RAINFALL CLIMATOLOGY FOR POHNPEI ISLANDS, FEDERATED STATES OF MICRONESIA

Mark A Landers
and
Shahram Khosrowpanah

WATER AND ENVIRONMENTAL RESEARCH INSTITUTE
OF THE WESTERN PACIFIC
UNIVERSITY OF GUAM

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By

Mark A. Lander
and
Shahram Khosrowpanah

University of Guam
Water and Environmental Research Institute
of the Western Pacific
UOG Station, Mangilao, Guam 96923

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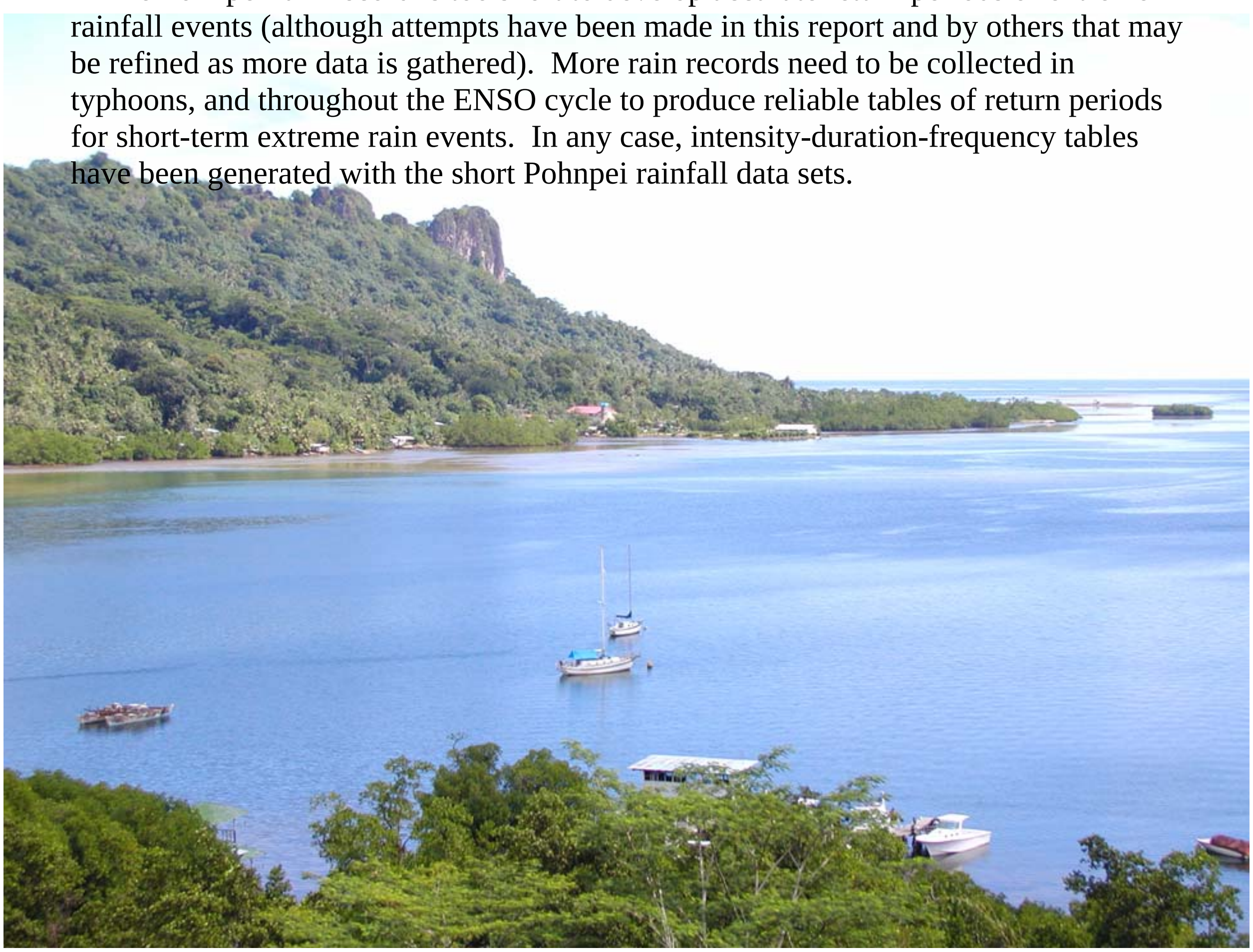
Abstract

This technical report presents the results of the first year of a collaborative effort between WERI and the Conservation Society of Pohnpei to measure the rainfall across the island of Pohnpei. Rain gages were placed in several locations to include the coastal perimeter, the mountain slopes, and the remote highland interior of the island. The discussion includes: general rainfall statistics, a summary of the annual distribution of rainfall, and an examination of the return periods of short-term high-intensity rainfall events (Section 2); the effects of ENSO on the climate and weather of Pohnpei (Section 3); a summary of tropical cyclones affecting the island (Section 4); and, an examination of month-to-month, inter-annual, and inter-decadal variations in mean annual rainfall (Section 5).

The distribution of rainfall on Pohnpei is affected by the topography, and the mean annual rainfall totals among recording stations on Pohnpei differ by as much as 150 inches! The region in the vicinity of Pohnpei's international airport receives the lowest annual total of about 120 inches. The highest measured annual average of approximately 300 inches occurs atop Nahna Laud in the highland rainforest of Pohnpei's interior. Charts of Pohnpei's mean annual rainfall were produced from the first year of data collected from the WERI/CSP rain gage network. Earlier charts of Pohnpei's mean annual rainfall using PRISM were found to be quite accurate. Future refinements are expected.

The Pohnpei rain record is too short to develop accurate return periods of extreme rainfall events (although attempts have been made in this report and by others that may be refined as more data is gathered). More rain records need to be collected in typhoons, and throughout the ENSO cycle to produce reliable tables of return periods for short-term extreme rain events. In any case, intensity-duration-frequency tables have been generated with the short Pohnpei rainfall data sets.



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1. Introduction

a. Local Setting

Pohnpei Island is a "high" volcanic island, having a rugged, mountainous interior with some peaks as high as 2600 feet. It measures about thirteen miles across and is roughly circular in shape. It is the largest and tallest island in the FSM. The interior peaks get plenty of rainfall annually and this creates more than 40 rivers that feed the lush upper rain forest. A coral reef surrounds the island, forming a protected lagoon. There are few beaches on Pohnpei — mangrove swamps surround the coast. Several smaller islets and atolls, many of them inhabited, lie nearby and are included in the State of Pohnpei. The world-famous Nan Madol islet complex is located on the southeast coast of Madolenihmw municipality on Pohnpei Island (Fig. 1). The ruins at Nan Madol consist of 92 man-made islets covering an area of approximately 200 acres. The most spectacular of the islets have remains of sea walls, tombs and other structures built of large columnar basalt stones, brought to Nan Madol from other parts of Pohnpei Island.

The island of Pohnpei (6.9N 158.2E) lies about halfway between Hawaii and the Philipines in the recently formed country of the Federated States of Micronesia (FSM) (Fig. 2). Pohnpei State is made up of one large volcanic island and six inhabited atolls, with most of its 133 square miles on Pohnpei Island. Its population is 34,486 (census 2000). Pohnpei State is the national capital of the FSM. Pohnpei is a beautiful and fertile island with much local agriculture and a growing tourism industry. The main town on the island is Kolonia, on the north side.

The mountainous islands of the Pacific are seeing increased activity in development and agriculture. In addition, surface water is being increasingly tapped as a source of potable water and has been used for hydroelectric generation. The soils of these islands are for the most part extremely thin and very easily eroded. Episodes of high rainfall events make the islands very susceptible to soil erosion and slope failures (such as the slope failure at Sokehs in 1997 that killed 30 people, and the slope failures at Chuuk during tropical cyclone Chata'an in 2002). The United States Department of Agriculture Natural Resources Conservation Service (USDA/NRCS) has implemented several programs to help manage and reduce soil erosion on the islands. These programs require accurate estimates of annual soil erosion, which is calculated using the Revised Universal Soil Loss Equation (RUSLE). The Universal Soil Loss Equation (USLE) and its updated revision the Revised Universal Soil Loss Equation (RUSLE) are the equations used most commonly to predict soil erosion rates and soil losses in the tropical pacific. In tropical environments, climate or specifically the volume and intensity of rainfall is most significant cause of high soil erosion rates (Foster et al., 1982). This factor is identified in the USLE and RUSLE as the R or rainfall erosivity factor. It is important to have an accurate rainfall record with short-period (e.g., 15-minute duration) for calculating R-factor.

Existing annual rainfall maps for most of the islands of Micronesia are incomplete, inaccurate and/or non-existent for many areas. An assessment of existing analyses appear to overly favor trade-wind-type precipitation distribution patterns common to Hawaii and to the dry seasons of Guam and the CNMI. The isohyets of annual rainfall on Pohnpei Island (Fig. 3) are depicted in close association with the height contours of the island. The rain in the central highlands is shown as being double that of the rainfall on the coast. The influence of elevation on rainfall distribution and rainfall extreme events in the tropical latitudes needs to be better assessed and better depicted.

Pohnpei is affected by many weather systems (large and small) of the tropical atmosphere: typhoons; the east Asian Monsoon; the Pacific trade winds; the Inter-tropical Convergence zone (ITCZ); El Niño and La Niña; and, deep convection on scales ranging from individual towering cumulus clouds to mesoscale convective systems (Maddox 1980). At its latitude of approximately 7° N, Pohnpei does not have a prolonged dry season. Deep convection affects the island year-round. Because of its latitude and its longitude, Pohnpei is rarely hit by a typhoon. Pohnpei is, however, affected by many tropical disturbances, which later move to the northwest and intensify into tropical storms and typhoons that affect other places.

Inter-annual variations of Pohnpei's rainfall are closely linked to the El Niño/Southern Oscillation (ENSO) phenomenon. Most of Micronesia (including Pohnpei) is in an ENSO core region that features dry conditions in the year following El Niño (Ropelewski and Halpert 1987), and an increase in the level of threat from typhoons during an El Niño year. The causes of extreme daily rainfall events on Pohnpei are island thunderstorms, tropical disturbances, the rare occurrence of tropical storms and typhoons, deep convection associated with monsoon westerly winds, and other so-called mesoscale weather systems that are wide-spread throughout the deep tropics for most of the year.

b. Project Goals

With support from the United States Geological Survey (USGS) and with on-island help from the Conservation Society of Pohnpei (CSP), and the local affiliate of the Nature Conservancy, the WERI project team assembled a network of manual and electronic rain gauges around the island of Pohnpei (Fig. 4). This included the placement of rain gages in the remote interior upland rain forest regions where precipitation data has never been collected.

The project goals were:

(1) an accurate assessment of the spatial distribution of rainfall on Pohnpei (e.g., isohyets of annual mean rainfall);

(2) some preliminary estimates of the magnitudes of extreme short-term rainfall rates; and,

(3) an understanding of the general character of the rainfall (e.g., hourly distribution and month-to-month variability).

An ancillary goal of this study was to determine whether fog drip is a substantial contributor to the water budget on Pohnpei. Although the WERI study was primarily to examine the rainfall distribution and short-term rainfall rates on the island of Pohnpei, there is a strong likelihood that fog drip is an important part of the water budget in Pohnpei, so the problem was addressed (albeit so far with limited success).

The project required several phases: (1) design and testing of the manual and electronic rain gages on Guam, (2) assembling the rain gages at appropriate sites on the island of Pohnpei, and (3) collection and analysis of the rainfall data. On Guam, the researchers at WERI designed, constructed and tested PVC rain collection tubes intended as a possible cheap and easy way to measure rainfall differences among many locations. Also, on Guam, they tested the performance of the electronic rain gages. Tests were successful, and the WERI/CSP network of rain gauges was shipped to Pohnpei and installed there on June 23, 2003. It is hoped that a one-year continuous operation of the network would be adequate to determine the relative differences between mountain and coastal rainfall. The long-term records of the National Weather Service Office (WSO) in Kolonia are invaluable background information, and the instruments at the weather station provided a validation site for testing of our rain gauges.

This report presents a description of the weather and climate of Pohnpei to include: general rainfall statistics, a summary of the annual distribution of rainfall, and an examination of the return periods of short-term high-intensity rainfall events (Section 2); the effects of ENSO on the climate and weather of Pohnpei (Section 3); a summary of tropical cyclones affecting the island (Section 4); and, an examination of month-to-month, inter-annual, and inter-decadal variations in mean annual rainfall (Section 5).

Figure 1. The crowning achievement of Nan Madol is the royal mortuary islet of Nandauwas. Here, walls of 18 to 25 feet high surround a central tomb enclosure within the main courtyard. An impressive portal (shown here) marks the entry into the mortuary enclosure of Nandauwas. The second entryway in Nandauwas leads to the inner courtyard and central tomb, where the remains of the deceased *saudeleur* and, later, the *nahnmwarki* were interred.

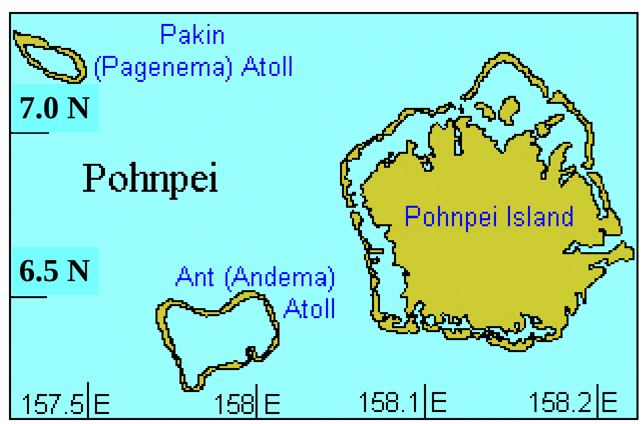
(a)

Figure 2. Pohnpei locator maps showing (a) world setting, (b) aerial photo of the Pohnpei International Airport (looking NE), (c) Pohnpei Island with Municipalities, and (d) Pohnpei Island and adjacent atolls.

(b)

(c)

(d)



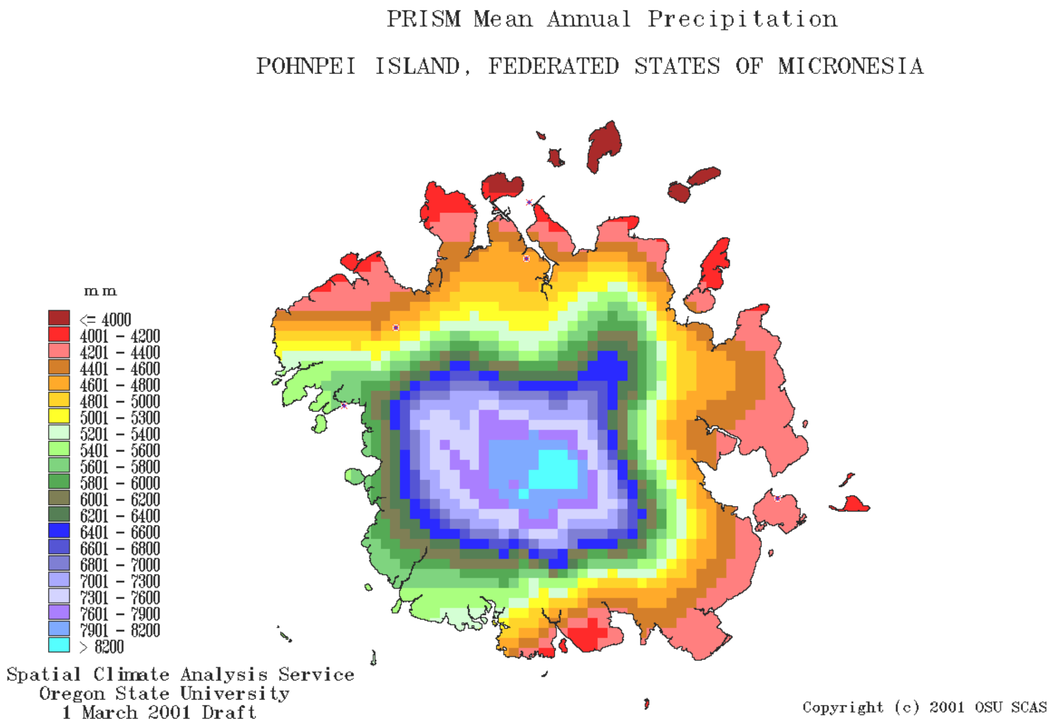


Figure 3. Estimated annual rainfall for Pohnpei prepared by the Spatial Climate Analysis Service, Oregon State University, using the Precipitation-elevation Regression Independent Slopes Model (**PRISM**) analysis (Daly, et al. 1994). Note that the rain in the central highlands is estimated to be nearly twice that of the rain along the coast.

2. Data Collection and Method

a. Data and method

There are very few locations on Pohnpei where rainfall has been measured in a consistent manner for any appreciable length of time. A continuous 30-year daily rainfall record is often considered sufficient to compute baseline monthly and annual averages, and to make accurate estimations of the recurrence intervals of heavy rainfall events. Monthly data for the Pohnpei Weather Service Office (WSO) exists for the period 1954 to present (see Table 1). Hourly rainfall data from Fischer-Porter type recording rain gages is available for Pohnpei at two locations: the WSO and the Hospital (near the current WSO). These gages record rainfall at 0.10-inch increments. They are somewhat difficult to maintain, so the records from these gages are often piecemeal. They are, however, the only sources of data for estimates of return-periods of short-term (e.g., hourly and 3-hourly) rainfall events. Monthly rainfall is available from several locations during the Japanese period of record (1926-1937) (Table 2). Table 3 is a summary of metadata (e.g., location and elevation) for the WERI/CSP rain gage network.

All of the historical rainfall readings acquired on Pohnpei are from stations located along the coastal perimeter of the island (Fig. 4). No sites have ever been located in the rain forests of the mountainous interior of the island. There are meteorological reasons why the interior highlands could receive more rain than the coastal perimeter of the island including the upslope ascent of moist air (the typical mechanism for the occurrence of heavy rainfall in the higher elevations of the Hawaiian Islands), and inland convection driven by daytime heating of the island. Also, there is evidence that the western side of the island is wetter than the eastern side of the island. Personal observation confirms that, as on Guam and other tropical islands, daytime convection forms and/or advects downwind of the island in the form of an island could plume. On Guam this manifests in a concentration of thunderstorm activity offshore to the west of the island in east wind conditions, and to the northeast of the island when the southwest monsoonal winds are blowing. Lightning observed after sunset on Pohnpei during travels there by the project investigators has a strong preference for the western side or offshore of the western side of the island in conditions of easterly wind flow. Winds on Pohnpei can become westerly, especially during El Niño, but the project investigators have not been on Pohnpei during such times.

The methodology used in the Precipitation-elevation Regression Independent Slopes Model (PRISM) analysis (Daly, et al. 1994) for Pohnpei Island also predicts that the interior highlands receive much more rain than the coastal perimeter (Fig. 3). The PRISM model indicates that the annual rainfall in the mountainous center of Pohnpei is over twice that of the coastal perimeter. This is an enormous amount of rainfall (over 300 inches per year) for the interior, and represents tremendous gradients of mean annual rainfall on this relatively small, 13-mile diameter, roughly circular island.

Table 1. Name, location, and length of record (years) for the rainfall databases collected and maintained by the Weather Service Office on Pohnpei.

WSO LOCATIONS		
SITE NAME	LOCATION	PERIOD
Kolonia WSO	N6 52 2100 E158 13 39.5	JAN 1950 CURRENT
Paies Kitti Coop Observer	N6 50 48.8 E158 15 30.4	SEP 1981 JUL 2002
Madolenimw Coop Observer	N6 50 37.5 E158 16 35.8	JAN 1974 CURRENT
Palikir Coop Observer	N6 50 00.9 E158 17 51.2	SEP 1991 CURRENT
Song Kroun Coop Observer	N6 54 31.4 E158 09 19.5	JAN 2002 CURRENT
Pohnpei Hospital	N6 58 46.8 E158 12 01.1	JAN 1980 DEC 2002

Table 2. Site Name and length of record (years) for the monthly rainfall pre-war Japanese rainfall databases on Pohnpei.

JAPANESE LOCATIONS	
SITE NAME	PERIOD OF RECORD
Palikir	APR 1934 DEC 1937
Paies Kitti	JAN 1931 DEC 1937
Kolonia	JAN 1926 DEC 1937
Madolenihmw	JAN 1929 DEC 1937

Table 3. Site Name and elevation (feet), location, and gage types for the WERI raingage network on Pohnpei.

WERI/CSP Network			
SITE NAME	LOCATION	Type Of RAINGAGE	Installation Date
Nahnalaud Summit (2,650 ft elevation)	N6 52 21.00 E158 13 39.5	Electronic #1 Electronic #2 1 manual	June 2003 July 2004 June 2003*
Nahnalaud forest (2,550 ft)	N6 52 19.80 E158 13 36.6	1 electronic	June 2003**
Nihpit (1,650 ft)	N6 50 48.8 E158 15 30.4	1 electronic 1 manual	June 2003
Near Mahnd village	N6 50 37.5 E158 16 35.8	1 manual	June 2003
Mayer office at Madolenihmw	N6 50 00.9 E158 17 51.2	1 electronic	June 2003
College of Micronesia	N6 54 31.4 E158 09 19.5	1 electronic 1 manual	June 2003
Pohnpei Airport	N6 58 46.8 E158 12 01.1	1 electronic 1 manual	June 2003
U Mayor's Office	N6 57 12.6 E158 16 40.0	1 electronic 1 manual	July 2004 August 2003
Peleng (School) Kitti	N6 52 47.0 E158 09 39.5	1 electronic 1 manual	August 2004

* Gage damaged April 2004 ** Gage failed March 2004

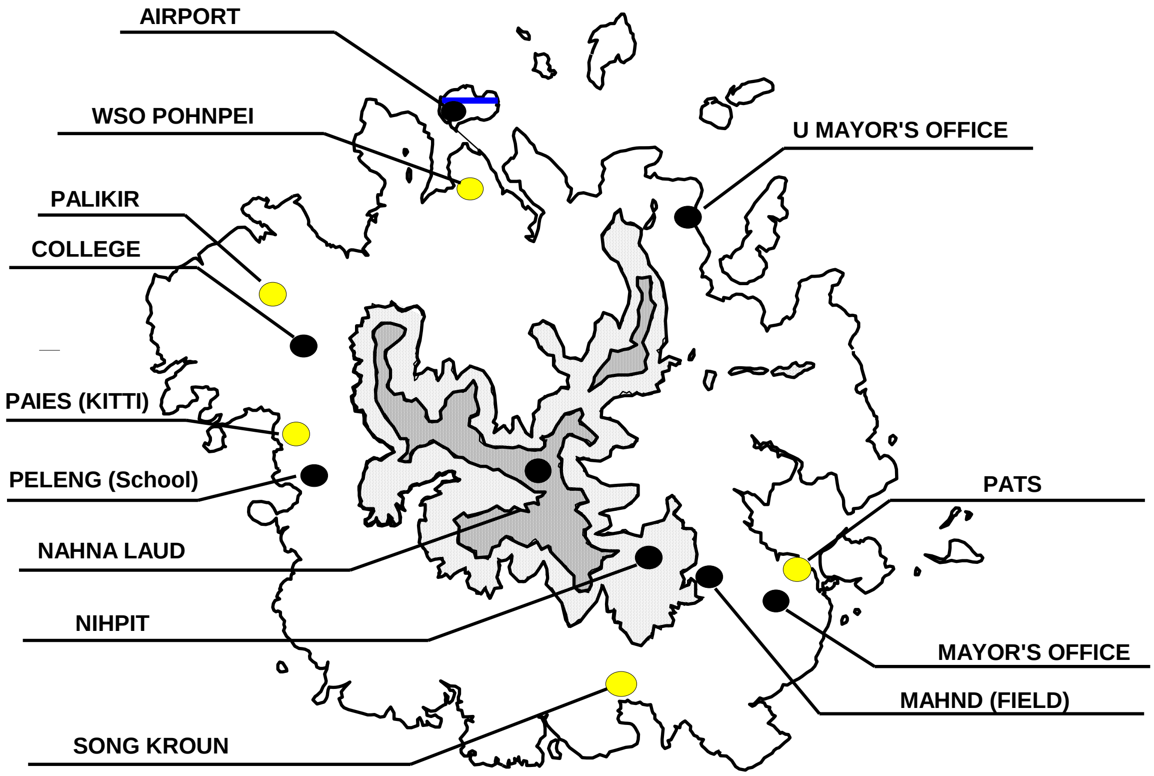


Figure 4. Stations on the island of Pohnpei where there are records of rainfall. Black dots are WERI/CSP Network. Gray dots are National Weather Service rain gauges. Half-tone shading indicates elevation: light gray ≥ 250 m; dark gray ≥ 500 m.

In order to investigate the rainfall differences between the highlands and the coastal regions of Pohnpei (which are currently depicted to differ by a factor of two for annual rainfall), a transect of manual and electronic rain gages was set up extending from the coast to the highlands of the island. These are listed in Table 3. Figure 4 shows the location of WERI/CSP and WSO rain gages. Since rainfall is so heavy on Pohnpei (nearly 20 inches per month), simple manual rain gauges that consist of a 56-inch tall 6-inch diameter PVC cylinder capped with a coupling holding a debris screen were constructed (Fig. 5a). These are cheap, easy to install and to maintain. Although not highly accurate, these crude manual gages may be able to adequately measure the relative differences of rainfall among the sites. Tipping bucket rain gages with data loggers (Fig. 5b) were set up at six of the transect sites (Madolenihmw Mayor's Office, Nihpit, Nahna Laud, the Airport, and the College of Micronesia). Two more electronic tipping bucket rain gages were added a year later: one at the Peleng site on the west side of the island, and the other at the U Mayor's Office on the northeast side of the island. At three of the sites (at the Airport, the College, and Nahna Laud), PVC manual rain gages were collocated with WERI/CSP electronic rain gages. A Manual rain gage was also placed at a site (Mahnd) along the mountain transect between the Mayor's Office and Nihpit, and on the grounds of the WSO. Nearly a year later, PVC manual rain gages were set-up at the U Mayor's Office, and at the school in Peleng.

The top of Nahna Laud was the selected site in the central highlands where two rain gages were set up near one another – one in an open area, and another under the canopy of the rainforest – to assess the impact of fog drip on the water budget of the island. The central highlands of Pohnpei are of sufficient height (~2,000 – 2,600 ft) to often be enshrouded in fog. Deposition of cloud droplets onto leaves and subsequent coalescence and drip may enhance the total water budget substantially. This so-called fog-drip may also be responsible for a substantial portion of the water budget on portions of the islands of Hawaii. An electronic gage is required at this site to determine the times when it is actually raining at the open-area location. The percent of time the highlands are enshrouded in cloud is itself an unknown. A project currently funded by the USGS is attempting to quantify the importance of fog drip to ecosystem hydrology and water resources in tropical mountain cloud forests on East Maui, Hawaii, where there is evidence that fog drip is substantial (Juvik, J.O. and P.C. Ekern, 1978). The investigators on the Maui project are measuring the amounts of water input from fog by analyzing for stable isotope composition. Previous work (Ingraham and Matthews, 1995) has shown that rain and fog have unique isotopic signatures, so that stable isotopes of water can be used to track the fog water through the hydrologic cycle.

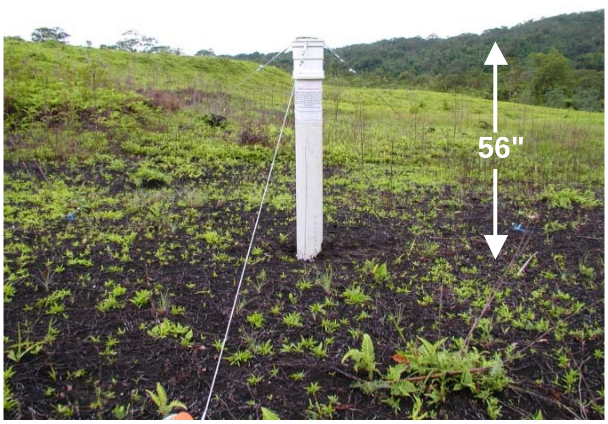
The WERI project investigators traveled to Pohnpei at least once every three months to perform maintenance on the gages and to collect the data. Personnel at the Pohnpei CSP were contracted to perform readings of the rain gauges and routine maintenance. An estimate of the contribution of fog-drip to the water budget of the highlands was expected from a careful analysis of the data from the dual open-area/canopy site. Satellite imagery will be monitored, and observations from the WSO archived, to help determine the precipitation event type, and the presence or absence of cloud cover over the highlands (probably only during daylight hours).

Before field installation, all rain gage equipment was evaluated by setting up a test site at the UOG campus where there already exists a dense network of manual and electronic rain gages: several 4-inch plastic manual gages, two Qualimetrics tipping bucket rain gages with data logger, and a National Weather Service (NWS) HANDAR station that contains a tipping bucket rain gage. Table 4 shows a comparison between the 56-inch PVC pipes and the very accurate 4-inch rain gages.

TABLE 4. A comparison of the rainfall accumulated in the 56-inch tall 6-inch diameter PVC tube versus a 4-inch diameter rain gage located at the University of Guam. The tube was expected to record higher than the smaller rain gauge because the diameter of the coupling at the top of the PVC tube is slightly larger than the tube itself.

56-Inch PVC Tube				4-Inch Rain Gage	
Date Read	**Time**	**Amount**	**Cumulative**		
(May 1, 2003)		**0**	**0**	**(May 1, 2003)**	**0**
8/12/2003	**1800**	**21.50**	**21.50**	*	*
9/9/2003	**1600**	**16.91**	**38.41**	*	*
12/4/2003	**1800**	**39.50**	**77.91**	*	*
(Dec 31, 2003)	**1800**	**11.00**	**88.91**	**(Dec 31, 2003)**	**80.10**

(a)



(b)

Figure 5. (a) A view of the specially designed 56-inch PVC pipe rain gage assembled in the field at the Mahnd site on Pohpei Island. (b) A view of the recording tipping bucket rain gage assembled in the field at the Nihpit site on Pohnpei Island.

3. Pohnpei's Rainfall

a. Rain-producing weather systems

Pohnpei is located in one of the wettest regions of the western North Pacific, and indeed, the world. The tropical Pacific east-west oriented band of maximum cloudiness known as the Inter-Tropical Convergence Zone (ITCZ), and also known as the trade-wind trough, near-equatorial trough, or at times, the monsoon trough, is usually anchored near Pohnpei. Deep convection in various stages of the mesoscale cycle of growth and decay populate the ITCZ. Large tropical disturbances pass through Pohnpei State, many of them the seedlings for the basin's tropical cyclones. For most of the year, the winds on Pohnpei are from the east, but during the spring through late autumn, the winds can become west to southwest for periods lasting up to one month. Generally, the swing of wind to the southwest is episodic and occurs in 3- to 10-day periods during which time the winds (on rare occasions) may approach gale force. The number, strength and duration of episodes of westerly winds on Pohnpei is highly variable from year to year. It is linked very closely to the status of ENSO: more and longer-lasting episodes of westerly winds occur during El Niño. The wind may become southwesterly on Pohnpei at any time of the year when a tropical cyclone passes to the north of the island. To varying degrees, Pohnpei and the other islands of Micronesia share much of the same large-scale weather features such as episodes of the southwest monsoon, tropical cyclones, and El Niño-related droughts.

One may separate the ITCZ of the tropical Pacific into two different regimes: (1) the trade-wind trough (an east-west axis along about 8-10° North latitude where the Northeast Trades merge with the Southeast Trades); and, (2) the monsoon trough of the western North Pacific that is a roughly east-west oriented linear shear zone between easterly and southwesterly wind currents. In the trade-wind trough, the axis of the converging wind currents also is coincident with a band of deep convective clouds. The distribution of cloudiness in a monsoon trough is a bit different: most of the cloudiness and deep convective elements are located to the south of the trough axis in the region of westerly wind. The monsoon trough (particularly its eastern terminus) is the preferred site for the development of most of the tropical cyclones of the western North Pacific. Tropical cyclones rarely form in the trade-wind trough of the central and eastern North Pacific. In the mean, Pohnpei lies right at the eastern terminus of the monsoon trough. During El Niño, the monsoon trough extends further eastward, and there is a greater frequency of westerly winds on Pohnpei during El Niño, and also a greater threat of tropical storms and typhoons.

During the summer months the monsoon trough generally becomes firmly established in the western North Pacific. It is usually during July that the trough makes its first migration to the northward to places like Guam and Saipan bringing those islands their first episodes of southwest monsoon winds. Throughout the summer, the monsoon trough undergoes substantial migrations and major changes to its shape and orientation. At times, the northward migration of the monsoon trough leaves the region of Pohnpei island in a weak area of high pressure associated with very light winds, bright sun and hot temperatures (broken only by a daily build-up of showers or an isolated thunderstorm over the mountains). During El Niño years, westerly winds may come early to Pohnpei, and are often associated with very heavy rainfall. The Sohkes disaster of April 1997 occurred during very heavy rains associated with monsoon westerlies and the early stages of the developing Super Typhoon Isa.

At the arrival of the boreal winter, the monsoon trough of the Northern Hemisphere disappears as northerly winds cross the equator and follow a curved path 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. Trade wind flow becomes firmly established over most of the western North

Pacific; although deep convection usually persists south of 10° North latitude, keeping Pohnpei wet as other islands of Micronesia located further to the north enter their dry seasons.

In summary, the origin of most of Pohnpei's rainfall can be attributed to deep convective clouds in various stages of organization and/or life cycle. Deep convection can be in the form of an isolated towering cloud column, which may produce a heavy downpour over only a very small area (e.g., a square kilometer), or individual convective clouds may coalesce into 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 large area. Prolonged island-wide downpours are often attributable to the formation (or passage) over Pohnpei of an MCS. Another important organized form of convective clouds is the tropical cyclone (with its core convection and peripheral rainbands).

b. Total rainfall

Unlike the islands of Guam, Saipan, Kwajalein and other islands further to the north, the island of Pohnpei does not experience a pronounced wet season and a dry season. The driest months are January and February and the wettest months are April and May. Pohnpei's mean monthly rainfall is nearly uniform at 16-17 inches per month from May through December, and then drops to its lowest value of just over 10 inches in February and thereafter rises to its peak value of nearly 20 inches in May (Fig. 6.). For most of the year the, the *mean* wind is from an easterly direction. Pohnpei is in the doldrums; that is, along the axis of the intertropical convergence zone (ITCZ). Winds are generally light, but can become fairly brisk trade winds in the winter and early spring (January through April). During the spring through fall months (May through December), Pohnpei can experience episodes of brisk monsoonal winds from a westerly direction (the more-so in El Niño years).

On the large scale, there is an east-west zone of maximum annual rainfall from 4-8°N across Micronesia. The amounts drop off steadily as one progresses northward (where the dry season becomes more prolonged). The islands of Kosrae and Pohnpei experience at least 160 inches of rain annually, with no appreciable wet or dry seasons. A bit further north at Chuuk and at Palau, the over-water annual rainfall is approximately 140 inches; falling to 120 inches at Yap, 100 inches at Guam, and to 80 inches at Saipan. Well north and east from Saipan, the region is dominated by the mid-Pacific subtropical high pressure area and its accompanying trade winds, and the annual rain decreases to values around 40 inches (Fig. 7).

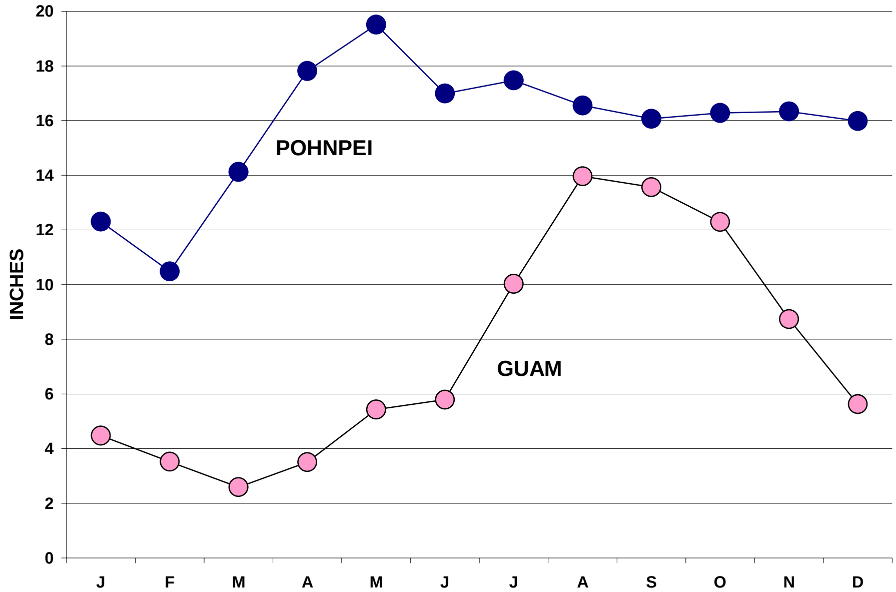


Figure 6. Monthly mean rainfall at WSO Pohnpei and at Guam's Andersen Air Force Base (in inches). Pohnpei receives much more rainfall than at Guam in every month of the year, and has only two months (January and February) of relatively drier conditions, compared to the sharply drier and prolonged "Dry Season" on Guam. The peak rainfall in April and May are explicable in terms of the persistence of deep convection along the near-equatorial trough that anchors in the region of Pohnpei in those two months.

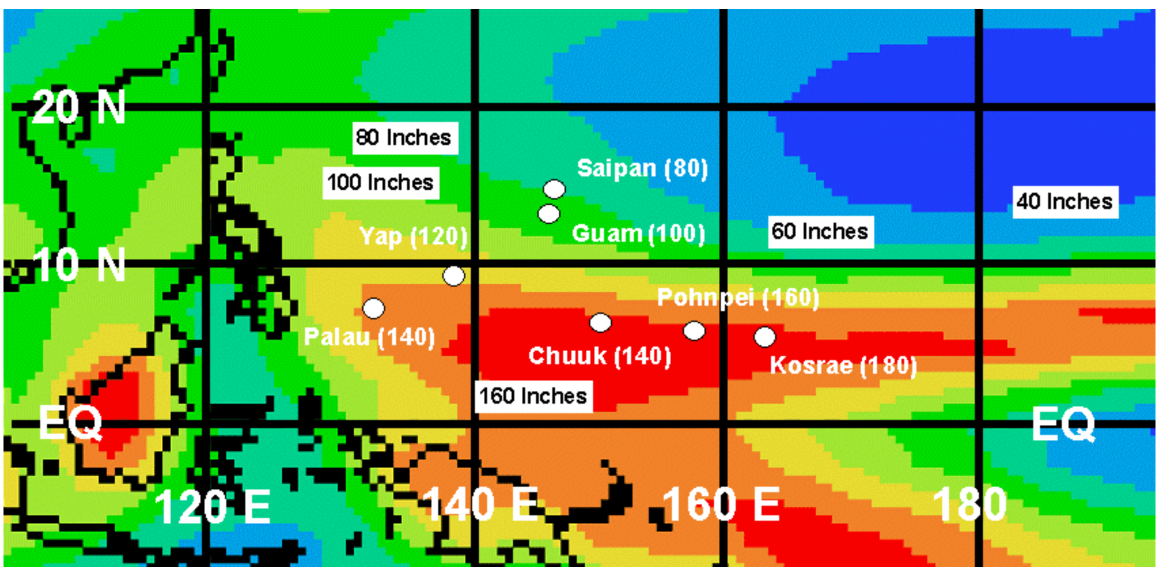


Figure 7. Mean annual over-water rainfall in Micronesia. Colors indicate rainfall pattern (amounts as labeled: red = 160 inches per year, orange = 140, yellow = 120, light green = 100, dark green = 80, teal = 60, light blue = 40, and within the blue there is a bit less than 40 inches of annual rainfall). Mean annual over-water rainfall at selected islands is indicated. Image adapted from figure on website URL http://orbit35i.nesdis.noaa.gov/arad/gpcp/

c. Temporal variability

In the vicinity of the Pohnpei WSO, the mean annual rainfall during the period 1953-2001 was 188.02 inches with a standard deviation of 14.28 inches. As mentioned earlier, Pohnpei does not usually experience a prolonged dry season. The months of January and February are the driest of the year, and the months of April and May are the wettest. The driest annual total in the time series is the 128.60 inches recorded in 1998. The second driest year was 1983 with 133.60 inches of rain (these years were follow-on years to strong El Niño events). The driest 5-month period occurred from January to May 1983 when a total of only 9.37 inches was recorded. The driest month of record was January 1998 when only 0.64 inches of rain was recorded. The wettest annual total in the time series is the 236.30 inches recorded during 1976 followed by 228.60 inches in 1991 (these two years were El Niño years). Nearly all extremely dry years on Pohnpei occur during the year following an El Niño event (See Section 3).

The lowest mean (10.49 inches) monthly rainfall occurs in February. The highest mean monthly rainfall (19.51 inches) occurs in May. Monthly rainfall values below one inch occurred only once (January 1998) during the major El Niño-related drought of 1998. Monthly rainfall values below 5 inches have occurred in December, January, February, March, April, and May. Five sequential months of rainfall below 5 inches occurred twice, both times in association with major El Niño events (1982-83 and 1997-98). Monthly rainfall values above 30 inches have occurred in April, May, July, August, September, and November. The lowest value of the monthly time series of the rainfall at the Pohnpei WSO is the reading of 0.64 inches during January 1998. The highest monthly value is the 38.81 inches recorded during August 1992.

d. Hourly Distribution of daily rainfall

Throughout much of the tropical Pacific there is a tendency for more rainfall to occur in the morning hours. Ruprecht and Gray (1976) analyzed 13 years of cloud clusters over the tropical western Pacific and found that over twice as much rain fell on small islands from morning (0700 to 1200L) clusters as from evening (1900 to 2400L) clusters. The heaviest rain fell when it was part of an organized weather system and when diurnal variation was most pronounced. Fu et al. (1990) used satellite infrared images over the tropical Pacific to confirm and refine these findings. Deep convective cloudiness was greatest around 0700L and least around 1900L. The morning rainfall maximum associated with western Pacific cloud clusters and the early morning instability in the trade winds both originate from the nocturnal radiational cooling of cloud tops. An analysis of the fraction of the rainfall accumulated during each hour of the day shows that there is a tendency for most rainfall to occur between local midnight and sunrise than during other hours, with an absolute minimum in net long-term accumulations contributed during the evening hours (e.g., Fig. 8). This is not the case at Pohnpei, where the island topography distorts the hourly rainfall distribution (Figs. 9a-c). At other small islands and atolls of Micronesia such as Wake, Majuro and Chuuk (Figs. 9d-f), the hourly distribution of rainfall is that which is found to be typical over the open-ocean. The hourly rainfall distribution is more complicated on the larger islands such as Pohnpei, Hawaii, and Guam (Figs. 9g-j). On mountainous islands such as Pohnpei and on the Hawaiian Islands, the large diurnal variations in rainfall (not necessarily synchronous with typical open-ocean variations) are driven by mountain- and sea-breeze circulations. Indeed, from personal experience on Pohnpei, during the summer months (May through October) when the winds are light, there is a strong tendency for heavy showers to develop over the mountains by noon. This is confirmed by the WERI/CSP rain gage atop Nahna Laud (Fig. 10). The interior early afternoon showers rain-out and die by evening. At almost all islands, there is an evening minimum of rainfall. ***Pohnpei's extreme amount of rain in the interior appears to derive from day-time convection over the mountains, and not from orographically enhanced rainfall as winds pass over the high terrain (as on many of the Hawaiian Islands).***

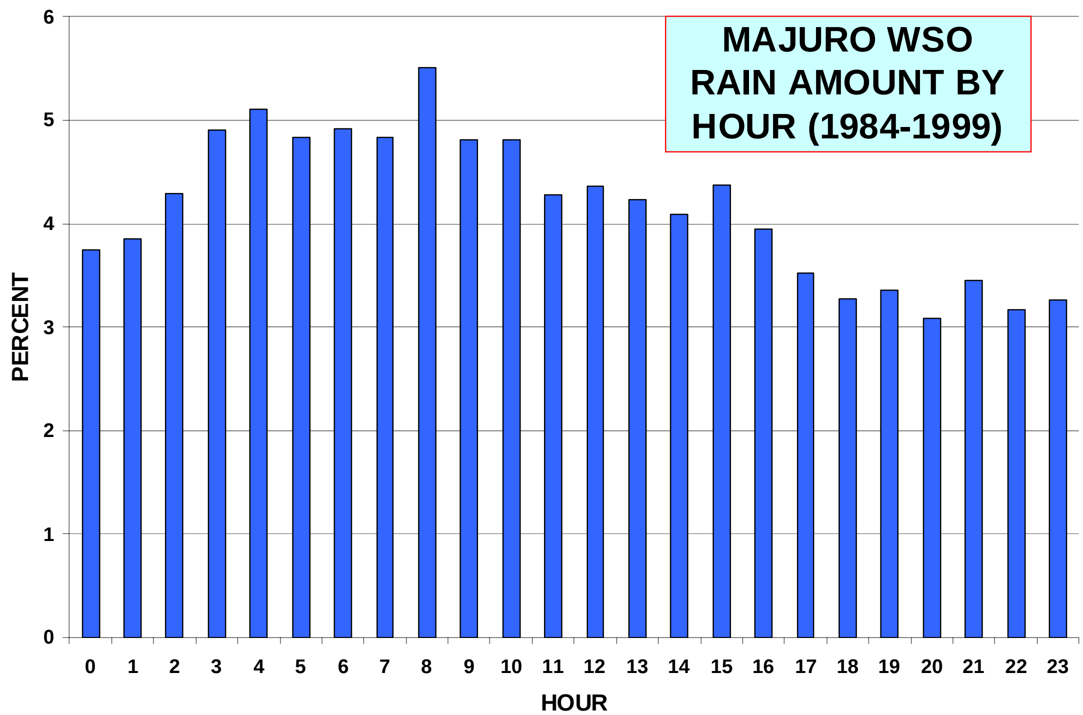
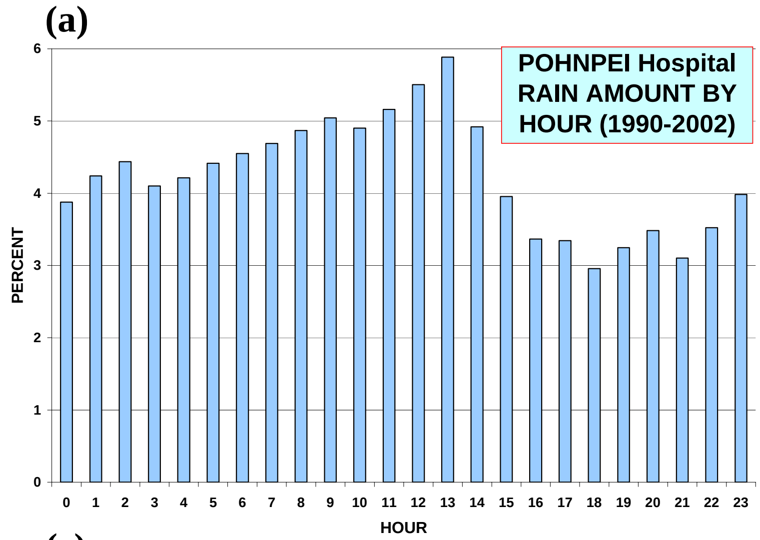
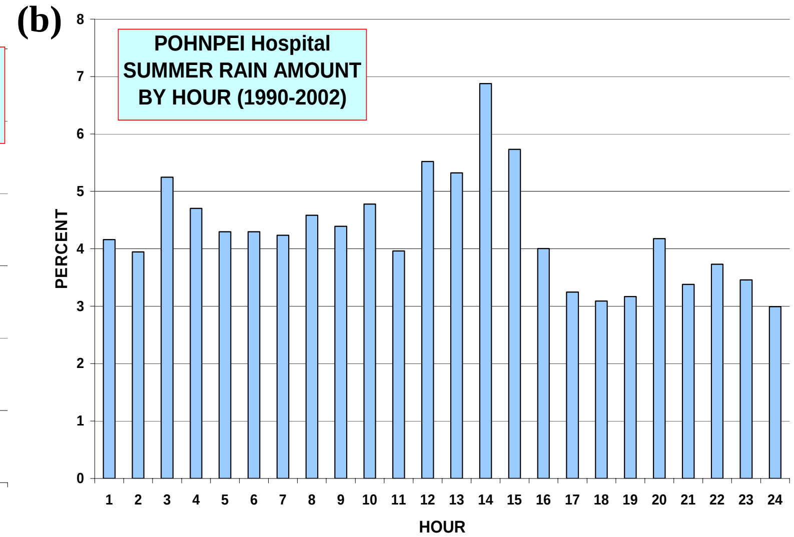


Figure 8. Example of the typical hourly distribution of rainfall in the tropical Pacific Ocean. The example chosen is Majuro Atoll.





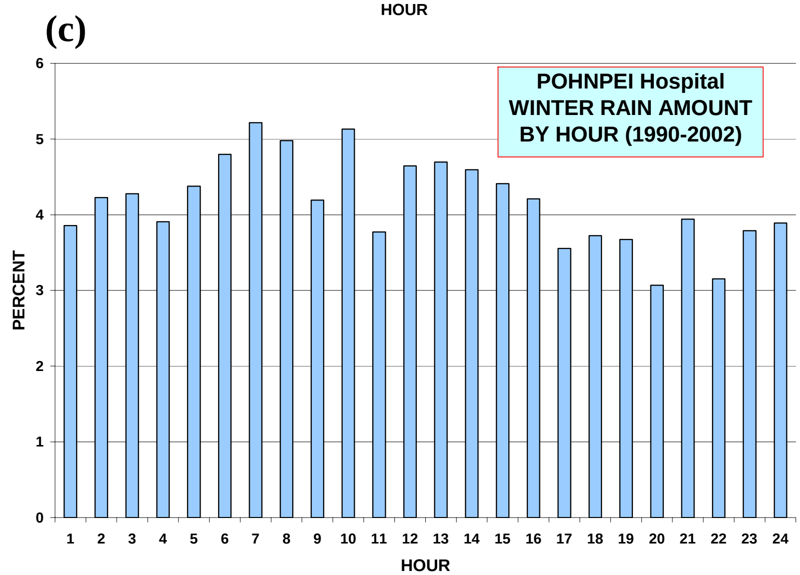
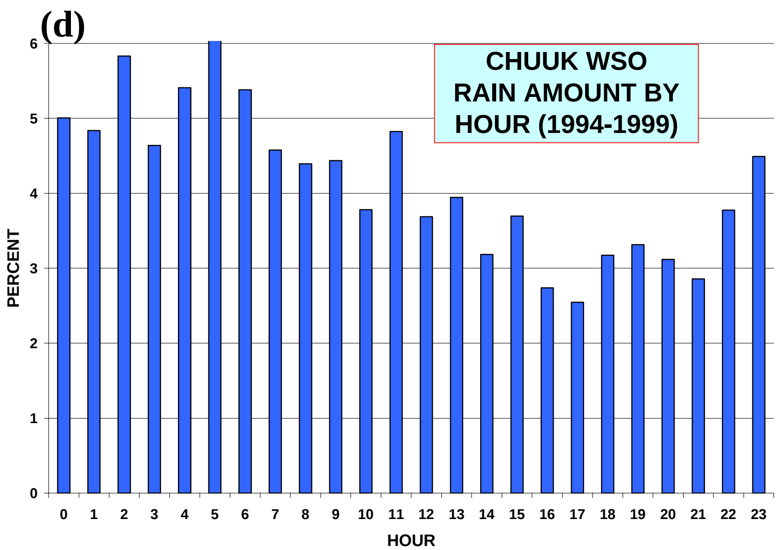
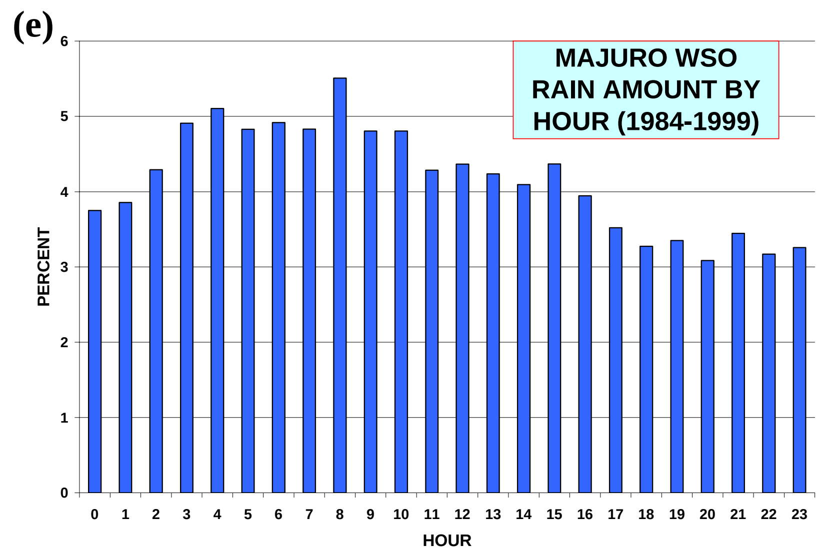


Figure 9a-c. Rainfall amount (in percent by hour) of the grand total of all rainfall at the Pohnpei Hospital in Kolonia. Year-round distribution is shown in panel (a), the summer-only distribution is shown in panel (b), and the winter-only distribution is shown in panel (c). There is a tendency for most of the rainfall on Pohnpei to occur in the middle of the day with a pronounced minimum at sunset (18L). The preference for mid-day rain is most pronounced in the summer.





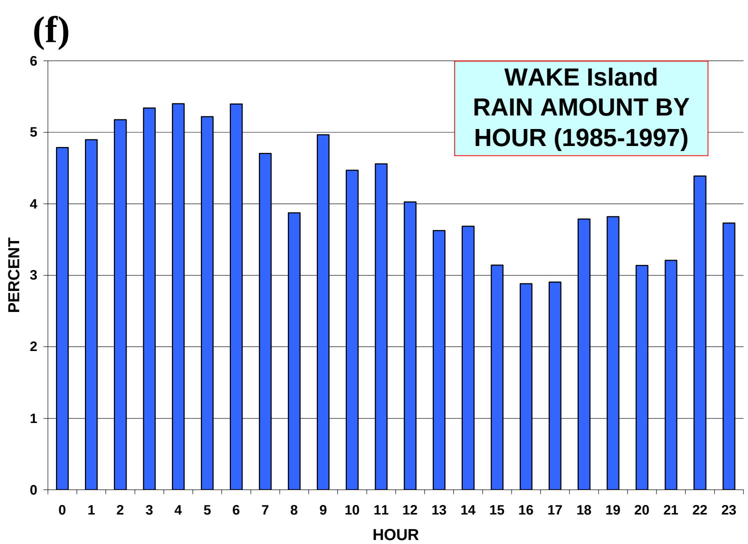


Figure 9d-f. Rainfall amount (in percent by hour) of the grand total of all rainfall at (d) Chuuk, (e) Majuro, and (f) Wake Island. The rainfall at these islands reflects the typical open-ocean rainfall distribution found for the tropics of the western Pacific. There is more rain in the morning hours and a pronounced minimum in the evening (18-20L). The ratio of the amount of rain from midnight to noon versus the rain from noon to midnight is 1.47 at Chuuk, 1.32 at Majuro, and 1.39 at Wake Island.

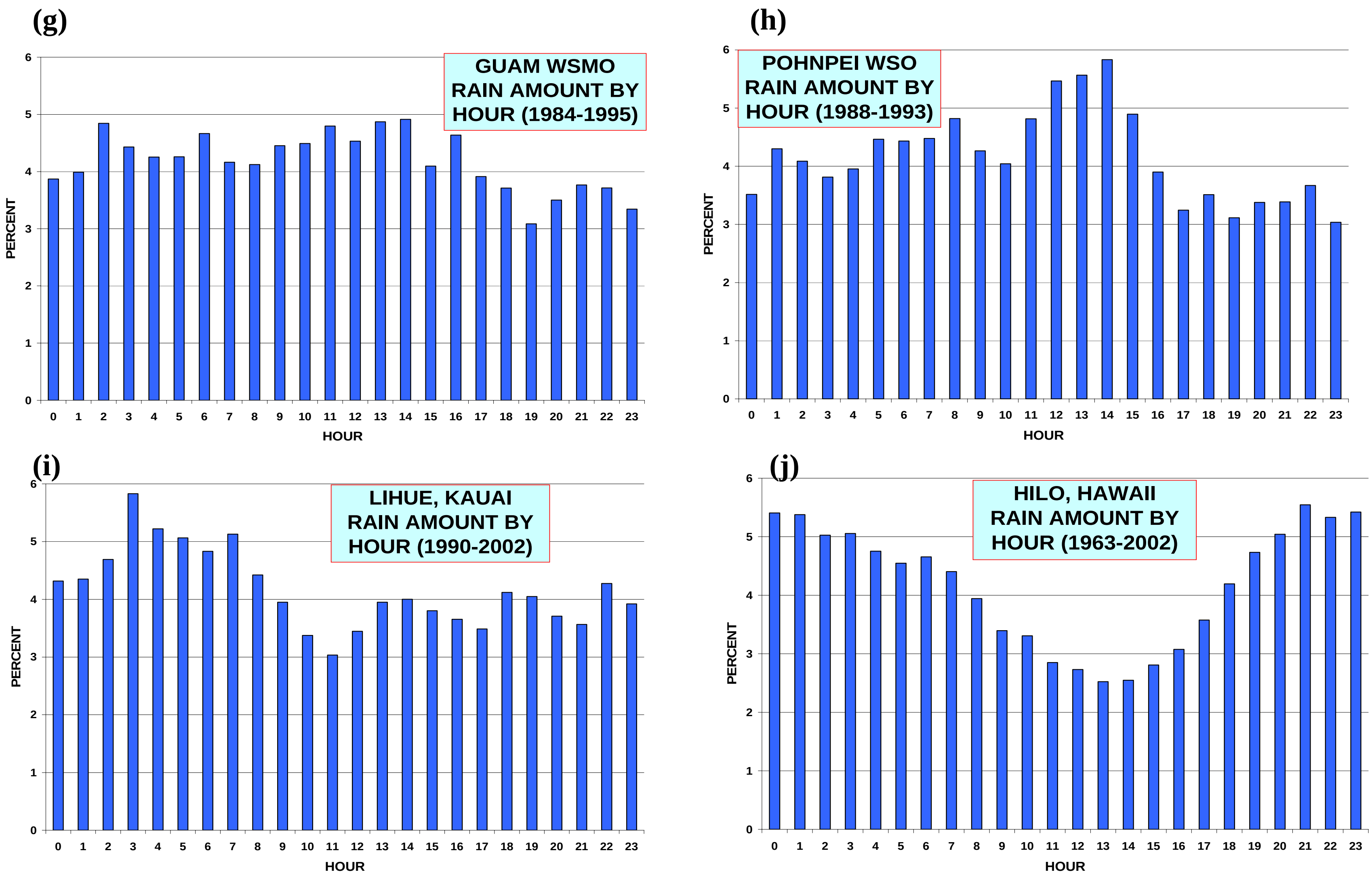


Figure 9g-j. Rainfall amount (in percent by hour) of the grand total of all rainfall at (g) Guam, (h) Pophnpei, (i) Lihue, and (j) Hilo. The hourly distribution of the rainfall on these larger and/or mountainous islands is quite different from the open-ocean distribution. Diurnal heating and cooling of the land and mountain areas may substantially affect the hourly distribution of rainfall.

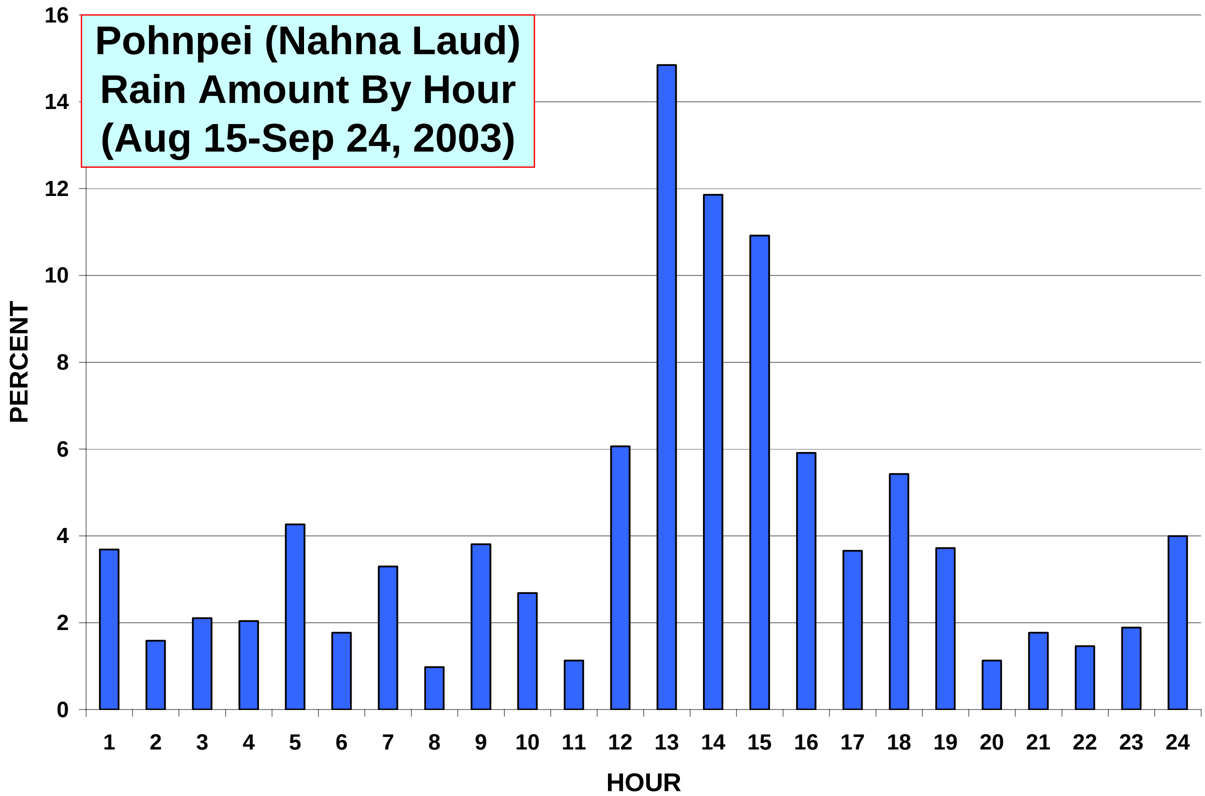


Figure 10. Preliminary data from the Nahna Laud site shows a sharp concentration of rainfall in the four hours of local noon through 4 PM in the afternoon. Convection induced by daily heating in light wind conditions allows for the build-up of thunderstorms nearly every day in Pohnpei's interior.

f. Spatial Distribution of annual rainfall

Historical records suggest that the annual mean rainfall on Pohnpei differs substantially across the island, and is heaviest in the interior of the island. While no rainfall measurements have ever been obtained in the interior highlands of the island (until the WERI/CSP transect was set-up in June 2003), the distribution of rainfall at existing locations on the perimeter of the island suggested the existence of steep rainfall gradients as one ascended into the interior. Using the historical rainfall records from Pohnpei, the PRISM analysis generated estimates of annual rainfall in the interior that were over twice the value of the rainfall along the north coast (Fig. 3). The first year of rain readings from the WERI/CSP network (Fig. 11) have revealed that this estimate is quite realistic.

According to measurements obtained by the WERI/CSP network, the distribution of rainfall on the island of Pohnpei is strongly affected by the topography, and the mean annual rainfall totals among recording stations on Pohnpei differ by more than 100 inches! The region in the vicinity of Pohnpei's international airport (Figs. 2c and 4) receives the lowest annual total of about 140 inches. The highest annual average of approximately 325 inches (2300 mm) occurs in the central highlands. The western side of the island is wetter than its eastern side.

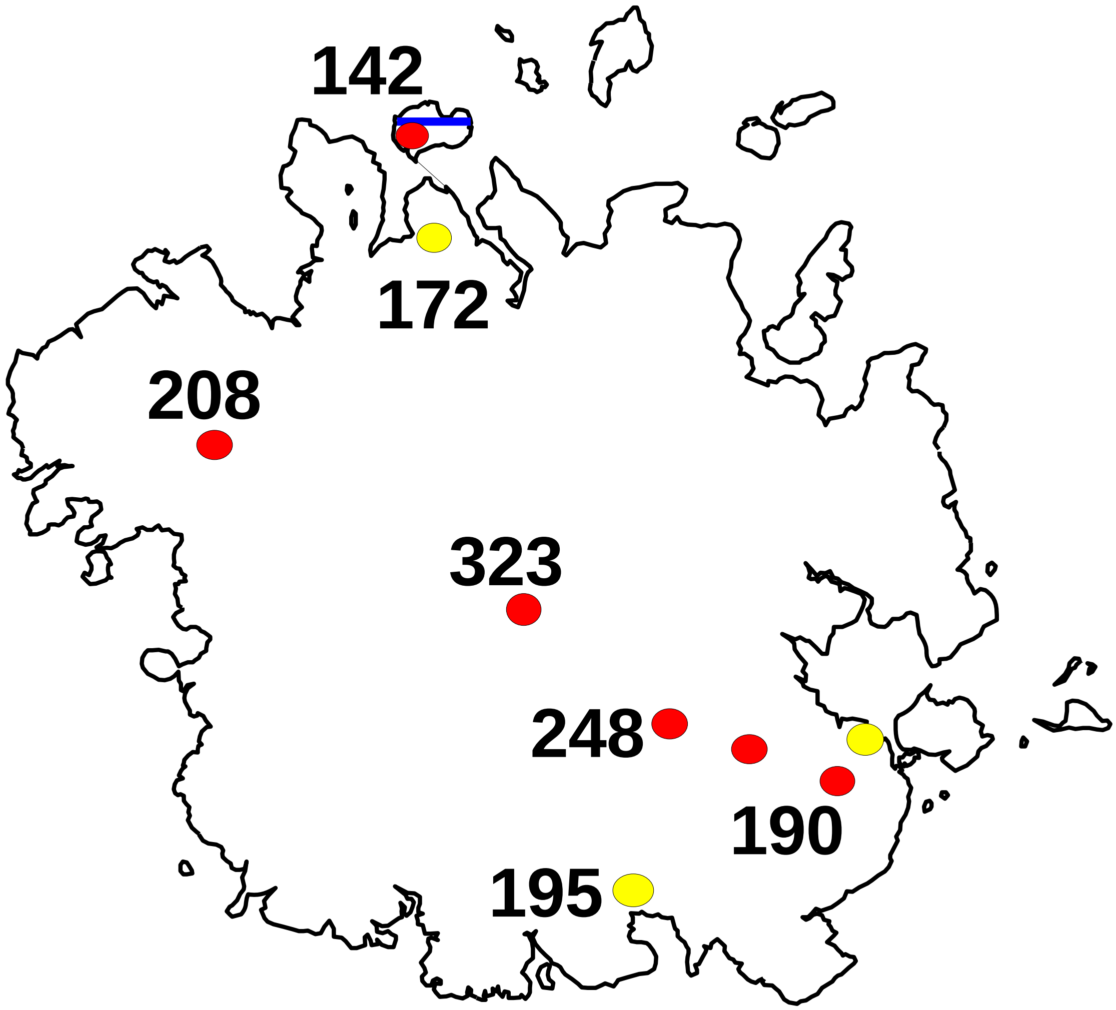


Figure 11. Mean annual rainfall measured on Pohnpei during the first year of operation of the WERI/CSP rain gage network.

The annual rainfall measured on Pohnpei during the first year of operation of the WERI/CSP rain gage network compares favorably with the PRISM estimates of mean annual rainfall (Figs. 12 and 13).

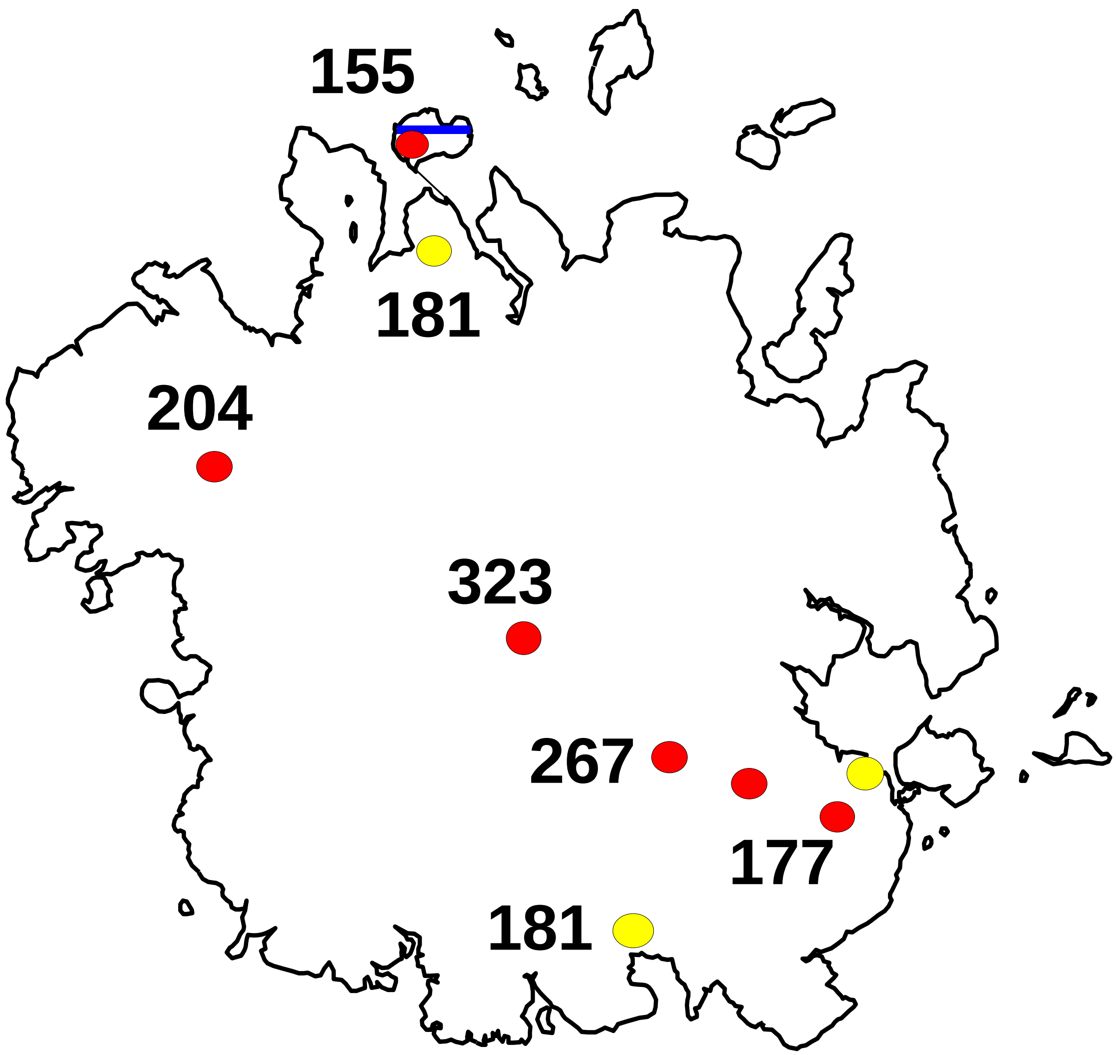


Figure 12. Values of mean annual rainfall based on the **PRISM** analysis at selected sites on the island of Pohnpei.

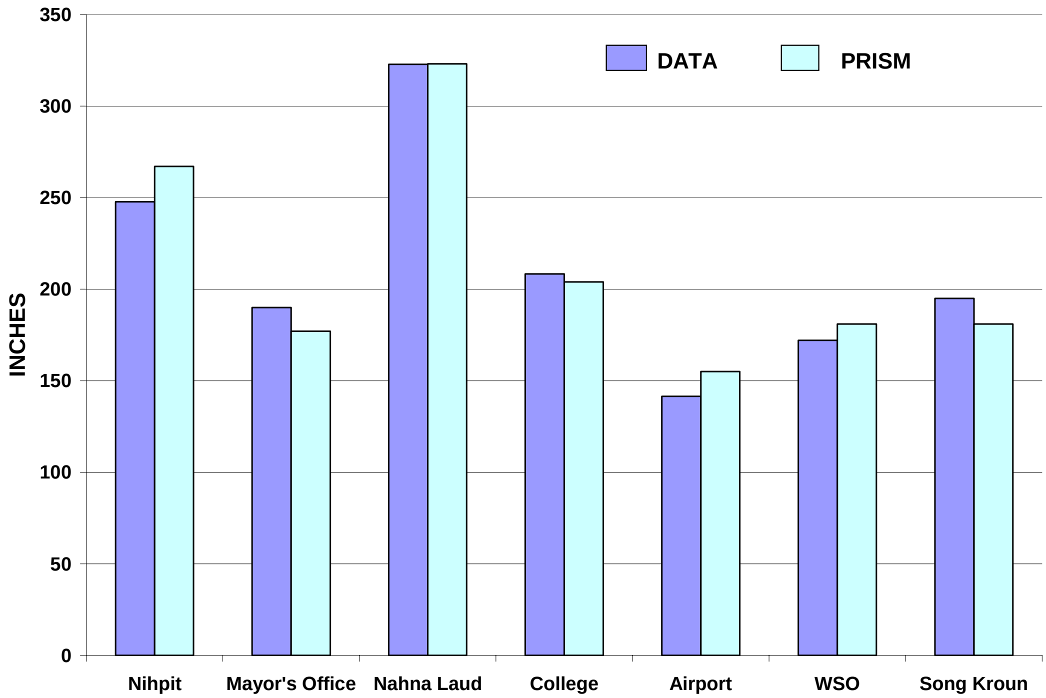


Figure 13. Comparison of extrapolated mean annual rainfall to those obtained from the PRISM analysis at selected sites on the island of Pohnpei.

g. Fog drip

The top of Nahna Laud was the selected site in the central highlands where two rain gages were set up near one another – one in an open area, and another under the canopy of the rainforest – to assess the impact of fog drip on the water budget of the island. The central highlands of Pohnpei are of sufficient height (~2,000 – 2,600 ft) to often be enshrouded in fog. Deposition of cloud droplets onto leaves, and subsequent coalescence and drip, may enhance the total water budget substantially. This so-called fog-drip may be responsible for a substantial portion of the water budget on portions of the islands of Hawaii. An electronic rain gauge in an open area atop Nahna Laud determines the times when it is actually raining. Another rain gauge under the forest canopy continues to receive water from residual drip, and/or cloud-droplet deposition onto leaves when it ceases to rain in the clearing. One of the problems with the forest site is the dwarf nature of the rain forest at high elevation. There are lots of shrubs and low trees across much of the summit area. Nevertheless, a rain gage was placed under the forest canopy at a site approximately 300 ft away from the gage located in the clearing within a small crater at the top of Nahna Laud. Analysis of the data is inconclusive. There are times, such as in Fig. 14, when the rain gauge under the forest canopy continues to receive water for many hours after the rain stops in the clearing. Assuming the first hour or so to be residual rain drip, one can see from

Fig. 15 that approximately .01 inches of rain accumulates every two hours. There is no way to know what portion of this is from the deposition of cloud liquid water onto the leaves or residual rain drip. If this rate continued non-stop, there would be an additional accumulation of .12 inches of rain per day from this source, which amounts to 14% of the net accumulation at the clearing. ***A 14% increase over the open-area rainfall may therefore be considered an upper limit for fog drip accumulation, but this result in not trusted***. In order to get a better picture of the contribution of fog drip at this site, the WERI/CSP team has proposed to set up a special fog-drip collector designed by Juvik.

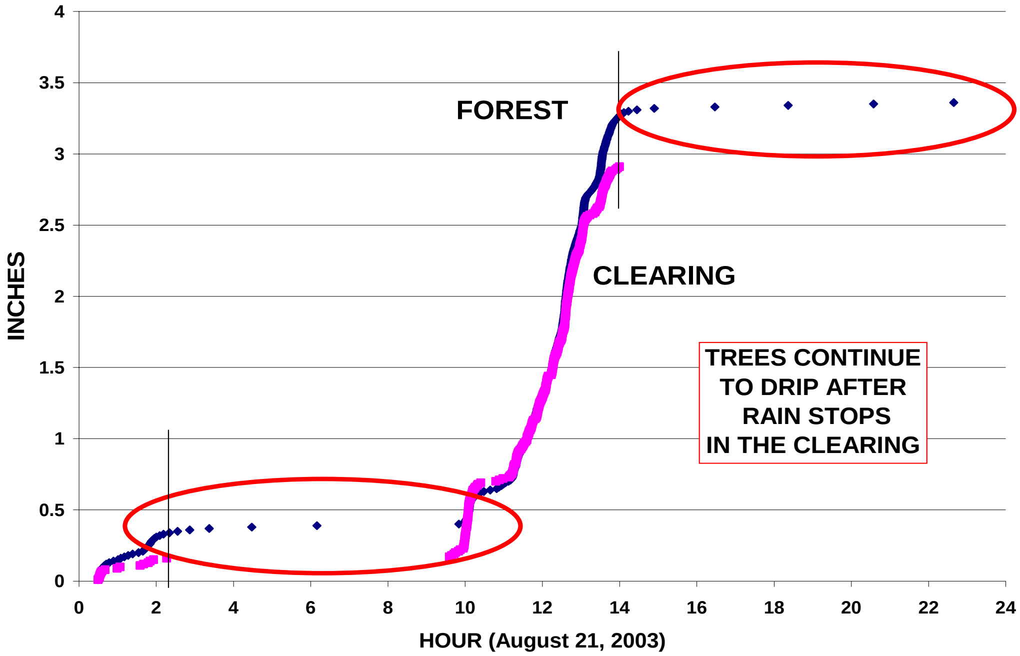


Figure 14. Rainfall on August 21, 2003 at two sites on Nahna Laud: one in a clearing, and the other under the canopy of the rainforest at a site located about 300 feet from the clearing. Each dot indicates an increment of .01 inch of rain. Note the continuation of rain accumulation at the canopy site after the rain stops in the clearing.

h. Return periods of short-term high-intensity rainfall events

Since the rainfall records on Pohnpei are so short and/or incomplete, calculations of return periods of extreme rain events may only be crudely estimated. The more complete record of rainfall on Guam allows for a comparison by proxy. Guam, however, experiences direct hits by full-fledged typhoon far more frequently than does Pohnpei. Return-period calculations for Guam's peak annual 24-hour rainfall (Fig. 15) yield a mixed distribution, with typhoons causing all daily rainfall events in excess of 10 inches.

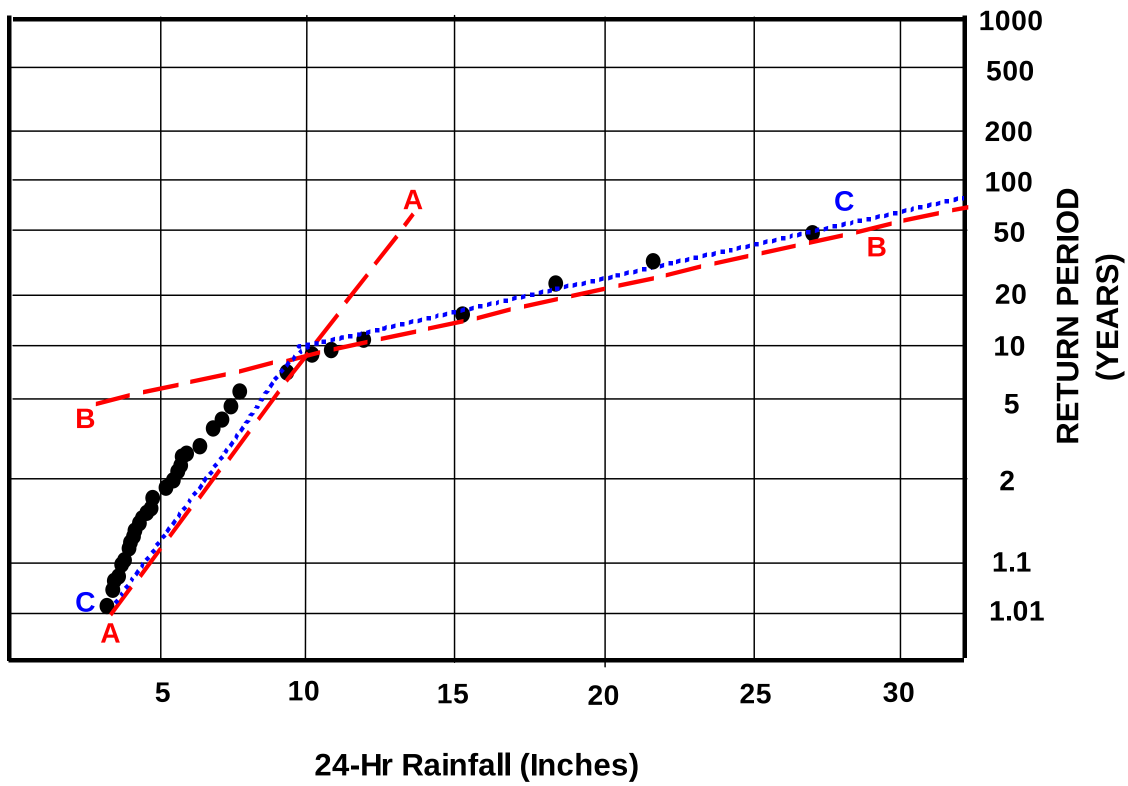
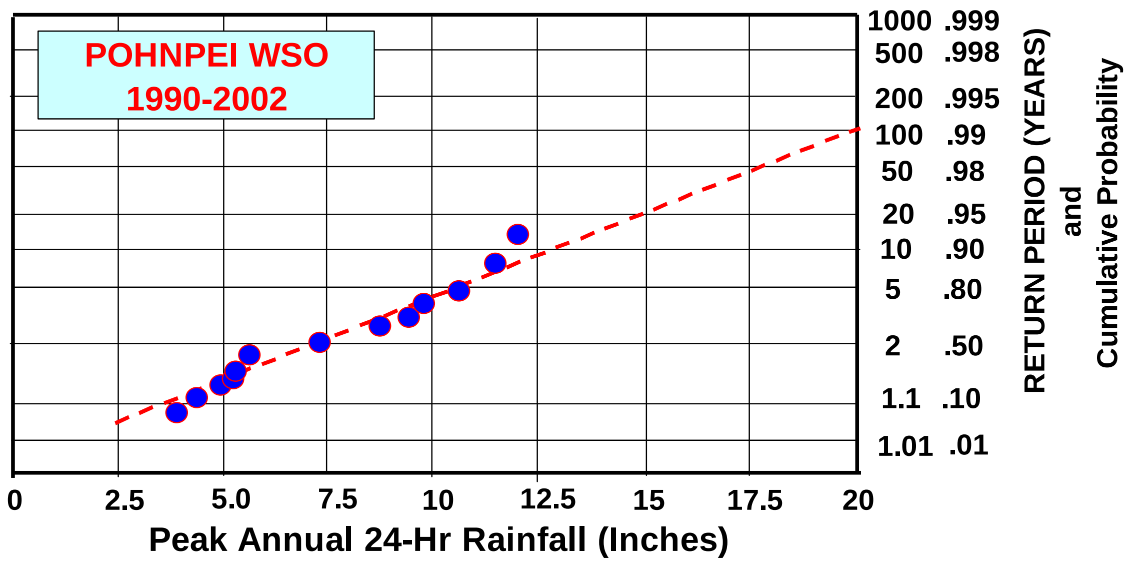


Figure 15. Return period for 24-hour rainfall totals computed for Guam. The change of slope of the lines that fit the individual realizations indicates that there is a mixed distribution of rainfall causes. This is indeed the case, as all rainfall totals in excess of 10 inches on this chart were caused by the direct passage of typhoons over the island. A conservative approach to estimating the return periods for 24-hour rainfall amounts on Guam would be to follow the curve "C-C" that has a breakpoint at the intersection of lines "A-A" and "B-B". The breakpoint value is 10 inches in 24 hours at the 10-year return period. Thus, one would estimate that at least one day in each year would have at least ~ 3.50 inches of rain. Similarly, the return period for 10 inches in 24 hours is 10 years; the return period for 20 inches of rain in 24 hours is 25 years, etc.

A similar return-period analysis of the extreme 24-hour rain rates and extreme 1-hour rain rates using Pohnpei's shorter and more incomplete record is shown in figures 16a,b and 17a,b respectively. Charts of intensity-duration-frequency (IDF) for Pohnpei (Fig. 18 and Table 5) can be derived from extrapolation.

(a)



(b)

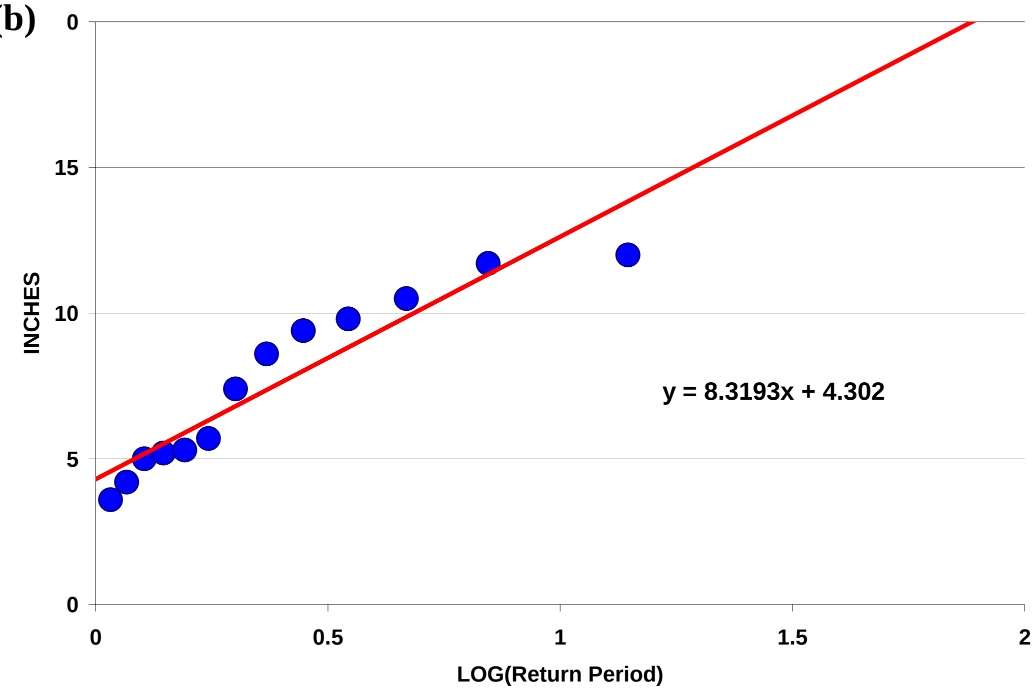


Figure 16. (a) Method-of-moments (ranking method) computations of 24-hour return period extreme rainfall events using Pohnpei WSO data. **(b)** Peak annual 24-hour rainfall at Pohnpei WSO versus the log of the estimated return period from the ranking method.

(a) (b)

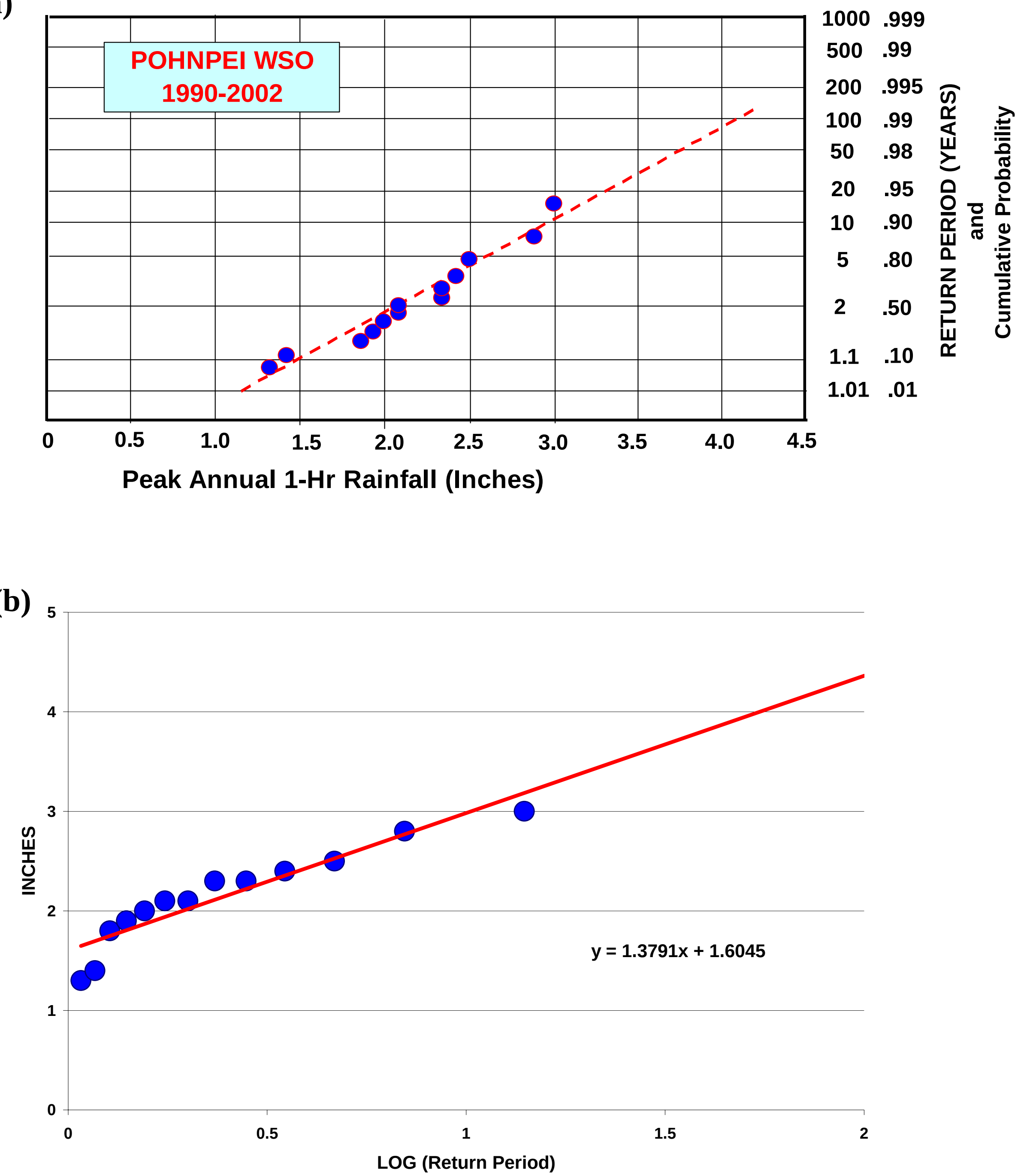


Figure 17. (a) Method-of-moments (ranking method) computations of 1-hour return period extreme rainfall events using Pohnpei WSO data. **(b)** Peak annual 1-hour rainfall at Pohnpei WSO versus the log of the estimated return period from the ranking method.

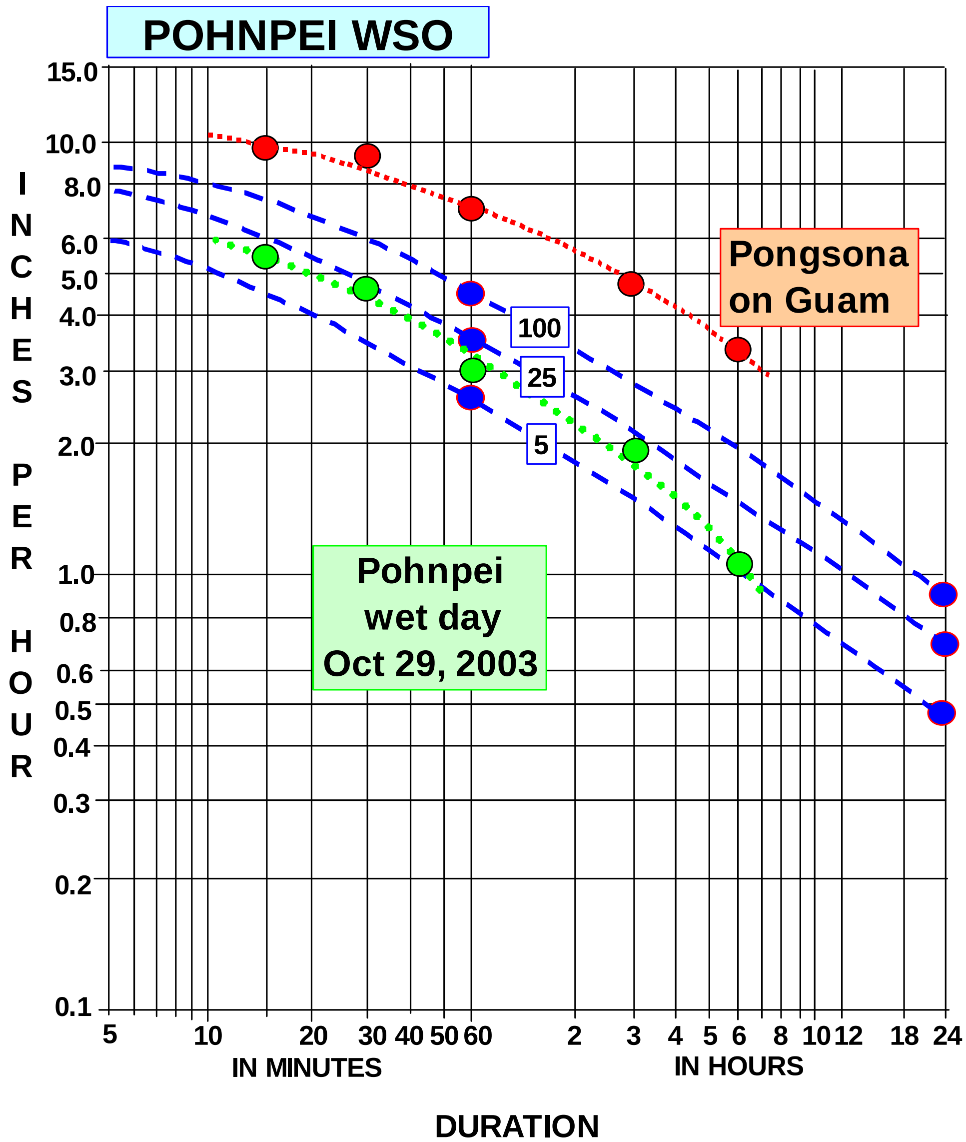


Figure 18. Intensity-Duration-Frequency (IDF) chart of selected return periods at the Pohnpei WSO (blue dots connected by blue dashed lines). For comparison, the IDF values measured during Typhoon Pongsona on Guam (red dots connected by red dotted line) are shown. Also, the highest IDF values measured within the past 9 months by the newly installed WERI/CSP rain gauge network on Pohnpei have been plotted (green dots connected by green dotted line). The Pohnpei event was a fairly typical afternoon thunderstorm.

Return Period	RAINFALL (Inches)								
	15 Minutes	30 Minutes	45 Minutes	60 Minutes (1 Hour)	120 Minutes (2 hrs)	180 Minutes (3 hrs)	360 Minutes (6 Hrs)	720 Minutes (12 Hrs)	1440 Minutes (24 Hrs)
X_{100}	2.13	3.00	3.98	4.60	6.60	8.55	11.70	15.60	20.40
X_{25}	1.98	2.43	3.00	3.70	5.50	6.30	9.60	12.60	16.08
X_5	1.48	1.85	2.12	2.70	3.90	5.10	6.60	7.92	11.76

Return Period	RAINFALL INTENSITY (Inches/Hour)								
	15 Minutes	30 Minutes	45 Minutes	60 Minutes (1 Hour)	120 Minutes (2 hrs)	180 Minutes (3 hrs)	360 Minutes (6 Hrs)	720 Minutes (12 Hrs)	1440 Minutes (24 Hrs)
X_{100}	8.50	6.00	5.30	4.60	3.30	2.85	1.90	1.25	0.85
X_{25}	7.90	4.85	4.00	3.70	2.75	2.10	1.60	1.05	0.67
X_5	5.90	3.70	2.95	2.70	1.90	1.70	1.10	0.67	0.49

TABLE 5. Charts of Pohnpei Rainfall Intensity-Duration-Frequency (IDF). Top panel is total rainfall, and the bottom panel is normalized to rainfall in inches per hour for the indicated return-period and duration.

4. El Niño and the Southern Oscillation

a. Description of El Niño, La Niña and the Southern Oscillation

Interannual variations of Pohnpei's rainfall are closely linked to the El Niño/Southern Oscillation (ENSO) phenomenon. Pohnpei and most of Micronesia are in an ENSO core region that features very dry conditions in the year following El Niño (Ropelewski and Halpert 1987), and an increase in the level of threat from typhoons during an El Niño year (Fig. 19).

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 fisherman 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 actions 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, 1997, and 2002], *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 meteorolgists "El Niño" signifies the major phenomenon. There is now general agreement on the broad features of El Ni El Niño. In the tropical eastern 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 synonymous with the east-west oriented band of heavy rain clouds of the eastern and central 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 20º of longitude east of the dateline. Sea surface temperatures are generally well above normal along the equator off South America, and positive anomalies may extend beyond 10ºN and 10º S.*

El Niño generally sets in around March or April and may last a year or more."

The atmospheric component tied to El Niño is termed the Southern Oscillation. The intense warmings of the eastern equatorial Pacific (the oceanographic 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, known as "La Niña", are seen to coincide with positive anomalies of indices of 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 Walktr, 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 (SOI) 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 warning of the sea surface temperature of the eastern equatorial Pacific during El Niño with negative anomalies of the SOI has prompted scientists to call the phenomenon of El Niño ENSO (an acronym derived from El Niño/Southern Oscillation). Several methods for calculating the SOI are in use. In this report the monthly values of the SOI as defined and computed by the U.S. Climate Prediction Center (formerly the U.S. Climate Analysis Center) are used.

Definitions of El Niño developed in the early 1980s were contingent on persistent SST anomalies of at least +1ºC along the tropical Pacific coast of South America. A Scientific Committee for Ocean Research working group, SCOR WG 55, was set up to define El Niño (SCOR 1983) and came up with the following:

> "El Niño is the appearance of anomalously warm water along the coast of Ecuador and Peru as far south as Lima (12°S). This means a normalized Sea surface temperature (SST) anomaly exceeding one standard deviation [approximately 1°C] for at least four (4) consecutive months. This normalized SST anomaly should occur at least at three (3) of five (5) Peruvian coastal stations."

More recent definitions of El Niño have focused on substantial and persistent SST anomalies in the central equatorial Pacific. The Japan Meteorological Agency (JMA) working definition of El Niño required that the 5-month running mean of the monthly SST anomaly in the area 4°N-4°S and 90°-150°W (essentially the region known as "Niño 3") be +0.5°C or more for at least six consecutive months. Kiladis and Van Loon (1988) suggested that an atmospheric index (i.e., the SOI) be combined with an SST anomaly index in a definition of El Niño. For them, a "warm event (i.e., El Niño) required that the SST anomaly index for the eastern tropical Pacific (within 4° of the equator from 160°W to the South American coast) had to be positive for at least three seasons and be at least 0.5°C above the mean, while the SOI had to remain negative and below -1.0 for the same duration. The "cold events" (i.e., La Niña) required the inverse of the conditions for El Niño. From observations and numerical simulations of coupled atmosphere-ocean interactions in ENSO, Trenberth (1997) argues for a definition of El Niño that is based upon SST anomalies in a region a bit farther west than "Niño 3". Since April 1996, the Climate Prediction Center (CPC) of NOAA's National Centers for Environmental Prediction introduced a new SST index called Niño 3.4 for the region 5°N-5°S and 120°-170°W. Trenberth (1997) proposed that El Niño and La Niña be defined by the JMA definition modified to apply to SST's in the Niño 3.4 region and with a threshold exceeding ± 0.4°C. During the summer of 2003, the CPC adopted a slightly modified version of Trenberth's proposed definitions of El Niño and La Niña that require the value of the SST anomaly thresholds in the Niño 3.4 region to be ± 0.5°C, instead of ± 0.4°C.

El Niño and La Niña events can be weak, moderate or strong. Since 1980 there have been two major El Niño events (1982 and 1997), and 5 weak-to- moderate events, including the moderate El Niño of 2002. In the same time frame, there were four periods of La Niña, with the years 1998-2001 comprising a prolonged strong La Niña event. ***The effects of El Niño and La Niña on Pohnpei and the rest of Micronesia include:***

(1) Changes in the rainfall distribution;
(2) Changes in the typhoon distribution; and,
(3) Changes in the sea level.

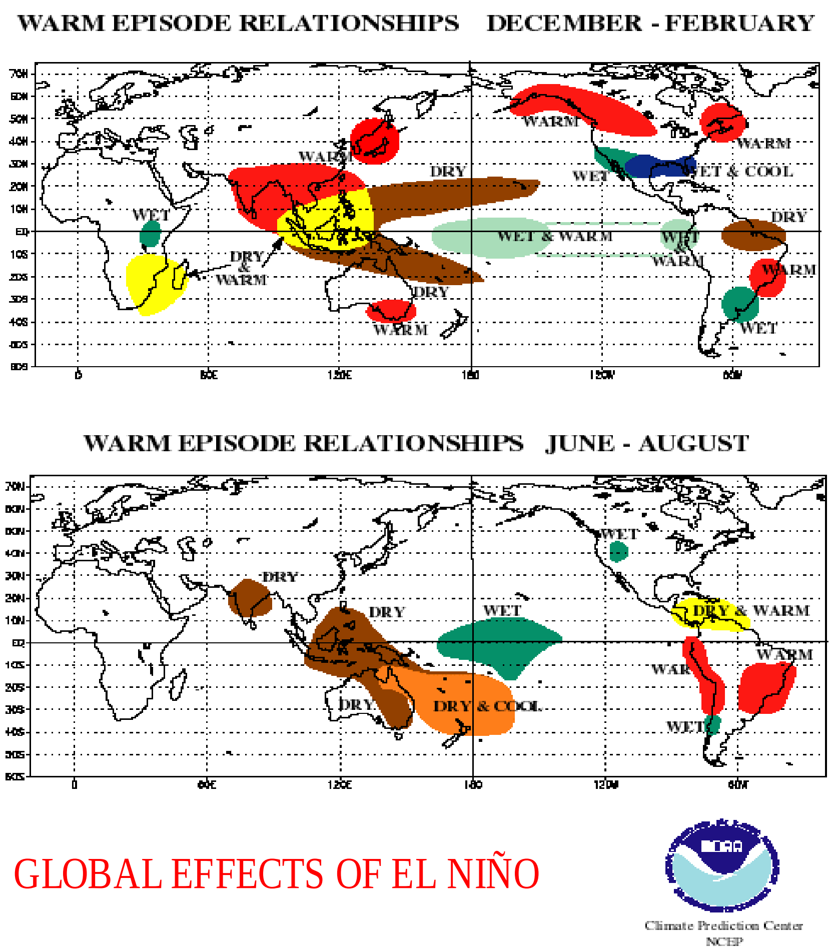


Figure 19. The effects of El Niño on global rainfall and temperature patterns. Note the large "boomerang"-shaped area of drought encompassing most of Micronesia in the months following El Niño, and the progression of drought during the El Niño year from Australia and Indonesia northward into Micronesia.

b. Effects of El Niño and La Niña on the weather and climate of Pohnpei

1) RAINFALL

Nearly all extremely dry years on Pohnpei occur during the year following an El Niño event (Figs. 20). The driest year on record in Pohnpei and throughout most of Micronesia occurred in 1998 (the follow-on year to the major El Niño of 1997). Some El Niño years are very wet depending upon the behavior of typhoons and the monsoon trough. Most La Niña years and non-ENSO years are near normal to slightly above normal (unless they are the year following an El Niño; then, they are dry).

On Pohnpei, persistent dryness tends to become established in the fall of the El Niño year (Fig. 21) (unless a late-season tropical cyclone makes affects the island. Deleterious effects of drought (e.g., desiccation of grasslands and forests, draw-down of streamflow and well-heads, and wildfires) are exacerbated by extreme dryness and extension of drier than normal conditions for several months.

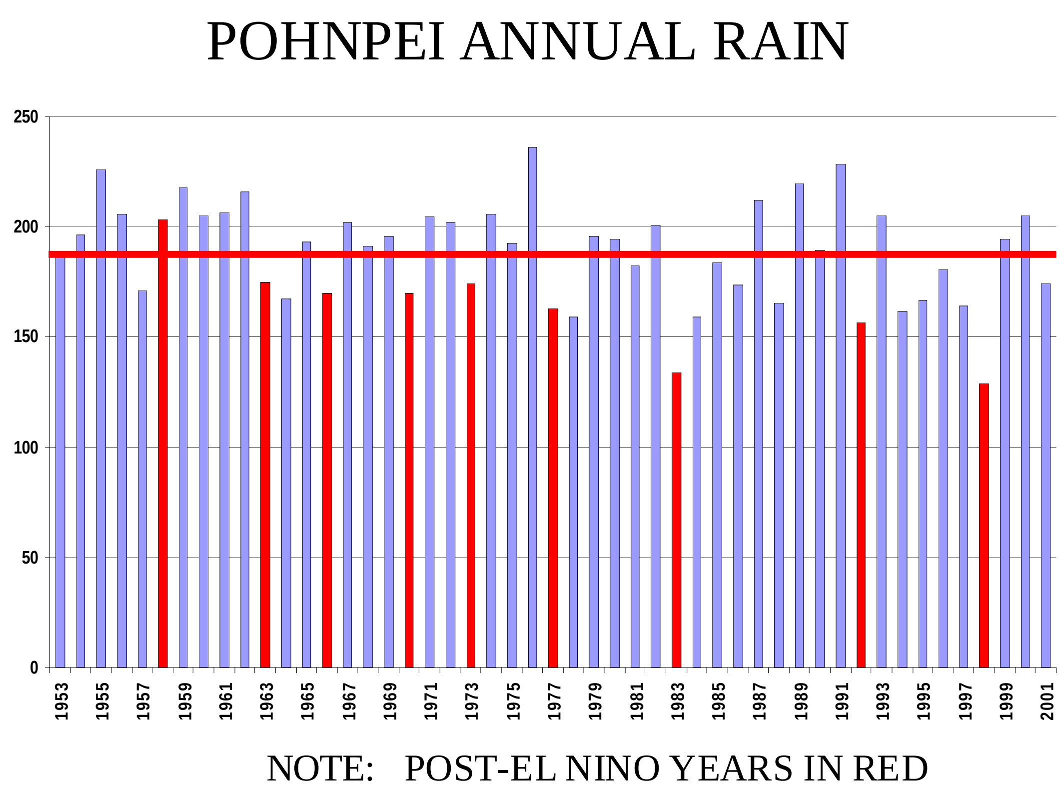


Figure 20. Pohnpei annual rainfall for the period 1953 through 2001. Post-El Niño years are indicated by darker bars. The mean annual rainfall is indicated by the horizontal line.

Percent of Normal

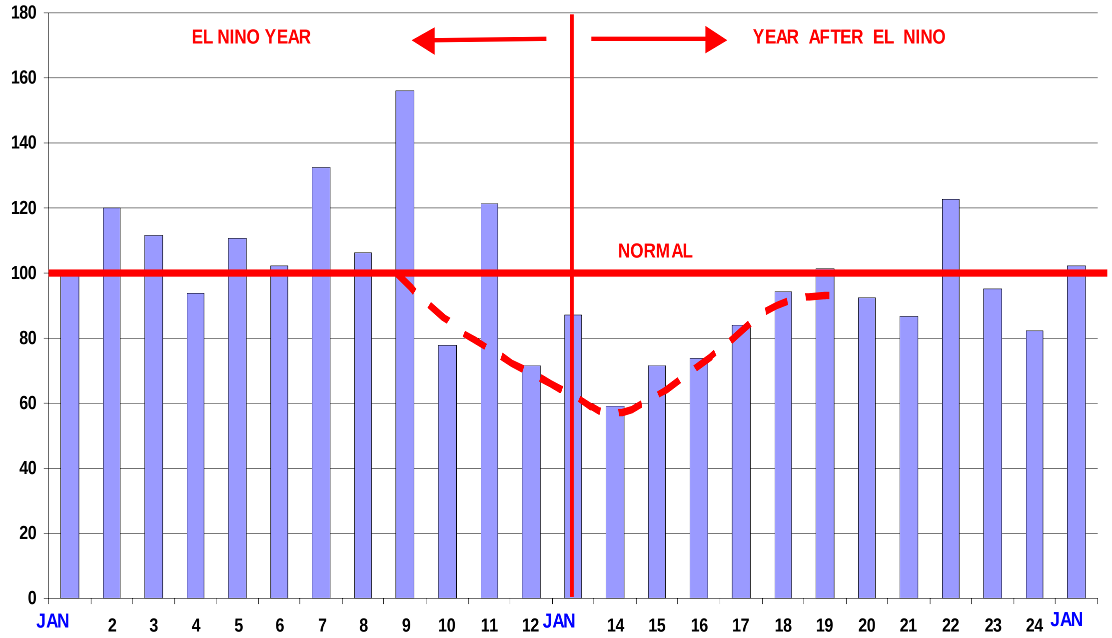


Figure 21. Rainfall at Pohnpei Island (in terms of percent of normal) composited during the course of several El Niño years through the years immediately following each El Niño.

2) SEA LEVEL

During an El Niño year, the mean sea level drops across most of Micronesia. Typically, the sea level in the region of Pohnpei falls to its lowest value in December of the El Niño year, then quickly recovers by the spring of the year following El Niño (Fig. 22). During La Niña, the sea level is elevated above its normal value. During the major El Niño of 1997, the sea level fell approximately 1 foot below its long-term average, and during the La Niña years that followed (1998-2001), the sea level rose to levels nearly 1 foot above its long-term average. The net difference of the sea level between the El Niño minimum in December 1997 and the La Niña high stands of the sea level during the summers of 1999, 2000, and 2001 was approximately 2 feet. This is substantial, considering that the normal range between the daily high and low astronomical tides is on the order of 4 feet! On the question of long-term sea-level rise due to global warming, it must be pointed out that the long-term rise of sea level due to large-scale global climate change is estimated to be on the order of 4 or 5 inches per century. The ENSO changes in sea level of 2 feet over the course of a year or two are enormous compared to this, and make it difficult to retrieve the long-term signal.

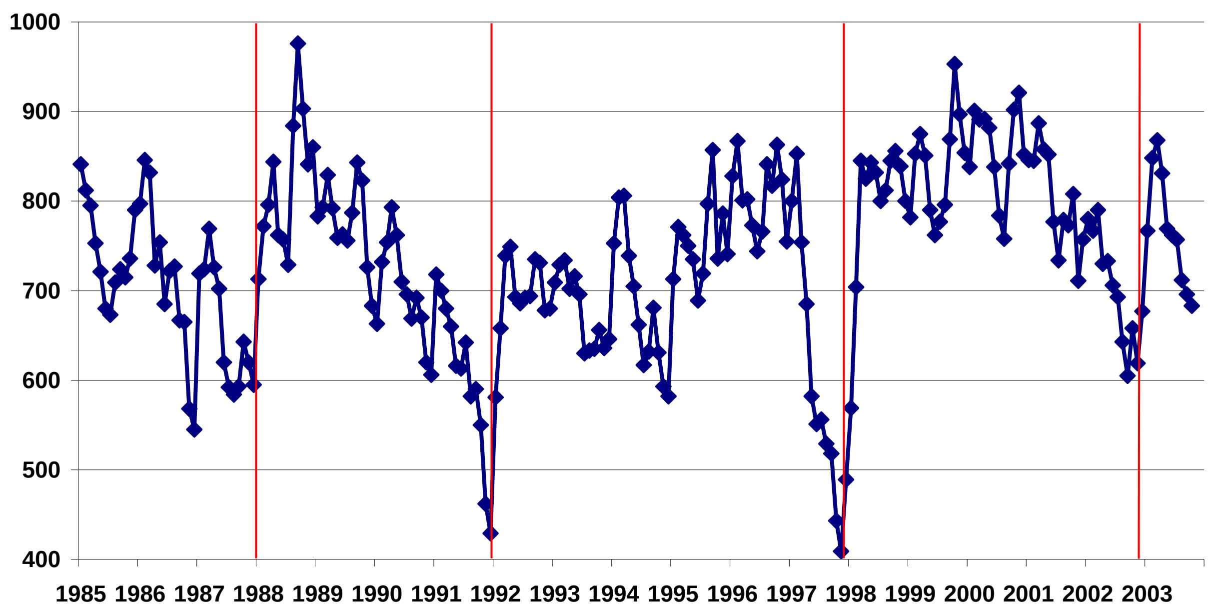


Figure 22. The record of monthly mean sea level at Pohnpei for the period 1985-2004. The large changes in sea level are highly coherent across the region from Yap to Guam, Chuuk, Pohnpei, and Kosrae. Note the low sea level at the end of El Niño years (1987, 1991, 1997, and 2002) and the high sea level in the summers of La Niña years (1988, 1994, 1996, and 1998-2001).

3) TROPICAL CYCLONES

The ENSO cycle has a profound effect on the distribution of tropical cyclones in the western North Pacific basin. The total number of tropical cyclones in the basin is not so much affected as is the formation region of the tropical cyclones. During El Niño, the formation region of tropical cyclones extends eastward into the eastern Caroline Islands and the Marshall Islands (see Fig. 23). During the year following an El Niño year, the formation region of tropical cyclones retracts to the west. This results in an increased risk of a typhoon for Pohnpei during El Niño years, and a decreased risk during the year following El Niño and during La Niña years. On Pohnpei, the risk of having typhoon force winds of 65 knots or greater is 1 in 10 for El Niño years, and approximately 1 in 50 for non-El Niño years. Pohnpei has not had heavy damage from a typhoon since Typhoon Lola in 1986 (an El Niño year), although deadly landslides have occurred in recent years associated with the heavy rains of developing tropical cyclones.

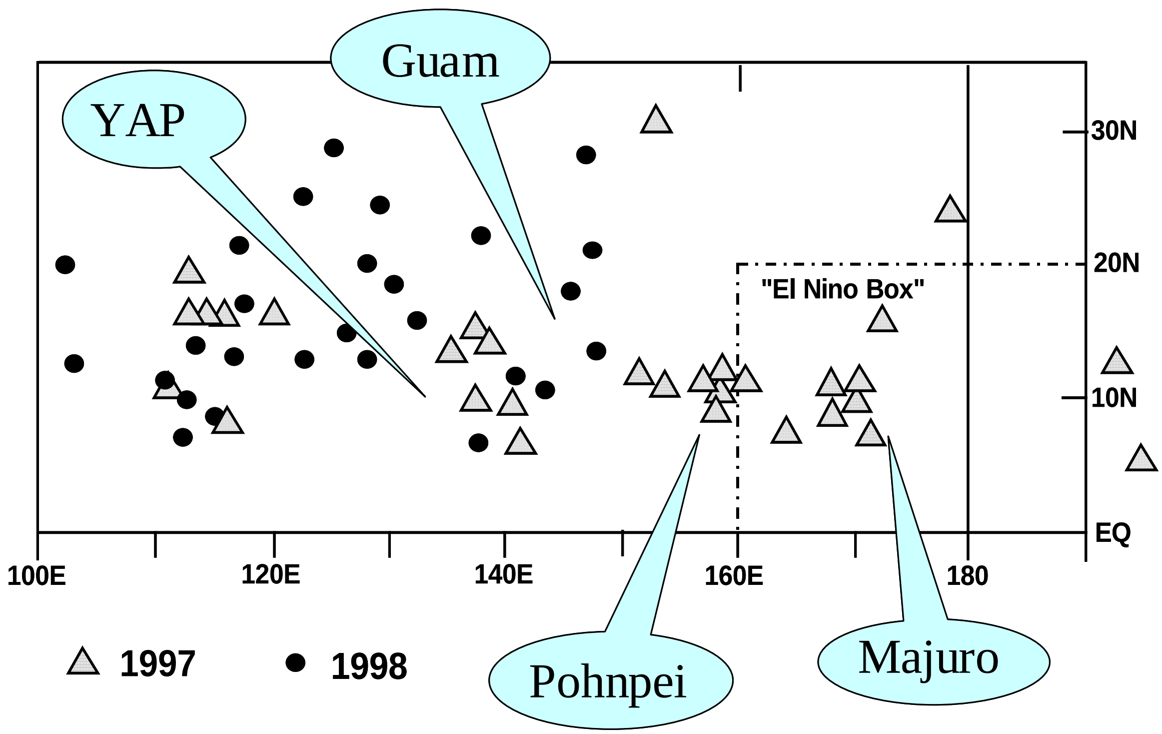


Figure 23. The formation locations for all western Pacific basin tropical cyclones during the El Niño year of 1997 (black dots) and the El Niño follow-on year of 1998 (gray triangles). Note the enormous difference in the formation region (especially in the area designated as the, "El Niño box"). Formation is defined as that point along the JTWC best-track that the tropical cyclone attained an intensity of 25 kt. During an El Niño year, the risk of a typhoon is enhanced for Pohnpei, the Marshall Islands, the eastern Caroline Islands, and for Guam.

5. Tropical Cyclones affecting Pohnpei

a. Tropical cyclone definitions

Typhoons rarely hit Pohnpei; more often they are spawned in Micronesia and sent on to Guam. Every several years or so on average, a mildly damaging tropical storm or depression will affect the island.

Tropical cyclone is a generic term for atmospheric cyclonic circulations that originate over the tropical oceans. As opposed to cyclones in the mid-latitudes, tropical cyclones usually develop a relatively narrow band of maximum winds encircling a calm center, or, for tropical cyclones that reach typhoon intensity, an eye. Tropical cyclones also develop spiral cloud bands that produce torrential rain and high winds, often causing structural damage, floods and sea inundation. Some definitions follow:

TROPICAL DISTURBANCE – A discrete system of apparently organized convection, generally100 to 300 nautical miles (n mi) in diameter, originating in the tropics or subtropics, having a non-frontal, migratory character and having maintained its identity for 12- to 24-hours. The system may or may not be associated with a detectable perturbation of the low-level wind or pressure field. It is the basic generic designation which, in successive stages of development, may be classified as a tropical depression, tropical storm, typhoon or super typhoon.

TROPICAL DEPRESSION – A tropical cyclone with maximum sustained 1-minute winds that do not exceed gale force (i.e., less than 34 knots).

TROPICAL STORM – A tropical cyclone with maximum sustained 1-minute mean surface winds in the range of 34-63 knots (39-73 mph).

TYPHOON – A tropical cyclone with maximum sustained 1-minute winds of 64 knots (74 mph) or higher.

SUPER TYPHOON – A typhoon with maximum sustained winds of 130 knots (150 mph) or higher.

MONSOON DEPRESSION – A tropical cyclonic vortex characterized by: (1) its large size, the outermost closed isobar may have a diameter on the order of 600 n mi; (2) a large loosely organized grouping of deep convective cloud elements; (3) a low-level wind distribution that features a 100 n mi diameter light wind core which may be partially surrounded by a band of gales; and, (4) a lack of a distinct cloud system center. Note: most monsoon depressions that form in the western north Pacific eventually acquire persistent central convection and accelerated core winds marking its transition into a conventional tropical cyclone.

INTENSITY – The maximum sustained wind averaged over a period of 1 minute, typically located within 60 n mi of the center of a tropical cyclone, and in the case of a typhoon, occurring in the eye wall. Other tropical cyclone advisory agencies, such as the Japan Meteorological Agency (JMA), use a 10-minute averaging interval to describe their sustained winds. The 1-

minute average is approximately 15% higher than the 10-minute average, and is one reason why warnings from the Joint Typhoon Warning Center may differ in wind speed from other international agencies. Peak gusts over water tend to be 20-25% higher than the sustained 1-minute wind.

Minimum sea level pressure at the center of a tropical cyclone is also used as a measure of its intensity. There are several wind-pressure relationships for tropical cyclones that are often used to obtain an estimate of the peak wind speeds from the minimum central sea-level pressure.

SIZE – The areal extent of a tropical cyclone, usually measured radially outward from the center to the outermost closed isobar, or to some other parameter such as the boundary of the 30-kt wind. Based on an average radius of the outer-most closed isobar, size categories in degrees of latitude (1 degree of latitude = 60 n mi) are: < 2º = very small (midget), 2º to 3º = small, 3º to 6º = medium (average), 6º to 8º = large, and 8º or greater = very large (giant) (Brand 1972, and a modification of Merrill 1982). The eye, the typhoon-force winds, and the area of gales of a midget typhoon could nearly fit over Saipan. Although it possessed a small 8 n mi eye, one of the largest typhoons ever observed, Typhoon Tip (1979), had a radius of gales of 600 n mi that nearly filled the western North Pacific basin from the equator to Japan and from the Philippines to Guam and the CNMI.

The term **knot** (abbreviated kt) is a unit of speed (one knot = one nautical mile per hour) that is used extensively in tropical meteorology as a unit of measure for wind speed or forward speed of motion. Knot has the built-in meaning of “per hour”, therefore the wind is properly be said to be blowing 10 knots (not at ten *knots per hour*). To convert kt to mph, multiply by 1.1538. For example, a tropical cyclone reaches tropical-storm intensity when its sustained winds reach 34 kt or approximately 39 mph. Other tropical cyclone thresholds include typhoon intensity at 64 kt (74 mph), and super typhoon intensity at 130 kt (150 mph).

Local time on Pohnpei is Universal Time Coordinated (**UTC**) or Greenwich Mean Time (GMT or Z) plus 11 hours. Because of greater seasonal changes in the amount of daylight hours, the U.S mainland shifts from standard time to daylight savings time from April to October. During the period of daylight savings time, each time zone adds one hour to its local time. Thus, Eastern Standard Time is 14 hours behind Pohnpei local time, and Eastern Daylight Time is 13 hours behind Pohnpei local time. The difference in the length of sunlight hours on Pohnpei differs by only about 1 hour from December to June. During late June, the sunrise on Pohnpei is at approximately 6:14 AM and sunset at 6:46 PM; during late December, the sunrise on Pohnpei is at approximately 6:35 AM and the sunset at 6:18 PM. Sunrise and sunset times for Pohnpei can be found at the wesbsite of the U.S. Naval Observatory (www.usno.navy.mil). Other astronomical and oceanographic information (such as tide tables and times of moonrise/moonset) can be found there or at the NOAA National Ocean Service site: www.co-ops.noaa.gov/tpred2.html#PI.

Tropical cyclone advisories for the western North Pacific are issued by the Joint Typhoon Warning Center (JTWC), now at Pearl Harbor, HI (web site: https://www.npmoc.navy.mil/jtwc.html). The JTWC tropical cyclone advisories contain information on the location and intensity of each active tropical cyclone, and the forecasts of the track and intensity out to 72 hours. Beginning in 2003, the advisories contain track and intensity forecasts out through five days. They are prepared every six hours valid at 0000, 0600, 1200, and 1800 UTC (10 AM, 4 PM, 10 PM and 4 AM local time) and are released to the public at a three-hour lag from the valid time of the current position and intensity; thus, the 0000, 0600, 1200 and 1800 UTC advisories are released at 0300, 0900, 1500, and 2100 UTC (1 PM, 7 PM, 1 AM, and 7 AM local time) respectively. Positions of tropical cyclones may be made on a more frequent basis when they threaten any part of Micronesia. For a list of products issued by the National Weather Service during times of typhoon threats to Pohnpei, contact the Weather Service Office in Kolonia:

691 320-2248

Or

National Weather Service
Guam Forecast Office
Hueneme Road, Bldg. 3232
Barrigada, Guam 96913

Phone: 671-472-0900
FAX: 671- 472-7405
http://www.prh.noaa.gov/pr/guam/.

OTHER USEFUL URL's

Naval Research Lab Monterey CA (Typhoon tracks and pics)
http://www.nrlmry.navy.mil/tc_pages/tc_home

Joint Typhoon Warning Center
https://metoc.npmoc.navy.mil//jtwc.html

Navy Fleet Numerical (Weather Forecast Maps)
https://www.fnmoc.navy.mil/

Climate Prediction Center
http://www.cpc.ncep.noaa.gov/products/monitoring_and_data/

ENSO Newsletter
http://lumahai.soest.hawaii.edu/Enso/subdir/update.dir/update.html

Or contact the local Office of Civil Defense.

The naming authority for tropical cyclones in the western North Pacific passed from the JTWC to the Japan Meteorological agency (JMA) starting in the year 2000. The JTWC numbers their tropical cyclones independently of the JMA, but uses the JMA name when it is available. It is possible (and has already occurred) that the JTWC may be issuing advisories on a numbered, but unnamed tropical storm, or that the JMA may have named a tropical storm that the JTWC has only as a numbered tropical depression.

The U.S. National Weather Service Forecast Office (NWSFO), Tiyan, Guam, is responsible for issuing tropical storm and typhoon *watches* and *warnings* for Guam, Pohnpei, the CNMI, and all states of the FSM. The local Governors and military commanders are responsible for placing their respective islands and military units into *Tropical Cyclone Conditions of Readiness.*

TROPICAL CYCLONE WATCHES AND WARNINGS

The tropical cyclone watches and warnings issued by the Tiyan NWSFO follow:

Tropical Storm Watch: A tropical cyclone (tropical depression, tropical storm or typhoon) poses a threat. The onset of damaging wind associated with the tropical cyclone is possible within the watch area within 48 hours. The winds are not expected to increase to typhoon force (64 kt /74 mph or higher). NOTE: Damaging winds are defined as a sustained 1-minute wind of at least 34 kt (39 mph).

Tropical Storm Warning: A tropical cyclone (tropical depression, tropical storm or typhoon) poses a threat. Damaging winds associated with the tropical cyclone are expected in the warning area within 24 hours, or are already occurring. The winds are not expected to increase to typhoon force (64 kt or higher).

Tropical Storm Warning/Typhoon Watch: A tropical cyclone (tropical depression, tropical storm or typhoon) poses a threat. Damaging winds associated with the tropical cyclone are expected in the warning area within 24 hours, or are already occurring. The wind may increase to typhoon force (64 kt/74 mph or higher).

Typhoon Watch: A tropical cyclone (tropical depression, tropical storm or typhoon) poses a threat. If the tropical cyclone is not already a typhoon, it may become one as it nears the watch area. Damaging winds associated with the tropical cyclone are possible within 48 hours. There is a possibility that winds in the watch area may increase to typhoon force after the onset of damaging winds.

Typhoon Warning: A tropical cyclone (tropical depression, tropical storm or typhoon) poses a threat. If the tropical cyclone is not already a typhoon, it is expected to become one as it nears the warning area. Damaging winds associated with the tropical cyclone are expected in the warning area within 24 hours, or are already occurring. Also, the winds are expected to increase to typhoon force after the onset of damaging wind, or typhoon force winds are already occurring.

NOTE: The generic typhoon warning specifies only that winds of at least 64 kt/74 mph are expected. Information regarding the peak wind expected for a particular typhoon will be provided by the NWSFO Tiyan and the local Office of Civil Defense on a case-by-case basis.

Tropical Cyclone hazards

There are several hazards associated with tropical cyclones. These are: (1) Destructive winds and wind-blown debris; (2) Coastal Inundation; (3) torrential rains and flooding; (4) wind shear and mechanical turbulence; (5) rough seas and hazardous surf; (6) tornadoes; (7) sea salt deposition; (8) erosion; and, slope failures. Pohnpei, to one extent or another, is susceptible to most typhoon-related hazards. Tornadoes probably do not occur in association with typhoons on Pohnpei. The four primary hazards are destructive winds, coastal inundation, flooding, and slope failures.

b. The historical record of tropical cyclones on Pohnpei

The western North Pacific is the most active tropical cyclone basin in the world. On average, 28 tropical storms and typhoons occur annually (this compares to about 10 for the North Atlantic Basin). Of the annual average of 28 tropical cyclones of tropical storm intensity or higher, 18 become typhoons, and 4 become super typhoons. Another distinguishing feature of the western North Pacific basin is that tropical cyclones, although most common in late summer and autumn, can occur at any time of the year, whereas over other basins, off-season occurrences are rare. The main TC season for the western North Pacific extends from mid-May through mid-December. For the basin as a whole, tropical cyclones are least likely during the month of February.

The highest frequency of occurrence of typhoons in the western North Pacific is in an area just to the northeast of Luzon in the Philippine Sea (Figure 24) where there are, on average, five passages of a tropical storm or typhoon per 5-degree latitude-longitude square per year. In the region of Pohnpei, the frequency of tropical cyclones of tropical storm intensity or higher is less than one per 5-degree latitude-longitude square per year. The frequency of tropical cyclones passing Pohnpei is less than one every three years within 75 n mi. (Fig. 25), with a sharp gradient that features almost no tropical storms south of 5° N to over 1 tropical storm or typhoon passing within 75 n mi of locations several hundred miles to the north and west of Pohnpei. The distribution of tropical cyclone tracks passing Pohnpei appears to be random (Fig. 26a-d) with a very sharp north-south gradient.

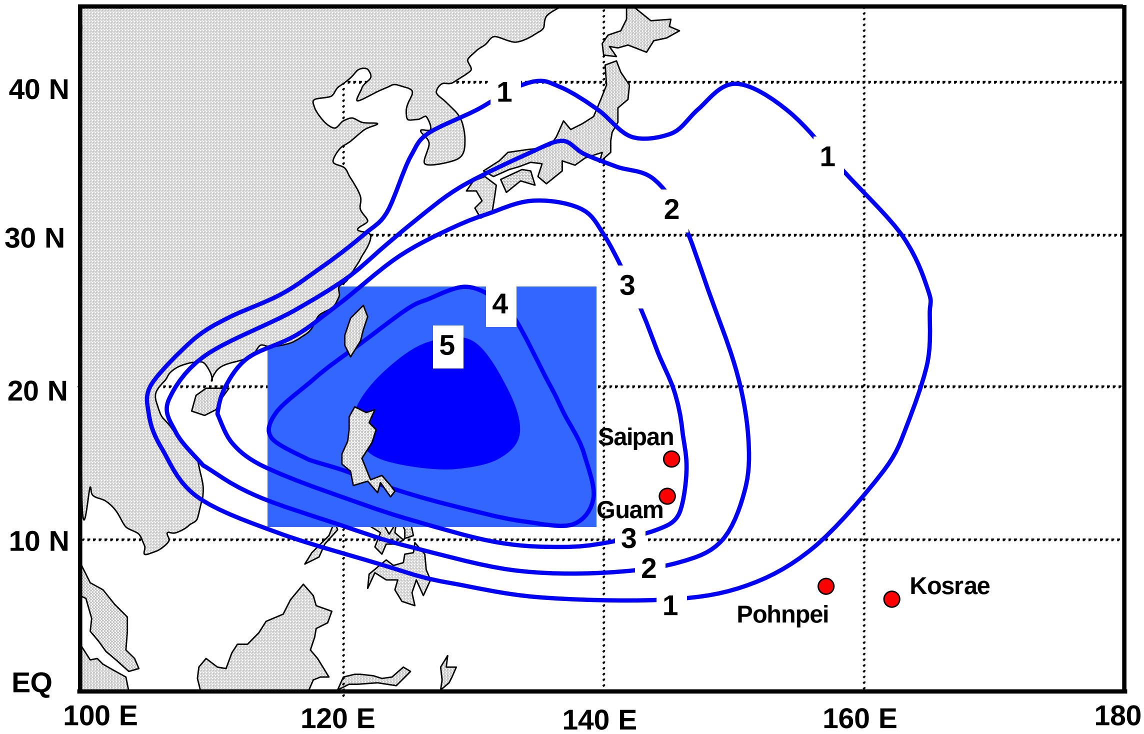


Figure 24. Mean annual number of tropical storms and typhoons traversing 5-degreee latitude by 5-degree longitude squares (adapted from Crutcher and Quayle 1974).

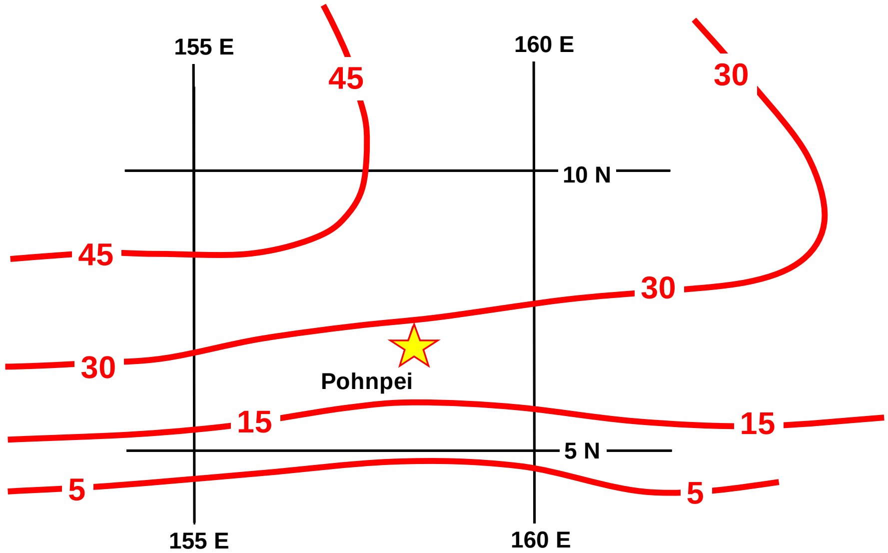
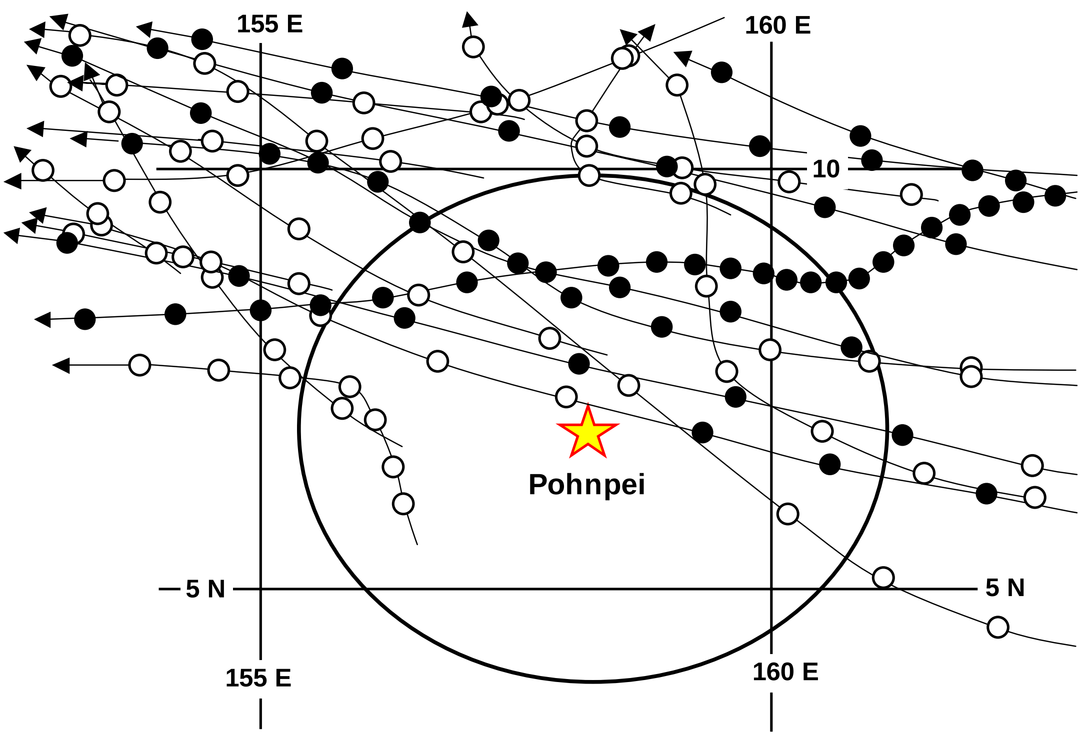
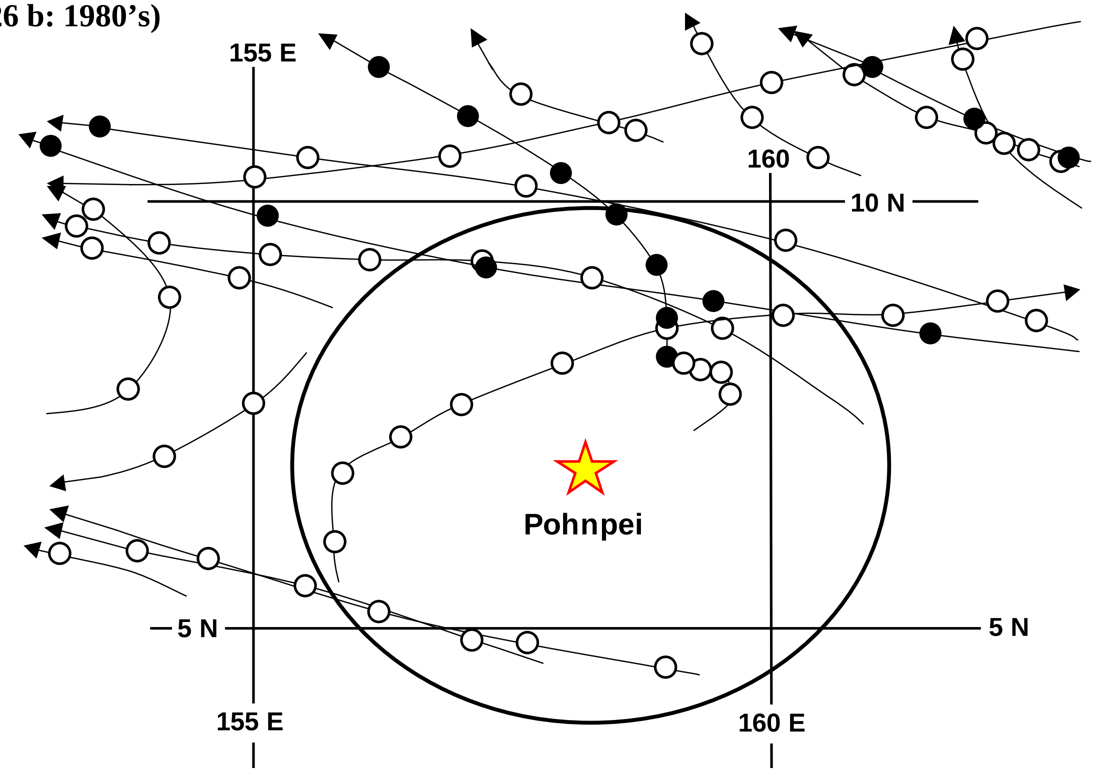


Figure 25. Number of tropical storms and typhoons per 100 years passing within 75 n mi of any map location. (Created from JTWC best-track data 1970-99.)

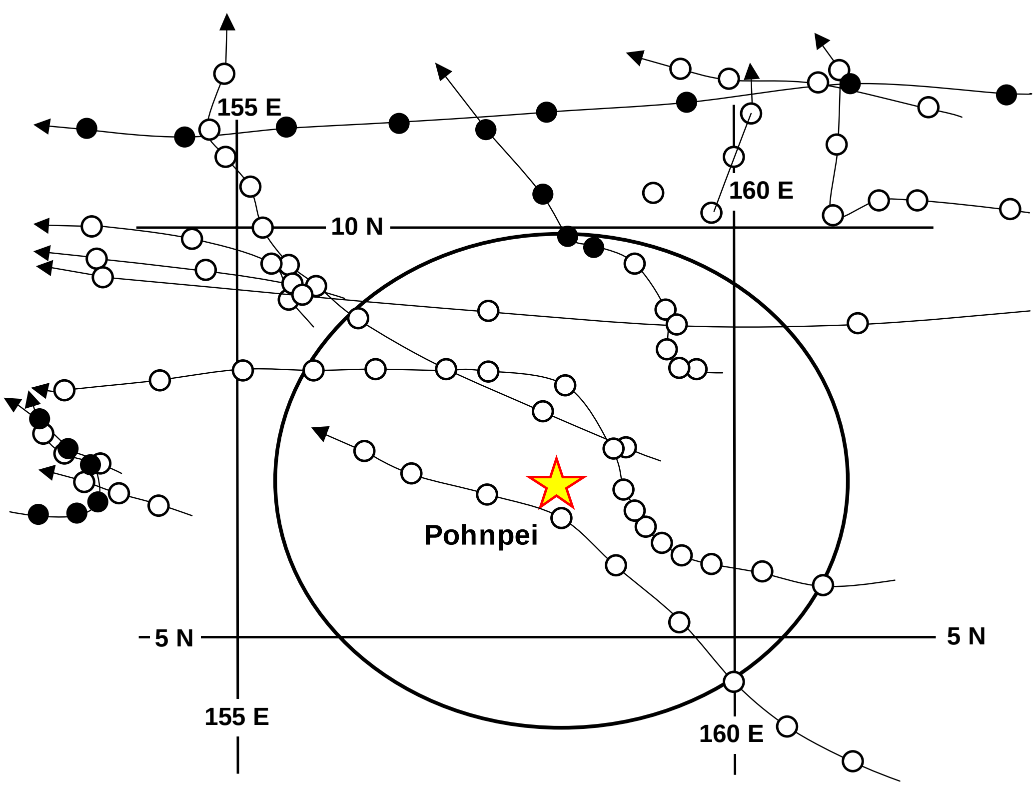
(Fig. 26 a: 1970's)



(Fig. 26 b: 1980's)



(Fig. 26 c: 1990's)



(Fig. 26 d: 1970-99)

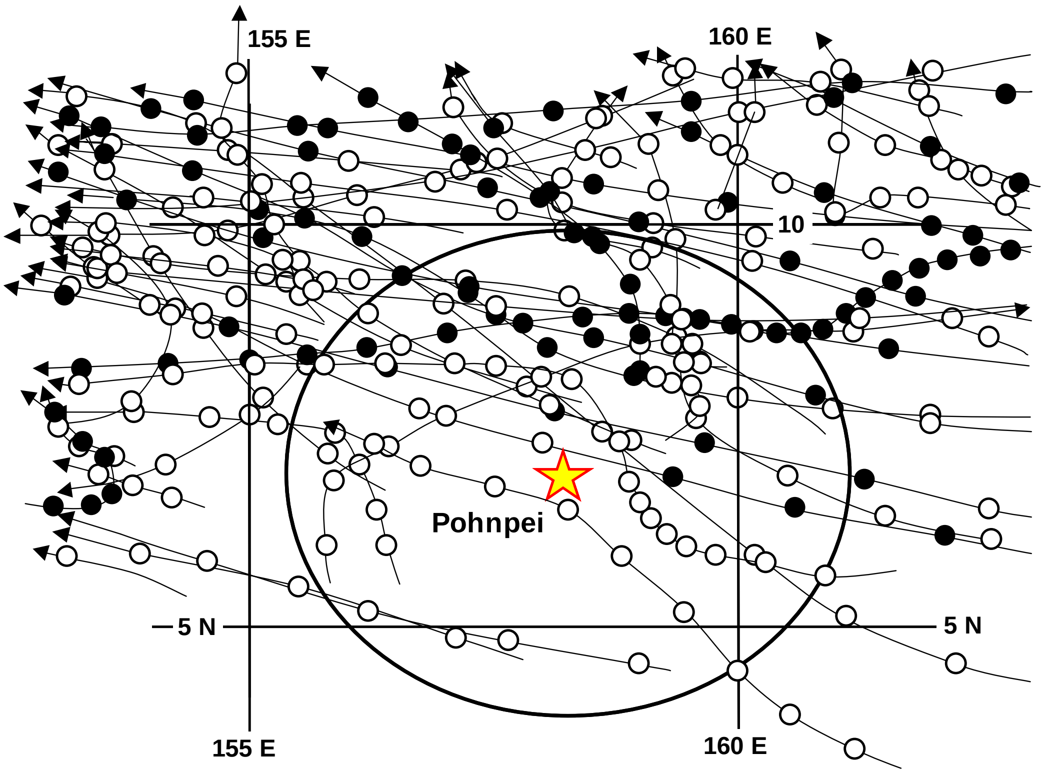


Figure 26. All tropical cyclone positions at six-hour intervals from the JTWC best-track archive. (a) The 1970's, (b), the 1980's, (c) the 1990's , and (d) the period 1970-1999. Open circles indicate tropical storm intensity, black dots indicate typhoon positions, star is the location of Pohnpei and the circle has a radius of 180 n mi from Pohnpei.

5. Month-to-month, Inter-annual, and inter-decadal variation

a. Month-to-month variation: The Madden-Julian Oscillation (MJO)

In 1971 Roland Madden and Paul Julian (1971) stumbled upon a 40-50 day oscillation when analyzing wind anomalies in the tropical Pacific. They used ten years of pressure records at Canton (at 2.8° S in the Pacific) and upper level winds at Singapore. The oscillation of surface and upper-level winds was remarkably clear in Singapore. Until the early 1980's little attention was paid to this oscillation, which became known as the *Madden and Julian Oscillation* (MJO), and some scientists questioned its global significance. Since the 1982-83 El Niño event, low-frequency variations in the tropics, both on intra-annual (less than a year) and inter-annual (more than a year) timescales, have received much more attention.

The MJO, also referred to as the 30-60 day or 40-50 day oscillation, turns out to be the main intra-annual fluctuation that explains weather variations in the tropics. The MJO affects the entire tropical troposphere but is most evident in the Indian and western Pacific Oceans. The

MJO involves variations in wind, sea surface temperature (SST), cloudiness, and rainfall. Because most tropical rainfall is convective, and convective cloud tops are very cold (emitting little longwave radiation), the MJO is most obvious in the variation of outgoing longwave radiation (OLR), as measured by an infrared sensor on a satellite (Fig. 27).

Associated with the propagation of convective anomalies, the MJO involves variations in the global circulation. The MJO affects the intensity and break periods of the Asian and Australian monsoons and interacts with El Niño. Wet spells in the Australian monsoon occur about 40 days apart. Fairly weak correlations with the midlatitude rainfall patterns and jet stream characteristics have also been found.

The rainfall on Pohnpei is affected by the MJO. The manifestation of the MJO signal at Pohnpei is to produce several weeks of wet weather broken by a week or two of hot dry weather. The signal is not always very strong, but an investigation of the first year of the WERI/CSP rainfall data set suggests that the MJO was present and acting to produce dry breaks in the weather at intervals of approximately 40-50 days (Fig. 28)

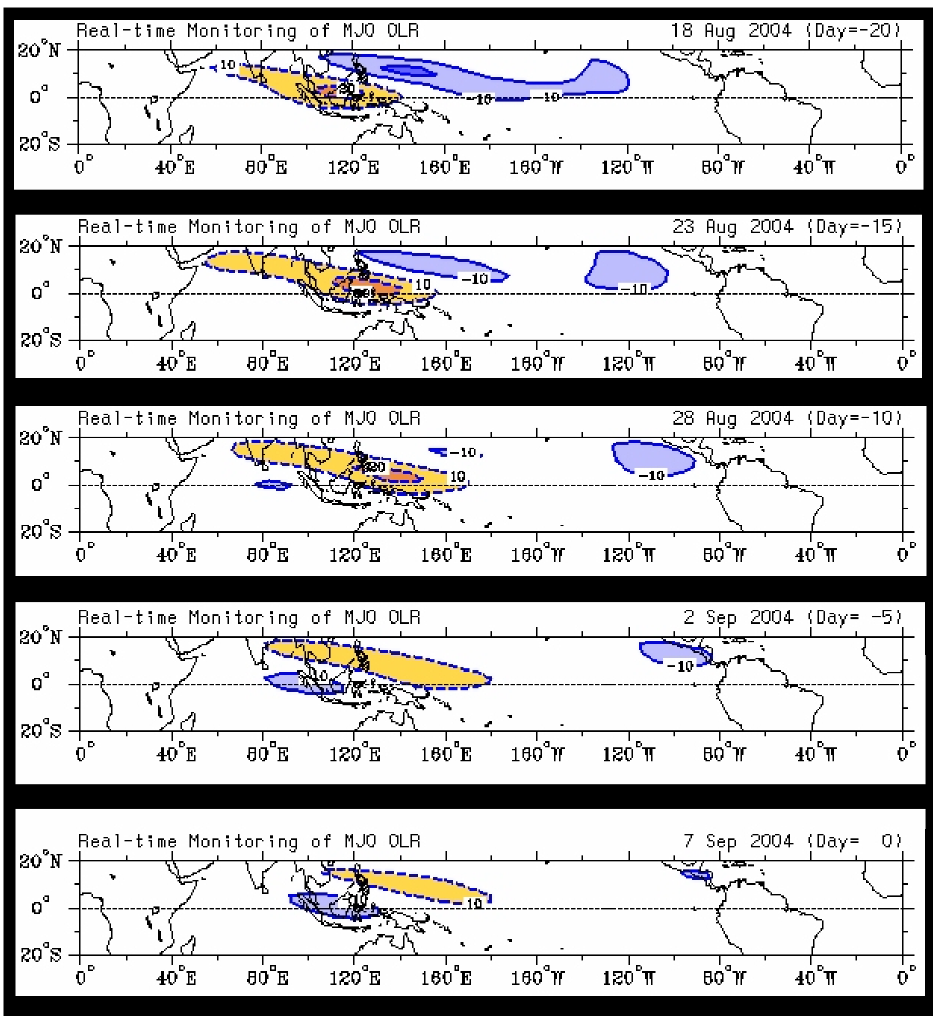


Figure 27. A strong episode of the MJO occurred in the Indian Ocean and the Pacific Ocean during the latter half of August 2004 into the first week of September 2004. The blue regions are areas of cloudy rainy weather, and the yellow regions are areas of abnormally dry weather. The panels show the rainy areas and dry areas at 5-day intervals from August 18 to September 7. This 20-day period represents one-half cycle of the MJO as the western Pacific went from being very wet to very dry. Note the slow eastward movement of the anomalies.

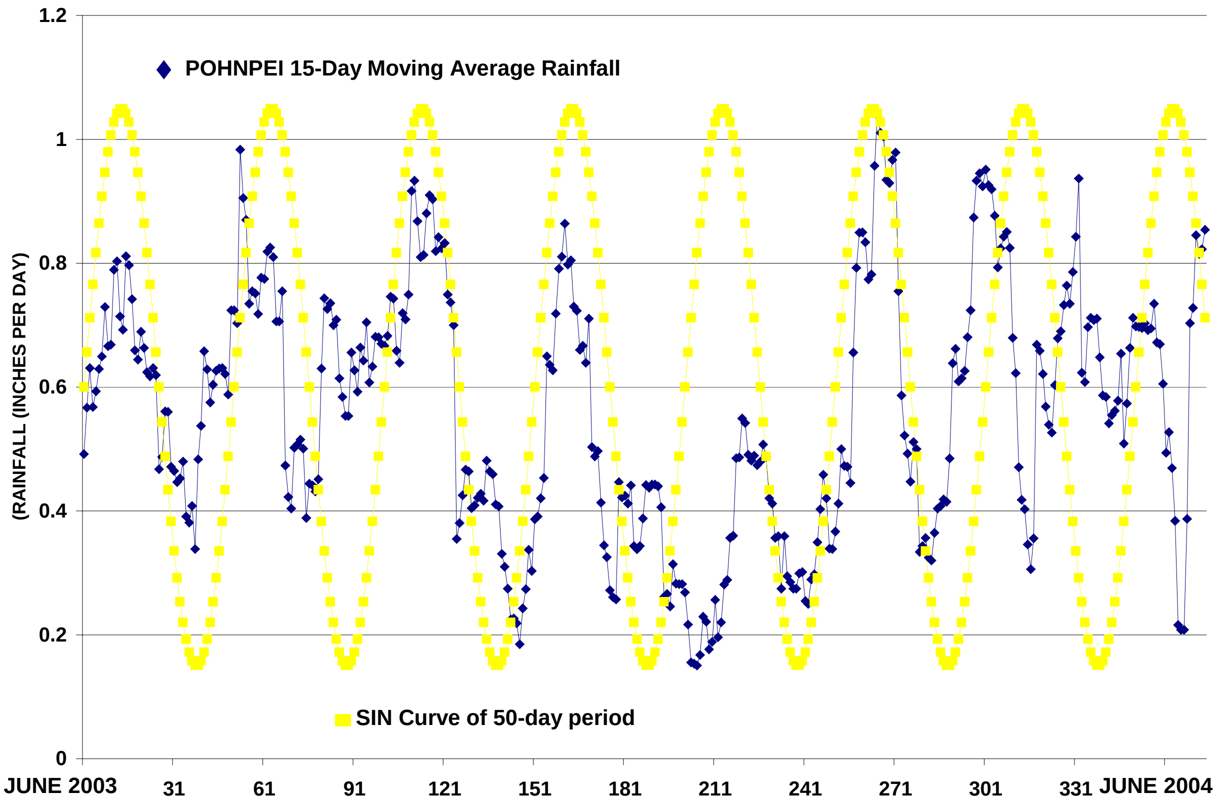


Figure 28. The rainfall at Pohnpei appears to be affected by the MJO. Dry spells and rainy spells occur at intervals of roughly 50 days. The dark line is a 15-day moving average of the daily rainfall at the College of Micronesia, and the gray line is a sine curve with a period of exactly 50 days. The 15-day moving average tends to filter the short-period fluctuations in the observed data, and exaggerates longer-period fluctuations (even if they occur by chance). The signal here, however, appears quite robust, and is likely a manifestation of the MJO that modulated the rain at Pohnpei with a period of approximately 50 days during the first year of operation of the WERI/CSP rain gage network. Day 1 = June 28, 2003; Day 331 = May 21, 2004.

b. Inter-annual variation

One of the strongest inter-annual variations of the global climate is the ENSO cycle (See previous discussion of ENSO in Section 4). On the basis of sea surface temperature in the El Nino 3.4 region (5 deg N.,-5 deg. S.,120-170 deg. W.) during the interval of 1950-1997, Kevin Trenberth (1997) previously has identified some 16 El Niño's and 10 La Niña's, these 26 events representing the extremes of the quasi-periodic El Nino-Southern Oscillation (ENSO) cycle. The duration, recurrence period, and sequencing of these extremes vary randomly. Hence, even the decade of the 1990's, with its abundance of weak, moderate and one very strong El Niño (i.e., 1997), is not significantly different from that of previous decadal epochs, at least, on the basis of the frequency of onsets of ENSO extremes. Additionally, the distribution of duration for both El Nino and La Nina looks strikingly bimodal, each consisting of two preferred modes, about 8- and 16-months long for El Niño and about 9- and 18-months long for La Niña, as does the distribution of the recurrence period for El Niño, consisting of two preferred modes about 21- and 50-months long (Wilson 2000). The effects of El Niño on the weather, typhoons, and sea level in the region of Pohnpei were discussed in Section 4.

c. Inter-decadal variation

There is intense pressure on the scientific community to predict the long-term fate of earth's climate (e.g., global warming); and further, to show the impact of such long-term climate change at regional scales (e.g., the tropical Pacific islands, Antarctica, and the world's grain belt). It has been suggested by some (e.g., Morrissey and Graham 1996) that the hydrologic cycle of the western Pacific may change in a warmer world in a manner that would see tropical islands in the northwest part of the basin (e.g., Yap, Palau, Guam and the CNMI) become drier while islands of the central equatorial and South Pacific (e.g., Kiribati southeastward through the Society Islands) become wetter. As research continues on the problem of long-term climate change, attention has recently been focused on climate fluctuations at periods of one to several decades. These inter-decadal climate variations are troubling because they may mask, or may be mistaken for, longer-term climate changes. A plethora of local and regional climate patterns have been defined, for example: the Pacific Decadal Oscillation (PDO) (Minobe 1997), the North Atlantic Oscillation (NAO) (Uppenbrink 1999), and the Southern Oscillation. Nearly all of these have prominent inter-decadal variations. Any projections of a change in the hydrologic cycle in the western Pacific in a warmer world must take account of the presence of susbstantial inter-decadal variations of rainfall, as observed on Pohnpei and throughout Micronesia.

The 50-year record allowed some assessment of inter-decadal variations in Pohnpei's rainfall. The mid 1950s through the mid-1960's was an exceptionally wet period, as indicated by the sharp upward slope of the running accumulations of rainfall anomalies shown in Fig. 29. The mid-1960s to the mid-1970s were near the long-term average, with another wet period occurring from the mid 1970's the mid-1980s. Thereafter, a long dry spell began lasting from the late 1980's to the current time (interrupted by a brief wet period in the mid-1990's). Superimposed on the long-term rise and fall of the integrated rainfall are sharp peaks and troughs that are primarily associated with ENSO: the period from the end of the El Niño year through the year following El Niño tends to be very dry. The period of Japanese record (the mid-1920's to the late-1930's) appears to have seen near normal rainfall overall, with some sharp short-term peaks and dips associated with ENSO.

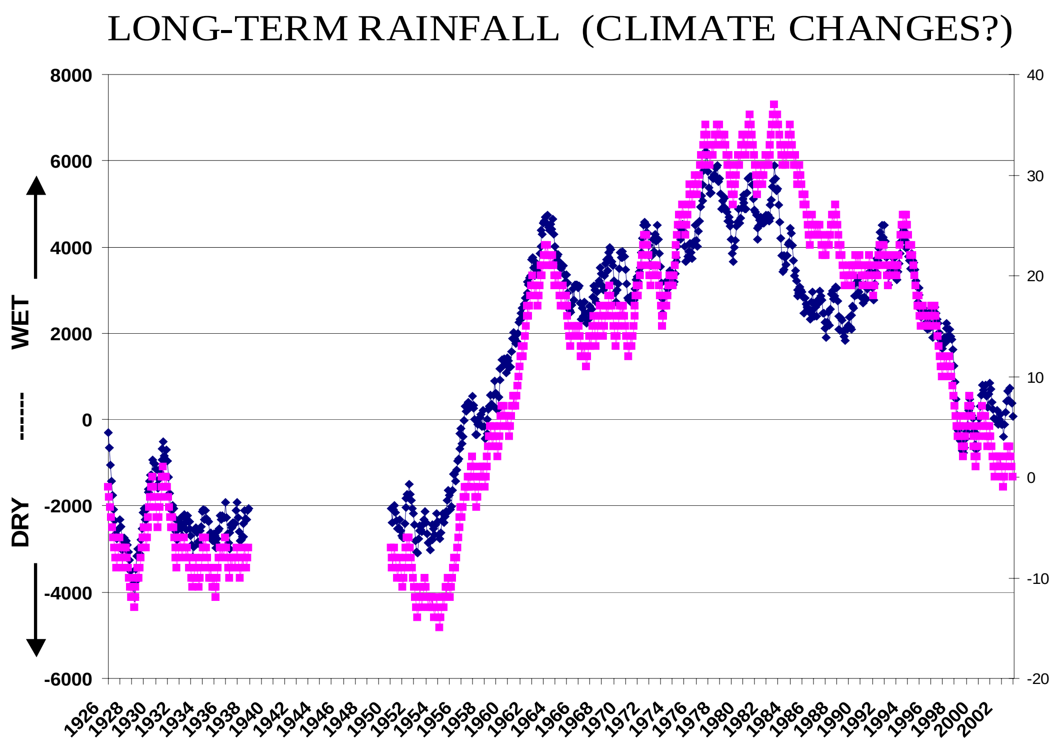


Figure 29. Running accumulations of the rank of each month's rainfall for the period 1926 to 2003 (Lowest month = rank -390; highest month = rank +390). Prominent features include a very wet period in the 1960's, and recent overall dryness in the 1990's. The sharp short-term fluctuations lasting a year or two are related to El Niño. There is a gap in the data from the Japanese period (1926-37) until the U.S. began taking measurements after WW II in 1950.

6. Principal findings

This technical report presents the results of the first year of a collaborative effort between WERI and the Conservation Society of Pohnpei to measure the rainfall across the island of Pohnpei. Principal findings include:

(1) The distribution of rainfall on Pohnpei is affected by the topography, and the mean annual rainfall totals among recording stations on Pohnpei differ by over 150 inches!

(2) Pohnpei's international airport received the lowest annual total of 142 inches. The highest measured annual total of 323 inches occurred on top of Nahna Laud in the highland rainforest of Pohnpei's interior.

(3) Most of the rainfall on Pohnpei occurs in the early afternoon when daily heating from the sun results in the build-up of showers over the island.

(4) Earlier charts of Pohnpei's mean annual rainfall using PRISM were found to be quite accurate.

The Pohnpei rain record is too short to develop accurate return periods of extreme rainfall events (although attempts have been made in this report and by others that may be refined as more data is gathered). Further high-resolution (time and space) rain records need to produce reliable tables of return periods for short-term extreme rain events. In any case, intensity-duration-frequency (IDF) tables were generated using the available short Pohnpei rainfall data sets.

Month-to-month fluctuations of rainfall on Pohnpei are influenced by the MJO. Inter-annual variations of Pohnpei's rainfall are closely linked to the El Niño/Southern Oscillation (ENSO) phenomenon. To some extent, the occurrence of typhoons in Pohnpei is also linked to ENSO. Large inter-decadal variations in rainfall (and also in the distribution of typhoons) are noted. The causes of these remain a mystery.

ACKNOWLEDGMENTS

The WERI project investigators would like to thank the U.S. Geological Survey for their support of this project. In addition, this project would not have been possible without the help of many people on Pohnpei. The WERI project investigators are thankful for the involvement in the project of the Conservation Society of Pohnpei (CSP), and the Pohnpei Nature Conservancy. We would like to acknowledge the help of the following people on Pohnpei without whom the project could not have taken place. There are so many to thank, and we regret that we can't list all who were of invaluable assistance, but several people deserve recognition.

From the CSP:
Willie Kostka (Director), Roseo Marquez, Valentine Santiago, and Kirino ??.

From the Nature Conservancy:
Bill Raynor (Director), and Mark Kostka

Local trail guides:
Richard

Pohnpei State Government
The honorable Lt. Governor, ????

And the mayors and chiefs of the municipalities of Madolenimhw, U, and Kitti

REFERENCES

Crutcher, H.L., and R.G. Quayle, 1974: Mariner's Worldwide Climatic Guide to Tropical Storms at Sea. NOAA/EDS. National Climatic Data Center, Asheville North Carolina. (Their tropical cyclone distribution in the Pacific adapted as Figure 4 in Tropical Cyclones Affecting Guam, NOCC/JTWC Tech Note 91-2).

Daly, C. R.P. Nielson, D.L. Phillips. 1994: A statistical-topographic model for mapping climatological precipitation over mountainous terrain. J. Appl. Met. 33:140- 158.

Foster, G.R., W.C. Moldenhauer and W.H. Wischmeier, 1982: Transferability of U.S. technology for prediction and control of erosion in the tropics. ASA special publication number 43, American Society of Agronomy Soil Science Society of America. 135-149.

Fu, R., A.D. Del Genio, and W.B. Rossow, 1990: Behavior of Deep COnvectiuve Clouds in the Tropical Pacific Deduced from ISCCP Radiances. *J. Climate*, 3, 1129-1152.

Ingraham, N.L., and Matthews, R.A., 1995: The importance of fog drip water to vegetation: Point Reyes Peninsula, California, J. Hydrology, 164, 269-285.

JTWC, (1991): Tropical cyclones affecting Guam (1671-1990). Naval Oceanography Command Center/Joint Typhoon Warning Center, Edited by F. Wells, COMNAVMARIANAS, FPO AP 96540-0051, 45 pp with appended updates to 1999.

Juvik, J.O. and P.C. Ekern, 1978: A climatology of mountain fog on Mauna Loa, Hawaii Island, Technical Report no. 118, Water Resources Research Center, University of Hawaii, Honolulu, HI, 63 pp.

Kiladis, G.N., and H. van Loon, 1988: The Southern Oscillation. Part VII: Meteorological anomalies over the Indian and Pacific sectors associated with the extremes of the Oscillation. *Mon. Wea. Rev.*, 116, 120-136.

Lander, M.A., and C.P. Guard, C.P., 2003: Monthly and Seasonal Rainfall Climatologies and Distribution Maps for Guam. Technical Report 102, Water and Environmental Research Institute of the Western Pacific, University of Guam, Mangilao.

Maddox, R.A., 1980: Mesoscale convective complexes. *Bull. Amer. Meteorological Soc.,* 61, 1374-1387.

Madden, R. A., and P. R. Julian, 1971: Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific.*J. Atmos. Sci*., 28, 702-708.

Madden, R.A., and P.R. Julian, 1994: Detection of the 40-50 day tropical oscillation: a review. *Mon. Wea. Rev*., 122, 814-837.

Maddox, R.A., 1980: Mesoscale Convective Complexes. *Bulletin American Meteorological Society*, 61, 1374-1387.

Minobe, S., 1997: A 50-70 year climatic oscillation over the North Pacific and North America. *Geophys. Res. Let.*, 24, 683-686.

Morrissey, M.L., and N.E., Graham, 1996: Recent trends in rain gauge precipitation measurements from the tropical Pacific: Evidence for an enhanced hydrologic cycle. *Bull. Amer. Meteoro. Soc.*, 77, 1207-1219.

Ramage, C.S., and A.M. Hori, 1981: Meteorological Aspects of El Niño. *Mon. Wea. Rev.*, 109, 1827-1835.

Ramage, C.S., 1986: El Niño. *Scientfic American.* May Issue. 77-84.

Ropelewski, C.F., and M.S. Halpert, 1987: Precipitation Patterns Associated with the El Niño/ Southern Oscillation. *Mon. Wea. Rev.*, 115, 268-284.

Ruprecht, C.F., and W.M. Gray, 1976: Analysis of Satellite-Observed Cloud Clusters, Papers I and II. *Tellus*, 28, 391-425.

SCOR, 1983: Prediction of El Niño. *Proc. No 19,* Paris, France, Scientific Committee for Ocean Research Working Group 55, 47-51.

Trenberth, K.E., 1997: The definition of El Niño. *Bulletin of the American Meteorological Society*. 78, 2771-2777.

Uppenbrink, J., 1999: Climate variability - The North Atlantic Oscillation, *Science*, 283, 948-949.

U.S. Army Corps of Engineers, 1980: Guam Storm Drainage Manual. U.S. Army Corps of Engineers, Honolulu District, Honolulu, HI.

U.S. Army Corps of Engineers, 2003: Rainfall-Frequency Study for Saipan, Commonwealth of Northern Marinas Islands. U.S. Army Corps of Engineers, Honolulu District, Honolulu, HI.

Wilson, Robert M., 2000: On the Bimodality of ENSO Cycle Extremes. NASA/TP-2000-209961. Space Science Department, Science Directorate, NASA Marshall Space Flight Center, AL 35812, February,2000, pp. 24.
PDF 227k. Download from http://trs.nis.nasa.gov/archive/00000514/.

APPENDIX. Constructed monthly time series of rainfall at Pohnpei WSO.

	January	February	March	April	May	June	July	August	September	October	November	December
1953	10.07	10.44	10.95	15.75	11.72	20.68	15.12	26.41	13.88	12.4	20.73	20.78
1954	11.95	8.44	13.38	18.2	21.38	18.43	11.37	17.89	17.73	14.65	22.52	20.21
1955	13.03	7.4	16.72	33.04	26.15	15.6	12.44	20.73	19.35	16.21	20.48	24.79
1956	17.61	6.51	18.33	28.08	23.4	13.41	16.9	17.43	13.29	15.4	15.68	19.98
1957	11.23	14.58	9.93	6.53	15.23	20.58	15.72	17.57	16.79	8.62	31.79	2.4
1958	9.72	15.71	17	23.59	20.4	16.62	21.28	11.23	14.89	20.56	23.16	9.35
1959	3.91	15.37	22.03	38.65	21.26	15.61	19.12	12.73	18.42	13.28	11.31	26.11
1960	13.82	12.45	15.81	25.72	22.08	18.36	12.01	16.02	13.11	16.18	18.88	20.85
1961	16.6	17.86	17.47	11.59	22.21	18.11	15.51	17.52	20.69	14.07	18.29	16.47
1962	26.67	16.04	11.04	11.94	22.41	11.89	13.6	18.54	22.91	18.57	28.39	13.6
1963	20.99	16.37	17.06	12.44	19.12	9.6	13.73	18.23	13.12	20.68	4.55	9.08
1964	3.59	19.76	14.03	16.02	12.69	13.16	14.33	16.47	15.44	11.02	12.66	18.22
1965	11.74	11.12	6.36	14.28	14.18	18.73	37.2	10.06	24.67	15.27	15.5	14.2
1966	15.84	1.71	14.77	6.07	21.27	11.87	24.22	10.18	10.65	16.61	18.74	18.12
1967	10.21	18.83	21.82	20.9	13.46	11.48	14.02	20.32	19.51	16.37	22.44	12.6
1968	9.88	13.6	24.47	21.09	16.99	10.54	22.32	17.36	17.58	14.65	9.32	13.33
1969	6.39	9.47	10.71	22.35	17.75	24.88	28.9	13.28	18.01	12.86	16.2	15
1970	7.98	7.14	7.35	14.58	15.73	16.8	12.4	16.1	15.74	20.4	15.62	19.93
1971	16.64	13.12	19.98	17.37	24.59	23.62	22.69	16.67	9.89	19.11	12.02	8.67
1972	10.52	11.79	14.66	20.39	33.46	9.73	36.31	12.38	29.53	7.98	7.3	7.71
1973	3.31	3.7	7.71	24.38	16.28	23.4	9.4	17.85	18.15	21.32	10.38	18.16
1974	10.66	16.56	18.81	22.24	16.74	21.27	21.57	18.77	8.84	17.3	20.79	12.32
1975	6.61	4.26	15.99	16.79	17.5	18.83	15.6	11.26	12.61	22.25	17.22	33.35
1976	6.02	12.76	25.3	20.18	24.39	20.99	13.04	32.74	24.11	16.94	26.34	13.48
1977	4.45	1.05	12.65	15.93	26.17	14.7	16.97	18.72	10.88	20	16.14	4.95
1978	16.38	6.18	6.17	18.91	12.82	19.27	10.28	13.62	11.44	16.97	13.19	14
1979	8.16	6.65	11.98	23.38	18.76	23.85	17.07	22.35	6.57	17.57	20.09	19.58
1980	14.01	18.63	8.11	15.1	38.43	23.21	15.87	15.79	15.32	11.7	7.96	10.07
1981	14.59	13.75	8.55	10.47	23	17.92	16.2	13.41	15.04	15.43	16.46	17.47
1982	14.06	16.35	12.94	16.59	22.67	17.28	23	17.99	25.58	8.42	9.94	16.05
1983	1.89	1.72	1.52	2.03	2.21	15.91	24.55	14.29	12.36	20.05	20.99	16.1
1984	23.24	13.24	9.43	5.85	6.73	17.49	10.49	11.49	12.51	16.75	17.79	13.89
1985	14.83	12.91	5.15	24.22	13.04	13.8	14.62	14.02	12.48	18.81	19.95	20.11
1986	10.14	9.02	19.8	11.03	28.35	14.16	21.47	13.22	16.88	7.67	15.48	6.33
1987	17.77	5.86	25.91	20.18	9.22	27.97	25.8	16.52	11.96	16.61	19.46	15.09
1988	8.62	5.74	8.93	14.85	21.92	14.06	10.54	13.15	13.45	21.58	15.16	17.06
1989	18.72	10.66	14.37	24.26	19.83	14.59	21.77	23.21	9.24	28.26	8.72	26.21
1990	11.72	8.24	13.2	17.87	21.56	15.13	8.37	20.37	26.72	15.94	15.12	15.34
1991	6.18	8.73	35.3	21.43	22.91	14.68	17.3	18.37	38.81	12.51	23.26	9.06
1992	21.77	2.28	2.6	5.95	9.98	19.16	19.06	15.89	15.36	19.94	14.85	9.45
1993	15.83	10.07	19.44	18.91	20.41	21.56	19.6	17.07	9.07	15.4	12.03	25.55
1994	8.34	10.94	13.24	12.27	25.16	12.34	14.74	11.98	10.23	12.73	4.75	24.92
1995	12.29	7.52	11.73	18.09	16.74	13.71	9.92	15.47	12.41	20.9	10.7	17.3
1996	23.33	6.84	8.68	24.3	28.01	12.62	12.27	13.57	11.54	12.3	14.08	12.84
1997	17.17	16.01	14.67	17.88	13.25	9.35	17.41	17.98	12.53	13.72	10.86	3.38
1998	0.64	1.98	2.95	4.96	16.08	16.19	8.09	14.93	10.75	14.81	17.35	19.91
1999	18.22	18.05	27.33	21.21	12.13	11.55	13.93	8.46	13.57	10.99	13.33	25.89
2000	19.5	18.63	21.68	21.18	20.09	13.33	13.58	19.56	10.44	15.14	10.35	21.95
2001	21.71	12.51	9	12.17	11.17	14.83	15.68	19.28	7.35	17.48	14.47	18.56
AVG	**12.30**	**10.48**	**14.12**	**17.81**	**19.51**	**16.99**	**17.47**	**16.55**	**16.06**	**16.27**	**16.33**	**15.98**