14 | Tonga

14.1 Summary

14.1.1 Climate

- Changes in air temperature from season to season are relatively small and strongly linked to changes in the surrounding ocean temperature. Tonga has two distinct seasons – a warm wet season from November to April and a cooler dry season from May to October.
- The seasonal cycle is strongly affected by the South Pacific Convergence Zone (SPCZ), which is most intense during the wet season.
- Annual and seasonal air temperatures at Nuku'alofa increased over the period 1951–2020.
- At Lupepau'u, May to October rainfall has increased along with the proportion of total rain that falls during extreme events.
- Tropical cyclones usually affect Tonga between November and April. Over the period 1969–2018, an average of 21 cyclones passed within the Tonga 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 seasons to six in 2015/16.
- There has been little change in the total number of tropical cyclones in the Southwest Pacific since 1981/82. The number of severe tropical cyclones has declined over the same period/region.

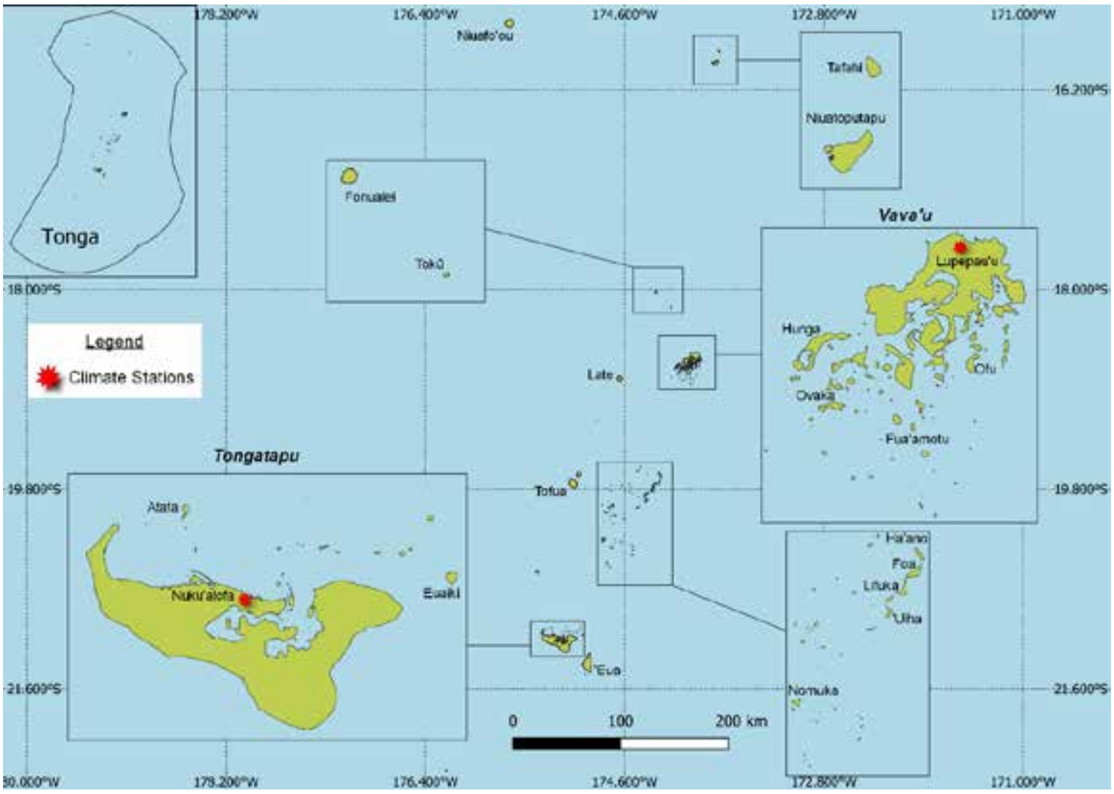
14.1.2 Ocean

- Highest sea levels typically occur in the months December–April.
- Sea-level rise within the EEZ, measured by satellite altimeters since 1993, is about 3.5 to 5 mm per year.
- Monthly average ocean temperature, as measured by the Nukualofa tide-gauge, ranges from 23 °C in August to 27.5 °C in the months February/March. However, monthly temperatures in any given year can be ±3 °C of these averages.
- The sea surface temperature (SST) trend, as per satellite observations, is 0.27 °C per decade.
- Dominant wave direction is from 60° (NE), with an average significant wave height of 1.30 m and average wave period of 13.48 s.
- Severe wave height was defined as 3.65 m, with an average of 3.1 severe events per year.
- Peak average significant wave height occurs around July.

14.2 Country description

The Kingdom of Tonga is located in the tropical western South Pacific Ocean between latitudes 15°S and 22°S, and longitudes 173°W and 176°W (Figure 14.1). Tonga is an archipelago of 169 islands of which 36 are inhabited and divided into three main groups, Vava'u, Ha'apai and Tongatapu, which extend over 800 km from north to south. Tonga has a total land area of 750 km^2 and an EEZ of 0.7 million km^2. The largest island Tongatapu, on which the capital Nuku'alofa is located, covers about 260 km^2. The highest elevation is 1078 m above sea level on Kao Island in the Ha'apai Group. Tonga's population is approximately 104,000. About 70% live on the main island of Tongatapu.

Figure 14.1:
Tonga and the locations of the climate stations used in this report



14.3 Data

Daily and monthly historical rainfall and air temperature records for Nuku'alofa and Vava'u–Lupepau'u from 1951 were obtained from the Tonga Meteorological Service. 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 Tonga 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 1969/70 season are available from the SHTC Data Portal http://www.bom.gov.au/cyclone/history/tracks/index.shtml.

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 Nuku'alofa, with data spanning from 1992 to present.

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

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 Nuku'alofa tide-gauge station, which dates back to 1988 at hourly intervals.

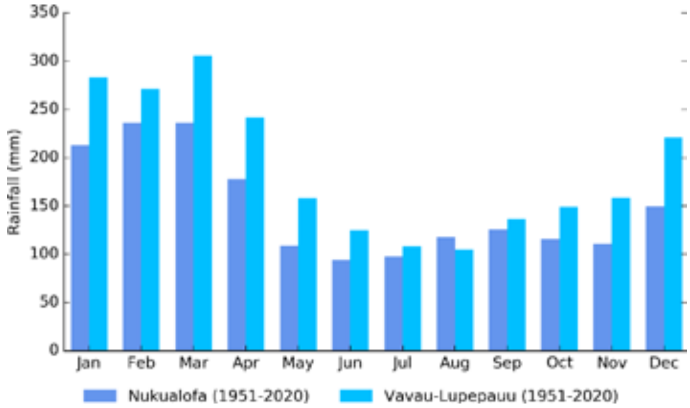
14.4 Rainfall

14.4.1 Seasonal cycle

The seasonal cycle of rainfall over Tonga is dominated by the SPCZ, which is most active and closest to Tonga during the wet season, resulting in average rainfall above 200 mm during January–March (Figure 14.2). Wet season rainfall between November and April accounts for 63% of Nuku'alofa's annual rainfall and 65% of Vavau–Lupepau'u's. Active phases of the Madden–Julian Oscillation (MJO) near Tonga can be associated with significant rainfall for several days in the wet season.

In the cooler/drier half of the year (May–October), less energy is received from the sun and subtropical high pressure systems move north, bringing cooler, drier conditions to Nuku'alofa and Vavau–Lupepau'u.

Figure 14.2:
Mean annual rainfall at Nuku'alofa and Vavau–Lupepau'u



14.4.2 Trends

May–October rainfall has been increasing significantly at Lupepau'u. All other trends in annual and seasonal rainfall at Nuku'alofa and Lupepau'u are not significant (Figure 14.2, Table 14.1). Notable year-to-year variability associated with El Niño–Southern Oscillation (ENSO) is evident at both sites, with La Niña years generally receiving more rainfall than El Niño years (Figure 14.2). Annual rainfall has varied from approximately 800 to 2700 mm at Nuku'alofa and approximately 1100 to 3300 mm at Lupepau'u.

Figure 14.3:
Annual rainfall (bar graph) and number of wet days (where rainfall is at least 1 mm; line graph) at Nuku'alofa (left) and Lupepau'u (right). Straight lines indicate linear trends for annual rainfall (in black) and number of wet days (in blue). Criteria for statistical robustness were not met for determining a linear trend for wet days at Nuku'alofa. The magnitudes of the trends are presented in Table 14.1. Diamonds indicate years with insufficient data for one or both variables.

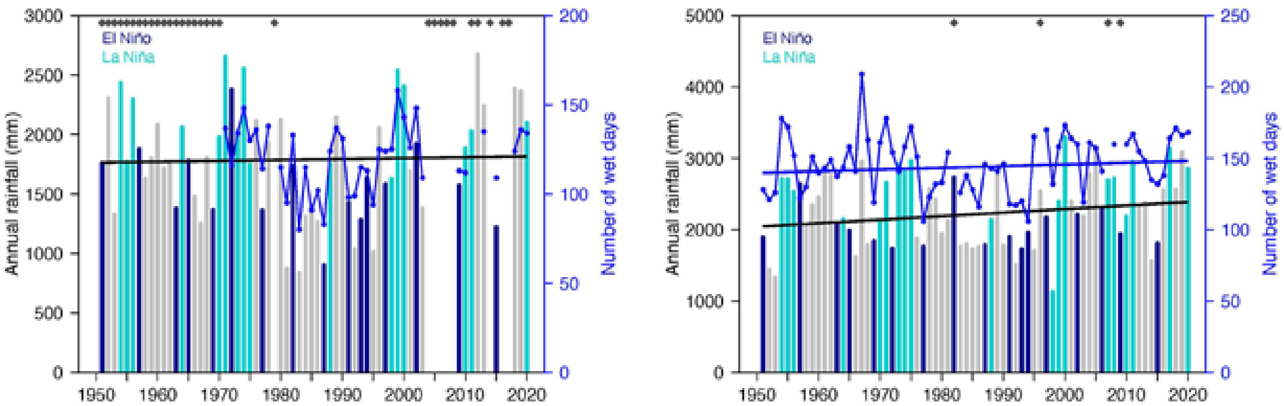
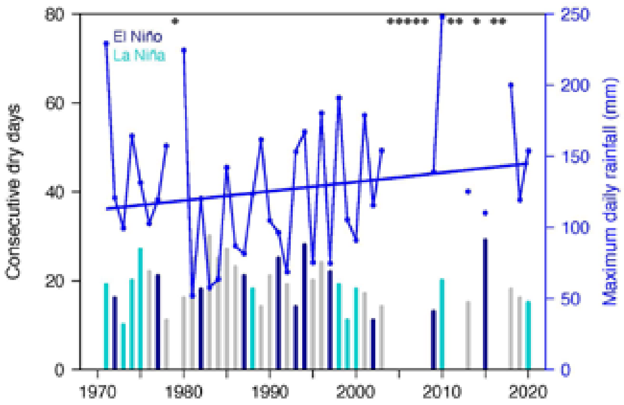


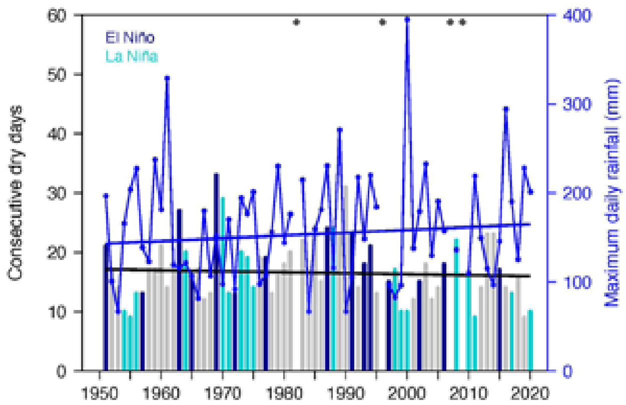
Table 14.1:
Trends in annual, seasonal and extreme rainfall at Nuku'alofa (left) and Lupepau'u (right). The 95% confidence intervals are shown in parentheses, and trends significant at the 95% level are shown in bold. The contribution to total rainfall from extreme events and the standardised rainfall evapotranspiration index are measured relative to 1961–1990 (see Chapter 1 for details). Criteria for statistical robustness were not met for determining linear trends for some rainfall extremes at Nuku'alofa. The standardised rainfall evapotranspiration index is not available for Lupepau'u due to the lack of daily temperature observations at this site.

	Nuku'alofa	Lupepau'u
	1951–2020	1951–2020
Annual rainfall (mm/decade)	+7.33 (-89.86, +100.78)	+49.62 (-37.24, +134.86)
November–April (mm/decade)	+4.34 (-63.35, +68.85)	-4.58 (-57.70, +50.92)
May–October (mm/decade)	+9.59 (-19.38, +36.86)	**+33.5** (+1.60, +61.41)
	1971–2020	1951–2020
Number of wet days (days/decade)	-	+1.20 (-2.41, +4.85)
Contribution to total rainfall from extreme events (%/decade)	-	**+1.47** (+0.04, +3.22)
Consecutive dry days (days/decade)	-	-0.16 (-1.12, +0.80)
Maximum one-day rainfall (mm/decade)	+6.50 (-6.00, +18.00)	+3.14 (-4.40, +10.69)
Standardised rainfall evapotranspiration index (November–April)	+0.36 (-0.04, +0.79)	-
Standardised rainfall evapotranspiration index (May–October)	+0.10 (-0.13, +0.30)	-

Numerous gaps exist in the daily rainfall record for Nuku'alofa, which prevents the robust calculation of trends for some rainfall extremes (Table 14.2). However, the proportion of total rain falling during extreme events has been increasing significantly at Lupepau'u. Maximum daily rainfall since 1971 has increased at Nuku'alofa, although this trend is not statistically significant (Figure 14.4).

Figure 14.4:
Annual longest run of consecutive dry days (bar graph) and maximum daily rainfall (line graph) at Nuku'alofa (left) and Lupepau'u (right). Straight lines indicate linear trends for dry days (in black) and maximum daily rainfall (in blue). Criteria for statistical robustness were not met for determining a linear trend for consecutive dry days at Nuku'alofa. The magnitudes of the trends are presented in Table 14.1. Diamonds indicate years with insufficient data for one or both variables.





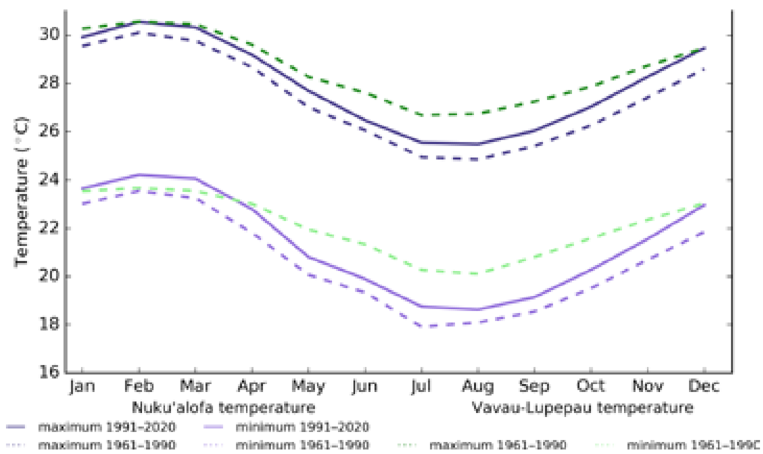
14.5 Air temperature

14.5.1 Seasonal cycle

Air temperatures at Tonga are driven by surrounding ocean temperatures, and during the dry season from May to October are also affected by subtropical high-pressure systems that direct cooler air from the south. Seasonal variations in maximum and minimum air temperatures at Nuku'alofa are in excess of 5 °C (Figure 14.5). Vavau–Lupepau'u has less pronounced seasonal changes in air temperatures, with variations for air temperatures across the year less than 4 °C. Air temperatures are generally much warmer in the middle months of the year at Vavau–Lupepau'u compared to Nuku'alofa, which is further to the south and close to the subtropics.

There has been warming across all months at Nuku'alofa for both maximum and minimum air temperatures between the 1991–2020 and 1961–1990 climatology periods. The largest difference between the climatology periods is 0.9 °C for maximum temperature during November and December.

Figure 14.5:
Maximum and minimum air temperature seasonal cycle for Nuku'alofa (purple) and Vavau – Lupepau'u (green), and for the periods 1961–1990 (dotted lines) and 1991–2020 (solid lines)



14.5.2 Trends

Average annual and seasonal temperatures have increased significantly at Nuku'alofa (Figure 14.6). Daily minimum temperatures are increasing faster than daily maximum temperatures and November–April temperatures are increasing faster than May–October temperatures (Table 14.2).

Figure 14.6:
Average annual, November–April and May–October temperatures for Nuku'alofa. Straight lines indicate linear trends. The magnitudes of the trends are presented in Table 14.2. Diamonds indicate years with insufficient data for one or more variables.

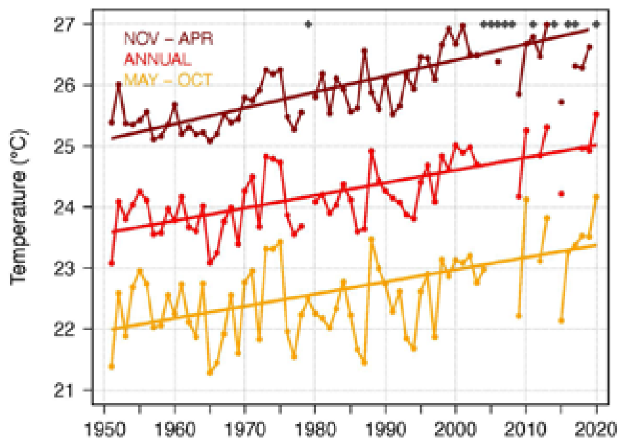
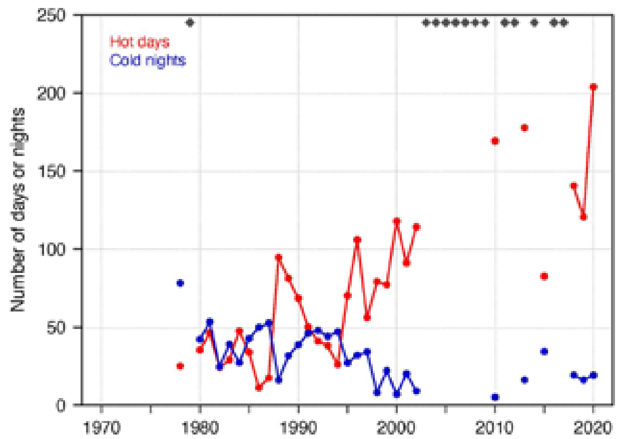


Table 14.2:
Trends in annual and seasonal air temperatures at Nuku'alofa. The 95% confidence intervals are shown in parentheses, and trends significant at the 95% level are shown in bold.

	Nuku'alofa Tmax (°C/decade)	Nuku'alofa Tmin (°C/decade)	Nuku'alofa Tmean (°C/decade)
		1951–2020	
Annual	**+0.18** (+0.09, +0.26)	**+0.23** (+0.13, +0.34)	**+0.21** (+0.11, +0.30)
November–April	**+0.21** (+0.16, +0.27)	**+0.29** (+0.18, +0.39)	**+0.26** (+0.18, +0.34)
May–October	**+0.16** (+0.07, +0.27)	**+0.22** (+0.09, +0.32)	**+0.20** (+0.08, +0.29)

Numerous gaps exist in the daily temperature record for Nuku'alofa, which prevents the robust calculation of trends in temperature extremes. Nevertheless, Figure 14.7 shows that several years since 2010 experienced more than three times as many hot days compared to the beginning of the record. This is consistent with the increases in average temperatures (Figure 14.6) and trends in temperature extremes in neighbouring Pacific Island countries.

Figure 14.7:
Annual number of hot days and cold nights at Nuku'alofa. Diamonds indicate years with insufficient data for one or both variables.



14.6 Tropical cyclones

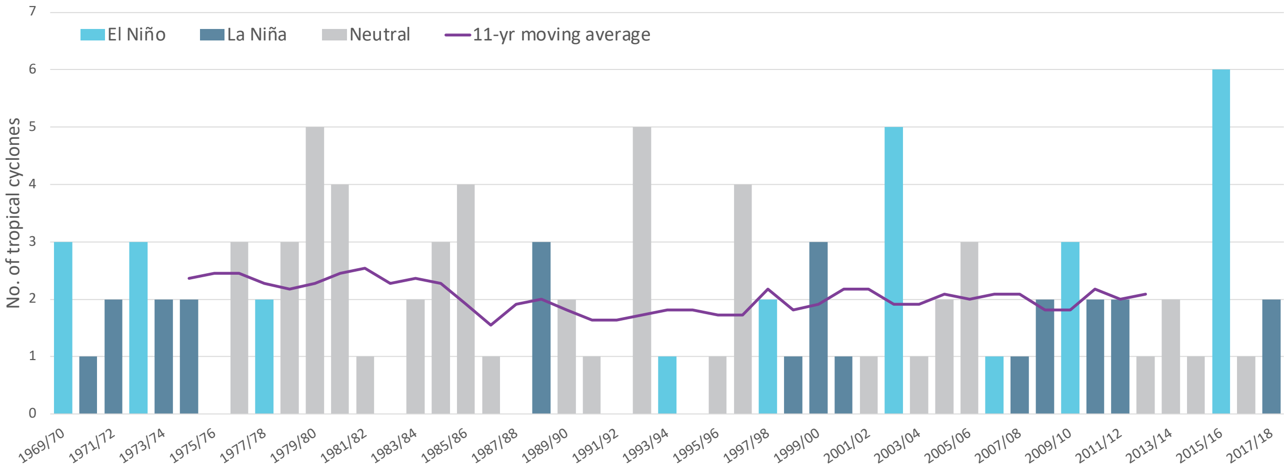
14.6.1 Seasonal cycle

Tropical cyclones usually affect Tonga during the southern hemisphere tropical cyclone season, which is from November to April, but also occasionally occur outside the tropical cyclone season. The Southern Hemisphere Tropical Cyclone Archive indicates that between the 1969/70 and 2017/18 seasons, 101 tropical cyclones (Figure 14.8) passed within the EEZ. This represents an average of 21 cyclones per decade. Tropical cyclones were most frequent in neutral years (23 cyclones per decade), followed by El Niño years (20 cyclones per decade) and least frequent in La Niña years (17 cyclones per decade).

Interannual variability in the number of tropical cyclones in the EEZ is large, ranging from zero in some seasons to six in 2015/16 and five in 1979/80, 1992/93 and 2002/03 (Figure 14.8). 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 14.8:
Number of tropical cyclones passing within the Tonga EEZ per season. Each season is defined by the 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.



14.6.2 Trends

Trends in total number of tropical cyclones (<995 hPa) and severe tropical cyclones (<970 hPa) are presented for the period 1981/82–2020/21 for the greater Southwest Pacific (135°E–120°W; 0–50°S). 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 -0.92 (-1.85, 0.01) tropical cyclones/decade. There has been little change/marginal decline in the total number of tropical cyclones over the last 40 seasons. This trend is not statistically significant.

For the total number of severe tropical cyclones, the trend is -0.80 (-1.32, -0.29) tropical cyclones/decade. There is a negative trend in the number of severe tropical cyclones over the last 40 seasons. There has been little change/marginal decline in the proportion of tropical cyclones reaching severe status. The trend is -0.04 (-0.08, 0.00) tropical cyclones/decade. The negative trend is statistically significant.

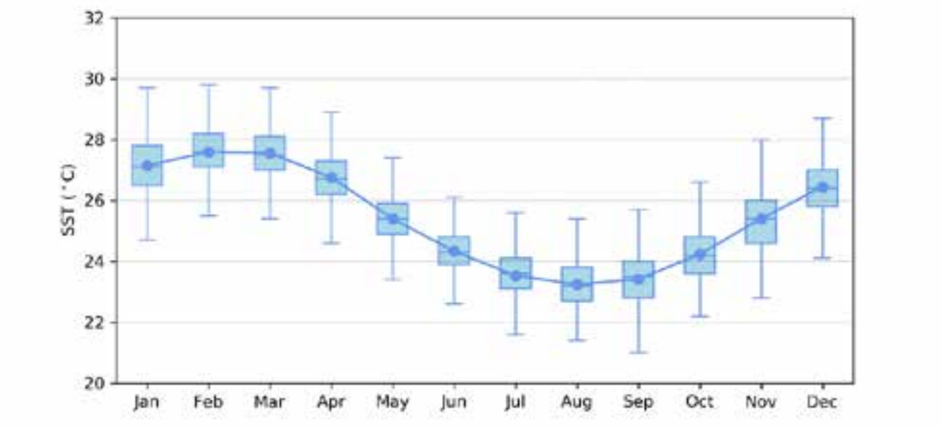
Records of tropical cyclones exist from the late 1800s in some countries in the Southwest Pacific, but trends in tropical cyclones have only been presented from 1981/82. Satellite-based observations began in the Southwest Pacific in the early 1970s, but consistent coverage and reliable intensity estimates 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 40 years.

14.7 Sea surface temperature

14.7.1 Seasonal cycle

Ocean temperature, as measured by the Nuku'alofa tide-gauge from 1992 to 2021, reaches on average a maximum of 27.5 °C in February/March, but individual months in January to March can get as high as almost 30 °C (Figure 14.9). Minimum average temperature is approximately 23 °C in August. Temperatures can be up to 3 °C higher or lower than these averages, although 50% of observations fall within 1.5 °C of the average.

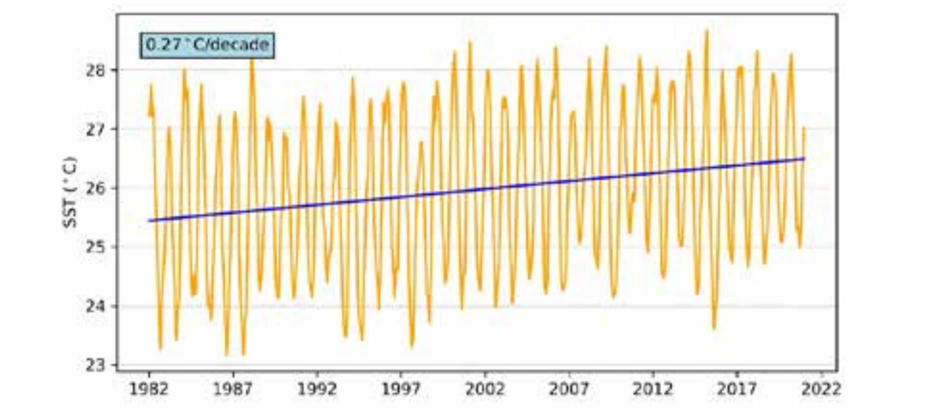
Figure 14.9:
Annual temperatures measured at the Nuku'alofa tide-gauge. Blue dots show the monthly average, and shaded boxes show the middle 50% of observations. Lines show the top and bottom 25% of observations.



14.7.2 Trends

Figure 14.10 shows the 1981–2021 SST from satellite observations averaged over the EEZ. The satellite data show a trend of 0.27 °C per decade with a 95% confidence interval of ±0.11 °C.

Figure 14.10:
Sea surface temperature from satellite observations averaged across the Tonga EEZ, shown as the orange line. The blue line shows the linear regression trend.



14.8 Sea level

14.8.1 Seasonal cycle

Tonga experiences a semidiurnal tidal cycle, meaning two high and two low tides per day. The highest predicted tides of the year typically occur during the wet season months of December–February. Figure 14.11 shows the number of hours the 99th percentile (1.91 m) sea level threshold is exceeded per month across the entire sea level record at Nuku'alofa. Peak sea levels typically occur over a significant portion of the year, ranging from December to April. Since approximately 2008, increasingly more hours each year exceed the 99th percentile threshold. This is due to a combination of sea-level rise and subsidence occurring at Tonga (Brown et al. 2020).

Figure 14.11:
Number of hours exceeding 99th percentile sea level threshold per month from 1993 to 2021 at the Nuku'alofa 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 1.91 m (Nuku'Alofa, Tonga)

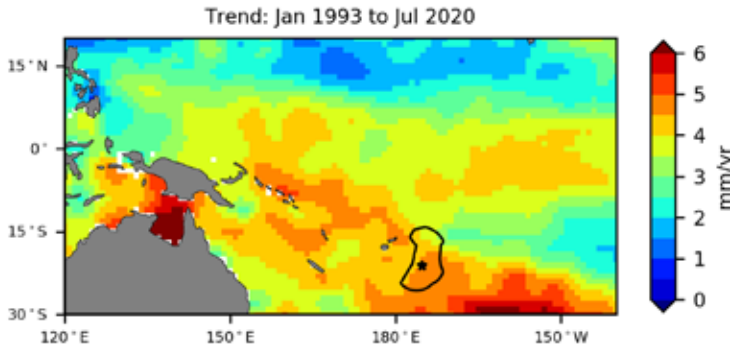
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	12	0	0	0	0	0	0	0	0	0	12
1998	0	0	0	0	0	0	0	0	0	0	0	2	2
1999	0	0	0	0	0	0	0	0	0	0	0	1	1
2000	9	0	2	0	0	0	0	0	0	0	0	0	11
2001	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	0	0	3	0	0	0	0	0	0	0	0	0	3
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	0	0	0	0	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0	1	2	0	3
2008	0	0	0	0	0	0	0	0	0	0	0	4	4
2009	14	0	0	0	0	0	0	0	0	0	0	0	14
2010	1	3	0	0	0	0	0	0	0	0	0	0	4
2011	0	0	0	2	0	0	0	0	1	0	0	0	3
2012	0	3	0	6	0	0	0	0	0	0	0	3	12
2013	3	0	0	0	0	0	1	0	0	0	0	0	4
2014	8	5	14	0	0	0	1	0	0	0	0	0	28
2015	0	0	2	0	0	0	0	0	0	0	0	0	2
2016	0	0	0	0	0	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0	0	0	0	5	5
2018	5	1	0	0	0	0	0	1	0	0	0	0	7
2019	4	3	4	0	0	0	0	0	1	0	0	0	12
2020	3	3	7	7	0	0	0	0	0	7	6	11	44
2021	0	1	0	3	1	0	0	0	0	0	0	7	12
Monthly Totals (%)	26	10	24	10	1	0	1	1	1	4	4	18	

14.8.2 Trends

Sea level at Tonga, measured by satellite altimeters (Figure 14.12) since 1993, has risen between 3.5 and 5 mm per year across most of the EEZ region, with a confidence interval between ±0.4 mm and ±0.6 mm. Sea-level rise for the EEZ is larger than the global average of 3.1 ± 0.4 mm per year (von Schuckmann et al. 2021), with higher estimates in the south. This rise is partly linked to a pattern related to climate variability from year to year and decade to decade.

Trend estimates at the Nuku'alofa tide-gauge over a similar time span to the altimetry observations (January 1993 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 Nuku'alofa, the trend is reported as 6.6 mm per year, significantly higher than altimetry trends shown in Figure 14.12 (tide-gauge indicated by star symbol). This difference is largely attributed to subsidence occurring at Nuku'alofa, Tonga (Brown et al. 2020).

Figure 14.12:
Satellite altimetry annual trend for the Pacific from 1993 to 2020, with the Tonga EEZ highlighted. The star symbol indicates the location of the tide-gauge.



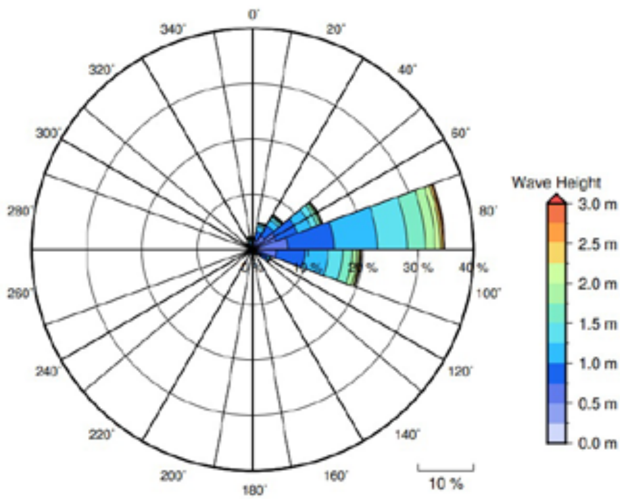
14.9 Waves

14.9.1 Seasonal cycle

The average wave climate in Nuku'alofa 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.

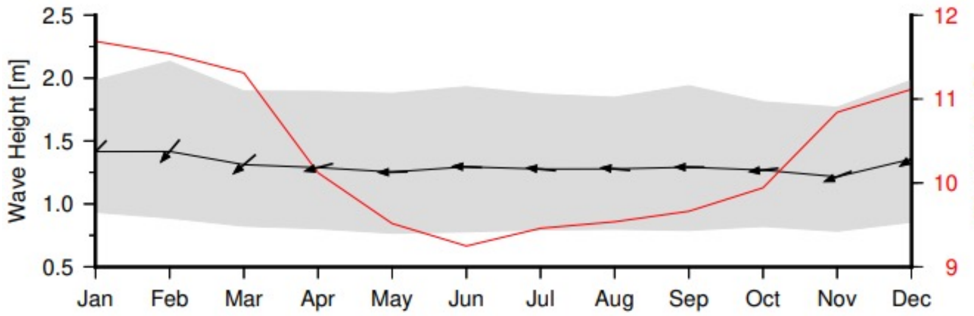
The average sea state is dominated by wind seas from the east. The annual mean wave height is 1.30 m, the annual mean wave direction is 60° and the annual mean wave period is 10.33 s. In the Pacific, waves often come from multiple directions and for different periods of time. In Nuku'alofa, there are often more than six different wave direction/period components coming from the southeast to southwest (Figure 14.13).

Figure 14.13:
Annual wave rose for Nuku'alofa. Note that direction is where the wave is coming from.



Seasonal wave height and period peaks between November and March due to North Pacific extra-tropical storm activity (Figure 14.14). Due to Tonga's location in the Southwest Pacific, swell waves from the North Pacific have weakened significantly before reaching Tonga and therefore do not show much of an effect on the wave height seasonal peak. Nuku'alofa's location on the northern shoreline of Tongatapu means there is little influence from Southern Ocean waves, with prevailing easterly waves from regional winds driving wave activity in May–October.

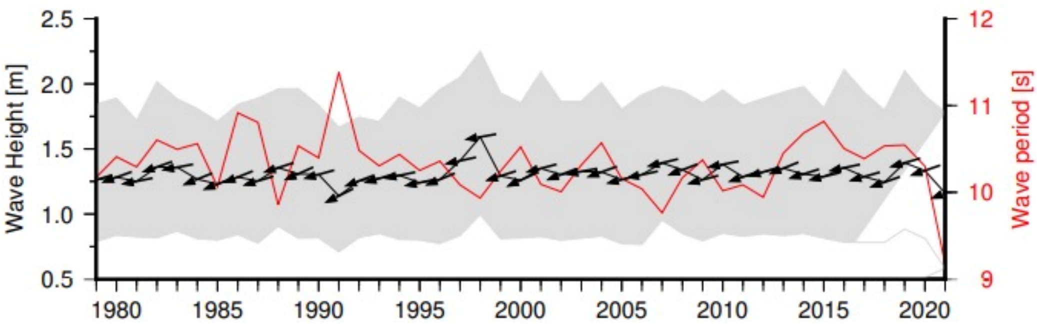
Figure 14.14:
Monthly wave height (black line), wave period (red line) and wave direction (arrows). The grey area represents the range of wave height between calm periods (10% of lowest wave height) and large wave events (10% of highest wave height).



14.9.2 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 Nuku'alofa, the mean annual wave height has remained unchanged since 1979 (Figure 14.15). The mean annual wave height in Nuku'alofa is not significantly correlated with the main climate indicators of the region.

Figure 14.15:
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).



14.9.3 Extreme waves

Extreme wave analysis completed for Nuku'alofa was done by defining a severe height threshold and fitting a generalized Pareto distribution (GPD). The optimum threshold selected was 2.95 m. In the 42-year wave hindcast, 169 wave events reached or exceeded this threshold, averaging four waves per year. The GPD was fitted to the largest wave height reached during each of these events (Figure 14.16, Table 14.4). 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 14.16:
Extreme wave distribution for Nuku'alofa. 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.

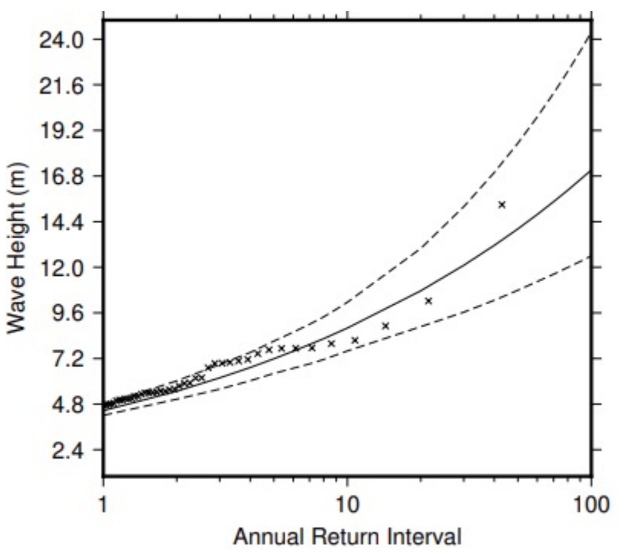


Table 14.4:
Summary of the results from extreme wave analysis in Nuku'alofa

Large wave height (90th percentile)	1.90 m
Severe wave height (99th percentile)	2.97 m
1-year ARI wave height	4.46 m
10-year ARI wave height	8.80 m
20-year ARI wave height	10.76 m
50-year ARI wave height	14.02 m
100-year ARI wave height	17.11 m