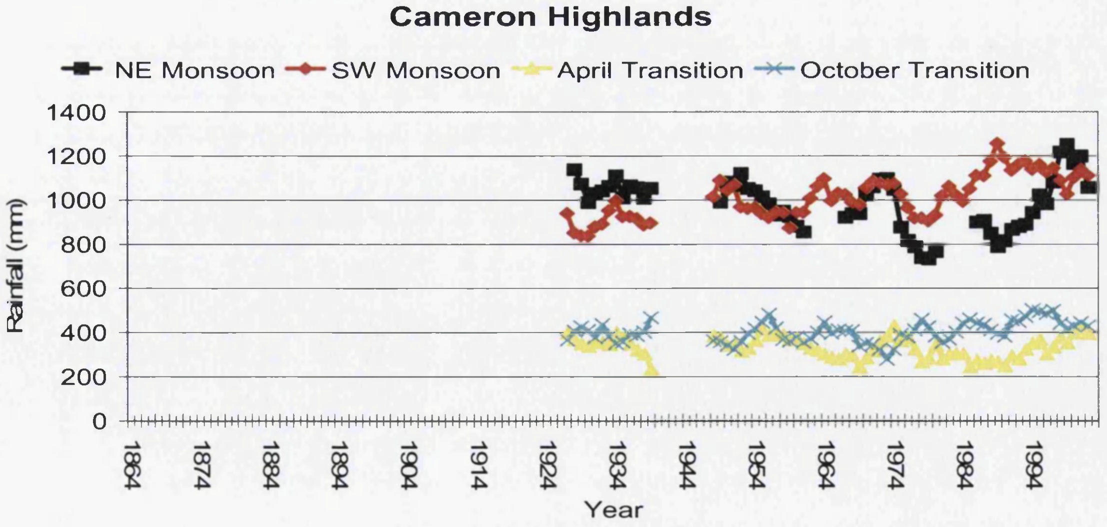


Figure 3.34 shows that the monsoon dominance switches throughout the record with periods of northeast monsoon dominance, then southwest dominance. This graph also demonstrates a pattern which is not seen at other stations as the southwest monsoon rainfall rises significantly throughout the record; $R^2 = 0.55$, $r=+0.74$ significant at 1% significance level. The northeast monsoon rain fell during the 1970s and the 1980s before a large rise in the 1990s.

Figure 3.34. *Five-Year Running Means of Rainfall for Monsoonal and Transition Months at the Cameron Highlands Station.*



At Tapah, which has a very long and continuous record (1889-2004), the main feature is overall decline from much higher rainfall of the 1910s and 1920s and after a major peak in the rainfall between 1964 and 1970 when both monsoons had high totals (Figures 3.35 and 3.37). Between 1971 and 1994 there are only 4 years with above average rainfall in comparison to the 19 years that were drier than average in the same period (Figure 3.36), this dry period continued to the end of the present record. The general reduction in rainfall since the 1970s seems to be a result of low rainfall in both monsoon seasons. The period 1972-1982, however, resulted mainly from reduced rainfall in the northeast monsoon, as it declined to values as low as the southwest monsoon (Figure 3.37).

Table 3.1 shows that (like Alor Star and Bayan Lepas on the west coast), rainfall at Tapah has reduced by 560mm (15%) from 3693mm in 1889-1940 to 3133mm in 1980-2004 (standard deviation also fell from 500mm in 1946 to 401mm in 1980-2004). The correlation coefficient for the annual rainfall trend of r = -0.4 is significant at the 1% level.

Figure 3.35. *Annual Rainfall at Tapah.*

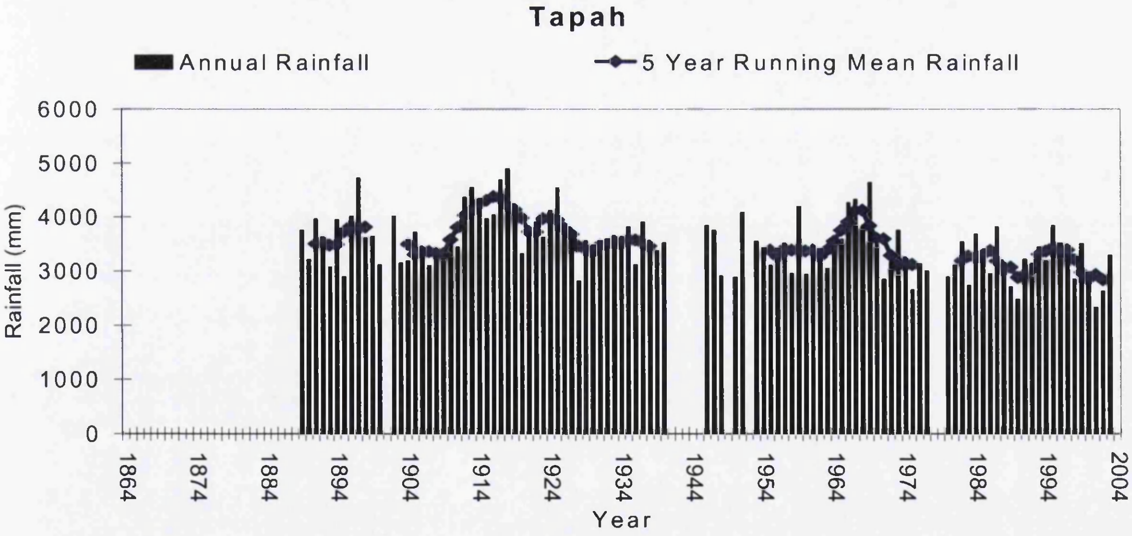


Figure 3.36. *Annual Deviation from the Long-term Mean Annual Rainfall at Tapah (Highs and lows relate to period of higher and lower rainfall)*

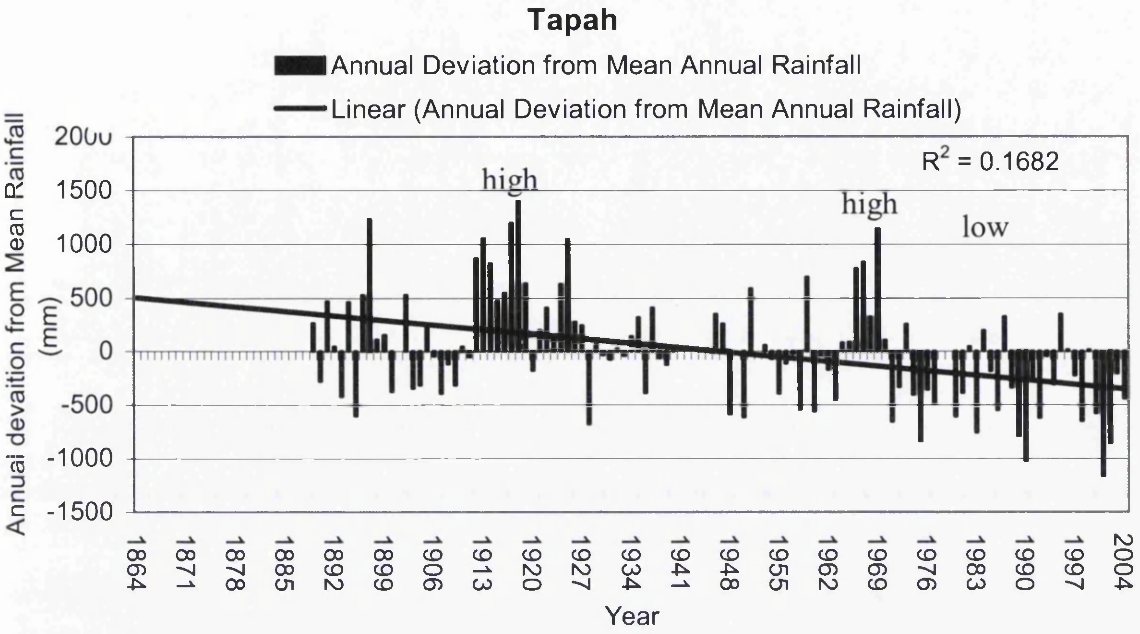
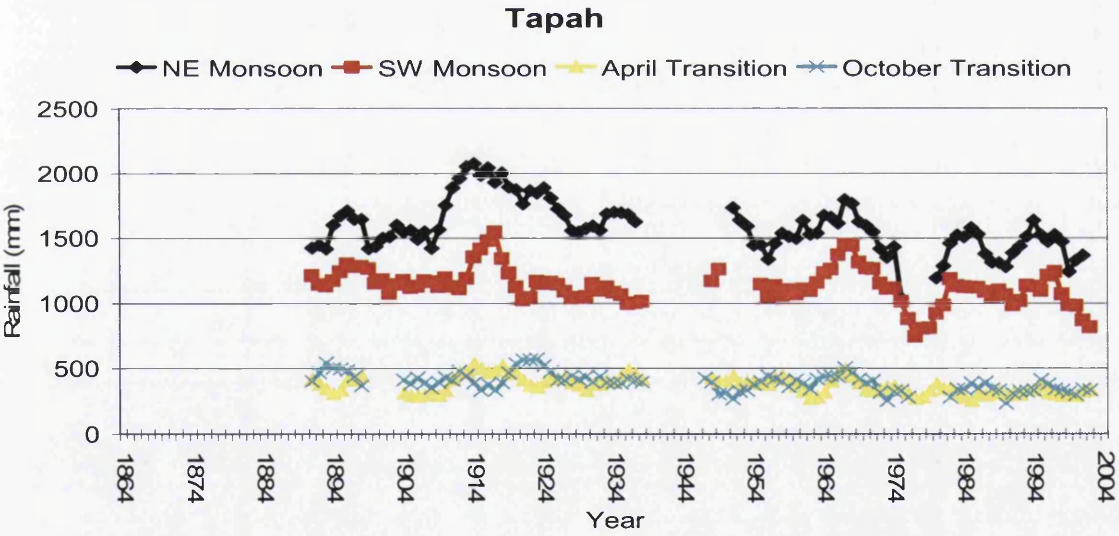


Figure 3.37. *Five-Year Running Means of Rainfall for Monsoonal and Transition Months at Tapah*



The main feature of the mainly post-war record at Kuala Lumpur is lower annual rainfall in 1970-1987, reflecting falls in both northeast and southwest monsoon rains (Figures 3.38-3.40). Thus between 1970 and 1990 16 out of 21 years had below average rainfall, with four over 600mm below the average, a figure which had only been previously recorded in 1938 when it was over 700mm below the mean (see Figure 3.39).

There has been a recent increase in rainfall since 1988, as both monsoons brought more rain (Figure 3.40). From 1988-2003 all but three years (1989, 1990 and 1998) had above average rainfall.

Figure 3.38. *Annual Rainfall at Kuala Lumpur (Subang)*

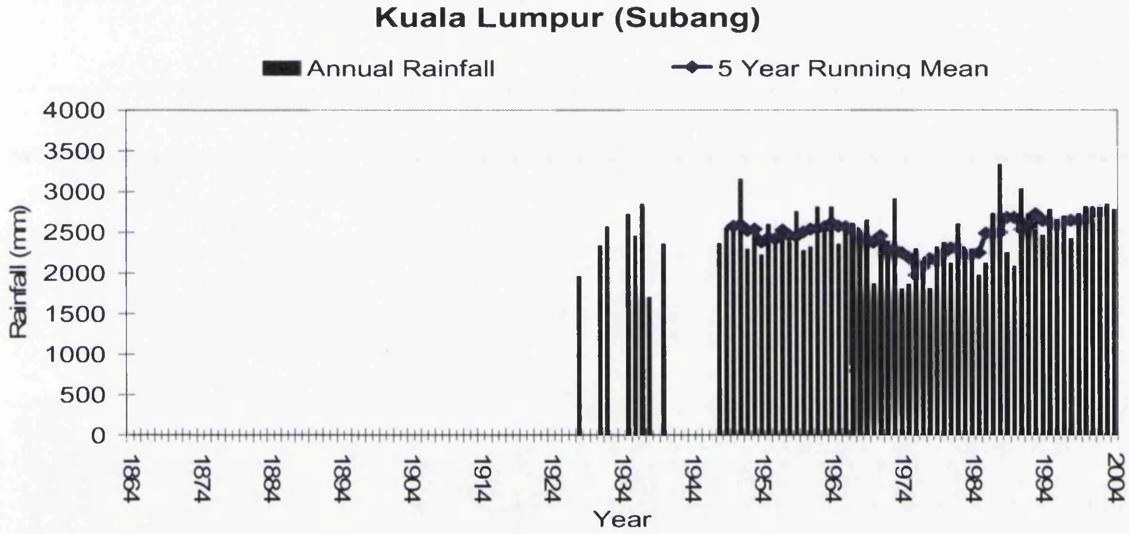


Figure 3.39. *Annual Deviation from the Long-term Mean Annual Rainfall at Kuala Lumpur (Subang).*

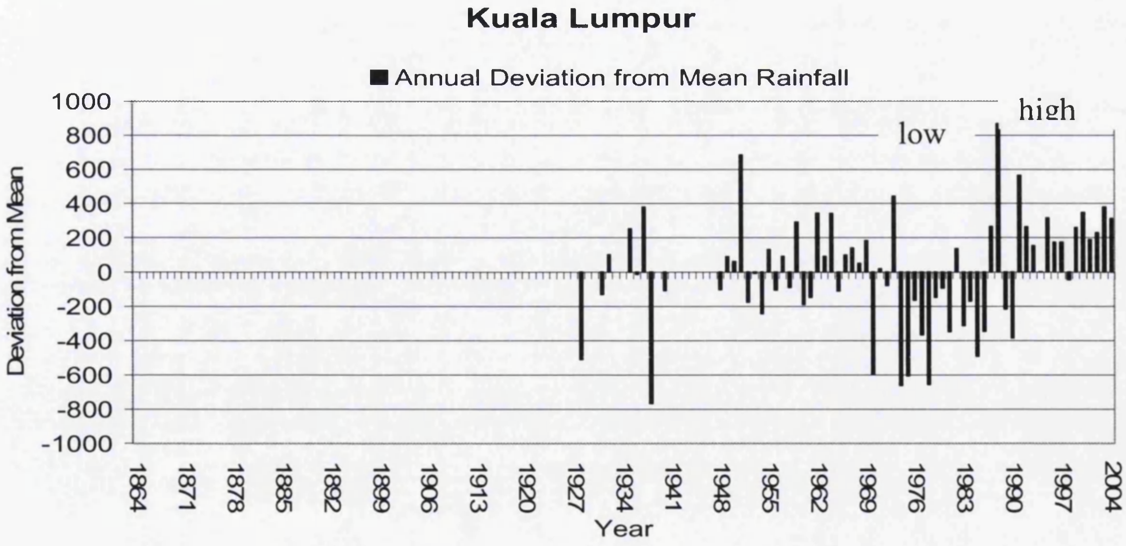
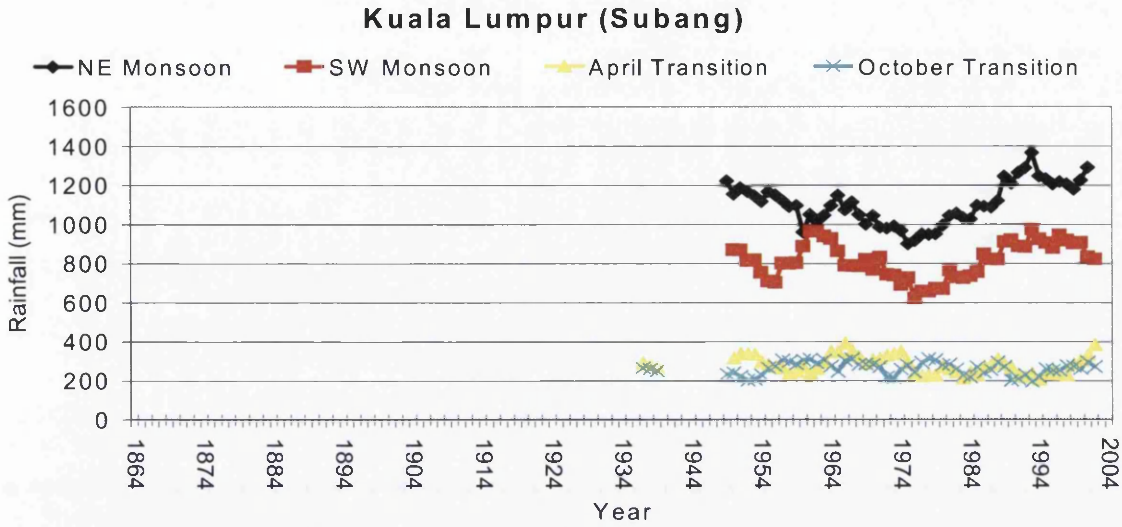


Figure 3.40. *Five-Year Running Means of Rainfall for Monsoonal and Transition Months at Kuala Lumpur (Subang)*



3.4.1 SINGAPORE – MACRITCHIE RESERVOIR (1875-2000)

One of the main features of the particularly long record here is the recent rise in rainfall following a rather drier period 1960-1984 (Figures 3.41 and 42). Apart from this there have been no major changes in mean annual rainfall over the whole record. Variability is also shown to have decreased in the standard deviation.

The dry periods seem to be a result of low rainfall principally of the northeast monsoon, which is the main source of rain throughout the record (Figure 3.43).

Figure 3.41. *Annual Rainfall at Macritchie Reservoir, Singapore*

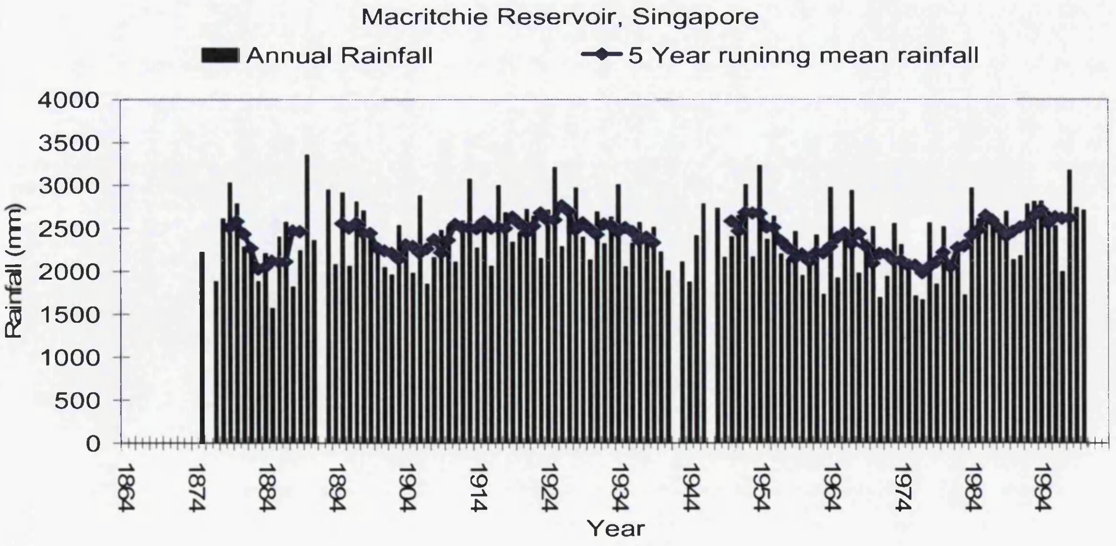


Figure 3.42. *Annual Deviation from the Long-term Mean Annual Rainfall at Macritchie Reservoir, Singapore.*

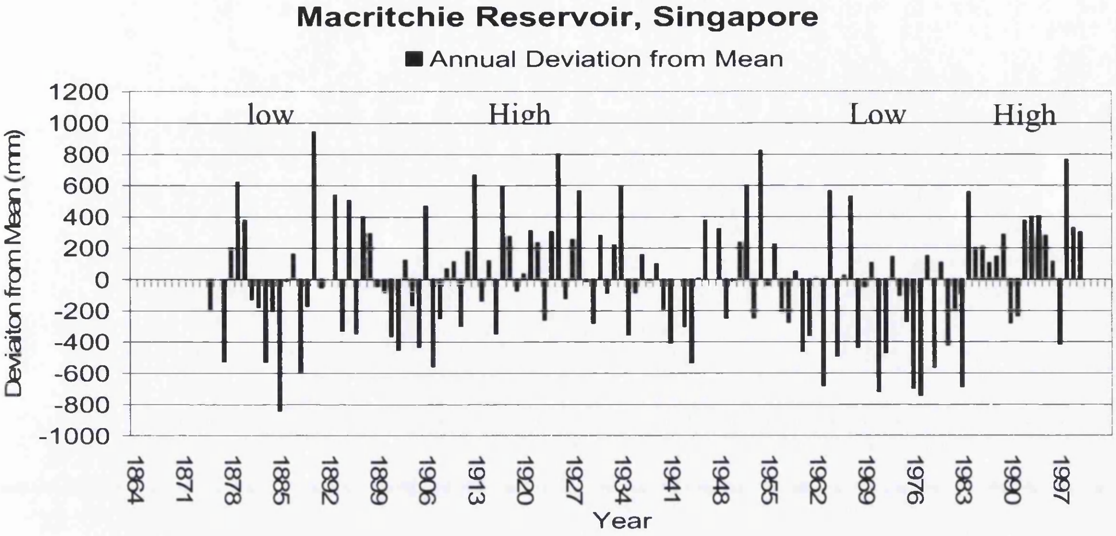
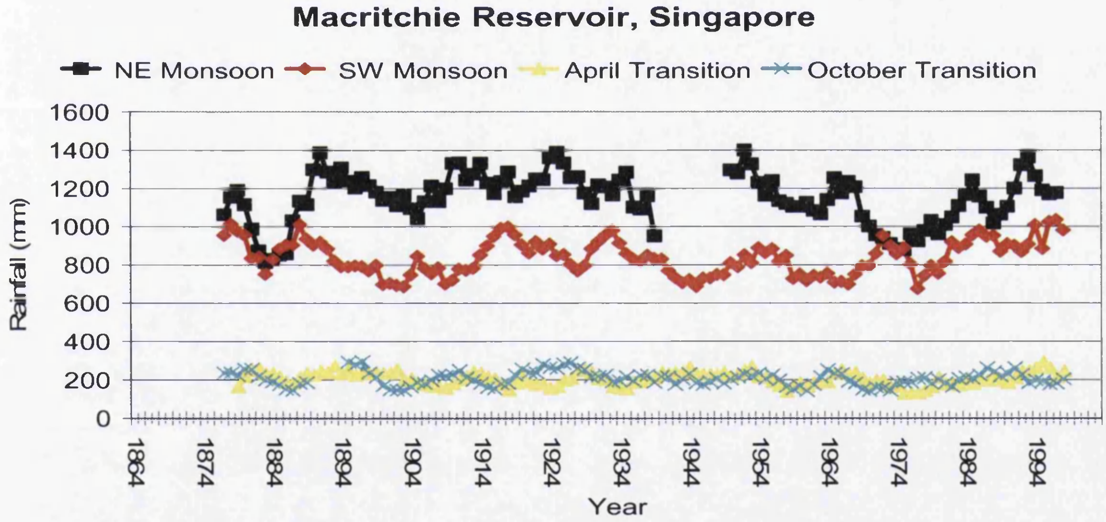


Figure 3.43. *Five-year Running Means of Rainfall for Monsoonal and Transition Months at Macritchie Reservoir, Singapore.*



3.4.2 ENSO CORRELATIONS AT CENTRAL PENINSULAR STATIONS

Relationships between annual rainfall and SOI at stations situated inland are all very weak and non-significant. At Tapah (r=-0.11) and Kuala Lumpur (r=-0.12) there are very weak negative relationships. At Kuala Lumpur, the recent period, from the late 1980s to 2004 when the frequency and intensity of El Niño events was high, there were only three years drier than average. The strong La Niña event in 1988 did correlate with annual rainfall as it had the highest annual total in the record.

Ipoh (r= +0.05) and the Cameron Highlands (r=+0.12) showed very weak positive relationships. Some years showed good correlation with El Niño events creating a decline in annual rainfall such as 1992 which had the lowest annual total. Some of the large negative annual rainfall anomalies occurred in strong/very strong ENSO events and no very strong ENSO event had rainfall significantly above the mean, whereas in weak ENSO events more years had above average rainfall.

At most inland stations the pattern of very little correlation of rainfall totals with ENSO events is evident in Tables 3.12 to 3.15 with almost as many ENSO years showing above average rainfall as below even for very strong ENSO events. The main feature is the number of weaker ENSO events that have above average rainfall, a common pattern inland. Singapore shows a higher degree of correlation (r=+0.26) which is statistically significant at the 1% level despite the weak relationship, due to the high number of years used in the correlation. The majority of very strong ENSO events have a negative deviation from the mean (Table 3.11).

Table 3.11. *ENSO severity and annual rainfall anomalies at Singapore in forty-five ENSO events.*

Singapore	Anomaly (mm) compared to annual average						
	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	3	0	5	3	3	0	2
Moderate to Strong	3	3	4	2	2	4	0
Very Stong	1	4	2	1	1	1	1
All	7	7	11	6	6	5	3

Table 3.12. *ENSO severity and annual rainfall anomalies at The Cameron Highlands in twenty-four ENSO events.*

Cameron Highlands

Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	1	3	0	3	2	2	1
Moderate to Strong	1	0	1	2	1	0	1
Very Strong	0	1	2	3	0	0	0
All	2	4	3	8	3	2	2

Table 3.13. *ENSO severity and annual rainfall anomalies at Kuala Lumpur in twenty-six ENSO events*

KL

Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	0	2	1	2	2	2	1
Moderate to Strong	0	1	1	2	1	0	1
Very Strong	0	1	1	1	7	0	0
All	0	4	3	5	10	2	2

Table 3.14. *ENSO severity and annual rainfall anomalies at Tapah in twenty-five ENSO events.*

Tapah

Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	3	2	2	0	2	1	4
Moderate to Strong	1	3	0	4	0	3	3
Very Strong	2	1	1	1	1	0	1
All	6	6	3	5	3	4	8

Table 3.15. *ENSO severity and annual rainfall anomalies at Ipoh in twenty-six ENSO events.*

Ipoh

Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	0	1	5	1	4	0	1
Moderate to Strong	0	2	0	4	0	1	0
Very Strong	1	3	0	2	0	1	0
All	1	6	5	7	4	2	1

3.5 ADDITIONAL ANALYSIS

In addition to the analysis already seen in this chapter it was decided that further analysis was appropriate in order to help highlight any trends and portray them in a clearer way.

Table 3.16 below shows the results of the new analysis. The effect of using the July to June in comparison to the calendar year is not as big a factor on the Peninsula as expected. A stronger correlation was expected and although some do show better correlation (Ipoh and Cameron Highlands), others do not and the differences are small. The coefficient of variation shows much higher values on the east coast, reflecting the variation in the northeast monsoon season. The change in mm per year supports earlier statements that rainfall is becoming less in the north, as Alor Star, Bayan Lepas, Parit Buntar and Kota Bharu all show reductions of between 3 and 6mm per year in the most recent period. This follows reductions in the previous period although the magnitude of these changes cannot be used due to the small number of years in the pre-1942 period.

Table 3.16 *Additional analysis of correlations between SOI and rainfall, changes (mm per year) between periods and coefficients of variation for the different periods.*

	SOI and rainfall correlation		Pre-1942	1942-79		1980-2004	
Station	r (Jul-June)	r (Jan-Dec)	CV	Change in rainfall (mm/yr)	CV	Change in rainfall (mm/yr)	CV
Alor Star	0.167	0.25	14.5	-5.3	12.1	-5.3	14.5
Bayan Lepas	0.125	0.18	15.3	-47.6	14.5	-3.7	16.5
Parit Buntar	0.079	0.2	15.4	-1.3	12.7	-4.1	19.1
Sitiawan	-0.026	-0.04	14.6	-9.6	14.3	-0.2	12.6
Malacca	0.139	0.19	12.5	-18.3	13.2	-1.6	14.3
Kota Bharu	0.379	0.38	19.4	-32	18.9	-6.4	24.9
Kuala trengganu	0.191	0.145	22.3	-27.8	23.3	-3.2	19.4
Kuantan	0.215	0.22	21.6	-3	20	3.9	18.7
Mersing	0.063	0.107	16.8	4.3	16.3	-2.3	19.8
Ipoh	0.191	0.05	6.5	24.3	12.9	2.3	15.9
Cameron Highlands	0.214	0.12	14.5	-6.2	12.6	4.2	13.4
Tapah	-0.088	-0.11	13	-4.5	14.5	-8.8	12.8
Kuala Lumpur	-0.179	-0.12	16.1	4.7	12.9	3.6	12.8
Singapore	0.136	0.26	15.3	-2.1	17.5	6	14.3

3.5 SUMMARY OF RESULTS FROM PENINSULAR MALAYSIA

The main findings from analysis of the annual and seasonal rainfall totals in Peninsular Malaysia are that:

1) There are decreases in annual rainfall during the period between 1970 and 1994 at all of the most northern stations situated on both the east and west coasts (including the far south at Malacca) and at one inland location (Tapah). This was caused throughout the peninsula by a reduction in the rainfall totals in the northeast monsoon season.
2) At Kuala Lumpur, the Cameron Highlands and Macritchie Reservoir (Singapore) the main features are high mid-20th century rainfall, lower rainfall in 1950s to late 1980s and a rise in recent years.
3) The two most northerly stations Alor Star and Kota Bharu have seen a reduction in the southwest monsoon rainfall more or less continuously throughout the record, creating more dependence on the variable northeast monsoon.
4) The main changes in annual rainfall are achieved mainly by changes in SW monsoon rain on the west coast and NE monsoon rain on the east coast.
5) Annual totals on the east coast are significantly more variable than on the west coast.
6) Correlations between Southern Oscillation Index and annual rainfall are very weak at most stations. Only at Kota Bharu, Alor Star and Macritchie Reservoir (Singapore) did the positive correlation coefficient ($r=+0.38$, $r=+0.25$ and $r=+0.26$) achieve statistical significance at 1% level.
7) During weak and moderate ENSO events many stations recorded more positive than negative annual rainfall anomalies.
8) Additional analysis shows that whether using July-June or January to December years makes little to correlation between SOI and rainfall. Changes in mm per year support previous data showing a reduction in northern regions and the CV analysis supports the high variation shown on the east coast.

CHAPTER 4:

RESULTS AND ANALYSIS: CHANGES IN ANNUAL AND SEASONAL RAINFALL IN MALAYSIAN BORNEO AND CORRELATION WITH ENSO EVENTS

This chapter presents results of the analysis of changes in annual and seasonal rainfall in Malaysian Borneo. As in the previous chapter an attempt is made to split the stations into groups that showed a similar record. Although many stations on the west coast could be grouped with another due to the similarity of rainfall records, many stations in other regions of Sabah had to be dealt with separately. Table 4.1 summarises the changes in mean and standard deviation for each station for the arbitrary three periods (pre-1942, post-war to 1979 and 1980 to date); this table will be referred to throughout the chapter.

4.1 THE NORTHWEST COASTLINE: Kota Kinabalu (1889-2004) and Labuan Island (1880-2004).

Figures 4.1 to 4.4 indicate a wet period at both stations in the 1930s and the 1950s at Kota Kinabalu. At both stations there appears to be a pattern with lower rainfall early in the record and higher rainfall from the 1920s to the mid-1950s before lower rainfall from the mid 1970s and a more recent rise in the late 1990s. At Labuan, between 1926 and 1941 there is a period with well above the average rainfall, with 8 of the years well above 500mm over the mean annual rainfall. At Labuan there has been a more recent recovery after a marked trough in the early 1990s, with especially low rainfall in 1990 and 1994. Mean annual rainfall at Labuan has fallen from 3671mm in pre-1940 to 3454mm in 1947-1979 and 3087mm in 1980-2004, a fall over the whole period of 583mm or 15.9% (Table 4.1). Table 4.1 also shows that the standard deviation at Kota Kinabalu increases towards the end of the record.

Both Labuan and Kota Kinabalu have annual totals that are dominated by the southwest monsoon rainfall, but with dry years associated more with a reduction in northeast monsoon rainfall (Figures 4.5 and 4.6). Rainfall both the SW and NE monsoon has continuously reduced at Labuan and the reductions are both statistically significant at 1% level with an r value of –0.68 for the SW monsoon and –0.65 for the NE monsoon.

Table 4.1. *Means, Standard Deviations and Differences Between Three Periods (pre-1942, 1942-79 and 1980-2004) at Stations in Malaysian Borneo and Brunei. If the reduction or increase from one period to the next is statistically significant at the 5% level an asterisk * is positioned in the column. Any periods with less than 10 years of record are placed in brackets.*

				Pre-1942			1942-79				1980-2004 (Kilanas 2002)			
STATION	Co-ordinates	Elevation (m)	REGION	Pre-1942 Years	MEAN	SD	MEAN	Difference	SD	Difference	MEAN	Difference	SD	Difference
Kota Kinabalu	5°56N 116°03E	2	West Sabah	1889-1939	2686.6	424.7	2664.6	-22.0	438.4	13.6	2508.2	-156.5	493.5	55.1
Labuan	5°17N 115°16E	30	West Sabah	1855-1940	3670.9	675.5	3454.4	-216.5	529.3	-146.2	3087.1	-367.3 *	597.4	68.0
Keningau	5°21N 116°52E	305	Inland Sabah	1894-1941	1588.5	321.0	1756.9	168.4 *	340	-19.0	1693.8	-63.1	380.6	25.9
Kudat	6°53N 116°52E	3	North Sabah	1884-1940	2273.2	530.4	2272.7	-0.5	420.1	-110.2	2142.3	-130.4	675.7	255.6
Sandakan	5°54N 118°04E	9	NE Sabah	1879-1939	3174.9	694.0	3040.0	-134.9	383.8	-310.2	2947.5	-92.5	646.6	262.8
Tawau	4°15N 117°53E	6	SE Sabah	1908-1940	1917.9	318.1	1765.3	-152.6	310.9	-7.2	1865.7	100.4	327.2	16.3
Miri	4°20N 113°59E	5	West Sarawak	1917-1940	3206.4	568.6	2921.1	-285.3 *	398.8	-169.8	2714.5	-206.6 *	376.2	-22.6
Bintulu	3°12N 113°2E	1	West Sarawak	1915-1940	3896.8	635.1	3766.4	-130.4	357.2	-277.9	3769.8	3.4	517.5	160.3
Kilanas	4°54N 114°51E	14	Brunei	1937-41	(2609.2)	(291.9)	2771.7	(162.5)	436.5	(144.6)	2628.7	-143.1	548.7	112.2
Kuching	1°29N 110°20E	7	SW Sarawak	1876-1940	4029.0	657.4	4044.6	15.5	529.1	-128.2	4161.8	117.3	577.5	48.3

Figure 4.1. *Annual Rainfall at Kota Kinabalu*

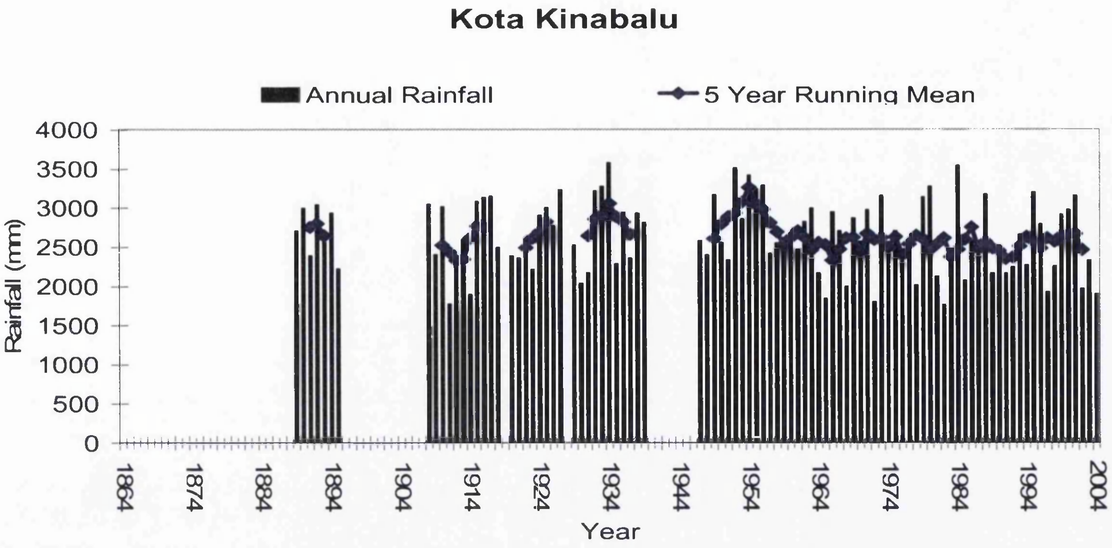


Figure 4.2. *Annual Rainfall at Labuan*

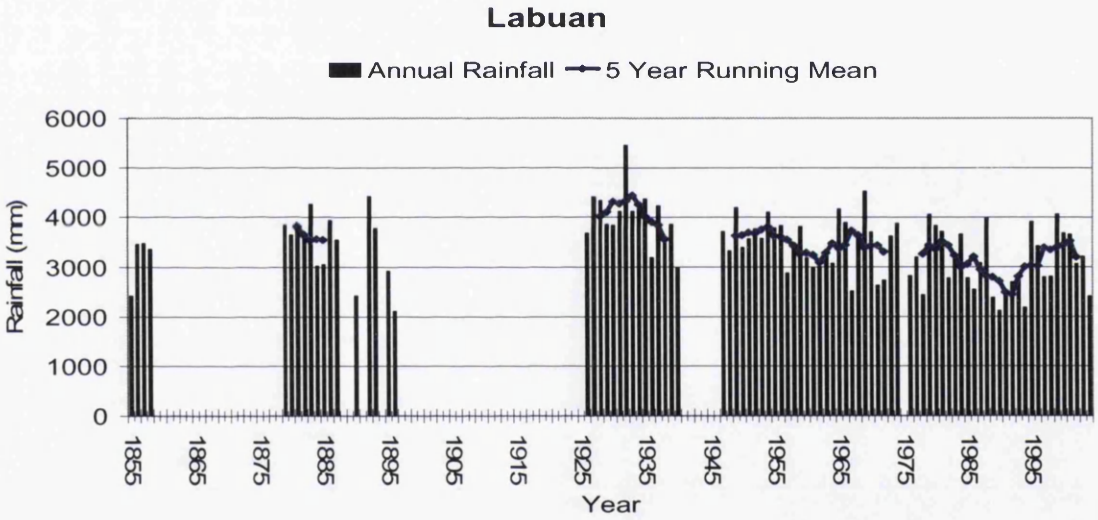


Figure 4.3. *Annual Deviation from the Long-term Mean Annual Rainfall at Kota Kinabalu*

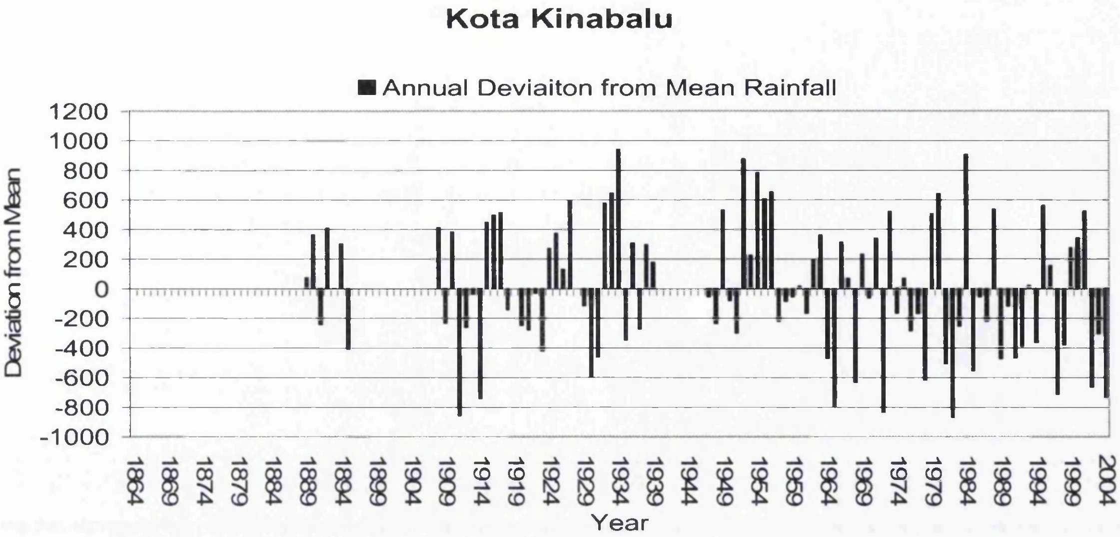


Figure 4.4. *Annual Deviation from the Long-term Mean Annual Rainfall at Labuan*

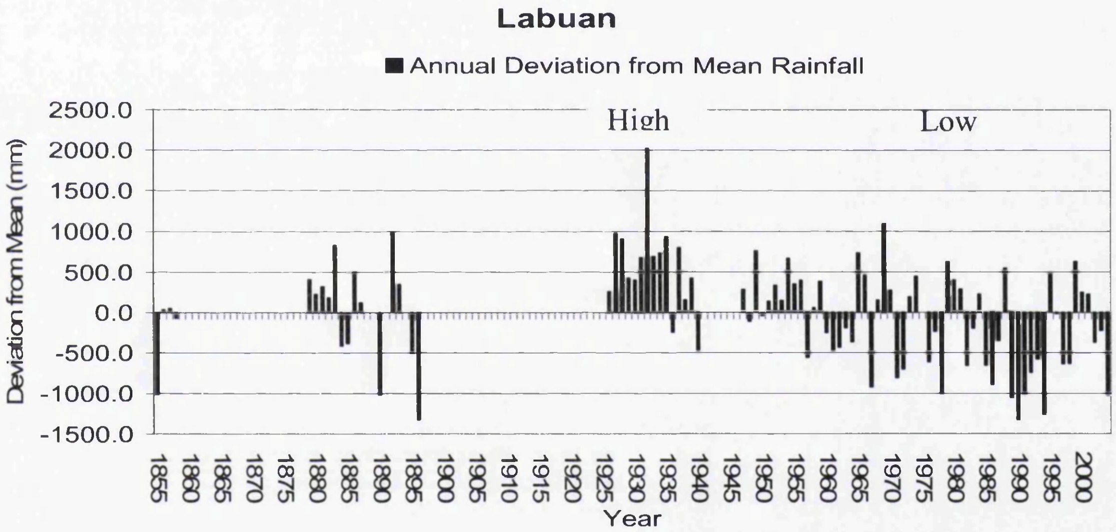


Figure 4.5. *Five-Year Running Means of Rainfall for Monsoonal and Transition Months at Kota Kinabalu.*

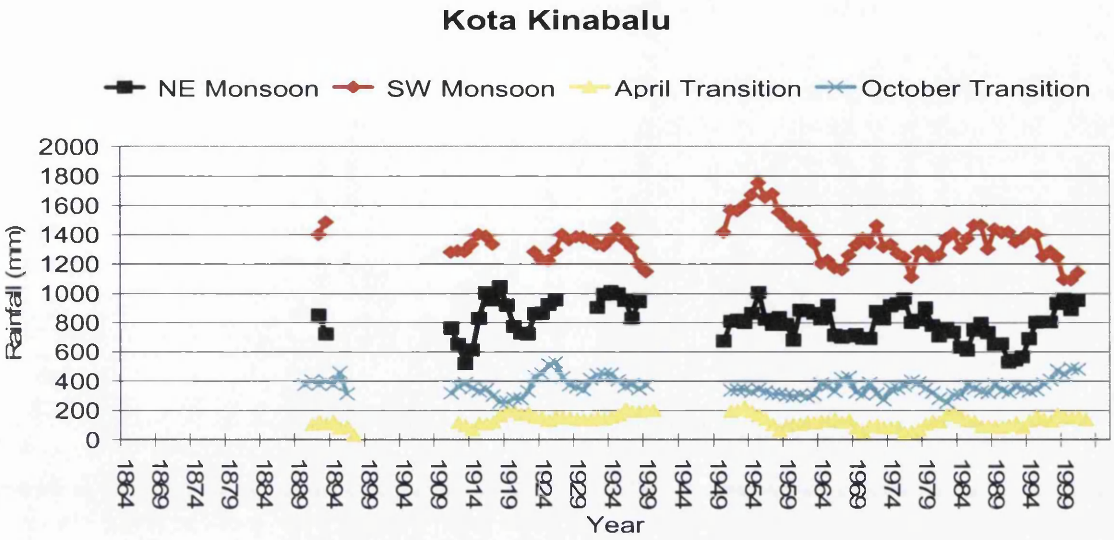
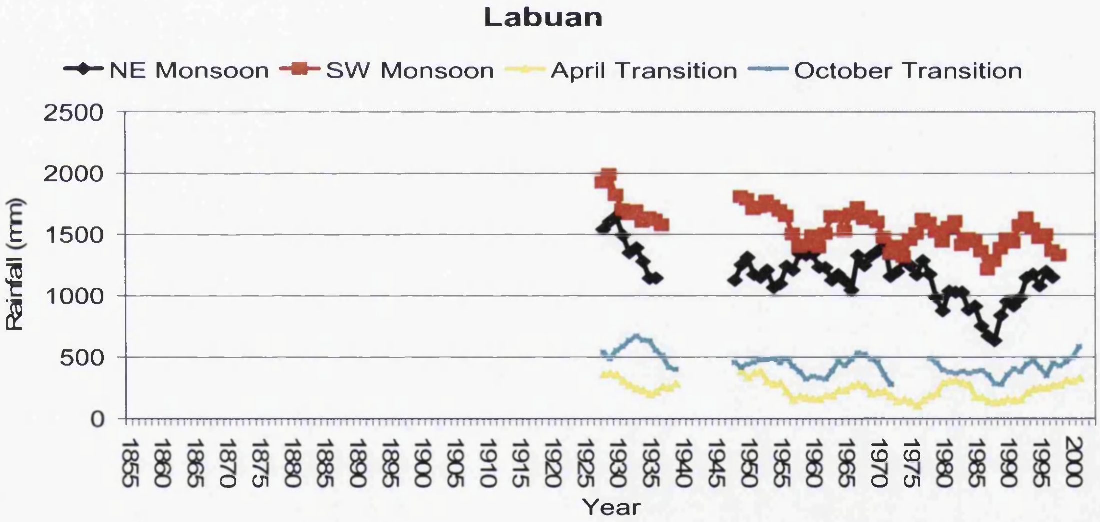


Figure 4.6. *Five-year Running Means of Rainfall for Monsoonal and Transition Months at Labuan*



Correlations between rainfall and SOI at Kota Kinabalu (r = +0.41) and Labuan (r=+0.33) are positive and stronger than in Peninsular Malaysia, both being statistically significant at the 1% significance level. The increase in dry years at both stations coincides with the increase in the frequency and intensity of ENSO events since the mid 1970s. At both stations, NE monsoon rainfall is more strongly correlated than SW monsoon rain with SOI, but only at Labuan is the positive correlation coefficient significant. At both stations correlations between annual rainfall and SOI are stronger in the pre-1942 and 1980- 2004 periods than the intervening 1942-1979 period (Tables 4.2 and 4.3). Tables 4.4 and 4.5 show the good correlation between ENSO years and negative anomalies in annual rainfall. At both stations ENSO events of moderate to very strong intensity are almost always much drier than normal, but weak ENSOs are more variable.

Figure 4.7. *Correlation between SOI and annual rainfall at Kota Kinabalu.*

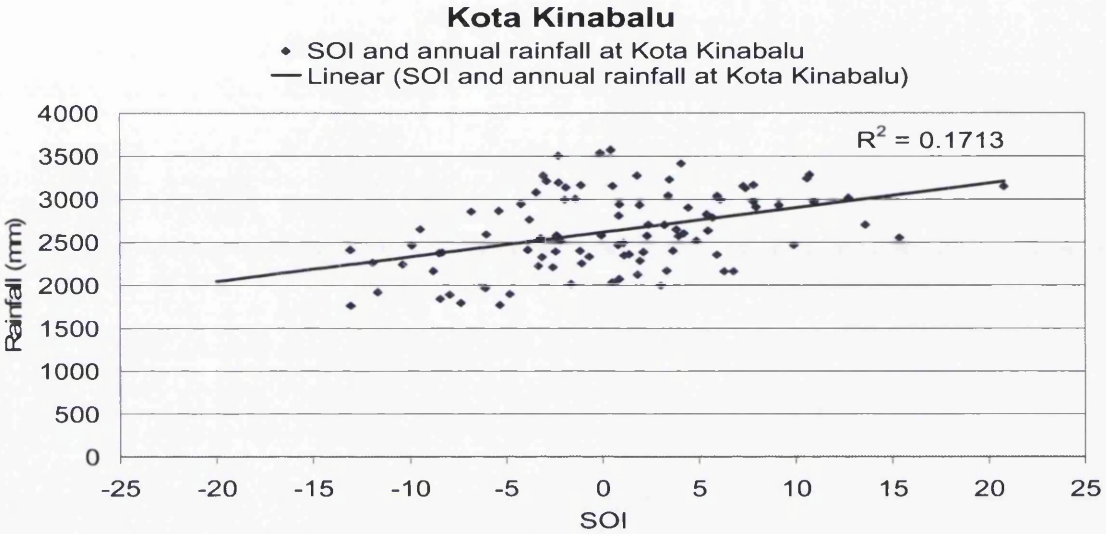


Table 4.2. *Correlation and statistical significance of annual rainfall and SOI in different periods and Seasonal rainfall and SOI at Kota Kinabalu.*

Variables	Period	r	R^2	Statistically significant at 5% level
Annual rainfall/SOI	Pre-1942	0.41	0.17	YES
	1942-79	0.28	0.08	NO
	1980-2004	0.49	0.24	YES
NE monsoon/SOI		0.22	0.05	YES
SW monsoon/SOI		0.03	0.0007	NO

Table 4.3. *Correlation and statistical significance of annual rainfall and SOI in different periods and seasonal rainfall and SOI at Labuan.*

Variables	Period	r	R^2	Statistically significant at 5% level
Annual Rainfall/SOI	Pre 1941	0.41	0.17	YES
	1942-79	0.08	0.01	NO
	1980-2004	0.51	0.26	YES
NE monsoon/SOI		0.43	0.18	YES
SW monsoon/SOI		0.28	0.08	NO

Table 4.4. *ENSO severity and annual rainfall anomalies at Kota Kinabalu during thirty-one ENSO events.*

KK

Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	2	1	3	2	3	3	1
Moderate to Strong	5	4	2	1	0	1	0
Very Strong	1	0	2	0	0	0	0
All	8	5	7	3	3	4	1

Table 4.5. *ENSO severity and annual rainfall anomalies at Labuan during thirty-two ENSO events.*

Labuan

Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	3	2	2	1	2	4	2
Moderate to Strong	4	1	1	0	1	0	1
Very Strong	5	2	1	0	0	0	0
All	12	5	4	1	3	4	3

4.2 KENINGAU (1918-2004)

Keningau shows rather marked short-term changes in the 5-year running mean and annual deviation charts (Figure 4.8). Peaks occur especially from 1949 to 1956 (where the 5-year running mean was up over 2000mm) and 1994 to 2001 and lower rainfall in the 1920s to early 1940s and mid-1950s to 1993.

Figure 4.8. *Annual Rainfall at Keningau*

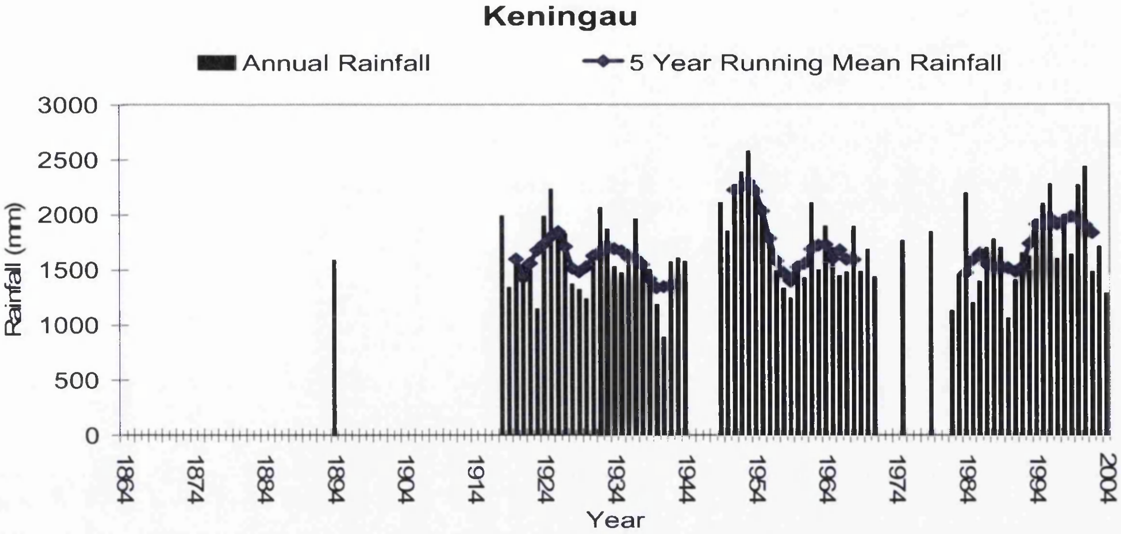
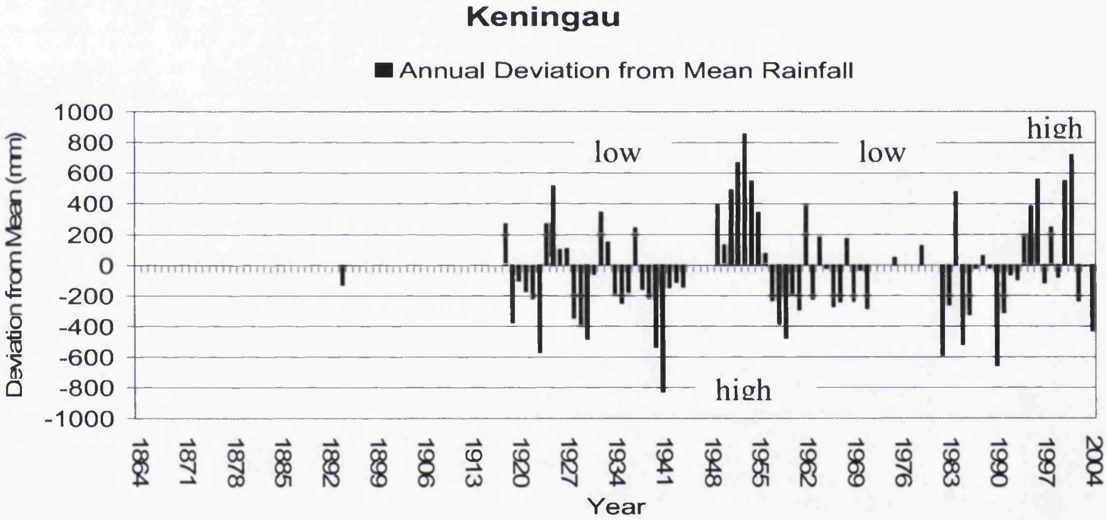


Figure 4.9. *Annual Deviation from the Long-term Mean Annual Rainfall at Keningau*



Throughout the record, contribution to annual totals is fairly even between the monsoon seasons. The peak in rainfall in 1994-2001 resulted from an increase in rainfall in both monsoon seasons (similar to some of the stations on the east coast of Peninsular Malaysia).

The correlation between annual rainfall and SOI (r=+0.26) is a positive but weak relationship, but significant at the 5% level.

4.3 KUDAT (1884-2004)

The patchiness of the record at Kudat limits the comments that can be made. It is clear, however, that 1982-2004 was drier and more variable than the interwar period (1946-1979). Thus in the recent period, 1982, 1987, 1990, 1992, 1993, 1997, 1998 and 2002 were all very dry with 1987, 1992 and 2002 over 800mm below the long-term mean (Figure 4.11). Both southwest and northeast monsoon rains were at their lowest during this period. The northeast monsoon provides the larger proportion of annual rainfall (Figure 4.12).

Figure 4.10. *Annual Rainfall at Kudat*

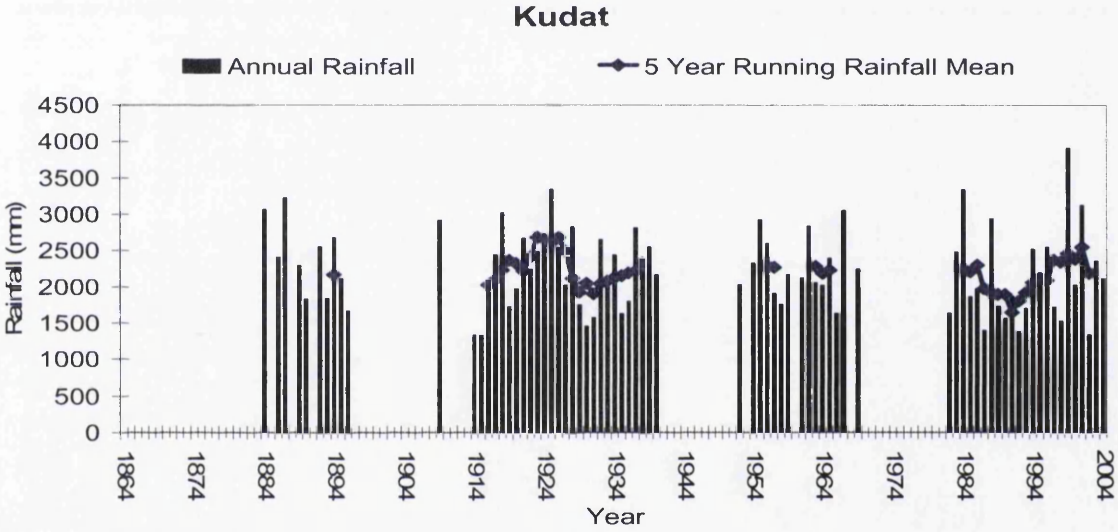


Figure 4.11. *Annual Deviation from the Long-term Mean Annual Rainfall at Kudat*

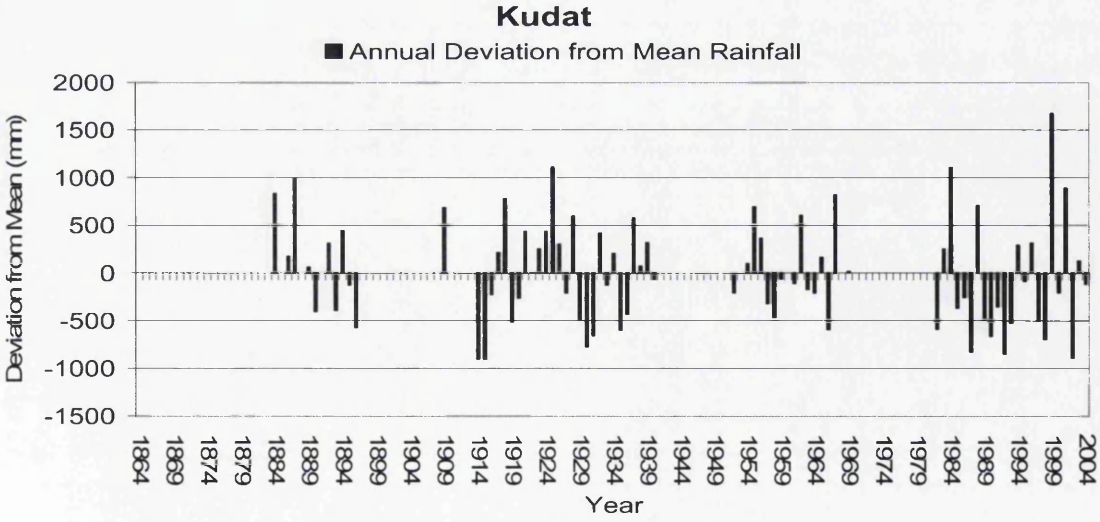
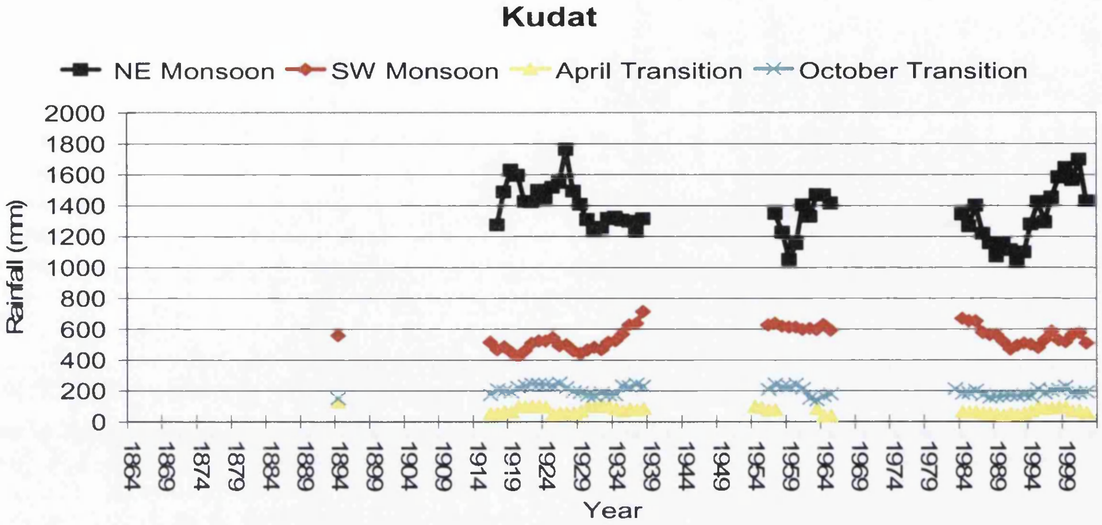


Figure 4.12. *Five-Year Running Means of Rainfall for Monsoonal and Transition Months at Kudat.*



The rainfall record at Kudat does show a significant (r=+0.41), positive relationship with SOI (Figure 4.13). Table 4.6 shows that very strong ENSO years are far more likely to have significant negative rather than positive deviations from the mean. There is no correlation between SW monsoon rain and SOI, but NE monsoon rain is more strongly correlated (r=+0.45) than is annual rainfall (Figure 4.14).

Figure 4.13. *Correlation between SOI and annual rainfall at Kudat*

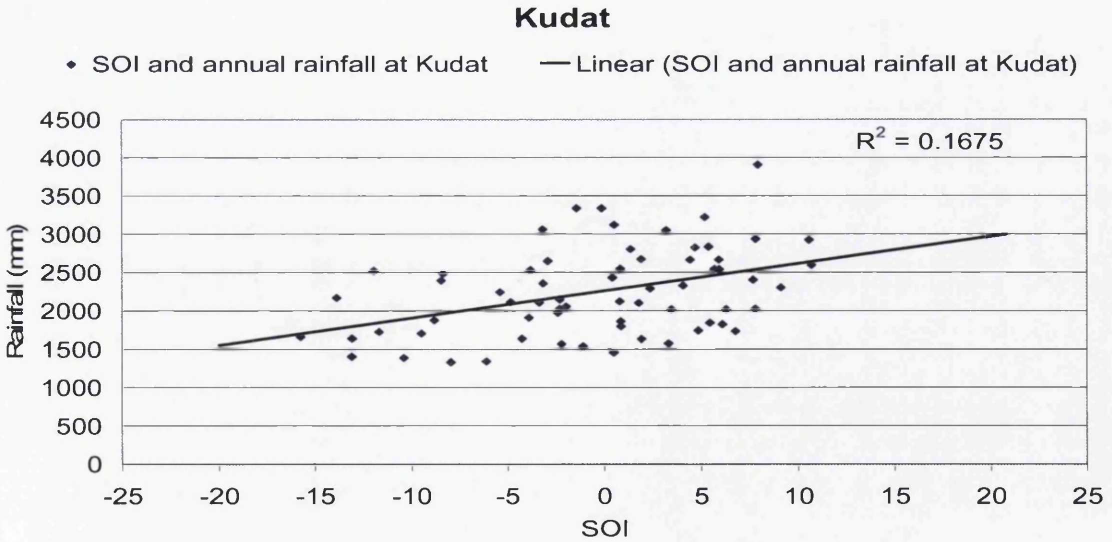


Figure 4.14. *Correlation between SOI and Rainfall in Different Monsoon Seasons at Kudat.*

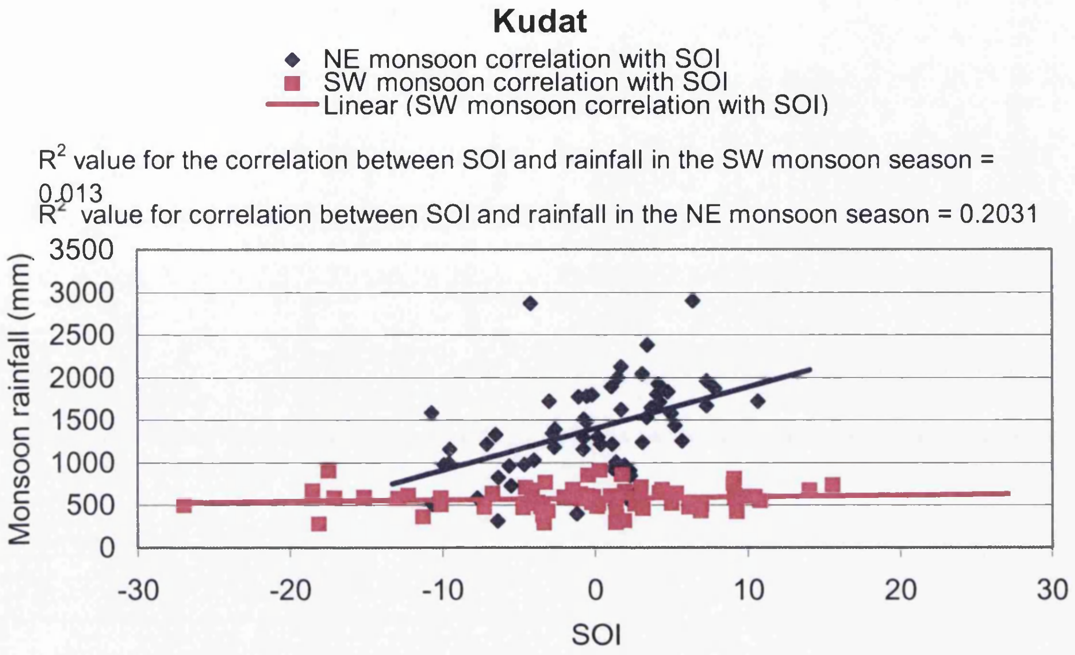


Table 4.6. *ENSO severity and annual rainfall anomalies at Kudat during twenty-six ENSO events.*

Kudat	Anomaly (mm) compared to annual average						
	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	3	0	4	1	2	1	2
Moderate to Strong	2	1	0	0	2	0	0
Very Stong	6	0	0	1	1	0	0
All	11	1	4	2	5	1	2

4.4 SANDAKAN (1879-2004)

The main features of the very long record at Sandakan are: the trough in annual rainfall from 1904-15 (lowest point in 5-year mean in 1913 at 2311mm), higher rainfall from 1916-1939 (where the 5-year running mean reaches its peak of 3759mm in 1923) and consistently intermediate rainfall for most of the post-war period, but with increased variability from the 1980s (Figures 4.15 and 4.16). This recent increase in variability is similar to that recorded at Kudat. The short dry period from

1985-1993 is of similar duration to other stations in Sabah, but shorter than most in Peninsular Malaysia.

High standard deviation of rainfall is also evident in the pre-war period (up to 1941) (Table 4.1). Variation at this time is a result of the highly erratic northeast monsoon rainfall (Figure 4.17). In troughs around 1914 and 1990 the NE and SW monsoon rainfall were almost equal because of sharp falls in the northeast monsoon totals.

Figure 4.15. *Annual Rainfall at Sandakan*

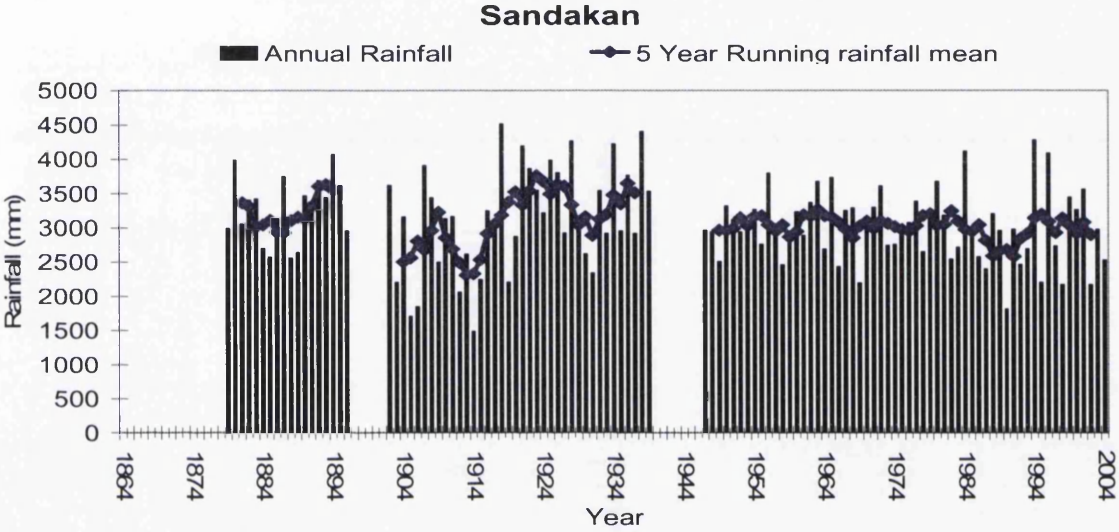


Figure 4.16. *Annual Deviation from the Long-term Mean Annual Rainfall at Sandakan*

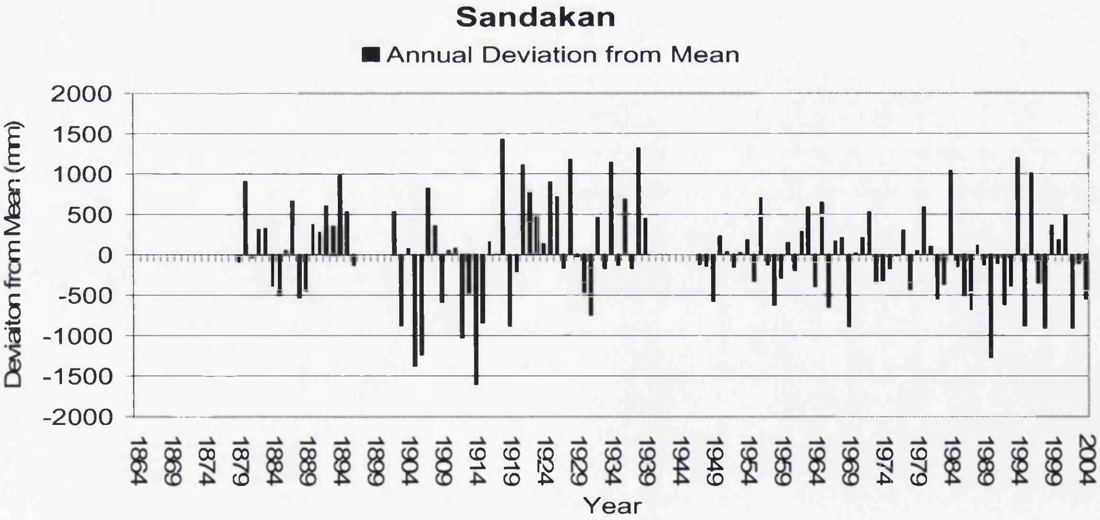
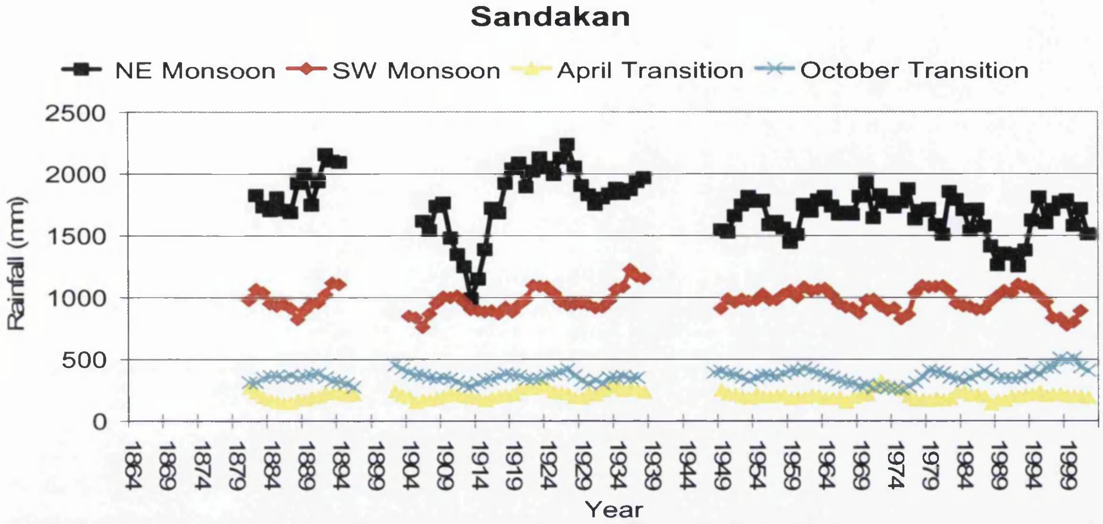


Figure 4.17. *Five-year Running Means of Rainfall for Monsoonal and Transition Months at Sandakan*



Annual rainfall is positively but relatively weakly related to SOI (Figure 4.18) (r = 0.32), a relationship that nevertheless is significant at the 1% significance level, because of the large number of years involved.

The Northeast monsoon rainfall is weakly positively correlated with SOI, but southwest monsoon rain is very weakly negatively correlated with SOI. Correlation between annual rainfall and SOI is strongest in the early period from 1880 to 1941 and also strong in 1980-2004, but with no significant correlation (r=0.04) in 1942-1979 (Table 4.7). This high correlation, low correlation, high correlation pattern parallels the pattern of ENSO magnitude-frequency change.

A clear majority of ENSO years experienced annual rainfall well below the long-term mean (25 out of 37 years below the mean, with 17 years over 500mm below the mean) (Table 4.8), but whereas very strong ENSO years were invariably anomalously dry, weak/moderate ENSO years were nearly as often wetter than normal.

Figure 4.18. *Correlation between SOI and annual rainfall at Sandakan*

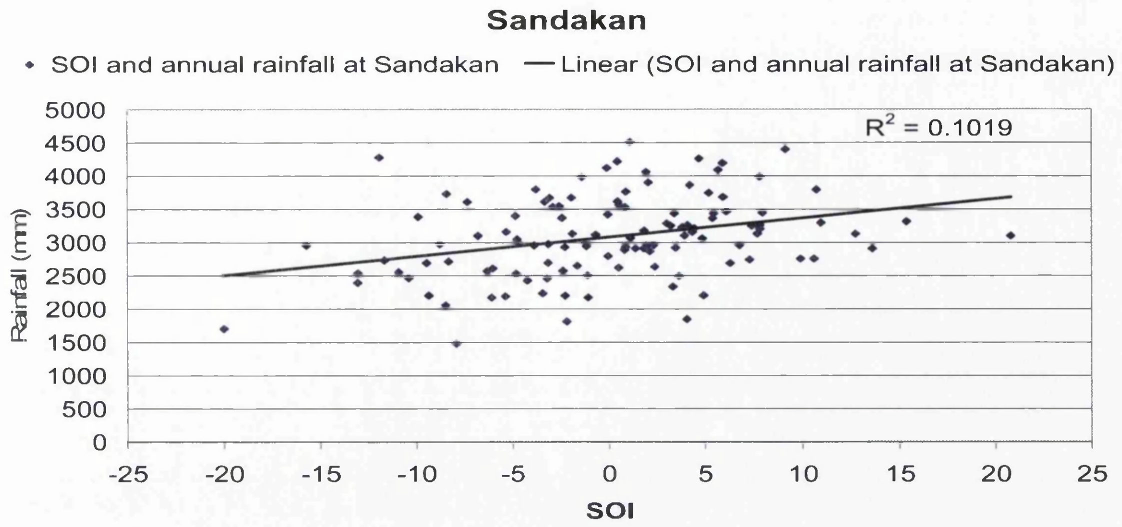


Table 4.7. *Correlation and statistical significance of annual rainfall and SOI in different periods and Seasonal rainfall and SOI at Sandakan.*

Variables	Period	r	R2	Statistically significant at 5% level
Annual Rainfall/SOI	Pre-1942	0.40	0.16	YES
	1942-79	0.04	0.002	NO
	1980-2004	0.32	0.10	NO
NE monsoon/SOI		0.14	0.02	NO
SW monsoon/SOI		0.1	0.01	NO

Table 4.8. *ENSO severity and annual rainfall anomalies at Sandakan during forty ENSO events.*

Sandakan	Anomaly (mm) compared to annual average						
	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	7	1	2	2	1	2	3
Moderate to Strong	6	1	1	1	1	2	3
Very Strong	5	2	1	0	0	0	0
All	17	4	4	3	2	4	6

4.5 TAWAU (1906-2004)

The record at Tawau shows peaks in annual rainfall in the 1920s, early 1950s and the late 80s-early 90s. Low rainfall characterised 1908-1918 and 1956-1972 in particular (Figures 4.19 and 4.20) when both southwest and northeast monsoon rainfall were lower than normal (Figure 4.21). It seems that the record here is much different to others in Sabah as there was no significant dry period anywhere between the 1970s and mid 1990s.

Figure 4.19. *Annual Rainfall at Tawau*

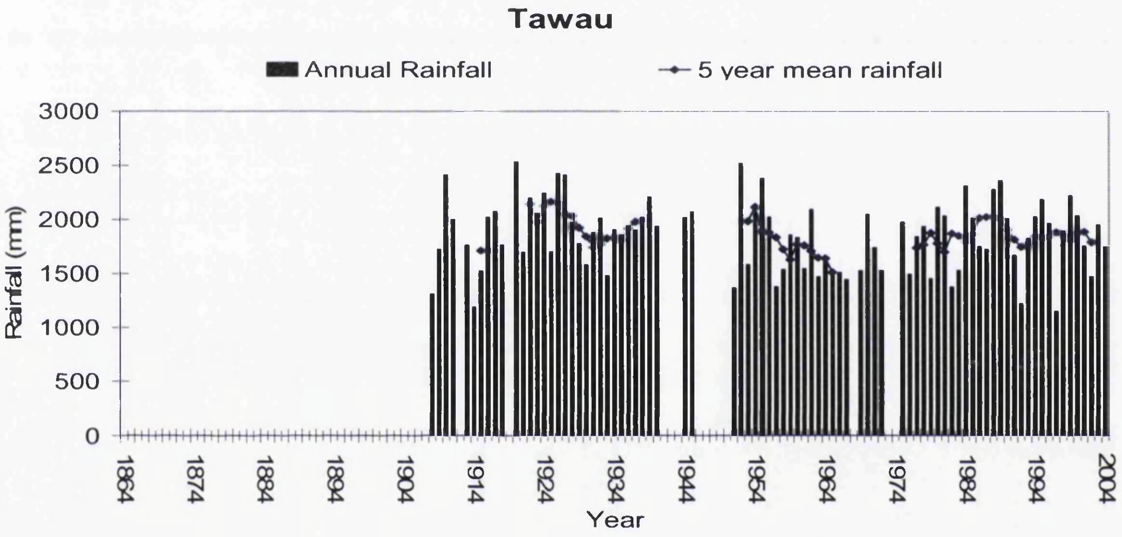


Figure 4.20. *Annual Deviation from the Long-term Mean Annual Rainfall at Tawau*

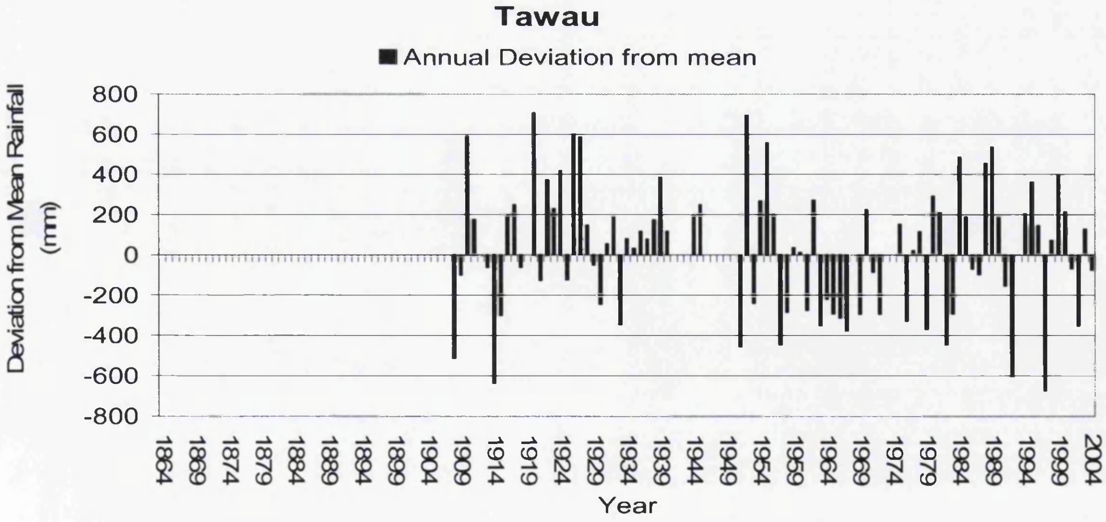
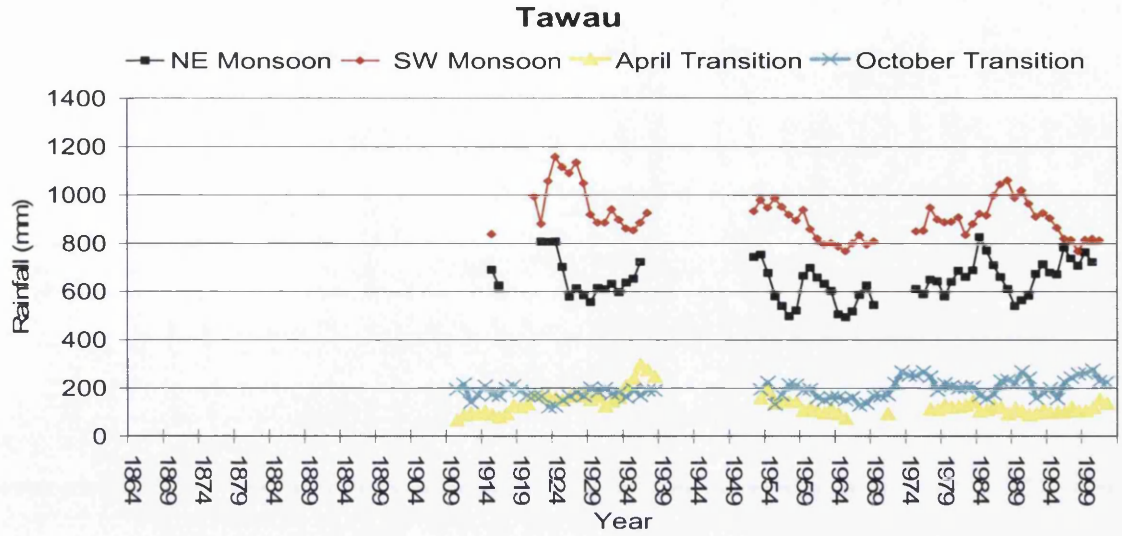


Figure 4.21. *Five-Year Running Means of Rainfall for Monsoonal and Transition Months at Tawau.*



Annual rainfall is more strongly and positively correlated with SOI than at most stations covered, and is significant at the 1% level with a regression coefficient of r = +0.46 (Figure 4.22) for the whole period and the relationship strengthening significantly in the most recent period 1980-2004 to r=+0.73. The northeast monsoon rainfall is positively correlated at the 5% significance level, but southwest monsoon rainfall shows a slightly negative trend (Table 9). Table 4.9 shows little difference in the chance of an ENSO event having above or below average rainfall, apart from very strong ENSO events.

Figure 4.22. *Correlation between SOI and annual rainfall at Tawau.*

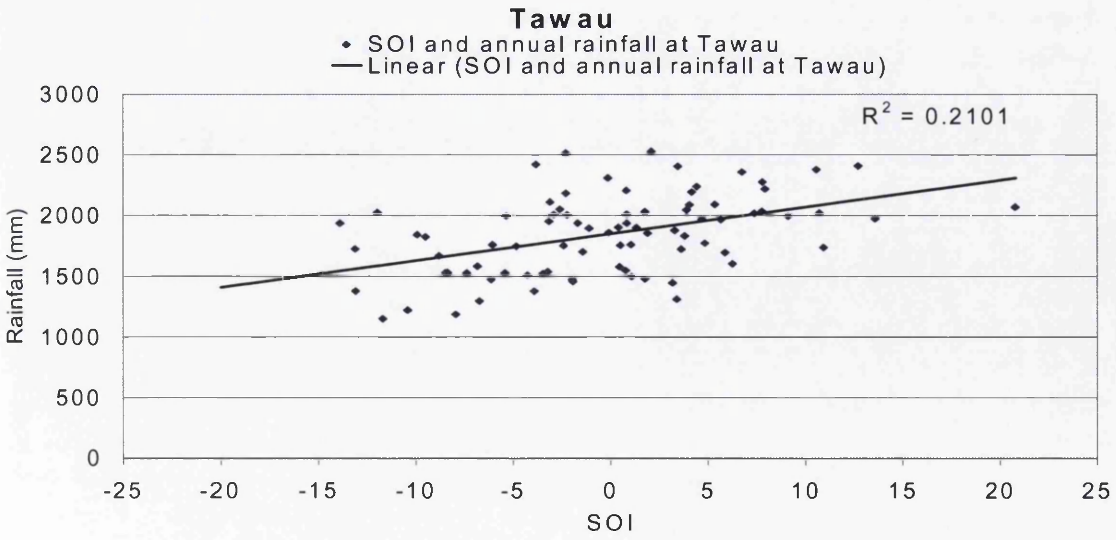


Table 4.9. *Correlation and statistical significance of annual rainfall and SOI in different periods and Seasonal rainfall and SOI atTawau.*

Variables	Period	r	R2	Statistically significant at 5% level
Annual Rainfall/SOI	Pre 1941	+0.14	0.02	NO
	1942-79	+0.49	0.24	YES
	1980-2004	+0.73	0.53	YES
NE monsoon/SOI		+0.42	0.18	YES
SW monsoon/SOI		+0.04	0.002	NO

Table 4.10. *ENSO severity and annual rainfall anomalies at Tawau during twenty-seven ENSO events.*

Tawau	Anomaly (mm) compared to annual average Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	0	2	2	2	2	1	2
Moderate to Strong	1	0	4	2	2	0	0
Very Strong	2	1	1	2	1	0	0
All	3	3	7	6	5	1	2

4.6 THE NORTHWEST COAST OF SARAWAK: Miri (1917-2003), Bintulu (1915-2003) and Kilanas in Brunei (1936-2001).

Temporal patterns in annual rainfall as shown by the 5-year running means and annual deviation graphs (4.23 to 4.28) are broadly similar at all three stations, but peaks and troughs are more pronounced at Kilanas than at the other two. Both Miri and Bintulu show lower rainfall from the beginning of the record until around 1932. A period of very high rainfall occurred in the 1930s when the 5-year running mean was at its highest in each record. Lower rainfall was recorded in the 1970s, 1980s and 1990s at all three stations with a marked trough in the early 1990s, before a rise from the later 1990s onwards.

This dry period in the 1980s and 1990s is of similar duration to that recorded from the mid-1970s to 1994 in Peninsular Malaysia and at the other west coast stations in Sabah. From 1975-1994 only four years had above average rainfall. The reduction from the first period (pre-Second World War) to the latter period (1980-2004) was over 15% at both Labuan and Miri. This mainly reflected reductions in northeast monsoon rainfall at Miri (Figure 4.29), but in the southwest monsoon also at Bintulu and Kilanas (Figures 4.30 and 4.31). At Bintulu and Kilanas annual rainfall variability increased in the 1980-2003 period of the record whereas at Miri it decreased (Table 4.1).

Figure 4.23. *Annual Rainfall at Miri.*

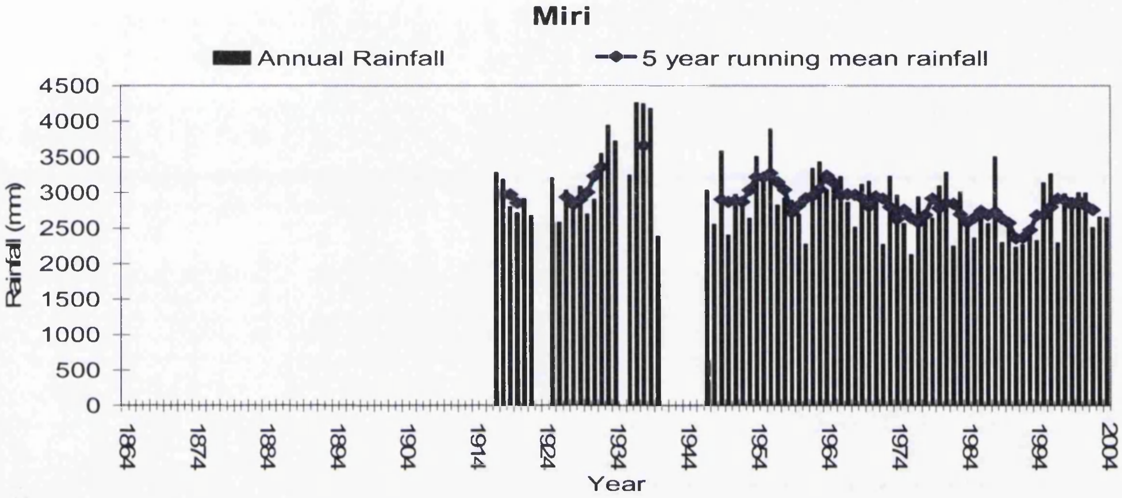


Figure 4.24. *Annual Rainfall at Annual Rainfall at Bintulu*

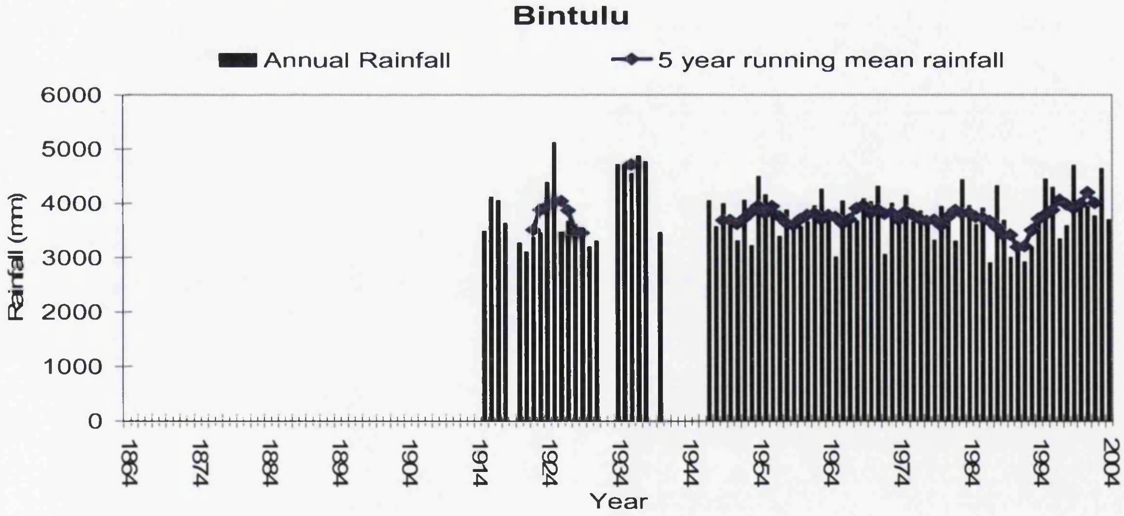


Figure 4.25. *Annual Rainfall at Kilanas, Brunei.*

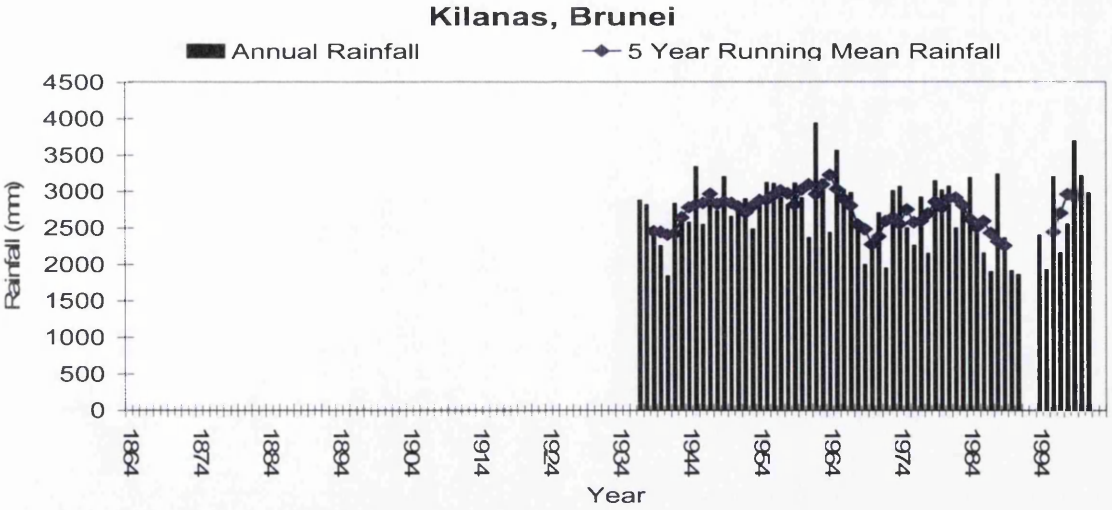


Figure 4.26. *Annual Deviation from the Long-term Mean Annual Rainfall at Miri*

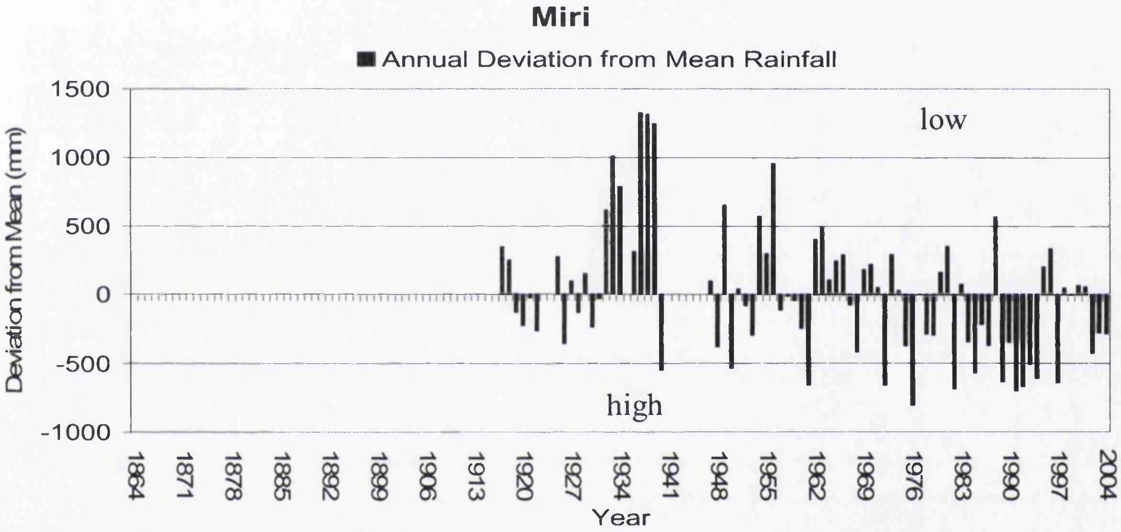


Figure 4.27. *Annual Deviation from the Long-term Mean Annual Rainfall at Bintulu*

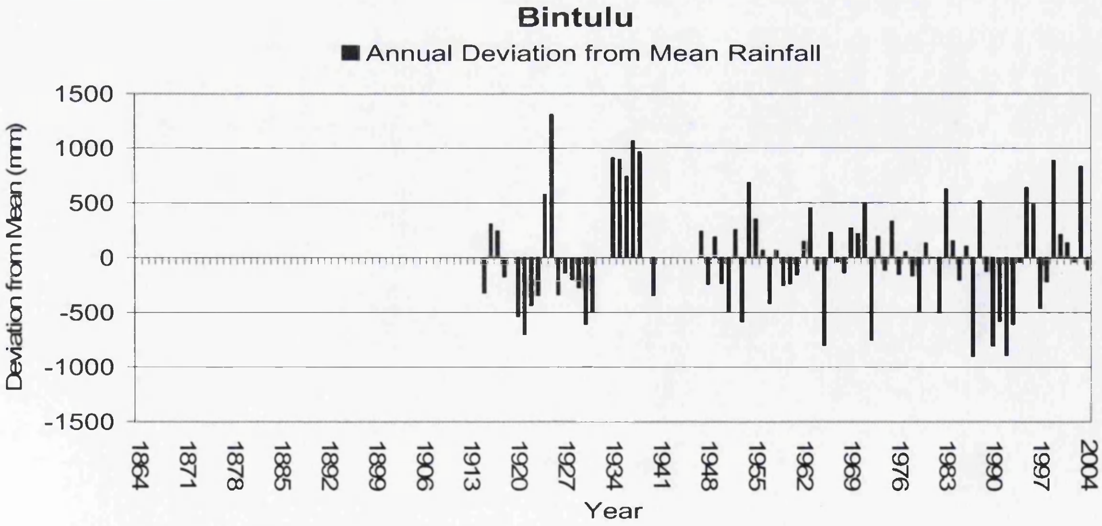


Figure 4.28. *Annual Deviation from the Long-term Mean Annual Rainfall at Kilanas, Brunei.*

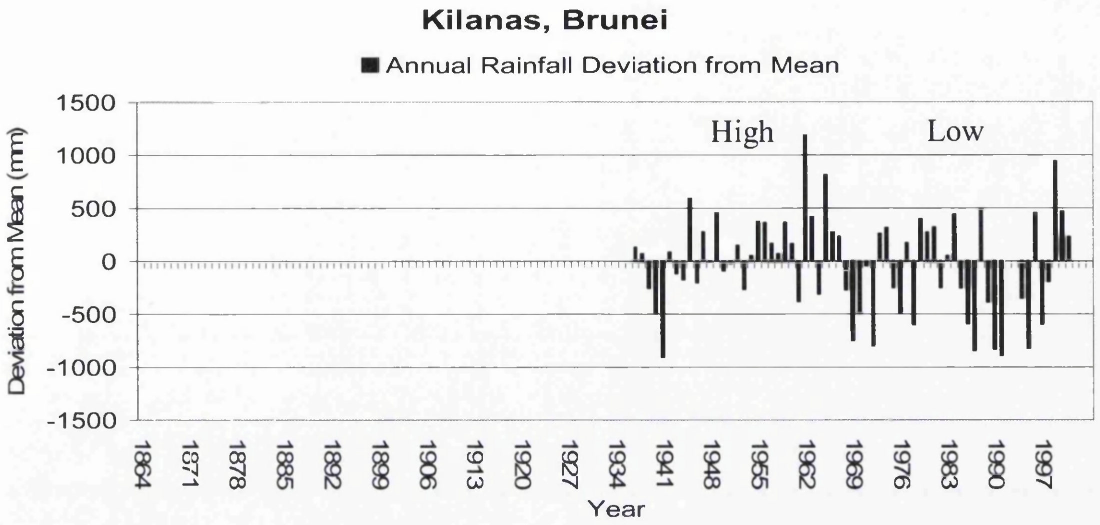


Figure 4.29. *Five-Year Running Means of Rainfall for Monsoonal and Transition Months at Miri.*

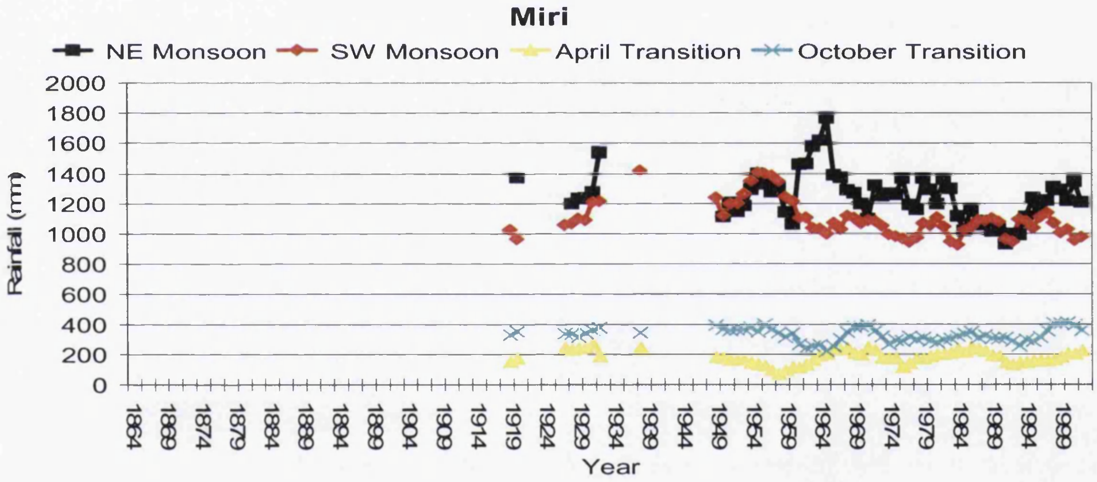


Figure 4.30. *Five-Year Running Means of Rainfall for Monsoonal and Transition Months at Bintulu.*

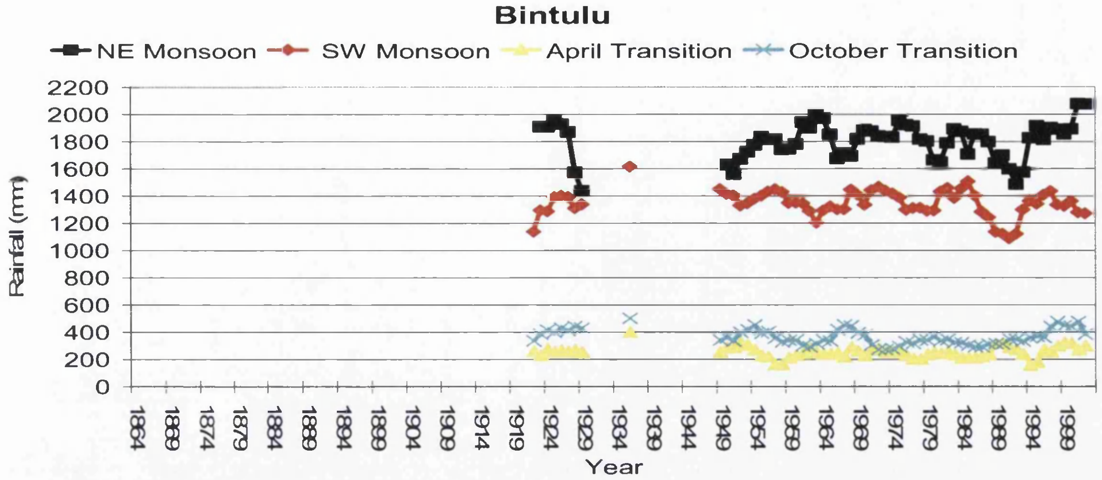
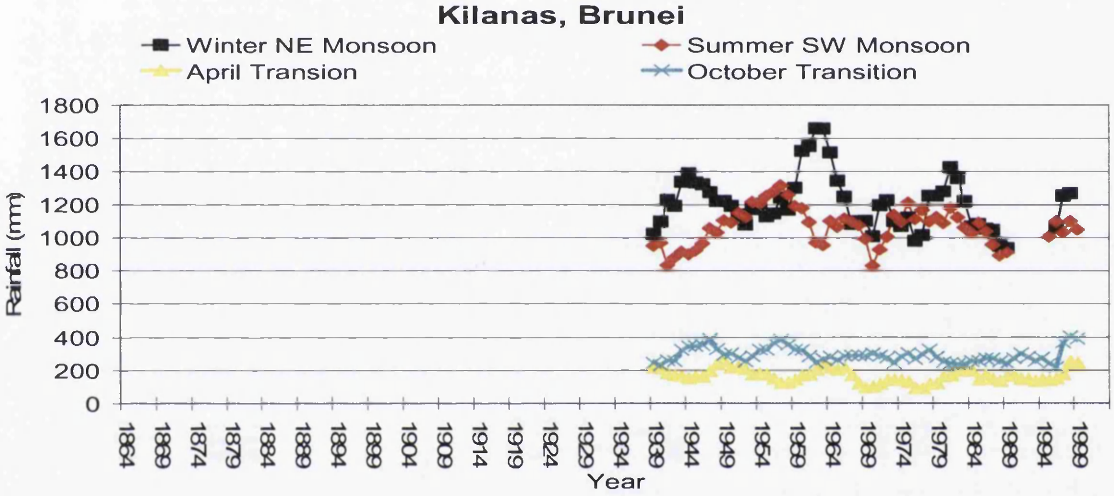


Figure 4.31. *Five-year Running Means of Rainfall for Monsoonal and Transition Months Kilanas, Brunei.*



Correlations of annual rainfall with SOI are positive and significant at the 1% level at all three stations (Kilanas r=+0.43, Bintulu r=+0.36 and Miri r=+0.36), but the relationships are generally weak. Southwest monsoon rainfall has a stronger positive relationship with SOI at all stations than has northeast monsoon rainfall, unlike at many other stations across Malaysia. At all three stations the correlation between annual rainfall and SOI increased in the final (1980 onwards) section of the records (Tables 4.11 to 4.13).

The majority of ENSO years had rainfall totals below the mean at all stations (Tables 4.14 to 4.16). Miri and Bintulu experienced negative annual rainfall anomalies during all but one very strong ENSO year and at Kilanas there were no very strong events with positive annual rainfall anomalies.

Table 4.11 *Correlation and statistical significance of annual rainfall and SOI in different periods and seasonal rainfall and SOI at Kilanas*

Variables	Period	R	R2	Statistically significant at 5% level
Annual Rainfall/SOI	ALL	0.42	0.18	YES
	Pre-1941		/	
	1942-79	0.39	0.15	YES
	1980-2004	0.64	0.41	YES
NE monsoon/SOI		0.36	0.13	YES
SW monsoon/SOI		0.37	0.14	YES

Table 4.12. *Correlation and statistical significance of annual rainfall and SOI in different periods and seasonal rainfall and SOI at Miri*

Variables	Period	R	R2	Statistically significant at 5% level
Annual rainfall/SOI	ALL	0.36	0.13	YES
	Pre-1941	0.28	0.08	NO
	1942-79	0.10	0.01	NO
	1980-2004	0.62	0.38	YES
NE monsoon/SOI		0.26	0.07	NO
SW monsoon/SOI		0.42	0.18	YES

Table 4.13 *Correlation and statistical significance of annual rainfall and SOI in different periods and seasonal rainfall and SOI at Bintulu*

Variables	Period	R	R2	Statistically significant at 5% level
Annual Rainfall/SOI	ALL	0.36	0.13	YES
	Pre-1941	0.14	0.02	NO
	1942-79	0.41	0.17	YES
	1980-2004	0.58	0.34	YES
NE monsoon/SOI		0.28	0.08	YES
SW monsoon/SOI		0.36	0.13	YES

Table 4.14 *ENSO severity and annual rainfall anomales at Miri during twenty-seven ENSO events.*

Miri — Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	0	3	3	3	3	1	1
Moderate to Strong	5	0	1	1	1	0	0
Very Strong	3	1	0	2	0	0	0
All	8	4	3	6	4	1	1

Table 4.15 *ENSO severity and annual rainfall anomalies at Bintulu during twenty-seven ENSO events*

BINTULU — Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	1	2	1	3	3	1	2
Moderate to Strong	4	2	0	2	0	0	0
Very Strong	3	2	1	0	0	0	1
All	8	6	1	5	3	1	3

Table 4.16. *ENSO severity and annual rainfall anomalies at Kilanas during twenty-three ENSO events.*

Kilanas — Anomaly (mm) compared to annual average

	Negative			Average	Positive		
El Niño Severity	>500	300-499	100-299	-99 to +99	100-299	300-499	>500
Weak	3	1	2	2	2	1	0
Moderate to Strong	2	0	1	0	1	0	1
Very Strong	3	1	2	1	0	0	0
All	8	2	5	3	3	1	1

4.7 KUCHING (1876-2004)

Apart from a short-lived and minor trough from 1902 to 1914, there are no indications of any shifts in the annual rainfall at Kuching (Figure 4.32), with the 5-year running mean varying little over the exceptionally long record, which extends back to 1876 (Figures 4.32 and 4.33). Kuching, unlike many other stations studied, shows no sustained period of dry years at any point between the 1970s and 1990s. There was a hint of slightly lower than average rainfall in the fragmented 1935-1954 period and also the short period around 1901-1905. From 1878 to 1986 most years were well above the mean annual rainfall and 1882 had the highest total in the whole record of 5738.2mm.

Figure 4.32. *Annual Rainfall at Kuching.*

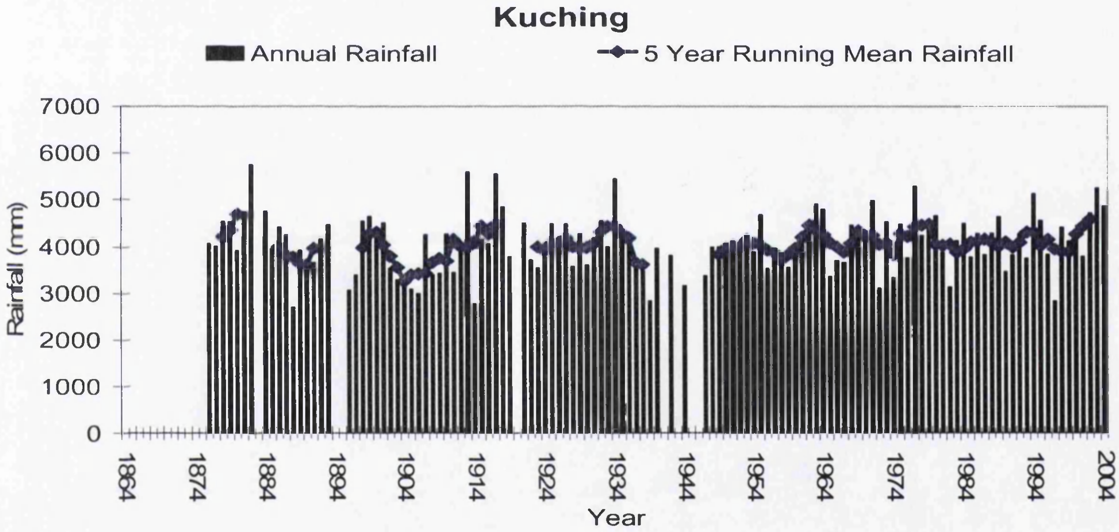
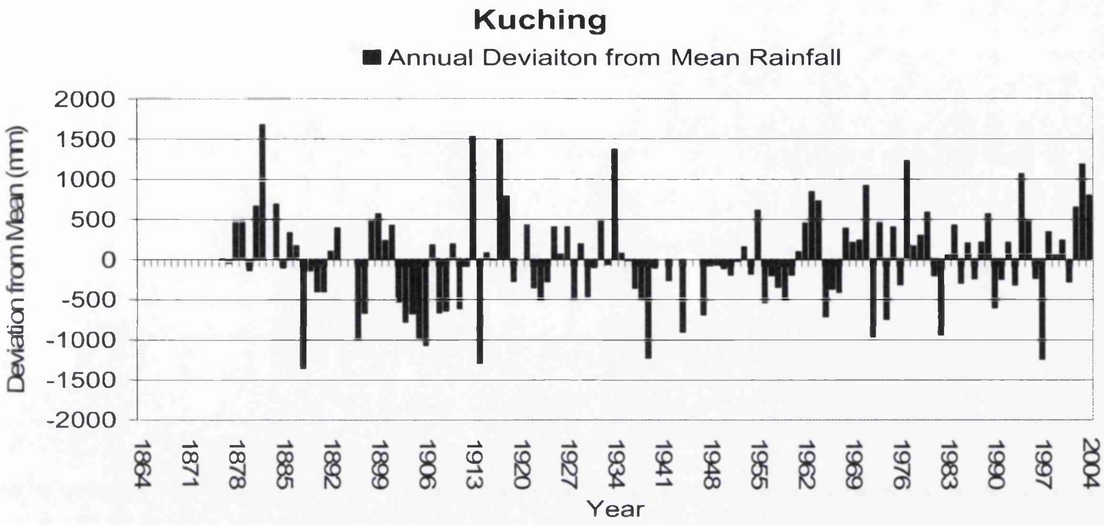
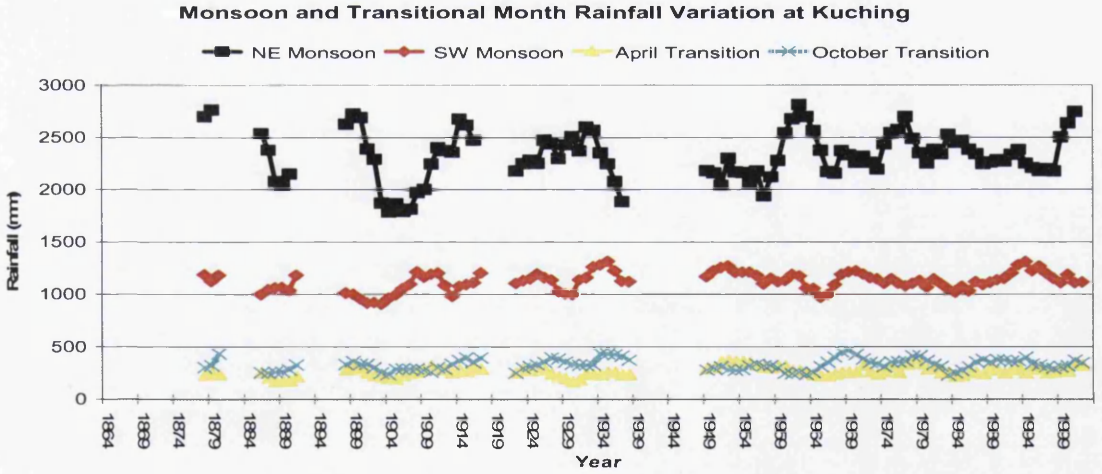


Figure 4.33. *Annual Deviation from the Long-term Mean Annual Rainfall at Kuching.*



Northeast monsoon rain shows more variation than southwest and annual rainfall (Figure 4.34), and the trough in annual rainfall in 1900-1908 directly resulted from anomalously low northeast monsoon rain.

Figure 4.34. *Five-year Running Means of Rainfall for Monsoonal and Transition Months at Kuching.*



There is a rather weak (r=+0.21) but statistically significant (at the 5% level) positive correlation between SOI and annual rainfall. The period of increased frequency and magnitude of ENSO events since the mid-1970s has had no impact on the rainfall here, unlike in much of Peninsular Malaysia and eastern Sabah. This was the case for all parts of the record.

4.8 ADDITIONAL ANALYSIS

As seen in Section 3.5, after consideration, additional analysis was carried out in order to try and identify patterns with more clarity and accuracy (Table 4.17).

Unlike in Peninsular Malaysia where the majority of stations did not show much difference when looking at the SOI correlation with rainfall in a July-June year, the correlations in Malaysian Borneo using July-June year are now very strong. At all stations, with the exception of Tawau and Kuching, correlations increased and in some cases by a large amount. R values at Kudat and Sandakan are above 0.6 and others (Kota Kinabalu, Miri, and Kilanas) are 0.5.

CV values in Malaysian Borneo are generally higher than on the Peninsula with the majority of values over 15 and some above 20, even as high as 31.5 at Kudat in the latter period. Considering changes in annual rainfall between the 1942-1979 and 1980-2004 period there are large variations between sites but they support trends seen earlier in the chapter with reductions in rainfall at Kota Kinabalu, Labuan, Kudat, Sandakan, and Miri.

Table 4.17 *Additional analysis of correlation between SOI and rainfall, changes (mm per year) between periods(pre1942, 1942-1979 and 1980-2004) and coefficient of variation for the different periods.*

	SOI and rainfall correlation		Pre-1942	1942-79		1980-2004	
Station	r (Jul-June)	r (Jan-Dec)	CV	Change in rainfall (mm/yr)	CV	Change in rainfall (mm/yr)	CV
Kota Kinabalu	0.543	0.41	15.8	-0.4	16.5	-4.2	19.7
Labuan	0.482	0.33	18.4	-2.5	15.3	-9.9	19.4
Keningau	0.403	0.26	20.2	3.6	19.4	-1.7	22.5
Kudat	0.667	0.41	23.3	0	18.5	-3.5	31.5
Sandakan	0.602	0.32	21.9	-2.2	12.6	-2.5	21.9
Tawau	0.429	0.46	16.6	-4.8	17.6	2.7	17.5
Miri	0.515	0.36	17.7	-12.4	13.7	-5.6	13.9
Bintulu	0.413	0.36	16.3	-5.2	9.5	0.1	13.7
Kilanas	0.528	0.43	11.2	40.6	15.7	-4.1	20.9
Kuching	0.218	0.21	16.3	0.2	13.1	3.2	13.9

4.9 SUMMARY OF RESULTS FROM MALAYSIAN BORNEO

The main findings from analysis of the annual and seasonal rainfall totals in Malaysian Borneo are that:

1) The west coast stations show the greatest changes in the record. On the west coast Miri and Labuan Island experienced a decrease in the annual rainfall in the 1970s, 1980s and 1990s. The decrease was over 15% between the pre-war period and 1980-2004 period.
2) West coast stations of Kota Kinabalu, Labuan, Miri and to a lesser extent Bintulu have seen a recent (1970s onwards) increase in the frequency of years with annual rainfall well below the mean, although at Kota Kinabalu and Bintulu this has not led to reduced annual rainfall because of intervening very wet years.
3) All stations with the exception of Miri show an increase in standard deviation in the recent period (1980-2004), with especially large increases at Kudat, Sandakan and Bintulu.
4) Across the region the standard deviation of annual rainfall in 1942-1979 was lower than in previous and subsequent periods.
5) All stations (with the exception of Kuching) on the north and west coasts show a period of reduced rainfall within the period 1975 to 1994. This is a similar finding to that recorded at stations on Peninsular Malaysia.
6) This dry period from the mid-1970s is mostly a result of reduced northeast monsoon rainfall, again as in Peninsular Malaysia.
7) The northeast monsoon rainfall is more variable than the southwest monsoon rainfall.
8) The relationship between annual rainfall and SOI was stronger at most stations in northern Borneo than in Peninsular Malaysia and the relationship between ENSO events and anomalously dry years was especially apparent in Sabah and northwest Sarawak.
9) At many stations annual rainfall had a much stronger correlation between SOI and rainfall in the most recent period since 1980. At Tawau on the east coast

of Sabah an R^2 of 0.53 was recorded for the relationship between annual rainfall and SOI.

10) The additional analysis shows that correlations between SOI and rainfall are stronger using the July-June year, with some strong correlations.

CHAPTER 5:

RESULTS AND ANALYSIS: CHANGES IN THE MAGNITUDE-FREQUENCY OF LARGE DAILY RAINFALLS

In this chapter changes in the magnitude-frequency of large daily rainstorms are analysed for stations in Sabah and Sarawak. Patterns of annual and seasonal changes are analysed and return periods of large falls are calculated for different periods in the record. On the annual frequency graphs plus signs above the bars indicate either one or two months data missing and the question marks indicate years with no data.

5.1 SABAH

5.1.1 KOTA KINABALU

Figure 5.1 shows that the main features of daily falls greater than 50mm were 1) higher frequencies in the 1930s and 1951-1963 than the 1910s and 2) increased year-to-year variability since 1965. Changes in the frequency of falls over 100mm (Figure 5.2) showed similarities to those over 50mm. In the 1930s and 1950s the 5-year running mean of 100mm falls was high (peaking at over 3.5 per year) during this time. This period in the record was also at a time when the annual rainfall was high (Figure 4.1). Similarly the 1950s especially the mid 1950s had high frequencies of falls over 50mm coinciding with the 5-year running mean of annual rainfall reaching its highest values.

Periods with a low frequency of 50mm falls occurred in the periods 1919-1921, 1929-1931, 1964-1968 and 1980-1983 (all just above or just below 10 falls per year), the latter being a period of lower than average annual rainfall. Falls over 50mm were generally of lower frequency from the 1960s onwards following a period of high frequency in the 1930s and 1950s.

Although the periods taken are somewhat arbitrary (see Chapter 2), Table 1 compares means and year-to-year variability in the frequencies of 50 and 100mm falls for 1908-1940, 1949-1979 and 1980-2004. There appears to have been a large reduction in the annual frequency of falls greater than 50mm. The mean annual frequency fell from 13.2 in the period from 1908 to 1940 and 13.3 from 1949-1979, to 11.3 in the period from 1980 to 2004, a reduction of 1.9 rainfall events over 50mm (decline is statistically significant at 5% level). It is possible that this decrease is linked to the more frequent and severe drought years in recent times shown in Figure 4.3. However, this reduction between the different periods is not mirrored in the table of 100mm rainfall events. Events larger than 100mm saw a rise from the first period (Table 5.1) to the second and then a reduction again in the last period to frequencies similar to the earliest period. The decline in variability since the first period was not shown by Walsh and Leong (2003) as rainfall records available to them were for 1960-2004. Table 5.2, giving the mean and standard deviation of 100mm falls during the three periods, shows that the period 1949-1979 had the highest mean frequency and highest variability.

Figure 5.1. *Annual frequency and five-year running mean of falls ≥ 50mm at Kota Kinabalu.*

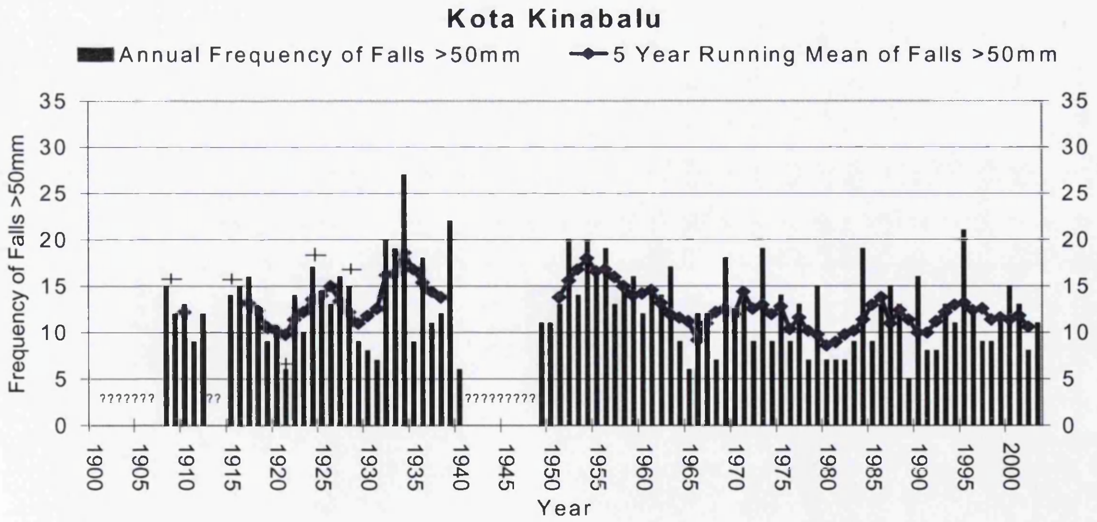


Figure 5.2. *Annual frequency of falls ≥ 100mm at Kota Kinabalu*

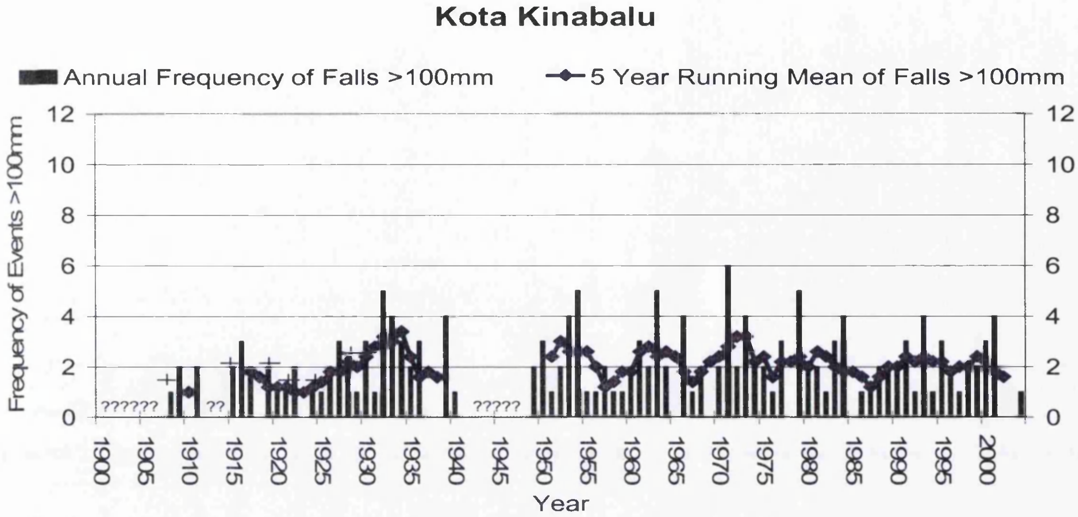


Table 5.1. *Mean and standard deviation of falls over 50mm in different periods at Kota Kinabalu*

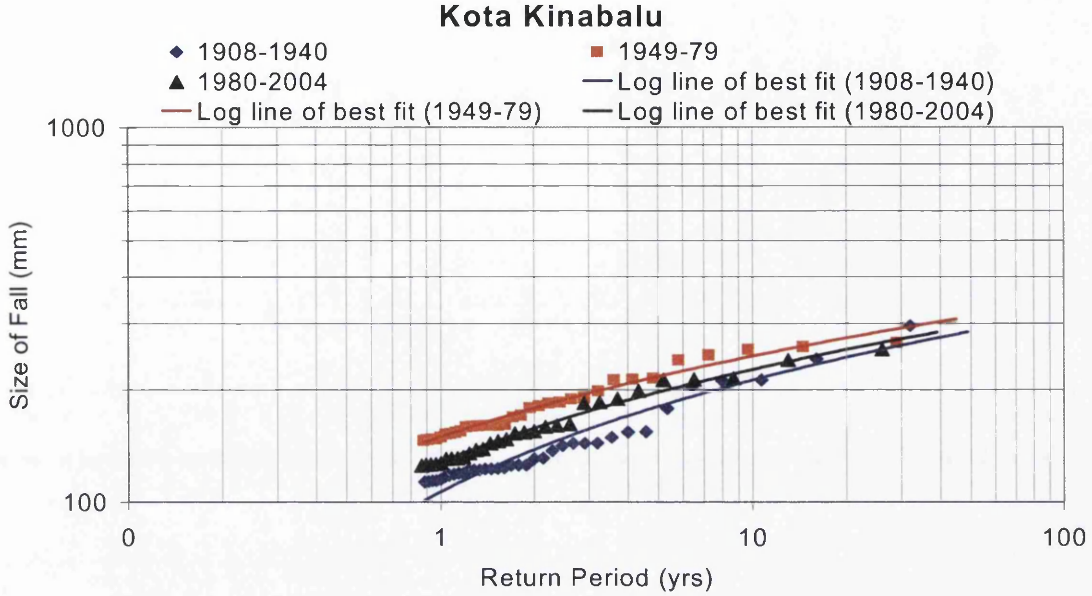
	Mean	SD
Pre-1941	13.2	4.8
1949-79	13.3	3.8
1980-2004	11.3	4.0

Table 5.2. *Mean and standard deviation of falls over 100mm in different periods at Kota Kinabalu*

	Mean	SD
Pre-1941	1.7	1.3
1949-79	2.3	1.6
1980-2004	1.9	1.2

The extreme value analysis graph (Figure 5.3) shows that there are some significant changes in return periods between the three periods. The period 1941-1979 had higher magnitude events (and therefore shortest return periods), whereas return periods were longest in the period from 1908-1940. Falls of 200mm had a return period of roughly 8 years in 1908-1940, just over 5 years during 1980-2004 and just over 2 years in the period from 1949-1979.

Figure 5.3. *Extreme Value Analysis of daily rainfall events at Kota Kinabalu.*



The seasonality of large rainfall events (Figure 5.4) shows that the recent reduction in falls over 50mm has occurred mainly as a result of reductions during May and June, where the mean frequency of falls in those months was halved between the first period (1908-1940) and the last period (1980-2004). The months December and January also showed substantial reductions. Other months showed little change in comparison. There has been a recent increase in falls ≥100mm in October November and December and a decrease during June and September, although this was only very small (Figure 5.5).

Figure 5.4. *Changes in monthly frequency of 50-99mm falls for different periods at Kota Kinabalu.*

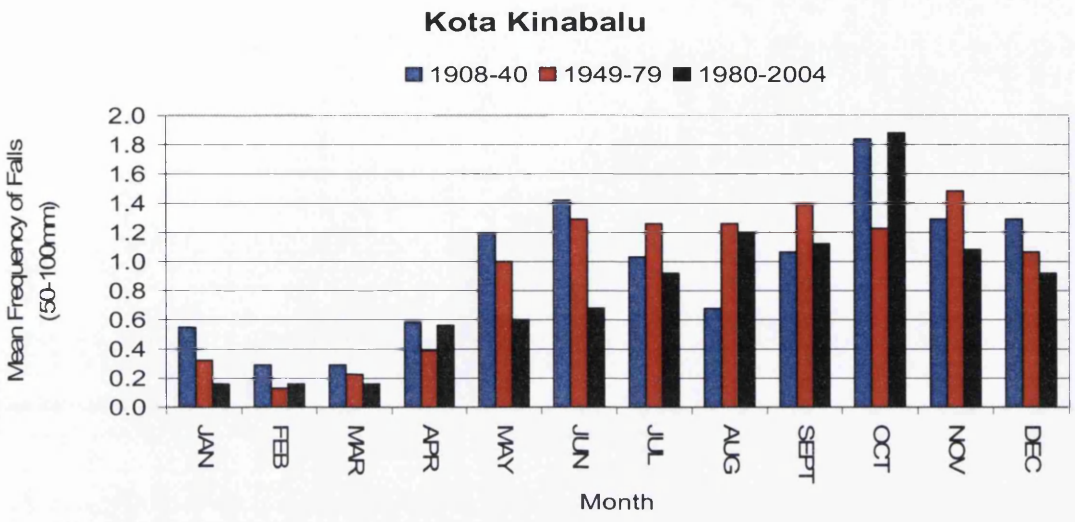
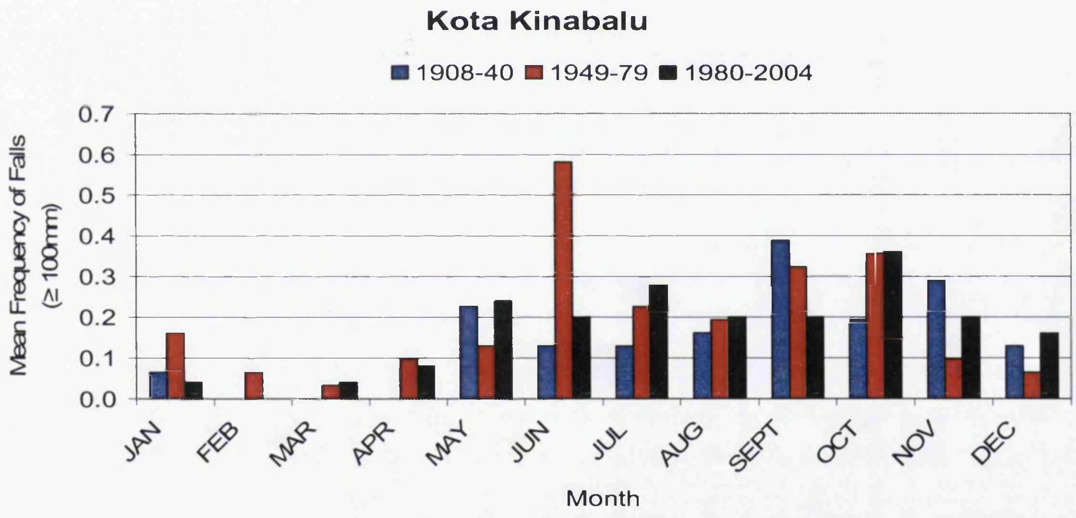


Figure 5.5. *Changes in the monthly frequency of falls ≥100mm for different periods at Kota Kinabalu.*



5.1.2 KENINGAU

The most significant feature of the record at Keningau is an increase in falls greater than 50mm since 1987 (Figure 5.6). As there are very few rainfall events over 100mm in magnitude, analysis of changes in 100mm frequency was not attempted. The period from 1933-1940 was excluded from analysis of changes between the periods due to the short record.

Figure 5.6. *Annual frequency and five-year running mean of falls ≥ 50mm at Keningau*

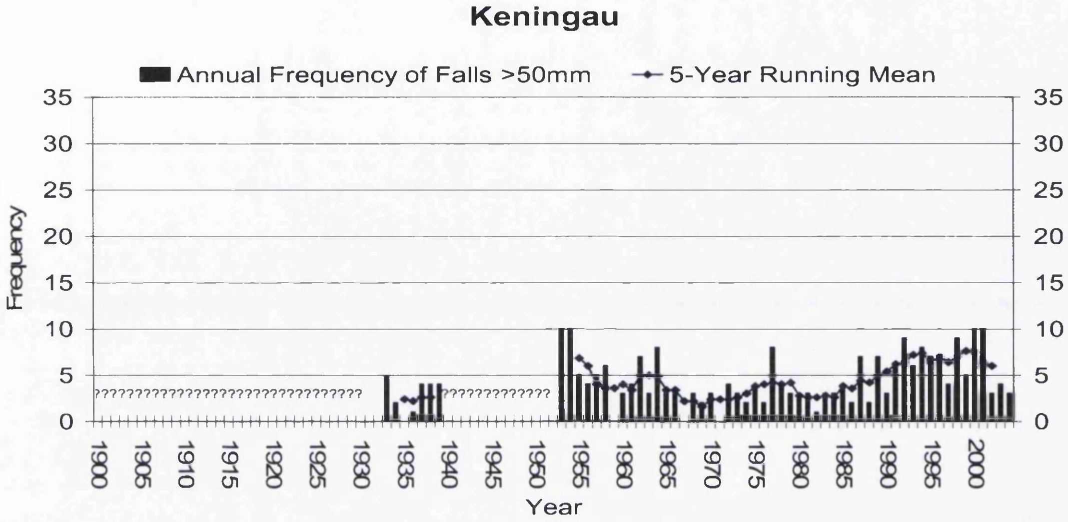


Table 5.3. *Mean and standard deviation of falls over 50mm in different periods at Keningau*

	Mean	SD
1953-79	4.0	2.7
1980-2004	5.2	2.7

Figure 5.7. Extreme Value Analysis of daily rainfall events at Keningau

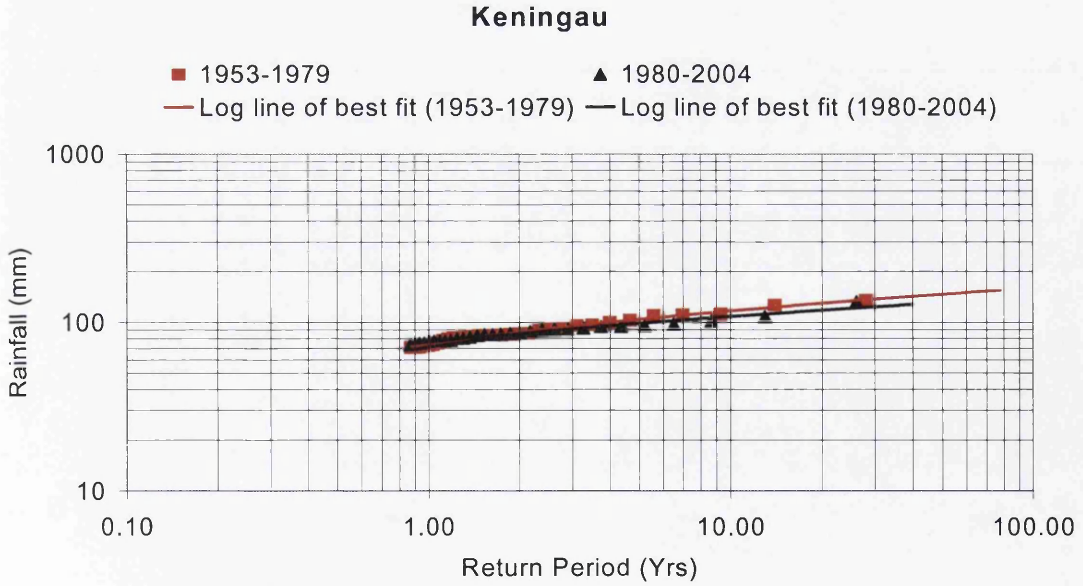
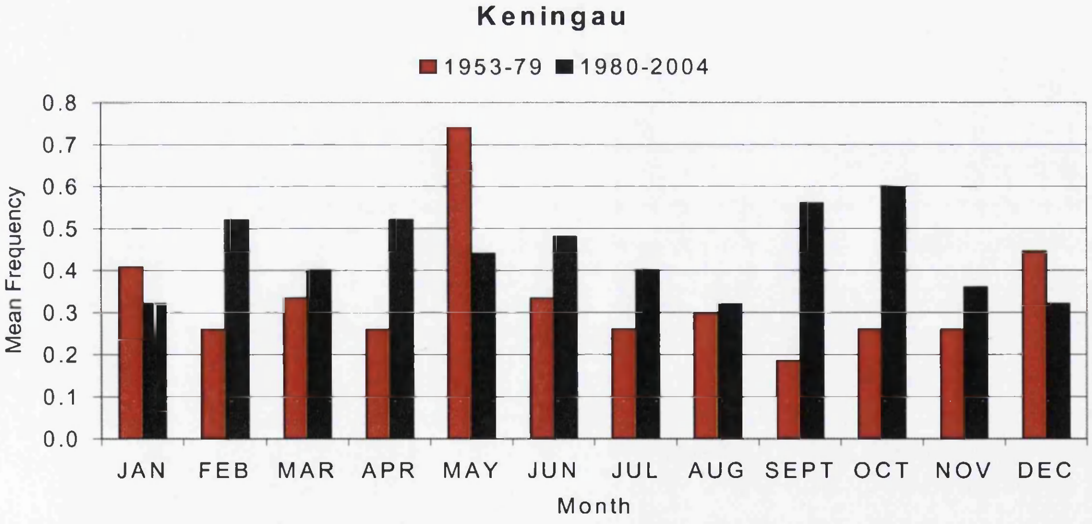


Figure 5.6 suggests that there has been an increase in the number of falls over 50mm, with the five-year running mean reaching its highest values in the 1990s. This increase is confirmed by consulting Table 3, which shows that the mean annual number of falls greater than 50mm has increased from 4.0 in 1953-1979 to 5.2 in 1980-2004 (though this increase is not statistically significant at the 5% level). The record of high magnitude daily falls roughly follows the trend in the five-year mean of annual totals (shown in Figure 4.8), which indicates no increase and has more complete data. Therefore the period with high annual rainfall from the late 1940s to the end of the 1950s could be reflected in the frequency of 50mm falls at Keningau.

Years with very few or no falls over 50mm occurred in 1935, 1936, 1959, 1967, 1971 and 1982. In the extreme value analysis of the two different periods throughout the record, it seems that during 1953-1979 there were slightly shorter return periods for higher magnitude rainfall events. This is explained by the higher frequency of falls over 100mm in this period (6) compared to 1980-2004 (3).

Figure 5.8. *Changes in monthly frequency of falls ≥50mm for different periods at Keningau.*



Increases in the mean annual frequency of falls greater than 50mm resulted from increases in most months, but more especially February, June, July, September and October (shown in Figure 5.8).

5.1.3 KUDAT

At Kudat, years of highest frequency of falls greater than 50mm occur at the beginning (1909-11) and end of the record (1999-2001). The latter period coincides with a period of high annual rainfall. The frequency of falls over 50mm was low from 1912 to 1916, (when there were also no falls over 100mm) and from 1989-1993, during which 1989, 1992 and 1993 had no 100mm falls. This period coincides with a dip in the annual rainfall figures. Years with particularly high numbers of 100mm falls occurred in 1910, 1926, 1932, 1934, 1988 and 2001. As mentioned in the methodology chapter the plus signs above the bars indicate years with missing monthly data.

Figure 5.9. *Annual frequency and five-year running mean of falls ≥ 50mm at Kudat*

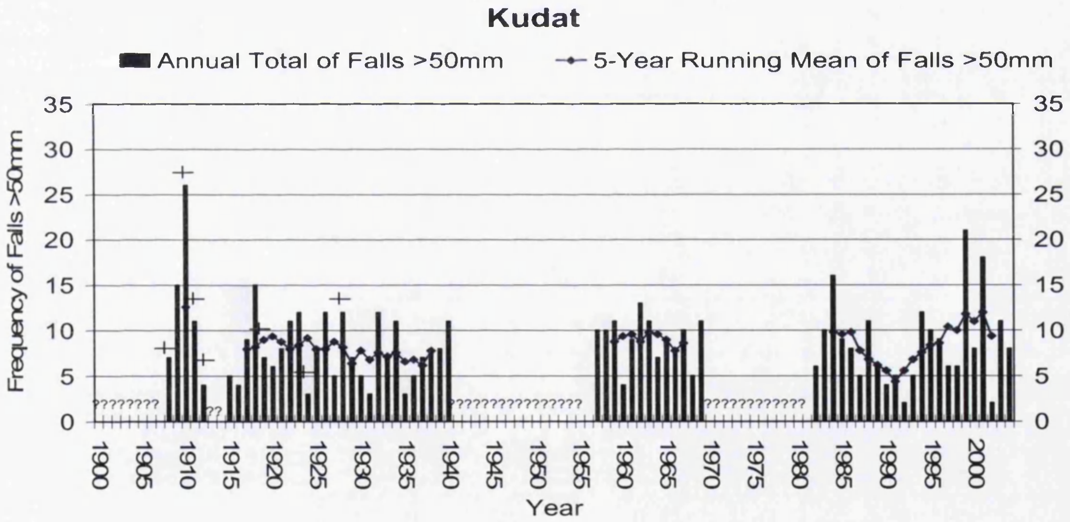


Figure 5.10. *Annual frequency of falls ≥ 100mm at Kudat*

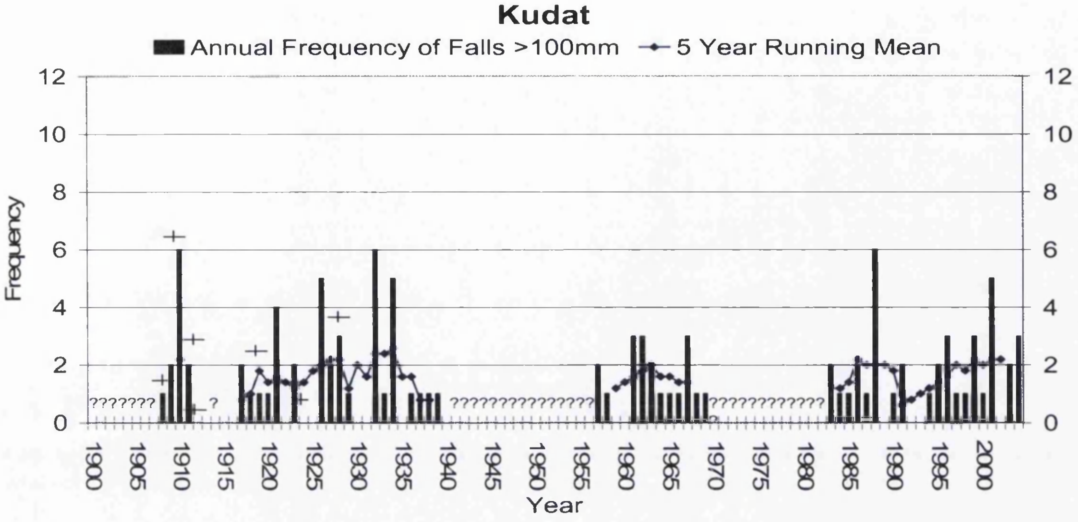


Table 5.4. *Mean and standard deviation of falls over 50mm in different periods at Kudat*

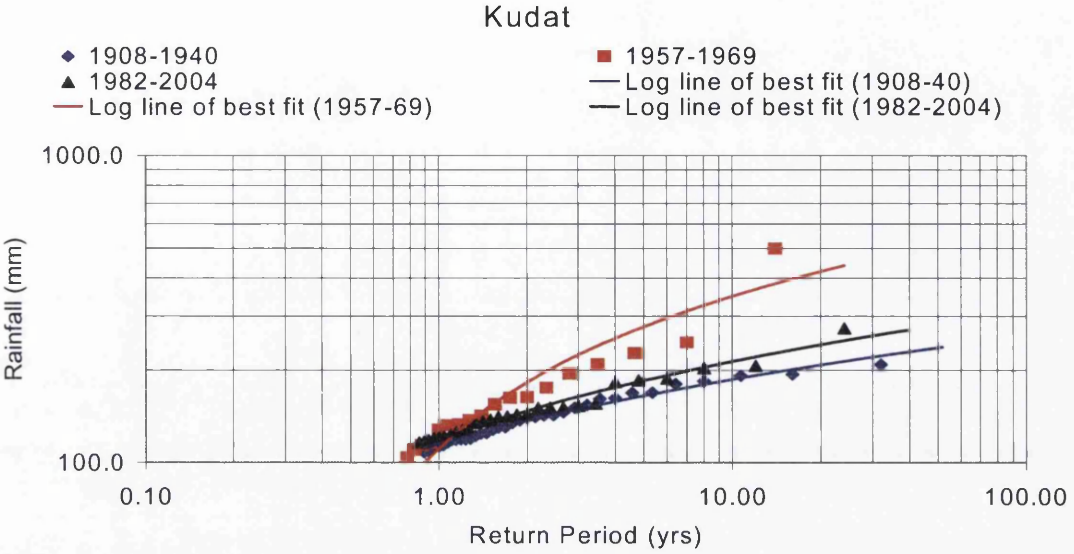
	Mean	SD
1906-1940	8.3	4.8
1957-69	9.1	2.5
1982-2004	8.6	4.8

Table 5.5. *Mean and standard deviation of falls over 100mm in different periods at Kudat*

	Mean	SD
1906-1940	1.5	1.8
1957-69	1.5	1.1
1982-2004	1.7	1.6

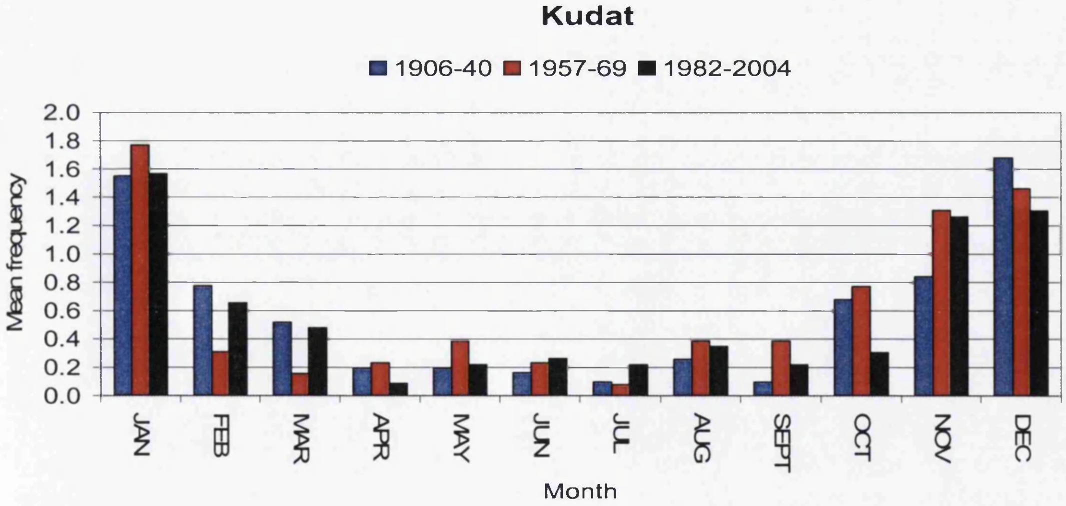
The mean frequency of falls over 50mm was 0.5 per annum greater in 1957-1969 than 1982-2004. Standard deviation of 50mm and 100mm falls were much lower in 1957-1969 than in both 1906-39 and 1982-2004.

Figure 5.11. *Extreme Value Analysis of daily rainfall events at Kudat*



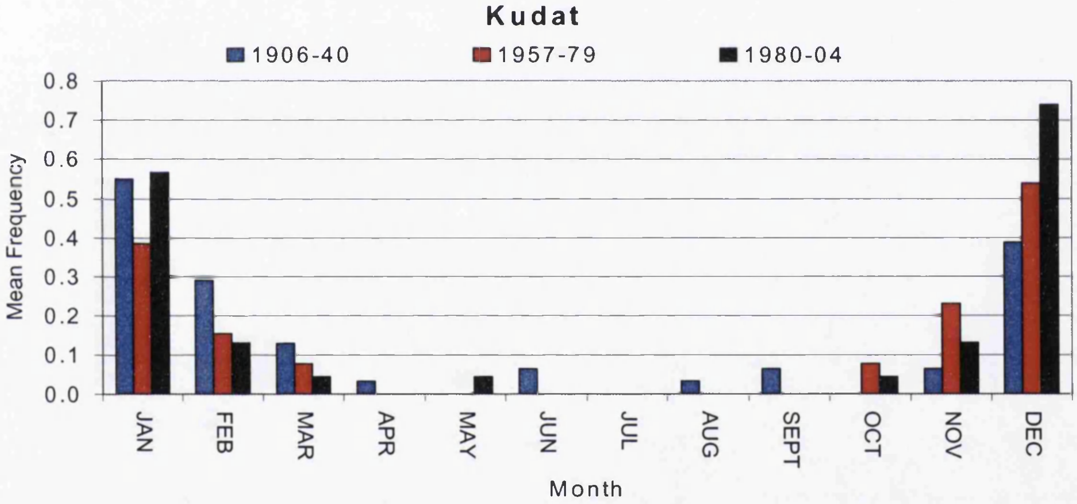
The extreme value analysis graph in Figure 5.11 confirms that rainstorm magnitude-frequency was higher in 1957-1969 than in the other two periods. However as this is a relatively short time it could be significantly influenced by very few large falls (4 >200mm).

Figure 5.12. *Changes in monthly frequency of 50-99mm falls for different periods at Kudat*



At Kudat 50-99mm falls occur predominantly during the northeast monsoon in all periods (Figure 5.12). October has seen a reduction from 0.7 falls of 50-99mm in the early period (1908-1940) to 0.3 in the most recent (1982-2004). The frequency in November increased from 0.8 in 1906-1940 to 1.3 in 1982-2004. February showed changes in the shorter middle period of the record (1957-1969), with a reduction from 0.8 to 0.3 and 0.7 for the respective periods. Falls over 100mm show a similar pattern with almost all occurring between October and March (Figure 5.13). The only difference between the 3 different periods occurs in December where the first period (1908-1940) has a mean frequency of 0.4 falls per month and the recent period (1982-2004) has a mean frequency of 0.7 falls per month.

Figure 5.13. *Changes in monthly frequency of falls ≥100mm for different periods at Kudat.*



5.1.4 SANDAKAN

At Sandakan there has been little change in either the magnitude or frequency of large rainfall events over the period of record (Figures 5.14 and 5.15). Years with 20 or more rainfall events over 50mm occurred in 1907, 1918, 1922, 1925, 1928, 1934, 1936, 1938, 1939, 1965, 1967, 1980, 1984, 1993 and 1994, with nine out of fifteen in the 34-year period 1908-1940 and only 6 in the 53 years since World War II. The highest frequency of 30 was in 1994. The highest number of falls greater than 100mm occurred between

1921 and 1929, coincident with high annual rainfall values (see Figure 4.16). The five-year means of high magnitude falls were low from around 1908 to around 1917, in the late 1950s early 1960s and from the mid 1980s to early 1990s.

Table 5.7 shows that the mean annual frequency falls over 50mm has dropped by 0.9 between the first period (1906-1940) and the final period (1980-2004). There was also a large reduction in the mean annual frequency of falls over 100mm between the first period (1906-1940) and the second period (1952-1979). This fall would have been even larger if one considered only the period 1918-1941 but the inclusion of data (and lower frequencies) pre-1918 reduced the mean in this pre-1941 period. Variability, like the mean frequency, was lowest in the period 1952-1979.

Figure 5.14. *Annual frequency and five-year running mean of falls ≥ 50mm at Sandakan.*

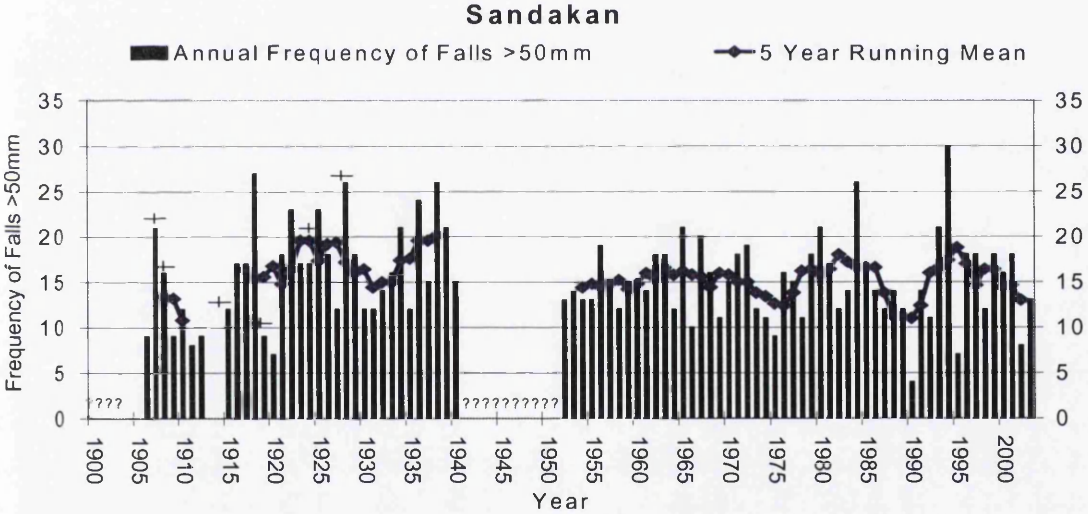


Figure 5.15. *Annual frequency of falls ≥ 100mm at Sandakan.*

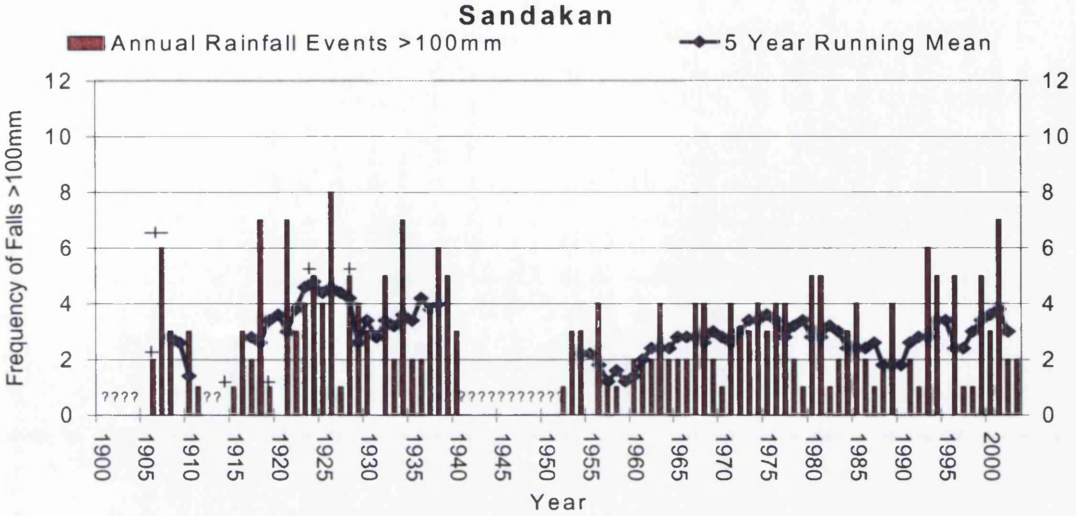


Table 5.6. *Mean and standard deviation of falls over 50mm in different periods at Sandakan*

50mm	SD	Mean
Pre-1941	5.6	16.2
1952-79	3.2	14.8
1980-2004	5.7	15.3

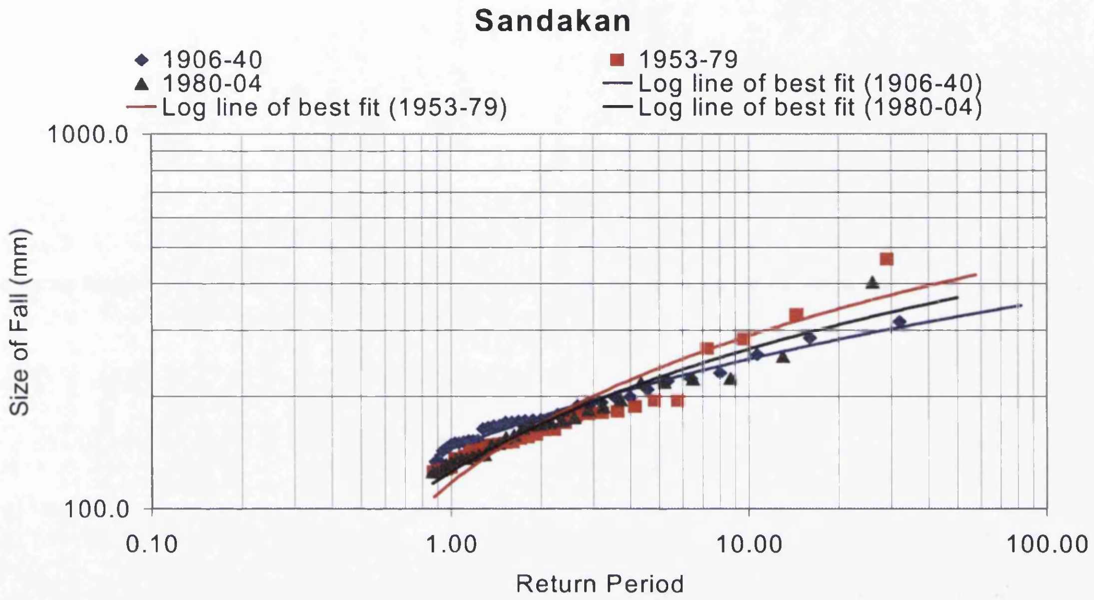
Table 5.7. *Mean and standard deviation of falls over 100mm in different periods at Sandakan*

100mm	SD	Mean
Pre-1941	2.3	3.3
1952-79	1.3	2.4
1980-2004	2.0	2.9

The extreme event analysis (Figure 5.16) shows that the period between 1952 and 1979 has shorter return periods for high magnitude falls than the other two periods, with the longest return period occurring in the early period of the record between 1908 and 1940. This is largely the product of three or four very high magnitude falls occurring between 1952 and 1979. During this period there were fewer high magnitude falls, but with higher magnitude ones, a pattern which was characteristic of many stations in northern

Borneo. Results here suggest, as at other stations covered, that there has been no recent increase in the likelihood of high magnitude rainfalls as a result of global warming.

Figure 5.16. *Extreme Value Analysis of daily rainfall events at Sandakan.*



At Sandakan falls greater than 50mm are more frequent during the winter monsoon season from September to February, but occur in all months (Figure 5.17). A similar pattern exists for falls greater than 100mm, with such falls rare in the Southwest monsoon (Figure 5.18). The highest frequency of 50mm falls occurred in December in 1980-2004, but in January in the two earlier periods. Frequencies in January, February, March and November have fallen whereas in July, August and December frequencies have increased. Falls over 100mm have reduced in numbers in the NE monsoon months of December, January and February (the season with the highest frequency).

Figure 5.17. *Changes in monthly frequency of 50-99mm falls for different periods at Sandakan.*

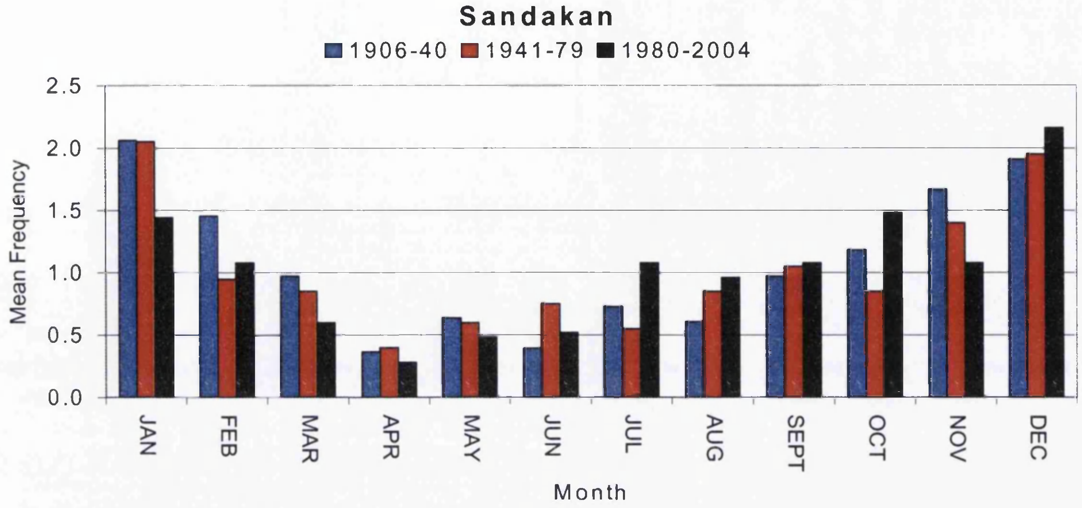
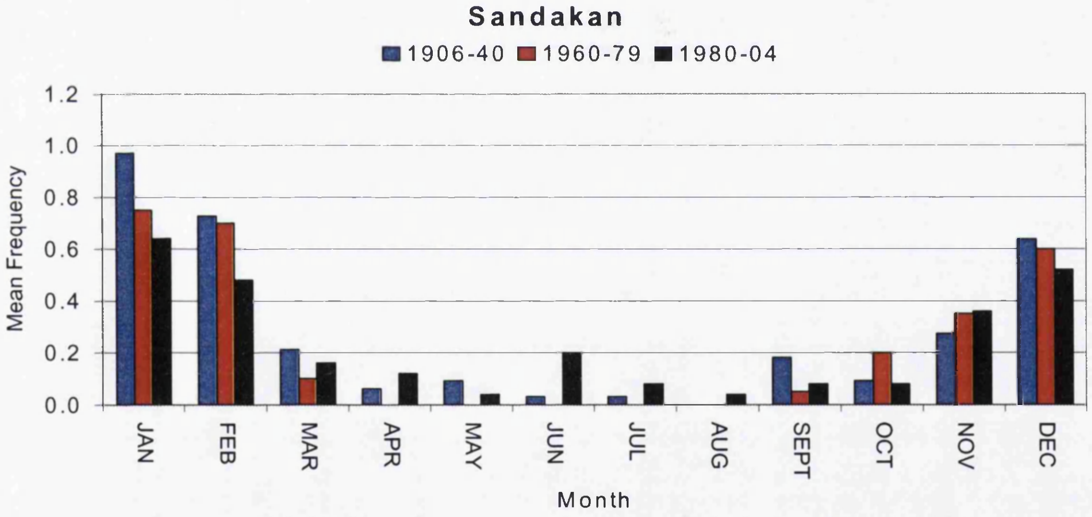


Figure 5.18. *Changes in the monthly frequency of falls ≥100mm for different periods at Sandakan.*



5.1.5 TAWAU

The five-year running mean of 50mm falls (Figure 5.19) was lowest (3.2 per annum) in 1910. In contrast, between 1920 and 1940, the mean number of falls greater than 50mm was consistently above five, coinciding with the wettest period in annual rainfall at the station. Falls of 50mm were less frequent from the mid 1950s to the late 1970s, averaging 4.6 per annum in the 1951-1979 period (Table 5.9). There were also very few 100mm falls during this period (Table 5.10). The frequency rose above 5 in the 1980s and remained around 5 in the 1990s. These changes roughly mirror the 5-year running mean in annual rainfall shown in Figure 4.19.

Figure 5.19. *Annual frequency and five-year running mean of falls ≥ 50mm at Tawau.*

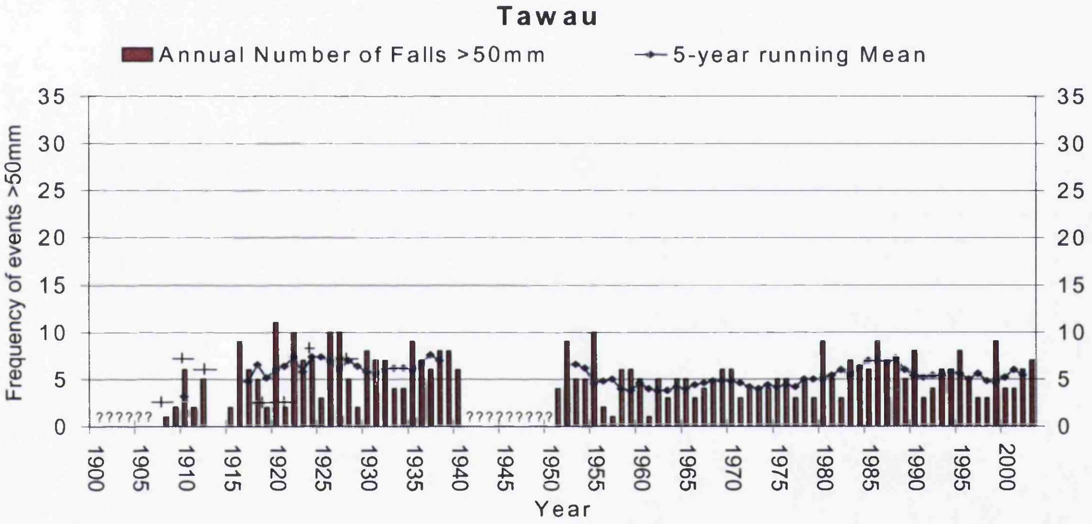


Figure 5.20. *Annual frequency of falls ≥ 100mm at Tawau*

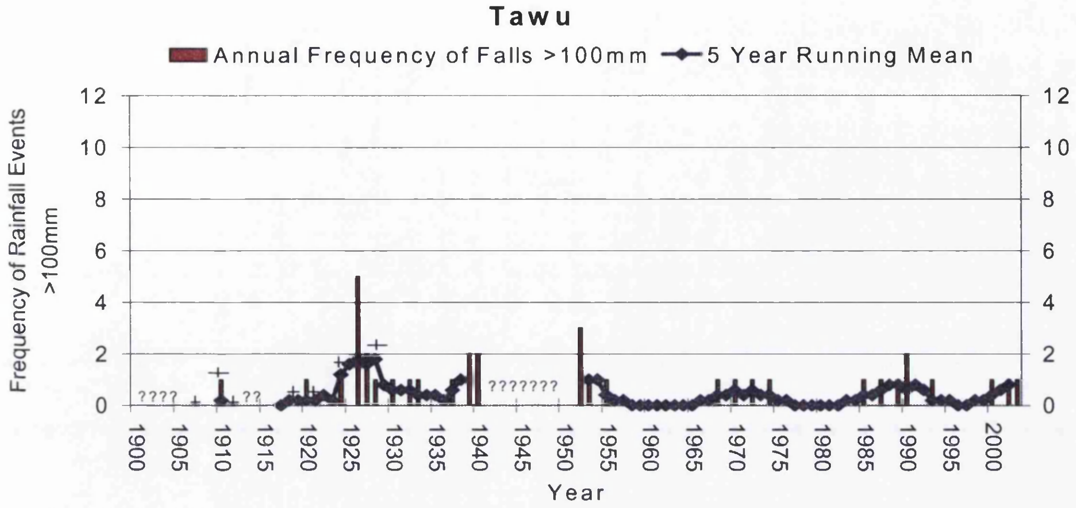


Table 5.8. *Mean and standard deviation of falls over 50mm in different periods at Tawau*

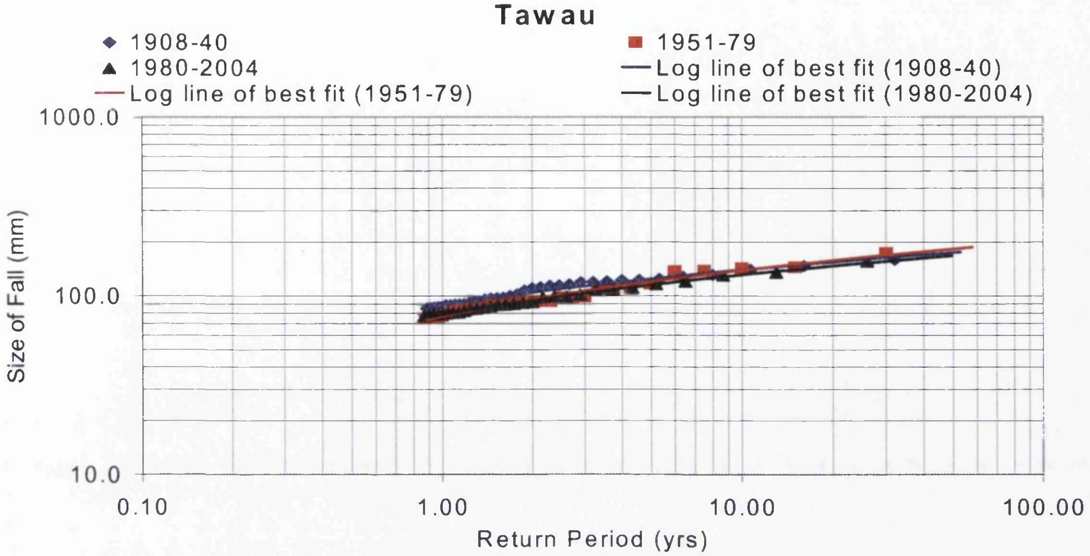
50mm	Mean	SD
1906- 1940	5.8	2.9
1951-79	4.6	1.9
1980-	5.8	2.0

Table 5.9. *Mean and standard deviation of falls over 50mm in different periods at Tawau.*

100mm	Mean	SD
1906- 1940	0.6	1.1
1951-79	0.3	0.7
1980 -	0.4	0.6

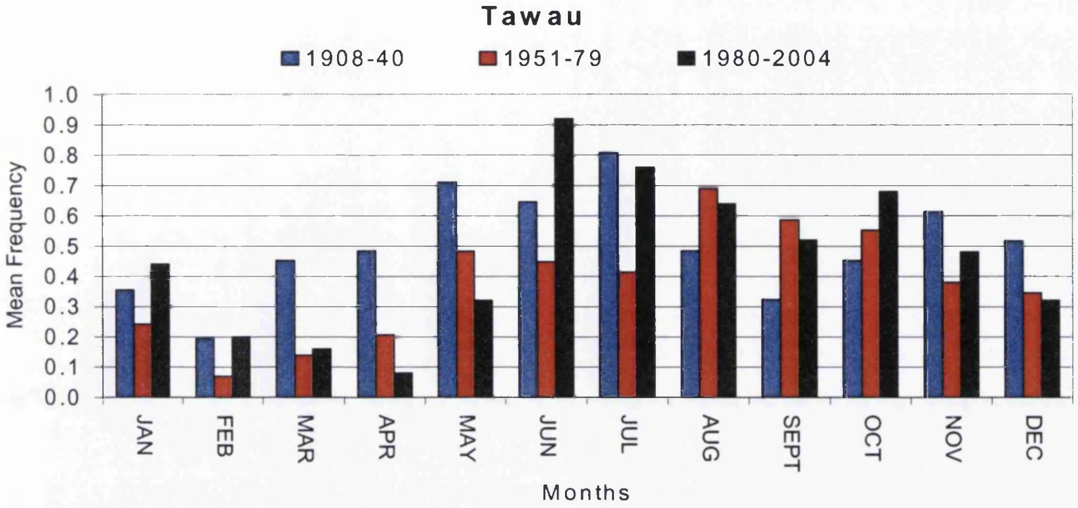
The extreme value analysis in Figure 5.21 shows no significant differences in the return periods of highest magnitude rainfalls between the different periods, but return periods of more moderate falls in 1906-1940 were shorter than in the rest of the record.

Figure 5.21. *Extreme Value Analysis of daily rainfall events at Tawau.*



The seasonal pattern of rainfalls exceeding 50mm shows considerable change (Figure 5.22) though the small number of falls involved means that caution needs to be used. The mean frequency of 50mm falls in August, September, October and June has increased from the first period (1908-1940) to the most recent (1980-2004), whereas reductions have occurred in March, April (from 0.3 to 0.4 per annum), May, July and December. In 1951-1979 mean frequencies in each month were much lower than in either the period from 1908-1940 or 1980-2004, with the exception of August, September and October. Falls over 100mm are too few to permit meaningful analysis of changing average frequencies in different months.

Figure 5.22. *Changes in monthly frequency of falls ≥50mm for different periods at Tawau.*



5.2 SARAWAK

5.2.1 KUCHING

The most significant feature is the increase in recent decades in the frequency of 50mm falls. The five-year running mean of 50mm (Figure 5.23) falls was mostly 15-17 per annum in 1900-1926 and dipped below 15 in the early 1950s. In contrast the five-year mean has risen three times above 20 per annum since 1970 reaching 23 per annum in 2000-2004. The pattern of 100mm falls (Figure 5.24) is less clear-cut, with shorter-term peaks and troughs throughout the entire record. Thus the mean annual frequency of 50mm falls has increased from 17.3 per annum in 1900-26 to 20.0 per annum in 1980-2004 (Table 5.10). This, however, is not statistically significant at 5% level using the t-test. The standard deviation of 50mm fall frequency fell from 6.0 in 1900-1926 to 4.2 in 1980-2001 (Table 5.10). The pattern in falls greater than 50mm is barely evident in the number of falls over 100mm (Table 5.11), as the annual mean frequency only increases by 0.2. The variability of 100mm falls (Table 5.11) was highest in the middle period when frequencies were lowest, but again changes were slight.

Table 5.10 *Mean and standard deviation of falls over 50mm in different periods at Kuching.*

50mm	Mean	SD
1900-1926	17.3	6.0
1951-79	18.1	5.3
1980-2004	20.0	4.2

Table 5.11. *Mean and standard deviation of falls over 100mm in different periods at Kuching*

100mm	Mean	SD
1900-1926	3.6	2.2
1951-79	3.4	2.5
1980-2004	3.8	2.3

Figure 5.23. *Annual frequency and five-year running mean of falls ≥ 50mm at Kuching.*

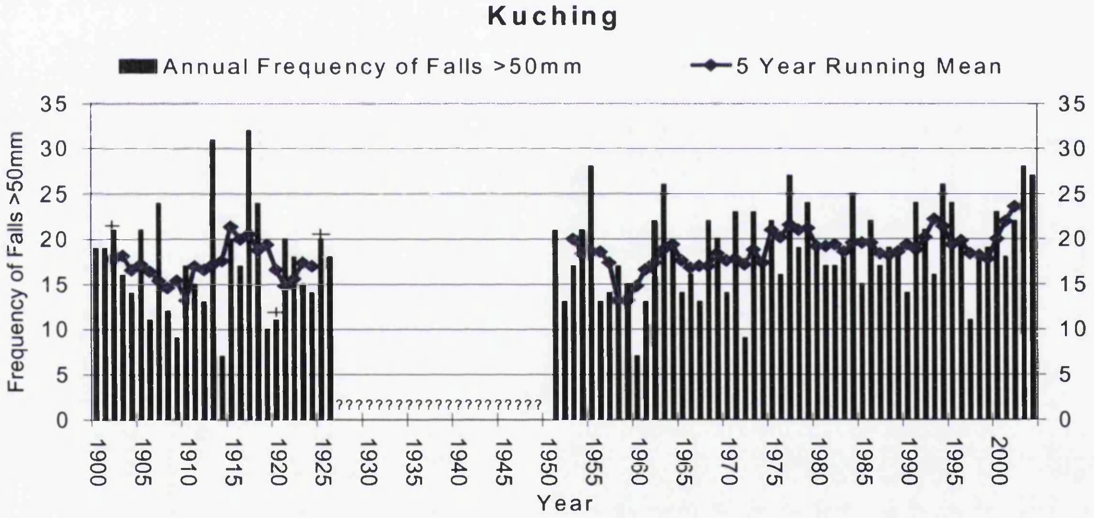
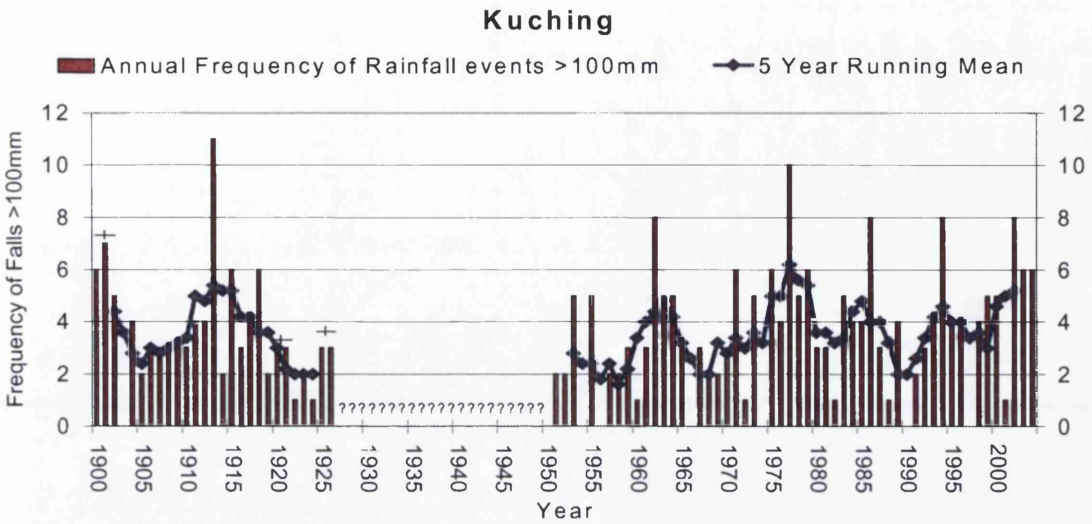
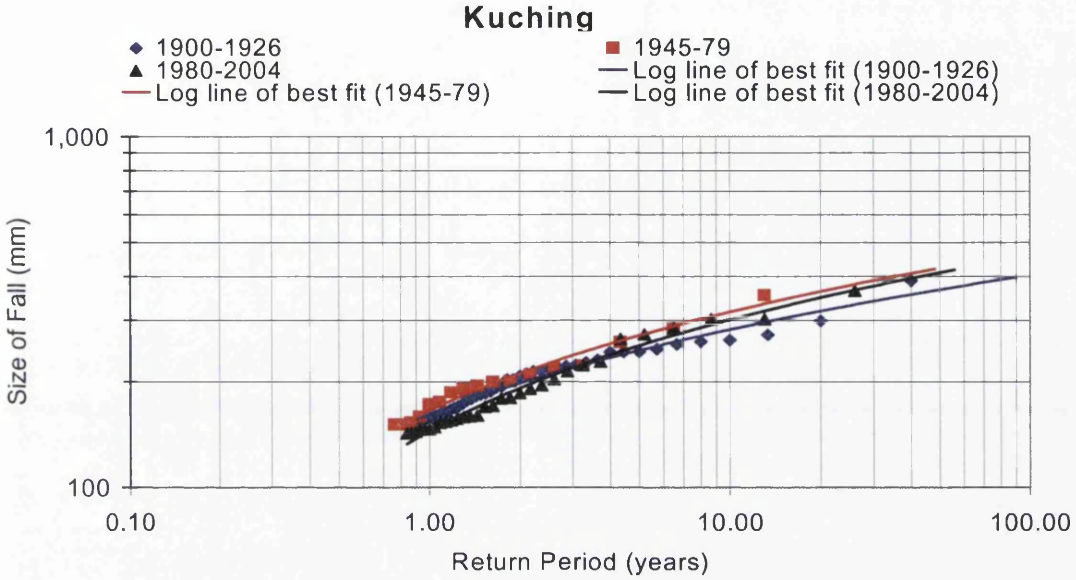


Figure 5.24. *Annual frequency of falls ≥ 100mm at Kuching.*



Extreme value analysis (Figure 5.25) shows that the middle period, between 1951 and 1979, had slightly shorter return periods for higher magnitude falls, due to some very large falls. The recent 1980-2004 period has longer return periods for very high magnitude falls than in the 1951-1979 period despite the frequencies of falls over 50mm and over 100mm seemingly having increased between the two periods (Tables 5.10 and 5.11). So although the frequency of large events increased the frequency of the very largest falls seems to have decreased, again a similar pattern to many of the stations previously covered in this chapter.

Figure 5.25. *Extreme Value Analysis of daily rainfall events at Kuching.*



Changes in seasonality of large rainstorms over the duration of the record appear to have been mostly minor (Figures 5.26 and 5.27). October and November both showed increases in the average monthly frequency of 50-99mm falls from 0.8 to 1.4 and 0.8 to 1.3 falls per month between 1900-1926 and 1980-2001 respectively. In May there has also been a large increase from 0.5 per annum in 1900-1926 to 1.0 falls in 1980-2004 (Figure 5.26). For falls over 100mm (Figure 5.27) the only substantial change occurred in February, in which the frequency fell from nearly 1.0 during 1900-1926 to 0.7 falls per annum during 1980-2001.

Figure 5.26. *Changes in monthly frequency of 50-99mm falls for different periods at Kuching*

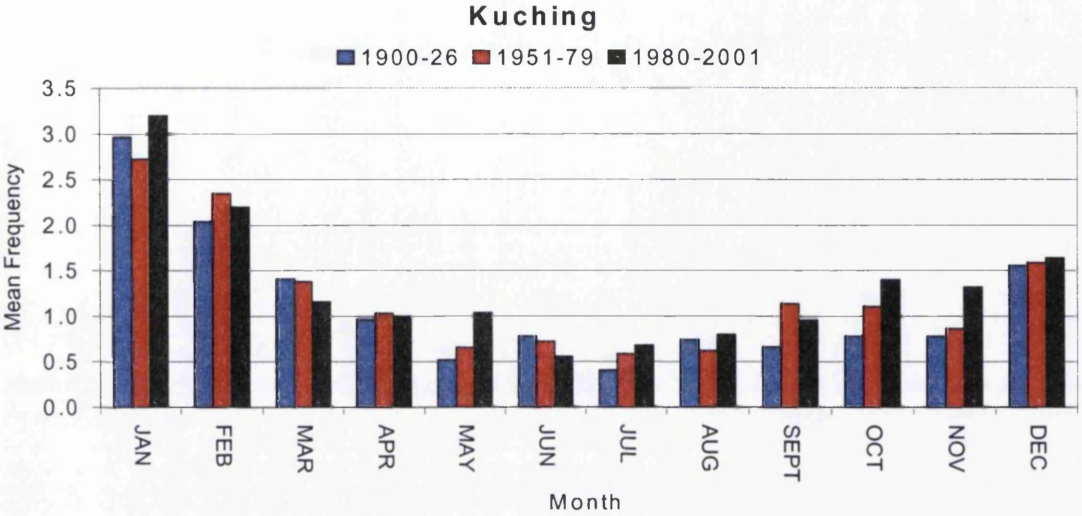
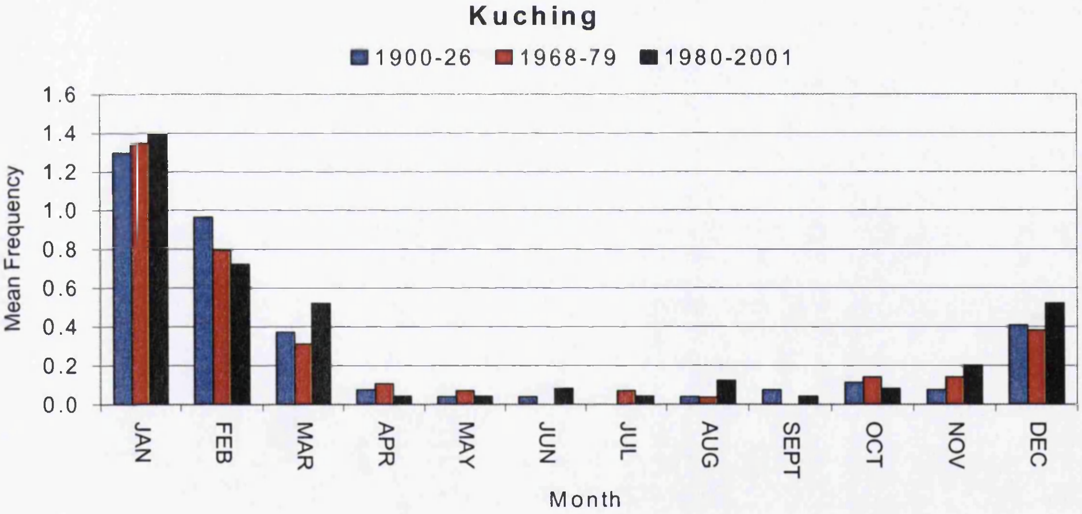


Figure 5.27. *Changes in the monthly frequency of falls ≥100mm for different periods at Kuching*



5.3 SUMMARY OF THE MAGNITUDE-FREQUENCY OF LARGE DAILY RAINFALL

The main findings from analysis of the magnitude and frequency of heavy daily rainfall in Malaysian Borneo are that:

1) Keningau and Kuching show an increase over the records in the frequency of falls over 50mm. Kota Kinabalu has seen a reduction in the frequency of falls over 50mm. All other stations show no statistically significant increase or decrease in the frequency of either falls over 50 or 100mm.
2) There has been no overall increase in the variability of extreme rainfall events since the records began. This is due to the high variability in extreme rainfall events in the early period of the record.
3) High and low frequencies of extreme rainfall events often mirror the pattern of high or low annual rainfall, as for example at Kudat between 1989 and 1993.
4) The period between 1949 and 1979 had shortest return periods for the highest magnitude falls even though the frequencies of falls over 50mm were greatest during another period.

CHAPTER 6:

RECONSTRUCTIONS OF RAINFALL AT DANUM VALLEY

6.1 INTRODUCTION

This chapter investigates the rainfall at Danum Valley and attempts to use a surrogate station with the closest correlation to the record at Danum to extend the record back. Reasons for extending the record at Danum are: 1) Danum is interesting scientifically in relation to droughts and rainfall changes in the primary rainforest; and 2) there is an absence of interior Sabah rainfall stations, so Danum provides an opportunity to look at rainfall patterns at an interior location in Sabah. The only other interior station with a long record is at Keningau. However, Keningau is an atypical station due to its surrounding topography. The mountains to the north and west create a rain shadow meaning Keningau has an unusually low annual rainfall for the region. The low correlation between Keningau and Danum shows that Keningau is not a typical inland site.

In order to reconstruct the record of rainfall at Danum Valley, stations with the best relationship between annual values in the period covered at Danum need to be identified. Once these are identified their equation for the reduced major axis regression is used to reconstruct the past annual rainfall record.

6.2 CORRELATIONS OF THE RECORDS FROM SABAH WITH THE DANUM RECORD

Correlations between the 19-year record of annual rainfall at Danum Valley and corresponding annual rainfalls at other stations in Sabah are shown in Table 6.1.

Table 6.1. *Correlation coefficients between annual rainfall at Danum Valley and at other stations in Sabah for the period 1986-2004.*

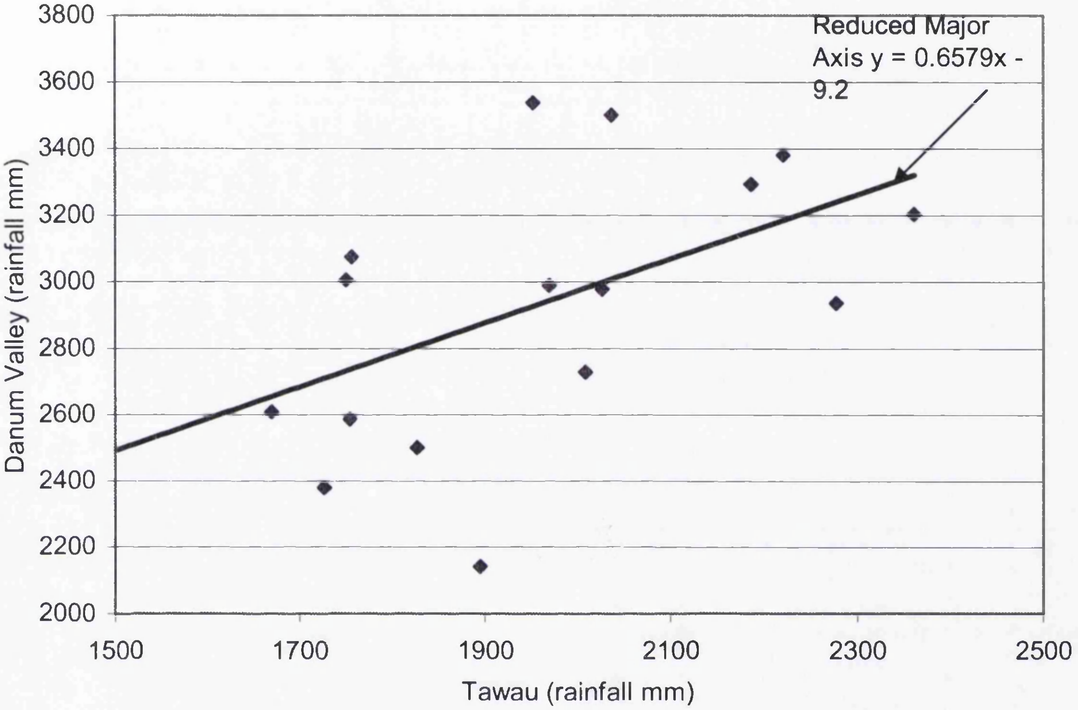
Station Name	r value	Significant at 5% level	Significant at 1% level
Tawau	0.69	YES	YES
Sandakan	0.41	YES	NO
Lahad Datu	0.41	YES	NO
Kudat	0.58	YES	YES
Kota Kinabalu	0.48	YES	NO
Keningau	0.33	NO	NO

Table 6.1 shows that at all stations except Keningau there is a statistically significant relationship at the 5% level between the annual total for this station and Danum, but at many of the stations the relationship is relatively weak. Only at Tawau and Kudat is it statistically significant at 1% significance level. Predictions of past conditions at Danum therefore are made using the records of rainfall at Tawau as it shows the strongest relationship.

6.3 RECONSTRUCTION OF ANNUAL RAINFALL TOTALS AT DANUM VALLEY USING THE REGRESSION EQUATION OF THE REDUCED MAJOR AXIS (RMA)

Figure 6.1 shows the correlation between annual rainfall at Danum Valley and Tawau. The reduced major axis equation shown on the graph was then used to predict values at Danum using the data from Tawau. The vertical residuals of Figure 6.1 represent the differences between the predictions of annual rainfall at Danum, using the RMA equation from the correlation with Tawau (the reduced major axis line), and the actual annual totals that were recorded at Danum Valley.

Figure 6.1. *RMA for the relationship between annual rainfall at Danum and Tawau ($r=+0.69, R^2=46.8$)*



In most years predicted values deviate by no more than a few hundred millimetres and only a few vary by over 500mm from the actual values. In the context of tropical rainfall, such a deviation is not very much. With the close similarity in the annual totals using the equation of reduced major axis, it seems appropriate that the record at Danum can be extended using this equation. The record at Danum will now include all years for which there is a recorded annual total at Tawau.

Figure 6.2. *Annual rainfall at Danum a) for 1909 to 1985 calculated using the reduced major axis equation between annual rainfall at Danum and Tawau and b) using actual data for Danum for 1986-2004.*

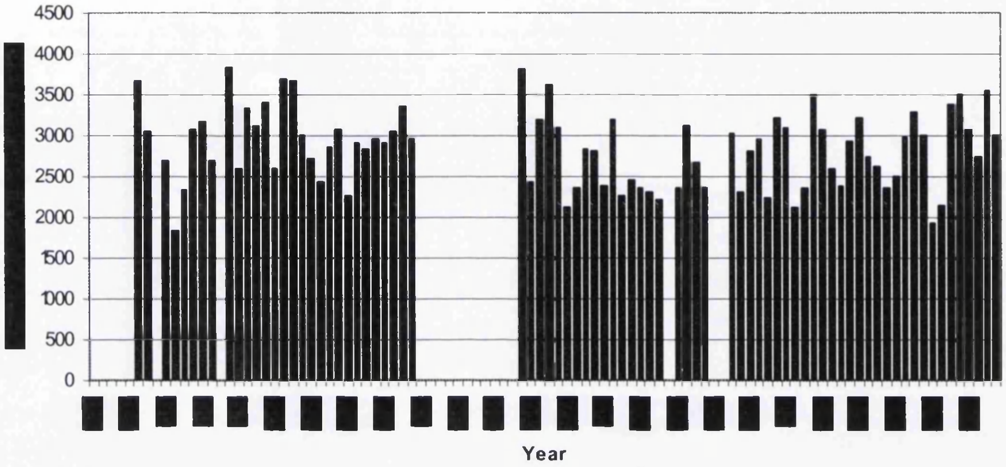


Table 6.2. *Mean and standard deviation for the predicted rainfall at Danum combined with actual data for 1986-2004.*

	Mean	S.D
19010-40	2966.4	455.3
1940-79	2688.8	461.1
1980-2004	2849.2	465.1

The reconstructions of annual rainfall at Danum from the RMA equation at Tawau produced a record of rainfall shown in Figure 6.2. Dry years were predicted to have been 1914, 1957 and 1982. In the period of measurements made at Danum Valley the major ENSO years of 1997 and 1998 were also very dry. Especially wet years are predicted to have occurred in 1910, 1920, 1922, 1924, 1926, 1927, 1939, 1952, 1955, and 1984. In addition the actual record showed very wet years in 1995, 1999, 2000 and 2003. The driest period of the record occurs in the middle period between 1957 and 1983. During this period there were fewer years with high annual totals and more years with low annual totals. Table 6.2 shows the predicted average rainfall from different periods in the record (1910-1940, 1940-1979 and 1980-2004).

The averages values were created from the predictions using Tawau's record and a combination of predicted and actual values in the 1980 to 2004 period. Clearly it is very similar to the table created for Tawau with the period in the middle of the record containing the lowest annual mean. The most recent period from 1980 to 2004 and the period from 1910 to 1939 have the highest means, with very similar averages.

6.4 CORRELATIONS BETWEEN THE RAINFALL VALUES IN THE MONSOON SEASONS AT DANUM AND THOSE IN OTHER STATIONS THROUGHOUT SABAH.

Table 6.3 *Correlations between the northeast and southwest monsoon rainfall values at Danum and at other stations in Sabah.*

Station Name	Northeast (r value)	Significance at 5% / 1% level	Southwest (r value)	Significance at 5% level
Tawau	+ 0.71	YES / YES	+0.23	NO
Sandakan	+0.62	YES / YES	+0.25	NO
Lahad Datu	+0.54	YES / NO	+0.11	NO
Kudat	+0.57	YES / YES	+0.28	NO
Kota Kinabalu	+0.59	YES / YES	+0.22	NO
Keningau	+0.65	YES / YES	+0.11	NO

Table 6.3 shows that the correlations between rainfall totals at Danum and the other stations are stronger for northeast monsoon rainfall (from November to March). At the 5% significance level, all stations show a significant positive relationship and only Lahad Datu is not significant at the 1% level. Tawau has the strongest relationship between rainfall totals in the northeast monsoon. Keningau has quite a low correlation between its annual totals and those at Danum, but looking solely at the rainfall amounts in the northeast monsoon shows a much higher correlation

coefficient and this is the station with the second strongest relationship. The relationships between all the stations in Sabah and Danum rainfall totals in the southwest monsoon are very weak and non-significant.

6.5 DISCUSSION

Correlations between annual rainfall totals in Danum Valley and stations throughout Sabah were generally not very strong. The strongest correlations between annual totals are for the stations of Tawau and Kudat. Surprisingly the record at Kudat shows more resemblance to the record at Danum despite the stations of Lahad Datu and Sandakan being located much closer to the Danum Valley Field Centre. The strongest correlation was the record at Tawau situated on the south-east coast of Sabah.

Relationships between rainfall at Danum and stations in the rest of Sabah are much stronger for northeast monsoon rainfall than for southwest monsoon rainfall. This can be explained by the strength and rainfall mechanisms of the two monsoon seasons. The northeast monsoon here is significantly stronger than the southwest monsoon; during the southwest monsoon when the winds are less dominant and less strong, localized convectional thunderstorms are dominant affecting one station and increasing its monthly values considerably, whereas other stations may not receive any rain during that day. During the stronger northeast monsoon season, rainfall is more regional in nature associated often with westward-moving disturbances in the northeasterly flow.

The implications of having a record showing a similar pattern to that at Tawau is that perhaps in the past the rainforest at Danum was subject to long-duration drought events of similar duration and intensity to those at Tawau. The drought frequency and intensity record at Tawau shows predominantly short dry periods of 1-2 months, but occasionally longer droughts and rare very long droughts of 5-6 months (Walsh 1996). Keningau is the only other interior station with a long record covered in

Walsh (1996) that can be compared to Danum, especially during the northeast monsoon season where the correlation coefficient is statistically significant at the 5% level. At Keningau very long droughts of 5-8 months duration have occurred 6 times in the 76 years of record analyzed in Walsh's study. At Danum Valley Field Centre, the longest dry period in the 19-year record is of 4 months duration in 1992, the same duration was experienced at this time at Tawau.

Chapter 7: DISCUSSION

7.1 INTRODUCTION

This chapter first summarises the key findings with reference to the aims and hypotheses outlined in Section 1.7. Annual and seasonal rainfall changes and inter-annual variability are examined with reference to temporal and spatial patterns, along with the changes in the rainfall in the monsoon seasons. Changes in large rainstorms are investigated, focussing on the temporal and spatial pattern of changes in magnitude and frequency and also seasonal changes in their frequency.

Relationships between ENSO events and annual and seasonal rainfall totals are explored in different regions within Malaysia, along with other possible influences on annual totals, seasonal totals and high magnitude rainfall events. Relationships between sea surface temperature data at locations in the South China Sea and Straits of Malacca are explored when examining links between rainfall changes and ENSO changes.

The results shed new light on findings given in the IPCC (2001) report and those that use GCMs to predict changing rainfall patterns in the tropics and Malaysia. Some implications of the results for both the human and natural environments are then considered and also for the future prediction of climate in Malaysia.

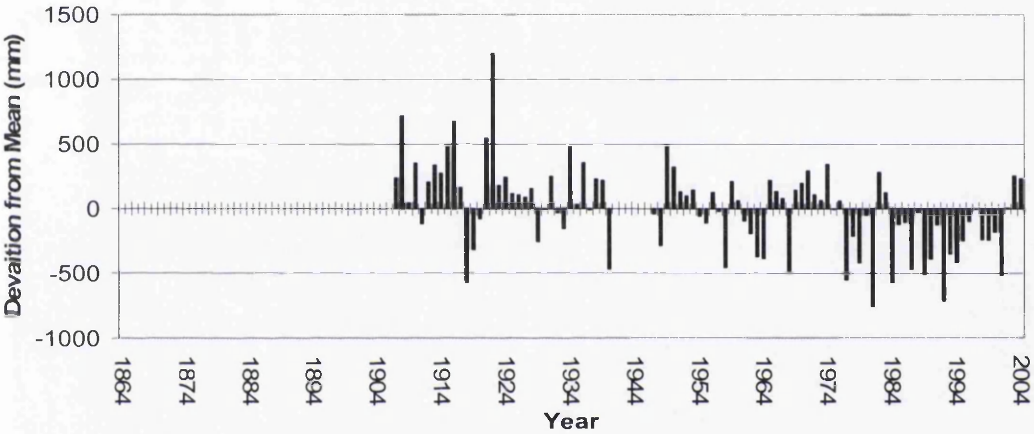
Finally, deficiencies in the techniques and approaches used in this study are considered and some suggestions are made for future studies in this area of research and the geographical region.

7.2 PATTERNS IN ANNUAL AND SEASONAL RAINFALL AND SPATIAL SIMILARITIES

Decreases in annual rainfall since the mid-1970s have occurred at many northern stations in Peninsular Malaysia and at stations on the west coast of Sabah in

Malaysian Borneo. On the Peninsula, the four most northern coastal stations (Alor Star, Kota Bharu, Bayan Lepas, and Parit Buntar), on both east and west coasts, show reductions in mean annual rainfall over the course of the record from pre-1941 to the 1946-1979 period, and also from the 1946-79 to the 1980-2004 period. These reductions total 220mm (Parit Buntar) – 471.6mm (Bayan Lepas) (10-17% reduction) between the first and last periods. Figure 7.1 below illustrates the pattern of decreases at northern stations using Alor Star as an example.

Figure 7.1. *Illustration of the change in rainfall in the north of the Peninsula using Alor Star as the example.*

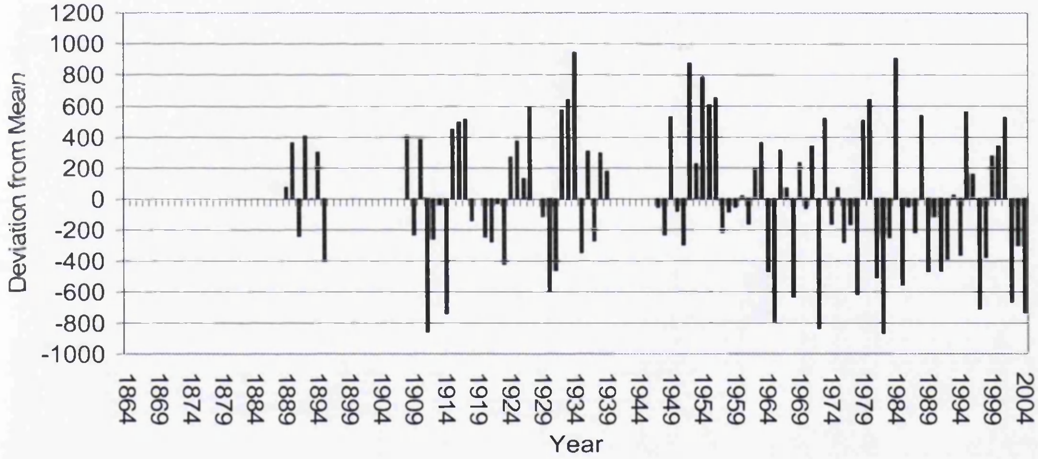


Reductions are clearer on the west coast than the east coast, as a recent increase (since the late 1990s) in rainfall on the east coast is absent or less marked on the west coast. Farther south down the west coast, decreases in annual rainfall are smaller (220mm-258.7, 10%-11% reduction at Parit Buntar and Malacca) but still evident at all stations except Sitiawan.

A similar pattern in annual rainfall is evident on the west coast (Labuan and Kota Kinabalu) and north (Kudat) of Sabah and at some stations (Miri and Bintulu) in Sarawak, all of which have seen an increase in the frequency of years with annual rainfall well below the mean since the mid-1970s. All these changes are backed up by the change in mm per year shown in the additional analysis (Tables 4.17 and 3.16).

The five-year running means at Kudat (north coast), Kota Kinabalu (north-west coast) and Bintulu (west coast) are steady despite a recent increase in very dry years. Figure 7.2 illustrates this pattern using Kota Kinabalu's deviation from the mean graph. At other stations in Borneo decreases in annual rainfall are either less pronounced or absent. Sandakan (east coast) shows an increase in dry years towards the end of the record, but the period of lower rainfall (from 1985-93) is much shorter than at other stations. Neither Tawau in eastern Sabah or Kuching in the far south of Sarawak show an increase in the frequency of dry years at any point after the 1970s. The increase in variability is expressed well in the additional analysis (Tables 3.16 and 4.17) showing coefficient of variations have increased at the stations mentioned to some high values for the tropics, especially Kudat.

Figure 7.2 *Annual deviation from mean at Kota Kinabalu illustrating the increase in high negative deviations from the mean annual total.*



A very recent rise in the 5-year running mean of annual rainfall at many stations inland and on the east coast of the Peninsula occurs from 1998 at some stations and earlier at others (1988 at Kuala Lumpur and 1994 at Cameron Highlands, both rising over 400mm in a few years) and since the late 1980s at Macritchie Reservoir, Singapore. At Keningau, in central Sabah, a similar rise has occurred since 1993. These increases, however, have earlier precedents in the record and may just be part of the naturally oscillating rainfall cycle seen throughout the records.

The higher year-to-year variation in annual rainfall on the east coast of Peninsular Malaysia than in other areas is associated with the very high variability of the dominant northeast monsoon rain. The reduction in annual rainfall from the mid-1970s to the 1990s coincides at most stations across Malaysia with the decline in northeast monsoon rain, whether rainfall at the station is dominated by the northeast monsoon or not. The rise in annual rainfall noted in the 1990s at many central and eastern peninsula stations is also a result of rising northeast monsoon rainfall, especially at Kuala Trengganu and Kota Bharu.

At Alor Star and Kota Bharu, the two stations farthest north on the Peninsula, there has also been a reduction of over 300mm between the pre-1941 and most recent periods in southwest monsoon rainfall. This reduction is significant at the west-coast station of Alor Star where it is the dominant rain bearer. The decrease in southwest monsoon rain also affects the west coast of Sabah at Labuan and to a lesser extent Kota Kinabalu. Webster and Yang (1992) and similarly Xie *et al.* (1998) suggested that ENSO events influence the inter-annual variability of the Southeast Asian southwest monsoon, by causing a delay in the start of the southwest monsoon.

7.3 <u>HIGH MAGNITUDE DAILY RAINFALL EVENTS</u>

This study is one of very few studies that have analysed long series of daily rainfall data from the tropics. Most studies considering changes in the magnitude-frequency of large rainfall events use GCMs to predict future changes, not actual changes that are occurring now due to global warming and climate change. Those that have used data from tropical locations have often had to work with shorter rainfall series (e.g. Manton *et al.* 2001).

In Malaysian Borneo there is little evidence of any long-term increase in the magnitude or frequency of extreme rainfall events in recent years compared with earlier periods of the rainfall series stretching back to the early twentieth century. Although peaks and troughs are evident at most stations, the majority show no statistically significant changes in overall magnitude or frequency either in the graphs of the frequencies of falls greater than 50 and 100mm or in the extreme value analysis. The only marked changes indicated by the analysis are summarised below.

The inland station of Keningau in Sabah showed a slight increase in the frequency of rainfall events over 50mm (from an average of 4 in the period 1940-79 to 5.2 from 1980-2004 (Figure5.6)). There was a statistically significant (5% level) reduction in the mean frequency of 50mm rainfall events at Kota Kinabalu (north-west coast) of 1.9 rainfall events per year from 13.2 in 1908-1940 to 11.3 in 1980-2004. At Kuching (south-west coast of Sarawak) falls >50mm increased by nearly 3 falls a year from an average of 17.3 falls per annum in 1900-1926 to 20 falls per annum in 1980-2004. Throughout the duration of the record, temporal patterns in the frequency of falls at Kuching varied differently to those in more northerly Sabah.

Chapter Five showed that in some cases changes in the line of return period in the extreme value analysis graphs were different to those of threshold frequencies. At Keningau, for example, although the analysis of threshold frequencies of >50mm falls showed an increase in frequency, the extreme value analysis showed that the more recent period had a longer return period for high magnitude falls due to the effect of more very high magnitude falls from 1953-1979 (6 falls >100mm in 1953-1979, 3 in 1980-2004). At Kudat, although the mean frequency of falls >100mm were higher in 1980-2004, return periods of higher magnitude falls were shortest in the period 1957-69 as a result of some very large falls during this period. The same is true at Sandakan. Tables 5.6 and 5.7 show the period 1953-1979 to have had the lowest mean frequencies of both falls >50mm and >100mm. Extreme value analysis, however, takes into account some of the very high magnitude falls that occurred in this period, meaning that for high magnitude falls over 200mm this period (1953-1979) has the shortest return period.

Generally, frequencies of high magnitude falls loosely follow the annual totals, especially the years with very high frequencies or very low frequencies coinciding with years of very high and very low annual totals.

This study of extreme daily rainfall events extends the record used by Walsh and Leong (2003) and demonstrates that the higher variability in frequency in recent years, noted by them at some stations, is not unprecedented in the record as variability was also high in the period from 1906 or 1908 to 1940. Also the recent increase in variability suggested by them was not found at some stations. For example, variability of falls greater than 50mm has decreased significantly at Kuching where the mean standard deviation of annual frequency fell by 2.3 events from 6 events in 1900-1926 to 4.2 in 1980-2004.

Although changes in variability have followed a 'high-low-high' pattern at Kota Kinabalu, (with variability starting high at the start of the record, lower in the middle and higher at the end) there has been overall a slight decrease in the variability of 0.8 falls per year between 1908-1940 and 1980-2004 from 4.8 events to 4 events.

Year-to-year variability in the frequency of falls greater than 100mm shows different temporal patterns to that of >50mm falls. At Kuching and Sandakan there has been little change over the record. Kudat has had a similar pattern to the frequency of falls greater than 50mm. Kota Kinabalu has the greatest variability in the middle period (1949-1980). Thus the record of falls greater than 100mm appears to be more random, not following any region-wide patterns and with big differences between stations.

7.3.1 CHANGES IN THE SEASONAL DISTRIBUTION OF HIGH MAGNITUDE RAINFALL EVENTS AND RELATIONSHIPS WITH SEASONAL TOTALS

In this section variations in the frequency of high-magnitude rainfall events in different months of the year are examined.

At Kota Kinabalu (NW coast) the reduction in 50-99mm falls in 1980-2004 compared with in 1908-1940 results mainly from 50% reductions in frequency in May and June, from 1.2 and 1.4 falls per month to 0.6 and 0.7 respectively. Large reductions also occurred in December (0.4 falls per month) and January (0.3 falls per month). The reductions in December and January appear to be linked to an extension of the dry season at Kota Kinabalu, which results from reduced convection caused by low-level divergence resulting from winds paralleling the coastline.

At Keningau (inland) the increases between the periods 1953-1979 and 1980-2004, seen in the frequency of falls greater than 50mm (in contrast to the nearby coastal station at Kota Kinabalu), result mainly from large increases in frequencies of falls between 50 and 100mm in February (by 0.2 events per month), June (0.2), September (0.4) and October (0.3). The increase in high-magnitude rainfall events at Keningau appears to be related to changes in annual rainfall as both high-magnitude events and annual rainfall rose from 1990. The increase in high-magnitude rainfall events coincides with a marked increase in rainfall of the transition month of October (Figure 3, chapter 4.2). Also all months from June to September (southwest monsoon) have seen an increase in the frequency of falls between 50 and 100mm. Tawau (east coast) has seen similar increased frequencies of high magnitude falls between 50 and 100mm in the southwest monsoon months (June, August, September and October). The month of October is bordering the southwest monsoon period as the transition usually occurs at some point in October.

At Kudat (north coast) there has been a marked decrease in the mean frequency of falls between 50 and 100mm in the month of October from 0.7 to 0.3 between the early (1906-1940) and recent (1982-2004) periods of the record in conjunction with a decrease in monthly rainfall in October. The large increase in falls between 50 and 100mm seen in November is reflected also in the increased rainfall in November and over the whole northeast monsoon season. The same applies to the increase in falls greater than 100mm in December. It seems that the decrease in extreme precipitation events in October and increase in November and December may indicate that: (1) there has been a change in circulation at this time as perhaps the Northeast monsoon winds arrive later and do not now occur in October as much as in the past; and (2) that the northeast monsoon winds are stronger than previously.

In contrast, however, Sandakan (east coast) has seen reductions in >50mm falls between the periods 1906-1940 and 1980-2004, more especially in the northeast monsoon months January (from 2.1 to1.4 falls per month), February (1.5 to 1.1), March (1 to 0.6) and in November (1.7 to 1.1). Decreases in falls over 100mm over the same period also occurred in the months of January and February, by 0.4 and 0.2 falls per month respectively. This decrease is paralleled by a significant decrease in rainfall totals in the months of the northeast monsoon. Only December showed a slight increase in the frequency of 50-99mm falls by 0.3 falls per month. The other two months which showed an increase in the mean frequency of falls between 50 and 100mm were July and August, which both rose by a mean of 0.4 falls in the month.

The fact that Kudat experienced an increase and Sandakan a reduction in heavy fall frequency in the northeast monsoon might suggest a change in the wind direction (e.g. north to northeast) of the northeast monsoon in relation to local topography.

Kuching's 50-100mm rainfall events have increased since 1980 in July to November, most notably in October and November where totals rose from 0.8 in the period 1900 to 1926 to 1.4 and 1.3 respectively for the period form 1980 to 2001. This increase could be a result of increased cold surges coming down on strong northeast monsoon winds during these months, but this pattern was not shown at the north-facing station of Kudat. The contrasting changes to Kudat could be linked to changes in the latitudinal position of the ITCZ in October as Kuching and Kudat are at different latitudes. The transitional month May has also seen a doubling in frequency from 0.5 to 1.0 falls per month at Kuching. Thus both October and May transition months exhibit the highest increases.

7.4 EXPLANATIONS RELATED TO THE SOUTHERN OSCILLATION INDEX AND SEA SURFACE TEMPERATURES

As Tables 3.2 to 3.14 and 4.2 to 4.16 in Chapters 3 and 4 respectively demonstrated for individual stations, the link between ENSO events and dry years does not appear to be as strong in northern Borneo and especially Peninsular Malaysia as that reported by Leighton (1984) in East Kalimantan. At most stations, only 'very strong' ENSOs tended to produce anomalously low annual rainfall and less strong ENSOs in most cases were as likely to be associated with anomalously high as with anomalously low annual rainfall.

Correlations between the SOI and annual rainfall at most stations in Malaysia were found to be non-significant or weak (Chapters 3 and 4), a finding that is contrary to the general predictions that El Niño and La Niña events regulate the abnormally dry and wet years in South-East Asia. However, to some extent this is to be expected as ENSO events and the SOI do not coincide with calendar years and therefore annual values can be misleading, as often the end of an ENSO event is marked by anomalously high rainfall in La Niña conditions in the second half of an ENSO year. There is, however, a clear association between stronger ENSO events and large negative deviations from the mean annual rainfall, especially in the more recent period of the record, which has a much stronger relationship between SOI and annual rainfall.

Interactions between sea surface temperatures (SST) in the South China Sea and winds are complex across much of Malaysia and it seems that it is only the strongest ENSO events that produce region-wide negative rainfall anomalies. Therefore the weather of the region during ENSO events is more complex than the traditional Pacific-related anomalies. There is a strong negative correlation between the SOI and sea surface temperatures of the South China Sea. This is a result of the warmer seas (a result of reduced NE monsoon winds being less effective in pushing upwelled cold water from the north) in moderate/weak ENSO events, such that northeast monsoon rain is often increased above the mean as the warm moist air rises over the land. Reduced wind can also be advantageous for the formation of convectional thunderstorms inland (Subramaniam, 2004). This can be observed in the graph in Figure 7.3 which shows that when SOI is low (during ENSO events) sea surface temperatures are often warmer off the east coast of

Peninsular Malaysia. This is more significant during the winter monsoon months (Figure 7.4).

Figure 7.3. *Comparisons between annual sea surface temperatures off the east coast of Peninsular Malaysia and annual SOI.*

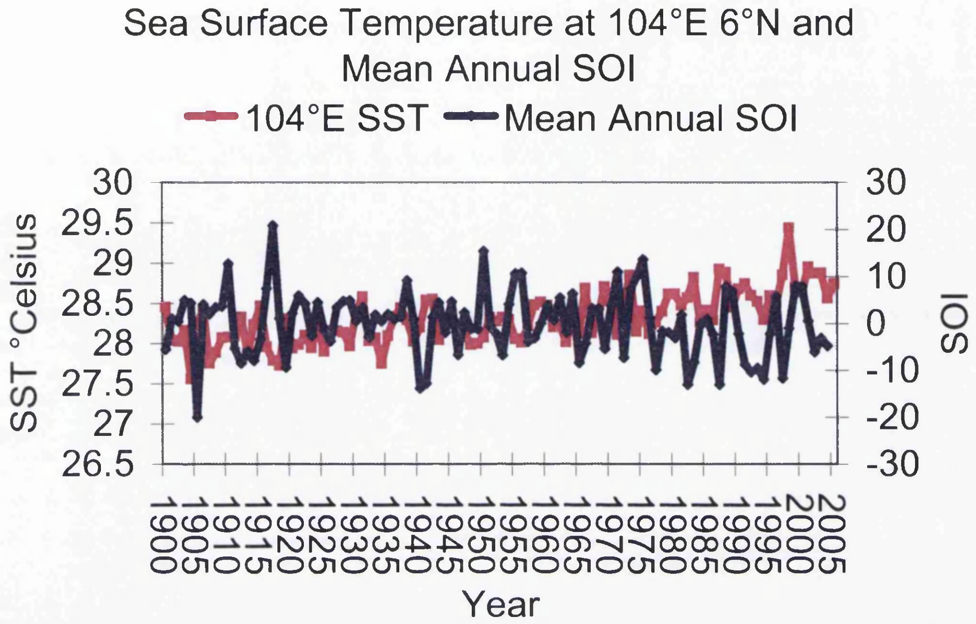
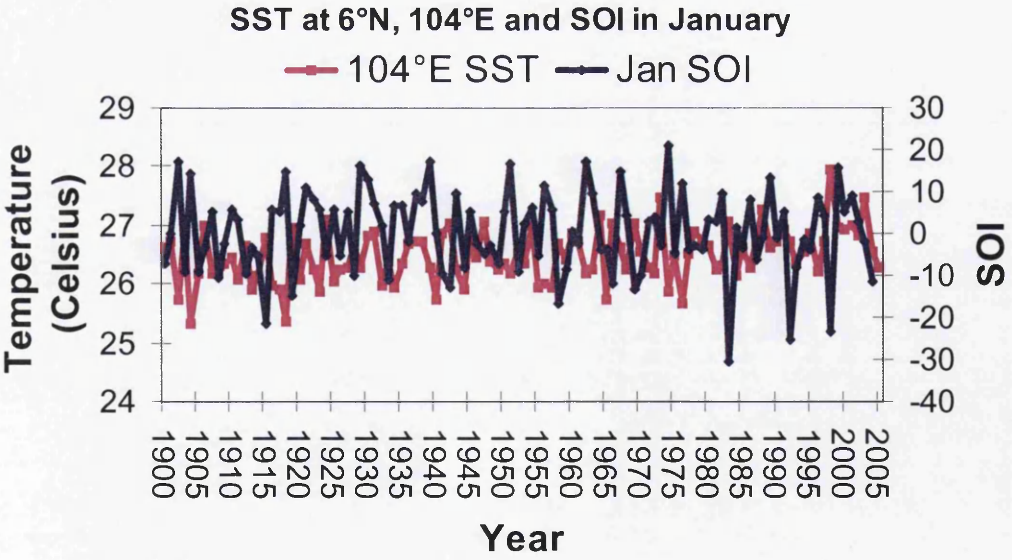


Figure 7.4. *Sea surface temperatures off the east coast of Peninsular Malaysia and SOI in the month of January.*



These graphs help to explain the poor correlation between SOI and annual rainfall on the Peninsula and possibly why there is a better correlation in Sabah as the sea surface temperatures are less affected by the warmer conditions in ENSO years. The inverse correlation between sea surface temperature and SOI at 104°E in January is strong with $r = -0.42$, whereas correlations at the other two sites at 98°E and 114°E are weak and not significant.

When comparing sea surface temperatures at locations off the Peninsula and coast of North Borneo with annual and seasonal rainfall totals, there is again a poor correlation between the two. This suggests that the effect of different sea surface temperatures is just another condition that complicates the region's rainfall.

These findings and the inconclusive data in Tables 3.2 to 3.14 and 4.2 to 4.16 support the theory of Harger (1995), who suggested, based on research in the Philippines and Indonesia, that each ENSO event leaves a different signature on different areas and that no two events are the same. Predictions of drought events from the SOI are therefore more difficult to predict, as the link is not straightforward.

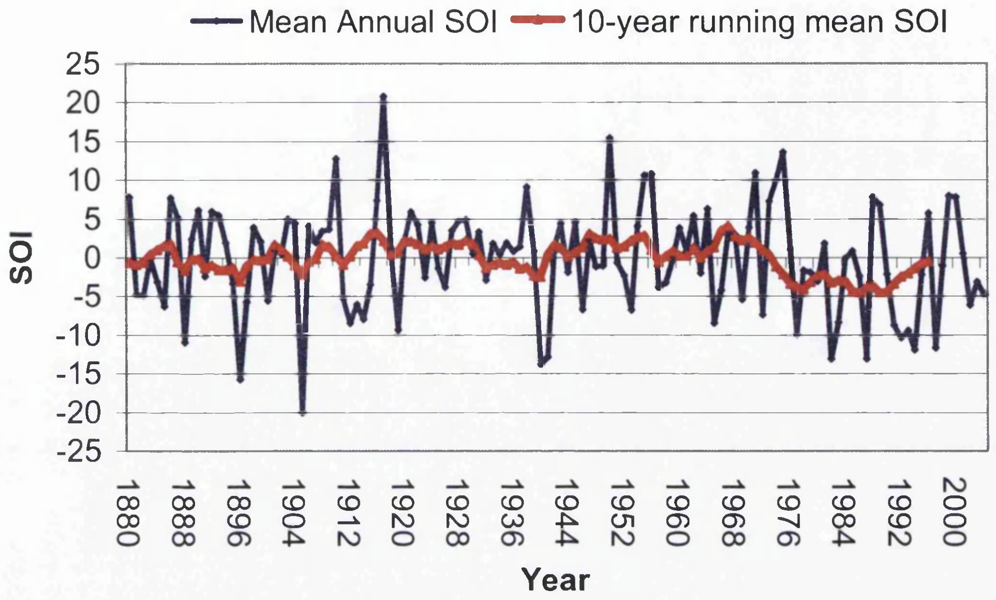
Many of the locations in Peninsular Malaysia show that during weak and moderate El Niño events rainfall totals are often similar to or above the mean, in contrast to the expectation that the colder waters from the Pacific might affect the region (Tables 3.2 to 3.14). In the strongest ENSO events, dry conditions do prevail over the majority of Malaysia. Thus the tables show that in the strong and very strong events a much greater proportion of years experience below-average annual rainfall.

The northern and eastern coasts of Sabah and Sarawak react in a different way to ENSO events. Winds in the northeast monsoon season here do not come from the warmer waters of the western South China Sea, but from water off the east coast, which is more vulnerable to the cool sea surface temperatures affecting the Western Pacific during ENSO events. This is why there is a stronger correlation between annual rainfall totals and ENSO events in Malaysian Borneo than the Peninsula. This may also be because of the anomalously stable atmospheric conditions over the Malaysian region in such strong ENSO years, when the atmospheric stability factor overrides the SST factor in the Peninsula region.

A possible explanation for the increased rainfall at many interior stations and dry conditions at west coast stations throughout the 1990s is that during ENSO events trade winds and hence monsoon wind strengths are reduced (Webster *et al.* 1998). The consequences of this could be a reduction in orographic rainfall in coastal regions as the onshore winds are less strong. Inland with less wind there may be the opportunity for more convectional rainfall leading to inland stations having higher totals. As no wind strength data were used in the analysis, it can only be assumed that the different SOI conditions create different wind strengths, directions and conditions. This constitutes yet another feature that would need to be included into the model for predicting and explaining rainfall changes in the region.

Stations with long-term records show that dry years follow a similar pattern to ENSO magnitude-frequency as indicated by the temperature anomalies in the equatorial Pacific since 1890 (McPhaden, 1999) and the SOI record. Annual rainfall totals in Malaysia were high during the late 19th century, low until the 1920s and then there was a period between the 1920s and 1960s which had relatively few years with low annual totals. This pattern roughly mirrors ENSO events, with few at the end of the 19th century, some strong events from the beginning of the 20th century to the 1920s and then a relatively long period up until the 1970s that was relatively ENSO-free (Walsh, 1996). Figure 7.5 gives the annual and 10-year running mean of SOI and shows that from the 1970s SOI is reduced, a period when many stations showed a reduction in annual rainfall.

Figure 7.5 *Mean Annual SOI and 10-year Running Mean SOI*



One of the limitations of this study lies in the use of the correlation between calendar annual rainfall totals and annual SOI conditions. The correlation between annual rainfall totals and annual SOI conditions does not represent the true story of the SOI and its effect on annual rainfall. When taking an average SOI value for the year it evens out any periods of large but opposite deviations that could occur in the same year. For example an ENSO event could begin in one year and continue as a moderate or strong event until the middle of the next year. Then in the rest of the year La Niña conditions could prevail making the average much lower. The rainfall deficit may be significantly below the average in the early part of the year during the ENSO periods, but could then rise well above the mean if the La Niña conditions prevail. So the use of annual totals and annual SOI can hide the influence of any significant, strong El Niño/La Niña events.

This issue was followed up in the additional analysis sections of Chapters 3 and 4. (Sections 3.5 and 4.8) and correlations were carried out for a July to June years additional to calendar years. This analysis yielded much stronger correlations in Malaysian Borneo, but no real difference on the Peninsula. This supports what was said earlier about the effect of the SSTs in the South China and the northeast monsoon have during ENSO periods on rainfall in the region (weaker ENSO events often create an increase in rainfall on the Peninsula).

ENSO events therefore seem to explain some but not all of the variation in the annual and seasonal rainfall totals at some stations. The well documented increase in ENSO frequency and intensity in the period since the 1970s (Cheang, 1987; Wang, 1995) may partly account for the increase in very dry years in this study of Malaysia. This increase has been attributed to warming in the Pacific, changing the characteristic evolution of the El Niño onset, with events becoming more frequent, intense and persistent (Wang, 1995; Marengo, 2004). It does appear, however, that it is only in stronger ENSO conditions that the rainfall is affected significantly in the region, especially the northern areas. Changes in the rainfall record appear also to be secular with phases of wetter and drier conditions, only partly modulated by the ENSO cycle.

7.5 COMPARISONS WITH OTHER STUDIES, AREAS AND GCMs

7.5.1 CHANGES IN ANNUAL AND SEASONAL RAINFALL

Decreases in seasonal rainfall totals could be explained (as already mentioned in 7.4) by changes in the strength of the monsoon winds. The strength of the trade or monsoon winds was an explanation given by Marengo (2004) in northern Amazonia, suggesting that a drier climate (and deficient rainy season) since 1976 was associated with weakened Atlantic Northeast Trade winds over the region. The wetter period in Amazonia from 1950-1975 had enhanced Northeast Trade winds. Similarly the decline in precipitation in the Caribbean at the beginning of the 20th century was associated by Kraus (1955) with a decrease in the trade-wind circulation and corresponding decrease in evaporation, and efficiency of the evaporation-precipitation cycle.

The increase in dry season length that appears to be occurring since the mid-1970s in northern Peninsular Malaysia has also occurred in other locations in the tropics.

At Barro Colorado Island in the Panama, with two distinct seasons of either wet or dry, there has been an increase in the intensity of the seasonal droughts between December and April (Condit, 1998; Condit *et al.,* 1996).

In tropical Southeast Asia, Xu *et al.* (2004) found a strong and statistically significant relationship between SOI and rainfall. Previously Quah (1988) looking at the effect of SOI on seasonal rainfall in the northeast monsoon in Malaysia found a strong positive relationship between the SOI and northeast monsoon rainfall in Borneo, a moderate to weak relationship in west Peninsular Malaysia and no relationship in east Peninsular Malaysia. Results from the present study show a similar pattern with weak, but statistically significant, positive relationships at a few stations in Borneo, but no relationship between the two variables over most of Peninsular Malaysia.

The increase in the frequency and intensity of dry years found at many stations in the 1980-2004 period of this study does not necessarily indicate unprecedented levels in the past at locations across Malaysia. Walsh (1996) and Walsh and Newbery (1999) found that in Sabah droughts of equal or greater intensity to those of 1982-83 and 1997-98 took place in 1902 and probably also 1877-78.

7.5.2 CHANGES IN HIGH MAGNITUDE RAINFALL EVENTS

The IPCC (2001:section 2.7.2.2) report predicted an increase in the frequency of intense rainfall events throughout the tropics with global warming. Alexander et al. (2006) have also reported a general increase globally, but the changes are much less spatially coherent than changes in temperature. This study, however, shows an increase in the frequency of high magnitude falls only at two stations (Keningau and Kuching) whereas a reduction in frequency is evident at Kota Kinabalu. These findings are similar to the results found by Walsh and Leong (2003), but this study found the size of reduction in the mean frequency of 50mm rainfall events at Kota Kinabalu in 1980-2004 to be even greater (1.9 falls per year) when compared with 1908-40 than with 1946-79. Walsh and Leong (2003) also found that most stations in Borneo and Kota Bharu on the northeast coast of the Peninsula had experienced a recent increase in the year-to-year variability of large falls. This increase has been confirmed in this study, but in Borneo the earlier pre-1942 period had equally high year-to-year variability. This could also be the case at Kota Bharu, but the length of records prior to the Second World War is too short to be conclusive.

Walsh (1998b) also reported a reduction in the frequency of high magnitude daily rainfalls in the Caribbean since 1959, and much lower magnitude-frequency compared with the late nineteenth century. In the Caribbean high and low frequencies of high magnitude falls coincided with the epochs of high and low annual rainfall totals. This relationship was also found in Niger by Shinoda *et al.* (1999), and in central Sudan by Walsh et al. (1988) where it coincided with the decline in rainfall since 1965. Such clear patterns did not emerge for Malaysia, though the northernmost Peninsular Malaysian stations may conform.

Manton *et al.* (2001) found that generally across Southeast Asia there had been a recent reduction in frequency of extreme rainfall events, with each extreme event having an impact on annual totals and trends. Findings from this thesis do not support either a regional reduction or a regional increase in extreme rainfall across Sabah or Sarawak. Only at Kota Kinabalu do results suggest a decrease in frequency of high-magnitude events.

At Keningau the increase in falls of 50-100mm in all months from June to September suggests an increase in the frequency of high-magnitude falls in the southwest monsoon season. Unlike at the other stations, it appears that the increase in SW monsoon rainfall is in agreement with predictions of an increase in rainfall within the southwest monsoon (Anderson *et al.*, 2002).

7.5.3 COMPARISONS WITH GCM PREDICITONS

The IPCC (2001) report suggested that the recent increase in the precipitation in high latitudes has been balanced by a decrease in the tropics and sub-tropics. This may be true across the more northern regions of Malaysia as the drying trend from the 1970s illustrates, but some stations saw a rise in annual rainfall from the early 90s and at other stations a rise in annual rainfall since 1998. It is too early to tell whether this is a short-lived rise in a generally decreasing trend or whether it marks a new longer-term phase of wetter climate as experienced at other times in the records.

The reduction in southwest monsoon rainfall that has occurred in the north of Malaysia could be a result of increased snow cover and cooler temperatures over Eurasia in winter. This theory that low SW monsoon rainfall is linked to lower temperatures and increased snow cover over Eurasia in the previous year has been suggested by many studies (Kumar *et al.,*1999; Anderson *et al.*, 2002; Gupta *el al.,* 2003; Meehl, 1994) This decrease in rainfall in the southwest monsoon is in contrast to predictions by Anderson *et al.* (2002) who predicted that with increases in temperature in the North Atlantic and an increase in greenhouse gases the Indian monsoon should increase in strength. An increase in the rainfall in the summer monsoon between June and August was also predicted by Vein of the Malaysian Meteorological Service, **(www.apcn21.net/common/download.php?filename=sem/tan.pdf).**

The Asian Development Bank (1994) suggested that in Sarawak, using a model based on a doubling of CO_2 , there would be a significant increase in rainfall during the northeast monsoon months of January and February. This has not materialized yet in either seasonal totals or high-magnitude rainfall events.

7.6 IMPLICATIONS OF RESEARCH FINDINGS

7.6.1 IMPLICATIONS FOR FUTURE PREDICTION OF MALAYSIAN CLIMATE

In the future in Malaysia, especially when using models to try and predict the future of the climate in this area under different conditions, it is important that the complex relationship between SOI, monsoon wind strength, and SST of the South China Sea is considered. Models must allow for spatial variation in impacts on rainfall during ENSO events and differing effects with the intensity of ENSO episodes. This is relevant for annual, seasonal and high magnitude rainfalls. Also, as climatic changes in Malaysia vary greatly locally, so the scale of GCMs must be fine enough to allow for differences in models between west, east and central Peninsular Malaysia.

7.6.2 IMPLICATIONS FOR THE HUMAN AND NATURAL ENVIRONMENT IN MALAYSIA

During the strong 1997-98 ENSO event, water shortages were experienced across most of Malaysia and the domestic water supply was disrupted in Kuala Lumpur from April to September in 1998 (Shaaban and Sing, 2003). With increased ENSO magnitude-frequency, water shortages like these are likely to become more common and possibly more severe. The water shortages will also probably affect the agriculture of the region. Changes could affect reservoir levels and also river flows.

An increase in frequency of very dry years will have serious implications for the rainforest regions, especially the large areas of lowland evergreen rainforest of Borneo, and particularly if such droughts have not been experienced in the past (Walsh, 1996). The effect of droughts can lead to a significant change in the forest structure with fewer very large trees and a large proportion of trees with a similar age and size (see Walsh, 1996).

It was suggested by Walsh (1996) that a rare and prolonged drought may have a more severe impact on the rainforest, with immediate canopy tree deaths as the species may be unable to survive the soil water stress. In areas where the droughts are episodic, the species may already have attributes that benefit them in times of drought, or during the recovery from the drought.

The recent increase in the years with rainfall significantly below that of the mean annual rainfall is having a magnified effect on the rainforests in comparison to earlier periods of low rainfall. This is because extensive logging in Sabah's forests is increasing the fire risk during droughts, and has arguably lowered the threshold of drought level at which fire occurs in adjacent primary rainforests (Walsh, 1996).

On the other hand, Walsh (1996: 404) also suggested that the drought pattern in Sabah was part of a longer-term “episodic drought climate”. Rainforests in the region may be able to withstand this pattern of episodic drought, in which the drought-free periods are necessary to maintain the dipterocarp canopy population and to provide the sapling dipterocarps to ensure recovery from the next episodic drought.

CHAPTER 8: CONCLUSIONS

In this chapter the key findings of the thesis are summarised, some limitations are highlighted, and some ideas for future research suggested.

8.1 KEY FINDINGS

8.1.1 ANNUAL RAINFALL

1. Reductions in annual totals and an increase in the frequency of dry years have been influencing regions of northern Peninsular Malaysia, the west coast of Sabah, Brunei and the northwest coast of Sarawak since the mid-1970s.
2. The four northernmost stations on the Peninsula (Alor Star, Kota Bharu, Bayan Lepas, and Kuala Trengganu) showed reductions in annual rainfall of 375.7mm – 524.9mm between the pre-1942 and 1980-2004 periods (Table 3.1).
3. Not at not all stations in the regions mentioned in point 1 were the reductions in annual rainfall statistically significant at the 5% level. This was due to very high rainfall in the recent years (1999 onwards) and some very wet years in the latter period (1980-2004) between the dry years (Sabah and Sarawak CVs on Table 4.17).
4. The majority of stations throughout Malaysia experienced a marked, and intense dry period (of varying lengths) at some time between the mid-1970s and the mid-1990s. At the same time SOI was generally low.

8.1.2 SEASONAL RAINFALL CHANGES

1. In the far north of the Malay Peninsula (Alor Star and Kota Bharu, Figures 3.7 and 3.20), there has been a statistically significant (5% level) decrease in

southwest monsoon rain. At both locations the rainfall decreased by at least 200mm over the period of the record.

2. Northeast monsoon rainfall exhibits high year-to-year variability across the entire region whereas the southwest monsoon is much less variable.
3. Changes in the intensity of the northeast monsoon season were found to be usually responsible for the main changes in annual rainfall at north and east coast stations and also inland stations. Southwest monsoon rain changes are responsible for the majority of annual changes on the western coasts.

8.1.3 HIGH MAGNITUDE RAINFALL CHANGES

1. The daily rainfall series and extreme value analysis in Malaysian Borneo show there has been no region-wide pattern of change in the frequency or magnitude of intense daily rainfall events. Therefore it cannot yet be concluded that global warming is having a significant effect on the overall frequency or magnitude of extreme rainfall events. There are some exceptions at individual stations.
2. At Kuching (South-west Sarawak) the mean number of falls greater than 50mm over the three periods (1900-1926, 1951-79 and 1980-2004) increased from 17.3 to 20 in a year (Figure 5.10). Since 2000, the frequency of falls >50mm appears to have increased here (Figure 5.23).
3. Keningau (Inland Sabah) saw an increase in the mean annual frequency of falls greater than 50mm from 4.0 to 5.2 between the periods 1940-1979 and 1980-2004.
4. Kota Kinabalu (North-west Sabah) showed a decrease in the mean annual frequency falls over 50mm (Figure 5.1) from 13.2 in 1908-1940 to 11.3 in 1980-2004 (the only change in high-magnitude falls significant at 5% level).
5. Generally when there is a high frequency of high-magnitude rainfall events annual rainfall totals are high. Similarly, periods of low frequencies of high-magnitude rainfall events often correspond to low annual rainfall totals.

8.1.4 CHANGES IN VARIABILITY OF HIGH MAGNITUDE RAINFALLS.

This study has shown that the increase in year-to-year variability evident at a few stations in high-magnitude daily rainfalls in Malaysia since the 1980s are not unprecedented as similarly high levels characterised the pre-1942 period. The only two stations to show large changes in variability are:

1. Kota Kinabalu, which shows a slight decrease in variability (from 4.8 to 4 falls over 50mm) over the record (Table 5.1).
2. Kuching in contrast, experienced a decrease in the standard deviation of the frequency of >50mm falls 2.3 between the periods 1900-1926 and 1980-2004 (Table 5.10).

8.1.5 SEASONAL HIGH-MAGNITUDE RAINFALL CHANGES

1. There are no spatially conclusive patterns. In general, the frequency of high-magnitude rainfall events of 50-100mm have shown a strong relationship with the seasonal rainfall totals. However the largest falls (>100mm) at each station appear to be less strongly related to annual and seasonal rainfall totals.
2. On the northwest coast of Sabah at Kota Kinabalu, frequencies of falls of 50-99mm in the southwest monsoon months of May and June, fell from 1.2 and 1.4 falls per month (1908-41) to 0.6 and 0.7 respectively (1980-2004). The winter monsoon months January and December also saw lower reductions (of 0.5 and 0.4 falls per months respectively between 1908-41 and 1980-2004) (Figure 5.4).
3. Sandakan has also seen decreases in 50-99mm rainfall events in the northeast monsoon occurring in November, January, February and March (0.4-0.5 fewer falls a year between 1906-41 and 1980-2004). Falls over 100mm have also decreased during January and February. Slight increases in 50-99mm falls in southwest monsoon frequencies occurred in July and August (0.4 and

0.3 falls increase respectively between 1906-41 and 1980-2004) (Figures 5.17 and 5.18).

4. The rise in the frequency of 50-99mm falls at Keningau in 1980-2004 was achieved in part by a rise in February falls by 0.3 falls per year (Figure 5.8).
5. At Kudat the decrease in October frequency of 50-99mm falls has been compensated by increases in November and December, suggesting that the commencement of the northeast monsoon season occurs later in the year (Figure 5.12).
6. Farther south, in contrast, Kuching has had a marked increase in high-magnitude falls (50-99mm) in July to November (especially the months of October and November) and also in May. These constitute the transition periods of the year (Figure 5.26).

8.1.6 LINKS TO ENSO CYCLE CHANGES, SEA SURFACE TEMPERATURES AND OTHER FACTORS

1. The temporal fluctuations in annual rainfall at the majority of stations, especially those with longer rainfall series, are only in part produced by changes in the frequency and intensity of ENSO events.
2. Changes in rainfall variability follow the pattern in the frequency and intensity of ENSO events at Kota Kinabalu, Sandakan, Tawau and Kudat, with high variability occurring during periods of increased ENSO activity.
3. Although many stations show weak correlations between SOI and annual rainfall, this may reflect in part the non-correspondence of calendar years with ENSO-phase periods. Additional analysis using, July to June years, increased levels of correlation in Malaysian Borneo, but made no difference on the Peninsula.
4. There is a much closer relationship between rainfall and **intense** (four months below -15 SOI) ENSO events. In strong El Niño events all stations experience annual totals below the mean, by over 500mm at some stations.

5. Weaker ENSO events can result in wetter conditions in part due to the complex interaction with the South China Sea and surface wind conditions that create regional differences. Rainfall over the Malay Peninsula often responds in a different way to that of northern Borneo as a result of the effect of the temperature of the South China Seas during ENSO events compared with non-ENSO years.
6. Sea surface temperatures off the east coast of the Peninsula have a high negative correlation with SOI, especially in the northeast monsoon months. The warmer seas that often accompany ENSO events are another variable that makes the rainfall in the region difficult to predict. It can create wetter years but can also lead to no change.
7. The reduction in the annual rainfall since the 1970s seen at many stations is largely the result of a reduction in northeast monsoon rainfall.
8. Reductions in strength of the northeast monsoon during ENSO events can reduce the rainfall in coastal regions but produce more convectional activity inland. This pattern seems to be occurring in Peninsular Malaysia. Thus inland stations in Peninsular Malaysia and Sabah have seen a recent rise in annual rainfall.
9. Changes in the strength of the monsoon winds may constitute the principal reason for changing annual rainfall totals especially the reduction in rainfall during the northeast monsoon season.

It is evident that the cycle of ENSO events has a large effect on the rainfall across Malaysia, but the complicated reaction of rainfall in the region must be affected by other factors (e.g. wind strength, direction, ITCZ position) creating local variations. Changes in extreme daily rainfall events, however, vary depending on the strength of an El Niño or La Niña event, but more importantly in Malaysia, on the location of the station in relation to the distance from the South China Sea and the Pacific which act differently and to some extent independently during El Niño events.

8.2 IMPLICATIONS FOR FUTURE CLIMATIC CHANGES

The main finding of this thesis is that models predicting rainfall throughout Southeast Asia and especially in the regions surrounding the South China Sea need to include more detailed projections of changing sea temperatures in the South China Sea during ENSO events. The different temperatures in the South China Sea create regional differences in sea surface temperature and rainfall across the region that are far more complicated than the Pacific model of ENSO events.

The reduction in rainfall during the southwest monsoon in northern Peninsular Malaysia is contrary to the predictions of many models and studies (e.g. Anderson *et al.,* 2002; Gupta *el al.,*2003) that envisage an increase in the strength of the southwest monsoon with global warming. The reduction in southwest monsoon rainfall could be a result of a later start to the monsoon season related to ENSO conditions. The increase in the frequency and severity of ENSO events since the late 1960s could be reducing the duration of the southwest monsoon. Annual rainfall totals will become more dependent on the more variable northeast monsoon and thus in years when the northeast monsoon fails there will be more severe rainfall deficits in this region. This is of major concern as regards water resources and the environment of the region. The dry season could also be extending in the northwest of Sabah with decreasing rainfall in the NE monsoon months and decreasing high-magnitude rainfalls.

The IPCC 2001 report and studies by Groisman *et al.* (1999) and Kharin and Zwiers (2000) suggest that global warming will lead to an increase in the frequency of high rainfall events in the tropics. However, other studies contradict or are unable to provide support for such an increase. Frequencies have often followed annual totals and many tropical locations show signs of a reduction in annual rainfall totals, especially from the mid-1970s through to the 1990s (Walsh, 1998b; Shinoda *et al.,*1999). As suggested by Alexander *et al.* (2006) although there seems to be a general increase globally in precipitation extremes changes are very spatially incoherent.

Increases have been noted in high-magnitude rainfall events in the southwest monsoon months of June and July at Keningau and June, August and September at Tawau. This supports predictions which suggest an increase in rainfall amounts during a southwest monsoon (Zveryaev and Aleksandrova, 2004). This increased rainfall may be due to increased convection because of decreased strength of the SW monsoon (especially inland).

Many of the predictions involving changing frequencies in high magnitude falls and changing annual and seasonal rainfall totals may be long-term and such changes may not have taken hold yet.

Besides changes in sea surface temperatures and ENSO events, there are other influences that could create local rainfall changes: (1) wind direction changes in relation to the local topography and coastal alignment could be a very important factor in rainfall totals as a result of coastal mountain uplift and coastal alignment (for example at Kota Kinabalu a slight change in the direction could result in an increase in the dampening of convection due to winds paralleling the coast); (2) changes in the upper air circulation; (3) changes in the strengths of the two monsoons (decreasing strengths could result in more convective activity over land, increasing strengths could change the balance of rainfall at coastal locations and override any land-sea breezes that can create rainfall in coastal locations); and (4) changes in the seasonal positions and activity of the ITCZ.

8.3 EVALUATION POINTS AND FUTURE WORK

Segregation of the data set into periods (pre-1942, 1943-79 and 1980-2004) for analytical purposes has been a concern in this thesis. The data series indicate different natural boundaries in the rainfall record that could be used to identify and separate periods for analysis. However, as these periods vary between stations, objective regional analysis and inter-station comparisons would have been difficult.

Future studies into the changing climate of this region need to examine in more detail the links between heavy rainfall events, annual and seasonal rainfall totals, and ENSO events. Improved relationships between SOI and rainfall might be achieved using monthly (rather than annual) values of SOI as the redefining of the 'year' to July to June rather than Jan-Dec which have made a notable difference to correlations in Malaysian Borneo.

With the use of additional data, such as sea surface temperatures from the South China Seas, Indian Ocean and Straits of Malacca and also the strengths and precise direction of the monsoon winds, links could be explored between the changing rainfall patterns and any changes in wind strength and direction and sea surface temperature. This can establish in greater detail whether these features (SST and wind strength/direction) are the principal causes of changes in rainfall patterns in the region. Predictions of the effect of different strengths and durations of ENSO events might then be possible for specific regions in Malaysia in more detail.

Currently, the Malaysian Meteorological Service provides a rough prediction of expected rainfall for the next few months of the year on their web site. With better analysis of the climatic conditions surrounding and including Malaysia during ENSO years these predictions could become more detailed and help plan for future water shortages in the region, and also for other impacts of drought, such as fire risk. Planners could then use these forecasts to reduce drought impacts on the human and natural environment in Malaysia.

It would also be worthwhile to carry out similar analysis with more stations in Peninsular Malaysia in order to build up a better picture of the effect of ENSO events and other factors on the different regions of the Peninsula.

Pre-1960 daily rainfall data from the Peninsula may be available from archives in the Malaysian Meteorological Service in Kuala Lumpur spanning periods back to the early 20th Century similar to those found in Sabah. These may help to extend the period of analysis of changes in daily rainfall magnitude-frequency. Regional Gazettes from the Peninsula could provide some of this information. At the Sabah branch of the Malaysian

Meteorological Service in Kota Kinabalu daily and monthly rainfall information for other stations across Sabah could be used for more detailed analysis of the rainfall pattern in the region. With longer series across Malaysia the changing pattern of high magnitude falls can be examined in much greater detail and connections could be made between the high-magnitude rainfall events and the factors influencing them.

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