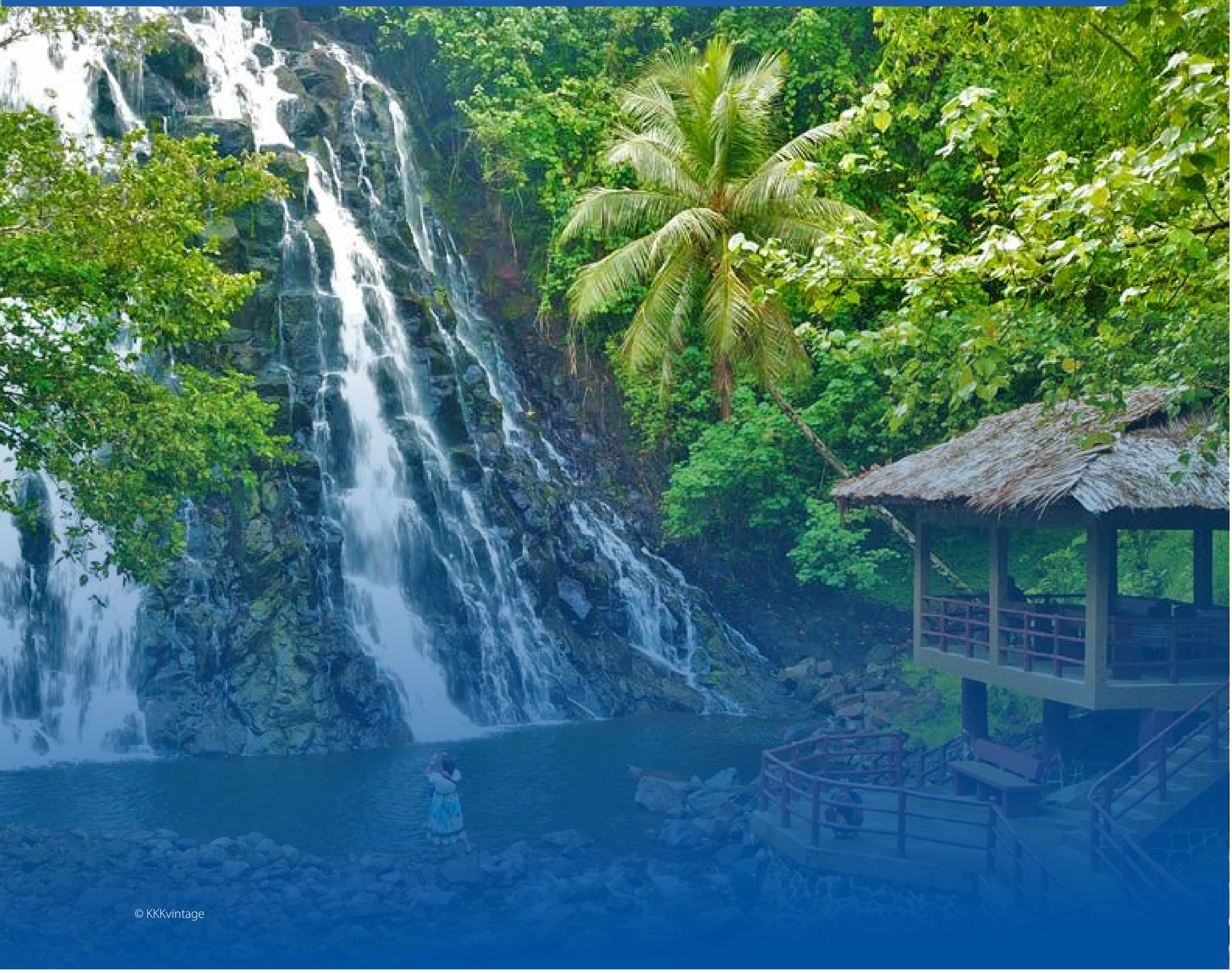
3 | Federated States of Micronesia



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3.1 Summary

3.1.1 Climate

- Changes in air temperature from season to season are relatively small and strongly linked to changes in the surrounding ocean temperature. The Federated States of Micronesia (FSM) has two seasons – the wet season from May to October and the dry season from November to April.
- The seasonal cycle is strongly affected by the Intertropical Convergence Zone (ITCZ) and West Pacific Monsoon (WPM), which are most intense during the wet season.
- Annual and seasonal air temperatures at Pohnpei and Chuuk increased over the period 1952–2020. The number of hot days and warm nights has increased at both sites, while the number of cool days and cold nights has decreased. The energy required for cooling indoor environments has also increased at both sites.
- May to October rainfall has decreased and drought conditions have increased at Pohnpei since 1952. No significant rainfall trends were detected at Chuuk.
- Tropical cyclones affect FSM year-round. Over the period 1969–2017, an average of 74 cyclones passed within the FSM exclusive economic zone (EEZ) per decade. Tropical cyclones were most frequent in El Niño years and least frequent in La Niña years. Year-to-year variability is large, ranging from no tropical cyclones in some years to 14 in 1974.
- There has been little change in the number of severe tropical cyclones or the total number of tropical cyclones in the Northwest Pacific since 1981.

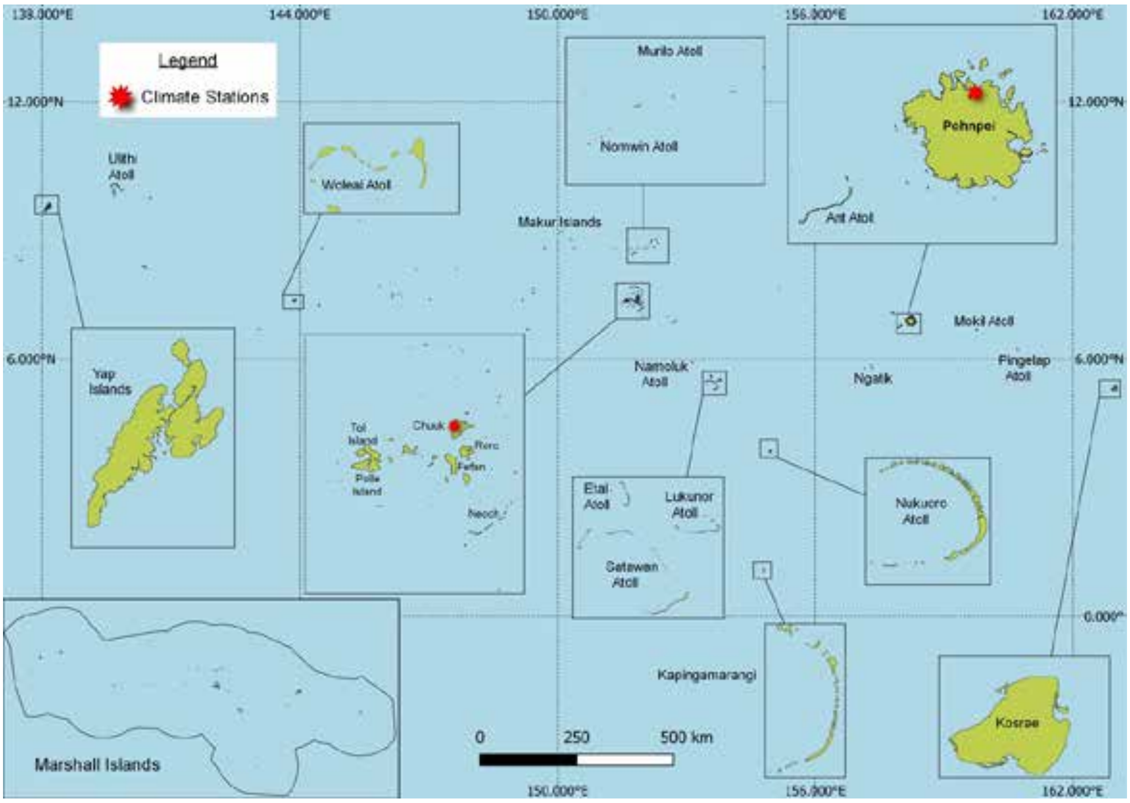
3.1.2 Ocean

- Highest sea levels typically occur in the months October to January. La Niña brings noticeably higher sea levels in the months leading up to winter (October–December).
- Sea-level rise within the EEZ, measured by satellite altimeters from 1993 to mid-2020, ranges from about 3 to 4.5 mm (0.11 to 0.18 in) per year, with highest estimates in the southeast.
- Monthly average ocean temperature, as measured by the Pohnpei tide-gauge, ranges from approximately 29 °C (84.2 °F) in February to 30 °C (86.0 °F) from August to November. However, monthly temperatures in any given year can be up to ±2 °C (±3.6 °F) of these averages.
- The sea surface temperature (SST) trend within the EEZ is 0.25 °C (0.45 °F) per decade.
- Dominant wave direction is from 23° (NNE), with an average significant wave height of 1.20 m (3.94 ft) and average wave period of 10.23 s.
- Severe wave height was defined as 2.45 m (8.04 ft), with an average of 3.8 severe events per year.
- Peak average significant wave height occurs between November and March.

3.2 Country description

Located in the equatorial/tropical North Pacific Ocean, FSM consists of four states. From west to east, these are Yap, Chuuk, Pohnpei and Kosrae (Figure 3.1). The nation has approximately 607 islands that cover a longitudinal distance of 2700 km located between latitudes 1°N and 11°N, and longitudes 136°E and 164°E. FSM has a total land area of 702 km^2 and an EEZ of 2.6 million km^2. The four states are centred on one or more main high islands, and all but Kosrae include numerous outlying atolls. The nation's capital is Palikir, located on Pohnpei Islands. The largest city is Weno, located in Chuuk State. The highest elevation is 782 m (2566 ft) above sea level on Pohnpei. FSM's population is approximately 104,000, with about 11% residing in Yap, 47% in Chuuk, 35% in Pohnpei and 7% in Kosrae.

Figure 3.1:
Federated States of Micronesia and the locations of the climate stations used in this report



3.3 Data

Daily historical rainfall and air temperature records for Chuuk and Pohnpei from 1951 were obtained from the Pohnpei Weather Service Offices of the United States National Oceanic and Atmospheric Administration. These records have undergone data quality and homogeneity assessment. Where the maximum or minimum air temperature records were found to have discontinuities, these records have been adjusted to make them homogeneous (further information is provided in Chapter 1). Additional information on historical climate trends for FSM can be found in the Pacific Climate Change Data Portal http://www.bom.gov.au/climate/pccsp.

Tropical cyclone data and historical tracks starting from the 1969 season are available from the Western North Pacific Tropical Cyclone Data Portal http://www.bom.gov.au/cyclone/history/tracks/beta/?region=wnp.

SST covering the EEZ was obtained via the daily Optimum Interpolation SST version 2.1 (OISST v2.1) dataset from NOAA (Reynolds et al. 2007; Banzon et al. 2016). In situ ocean temperature data were obtained from the PSLGM Project tide-gauge located at Pohnpei, with data spanning from 1993 to 2021.

Wave data were obtained from the PACCSAP wave hindcast (Smith et al. 2021), available hourly from 1979 to 2021, with a grid resolution near FSM of 7 km (4.3 mi).

Regional sea level data were obtained from CSIRO satellite altimetry (updated by Benoit Legresy, Church and White 2011), with correction for seasonal signals, inverse barometer effect and glacial isostatic adjustment. Tide-gauge data were sourced from the Pohnpei tide-gauge station, spanning from 2001 to 2020 at hourly intervals.

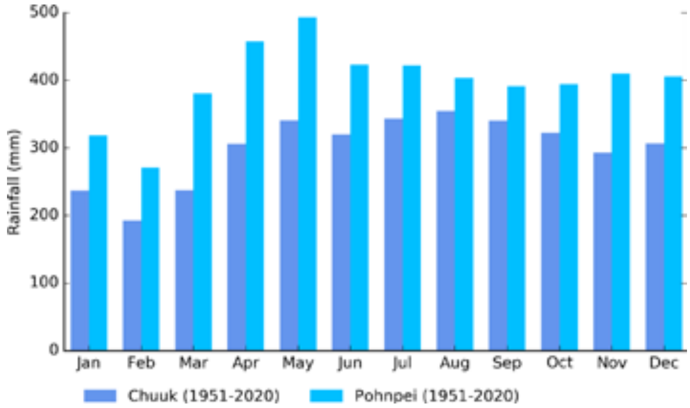
3.4 Rainfall

3.4.1 Seasonal cycle

The wet season occurs between May and October at Chuuk, while the dry season is from November to April. At Pohnpei, the wettest months are April and May, with January and February being the driest months (Figure 3.2). Wet season rainfall is driven by the ITCZ, which is strongest during the middle of the year and located furthest north, close to FSM. Chuuk receives 57% of its annual rainfall, over 2000 mm (78.7 in) of rain, during the wet season. Rainfall in Chuuk is lower than Pohnpei due to its location further west and away from the ITCZ. Pohnpei receives over 4700 mm (185.0 in) of rainfall annually, with a monthly average of nearly 500 mm (19.7 in) in May.

The WPM also affects rainfall in FSM, bringing additional rainfall during the wet season. This influence is strongest across the western islands and weaker in Pohnpei and the islands in the east.

Figure 3.2:
Mean annual rainfall at Chuuk and Pohnpei



3.4.2 Trends

May to October rainfall has been decreasing at Pohnpei since 1952 (Table 3.1). All other trends in annual and seasonal rainfall at Pohnpei and Chuuk are not statistically significant (Figure 3.3, Table 3.1). Annual rainfall has varied from approximately 3300 to 6300 mm (129.9 to 248.0 in) at Pohnpei and 2300 to 4500 mm (90.6 to 177.2 in) at Chuuk.

Figure 3.3:
Annual rainfall (bar graph) and number of wet days (where rainfall is at least 1 mm; line graph) at Pohnpei (left) and Chuuk (right). Straight lines indicate linear trends for annual rainfall (in black) and number of wet days (in blue). The magnitudes of the trends are presented in Table 3.1. Diamonds indicate years with insufficient data for one or both variables.

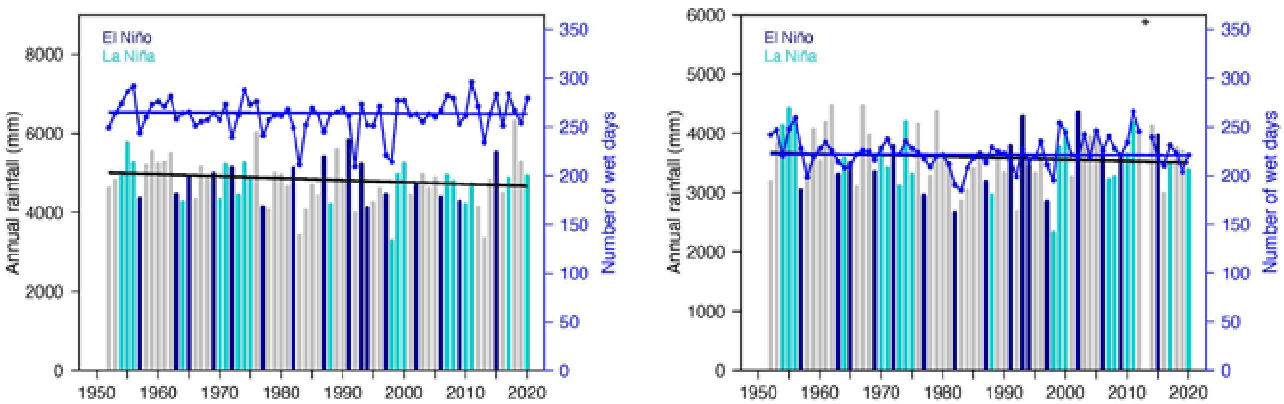


Table 3.1:
Trends in annual, seasonal and extreme rainfall at Pohnpei (left) and Chuuk (right). The 95% confidence intervals are shown in parentheses, and trends significant at the 95% level are shown in bold. The contribution to total rainfall from extreme events and the standardised rainfall evapotranspiration index are measured relative to 1961–1990 (see Chapter 1 for details).

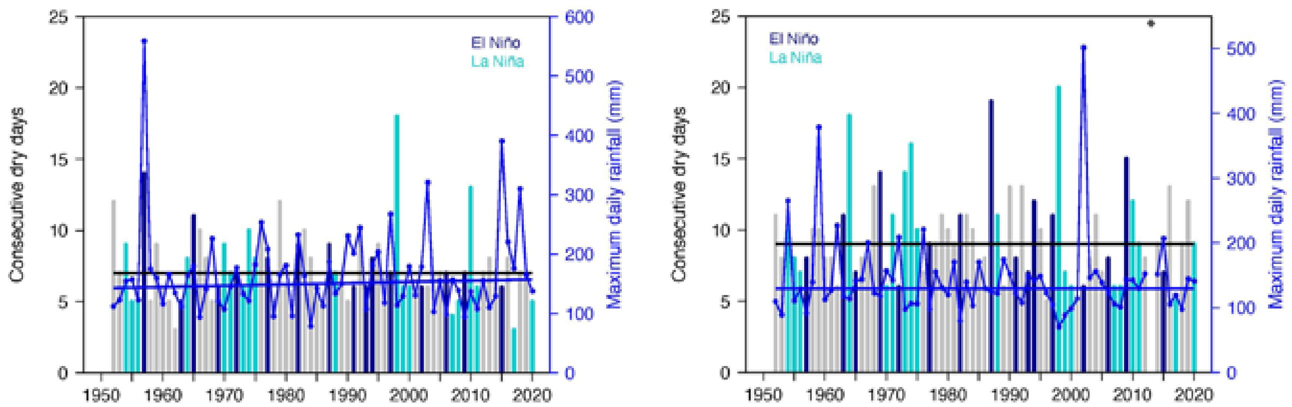
	Pohnpei	Chuuk
	1952–2020	
Annual rainfall (mm/decade)	-50.06 (-118.75, +14.42)	-26.04 (-102.27, +52.03)
November–April (mm/decade)	-18.74 (-81.22, +48.80)	+0.60 (-44.39, +43.77)
May–October (mm/decade)	**-44.32** (-88.84, 0.60)	-23.81 (-79.33, +33.43)
Number of wet days (days/decade)	-0.31 (-2.18, +1.95)	-0.21 (-2.76, +2.71)
Contribution to total rainfall from extreme events (%/decade)	-0.21 (-1.09, +0.77)	-0.40 (-1.37, +0.60)
Consecutive dry days (days/decade)	0.00 (-0.38,0.00)	0.00 (-0.43, +0.18)
Maximum one-day rainfall (mm/decade)	+2.08 (-3.57, +8.25)	0.00 (-4.08, +3.70)
Standardised rainfall evapotranspiration index (November–April)	-0.08 (-0.20, +0.09)	-0.02 (-0.14, +0.11)
Standardised rainfall evapotranspiration index (May–October)	-0.12 (-0.27,0.00)	-0.07 (-0.26, +0.10)

The May to October standardised rainfall evapotranspiration drought index indicates increasing drought conditions at Pohnpei since 1952, consistent with the decrease in May to October rainfall (Table 3.1).

Figure 3.4 shows change and variability in the longest run of days without rain and maximum daily rainfall at Pohnpei and Chuuk. Both sites rarely experience more than two weeks without rain.

Unusually high maximum daily rainfall at Pohnpei in 1957 was likely associated with Typhoon Lola, and the high daily rainfall in 2002 at Chuuk was associated with tropical storm Chataan (Figure 3.4).

Figure 3.4:
Annual longest run of consecutive dry days (bar graph) and maximum daily rainfall (line graph) at Pohnpei (left) and Chuuk (right). Straight lines indicate linear trends for dry days (in black) and maximum daily rainfall (in blue). The magnitudes of the trends are presented in Table 3.1. Diamonds indicate years with insufficient data for one or both variables.

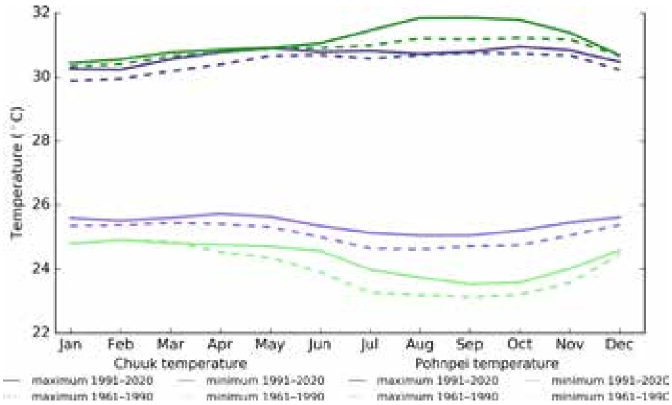


3.5 Air temperature

3.5.1 Seasonal cycle

Seasonal variations in monthly maximum and minimum air temperatures are less than 1.5°C (2.7 °F) between the average warmest and coolest months for Chuuk and Pohnpei. There has been a clear shift towards warmer average monthly temperatures between the climatology periods of 1961–1990 and 1991–2020 (Figure 3.5), with warmer average air temperatures occurring in all months throughout the year for both locations. The largest increase in average monthly maximum temperatures occurs at Pohnpei and is in excess of 1°C (1.8 °F) for August to October. Seasonal variations in air temperatures are driven by the surrounding SST.

Figure 3.5:
Maximum and minimum air temperature seasonal cycle for Chuuk (purple) and Pohnpei (green), and for the periods 1961–1990 (dotted lines) and 1991–2020 (full lines)



3.5.2 Trends

Average annual and seasonal temperatures have increased significantly at Pohnpei and Chuuk (Figure 3.6, Table 3.2). At Pohnpei, substantial decade-to-decade variability is evident, and May–October temperatures are warming faster than November–April temperatures (Figure 3.6).

Figure 3.6:
Average annual, November–April and May–October temperatures for Pohnpei (left) and Chuuk (right). Straight lines indicate linear trends. The magnitudes of the trends are presented in Table 3.2. Diamonds indicate years with insufficient data for one or more variables.

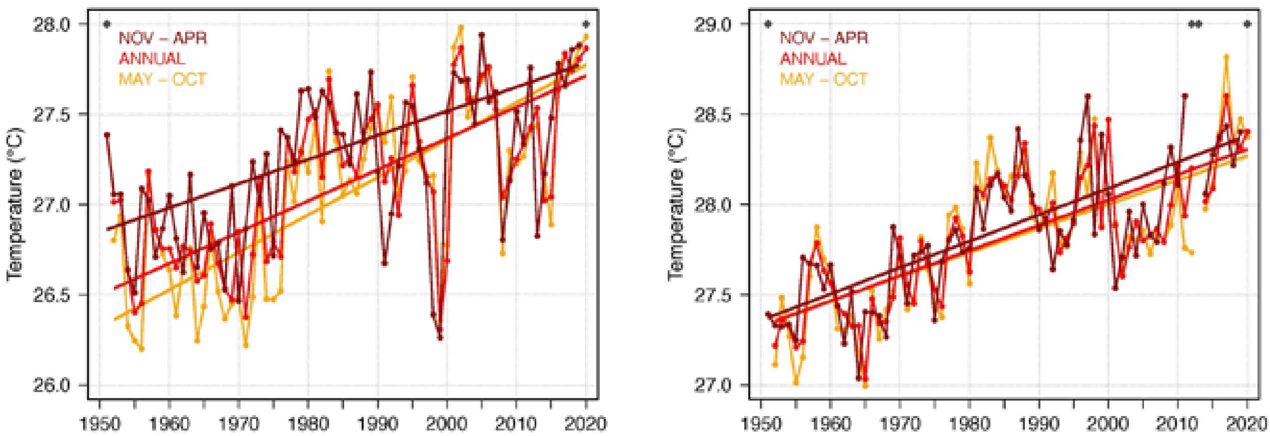


Table 3.2:
Trends in annual and seasonal air temperatures at Pohnpei (top) and Chuuk (bottom). The 95% confidence intervals are shown in parentheses, and trends significant at the 95% level are shown in bold.

	Pohnpei Tmax (°C/decade)	Pohnpei Tmin (°C/decade)	Pohnpei Tmean (°C/decade)	Chuuk Tmax (°C/10yrs)	Chuuk Tmin (°C/10yrs)	Chuuk Tmean (°C/10yrs)
	1952–2020					
Annual	**+0.18** (+0.12, +0.23)	**+0.14** (+0.06, +0.22)	**+0.17** (+0.11, +0.23)	**+0.15** (+0.07, +0.24)	**+0.12** (+0.07, +0.17)	**+0.14** (+0.08, +0.19)
November–April	**+0.16** (+0.10, +0.23)	**+0.10** (+0.02, +0.18)	**+0.13** (+0.07, +0.19)	**+0.20** (+0.11, +0.30)	**+0.10** (+0.06, +0.14)	**+0.15** (+0.1, +0.19)
May–October	**+0.20** (+0.14, +0.25)	**+0.19** (+0.09, +0.28)	**+0.21** (+0.14, +0.27)	**+0.12** (+0.03, +0.20)	**+0.14** (+0.08, +0.20)	**+0.13** (+0.07, +0.20)

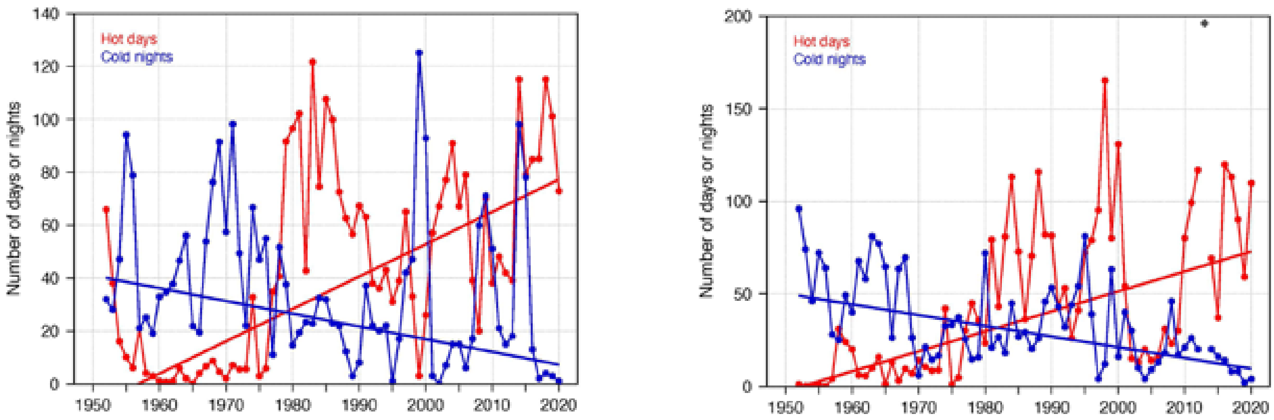
The number of hot days and warm nights has increased, and the number of cool days and cold nights has decreased at Pohnpei and Chuuk (Figure 3.7, Table 3.3). Large variability is evident, particularly at Pohnpei. For example, some years experienced fewer than 20 hot days while others experienced over 100 hot days. This may be partly attributed to the tropical location of both sites, which makes only small temperature increases necessary for a day to be considered hot, i.e., to be in the hottest 10% of days compared to 1961–1990 (see Chapter 1 for details). However, quality issues may also be affecting these records.

The cooling degree days index provides a measure of the energy demand needed to cool a building down to 25 °C (77.0 °F), with the assumption that air conditioners are generally turned on at this temperature. At both Pohnpei and Chuuk, there has been a strong increase in the cooling degree index, suggesting the energy needed for cooling has increased significantly since 1952.

Table 3.3:
Trends in annual temperature extremes at Pohnpei (left) and Chuuk (right). The 95% confidence intervals are shown in parentheses, and trends significant at the 95% level are shown in bold. Hot and cool days, and warm and cold nights are measured relative to 1961–1990 (see Chapter 1 for details).

	Pohnpei	Chuuk
	1952–2020	
Number of hot days (days/decade)	**+12.23** (+6.02, +17.17)	**+10.79** (+3.69, +20.63)
Number of warm nights (nights/decade)	**+8.69** (+4.69, +13.51)	**+8.05** (+2.66, +13.47)
Number of cool days (days/decade)	**-5.87** (-7.59, 4.11)	**-4.37** (-6.38, 2.22)
Number of cold nights (nights/decade)	**-4.81** (-9.24, 0.50)	**-5.79** (-8.93, 2.22)
Cooling degree days (degree days/decade)	**+61.25** (+39.72, +81.18)	**+48.7** (+30.24, +65.11)
Daily temperature range (°C/decade)	+0.05 (-0.03, +0.13)	+0.05 (-0.02, +0.15)

Figure 3.7:
Annual number of hot days and cold nights at Pohnpei (left) and Chuuk (right). Straight lines indicate linear trends. The magnitudes of these trends are presented in Table 3.3. Diamonds indicate years with insufficient data for one or both variables.



3.6 Tropical cyclones

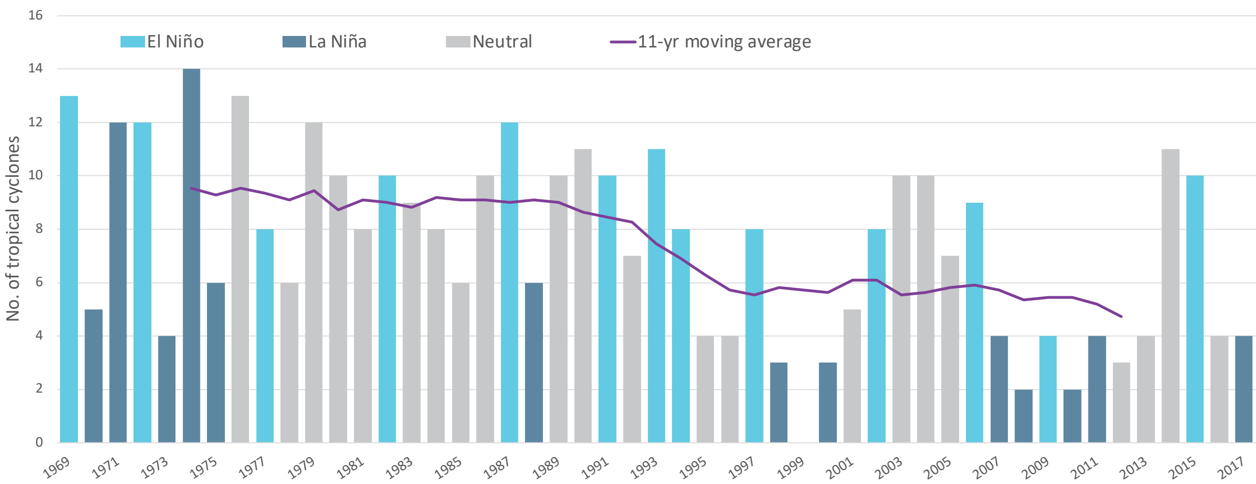
3.6.1 Seasonal cycle

Tropical cyclones affect FSM year-round. The tropical cyclone archive of the western North Pacific indicates that between the 1969 and 2017 seasons, 364 tropical cyclones (Figure 3.8) passed within the EEZ. This represents an average of 74 cyclones per decade. Tropical cyclones were most frequent in El Niño years (95 cyclones per decade), followed by neutral years (78 cyclones per decade) and least frequent in La Niña years (46 cyclones per decade).

Interannual variability in the number of tropical cyclones in the EEZ is large, ranging from zero in 1999 to 14 in 1974 (Figure 3.8). High interannual variability and the small number of tropical cyclones occurring in the EEZ make reliable identification of long-term trends in frequency and intensity difficult.

Some tropical cyclone tracks analysed in this section include the tropical depression stage (sustained winds ≤34 knots) before and/or after tropical cyclone formation.

Figure 3.8:
Number of tropical cyclones passing within the FSM EEZ per season. Each season is defined by the El Niño–Southern Oscillation (ENSO) status, with light blue being an El Niño year, dark blue a La Niña year and grey showing a neutral ENSO year. The 11-year moving average is presented as a purple line and considers all years.



3.6.2 Trends

Trends in total number of tropical cyclones (<995 hPa) and severe tropical cyclones (<970 hPa) are presented for the period 1981–2021 for the Northwest Pacific (125°E–180°W; 0–20°N). Trends are presented at a regional scale as the number of tropical cyclones occurring within Pacific Island EEZs is insufficient for reliable long-term trend analysis.

For the total number of tropical cyclones, the trend (and 95% confidence interval) is -0.56 (-1.84, 0.72) tropical cyclones/decade. There has been little change in the total number of tropical cyclones over the last 41 seasons.

For the total number of severe tropical cyclones, the trend is -0.15 (-1.19, 0.89) tropical cyclones/decade. There has been little change in the number of severe tropical cyclones over the last 41 seasons. There has also been little change in the proportion of tropical cyclones reaching severe status. The trend is 0.01 (-0.04, 0.05) tropical cyclones/decade.

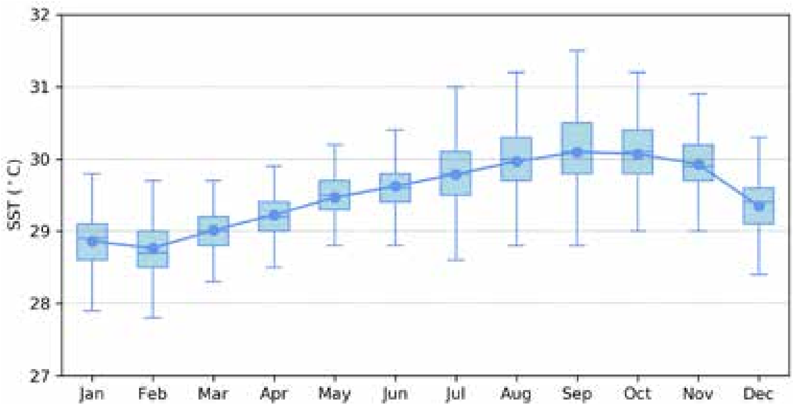
Records of tropical cyclones exist from the late 1800s in some countries in the Northwest Pacific, but trends in tropical cyclones have only been presented from 1981/82. Satellite-based observations began in the early 1970s, but consistent coverage and reliable intensity estimates have only been available since the early 1980s. Confidence in tropical cyclone trends is moderate as the definition of a tropical cyclone has changed and satellite observation methods have continued to improve over the last 41 years.

3.7 Sea surface temperature

3.7.1 Seasonal cycle

Ocean temperature, as measured by the Pohnpei tide-gauge from 2001 to 2021, reaches on average a maximum of approximately 30.0 °C (86.0 °F) from August to November but can get as high as 31.5 °C (88.7 °F) in September. Minimum average temperature dips below 29.0 °C (84.2 °F) in February. Temperatures can be up to 1.5 °C (2.7 °F) higher or lower than these averages in the warmer months. In cooler months, the temperature range is usually within ±1 °C (±1.8 °F), although 50% of observations fall within 0.8 °C (1.4 °F) of the average.

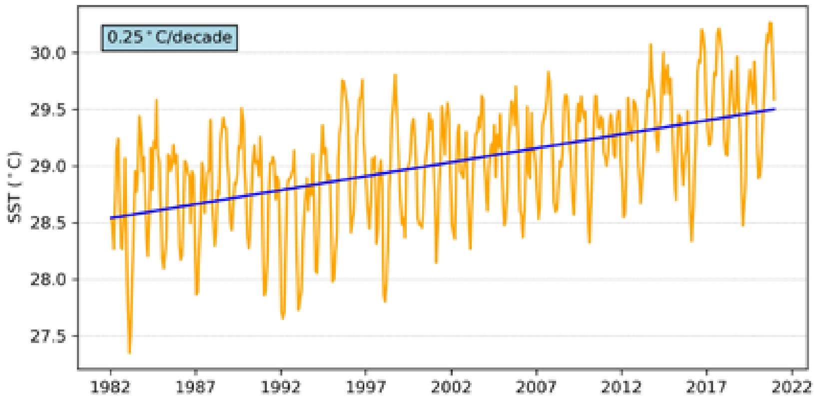
Figure 3.9:
Annual temperatures measured at the Pohnpei tide-gauge. Blue dots show the monthly average, and shaded boxes show the middle 50% of observations. Lines show the top and bottom 25% of observations.



3.7.2 Trends

Figure 3.10 shows the 1981–2021 SST from satellite observations averaged over the FSM EEZ. The data show a trend of 0.25 °C (0.45 °F) per decade with a 95% confidence interval of ±0.04 °C (±0.07 °F).

Figure 3.10:
Sea surface temperature from satellite observations averaged across the FSM EEZ, shown as the orange line. The blue line shows the linear regression trend.



3.8 Sea level

3.8.1 Seasonal cycle

Tidal analysis of Pohnpei sea level data shows that it experiences a mixed tidal cycle. Typically, there are two high and two low tides a day during the new moon and full moon. However, there is only one high tide a day around the first and last quarter moons. The highest predicted tides of the year typically occur in both May/June as well as December/January. Figure 3.11 shows the number of hours the 99th percentile (1.64 m, 5.38 ft) sea level threshold is exceeded per month across the entire sea level record at Pohnpei. Peak sea levels typically occur from October to January. La Niña years typically have higher sea levels from October to December during a developing La Niña (2007, 2017, 2020).

Figure 3.11:
Number of hours exceeding 99th percentile sea level threshold per month from 2001 to 2020 at the Pohnpei tide-gauge. Blue shading indicates the number of hours, and the final row provides a percentage summary of all the years.

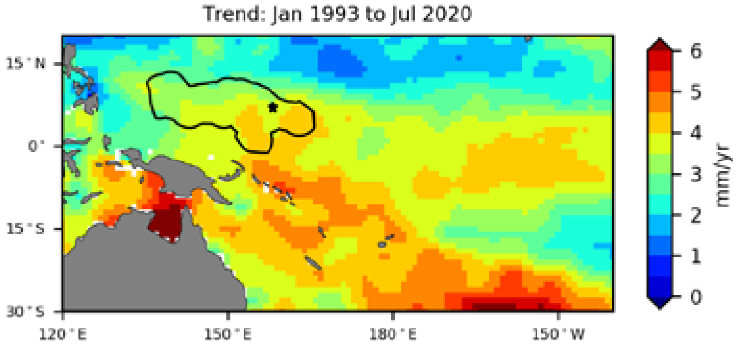
Number of hours exceeding 1.64 m (Dekehtik, Federated States of Micronesia)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2001	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0	0	0	0	0	0
2006	0	2	0	0	0	0	0	0	0	0	0	0	2
2007	0	0	0	0	0	1	0	0	0	9	11	2	23
2008	0	0	0	0	1	0	0	0	0	0	0	3	4
2009	1	0	0	0	0	0	0	0	0	0	0	0	1
2010	0	0	0	0	0	0	0	0	0	0	2	0	2
2011	3	0	0	1	0	0	0	0	0	2	2	1	9
2012	0	0	0	1	0	4	0	0	0	0	0	1	6
2013	0	0	0	3	0	0	0	0	0	0	1	0	4
2014	1	0	0	0	0	0	0	0	0	0	0	0	1
2015	0	0	0	0	0	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0	0	1	7	0	8
2017	0	0	0	0	0	0	0	0	0	0	17	0	17
2018	3	4	0	0	0	0	0	0	0	0	0	0	7
2019	0	0	0	0	0	0	1	0	0	0	0	0	1
2020	0	0	0	0	0	0	0	0	0	1	9	6	16
Monthly Totals (%)	8	6	0	5	1	5	1	0	0	13	49	13	

3.8.2 Trends

Sea level at FSM, measured by satellite altimeters (Figure 3.12) since 1993, has risen between 3 and 4.5 mm (0.12 and 0.18 in) per year. Trend estimates in the southeast are highest, ranging from 4 to 4.5 mm (0.16 to 0.18 in) per year, which is larger than the global average of 3.1 ± 0.4 mm (0.12 ± 0.02 in) per year (von Schuckmann et al. 2021). The 95% confidence interval is as high has ±1.6 mm (±0.06 in) in the west and down to 0.6 mm (0.02 in) in the southeast. This rise is partly linked to a pattern related to climate variability from year to year and decade to decade.

Figure 3.12:
Satellite altimetry annual trend for the Pacific from 1993 to 2020, with the FSM EEZ highlighted. The star symbol indicates the location of the tide-gauge at Pohnpei.



Trend estimates at the Pohnpei tide-gauge over a shorter time span than for the altimetry observations (December 2001 to July 2020) are provided in the PSLGM Monthly Data Report for July 2020 (http://www.bom.gov.au/ntc/IDO60101/IDO60101.202007.pdf). For Pohnpei, the trend is reported as 4.9 mm (0.19 in) per year, higher than the altimetry trends shown in Figure 3.12 (tide-gauge indicated by star symbol). This discrepancy could be an artefact of the different data time spans but can also be attributed to subsidence occurring at Pohnpei (Brown et al. 2020).

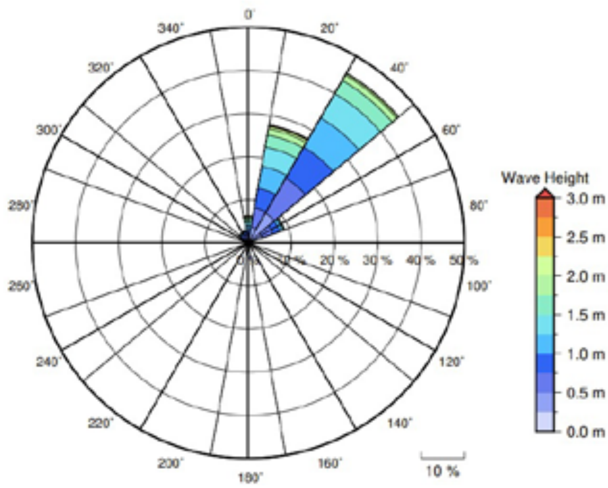
3.9 Waves

3.9.1 Seasonal cycle

The average wave climate at Pohnpei is defined by the significant wave height, peak period and peak direction. The significant wave height is the mean wave height (from trough to crest) of the highest one third of waves and corresponds to the wave height that would be reported by an experienced observer. Peak period is the time interval between two waves of the dominant wave period. Peak direction is the direction from which the dominant waves are coming.

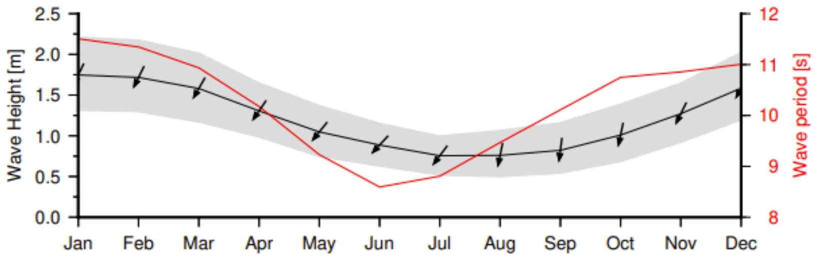
The average sea state is dominated by winds from the northeast. The annual mean wave height is 1.20 m (3.9 ft), the annual mean wave direction is 23° and the annual mean wave period is 10.23 s. In the Pacific, waves often come from multiple directions and for different periods of time. In Pohnpei, there are often more than four different wave direction/period components coming from the northeast (Figure 3.13).

Figure 3.13:
Annual wave rose for Pohnpei. Note that direction is where the wave is coming from.



Seasonal wave activity peaks between November and March in terms of both wave height and period (Figure 3.14) due to North Pacific extra-tropical storm activity. Conversely, there is a distinct lull from late autumn to midsummer in terms of wave activity.

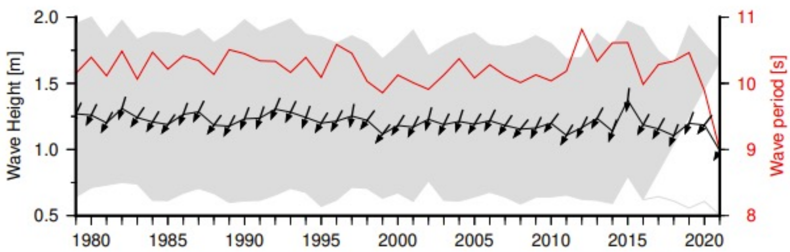
Figure 3.14:
Monthly wave height (black line), wave period (red line) and wave direction (arrows). The grey area represents the range of wave height between calm periods (10% of lowest wave height) and large wave events (10% of highest wave height).



3.9.2 Trends

Waves change from month to month with the seasons, but they also change from year to year with climate oscillations. Typically, these changes are smaller than the seasonal changes but can be important during phenomena such as ENSO. In Pohnpei, the mean annual wave height has remained unchanged since 1979 (Figure 3.15). The mean annual wave height in Pohnpei is not significantly correlated with the main climate indicators of the region.

Figure 3.15:
Annual wave height (black line), wave period (red line) and wave direction (arrows). The grey area represents the range of wave height between calm periods (10% of lowest wave height) and large wave events (10% of highest wave height).



3.9.3 Extreme waves

Extreme wave analysis for Pohnpei was done by defining a severe height threshold and fitting a generalized Pareto distribution (GPD). The optimum threshold selected was 2.45 m (8.04 ft). In the 42-year wave hindcast, 162 wave events reached or exceeded this threshold, averaging 3.9 per year. The GPD was fitted to the largest wave height reached during each of these events (Figure 3.16, Table 3.4). Extreme wave analysis is a very useful tool but is not always accurate because the analysis is very sensitive to the data available, the type of distribution fitted and the threshold used. For example, this analysis does not accurately account for tropical cyclone waves. More in-depth analysis is required to obtain results appropriate for designing coastal infrastructure and coastal hazard planning.

Figure 3.16:
Extreme wave distribution for Pohnpei. The crosses represent the wave events that have occurred since 1979. The solid line is the statistical distribution that best fits past wave events. The dashed lines show the upper and lower confidence limits of the fit. There is a 95% chance that the fitted distribution lies between the two dashed lines. Note that the annual return interval is in logarithmic scale.

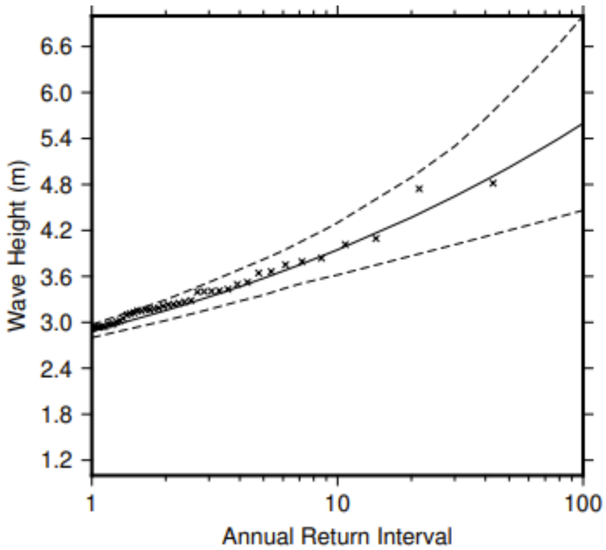


Table 3.4:
Summary of the results from extreme wave analysis in Pohnpei

Large wave height (90th percentile)	1.84 m (6.04 ft)
Severe wave height (99th percentile)	2.44 m (8.01 ft)
1-year ARI wave height	2.88 m (9.45 ft)
10-year ARI wave height	3.95 m (12.96 ft)
20-year ARI wave height	4.37 m (14.38 ft)
50-year ARI wave height	5.02 m (16.47 ft)
100-year ARI wave height	5.60 m (18.37 ft)