2 | Cook Islands

2.1 Summary

2.1.1 Climate

- Changes in air temperature from season to season are relatively small and strongly linked to changes in the surrounding ocean temperature. The Cook Islands have 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 Rarotonga increased over the period 1951–2020. The annual number of hot days and warm nights has increased, while the number of cool days and cold nights has decreased. The energy required for cooling indoor environments has increased and the difference between daytime and night-time temperatures has decreased.
- Annual rainfall has decreased at Rarotonga. Most of this has occurred during May to October. The annual number of wet days has also decreased.
- Tropical cyclones usually affect the Cook Islands between November and April. Over the period 1969–2018, an average of 16 cyclones passed within the Cook Islands' 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.
- 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.

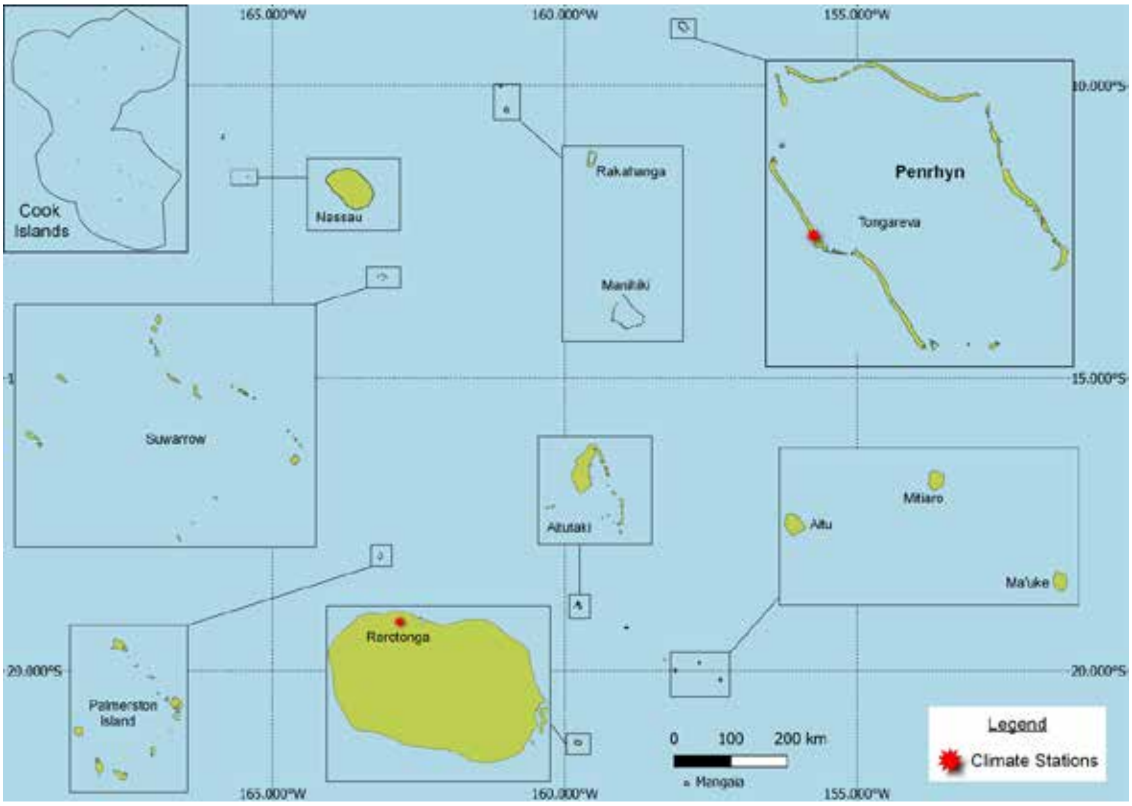
2.1.2 Ocean

- Highest sea levels typically occur from October to April.
- Sea-level rise within the Cook Islands EEZ, measured by satellite altimeters from 1993 to mid-2020, ranges from about 2.5 to 5.5 mm per year across the majority of the EEZ, with highest estimates in the far south.
- Monthly average ocean temperature, as measured by the Rarotonga tide-gauge, ranges from 24.5 °C in August to 28 °C in February and March. However, monthly temperatures in any given year can be up to ±2 °C of these averages.
- Sea surface temperature increased within the Cook Islands EEZ by 0.21 °C per decade from 1981 to 2021.
- Dominant wave direction is from 190° (south), with an average significant wave height of 2.04 m and average wave period of 12.64 s.
- Severe wave height was defined as 4.01 m, with an average of three severe events per year.
- Peak average significant wave height occurs around June.

2.2 Country description

The Cook Islands are located in the tropical western South Pacific Ocean between latitudes 9°S and 23°S, and longitudes 157°W and 166°W (Figure 2.1). The country is made up of 15 islands divided into two distinct north and south groups. The total land area is 237 km^2 and the Cook Islands have an EEZ of about 2.0 million km^2. The chief town Avarua (the capital, referred to as Rarotonga) is located on the island of Rarotonga (67 km^2) in the Southern Cook Islands. The highest elevation is 652 m above sea level on Rarotonga. The Cook Islands population is approximately 17,000 and about 13,000 live on Rarotonga.

Figure 2.1:
Cook Islands and the locations of the climate stations used in this report



2.3 Data

Daily historical rainfall and air temperature records for Penrhyn (northern Cook Islands) and Rarotonga (southern Cook Islands) from 1951 were obtained from the Cook Islands 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 were adjusted to make them homogeneous (further information is provided in Chapter 1). Additional information on historical climate trends for the Cook Islands 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.

Sea surface temperature (SST) covering the EEZ for the Cook Islands 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 Rarotonga, 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 the Cook Islands 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 Rarotonga tide-gauge station, spanning from 1993 to 2021 at hourly intervals.

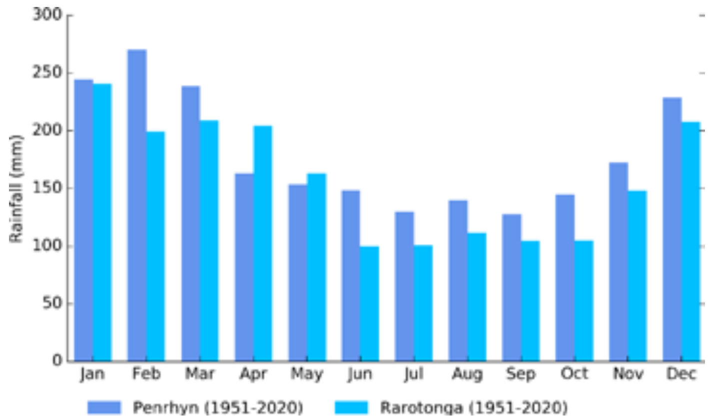
2.4 Rainfall

2.4.1 Seasonal cycle

Rainfall in the Cook Islands is strongly affected by the SPCZ and is centred close to or over the Southern Cook Islands (Southern Group) from December to April, when the SPCZ is most active and furthest south. From November to March, the SPCZ is wide and strong enough for the Northern Group to also receive significant rainfall.

The percentage of rainfall received in Penrhyn during the wet season months from November to April is 61%. Similarly, Rarotonga receives 64% of its annual rainfall during the wet season (Figure 2.2). The driest months of the year in the Cook Islands are from June to October. During these months, there is a significant reduction in rainfall in the northern and southern Cook Islands.

Figure 2.2:
Mean annual rainfall at Penrhyn and Rarotonga



2.4.2 Trends

Annual rainfall has decreased significantly at Rarotonga since 1951. This is attributed to decreases during May to October (Figure 2.3, Table 2.1). Correspondingly, the number of rainy days at Rarotonga has also decreased. Annual and seasonal rainfall at Penrhyn has not changed significantly. Year-to-year variability associated with El Niño–Southern Oscillation (ENSO) is evident at Rarotonga, with La Niña years typically experiencing higher rainfall than El Niño years (Figure 2.3). Pronounced decade-to-decade variability is evident at Penrhyn. Annual rainfall has varied from approximately 1100 to 3000 mm at Rarotonga and from approximately 800 to 4700 mm at Penrhyn.

Figure 2.3:
Annual rainfall (bar graph) and number of wet days (where rainfall is at least 1 mm; line graph) at Rarotonga (left) and Penrhyn (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 2.1. Diamonds indicate years with insufficient data for one or both variables.

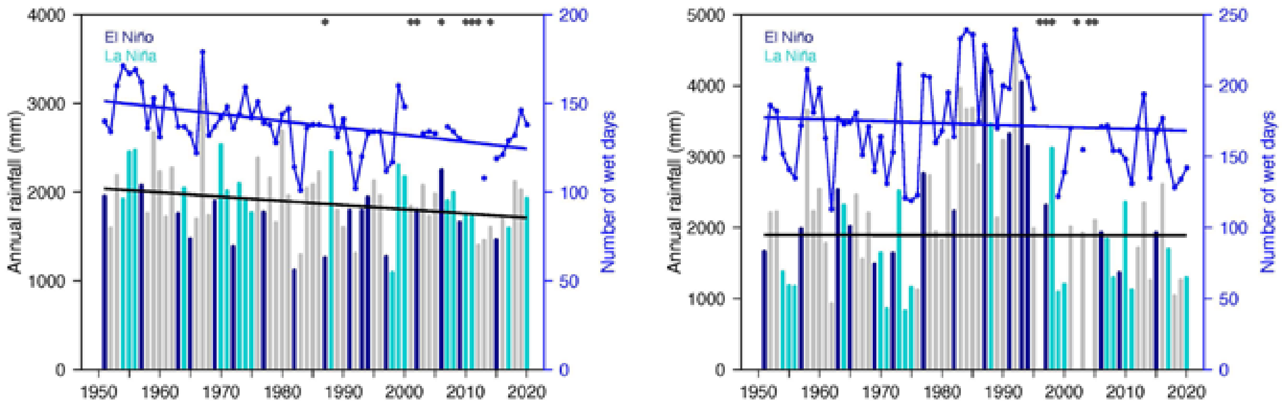
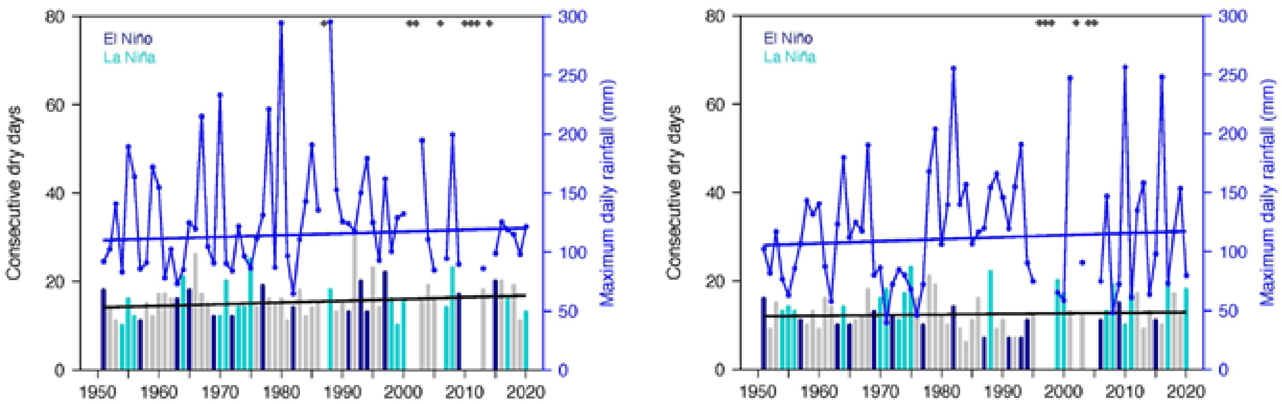


Table 2.1:
Trends in annual, seasonal and extreme rainfall at Rarotonga and Penrhyn. The 95% confidence intervals are shown in parentheses, and trends significant at the 95% level are shown in bold. The contribution to total rainfall from extreme events and the standardised rainfall evapotranspiration index are measured relative to 1961–1990 (see Chapter 1 for details). The standardised rainfall evapotranspiration index is not available for Penrhyn due to daily temperature observations not being available for this site.

	Rarotonga	Penrhyn
	1951–2020	
Annual rainfall (mm/decade)	**-47.59** (-90.85, 3.13)	-1.03 (-249.2, +191.97)
November–April (mm/decade)	-23.12 (-66.6, +20.94)	+18.66 (-94.19, +111.76)
May–October (mm/decade)	**-21.54** (-37.45, 3.5)	-38.36 (-109.18, +27.36)
Number of wet days (days/decade)	**-3.87** (-6.44, 1.08)	-1.35 (-7.54, +5.05)
Contribution to total rainfall from extreme events (%/decade)	-0.77 (-2.03, +0.71)	+0.71 (-1.6, +2.68)
Consecutive dry days (days/decade)	+0.39 (0, +0.87)	+0.14 (-0.47, +0.74)
Maximum one-day rainfall (mm/decade)	+1.50 (-3.22, +5.91)	+1.72 (-3.59, +8.34)
Standardised rainfall evapotranspiration index (November–April)	-0.08 (-0.22, +0.07)	-
Standardised rainfall evapotranspiration index (May–October)	-0.12 (-0.24, +0.02)	-

No significant trends in extreme rainfall indices, including the standardised rainfall evapotranspiration drought index, are present at Rarotonga and Penrhyn (Table 2.1). Figure 2.4 shows change and variability in the longest run of days without rain and maximum daily rainfall at both sites. Variability associated with ENSO is evident at Penrhyn, with longer dry spells and lower daily rainfall maximums occurring during La Niña years compared to El Niño years.

Figure 2.4:
Annual longest run of consecutive dry days (bar graph) and maximum daily rainfall (line graph) at Rarotonga (left) and Penrhyn (right). Straight lines indicate linear trends for dry days (in black) and maximum daily rainfall (in blue). The magnitudes of these trends are presented in Table 2.1. Diamonds indicate years with insufficient data for one or both variables.



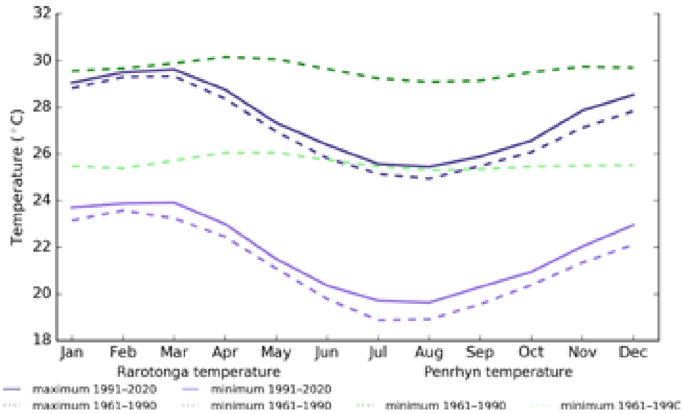
2.5 Air temperature

2.5.1 Seasonal cycle

There is a significant difference in seasonal temperatures between the northern and southern Cook Islands. The position of the northern Cook Islands (Northern Group) so close to the equator results in fairly constant temperatures throughout the year, while in the southern Cook Islands (Southern Group), temperatures cool off during the dry season. Changes in temperatures are strongly linked to changes in the surrounding ocean temperature. The range in average monthly maximum temperature is 1.1 °C at Penrhyn in the Northern Group and 4.4 °C at Rarotonga in the Southern Group (Figure 2.5). The range in average monthly minimum temperature at Penrhyn is 0.75 °C and at Rarotonga, it is 4.7 °C.

There has been a clear shift towards warmer average monthly temperatures between the climatology periods of 1961–1990 and 1991–2020 (Figure 2.5), with warmer average air temperatures occurring in all months throughout the year for Rarotonga.

Figure 2.5:
Maximum and minimum air temperature seasonal cycle for Penrhyn (purple) and Rarotonga (green), and for the periods 1961–1990 (dotted lines) and 1991–2020 (solid lines)



2.5.2 Trends

Average annual and seasonal temperatures have increased significantly at Rarotonga (Figure 2.6). November–April temperatures are warming at approximately the same rate as May–October temperatures (Table 2.2). Daily minimum temperatures are warming faster than daily maximum temperatures.

Figure 2.6:
Average annual, November–April and May–October temperatures for Rarotonga. Straight lines indicate linear trends. The magnitudes of the trends are presented in Table 2.2. Diamonds indicate years with insufficient data for one or more variables.

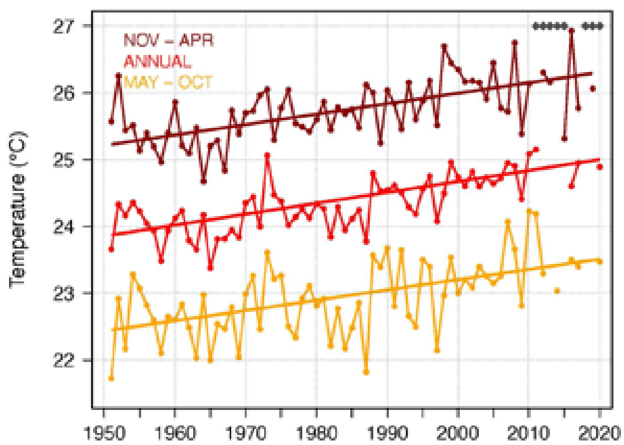


Table 2.2:
Trends in annual and seasonal air temperatures at Rarotonga. The 95% confidence intervals are shown in parentheses, and trends significant at the 95% level are shown in bold.

	Rarotonga Tmax (°C/decade)	Rarotonga Tmin (°C/decade)	Rarotonga Tmean (°C/decade)
		1951–2020	
Annual	**+0.14** (+0.06, +0.21)	**+0.18** (+0.14, +0.23)	**+0.16** (+0.11, +0.21)
November–April	**+0.13** (+0.07, +0.19)	**+0.18** (+0.13, +0.23)	**+0.16** (+0.11, +0.20)
May–October	**+0.11** (+0.04, +0.20)	**+0.18** (+0.13, +0.25)	**+0.15** (+0.08, +0.22)

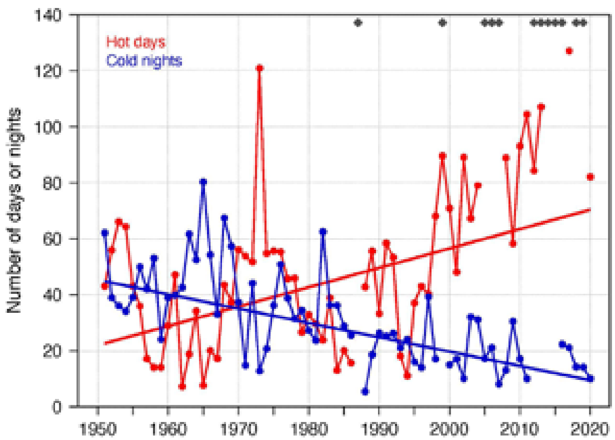
The number of hot days and warm nights has increased, and the number of cool days and cold nights has decreased at Rarotonga (Table 2.3, Figure 2.7).

The cooling degree days index provides a measure of the energy demand needed to cool a building down to 25 °C, with the assumption that air conditioners are generally turned on at this temperature. There has been an increase in the cooling degree index, suggesting the energy needed for cooling has increased significantly since 1951. The difference between daytime and night-time temperatures at Rarotonga has been decreasing.

Table 2.3:
Trends in annual temperature extremes at Rarotonga. 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).

	Rarotonga
	1951–2020
Number of hot days (days/decade)	**+6.92** (+0.52, +13.34)
Number of warm nights (nights/decade)	**+6.81** (+4.69, +9.28)
Number of cool days (days/decade)	**-4.12** (-6.40, 1.75)
Number of cold nights (nights/decade)	**-5.12** (-6.86, 3.65)
Cooling degree days (degree days/decade)	**+22.34** (+14.50, +29.72)
Daily temperature range (°C/decade)	**-0.08** (-0.16, 0.01)

Figure 2.7:
Annual number of hot days and cold nights at Rarotonga. Straight lines indicate linear trends. The magnitudes of the trends are presented in Table 2.3. Diamonds indicate years with insufficient data for one or both variables.



2.6 Tropical cyclones

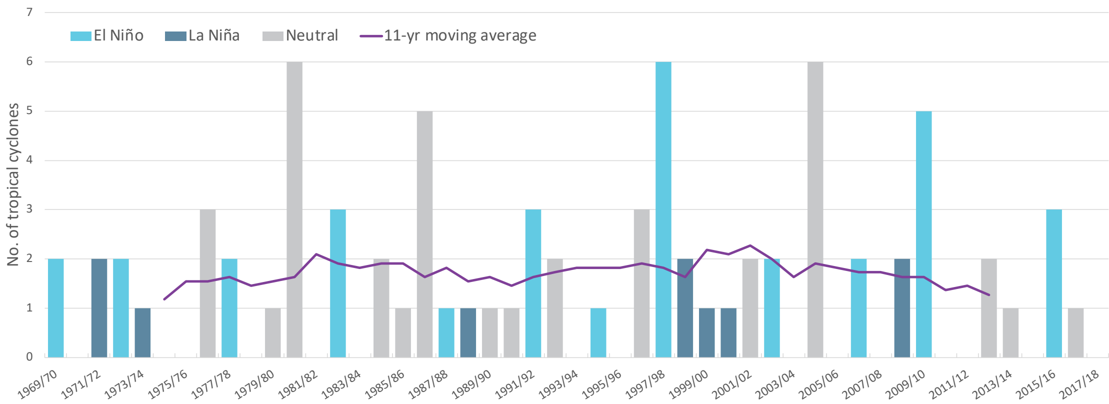
2.6.1 Seasonal cycle

Tropical cyclones usually affect the Cook Islands during the southern hemisphere tropical cyclone season, which is from November to April, but also occasionally occur outside the tropical cyclone season. The tropical cyclone archive of the southern hemisphere indicates that between the 1969/70 and 2017/18 seasons, 79 tropical cyclones (Figure 2.8) passed within the Cook Islands EEZ. This represents an average of 16 cyclones per decade. Tropical cyclones were most frequent in El Niño years (25 cyclones per decade), followed by neutral years (17 cyclones per decade) and least frequent in La Niña years (7 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 1980/81, 1997/98 and 2004/05 (Figure 2.8). 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 2.8:
Number of tropical cyclones passing within the Cook Islands 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.



2.6.2 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.

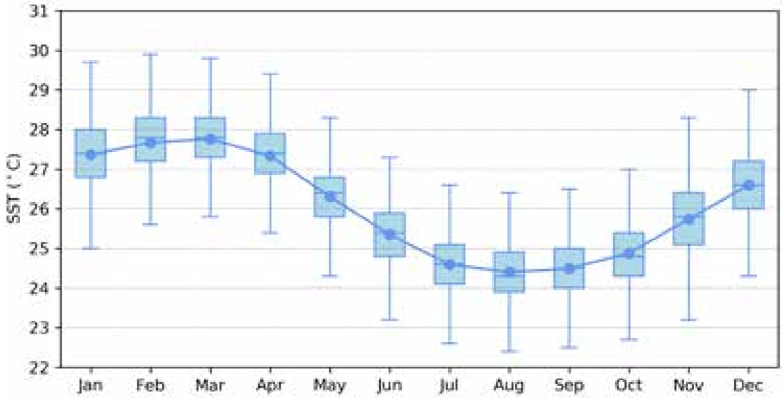
Records of tropical cyclones exist from the late 1800s in some countries in the Southwest Pacific, but trends in tropical cyclones have only been presented from 1981/82. Satellite-based observations began in the Southwest Pacific in the early 1970s, but consistent coverage and reliable intensity estimates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

2.7 Sea surface temperature

2.7.1 Seasonal cycle

Ocean temperature, as measured by the Rarotonga tide-gauge from 1993 to 2021, reaches on average a maximum of almost 28 °C in February/March but can get as high as 30 °C (Figure 2.9). Minimum average temperature reaches a low of approximately 24.5 °C in August. Temperatures can be up to 2 °C higher or lower than these averages, although 50% of observations fall within 1 °C of the average.

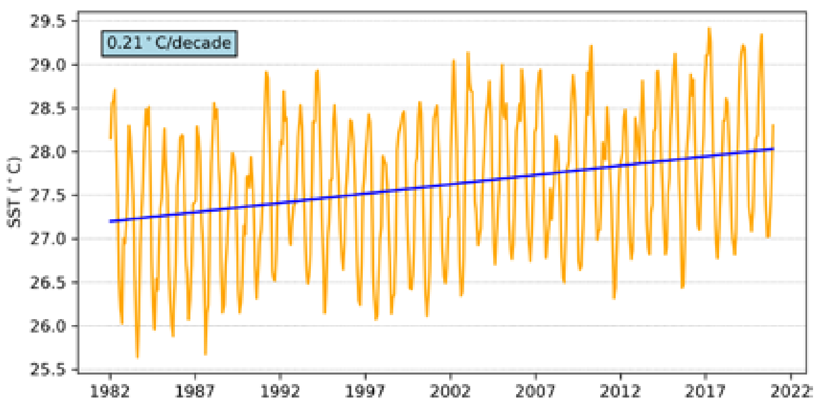
Figure 2.9:
Annual temperatures measured at the Rarotonga tide-gauge. Blue dots show the monthly average, and shaded boxes show the middle 50% of observations. Lines show the top and bottom 25% of observations.



2.7.2 Trends

Figure 2.10 shows the 1981–2021 SST from satellite observations averaged over the Cook Islands EEZ. The data show a trend of 0.21 °C per decade with a 95% confidence interval of ±0.06 °C.

Figure 2.10:
Sea surface temperature from satellite observations averaged across the Cook Islands EEZ, shown as the orange line. The blue line shows the linear regression trend.



2.8 Sea level

2.8.1 Seasonal cycle

The Cook Islands experience 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 November to April. Figure 2.11 shows the number of hours the 99th percentile (1.15 m) sea level threshold is exceeded per month across the entire sea level record at Rarotonga. Peak sea levels typically occur over a significant portion of the year ranging from October to April. Since approximately 2006, increasingly more hours each year exceed the 2.0 m sea level threshold. This is due to a combination of sea-level rise and minor subsidence occurring at Rarotonga (Brown et al. 2020).

Figure 2.11:
Number of hours exceeding 99th percentile sea level threshold per month from 1993 to 2021 at the Rarotonga tide-gauge. Blue shading indicates the number of hours, and the final row provides a percentage summary of all the years.

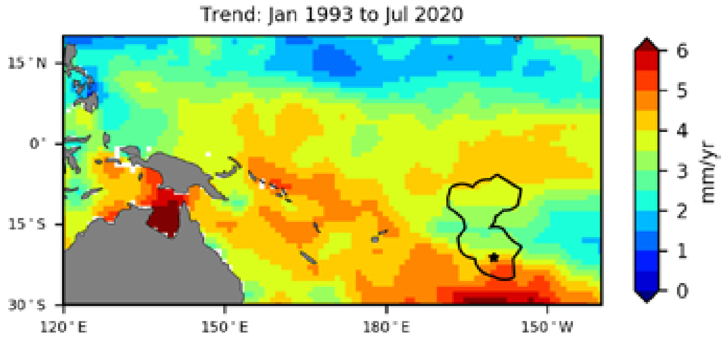
Number of hours exceeding 1.15 m (Avatiu, Cook Islands)

	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	6	0	0	0	0	0	0	0	0	6	12
1998	0	0	0	0	0	0	0	0	0	0	0	0	0
1999	0	0	0	0	0	0	1	0	0	0	0	2	3
2000	0	0	0	0	0	0	0	0	0	0	0	0	0
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	2	0	0	0	0	0	0	0	0	0	0	2
2006	5	3	5	0	0	0	0	0	0	0	0	0	13
2007	4	0	0	1	0	0	0	0	0	2	6	0	13
2008	0	0	0	0	0	0	0	0	0	0	0	0	0
2009	1	0	0	0	0	0	0	0	0	0	0	0	1
2010	5	2	0	0	0	0	0	0	0	0	0	0	7
2011	1	0	0	2	0	0	0	6	0	6	0	1	16
2012	0	0	0	0	0	0	0	0	0	0	0	12	12
2013	0	0	0	0	0	0	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0	0	0	0	0	0	0
2015	0	0	5	0	0	0	0	0	0	0	0	0	5
2016	0	0	8	0	0	0	0	2	0	5	0	0	15
2017	0	0	0	2	0	0	0	0	0	0	0	1	3
2018	0	0	0	0	0	0	0	0	0	0	0	0	0
2019	6	1	1	0	0	0	0	0	0	4	0	0	12
2020	0	5	4	9	0	0	0	0	0	1	0	0	19
2021	0	0	8	6	11	1	0	0	0	5	2	8	41
Monthly Totals (%)	13	7	21	11	6	1	1	5	0	13	5	17	

2.8.2 Trends

Sea level at Cook Islands, measured by satellite altimeters (Figure 2.12) since 1993, has risen 2.5–5.5 mm per year across most of the EEZ, with a 95% confidence interval of ±0.4 mm in the south and up to ±0.8 mm in the north. Trend estimates in the south are higher, ranging from 3.5 to 5.5 mm per year, which is larger than the global average of 3.1 ± 0.4 mm per year (von Schuckmann et al. 2021). This rise is partly linked to a pattern related to climate variability from year to year and decade to decade.

Figure 2.12:
Satellite altimetry annual trend for the Pacific from 1993 to 2020, with the Cook Islands EEZ highlighted. The star symbol indicates the location of the tide-gauge at Rarotonga.



Trend estimates at the Rarotonga tide-gauge over a similar time span to the altimetry observations (February 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 Rarotonga, the trend is reported as 3.9 mm per year, very similar to the altimetry trends shown in Figure 2.12 (tide-gauge indicated by star symbol).

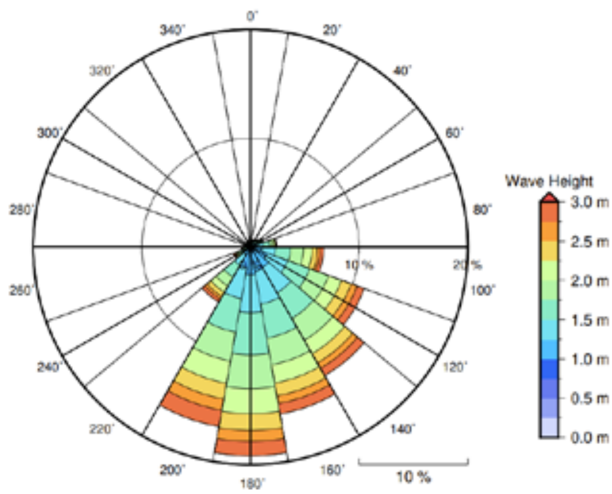
2.9 Waves

2.9.1 Seasonal cycle

The average wave climate at Rarotonga 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.

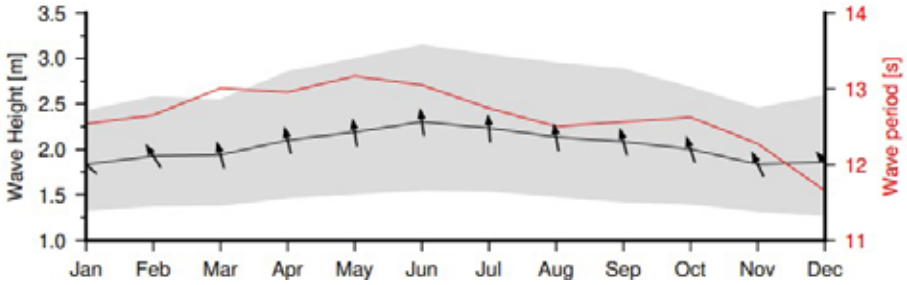
The average sea state is dominated by swells from the south. The annual mean wave height is 2.04 m, the annual mean wave direction is 190° and the annual mean wave period is 12.64 s. In the Pacific, waves often come from multiple directions and for different periods at a time. In Rarotonga, there are often more than six different wave direction/period components coming from the southeast to southwest (Figure 2.13).

Figure 2.13:
Annual wave rose for Rarotonga. Note that direction is where the wave is coming from.



Seasonal wave height peak is in June, whereas the seasonal wave period peaks in May (Figure 2.14). This is related to the intensification of the Southern Ocean storm track during winter. Conversely, there is slightly reduced wave activity between November and December.

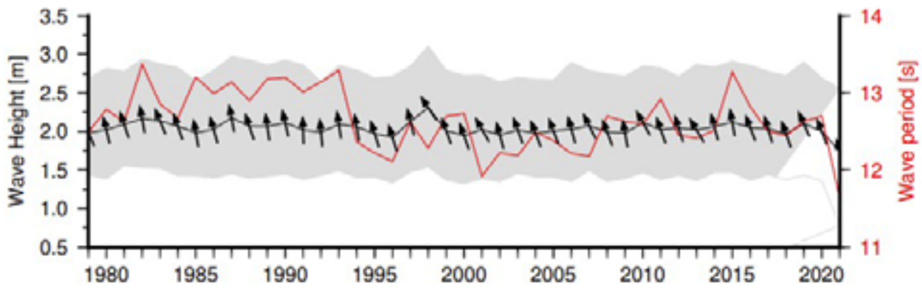
Figure 2.14:
Monthly wave height (black line), wave period (red line) and wave direction (arrows). The grey area represents the range of wave height between calm periods (10% of lowest wave height) and large wave events (10% of highest wave height).



2.9.2 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. At Rarotonga, the mean annual wave height has remained unchanged since 1979 (Figure 2.15). The mean annual wave height in Rarotonga is not significantly correlated with the main climate indicators of the region.

Figure 2.15:
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).



2.9.3 Extreme waves

Extreme wave analysis completed for Rarotonga was done by defining a severe height threshold and fitting a generalized Pareto distribution (GPD). The optimum threshold selected was 4.01 m. In the 42-year wave hindcast, 127 wave events reached or exceeded this threshold, averaging three per year. The GPD was fitted to the largest wave height reached during each of these events (Figure 2.16, Table 2.4). 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 2.16:
Extreme wave distribution for Rarotonga. 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.

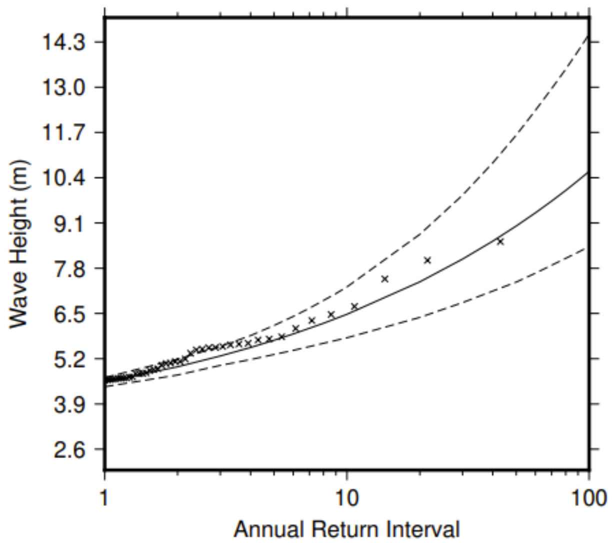


Table 2.4:
Summary of the results of extreme wave analysis for Rarotonga

Large wave height (90th percentile)	2.79 m
Severe wave height (99th percentile)	3.75 m
1-year ARI wave height	4.53 m
10-year ARI wave height	6.48 m
20-year ARI wave height	7.41 m
50-year ARI wave height	9.01 m
100-year ARI wave height	10.58 m