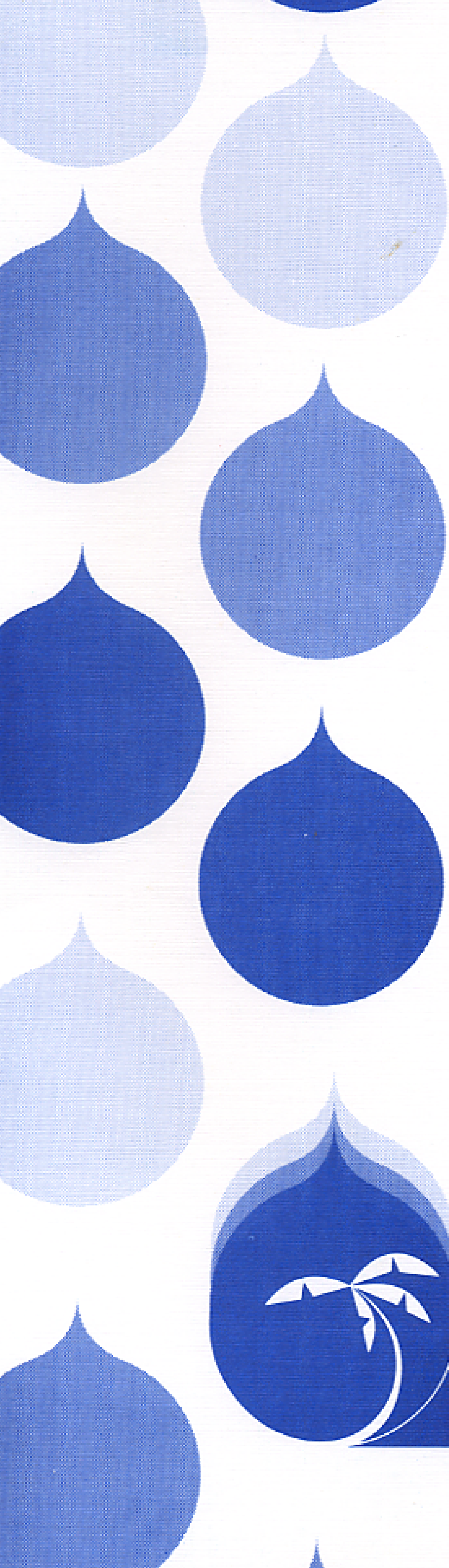

METEOROLOGICAL FACTORS ASSOCIATED WITH DROUGHT ON GUAM

by

Mark A. Lander

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WATER AND ENERGY RESEARCH INSTITUTE
OF THE WESTERN PACIFIC
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Abstract

The rainfall on the island of Guam, at 13.5°N, 144.8°E, has a pronounced temporal asymmetry: roughly one-third of the annual rainfall accumulates during the dry-season months of January through June while two-thirds of the annual rainfall accumulates during the wet-season months of July through December. The mean annual total rainfall on Guam varies from about 85 inches (2170 mm) at drier spots to a little over 100 inches (2540 mm) in wetter areas.

Despite the relatively high annual rainfall amounts, Guam suffers deleterious effects of drought almost every dry season: dessication of grasslands, desiccation and defoliation of some species of trees, significant reduction of streamflow, and significant reduction of the water level in many of Guam's wells. Wildfires burn thousands of acres during many dry seasons. Every three or four years, the dry season is especially dry and prolonged. Wildfires and stress to local crops are thereby aggravated and prolonged.

The seasonal asymmetry of the rainfall on Guam is governed primarily by the seasonal shift of the monsoon trough and its associated zone of monsoonal cloudiness. During January through June, northeasterly tradewinds blow on Guam. In a tradewind regime the air is subsiding, clouds lack vertical development, and rainfall comes in the form of sporadic tradewind showers. During the rainy season, the monsoon trough becomes active in the western North Pacific, allowing deep convective clouds, meso-scale convective cloud systems, and tropical cyclones (with their torrential rains) to affect Guam.

The interannual variation in the rainfall on Guam is strongly affected by episodes of El Niño/Southern Oscillation (ENSO). Exceptional dryness during the dry season and a prolongation of dryness into the early part of the rainy season are an effect that ENSO episodes have upon Guam and all of Micronesia.

As with many meteorological phenomena in the tropics, persistence also plays a role in the variation of rainfall on Guam. Oddly, the persistence works only one way. If the dry season of a particular year is very dry or very wet, the wet season of that same year tends to be likewise; however, if the wet season of a particular year is very dry or very wet, the condition of the following dry season is just as likely to be the same as the opposite.

Through use of the relationship of Guam's rainfall to ENSO and the one-way persistence of dry-season anomalies into the wet season, some regression equations were developed which have some skill (when applied to the dependent data sets) at predicting Guam's annual and seasonal rainfall totals. A 77% success rate was thereby achieved in a simple forecast of whether the dry-season rainfall would be above or below normal. Given the evolution of, and accurate forecasts of, the ENSO indices and, also, given the ongoing rainfall anomalies, skillful forecasts (6 to 12 months in advance) of the annual and seasonal rainfall totals on Guam may be possible.

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Introduction

The island of Guam is the largest and southernmost of the Mariana Islands -- a chain of high islands of volcanic origin in the tropical western North Pacific (WNP). The topography of the northern half of Guam differs greatly from that of the southern half. The southern half of the island is rugged (see Fig. 1); a ridge of high ground runs north-south close to the western coast. The slope of the terrain is very steep from this ridge line to the western coast; from the ridge line towards the eastern coast the slope is more gradual. The highest point on the ridge, which is known as Mount Lam Lam in the indigenous island language, rises to 401 m above sea level. Streams have cut deep valleys into the elevated terrain of southern Guam.

In the simplest of terms, the topography of the northern half of Guam can be described as a limestone plateau, raised above the sea nearly 200 m in some places, which overlies rock of volcanic origin; it is karst topography replete with sink holes, limestone caverns, no permanent above-ground streams, and many natural springs of fresh water at the shore (which, along most of northern Guam, lies at the base of precipitous limestone cliffs). Groundwater occurs as a lens of fresh water floating upon underlying sea water within this limestone (Ikehara, personal communication).

Roughly 100 inches (2540 mm) of rain falls on Guam during the calendar year. Even though the island is quite small (535 km^2) and its mountains are relatively low (401 m or less) for a Pacific high island, distribution of rainfall on the island is significantly affected by the orography, and mean annual rainfall totals among recording stations on Guam differ by as much as 400 mm. Despite its relatively high annual rainfall, Guam suffers minor to severe deleterious effects of drought almost every dry season: Grasslands become desiccated, some species of trees defoliate, and there is a significant reduction of streamflow. Wildfires burn several thousand acres of grassland nearly every dry season. Potable water on Guam is obtained in the south by the damming of streamflow (Fena Lake) and by direct pumping of stream water (e.g., the Ugum River pumping station). In the north, fresh water is drawn from wells which tap the freshwater aquifer.

At a rate of about one year in four, the dry season is especially dry and prolonged. Problems with wildfires and stress to local agriculture are thereby aggravated. So far, the government of Guam has not had to impose mandatory water rationing, but at worst to recommend conservation. Mandatory water-hour restrictions and rationing have been imposed by the military in the past, however, because of shortages in the Fena Reservoir (Ikehara, personal communication). These more serious droughts are closely related to episodes of El Niño/Southern Oscillation (ENSO).

This paper examines the meteorological factors which are associated with long-term (six months to several years) fluctuations of the rainfall on Guam. Statistical properties of the time series of Guam's rainfall and the characteristics of the rain-producing weather disturbances of the wet and dry season are discussed first. The effects of ENSO upon the rainfall on Guam are then described. The next section examines the predictability of rainfall on Guam using indices of ENSO and information from the rainfall time series; prediction equations are developed. Finally, the effects of prolonged rainfall deficits on the flow of the Ugum River and the water level in a well which taps the northern aquifer are examined. The **Conclusions** section summarizes the findings.

Data

Data used in this study include:

1) Monthly rainfall values (Table 1) at the Weather Service Meteorological Observatory (WSMO) located at Taguac, Guam (shown on Fig. 1) for the period 1957-1992.

2) Annual rainfall statistics (Table 2) from the Naval Air Station (location is shown on Fig. 1).
3) Monthly values of the Southern Oscillation index (SOI) (Table 3) as computed by the United State's Climate Analysis Center (CAC) for the period 1957-1992.
4) Monthly values of the Sea Surface Temperature (SST) anomalies (Table 4) in the eastern equatorial Pacific as tabulated by the Japanese Meteorological Agency (JMA) for the period 1957-1992.
5) Individual monthly mean values of the streamflow (Table 5) at the Ugum River gage (location is shown on Fig. 1), and
6) Individual monthly mean values of the water level (Table 6) in well A-20 (location shown in Fig. 1).

Methodology

To examine the relationship between Guam's rainfall and ENSO, simultaneous and time-lag cross-correlations were computed between the annual, wet-season, and dry-season rainfall totals at the Taguac WSMO and the annual, wet-season, and dry-season averages of two ENSO indices (the CAC's SOI and JMA's SST). Time-lag auto-correlations of the rainfall time series and of the time series of the ENSO indices were computed and compared. Time-lag and simultaneous cross-correlations between rainfall and the trend of the ENSO indices were also computed.

In order to study the response of the streamflow and the groundwater level in well A-20 to variations in rainfall, the record of monthly rainfall at the Taguac WSMO was decomposed into three components:

1) An "annual cycle" (Fig. 2a)
2) A" trend" (Fig. 2b)
3) An "irregular" component (Fig. 2c).

The decomposition of the rainfall record into the "annual cycle," "trend," and "irregular" components was accomplished as follows:

1) A five-year moving average composed of the rainfall value of the month in question plus the values of the rainfall from that month during the preceding two years and the rainfall values from that month during the following two years is applied to the time series. The moving average for a particular month is given by the average value of the rainfall of the remaining three months after the lowest value and the highest value are discarded. The time series of the values of the moving average depict the "annual cycle."

2) The raw monthly rainfall values were compared to the values of the moving average for the respective month, and the differences constitute the monthly "anomalies." The monthly "anomalies" were then smoothed by using a five-month moving average comprised of the month in question plus the two preceding and the two following months. The three remaining monthly values, after the highest and lowest values were discarded, were averaged to yield the value of the "trend" for that month.

3) The difference between each month's "anomaly" and the value of its "trend" was deemed to be the "irregular" component of the time series.

A running accumulation of the "trend" of the rainfall was used to identify major drought periods and was compared with running accumulations of the anomalies of streamflow at the Ugum River gage and with the running accumulation of the water-level anomalies at well A-20.

Long-term deficits in all three aforementioned running accumulations are coherent and indicate the same drought periods; this is discussed more fully on page 13.

Meteorological Roots of Guam's Wet and Dry Seasons

Monthly rainfall distribution

At the Taguac WSMO, the mean annual rainfall during the period 1957-1992 was 101.84 inches with a standard deviation of 22.2 inches. The mean dry-season (January through June) rainfall was 31.63 inches with a standard deviation of 16.62 inches; the mean wet-season (July through December) rainfall was 70.21 with a standard deviation of 9.79 inches (see Table 7). The wet-season/dry-season split of the annual total is thus 69%/31%. The wettest annual total in the time series is the 165.91 inches recorded during 1976. The driest annual total in the time series is the 67.06 inches recorded during 1983. The wettest dry season (93.89 inches) occurred in 1976, and the driest dry season (9.59 inches) occurred in 1983. The wettest wet season (92.08 inches) occurred in 1962, and the driest wet season (50.50 inches) occurred in 1973 (see Table 7).

The lowest mean (4.06 inches) and median (2.66 inches) monthly rainfall occur in March. The highest mean monthly rainfall (15.17 inches) occurs in August; however, the highest median monthly rainfall (14.40 inches) occurs in September (see Table 8). Monthly rainfall values below one inch have occurred in February, March, April, May, and June (see Fig. 3). Monthly rainfall values above 20 inches have occurred in January, May, July, August, September, and October. The lowest value of the monthly time series of the rainfall at the Taguac WSMO is the reading of 0.50 inches during April, 1965. The highest monthly value is the 40.13 inches recorded during May 1976. The 40.13 inches of rainfall recorded during May of 1976 has resulted in the largest difference (2.47 inches) between the mean monthly and median monthly rainfall for any month (Table 8).

Weather systems affecting Guam

Guam is located in a region of the world that participates in the large-scale seasonal weather changes associated with the monsoons of the eastern hemisphere. During the wet season on Guam, a monsoon trough (a zone of low pressure which extends, in the mean, from the Asian mainland to the south of Guam; see Fig. 4a, b) is the major large-scale weather system which influences the wind, cloudiness, and rainfall.

In late spring, a low-pressure trough becomes established over South Asia. It extends from the deserts of Saudi Arabia eastward across Iran, Pakistan, Afghanistan, northern India, and southern China (Sadler *et al.*, 1987). Low-level winds are drawn into this low-pressure trough until the cooling of the Asian land mass in autumn leads to a rise in pressure over land and a consequent reversal of the large-scale low-level wind. The low-pressure trough of summer is known as the monsoon trough; the accompanying southwesterly wind flow feeding into it is called the Southwest Monsoon. In winter, the winds become northeasterly and are called the Northeast Monsoon. The effects of the monsoon winds upon the climate of India are well-known throughout the world: Life-giving rains come with the southwesterly winds of summer, and a long succession of dry days accompanies the northeasterly winds of winter and early spring. As with many large-scale atmospheric phenomena (for example, El Niño, 40-50 day oscillations, etc.), the attempt to generalize and standardize the definition of a monsoonal climatic regime has lead to some disparity among authors. In particular, the disparity concerning the appropriate delimiting elements has lead to a consequent disparity of opinion about what regions of the globe experience a monsoonal climate. According to Ramage's (1971) definition[1], the monsoon region lies between 35°N and 25°S and between 30°W and 170°E.

It is universally recognized that the large-scale periodic reversal of wind currents over the Indian subcontinent and in other regions commonly acknowledged to possess a monsoonal climate (e.g., northern Australia and sub-Saharan Africa) is due to the seasonal changes in the differential heating of continents and oceans. The sharp land-sea contrast contributes to the formation of the monsoonal low-pressure trough which stretches across south Asia in summer. A similar low-pressure trough, not associated with land-sea contrast, is often found over the tropical western North Pacific (WNP) in the summer. This trough, and its associated cloudiness, has often been called an Inter-tropical Convergence Zone (ITCZ), lumping it together with the east-west-oriented cloud band of the same name found in the central and eastern North Pacific and also in the tropical Atlantic. The low-pressure trough of summer in the tropical WNP, however, has several dynamic and kinematic features which sharply distinguish it from the ITCZ of the Atlantic and eastern North Pacific (see Atkinson 1971; Sadler 1975; and Sadler *et al.* 1987). In order to emphasize these differences -- in particular, the presence of deep moist southwesterly wind flow to the south of the trough axis in the WNP -- the low-pressure trough in the tropical WNP will herein be called a monsoon trough. The term ITCZ describes only those regions where the over-water low-pressure trough is collocated with the confluent asymptote of northeasterly and southeasterly tradewind currents. Much of Guam's wet-season rainfall is derived from cloud clusters and tropical disturbances which form in or near the monsoon trough of the WNP.

In long-term averages of low-level wind flow and sea-level pressure (see Sadler *et al.*, 1987), the monsoon trough of the WNP appears to extend eastward from the South Asian low-pressure trough and is accompanied by low-level southwesterly winds to the south of the trough axis. This over-water monsoon trough of the tropical WNP, though loosely anchored to the region of highest sea surface temperature, undergoes substantial migrations and major changes to its shape and orientation (unlike the monsoon trough over South Asia, which is firmly anchored by topography, and unlike the ITCZs of the eastern Pacific and the Atlantic, whose axes do not stray far from their mean-monthly positions). During the summer, the monsoon trough of the WNP may be found at a low latitude, such as 10°N, or at a high latitude, such as 25°N. It may be oriented NW-SE (the orientation of the mean trough); it may stretch 2000 km along an east-west line from the Philippines to the International Date Line; it may be found in a reverse (SW-NE) orientation; or it may not be present (as an episodic event) when easterly flow is found throughout the tropical WNP. Most of the time, the monsoon circulation of the western North Pacific takes the form of an elongated boundary between easterly winds to its north and southwesterly winds to its south (for example, see Fig. 5).

The general properties of the over-water monsoon trough of the WNP are as follows:

1) It is elongated east-west.
2) It is a nearly linear shear zone between easterly and southwesterly wind currents.
3) It possesses a nearly linear zonally oriented cloud band with most of the cloudiness and deep convective elements located to the south of the trough axis, and
4) It is the genesis site of most tropical cyclones of the WNP.

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[1] Ramage defines the monsoon area as encompassing 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 winds in at least one of the months exceeds 3 ms^{-1}; and 4) fewer than one cyclone-anticyclone alternation occurs every two years in either month in a 5° latitude-longitude rectangle.

By November, the axis of the monsoon trough moves southward from its mean summer location and extends further to the east. Westerly winds blow at low latitudes of the WNP, and a second monsoon trough axis develops in the southern hemisphere (at this time of year, these monsoon troughs are sometimes called, "near-equatorial troughs") (Fig. 4d). At the arrival of the boreal winter, the monsoon trough of the northern hemisphere disappears as northerly winds cross the equator and then turn to become the northwesterly flow of the Australian Northwest Monsoon. By early January, the monsoon trough axis of the southern hemisphere becomes firmly anchored across northern Australia eastward into the Solomon Islands (Fig. 4e). In addition, tradewind flow becomes firmly established over Guam, and the character of the cloudiness and rainfall on Guam (apart from late-season tropical cyclones) becomes that of a tradewind regime. Tradewind weather conditions dominate the dry season. By July, the tradewinds give way, in the mean, to light southeasterly flow (Fig. 6) as the monsoon trough of the WNP forms and begins to affect Guam's weather.

1) Dry season weather systems

The dry season on Guam is dominated by tradewinds. In a tradewind regime the air is subsiding, clouds lack vertical development, and rainfall comes in the form of sporadic tradewind showers. Although the rainfall in tradewind showers may be heavy locally, its normal character is brief spates of light to moderate rainfall. The rain of these showers is composed of smaller droplets than the heavy deluges produced by the deep convective clouds of summer. Even in the absence of organized cloud systems, the tradewind flow is usually peppered with a random distribution of clusters of tradewind showers. Thus, even during the dry season, a few light showers may be experienced almost daily on Guam (but the accumulated amounts are usually very small). Two types of organized weather systems can bring substantial rainfall to Guam during the dry season; these are an off-season tropical cyclone and a "shear line."

During the period 1960-1990, the Joint Typhoon Warning Center (JTWC) on Guam has recorded an average of 5.5 tropical cyclones in the WNP during the dry season (JTWC, 1990) with a monthly distribution as follows:

January -- 0.6
February -- 0.2
March -- 0.5
April -- 0.7
May -- 1.3
June -- 2.2.

During the period 1945-1990, twenty-six tropical cyclones passed within 180 nautical miles (n mi) of Guam during the dry season (an average of about one such tropical cyclone every other dry season) (JTWC, 1991).

The other important rain-producing weather system of the dry season is the "shear line" (Fig. 7a). A "shear line" accompanies (or can be said to be) that band of clouds and showers which are the extension into the tropics of the cloud band associated with the cold fronts of the large extra-tropical storm systems which traverse the mid-latitudes of the North Pacific, particularly during winter and early spring. The "shear line" portion of the cold front of a mid-latitude storm system is defined by the behavior of the wind shift across the cloud band: Along the cold-front portion of the cloud band, the wind shifts from southwesterly ahead (that is, to the east) of the cloud band to northwesterly behind (to the west of) the cloud band. Along the "shear line" portion of the cloud band the winds have an easterly component on both sides, but the wind behind the cloud band is stronger and usually has a more northerly component than the wind ahead of it (Fig. 7b). Hence, rather than the abrupt and relatively large directional shift of the wind experienced with the passage of a cold front in the mid-latitudes, a "shear line" passage in the tropics or subtropics often brings a dramatic strengthening -- but little change in direction -- of the pre-existing easterly flow. (Note: a gradient of wind speed perpendicular to the direction of a flow is called shear.)

Shear lines can bring significant rainfall to Guam. The rain is often light and misty (as is its character in some tradewind showers), but it persists intermittently for a day, or longer. At times there are embedded heavier showers, and occasionally there is even an outbreak of deeper convective rain clouds along the leading edge of the shear line. Rainfall totals of a half-inch to over an inch are common during the one-to-two days of the passage of a strong shear-line cloud band over Guam.

2) Wet season weather systems

During the wet season, the atmosphere over Guam becomes deeply moist and more unstable than the atmosphere of the dry season. Large billowing thunderheads (deep convective clouds) can grow vertically to great heights and produce very heavy deluges of large-drop rainfall. The origin of most of the wet-season rainfall can be attributed to deep convective clouds in various stages of organization and/or life cycle. Deep convection can be of the form of an isolated towering thunderhead (which may produce a heavy downpour over a very small area, such as a square kilometer), or individual large convective clouds may coalesce into a larger clusters known as Mesoscale Convective Systems (MCSs) (Maddox, 1980). An MCS may cover 10,000 to 50,000 square kilometers and produce steady moderate to heavy rainfall over a similar area. Prolonged island-wide downpours are often attributable to the formation (or passage) over Guam of an MCS. Two other important organized forms of convective clouds are the tropical cyclone and monsoon squall lines.

In the formative stages, a tropical cyclone may consist of a loosely organized collection of MCSs. As it intensifies, it develops a persistent central MCS with peripheral convective cloud bands. The core of a typhoon can be said to be a persistent self-sustaining MCS with a hole (the eye) in it. Based on maximum sustained central wind speed, a tropical cyclone is classified as follows:

Tropical depression -- <34 knots (kts)
Tropical storm -- 34-63 kts
Typhoon -- ≥64 kts
Super typhoon -- ≥ 128 kts

Sometimes when the axis of the monsoon trough moves to the north of Guam, strong southwesterly winds occur; in this southwesterly wind flow, heavy convective clouds can organize into long SW-NE oriented squall lines. While passing over Guam, these monsoon squall lines may bring gales and very heavy rain.

In addition to the monsoon trough, disturbances in the upper troposphere (25,000 - 60,000 ft) influence the distribution and organization of convective clouds in the WNP during the wet season. Further technical description of how the monsoon trough and disturbances in the upper troposphere affect the distribution and organization of convection in the WNP is beyond the scope of this paper.

In summary, wet-season precipitation is predominantly of convective origin. Much of the wet-season precipitation falls as heavy downpours from individual active convective clouds although some wet-season rain comes from stratiform (flat) clouds which are the decaying remnants of a prior MCS. Heavy downpours from isolated convective clouds may cover only small portions of the island at a given time. Island-wide downpours may result from the formation (or passage) over Guam of an MCS. Other causes of island-wide heavy rain events are:

1) Squall lines in strong southwesterly monsoon flow;
2) Convective cloud bands in the peripheral flow of a tropical cyclone; and,
3) Direct passage over the island of the central MCS of a tropical storm (or in the case of a typhoon, the eye wall).

An MCS in its decaying stage may spread steady light to moderate rain over the entire island. In the decay stage of an MCS, the convective clouds become stratiform (i.e., spread out and flattened). Rain from stratiform cloud may comprise a substantial fraction of the net wet-season rainfall on Guam. The proportion of rainfall in the tropics of convective-cloud origin versus rainfall of stratiform-cloud origin is a general question of tropical meteorology that has not yet been answered.

Impacts of tropical cyclones on the rainfall of Guam

The tropical WNP is the world's most active oceanic basin for the formation of tropical cyclones. On average, there are approximately 28 named tropical cyclones there each year; of these, an average of 18 become typhoons (and of the typhoons, an average of four become super typhoons). Guam is located in a region of the tropical WNP where many tropical cyclones are in their formative stages; these storms usually reach their peak intensity after passing Guam. Of 617 tropical cyclones warned on by the JTWC during the period 1970-1991, 41% of them (251) formed east of Guam's longitude (see Fig. 8). During 1957-1991, 131 tropical cyclones passed within 180 n mi of Guam (JTWC, 1991); 30 passed within 60 n mi of Guam; and six passed within 10 n mi or less. After adding the statistics for 1992 (an unprecedented year for numbers of typhoons hitting Guam) the aforementioned numbers become: 138 within 180 n mi; 25 within 60 n mi, and 13 within 10 n mi or less.

Summing the maximum rainfall measured on Guam for each of the tropical cyclones which passed within 180 n mi of Guam during the period 1957-1992, and comparing that value to the total rainfall at the Taguac WSMO (Note: The maximum rainfall recorded during the passage of a tropical cyclone within 180 n mi of Guam was not always recorded at the Taguac WSMO, but herein will be treated as if it had been.) shows that about 12% of the long-term (1957-1992) mean rain-fall (annual -- 11.7%; dry season -- 9.0%; and, wet season -- 12.9%) can be attributed to tropical cyclones passing within 180 n mi of Guam. Variability in the rainfall on Guam attributable to tropical cyclones passing within 180 n mi ranges from 41% in 1992, 28% in 1986, 21% in 1976, to none in 1973 and 1975. The rank cross-correlation of +.40 between the annual rain totals and the number of tropical cyclones passing within 180 n mi of Guam is statistically significant at the 95% level of confidence. The highest daily rainfall total ever measured on Guam was the 27.01 inches recorded at the Taguac WSMO on May 24, 1976, during the passage of Typhoon Pamela directly over Guam.

While it is true that much of Guam's rainfall occurs in tropical disturbances that eventually develop into tropical cyclones after moving beyond 180 n mi from Guam, and also that some of the rainfall on Guam can be produced by bands of clouds associated with tropical cyclones passing more than 180 n mi from Guam, statistics for such events have never been collected. Even if they were, they would often be difficult to interpret. For example, suppose that a tropical storm is embedded in a monsoon cloud band and that the tropical storm is more than 180 n mi from Guam. Suppose further that Guam is receiving heavy rain from monsoon squalls in the monsoon cloud band. The further the distance, the more arbitrary and/or ambiguous the point at which the rainfall attributable to the tropical cyclone becomes.

In summary: Over the long run, approximately 12% of Guam's rainfall is associated with tropical cyclones passing within 180 n mi. Certainly, some of the cloud clusters which produce rain on Guam later become tropical cyclones; however, no statistics are available on the magnitude of their contribution to Guam's long-term rainfall totals. Many tropical cyclones passing Guam beyond 180 n mi also directly or indirectly produce rainfall on Guam, but at larger distances it becomes more difficult to separate the clouds and rain directly associated with a tropical cyclone from the clouds and rain due to other factors such as the monsoon trough or upper-level disturbances.

Effects of ENSO Upon the Rainfall on Guam

Description of El Niño and the Southern Oscillation

1) El Niño

Ramage (1981 and 1986) describes the El Niño phenomenon as follows:

> For more than a century the name El Niño, the Spanish term for the Christ child, has been applied by fishermen to the annual appearance at Christmas time of warm water off the coast of Ecuador and northern Peru.
>
> For most of the year, the ocean surface waters off Peru and Ecuador are cool. The combined action of southerly winds blowing parallel to the South American coast and the earth's rotation, forces cool, nutrient-rich water to "upwell" to the surface. In the sunlit upper layers phytoplankton grow in profusion and are grazed by zooplankton. These in turn are eaten by anchovies which comprise the world's largest single fishery resource.
>
> Every year, around Christmas a warm current moves south off Ecuador, displacing the cool surface waters -- the phenomenon known as El Niño. Fishing is slightly disrupted but the effect is short-lived. Occasionally, however (in 1891, 1925, 1941, 1957-58, 1965, 1972-73, and 1976 [subsequently also: 1982-83, 1987, 1991-93]), El Niño is much more intense and prolonged. Sea-surface temperatures rise along the coast of Peru, and in the equatorial eastern Pacific, and may stay high for more than a year. The anchovy fishery is disrupted, and unusually heavy rain may fall over western tropical South America. In recent years its original meaning has lapsed, now to oceanographers and meteorologists "El Niño" signifies the major phenomenon. There is now general agreement on the broad features of El Niño. In the tropical east Pacific beyond the immediate South American coastal waters, El Niño is associated with South Pacific trade winds relatively weaker than North Pacific trade winds, the North Pacific near-equatorial convergence zone [which is coincident with the east-west oriented band of heavy rain clouds of the eastern North Pacific commonly referred to as the Inter-Tropical Convergence Zone] nearer than normal to the equator, and development of equatorial westerlies and bad weather up to 20° of longitude east of the dateline. Sea surface temperatures are generally well above normal along the equator and off South America, and positive anomalies may extend beyond 10°N and 10°S.
>
> El Niño generally sets in around March or April and may last a year or more

The intense warmings of the eastern equatorial Pacific (the meteorological El Niños) are known to be closely linked with the behavior of the Southern Oscillation (a massive seesawing of atmospheric pressure between the southeastern and the tropical western Pacific). Many indices of the Southern Oscillation have been proposed and used. The warm-water episodes of El Niño coincide with negative anomalies of indices of the Southern Oscillation. The cold episodes are seen to coincide with positive anomalies of indices of the Southern Oscillation.

2) The Southern Oscillation

Quoting again from Ramage (1986):

> The first major step toward understanding El Niño was taken in 1966 by Jacob Bjerknes of the University of California at Los Angeles, who noted that the anomalous warming of the sea is associated with the Southern Oscillation. The Southern Oscillation, first observed in 1924 by Sir Gilbert Walker, is a transpacific linkage of atmospheric pressure systems. When pressure rises in the high-pressure system centered on Easter Island, it falls in the low-pressure system over Indonesia and northern Australia, and vice versa. To quantify the phenomenon Walker

> defined the Southern Oscillation index, which is calculated by subtracting pressure in the western Pacific from pressure in the eastern Pacific. The index is positive when the difference between east and west is higher than normal and negative when the difference is lower than normal.

The close link of the major warming of the sea surface temperature of the eastern equatorial Pacific during El Niño with negative anomalies of the Southern Oscillation index has prompted scientists to call the phenomenon of El Niño, ENSO (an acronym derived from El Niño/Southern Oscillation). In this report the monthly values of the Southern Oscillation index, as defined and computed by the United States Climate Analysis Center, are used (See CAC, 1986, for a description and long-term tabulations of several indices of the Southern Oscillation.)

Global and regional precipitation anomalies associated with ENSO

Rasmusson and Carpenter (1982) (referred to hereafter as RC) constucted a composite of several ENSO events to describe the typical evolution of atmospheric and oceanic anomalies associated with an ENSO event. The terminology which RC used in the description of their composite ENSO event is widely used. RC established that an ENSO event lasts one year, with some precursory changes noted in the year before ENSO and some effects lingering into the year following the ENSO year. The ENSO year was designated as year (0); the preceding year as year (-1); and, the year following the ENSO year was designated year (+1). In a further breakdown of the evolution of the wind (Fig. 9a), the Southern Oscillation (Fig. 9b), and the sea surface temperature (Fig. 9c) during their composite ENSO, RC describe four phases of ENSO:

1) The onset phase
2) The peak phase
3) The transition phase
4) The mature phase

Using the RC scheme, Ropelewski and Halpert (1987) investigated the typical global and large-scale regional precipitation patterns that are associated with ENSO. They identified several global core regions that appeared to have a clear ENSO-precipitation relationship (see Fig. 10). Guam and Micronesia lie within an ENSO core region which, according to Ropelewski and Halpert, features less than normal rainfall from October of year (0) to May of year (+1).

The relationships of the rainfall on Guam with indices of ENSO

In order to compare the rainfall on Guam with ENSO indices, the monthly rainfall statistics at the Taguac WSMO were compiled into calendar-year totals, January-to-June (dry season) totals and July-to-December (wet season) totals (see Table 6). Two ENSO indices (the CAC's monthly SOI and JMA's eastern equatorial Pacific SST monthly SST anomalies) were also averaged for the annual, dry-season and wet-season periods. In addition, the change of the ENSO indices between several pairs of back-to-back four-month periods were tabulated.

In summary, the following statistics of the rainfall at the Taguac WSMO and of the ENSO indices were computed:

1) The annual rainfall totals at the Taguac WSMO:	**<Rain>**
2) The January-to-June dry-season rainfall:	**Rain Dry**
3) The July-to-December wet-season rainfall:	**Rain Wet**
4) The annual average of the CAC's SOI:	**<SOI>**
5) The annual average of the JMA's SST:	**<SST>**
6) The dry-season average of the CAC's SOI:	**SOI Dry**
7) The dry-season average of JMA's SST:	**SST Dry**

8) The wet-season average of the CAC's SOI: **SOI Wet**
9) The wet-season average of JMA's SST: **SST Wet**
10) The change of the SOI between Nov-Feb and Mar-Jun: **D_1SOI**
11) The change of the SST between Nov-Feb and Mar-Jun: **D_1SST**
12) The change of the SOI between Jan-Apr and May-Aug: **D_2SOI**
13) The change of the SST between Jan-Apr and May-Aug: **D_2SST**
14) The change of the SOI between Jan-Jun and Jul-Dec: **D_3SOI**
15) The change of the SST between Jan-Jun and Jul-Dec: **D_3SST**
16) The change of the SST between Jun-Sep and Oct-Jan: **D_4SST**
17) The annual number of tropical cyclones passing within 180 n mi of Guam: **<TC-180>**

Some cross-correlations among these statistics were computed (Table 9). The values of the cross-correlations and of the time-lag cross-correlations appearing in Table 9 indicate that the annual, dry-season, and wet-season rainfall totals are significantly related to ENSO indices. The strongest relationship is that between **<Rain>** and **D_1SST**. The cross-correlation value of .57 indicates a shared variance of 32% between these two time series. Thus, when the SST of the eastern equatorial Pacific warms (cools) during the boreal winter into spring, there is a statistically significant tendency for the annual rainfall total to be above (below) normal.

Among only the dry-season rainfall totals (**Rain Dry**), the highest cross-correlation is with the simultaneous dry-season average of the SOI (designated **SOI Dry**). The second highest cross-correlation is with the change of the SOI between January-to-April and May-to-August (designated **D_2SOI**). Thus, when the SOI is rising (falling) during the dry season, the dry-season rainfall total tends to be below (above) average. The association of below-average dry-season rainfall with a simultaneous rise of the SOI is consistent with the finding of Ropelewski and Halpert (1987) that Micronesia experiences a drought during October (0) to May (+1) of an ENSO episode. During this part of the ENSO cycle Rasmusson and Carpenter (1982) showed that the SOI steadily rises.

The wet-season rainfall totals are significantly correlated (at a time lag) with the same ENSO indices with which the dry-season rainfall totals show statistically significant simultaneous correlations. Interestingly, the wet-season rainfall totals are not significantly correlated with simultaneous averages of ENSO indices. In addition to the statistically significant time-lag cross-correlations of the wet-season rainfall totals with ENSO indices, there is a statistically significant cross-correlation between the dry-season rainfall anomaly and the wet-season rainfall anomaly. This carry-over of the dry-season anomaly into the wet season is known as persistence. Thus, if a dry season of a particular calendar year is drier or wetter than normal, the following wet season of that same calendar year has a tendency to be likewise. The persistence of rainfall anomalies is only one way, however. Wet-season anomalies are not carried over into the following dry season. The time-lag cross-correlation between the wet seasons and their following dry seasons does not differ significantly from zero (Table 9).

Additional evidence of a strong relationship between Guam's rainfall and ENSO is shown by a comparison of the time-lag auto correlation of Guam's annual rainfall with a time-lag auto-correlation of an ENSO index (Fig. 11). A 4 to 5 year periodicity is common to the time series of Guam's annual rainfall totals and the time series of the SOI and the SST anomalies of the eastern equatorial Pacific. The length of the periodicity is roughly the average interval between moderate-to-strong El Niño events (Quinn, *et al.*, 1978).

In summary, the annual rainfall totals on Guam are influenced by ENSO. Exceptionally dry years tend to occur when the SST anomalies of the eastern equatorial Pacific fall sharply during the dry season. Two such years, 1973 and 1983, are the driest years in the record. Dry-season rainfall totals are also related to ENSO. Exceptionally low dry-season rainfall totals occur when the SST anomalies of the eastern equatorial Pacific cool (and the SOI rises) during the dry season. This is consistent with the finding by Ropelewski and Halpert (1987) that Micronesia experiences a drought during the winter and spring of the year following an ENSO event. Wet-season rainfall is also related to ENSO in a manner similar to the dry season; but an additional factor is a persistence of dry-season anomalies into the wet season of the same calendar year.

Prediction of Seasonal Rainfall on Guam

Herein, the utility of ENSO (specifically, the SOI and eastern equatorial Pacific SST as indices of ENSO) and the persistence of seasonal rainfall anomalies as predictors for seasonal rainfall totals on Guam are examined. Two forecasting strategies were used:

1) Forecast the seasonal rainfall on Guam based on forecast values of ENSO indices expected to occur simultaneously with that rainfall and
2) Forecast the seasonal rainfall on Guam based on the magnitude and evolution of ENSO indices and seasonal rainfall anomalies prior to the period for which the forecast of rainfall is desired.

These two strategies were tested using known ENSO indices and seasonal rainfall totals during the period 1957-1991. The first strategy was evaluated using a perfect-prog approach (that is, the known future values of ENSO indices were used as the forecast values). The second strategy, a time-lag approach, was evaluated by comparing ENSO indices and rainfall anomalies occurring prior to the season for which a rainfall forecast is desired.

The perfect-prog approach

The cross-correlation coefficients between ENSO indices and seasonal rainfall totals (Table 7) can be used in a linear regression to predict the value of one variable given the value of the other. The best prediction that a linear regression can yield is given by

$$(A_i)^* = (r)(s_A / s_B)(B_i)' + \bar{\bar{A}} \qquad (1)$$

where: $( )^*$ indicates predicted value;
$( )'$ indicates departure from the mean value;
subscript i indicates the i^{th} value of the time series;
s_A and s_B are the standard deviations of variables A and B respectively;
r is the cross-correlation coefficient between variables A and B; and
the overbar indicates the mean value of the time series.

A regression equation of the form of equation (1)

$$\textbf{Rain Dry} = (11.45)\,(\textbf{SOI Dry})' + 31.63 \qquad (2)$$

is successful 26 times out of 35, or 74%, in predicting whether **Rain Dry** would be above or below normal for the years 1957-1991. Additional skill is obtained by adding a second variable to equation (2). The following multiple-linear regression equation

$$\textbf{Rain Dry} = 11.45\,(\textbf{SOI Dry})' - 4.15\,(\mathbf{D_2}\ \textbf{SOI})' + 31.63 \qquad (3)$$

is successful 27 times out of 35, or 77%, in predicting whether **Rain Dry** would be above or below normal for the years 1957-1991. Another regression equation that shows some predictive skill in a perfect-prog mode is:

$$\langle \mathbf{Rain} \rangle = -9.57\,(\mathbf{D_3\ SOI})' + 101.84 \tag{4}$$

Equations (2), (3), and (4) are based upon ENSO indices occurring simultaneously with the rainfall. In order to use these equations to predict Guam's rainfall in advance, an accurate forecast of the ENSO indices must be available. Forecasts of ENSO indices at up to a 15-month lead time are routinely published in the *Climate Diagnostics Bulletin*[2] issued by the United States Climate Analysis Center. Forecasts of ENSO indices have appeared in the *Climate Diagnostics Bulletin* since 1988. Given this short record, it is too early to perform a meaningful evaluation of their use in making long-range (6-12 month) rainfall forecasts for Guam. The relatively high (71 77%) rate of success of the perfect-prog forecasts in making some simple above- or below-normal rainfall forecasts for Guam suggests that accurate forecasts of ENSO indices could be helpful in making long-range rainfall predictions for Guam.

Time-lag forecasts

Because perfect long-range forecasts of ENSO indices are not available and because forecasts of ENSO indices have only been issued for a few years (and are still considered experimental), a time-lag forecast might be more successful. The finding in Reid *et al.* (1984) that there is a 2- to 5-month lag of the tropical atmospheric temperature to the tropical SST lends support to a time-lag approach. In addition, at a time lag, the strong persistence of rainfall anomalies from the dry season of a given calendar year into the wet season of that same calendar year can be used as a predictor.

For dry-season rainfall totals, there is no persistence of the prior year's annual or wet-season anomalies. Thus, only ENSO indices offer hope as useful predictors. Only one index (in a time-lag mode), the change of the SST between the June-to-September average and the October-to-January average (designated **D₄ SST**) has a statistically significant rank cross-correlation (see Table 7). A regression equation of the form of Equation (1) developed from the cross-correlation between these two variables

$$\mathbf{Rain\ Dry} = (-12.25)\,(\mathbf{D_4\ SST})' + 31.63 \tag{5}$$

is successful 19 times out of 35, or 54%, in making a simple predicition whether the dry-season rainfall total would be above or below normal (not a very skillful prediction).

For the wet-season rainfall totals, ENSO indices and the persistence of dry-season anomalies into the wet season yield much more skillful regression equations. The following linear and multiple-linear regression equations:

$$\mathbf{Rain\ Wet} = (0.22)\,(\mathbf{Rain\ Dry})' + 70.21 \tag{6}$$

$$\mathbf{Rain\ Wet} = (0.22)\,(\mathbf{Rain\ Dry})' + 3.49\,(\mathbf{D_2\ SST})' + 70.21 \tag{7}$$

$$\mathbf{Rain\ Wet} = (0.22)\,(\mathbf{Rain\ Dry})' + 3.76\,(\mathbf{D_1\ SST})' + 70.21 \tag{8}$$

are correct 25 times out of 35 (71%), 26 times out of 35 (74%) and 23 times out of 35 (66%), respectively, in making a simple forecast of above or below normal wet-season rainfall.

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[2] The *Climate Diagnostics Bulletin* issued by the United States Climate Analysis Center can be obtained from: The U.S. Department of Commerce, NOAA/National Weather Service, W/NMC52, Climate Diagnostics Bulletin, Washington, DC 20233.

Rainfall, Streamflow, and Groundwater

The streams of southern Guam and the freshwater aquifer of northern Guam are fed and recharged solely by the rain which falls on Guam. The mountains of Guam are relatively low; the highest peak is 401 m. They are rarely enshrouded in cloud as the typical cloud base of tropical cumulus clouds ranges from 500 to 700 m. Fog-drip is therefore unlikely to contribute to Guam's water supply. By contrast, in Hawaii, fog-drip can contribute on the order of 1000 mm of equivalent annual precipitation in cloud-enshrouded forests at higher elevations.

Rainfall of convective origin, though very heavy, can cover an extremely small area. A few inches of rain may fall during an hour or two over the small watersheds of one or two streams while adjacent watersheds and streams may be unaffected. Island-wide downpours may cause flooding in most, or all, of Guam's southern streams and temporary surface ponding of water in depressions in the topography of the limestone plateau of northern Guam.

The recharge value of small and isolated versus island-wide heavy rain to, and its distribution within, Guam's northern aquifer is not fully documented. The water level in most of the wells tapping the northern aquifer varies not only with variations in rainfall but also with the surrounding ocean's tidal signals. A majority of wells drilled in the limestone of northern Guam show a strong annual cycle largely due to the influence of the ocean's tidal cyclicity, not necessarily just from Guam's dual seasonality (Ikehara, personal communication). Well A-20 in Ordot, Guam (see Fig. 1 for its location), was chosen for comparison with rainfall because the water level records for this well do not indicate tidal fluctuations which can obscure evidence of recharge events.

In order to study the effects of temporal variations of rainfall on Guam to temporal variations in streamflow and groundwater, statistics derived from the time series of the streamflow at the Ugum River gage (Table 5) and the time series of the water level in well A-20 were compared with temporal variations in the rainfall at the Taguac WSMO (Table 1). The response of streamflow and groundwater to the normal annual cycle of wet and dry seasons and to extended periods of rainfall deficits and surpluses is examined next.

The annual cycle

Guam's long-term (1957-1991) mean monthly rainfall features a strong annual cycle composed of a dry season (January through June) and a wet season (July through December). Of the 101.84 inches of annual mean rainfall at the Taguac WSMO, 31.63 inches falls during January through June and 70.21 inches falls during July through December. The monthly distribution of rainfall during the calendar year is nearly sinusoidal (Fig. 12) with a minimum median rainfall of 2.7 inches during March and a maximum median rainfall of 14.4 inches during September.

The long-term (1978-1992) mean monthly streamflow at the Ugum River gage is essentially in phase with the long-term mean monthly rainfall distribution (Fig. 12). There is a one-month lag in the minumum streamflow (April versus the March minimum of the rain), but the maximum streamflow peaks along with the maximum median rainfall in September. Because the watersheds for Guam's streams are so small, an in-phase tracking of streamflow with rainfall is to be expected.

The long-term (1978-1991) mean monthly water level in well A-20 is almost 180 degrees out of phase with the long-term monthly rainfall distribution (Fig. 12). The water level in the well peaks in February (one month behind the minimum monthly rainfall in March) and falls to its lowest level in September just as the monthly rainfall reaches its peak. These data show that a considerable time lag exists from the moment rainfall begins to fall on the ground at the onset of the rainy season until the rain as recharge has actually reached the water table. The time lag may actually be shorter or longer in other areas depending on the hydraulic characteristics of the aquifer there (Ikehara, personal communication).

Drought

One may argue that Guam experiences a six-month drought almost every year during the dry season. Deleterious effects of lack of rainfall occur almost every dry season: desiccation of grasslands, desiccation and defoliation of some species of trees, and significant reduction of streamflow. The drying of the grasslands leads to a problem with wildfires, and the drawdown of streamflow leads to a depletion of water reserves in the Fena reservoir.

Every three or four years, the dry season is especially dry and prolonged. Problems with wildfires and stress to local crops and golf-course grasses are thereby aggravated. Exceptional dryness during the dry season tends to persist into the wet season of the same calendar year. These periods of extended monthly rainfall deficits are usually linked with ENSO episodes. In order to identify the effect of prolonged monthly rainfall deficits on streamflow and groundwater, a running accumulation of monthly rainfall anomalies was compared with a running accumulation of the monthly anomalies of the streamflow at the Ugum River gage and with a running accumulation of the water-level anomalies in well A-20. The rainfall anomalies used in the comparison are the rainfall "trend" (Fig. 2b) which was calculated in accordance with the methodology described under that heading.

Running accumulations of the anomalies of the rainfall, streamflow and well level (Fig. 13) all indicate the same periods of long-term rises and falls. Long-term (on the order of two years) running deficits (defined herein as drought periods) in the rainfall, streamflow, and well level have occurred three times since the time series of the streamflow and well level began in late 1977 (see Fig. 13): late 1977 through late 1979; mid-1982 through mid-1984; and late 1986 through 1988. The latter two drought periods coincided with strong ENSO episodes. The running accumulations of the anomalies of the rainfall, streamflow, and well level appear to be in phase (i.e., no time lags are apparent).

A longer running accumulation of rainfall anomalies for the period 1959 through early 1991 adds the following drought periods to those appearing in Figure 13: 1959 through mid-1962; mid-1964 through 1966; late 1968 through late 1969; and 1973 through early 1974. The last three of these four drought periods coincide with ENSO episodes.

Conclusions

Guam lies within the large region of the globe affected by the monsoons of the eastern hemisphere. The monthly rainfall distribution on Guam has a marked seasonal asymmetry, with about 30% of the rain accumulating during the dry-season months of January through June and 70% of the annual rain accumulating during the wet-season months of July through December. The normal seasonal inequity of rainfall can be directly attributed to the seasonal behavior of the monsoon trough of the WNP.

During the dry season, the monsoon trough in the northern hemisphere is not present, or lies at a very low latitude. Throughout most of the dry season, tradewinds blow on Guam. In the generally subsident atmosphere of a tradewind regime, clouds lack vertical development, and rainfall is usually very light. Occasionally, the low latitude portions of the frontal cloud bands associated with the mid latitude storm systems of winter and spring pass over Guam in the form of a "shear line." The "shear lines" of the dry season may be responsible for a large fraction of

Guam's dry-season rainfall. Off-season tropical cyclones passing near Guam during the dry season account for about 10% of Guam's long-term (1957-1992) dry-season rainfall.

During the wet season, the monsoon trough moves to a higher latitude. In the mean, it moves to a position just south of Guam during August and September. Tropical cyclones, squall lines, and other forms of cloud clusters associated with the monsoon trough affect Guam throughout the rainy season. In addition, deep convective clouds associated with upper-atmospheric disturbances also contribute to Guam's wet-season rainfall. Of the aforementioned specific cloud systems, this report addressed only the relative contribution to Guam's rainfall of tropical cyclones passing within 180 n mi. Tropical cyclones passing within 180 n mi of Guam contribute about 12% of the total long-term (1957-1992) accumulated rainfall. During 1992, the seven tropical cyclones passing within 180 n mi of Guam contributed 41% to that year's annual total. During 1973 and 1975, no tropical cyclones passed within 180 n mi of Guam.

ENSO episodes have a strong influence on the interannual fluctuations of rainfall on Guam. During some ENSO events in the past, Guam (and all of Micronesia) experienced drought. These droughts typically occurred during the year in which the ENSO indices were recovering from El Niño anomalies. ENSO events recur about once every four years, and this is also true of exceptionally dry years on Guam.

Persistence also plays a role in the seasonal distribution of rainfall on Guam: If the dry season of a particular calendar year is unusually dry, the wet season of that same calendar year tends to be unusually dry. Persistence does not carry over from the wet season into the next year's dry season. The correlation between wet-season anomalies and the anomalies of the following year's dry season is zero.

Through use of the known effects of ENSO and persistence on the annual and seasonal rainfall on Guam, prediction equations (in the form of simple linear and multiple linear regressions) show as much as 77% skill in simple predictions of above or below normal rainfall for some given time periods. Because some of the prediction equations use ENSO indices occurring simultaneously with the desired period of predicted rainfall, accurate forecasts of the ENSO indices are an additional requirement to make the equations useful. Routine forecasts of ENSO indices are produced by the U.S. Climate Analysis Center. Insofar as they are accurate, and as they improve, long-term (six months to a year in advance) rainfall prediction on Guam has the potential of becoming a useful civic planning tool.

Because of its small size, the island of Guam experiences deleterious effects of drought even during the normal dry season. Prolonged periods of below-normal monthly rainfall are especially hard on the flora, fauna, and human users of water on Guam. Accumulative anomalies of the monthly mean streamflow and groundwater levels show an in-kind and simultaneous response to the accumulative anomalies of monthly rainfall. Prolonged droughts have a strong ENSO connection. Very dry years, such as 1973 and 1983, were the recovery years of strong ENSO episodes. Potable fresh water is a precious resource on Guam, and it is hoped that this technical report will promote a greater appreciation for, and understanding of, the complexities of the local meteorology and hydrology.

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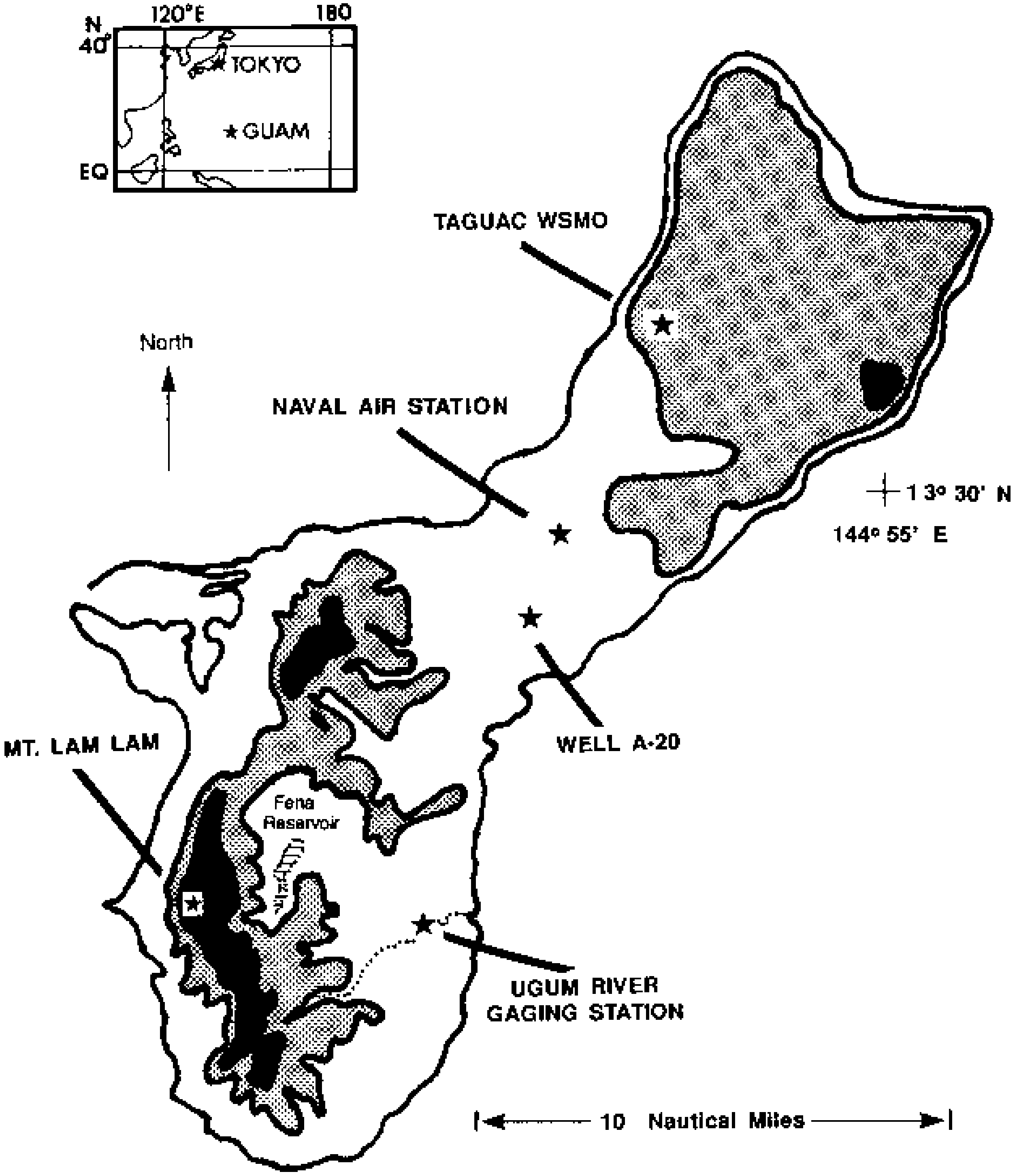

Figure 1. The Island of Guam. Elevation is indicated by shading: half-tone > 100 m and black > 200 m. Some sites relevant to the discussion in the text are labeled.

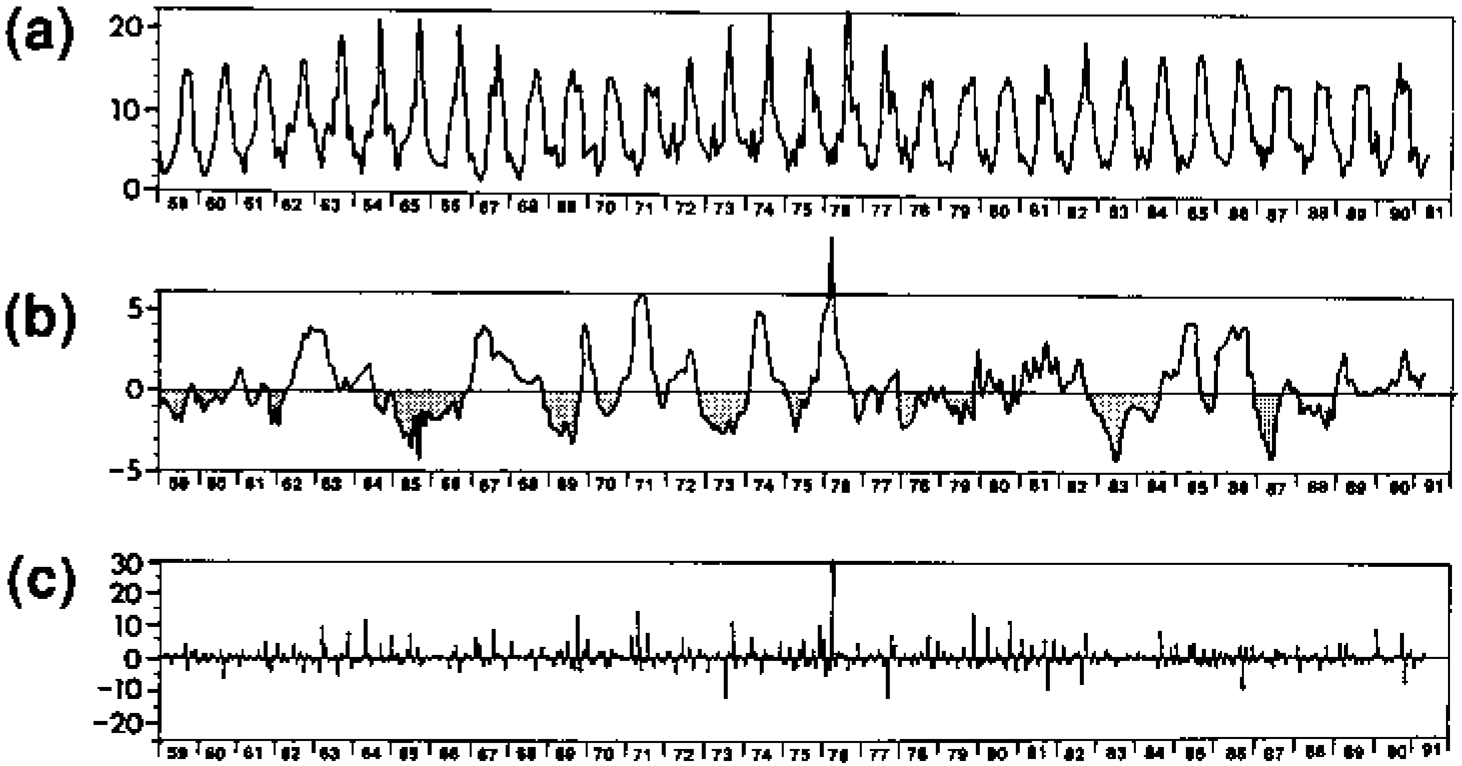

Figure 2. A decomposition of the time series of the monthly rainfall at the Taguac WSMO: (a) the annual cycle; (b) the trend; and (c) the irregular component. Units are inches. Prolonged negative anomalies of the trend are shaded.

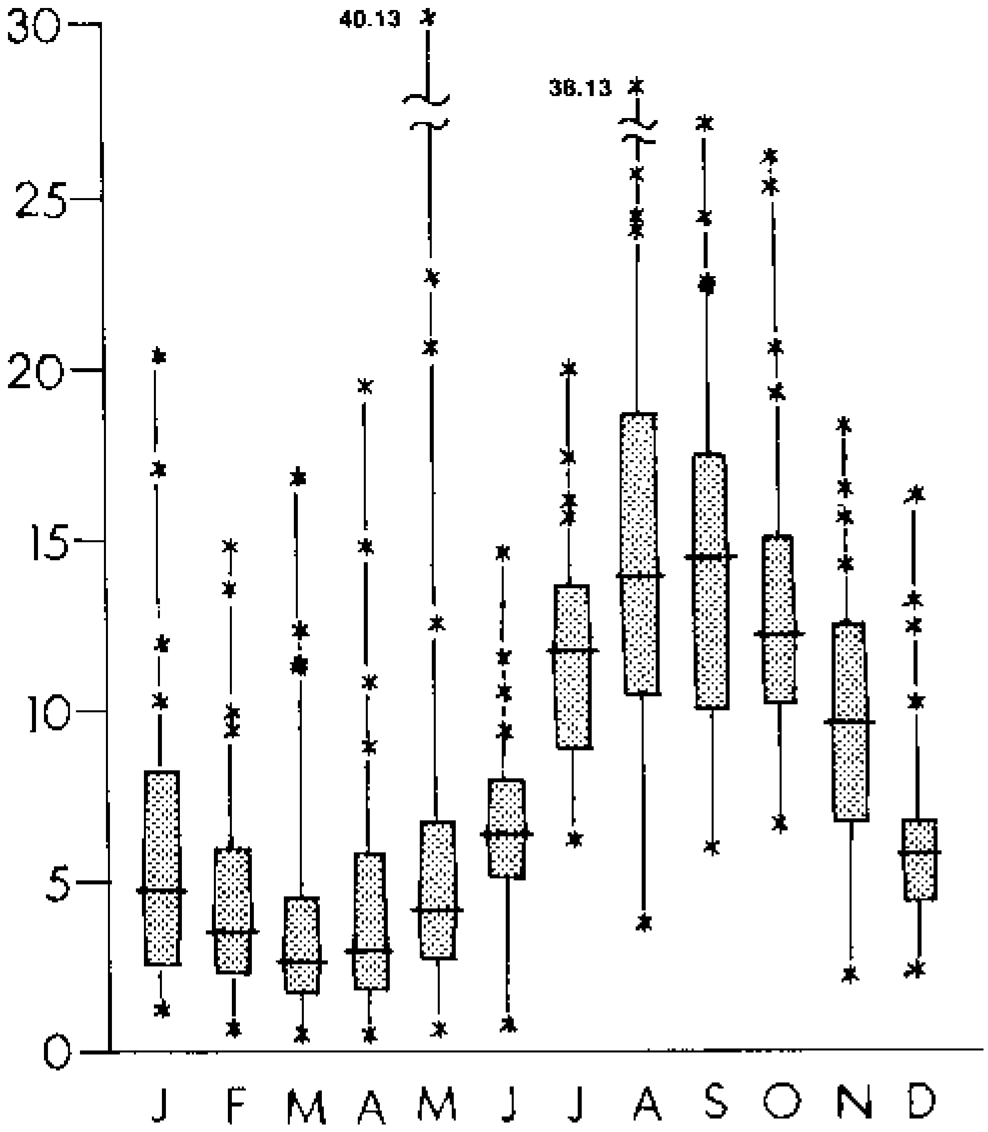

Figure 3. Monthly rainfall distribution at the Taguac WSMO. Median rainfall during the period 1957-1991 is indicated by the short horizontal bars within the shaded boxes. The shaded area above each bar is the range of the second quartile, the shaded area below each bar is the range of the third quartile. The extreme minimum monthly values and the four highest monthly values are indicated by asterisks.

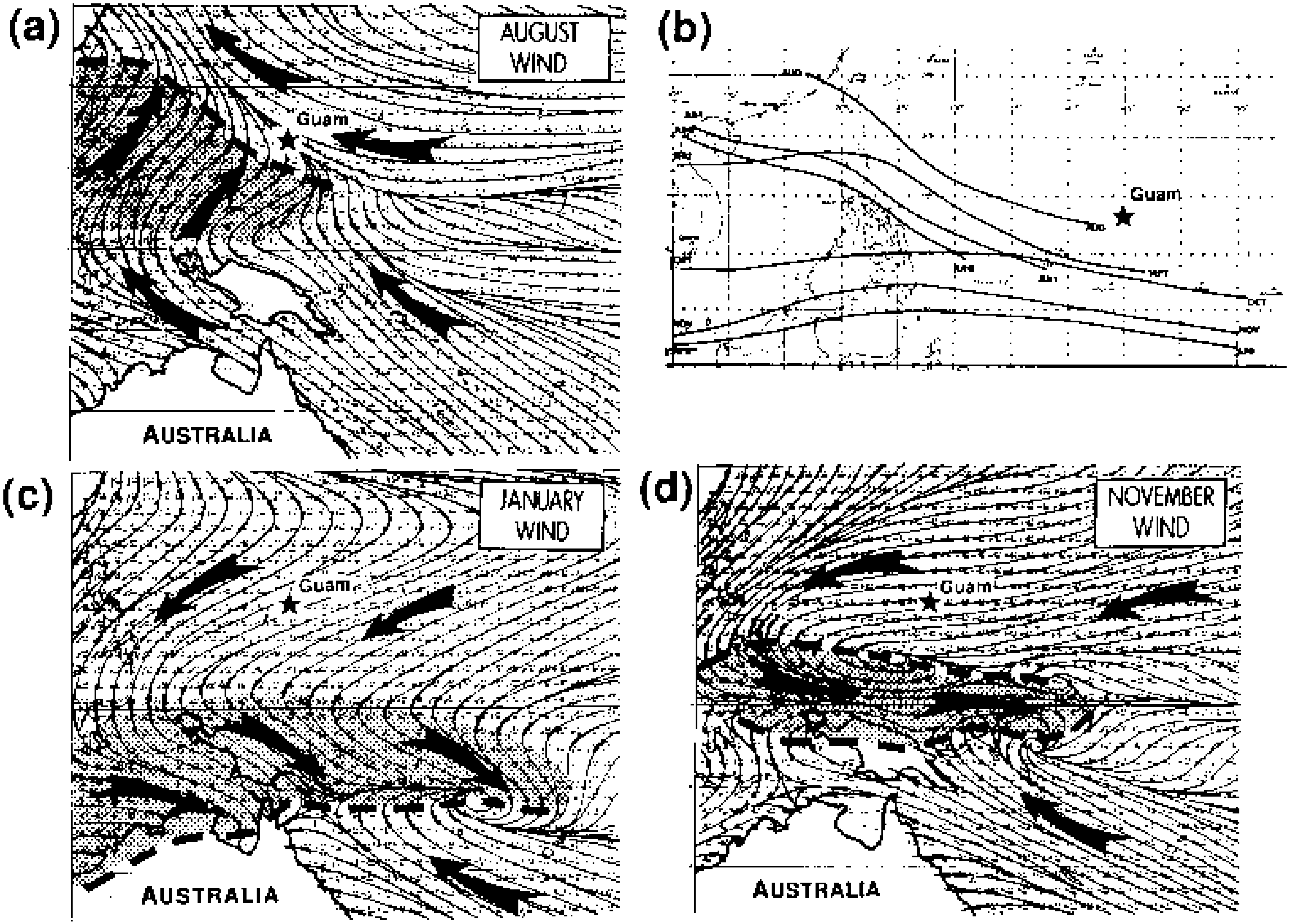

Figure 4. Long-term (1900-1979) mean surface wind flow in the western North Pacific for selected months: (a) August: (c) January; and, (d) November. The monsoon trough axes are indicated by the thick dashed lines. The thin lines are streamlines, and the thick arrows help to depict the wind direction. Winds with a westerly component are shaded. Panel (b) shows the monthly mean positions of the monsoon trough. Panels (a), (c) and (d) are adapted from Sadler, et al. (1987). Panel (c) is based on Atkinson (1970) and Sadler and Harris (1970).

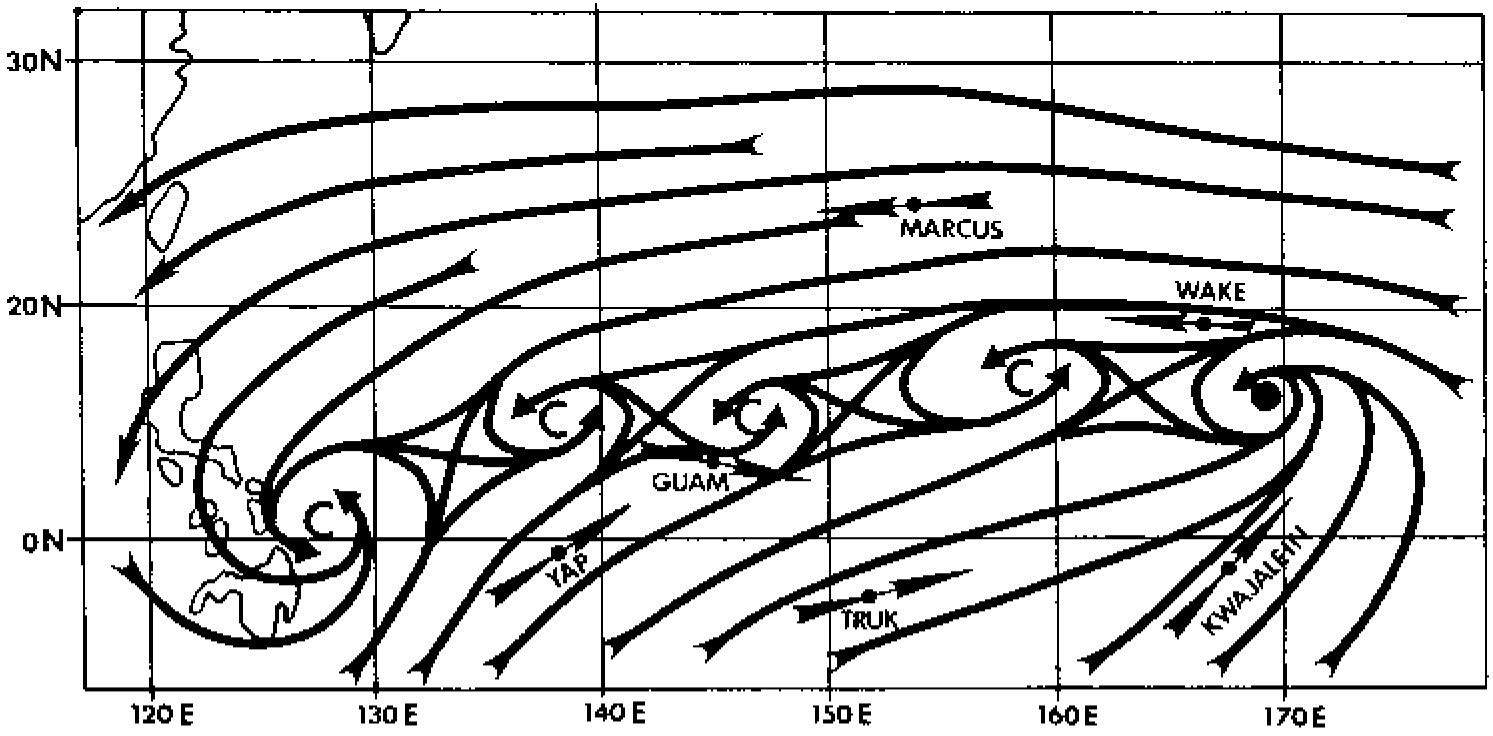

Figure 5. Example of the wind flow in an active monsoon trough. Streamlines show low-level wind in the tropical western North Pacific at 00 UTC August 12, 1986. Low-level wind directions are shown for some selected island locations. Typhoon Georgette (located between Wake and Kwajalein) is the only named tropcal cyclone in this trough at this time. "C"s are cyclonic circulation centers. (Adapted from JTWC, 1986.)

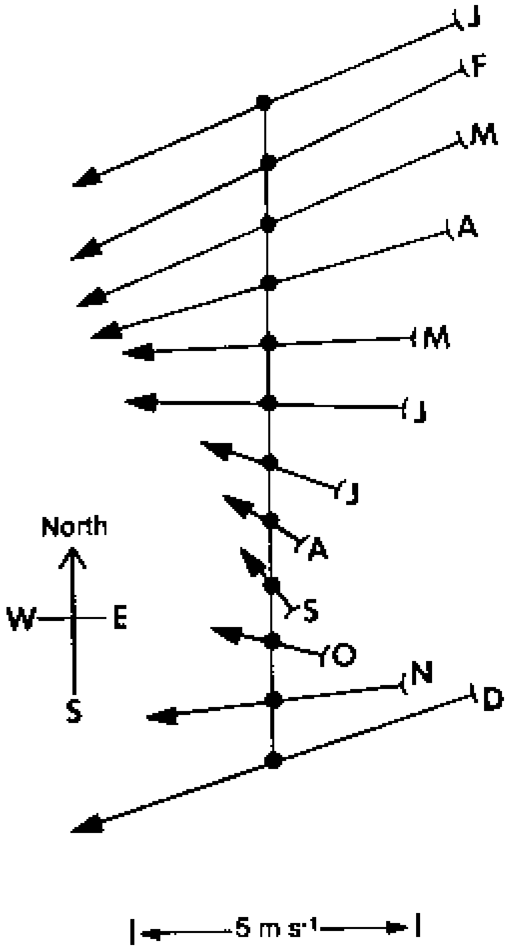

Figure 6. Monthly distribution of the long-term (1900-1979) mean surface wind near Guam (adapted from Sadler, et al., 1987). Arrows show wind direction. Arrow length indicates wind speed.

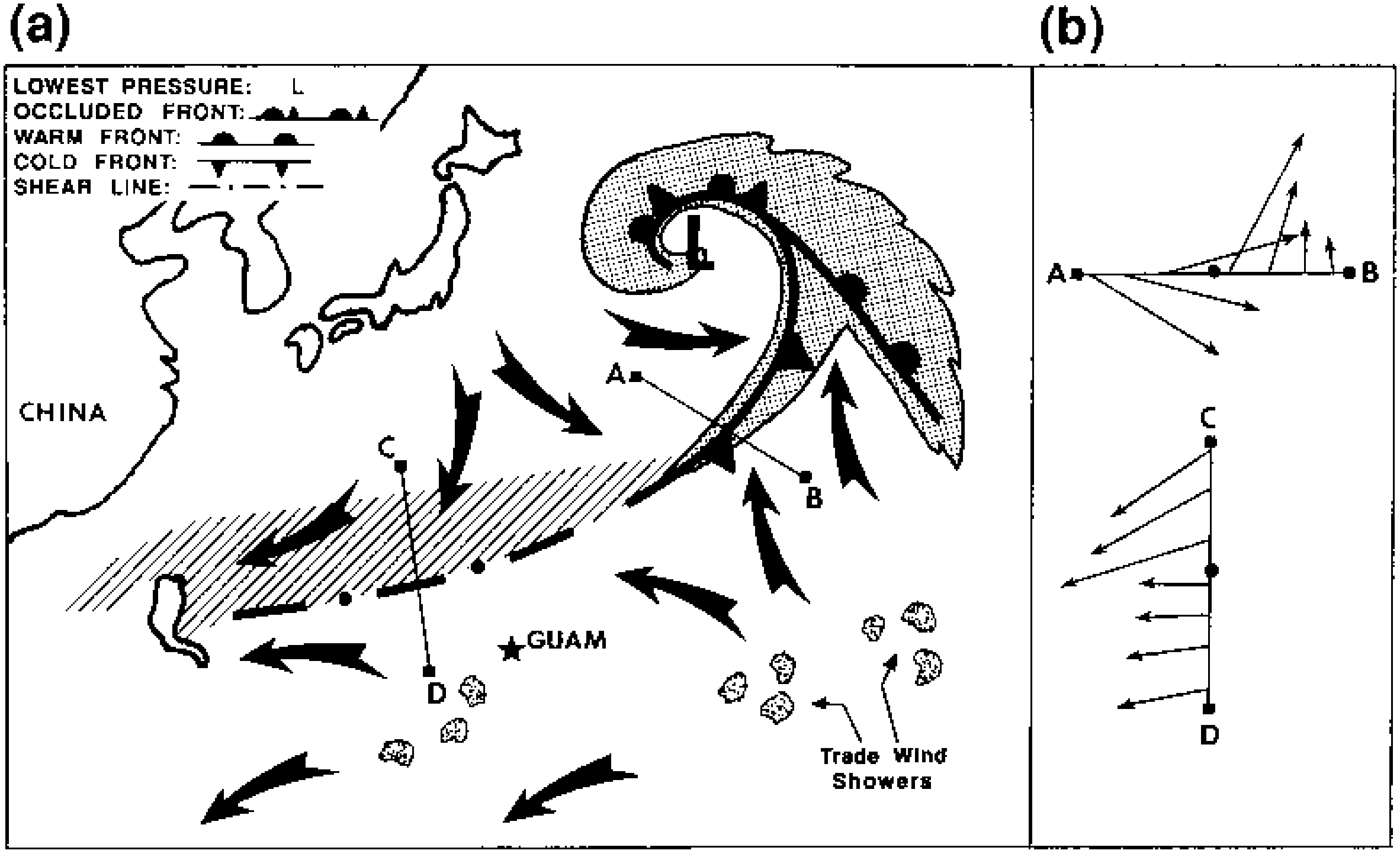

Figure 7. Graphic illustration of the structure of a shear line. (a) Typical cloud and wind distribution accompanying a shear line in the western North Pacific. The thick cloud system of the parent mid-latitude low is shaded. The band of low-cloud cover along and behind the shear line is indicated by diagonal lines. Bold arrows show wind direction. (b) The wind profile along a line passing through the cold front -- point A to point B in panel (a); and the wind profile along a line passing through the shear line -- point C to point D in panel (a).

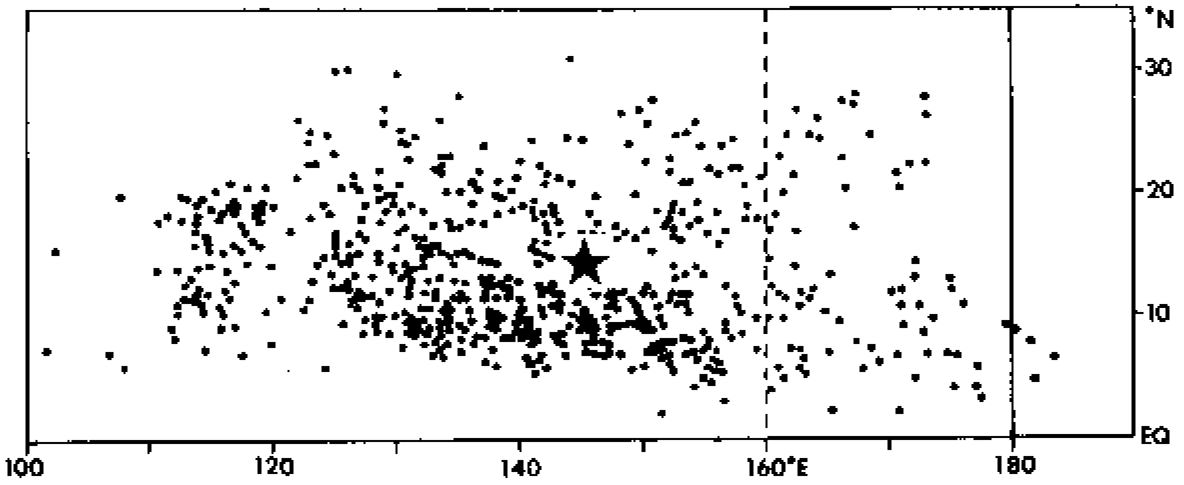

Figure 8. Origins of all tropical cyclones warned upon by the JTWC during the period 1970-1991. Origin location of each cyclone was considered to be that point where the cyclone first attained a 25 kt central wind speed. Large star shows location of Guam.

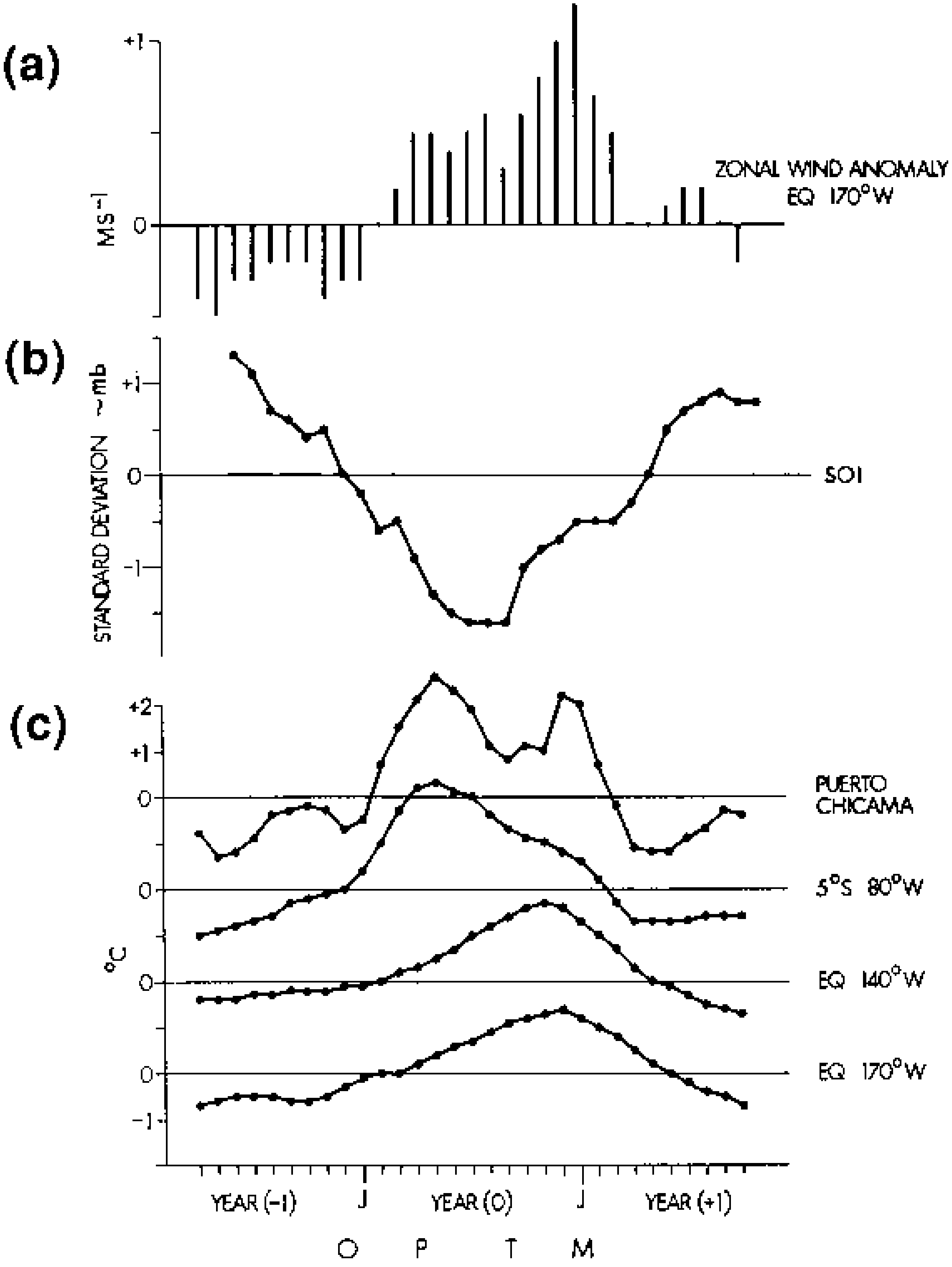

Figure 9. Rasmusson and Carpenter's (1982) composite El Nino. The evolution of anomalies of the surface wind at the indicated location (a), the evolution of the Southern Oscillation (b) and the evolution of the SST at the indicated locations (c) for a composite of several El Nino events are shown. O = Onset phase; P= Peak phase; T = Transition phase; and M = Mature phase.

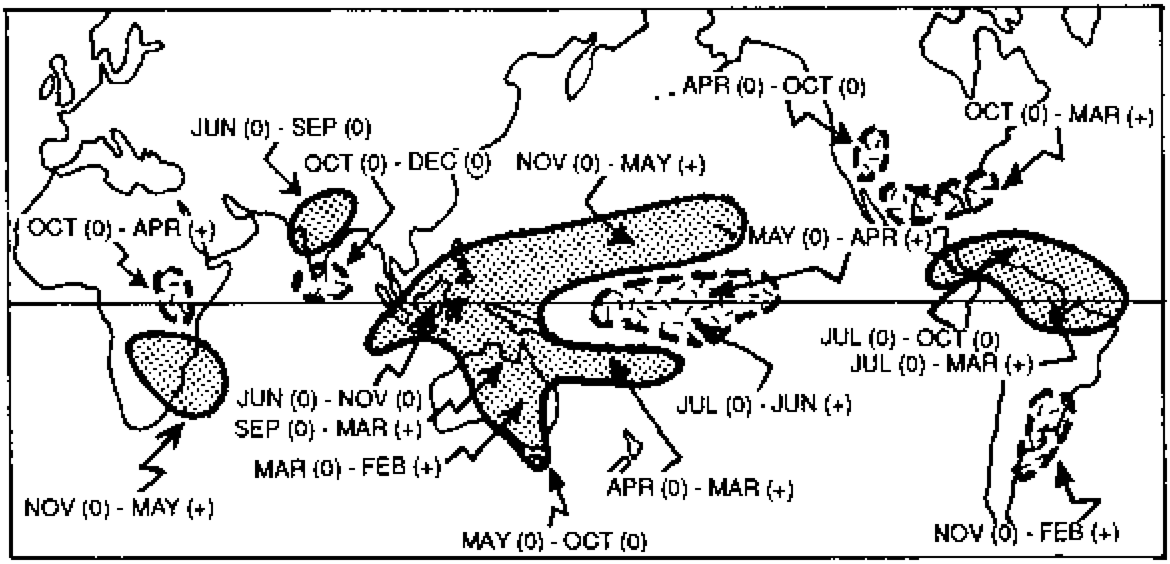

Figure 10. Principal ENSO-related precipitation anomalies (adapted from Fig. 21 of Ropelewski and Halpert, 1987). Solid lines encompassing shaded areas indicate ENSO-related dryness; dashed lines encompassing areas with "chicken scratches" indicate ENSO-related wetness. Period of ENSO cycle when the indicated anomaly occurs is indicated: year (0) is the El Nino year as defined by Rasmusson and Carpenter (1982).

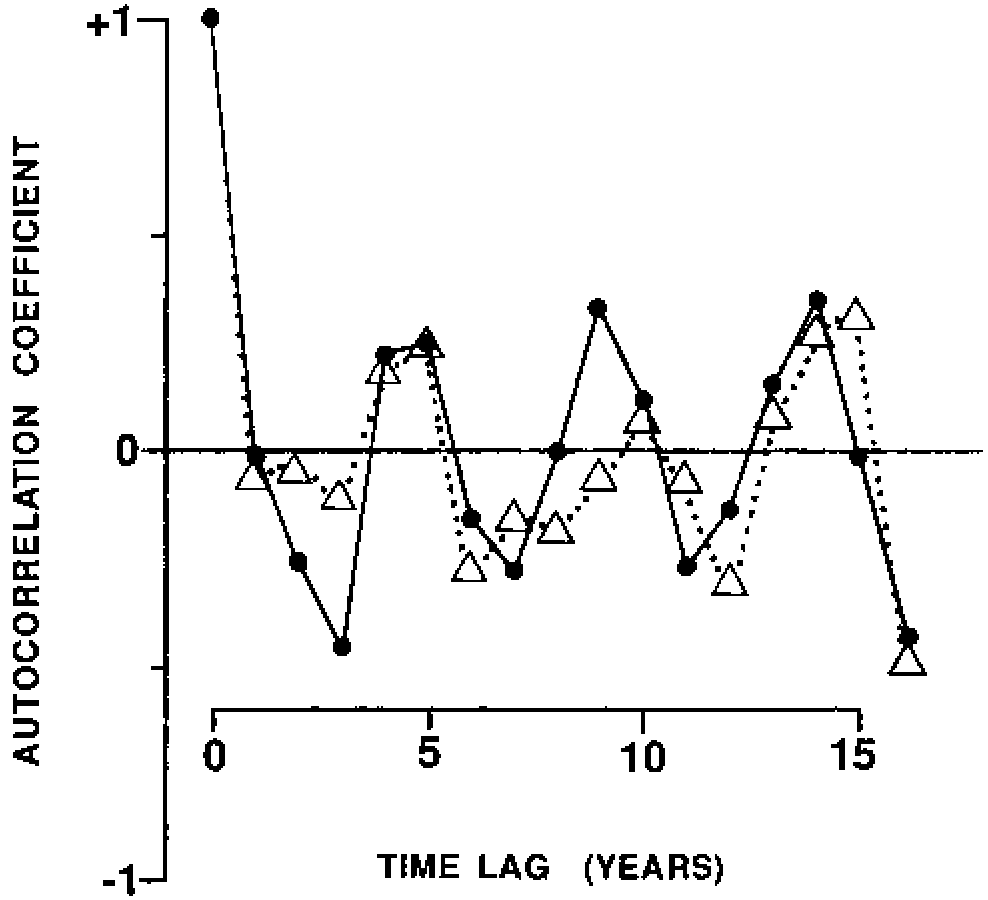

Figure 11. Time-lag auto-correlations of the annual rainfall at the Taguac WSMO for the period 1957-1991 (solid line connecting black dots) and the time-lag auto-correlation of the CAC's SOI (dotted line connecting open triangles).

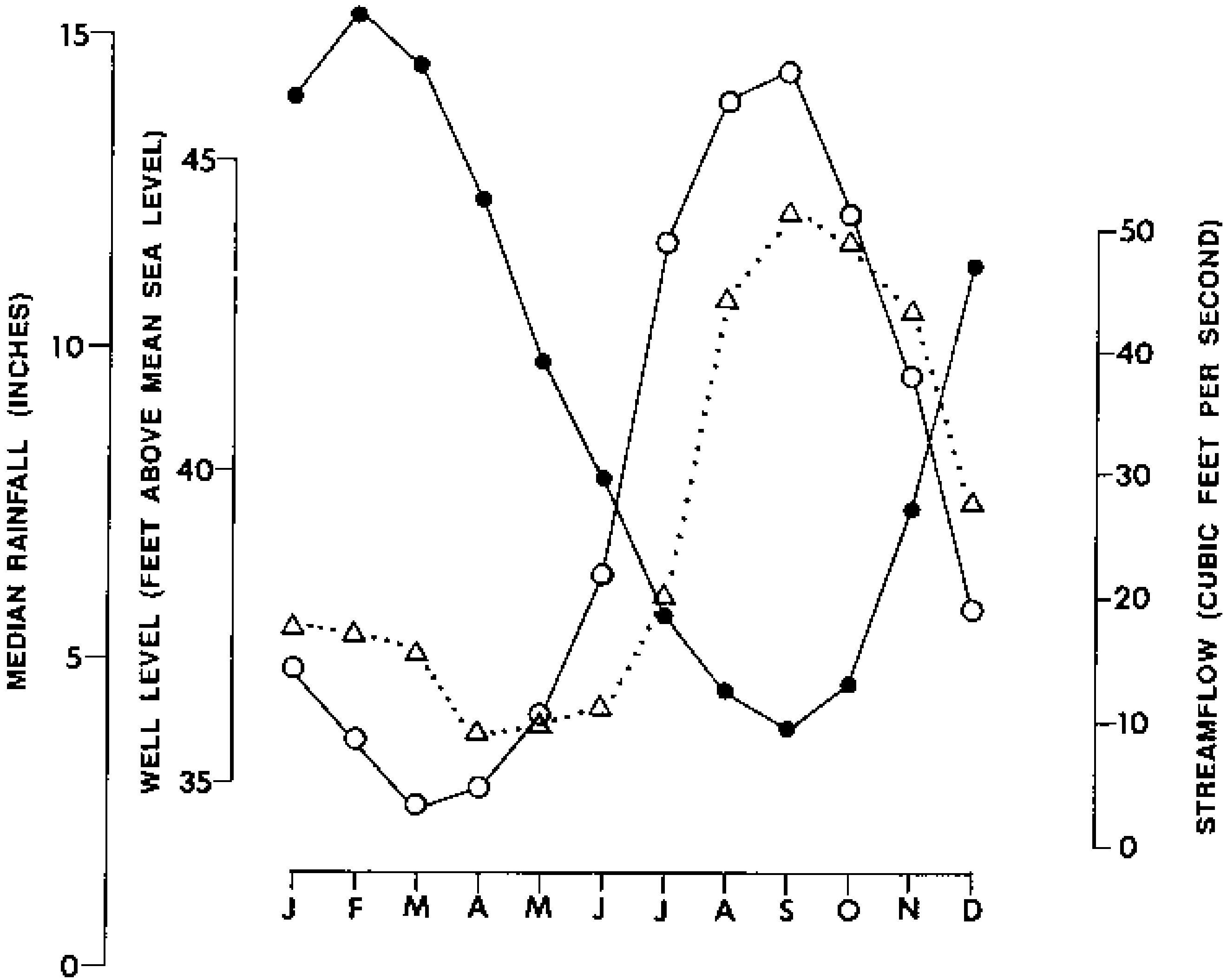

Figure 12. Annual cycle of: the rainfall at the Taguac WSMO (solid line connecting open circles); the streamflow at the Ugum River gaging station (dotted line connecting open triangles); and, the water level in well A-20 (solid line connecting black dots).

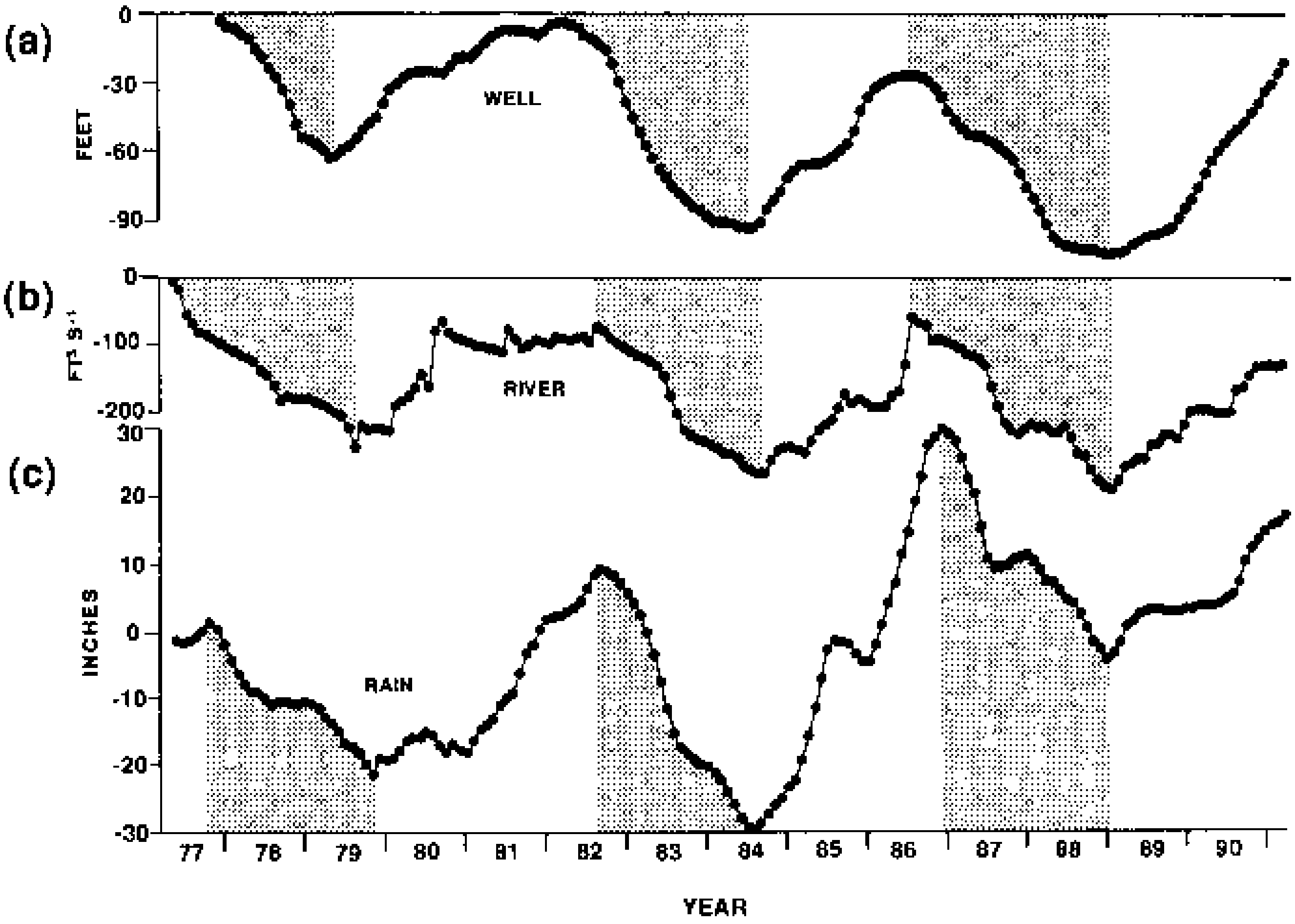

Figure 13. Running accumulations of the monthly anomalies of: (a) the water level in well A-20; (b) the streamflow in the Ugum River; and, (c) the rainfall at the Taguac WSMO. Shaded areas show periods of prolonged accumulations of negative anomalies.

Table 1. Monthly rainfall (in inches) at the Weather Service Meteorological Observatory (WMO 91217) at Taguac, Guam.

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	*Annual*
1956										8.16	13.45	10.44	n.a
1957	5.51	3.77	3.00	3.13	1.83	3.46	4.74	13.77	14.79	20.59	18.14	2.96	95.69
1958	7.91	2.23	1.70	2.44	3.87	11.53	12.89	11.22	14.43	12.12	5.80	4.62	90.76
1959	3.45	2.27	2.08	3.22	0.90	2.27	6.15	11.56	18.39	10.76	11.71	6.31	79.07
1960	2.71	0.67	1.73	1.44	5.69	7.54	7.93	14.82	9.35	11.78	11.30	6.23	81.19
1961	7.66	2.74	4.85	4.28	5.37	5.90	8.10	16.61	15.40	19.17	5.31	4.35	99.74
1962	2.24	9.17	1.66	8.66	6.68	7.97	14.98	14.12	21.86	14.95	13.09	13.08	128.46
1963	9.33	9.47	2.46	19.53	12.56	7.11	11.25	11.85	13.47	18.06	6.88	16.19	138.18
1964	1.99	4.11	4.44	7.48	20.69	7.49	7.67	8.92	19.30	14.62	6.05	6.92	109.68
1965	10.29	1.02	0.59	0.50	1.69	5.35	15.67	3.87	22.27	6.89	6.97	3.13	78.24
1966	2.13	1.69	1.71	1.31	2.51	5.72	6.74	11.39	22.28	6.96	7.26	4.76	74.46
1967	5.26	4.45	11.28	8.97	3.76	8.37	12.62	23.07	20.28	14.20	11.75	2.51	126.52
1968	5.79	8.48	3.71	1.69	3.16	6.17	12.36	14.61	11.82	13.31	11.92	3.36	96.34
1969	2.79	1.12	0.97	1.36	2.72	1.52	13.83	9.30	6.79	25.32	10.10	10.11	85.93
1970	11.93	3.60	2.68	1.22	2.96	5.60	8.99	10.42	13.70	11.65	9.77	5.71	88.23
1971	5.25	5.78	16.94	5.74	22.68	5.06	16.06	20.92	12.21	8.63	6.75	3.14	129.16
1972	4.86	6.40	11.29	3.35	3.02	7.95	20.00	18.09	16.09	7.09	4.83	6.35	109.32
1973	2.10	2.94	1.57	1.90	3.01	4.85	9.55	6.65	9.05	17.82	2.08	5.35	66.87
1974	4.27	3.13	12.25	14.83	12.00	10.46	9.32	25.66	9.96	10.00	8.03	6.20	126.11
1975	9.68	1.19	2.25	3.67	1.33	2.46	11.13	22.54	8.86	10.68	12.35	6.42	92.52
1976	20.39	13.56	9.04	4.37	40.13	6.40	13.38	24.40	10.79	6.63	7.91	8.91	165.91
1977	3.12	3.01	4.98	2.29	6.88	5.10	7.25	6.09	17.32	16.67	12.38	2.22	87.31
1978	2.44	4.99	0.85	2.65	3.48	7.89	8.91	19.63	10.01	10.49	14.10	4.80	90.24
1979	5.60	1.85	4.20	1.89	1.48	4.28	11.83	12.75	8.34	26.05	6.78	5.67	90.72
1980	2.07	14.79	3.42	2.92	8.60	7.96	10.93	9.42	24.34	12.02	7.76	6.14	110.37
1981	9.05	2.44	3.88	6.61	5.68	6.11	13.18	17.29	9.73	14.92	15.57	7.20	111.66
1982	2.92	8.77	2.46	0.99	6.35	8.77	13.61	6.32	27.13	11.86	9.34	6.33	104.85
1983	1.31	1.21	3.34	1.83	1.10	0.80	6.15	10.88	14.62	10.17	10.52	5.13	67.06
1984	3.19	4.19	4.02	1.56	3.10	6.69	6.58	24.05	17.41	9.40	12.93	5.89	99.01
1985	8.16	3.69	5.53	5.62	11.95	14.61	13.23	15.97	18.06	8.33	4.96	8.40	118.51
1986	2.01	8.71	5.60	8.36	7.77	9.08	17.41	24.87	8.02	19.71	6.05	12.43	130.02
1987	2.63	5.94	2.36	1.35	0.64	1.61	12.30	8.50	14.41	12.18	7.91	6.64	76.47
1988	8.71	1.30	1.50	2.95	2.33	7.93	14.37	9.21	10.67	14.56	5.54	4.33	83.40
1989	3.31	9.95	1.01	10.93	4.30	9.27	11.64	13.27	14.38	12.74	10.52	4.07	105.39
1990	17.01	3.72	2.64	2.52	4.95	6.28	14.49	17.25	22.00	8.46	16.41	7.35	123.08
1991	4.85	4.58	1.79	6.33	4.40	7.28	13.23	18.62	11.27	14.49	13.72	3.29	103.95
1992	9.81	1.75	2.28	2.57	6.23	3.40	10.08	38.13	5.95	15.01	12.91	2.17	110.34
1993	1.17	4.62	1.51	1.13	1.85	3.00	6.97	14.74					n.a

Table 2. Summary of the long-term (1945-1988) mean monthly rainfall (in inches) at the Naval Air Station, Agana, Guam.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	4.3	3.1	2.6	3.3	5.5	5.6	9.8	13.0	13.2	12.5	8.3	5.0

Annual Average	86.3
Dry-Season Avg.	24.4
Wet-Season Avg.	61.8

Table 3. Summary of the monthly values of the Climate Analysis Center's (CAC) Southern Oscillation index.

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960	0.0	-0.2	0.5	0.9	0.2	-0.5	0.4	0.5	0.7	-0.1	0.6	0.7
1961	-0.4	0.5	-2.6	1.1	0.2	-0.4	0.1	-0.3	0.0	-0.8	0.6	1.4
1962	1.7	0.5	-0.4	0.0	1.2	0.5	-0.1	0.3	0.5	0.9	0.2	0.0
1963	0.8	0.3	0.6	0.9	0.0	-1.5	0.3	-0.4	0.7	-1.6	-1.0	-1.4
1964	0.5	-0.2	0.6	1.7	-0.2	0.7	0.5	1.4	1.3	1.3	0.0	0.5
1965	-0.5	0.0	0.2	-1.1	0.0	-1.5	-2.3	-1.3	-1.4	-1.2	-1.8	0.0
1966	-1.4	-0.5	-1.6	-0.7	0.6	0.0	-0.1	0.3	-0.3	-0.3	-0.1	0.5
1967	1.5	1.2	0.8	-0.2	-0.4	0.6	0.0	0.4	0.5	-0.2	-0.7	-0.7
1968	0.5	0.8	0.5	0.3	1.2	1.4	0.6	-0.1	-0.3	-0.3	-0.4	0.0
1969	-1.4	-0.8	-0.1	-0.8	-0.8	0.2	-0.7	-0.6	-1.0	-1.4	-0.1	0.3
1970	1.2	-1.2	0.0	-0.5	0.1	1.1	-0.6	0.3	1.2	0.8	1.8	1.8
1971	0.2	1.4	2.0	2.6	0.9	0.2	0.1	1.4	1.5	1.8	0.5	0.1
1972	0.3	0.6	0.1	-0.5	-2.2	-1.7	-1.9	-1.1	-1.5	-1.1	-0.4	-1.5
1973	-0.4	-1.5	0.2	-0.4	0.3	1.2	0.5	1.2	1.3	0.6	2.9	1.7
1974	2.2	1.5	2.1	1.3	1.3	0.1	1.2	0.5	1.1	0.8	-0.4	0.0
1975	-0.6	0.5	1.1	1.5	0.5	1.7	2.1	2.0	2.2	1.7	1.3	2.0
1976	1.2	1.2	1.3	0.2	0.6	-0.2	-1.2	-1.5	-1.2	0.2	0.7	-0.5
1977	-0.5	0.8	-1.2	-1.3	-1.1	-2.3	-1.5	-1.4	-0.9	-1.4	-1.6	1.3
1978	-0.5	-2.6	-0.8	-0.9	1.3	0.4	0.4	0.1	0.0	-0.8	-0.1	-0.2
1979	-0.5	0.6	-0.5	-0.7	0.5	0.6	1.3	-0.7	0.1	-0.4	-0.6	0.9
1980	0.3	0.0	1.1	1.6	-0.3	-0.7	-0.2	-0.1	-0.5	-0.3	-0.5	-0.2
1981	0.3	0.5	2.0	0.6	0.8	1.6	0.8	0.4	0.3	-0.7	0.1	0.4
1982	1.0	0.0	0.0	-0.1	-0.6	-2.5	-2.0	-2.7	-1.9	-2.2	-3.2	2.5
1983	-3.4	-3.5	-3.2	-2.1	0.9	-0.5	-0.9	-0.4	0.9	0.3	-0.1	-0.1
1984	0.0	0.4	-0.8	0.4	0.0	-1.2	0.0	0.1	0.1	-0.6	0.3	-0.3
1985	-0.5	0.8	0.2	1.4	-0.2	-1.4	-0.3	0.7	0.0	-0.8	0.4	0.1
1986	0.8	1.2	0.1	0.1	-0.6	1.0	0.1	-0.9	-0.5	0.6	-1.6	-1.6
1987	-0.7	-1.5	-2.0	-2.7	-2.0	2.7	-1.8	-1.7	-1.1	-0.7	0.1	-0.6
1988	0.3	0.6	0.1	0.0	1.1	-0.3	1.1	1.4	1.9	1.3	1.9	1.3
1989	1.7	1.1	1.1	1.6	1.2	0.5	0.8	-0.8	0.6	0.6	-0.4	-0.7
1990	0.2	2.4	-1.2	0.0	1.1	0.0	0.5	-0.6	-0.8	0.1	-0.7	-0.5
1991	0.6	-0.1	-1.4	-1.0	-1.5	-0.5	-0.2	-0.9	1.8	1.5	-0.8	-2.3

Table 4. Summary of the monthly values of the Japanese Meteorological Agency's Index of the easterm equatorial Pacific SST averaged between 4°N to 4°S and 150°W to 90°W. Values are departures from normal in °C.

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960	0.0	0.3	0.1	0.2	0.1	-0.3	0.0	0.1	0.1	0.6	0.4	0.5
1961	0.3	0.1	0.0	0.2	0.0	0.4	-0.5	-0.5	-1.2	0.8	0.4	0.3
1962	-0.2	0.0	-0.4	0.5	0.4	0.3	0.3	0.2	0.6	-0.4	0.7	1.0
1963	0.5	0.4	0.0	0.3	0.3	0.5	1.1	0.9	0.5	0.7	1.0	0.9
1964	0.5	0.1	0.1	-0.7	-1.2	1.2	-0.5	1.1	0.9	0.8	1.1	1.3
1965	-0.8	-0.2	0.1	0.5	0.8	1.0	1.1	1.2	1.2	1.2	1.4	1.5
1966	1.1	0.6	0.1	0.1	-0.7	0.0	0.2	0.0	-0.7	0.2	0.5	0.8
1967	0.4	0.0	-0.7	-0.5	0.0	0.3	0.2	0.5	1.2	-0.9	0.8	0.9
1968	1.0	1.3	-1.1	-0.4	-0.7	0.1	0.6	0.3	0.2	0.3	0.5	0.7
1969	0.8	0.4	0.7	0.5	1.1	0.6	0.3	0.6	0.8	0.8	0.9	1.0
1970	1.0	0.3	0.1	0.3	-0.7	1.1	-2.0	-1.3	1.4	1.0	-1.5	1.8
1971	-1.3	-1.5	-1.1	0.5	0.6	-0.6	-0.4	-0.6	-0.9	1.0	0.7	-1.2
1972	-0.6	-0.1	0.1	0.5	0.7	0.9	1.5	2.1	1.5	1.9	2.4	2.3
1973	1.8	1.0	0.3	-0.5	-0.4	-0.7	-1.2	1.1	-1.4	-1.3	1.7	1.7
1974	-1.8	-1.2	0.7	-0.2	-0.2	0.2	-0.2	0.0	-0.3	-0.7	-0.6	0.7
1975	0.4	-0.6	-0.5	-0.1	0.8	-1.2	0.6	0.7	-1.1	-1.5	1.2	-1.8
1976	-1.7	-1.1	0.5	-0.2	0.0	0.7	1.0	0.9	1.1	0.9	1.1	0.8
1977	0.9	0.6	0.5	-0.4	0.1	0.3	0.3	-0.4	-0.1	0.2	0.5	0.4
1978	0.4	0.2	0.0	0.5	-0.6	-0.6	0.6	-0.7	-0.6	0.4	0.0	0.2
1979	-0.1	0.2	0.3	0.3	0.4	0.4	-0.1	0.2	1.0	0.4	0.3	0.4
1980	0.3	0.3	-0.1	0.1	0.3	0.5	0.2	-0.2	-0.2	-0.1	0.3	0.4
1981	0.6	-0.8	-0.2	-0.4	0.2	0.1	-0.3	0.6	-0.1	0.2	0.5	0.3
1982	0.4	0.3	0.2	0.3	0.9	0.9	0.7	1.1	1.6	2.3	2.5	3.3
1983	3.2	2.4	1.8	1.7	2.1	2.2	1.0	1.0	0.8	-0.3	-0.6	-0.6
1984	-0.5	0.4	-0.1	0.1	-0.4	-1.0	0.5	0.0	0.0	0.6	-0.7	-0.8
1985	-0.9	-0.4	0.3	-0.6	-0.7	0.8	-0.3	-0.6	-0.2	-0.7	-0.4	0.4
1986	-0.6	0.2	0.0	0.2	-0.1	0.1	0.5	0.2	0.8	0.7	1.1	1.0
1987	0.9	1.1	1.3	1.2	1.4	1.1	1.2	1.4	1.7	1.3	1.3	1.2
1988	0.6	0.0	0.5	-0.3	0.9	-1.9	-1.5	-1.2	-0.9	1.6	-1.5	1.6
1989	-1.2	-0.8	-0.6	-0.6	-0.2	-0.2	0.1	-0.3	-0.1	-0.3	-0.3	0.3
1990	-0.3	0.3	0.0	0.4	0.6	0.4	0.2	0.4	0.2	0.1	0.1	0.2
1991	0.2	0.2	0.1	0.3	0.8	1.2	1.3	0.8	0.4	0.8	1.2	1.2

Table 5. Summary of the monthly mean streamflow (in cubic feet per second) at the Ugum River gage.*

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1977						4.9	5.6	6.9	38.5	36.7	38.8	23.3
1978	11.0	11.0	9.5	5.5	4.4	5.0	8.3	36.4	35.0	27.2	50.3	24.2
1979	18.4	18.4	8.7	5.9	5.2	4.3	13.3	25.9	20.8	84.6	36.5	30.3
1980	14.9	14.9	54.6	12.7	18.0	23.2	40.1	26.1	131.9	63.2	27.4	20.2
1981	14.0	14.0	10.0	8.9	7.1	6.7	16.4	78.6	36.0	37.1	47.6	36.1
1982	14.5	14.5	22.8	8.1	7.7	13.6	23.6	32.6	76.2	46.8	33.1	19.0
1983	10.7	10.7	8.2	5.8	4.9	4.0	6.0	15.8	24.1	23.7	36.6	22.9
1984	11.8	11.8	9.8	5.6	4.8	6.1	9.4	38.5	45.9	48.1	64.2	39.9
1985	20.6	20.6	10.3	7.4	22.9	30.3	27.8	49.3	70.9	69.6	31.0	32.1
1986	12.7	12.7	13.9	10.0	24.6	18.9	56.3	113.7	43.7	45.6	21.1	31.0
1987	12.7	12.7	10.1	5.8	4.6	4.1	11.5	10.0	23.7	23.2	32.4	21.0
1988	25.6	25.6	11.1	7.8	5.0	9.6	28.8	27.3	29.2	43.4	21.9	12.1
1989	11.2	28.5	13.8	28.6	14.0	16.8	19.1	64.8	53.3	63.4	42.0	23.5
1990	37.9	17.9	11.1	8.2	10.3	7.6	19.2	43.7	84.6	52.4	60.1	39.4
1991	17.5	14.2	11.1	10.5	11.4	15.2	22.9	57.2	49.1	64.1	75.8	33.3
1992	32.4	15.2	11.2	9.0	7.3	6.5	8.7	79.8	49.7	55.0	76.1	25.0
1993	14.0	8.5	6.6	5.1	4.5							
Mean	**17.5**	**17.2**	**14.4**	**9.0**	**9.8**	**11.0**	**19.8**	**44.1**	**50.8**	**49.0**	**43.4**	**27.2**

* Values after 1989 have not been published and are considered provisional data subject to change.

Table 6. Summary of the monthly values of the water level (in feet above mean sea level) in well A-20, Ordot Guam.

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1978	42.1	44.4	45.8	42.6	39.2	36.2	34.1	32.5	31.5	30.9	32.5	33.2
1979	42.2	46.2	44.6	42.0	38.9	41.0	40.0	38.5	39.1	40.4	41.7	46.2
1980	53.0	52.3	49.0	46.9	44.0	40.9	38.2	36.7	35.4	35.7	42.2	46.9
1981	46.3	47.8	48.9	47.6	44.3	41.5	38.8	36.8	35.8	36.7	39.0	42.1
1982	48.2	49.2	47.3	44.4	41.0	38.4	36.1	34.6	33.7	33.2	33.3	35.4
1983	37.6	39.6	40.2	38.4	36.5	35.0	33.8	33.2	32.9	33.6	37.2	41.6
1984	43.7	44.8	46.3	43.8	41.3	38.8	37.2	36.7	38.6	42.1	43.6	46.9
1985	51.1	51.1	48.1	45.2	41.8	40.4	38.8	38.6	38.2	40.2	45.4	51.1
1986	52.6	51.6	47.9	46.0	43.3	40.6	38.2	36.2	34.8	34.4	36.6	39.8
1987	40.8	42.8	42.9	42.2	41.6	38.6	36.5	34.9	33.9	34.9	36.7	37.3
1988	39.3	43.0	41.2	38.4	35.8	37.5	36.0	35.8	35.3	35.6	39.1	43.1
1989	45.7	47.7	46.8	44.7	44.7	41.7	39.1	37.8	36.8	37.6	40.9	48.0
1990	50.7	50.2	51.3	50.2	47.4	44.6	41.3	39.8	38.9	39.7	43.9	47.3
1991	50.4	51.3	50.8	49.3	46.3	43.0	40.3	38.7	38.0	38.0	40.2	49.1
1992	50.0	51.5										
Mean	**46.0**	**47.3**	**46.5**	**44.4**	**41.8**	**39.9**	**37.7**	**36.5**	**35.9**	**36.6**	**39.4**	**43.4**

Table 7. Annual, wet- and dry-season rainfall (in inches) at the Weather Service Meteorological Observatory (WMO 91217) at Taguac, Guam. Italicized numbers in parentheses indicate the rank: (1) = highest; (35) = lowest value during 1957-1991. The years 1992 and 1993 are included but are not ranked. Mean values and standard deviations are for the period 1957-1991.

YEAR	ANNUAL	DRY SEASON	WET SEASON
1957	95.69 (20)	20.70 (25)	74.99 (10)
1958	90.76 (22)	29.68 (17)	61.08 (29)
1959	79.07 (30)	14.19 (33)	64.88 (24)
1960	81.19 (29)	19.78 (27)	61.41 (28)
1961	99.74 (17)	30.80 (15)	68.94 (20)
1962	128.46 (5)	36.38 (13)	92.08 (1)
1963	138.18 (2)	60.46 (2)	77.72 (7)
1964	109.68 (12)	46.20 (5)	63.48 (25)
1965	78.24 (31)	19.44 (28)	58.80 (32)
1966	74.46 (33)	15.07 (31)	59.39 (31)
1967	126.52 (6)	42.09 (6)	84.43 (5)
1968	96.34 (19)	29.00 (19)	67.34 (22)
1969	85.93 (27)	10.48 (34)	75.45 (9)
1970	88.23 (25)	27.99 (20)	60.24 (30)
1971	129.16 (4)	41.45 (8)	87.71 (3)
1972	109.32 (13)	36.87 (12)	72.45 (13)
1973	66.87 (35)	16.37 (30)	50.50 (35)
1974	126.11 (7)	56.94 (3)	69.17 (18)
1975	92.52 (21)	20.58 (26)	71.94 (15)
1976	165.91 (1)	93.89 (1)	72.02 (14)
1977	87.31 (26)	25.38 (21)	61.93 (27)
1978	90.24 (24)	22.30 (24)	67.94 (21)
1979	90.72 (23)	19.30 (29)	71.42 (16)
1980	110.37 (11)	39.76 (9)	70.61 (17)
1981	111.66 (10)	33.77 (14)	77.89 (6)
1982	104.85 (15)	30.26 (16)	74.59 (12)
1983	67.06 (34)	9.59 (35)	57.47 (34)
1984	99.01 (18)	22.75 (23)	76.26 (8)
1985	118.51 (9)	49.56 (4)	68.95 (19)
1986	130.02 (3)	41.53 (7)	88.49 (2)
1987	76.47 (32)	14.53 (32)	61.94 (26)
1988	83.40 (28)	24.72 (22)	58.68 (33)
1989	105.39 (14)	38.77 (10)	66.62 (23)
1990	123.08 (8)	37.12 (11)	85.96 (4)
1991	103.95 (16)	29.23 (18)	74.72 (11)
1992	110.34	26.04	84.30
1993	n/a	13.28	n/a
Mean	101.84	31.63	70.21
Std. Dev.	22.2	16.6	9.8

Table 8. Summary of the long-term (1957-1991) mean monthly rainfall (in inches), median monthly rainfall (in inches), and the difference between the median and mean monthly rainfall at the Taguac WSMO.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	5.9	4.7	4.0	4.5	6.6	6.4	11.3	15.2	14.6	13.3	9.6	6.1
Median	4.7	3.7	2.7	2.9	4.1	6.3	11.7	13.9	14.4	12.2	9.6	58
Difference:	1.2	1.0	1.3	1.6	2.5	0.1	-0.4	1.3	0.2	1.1	0.0	0.3

Table 9. Cross-correlation (r) and Spearman's rank cross-correlation coefficients (r_S) between selected pairs of variables. Variable descriptions are listed in section on Guam rainfall and ESNO indices.

				Significance of r_S			
Var. 1	**Var. 2**	**r**	**r_S**	**90%**	**95%**	**99%**	**years**
<Rain>	**<SOI>**	.22	29	Y	N	N	1957 1991
<Rain>	**D_1SST**	.57	.50	Y	Y	Y	1957-1991
<Rain>	**D_2SST**	.53	.44	Y	Y	Y	1957-1991
<Rain>	**D_3SOI**	-.37	-.45	Y	Y	Y	1957-1991
<Rain>	**D_3SST**	.50	.49	Y	Y	Y	1957-1991
<Rain>	**<TC-180>**	.42	42	Y	Y	N	1957-1992
Rain Dry	**Rain Wet**[*]	.09	.05	N	N	N	1957-1991
Rain Dry	**SOI Dry**	.52	.50	Y	Y	Y	1957-1991
Rain Dry	**D_1SST**	.44	.39	Y	Y	N	1957-1991
Rain Dry	**D_2SOI**	-.50	-.46	Y	Y	Y	1957-1991
Rain Dry	**D_3SST**	.43	36	Y	Y	N	1957-1991
Rain Dry	**D_3SOI**	-.21	-.41	Y	Y	N	1957-1991
Rain Dry	**D_4SST**	-.39	.39	Y	Y	N	1957-1991
Rain Wet	**Rain Dry**	.37	.49	Y	Y	Y	1957-1991
Rain Wet	**SOI Wet**	.22	.29	Y	N	N	1957 1991
Rain Wet	**D_1SST**	.50	.48	Y	Y	Y	1957-1991

[*] Wet season in this line refers to the wet season of the year prior to the dry season.