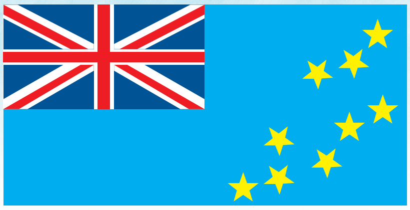

Chapter 15
Tuvalu

15.1 Climate Summary

15.1.1 Current Climate

- Annual and May–October mean and maximum air temperatures at Funafuti have increased since 1933. The frequency of night-time cool temperature extremes have decreased and warm temperature extremes have increased. These temperature trends are consistent with global warming.
- Annual and half-year rainfall trends show little change at Funafuti since 1927. There has also been little change in extreme daily rainfall since 1961.
- Tropical cyclones affect Tuvalu mainly between November and April. An average of 8 cyclones per decade developed within or crossed the Tuvalu Exclusive Economic Zone (EEZ) between the 1969/70 to 2010/11 seasons. Tropical cyclones were most frequent in El Niño years (12 cyclones per decade) and least frequent in La Niña years (3 cyclones per decade). Only three of the 24 tropical cyclones (13%) between the 1981/82 and 2010/11 seasons were severe events (Category 3 or stronger) in the Tuvalu EEZ. Available data are not suitable for assessing long-term trends.
- Wind-waves around Tuvalu do not vary significantly in height during the year. Seasonally, waves are influenced by the trade winds, extra-tropical storms and cyclones, and display variability on interannual time-scales with the El Niño–Southern Oscillation (ENSO) and the strength and location of the South Pacific Convergence Zone (SPCZ). Available data are not suitable for assessing long-term trends.

15.1.2 Climate Projections

For the period to 2100, the latest global climate model (GCM) projections and climate science findings indicate:

- El Niño and La Niña events will continue to occur in the future (*very high confidence*), but there is little consensus on whether these events will change in intensity or frequency;
- Annual mean temperatures and extremely high daily temperatures will continue to rise (*very high confidence*);
- It is not clear whether mean annual rainfall will increase or decrease, the model average indicating little change (*low confidence*), with more extreme rain events *(high confidence*);
- Incidence of drought is projected to decrease slightly (*low confidence*);
- Ocean acidification is expected to continue *(very high confidence);*
- The risk of coral bleaching will increase in the future (*very high confidence);*
- Sea level will continue to rise *(very high confidence); and*
- December–March wave heights and periods are projected to decrease slightly *(low confidence)*.

15.2 Data Availability

There are currently nine operational meteorological stations in Tuvalu. Multiple observations within a 24-hour period are taken at Nanumea, Nui, Funafuti and Niulakita. There are five single observation rainfall stations at Nanumaga, Niutao, Nukufetau, Vaitupu and Nukulaelae. The Funafuti station has the longest record, with monthly rainfall data available from 1927 and air temperature data from 1933. The Funafuti climate station is located on the Fongafale islet on the eastern side of the Funafuti Atoll in southern Tuvalu.

Funafuti monthly rainfall from 1927 (daily values from 1961) and air temperature from 1961 have been used in this report. The Funafuti record is considered homogeneous (given the available metadata). Additional information on historical climate trends in the Tuvalu region can be found in the Pacific Climate Change Data Portal www.bom.gov.au/climate/pccsp/.

Wind-wave data from buoys are particularly sparse in the Pacific region, with very short records. Model and reanalysis data are therefore required to detail the wind-wave climate of the region. Reanalysis surface wind data have been used to drive a wave model over the period 1979–2009 to generate a hindcast of the historical wind-wave climate.

15.3 Seasonal Cycles

Information on temperature and rainfall seasonal cycles can be found in Australian Bureau of Meteorology and CSIRO (2011).

15.3.1 Wind-driven Waves

Surface wind-wave driven processes can impact on many aspects of Pacific Island coastal environments, including: coastal flooding during storm wave events; coastal erosion, both during episodic storm events and due to long-term changes in integrated wave climate; characterisation of reef morphology and marine habitat/ species distribution; flushing and circulation of lagoons; and potential shipping and renewable wave energy solutions. The surface offshore wind-wave climate can be described by characteristic wave heights, lengths or periods, and directions.

The wind-wave climate of Tuvalu shows little spatial variability across its region.

On the east coast of the capital Funafuti, waves display strong seasonal variability with the trade winds. During June–September, mean wave period reaches its minimum (seasonal mean period around 8.6 s) with slightly larger than average waves (mean height around 1.8 m) consisting of trade wind generated waves from the east and south-east, and a small component of south-southwesterly swell propagated from storm events in the Southern Ocean (Figure 15.1). During December–March, mean waves reach a maximum period (seasonal mean around 9.6 s) with slightly smaller height (mean around 1.6 m) than in June–September (Table 15.1). These waves are directed from the north-east due to trade winds, with storm waves coming from the north. Waves larger than 2.6 m (99th percentile) at Funafuti occur predominantly during the dry season from the south-east, with some large north-westerly, northerly and north-easterly waves from cyclones in the wet season. The height of a 1-in-50 year wave event on the east coast near Funafuti is calculated to be 5.0 m.

To the north-west at Nanumea, waves are characterised by variability of trade winds and strength of the South Pacific Convergence Zone (SPCZ). Mean wave height and period do not vary significantly throughout the year on the south coast of Nanumea (Table 15.1), though waves are slightly smaller than average before the start of the wet season. During December–March, waves at Nanumea are on average north-easterly (Figure 15.2), associated with northern trade winds, with westerly and north-westerly waves from the WPM and tropical storms. During June–September, the observed south-easterly waves are generated by southern trade winds with some south to south-westerly swell from extra-tropical storms to the south. Waves larger than 2.7 m (99th percentile) occur predominantly in the wet season from highly variable directions around the north-west due largely to tropical cyclones and storms, with some large south-easterly waves observed in other months. The height of a 1-in-50 year wave event to the south of Nanumea is calculated to be 6.5 m.

No suitable dataset is available to assess long-term historical trends in the Tuvalu wave climate. However, interannual variability may be assessed in the hindcast record. The wind-wave climate displays strong interannual variability at both Funafuti and Nanumea, varying strongly with the El Niño–Southern Oscillation (ENSO). During La Niña years, waves are more strongly directed from the east in June–September at both locations, and also in December–March at Nanumea. Wave power is greater during La Niña years due to increased trade winds, and reduced winds during El Niño years due to the SPCZ being located over Tuvalu. When the Southern Annular Mode index is negative, there is a slight reduction in wave power at both Funafuti and Nanumea.

Table 15.1: Mean wave height, period and direction from which the waves are travelling around Tuvalu in December–March and June–September. Observation (hindcast) and climate model simulation mean values are given with the 5–95th percentile range (in brackets). Historical model simulation values are given for comparison with projections (see Section 15.5.6 – Wind-driven waves, and Table 15.7). A compass relating number of degrees to cardinal points (direction) is shown.

		Hindcast Reference Data (1979–2009), east Funafuti	Hindcast Reference Data (1979–2009), Nanumea	Climate Model Simulations (1986–2005) – Tuvalu
Wave Height (metres)	December–March	1.6 (1.2–2.2)	1.7 (1.2–2.3)	1.7 (1.4–2.0)
	June–September	1.8 (1.3–2.5)	1.7 (1.3–2.3)	1.6 (1.4–1.9)
Wave Period (seconds)	December–March	9.6 (7.8–11.7)	9.3 (7.6–11.3)	9.2 (8.1–10.5)
	June–September	8.6 (7.1–10.8)	8.8 (7.2–11.2)	8.0 (7.0–9.4)
Wave Direction (degrees clockwise from North)	December–March	50 (10–100)	50 (300–120)	40 (0–60)
	June–September	120 (90–160)	130 (100–170)	120 (110–140)

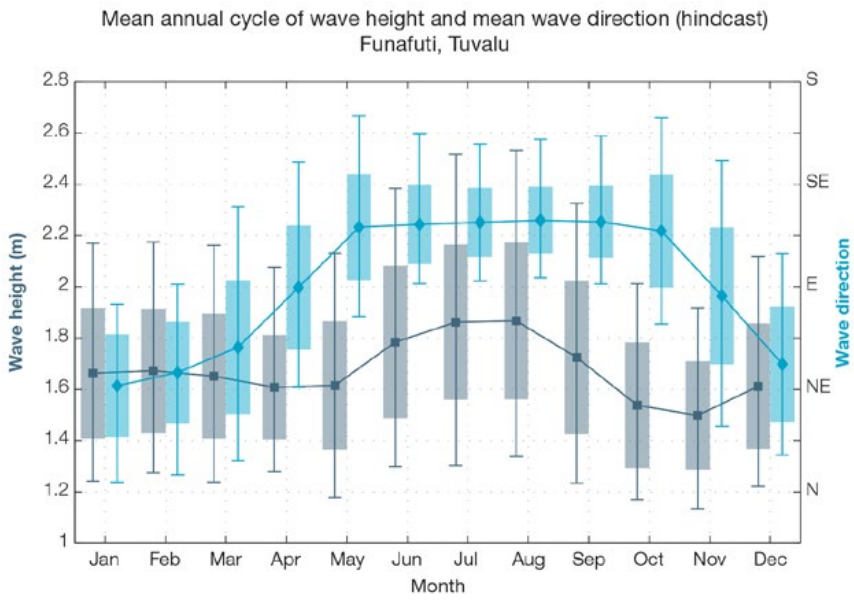

Figure 15.1: Mean annual cycle of wave height (grey) and mean wave direction (blue) at Funafuti in hindcast data (1979–2009). To give an indication of interannual variability of the monthly means of the hindcast data, shaded boxes show 1 standard deviation around the monthly means, and error bars show the 5–95% range. The direction from which the waves are travelling is shown (not the direction towards which they are travelling).

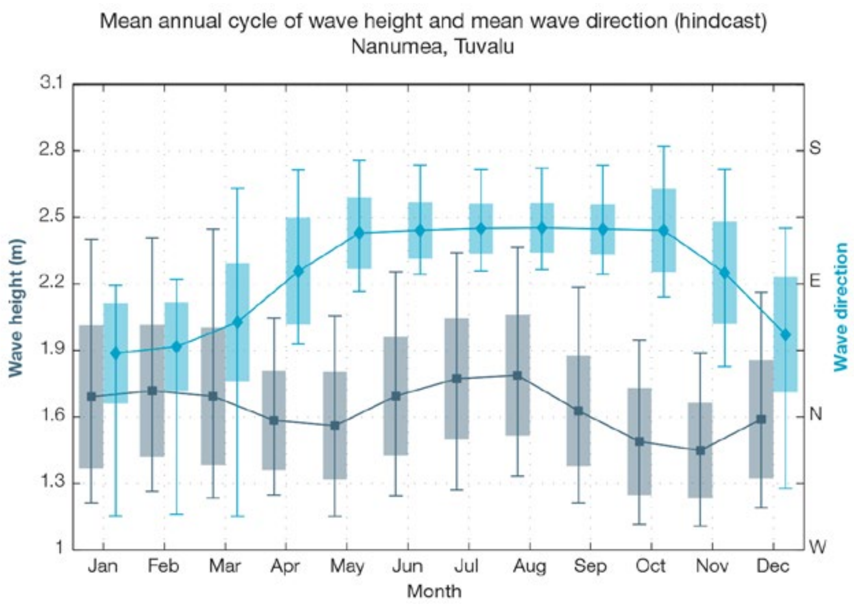

Figure 15.2: Mean annual cycle of wave height (grey) and mean wave direction (blue) at Nanumea in hindcast data (1979–2009). To give an indication of interannual variability of the monthly means of the hindcast data, shaded boxes show 1 standard deviation around the monthly means, and error bars show the 5–95% range. The direction from which the waves are travelling is shown (not the direction towards which they are travelling).

15.4 Observed Trends

15.4.1 Air Temperature

Annual and Half-year Mean Air Temperature

Annual and May–October mean and maximum temperatures increased at Funafuti over the period 1933–2011 (Figure 15.3, Table 15.2). These increasing trends are statistically significant at the 5% level. Minimum temperature and November–April trends show little change.

Table 15.2: Annual and half-year trends in air temperature (Tmax, Tmin, Tmean) and rainfall at Funafuti. The 95% confidence intervals are shown in brackets. Values for trends significant at the 5% level are shown in **boldface**.

Funafuti	Tmax (°C/10yrs)	Tmin (°C/10yrs) 1933–2011	Tmean (°C/10yrs)	Total Rain (mm/10yrs) 1927–2011
Annual	**+0.09** (+0.02, +0.15)	+0.09 (-0.01, +0.19)	**+0.10** (+0.02, +0.16)	-57.6 (-140.9, +25.6)
Nov–Apr	+0.03 (-0.03, +0.10)	+0.10 (-0.03, +0.23)	+0.06 (-0.02, +0.13)	-8.3 (-44.0, +25.9)
May–Oct	**+0.11** (+0.05, +0.18)	+0.09 (0.00, +0.18)	**+0.10** (+0.03, +0.16)	-10.8 (-53.6, +33.4)

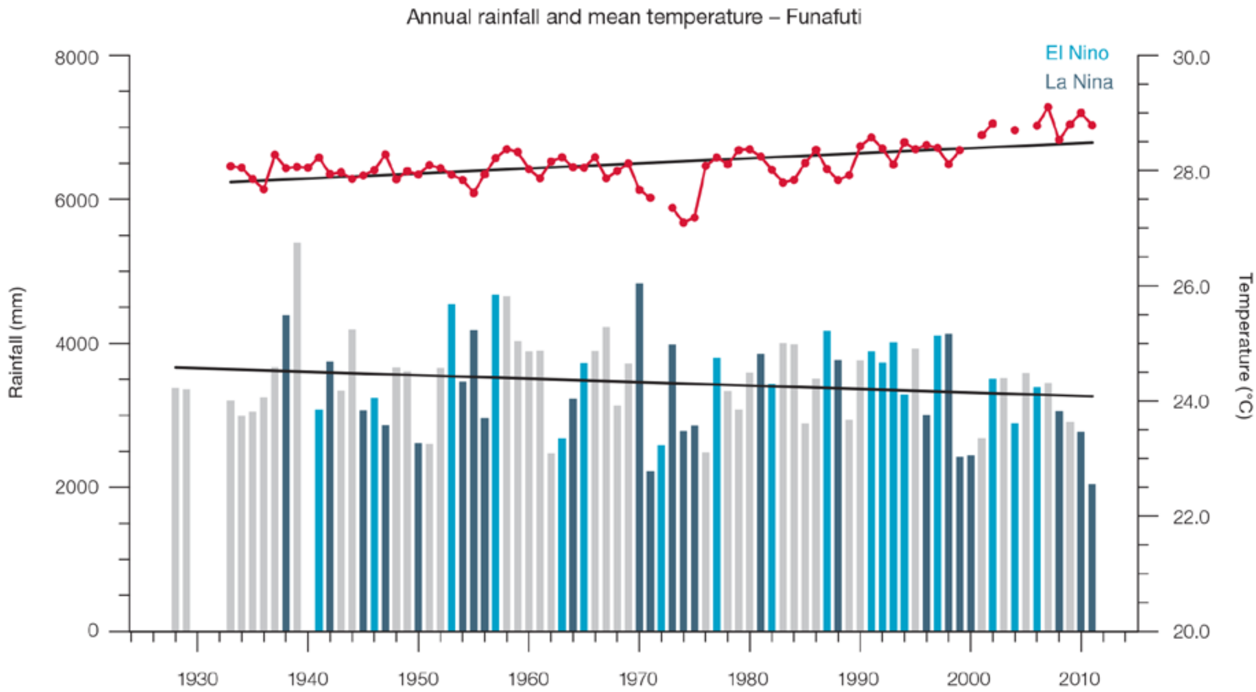

Figure 15.3: Observed time series of annual average values of mean air temperature (red dots and line) and total rainfall (bars) at Funafuti. Light blue, dark blue and grey bars denote El Niño, La Niña and neutral years respectively. Solid black trend lines indicate a least squares fit.

Extreme Daily Air Temperature

Trends in night-time extreme daily temperatures were found to be stronger than day-time extreme temperatures (Table 15.3, Figure 15.4). At Funafuti, there have been significant increases in Warm Nights and significant decreases in Cool Nights. Trends in Warm and Cool Days are not significant, suggesting there has been little change in day-time extreme daily temperatures since 1961, which is in line with the little change found in mean maximum air temperatures (Table 15.3).

15.4.2 Rainfall

Annual and Half-year Total Rainfall

Notable interannual variability associated with the ENSO is evident in the observed rainfall record for Funafuti since 1927 (Figure 15.3). Trends in annual and half-year rainfall presented in Table 15.3 and Figure 15.2 are not statistically significant at the 5% level. In other words, annual and half-year rainfall trends show little change at Funafuti.

Daily Rainfall

Daily rainfall trends for Funafuti are presented in Table 15.3. Due to large year-to-year variability, there are no significant trends in the daily rainfall indices. Figure 15.5 shows insignificant trends in annual Very Wet Days and Consecutive Dry Days.

Table 15.3: Annual trends in air temperature and rainfall extremes at Funafuti. The 95% confidence intervals are shown in brackets. Values for trends significant at the 5% level are shown in **boldface**.

	Funafuti
TEMPERATURE	**(1961–2011)**
Warm Days (days/decade)	+5.99 (-6.47, +23.83)
Warm Nights (days/decade)	**+11.73** (+6.21, +17.59)
Cool Days (days/decade)	-1.36 (-5.18, +3.25)
Cool Nights (days/decade)	**-8.00** (-18.59, -0.22)
RAINFALL	
Rain Days ≥ 1 mm (days/decade)	-0.67 (-4.59, +3.33)
Very Wet Day rainfall (mm/decade)	-39.78 (-134.21, +42.99)
Consecutive Dry Days (days/decade)	0.00 (-0.24, +0.67)
Max 1-day rainfall (mm/decade)	-1.23 (-8.63, +5.76)

Warm Days: Number of days with maximum temperature greater than the 90th percentile for the base period 1971–2000
Warm Nights: Number of days with minimum temperature greater than the 90th percentile for the base period 1971–2000
Cool Days: Number of days with maximum temperature less than the 10th percentile for the base period 1971–2000
Cool Nights: Number of days with minimum temperature less than the 10th percentile for the base period 1971–2000
Rain Days ≥ 1 mm: Annual count of days where rainfall is greater or equal to 1 mm (0.039 inches)
Very Wet Day rainfall: Amount of rain in a year where daily rainfall is greater than the 95th percentile for the reference period 1971–2000
Consecutive Dry Days: Maximum number of consecutive days in a year with rainfall less than 1 mm (0.039 inches)
Max 1-day rainfall: Annual maximum 1-day rainfall

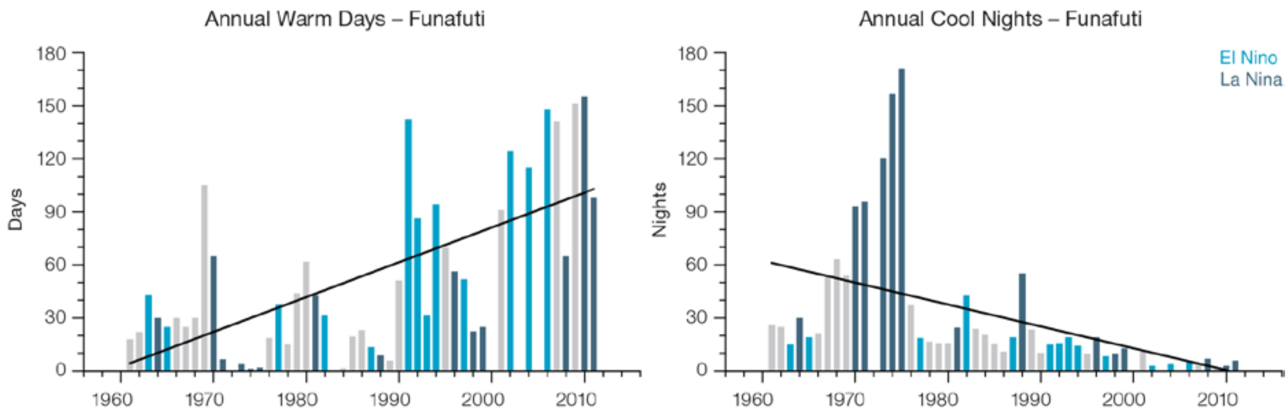

Figure 15.4: Observed time series of annual total number of Warm Nights (left) and Cool Nights (right) at Funafuti. Solid black trend lines indicate least squares fit.

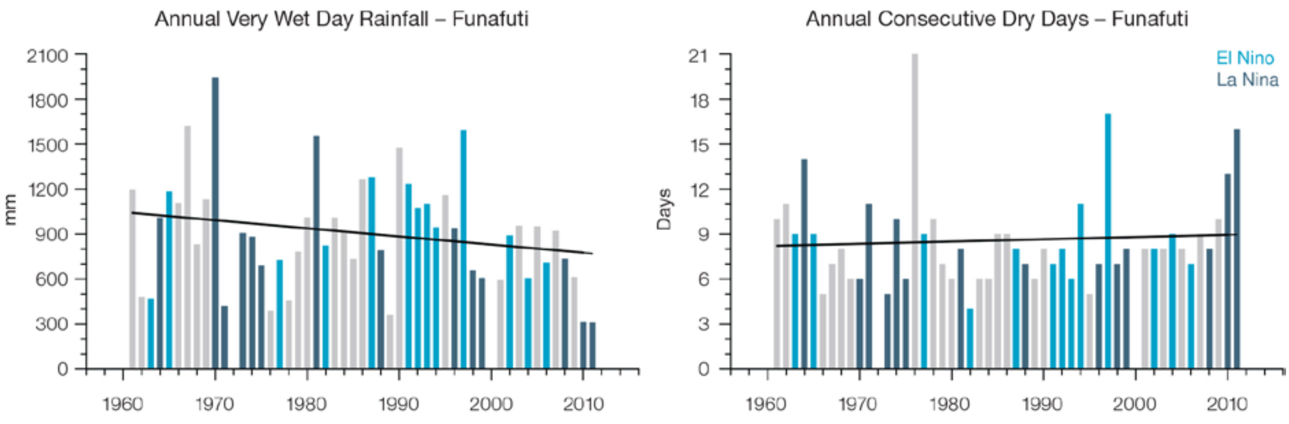

Figure 15.5: Observed time series of annual total values of Very Wet Days (left) and Consecutive Dry Days (right) at Funafuti. Solid black trend lines indicate least squares fit.

15.4.3 Tropical Cyclones

When tropical cyclones affect Tuvalu they tend to do so between November and April. Occurrences outside this period are rare. The tropical cyclone archive for the Southern Hemisphere indicates that between the 1969/70 and 2010/11 cyclone seasons 35 tropical cyclones developed within or crossed the Tuvalu EEZ (Figure 15.6) This represents an average of 8 cyclones per decade. Refer to Chapter 1, Section 1.4.2 (Tropical Cyclones) for an explanation of the difference in the number of tropical cyclones occurring in Tuvalu in this report (Australian Bureau of Meteorology and CSIRO, 2014) compared to Australian Bureau of Meteorology and CSIRO (2011). Tropical cyclones were most frequent in El Niño years (12 cyclones per decade) and least frequent in La Niña years (3 cyclones per decade). The neutral year average is 7 cyclones per decade. Only three of the 24 tropical cyclones (13%) between the 1981/82 and 2010/11 seasons were severe events (Category 3 or stronger) in the Tuvalu EEZ.

Long term trends in frequency and intensity have not been presented as country scale assessment is not recommended. Some tropical cyclone tracks analysed in this subsection include the tropical depression stage (sustained winds less than or equal to 34 knots) before and/or after tropical cyclone formation.

Additional information on historical tropical cyclones in the Tuvalu region can be found at www.bom.gov.au/cyclone/history/tracks/index.shtml

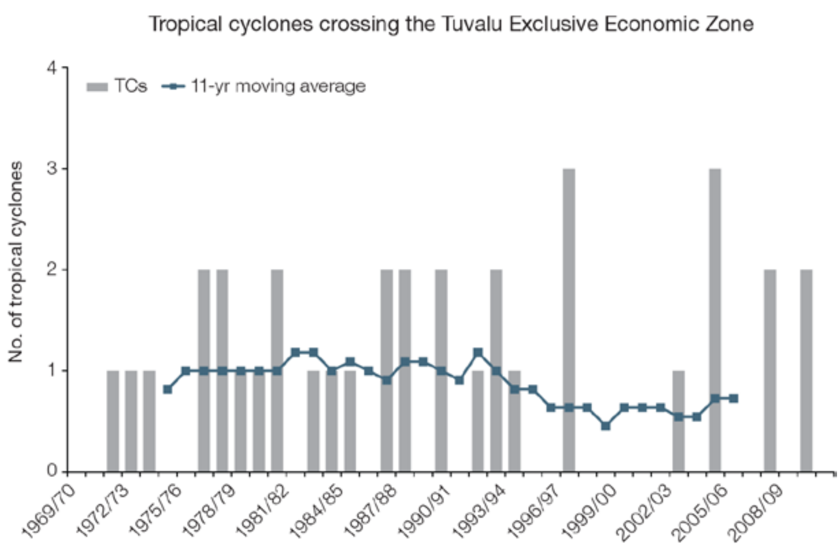

Figure 15.6: Time series of the observed number of tropical cyclones developing within and crossing the Tuvalu EEZ per season. The 11-year moving average is in blue.

15.5 Climate Projections

The performance of the available Coupled Model Intercomparison Project (Phase 5) (CMIP5) climate models over the Pacific has been rigorously assessed (Brown et al., 2013a, b; Grose et al., 2014; Widlansky et al., 2013). The simulation of the key processes and features for the Tuvalu region is similar to the previous generation of CMIP3 models, with all the same strengths and many of the same weaknesses. The best-performing CMIP5 models used here have lower biases (differences between the simulated and observed climate data) than the best CMIP3 models, and there are fewer poorly-performing models. For Tuvalu, there are two main issues that affect the confidence in climate projections. The simulated temperatures near the equator to the north are too cold compared too observations (the 'cold-tongue bias', also see Chapter 1) and therefore the region is too dry, and simulated rainfall in the SPCZ is too zonally (east-west) oriented and too wet in May–October due to the SPCZ extending too far east in this season. Also, the West Pacific Monsoon does not reach Tuvalu in the majority of CMIP5 models. These issues create biases in the mean annual rainfall and seasonal cycle of rainfall. This means there is not a single projected future for Tuvalu, but rather a range of possible futures for each emission scenario. Changes in large–scale climate features provide important contextual information for the regional climate projections (Chapter 1). Out of 27 models assessed, three models were rejected for use in these projections due to biases in the mean climate and in the simulation of the SPCZ. Climate projections have been derived from up to 24 new GCMs in the CMIP5 database (the exact number is different for each scenario, Appendix A), compared with up to 18 models in the CMIP3 database reported in Australian Bureau of Meteorology and CSIRO (2011).

15.5.1 Temperature

Further warming is expected over Tuvalu (Figure 15.7, Table 15.6). Under all RCPs, the warming is up to 1.0°C by 2030, relative to 1995, but after 2030 there is a growing difference in warming between each RCP. For example, in Tuvalu by 2090, a warming of 2.0–4.0°C is projected for RCP8.5 while a warming of 0.4–1.3°C is projected for RCP2.6. This range is broader than that presented in Australian Bureau of Meteorology and CSIRO (2011) because a wider range of emissions scenarios is considered. While relatively warm and cool years and decades will still occur due to natural variability, there is projected to be more warm years and decades on average in a warmer climate.

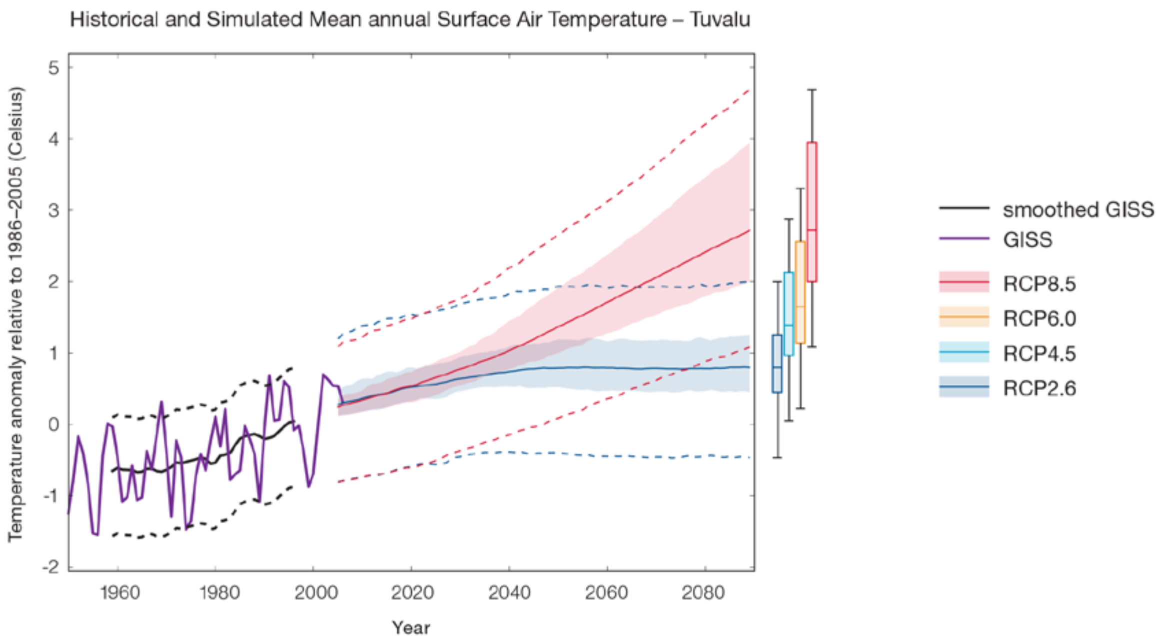

Figure 15.7: Historical and simulated surface air temperature time series for the region surrounding Tuvalu. The graph shows the anomaly (from the base period 1986–2005) in surface air temperature from observations (the GISS dataset, in purple), and for the CMIP5 models under the very high (RCP8.5, in red) and very low (RCP2.6, in blue) emissions scenarios. The solid red and blue lines show the smoothed (20-year running average) multi-model mean anomaly in surface air temperature, while shading represents the spread of model values (5–95th percentile). The dashed lines show the 5–95th percentile of the observed interannual variability for the observed period (in black) and added to the projections as a visual guide (in red and blue). This indicates that future surface air temperature could be above or below the projected long-term averages due to interannual variability. The ranges of projections for a 20-year period centred on 2090 are shown by the bars on the right for RCP8.5, 6.0, 4.5 and 2.6.

There is *very high confidence* that temperatures will rise because:

- It is known from theory and observations that an increase in greenhouse gases will lead to a warming of the atmosphere; and
- Climate models agree that the long-term average temperature will rise.

There is *medium confidence* in the model average temperature change shown in Table 15.6 because:

- The new models simulate the temperature change of the recent past in Tuvalu with reasonable accuracy; and
- Sea-surface temperatures north of Tuvalu are too cold in most CMIP5 climate models in the current climate, and this affects the projection into the future.

15.5.2 Rainfall

The CMIP5 models show a range of projected average annual rainfall change from an increase to a decrease, and the model average is near zero. The range is greater in the highest emissions scenarios (Figure 15.8, Table 15.6). Tuvalu sits between a region where rainfall is projected to increase to the north, and a region of little change or slight decrease to the south. In the November–April season and in the May–October season there is a wide spread in model projections. These results are very different from those found in Australian Bureau of Meteorology and CSIRO (2011), which reported an increase in rainfall in all seasons with *high confidence*. The range of new model results and new research into the drivers of change suggest that there is less certainty in the direction of projected change and the location of Tuvalu in relation to the regionos of increasing and decreasing rainfall than found previously.

The year-to-year rainfall variability over Tuvalu is generally larger than the projected change, except for the models with the largest projected changes in rainfall towards the end of the century. The effect of climate change on average rainfall may not be obvious in the short or medium term due to natural variability.

There is no strong agreement as to the direction of change in the models and some models project little change. This lowers the confidence that we can determine the most likely direction of change in annual rainfall, and makes the amount difficult to determine. The 5–95th percentile range of projected values from CMIP5 climate models is large, e.g. for RCP8.5 (very high emissions) the range is -1 to +9% by 2030 and -26 to +31% by 2090.

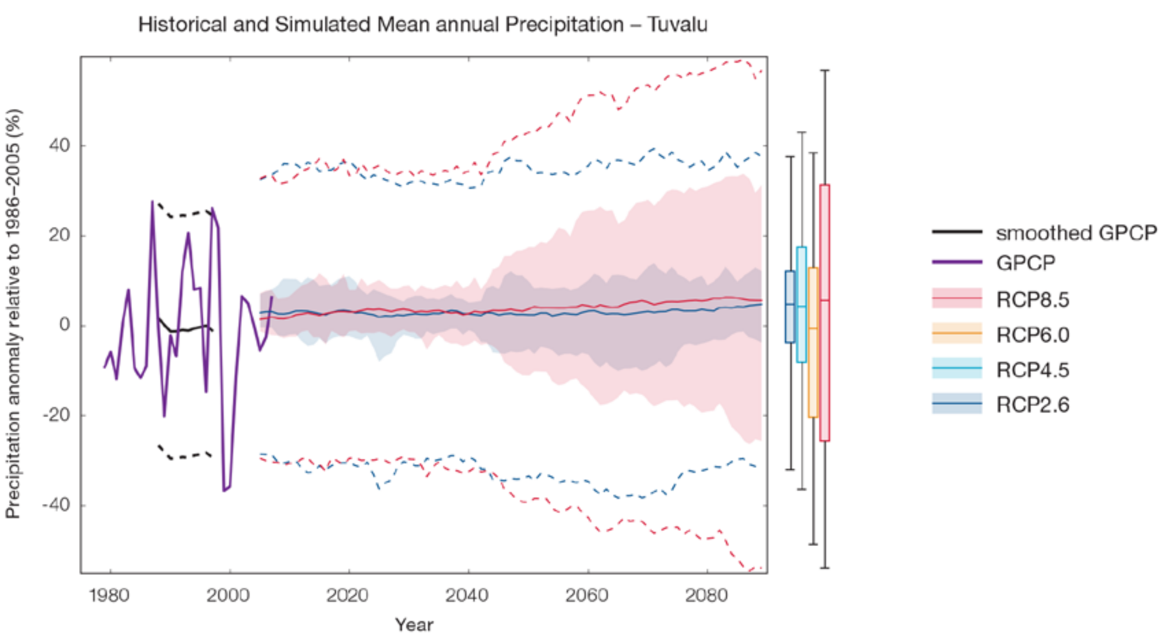

Figure 15.8: Historical and simulated annual average rainfall time series for the region surrounding Tuvalu. The graph shows the anomaly (from the base period 1986–2005) in rainfall from observations (the GPCP dataset, in purple), and for the CMIP5 models under the very high (RCP8.5, in red) and very low (RCP2.6, in blue) emissions scenarios. The solid red and blue lines show the smoothed (20-year running average) multi-model mean anomaly in rainfall, while shading represents the spread of model values (5–95th percentile). The dashed lines show the 5–95th percentile of the observed interannual variability for the observed period (in black) and added to the projections as a visual guide (in red and blue). This indicates that future rainfall could be above or below the projected long-term averages due to interannual variability. The ranges of projections for a 20-year period centred on 2090 are shown by the bars on the right for RCP8.5, 6.0, 4.5 and 2.6.

There is *low confidence* that there will be little change in average annual rainfall for Tuvalu because:

- This average finding of little change is the average of a large model spread from a projected rainfall increase to a large decrease, and also many models project little change; and
- The future of the SPCZ is not clear due to model biases in the current climate, and likewise the future behaviour of the ENSO is unclear (see Box in Chapter 1).

There is *low confidence* in the model average rainfall change shown in Table 15.6 because:

- There is a large spread in model rainfall projections, which range from a projected rainfall increase to a rainfall decrease;
- Simulated ocean temperatures are generally too cold to the north of Tuvalu, rainfall is too strong in the SPCZ to the south and the seasonal cycle of rainfall does not fully match observations for the current climate, lowering the confidence in the projections;
- The complex set of processes involved in tropical rainfall is challenging to simulate in models. This means that the confidence in the projection of rainfall is generally lower than for other variables such as temperature; and
- The future behaviour of the ENSO is unclear, and the ENSO strongly influences year-to-year rainfall variability.

15.5.3 Extremes

Extreme Temperature

The temperature on extremely hot days is projected to increase by about the same amount as average temperature. This conclusion is based on analysis of daily temperature data from a subset of CMIP5 models (Chapter 1). The frequency of extremely hot days is also expected to increase.

The temperature of the 1-in-20-year hot day is projected to increase by approximately 0.5°C by 2030 under the RCP2.6 scenario and by 0.7°C under the RCP8.5 scenario. By 2090 the projected increase is 0.7°C for RCP2.6 and 3°C for RCP8.5.

There is *very high confidence* that the temperature of extremely hot days and the temperature of extremely cool days will increase, because:

- A change in the range of temperatures, including the extremes, is physically consistent with rising greenhouse gas concentrations;
- This is consistent with observed changes in extreme temperatures around the world over recent decades (IPCC, 2012); and
- All the CMIP5 models agree on an increase in the frequency and intensity of extremely hot days and a decrease in the frequency and intensity of cool days.

There is *low confidence* in the magnitude of projected change in extreme temperature because models generally underestimate the current intensity and frequency of extreme events, especially in this area, due to the 'cold-tongue bias' (Chapter 1). Changes to the particular driver of extreme temperatures affect whether the change to extremes is more or less than the change in the average temperature, and the changes to the drivers of extreme temperatures in Tuvalu are currently unclear. Also, while all models project the same direction of change there is a wide range in the projected magnitude of change among the models.

Extreme Rainfall

The frequency and intensity of extreme rainfall events are projected to increase. This conclusion is based on analysis of daily rainfall data from a subset of CMIP5 models using a similar method to that in Australian Bureau of Meteorology and CSIRO (2011) with some improvements (Chapter 1), so the results are slightly different to those in Australian Bureau of Meteorology and CSIRO (2011). The current 1-in-20-year daily rainfall amount is projected to increase by approximately 0 mm by 2030 for RCP2.6 and by 5 mm by 2030 for RCP8.5. By 2090, it is projected to increase by approximately 7 mm for RCP2.6 and by 28 mm for RCP8.5.The majority of models project the current 1-in-20-year daily rainfall event will become, on average, a 1-in-10-year event for RCP2.6 and a 1-in-6-year event for RCP8.5 by 2090. These results are different to those found in Australian Bureau of Meteorology and CSIRO (2011) because of different methods used (Chapter 1).

There is *high confidence* that the frequency and intensity of extreme rainfall events will increase because:

- A warmer atmosphere can hold more moisture, so there is greater potential for extreme rainfall (IPCC, 2012);
- Consistent with the mixed changes in mean and extreme rainfall indices, the pattern of change in the extreme rainfalls shows considerable variation from station to station. For the lower recurrence intervals (2 and 5 years) there is little systematic change in rainfall intensity. In some contrast the very most extreme rainfall being that occurring with an average recurrence interval of 20 years shows a mean increase of 3.5%, (significant at the 10% level);
- Increases in extreme rainfall in the Pacific are projected in all available climate models; and
- An increase in extreme rainfall events within the SPCZ region was found by an in-depth study of extreme rainfall events in the SPCZ (Cai et al., 2012).

There is *low confidence* in the magnitude of projected change in extreme rainfall because:

- Models generally underestimate the current intensity of local extreme events, especially in this area due to the 'cold-tongue bias' (Chapter 1);
- Changes in extreme rainfall projected by models may be underestimated because models seem to underestimate the observed increase in heavy rainfall with warming (Min et al., 2011);
- GCMs have a coarse spatial resolution, so they do not adequately capture some of the processes involved in extreme rainfall events; and
- The Conformal Cubic Atmospheric Model (CCAM) downscaling model has finer spatial resolution and the CCAM results presented in Australian Bureau of Meteorology and CSIRO (2011) indicates a smaller increase in the number of extreme rainfall days, and there is no clear reason to accept one set of models over another.

Drought

Drought projections (defined in Chapter 1) are described in terms of changes in proportion of time in drought, frequency and duration by 2090 for very low and very high emissions (RCP2.6 and 8.5).

For Tuvalu the overall proportion of time spent in drought is expected to decrease under all scenarios. Under RCP8.5 the frequency of mild, moderate and severe drought events is expected to decrease while the frequency of extreme drought events is expected to remain stable (Figure 15.9). The duration of drought events in all categories is expected to remain stable under RCP8.5. Under RCP2.6 the frequency and duration of drought events in all categories is projected to decrease slightly. These results are similar to those found in Australian Bureau of Meteorology and CSIRO (2011), except the uncertainty related to projected rainfall change means that these drought projections have been given the rating of *low confidence*.

There is *low confidence* in this direction of change because:

- There is *low confidence* in the direction of mean rainfall change;
- These drought projections are based upon a subset of models; and
- Like the CMIP3 models, the majority of the CMIP5 models agree on this direction of change.

There is *low confidence* in the projections of drought duration and frequency because there is *low confidence* in the magnitude of rainfall projections, and no consensus about projected changes in the ENSO, which directly influence the projection of drought.

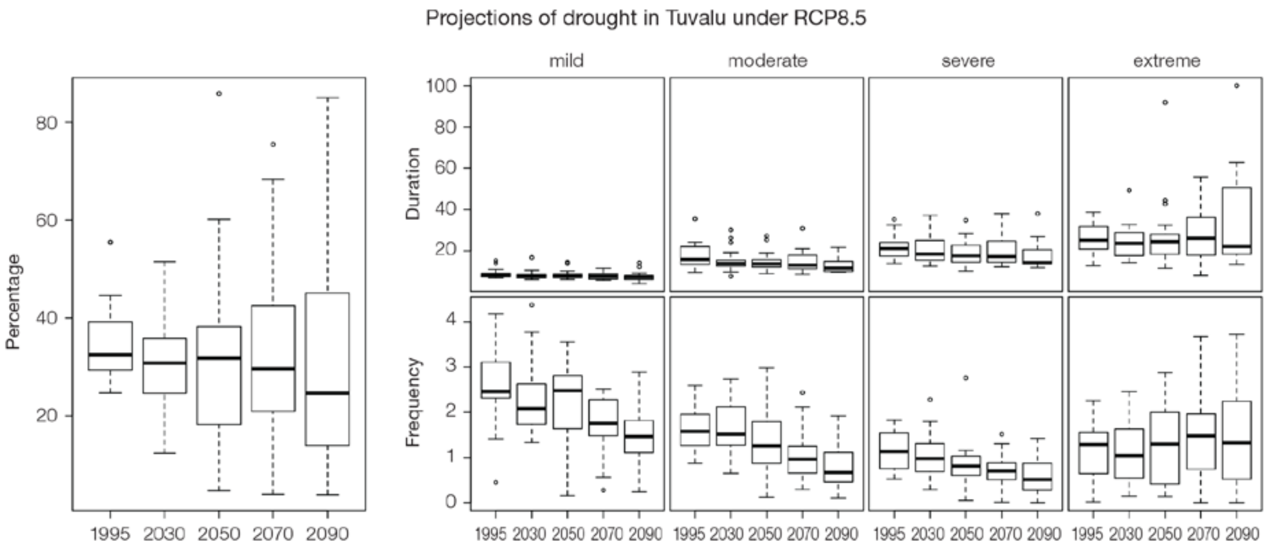

Figure 15.9: Box-plots showing percent of time in moderate, severe or extreme drought (left hand side), and average drought duration and frequency for the different categories of drought (mild, moderate, severe and extreme) for Tuvalu. These are shown for 20-year periods centred on 1995, 2030, 2050, 2070 and 2090 for the RCP8.5 (very high emissions) scenario. The thick dark lines show the median of all models, the box shows the interquartile (25–75%) range, the dashed lines show 1.5 times the interquartile range and circles show outlier results.

Tropical Cyclones

Global Picture

There is a growing level of consistency between models that on a global basis the frequency of tropical cyclones is likely to decrease by the end of the 21st century. The magnitude of the decrease varies from 6%–35% depending on the modelling study. There is also a general agreement between models that there will be an increase in the mean maximum wind speed of cyclones by between 2% and 11% globally, and an increase in rainfall rates of the order of 20% within 100 km of the cyclone centre (Knutson et al., 2010). Thus, the scientific community has a *medium* level of confidence in these global projections.

Tuvalu

In Tuvalu, the projection is for a decrease in cyclone genesis (formation) frequency for the south-east basin (see Figure 15.10 and Table 15.4). The confidence level for this projection is high. The GCMs show consistent results across models for changes in cyclone frequency for the south-east basin, using the direct detection methodologies (OWZ or CDD) described in Chapter 1. Approximately 80% of the projected changes, based on these methods, vary between a 5% decrease to a 50% decrease in genesis frequency with half projecting a decrease between 20 and 40%. The empirical techniques assess changes in the main atmospheric ingredients known to be necessary for cyclone formation. Projections based upon these techniques suggest the conditions for cyclone formation will become less favourable in this region with about half of projected changes indicating decreases between 10 and 40% in genesis frequency. These projections are consistent with those of Australian Bureau of Meteorology and CSIRO (2011).

Table 15.4 Projected percentage change in cyclone frequency in the south-east basin (0–40°S; 170 °E–130°W) for 22 CMIP5 climate models, based on five methods, for 2080–2099 relative to 1980–1999 for RCP8.5 (very high emissions). The 22 CMIP5 climate models were selected based upon the availability of data or on their ability to reproduce a current-climate tropical cyclone climatology (See Section 1.5.3 – Detailed Projection Methods, Tropical Cyclones). Blue numbers indicate projected decreases in tropical cyclone frequency, red numbers an increase. MMM is the multi-model mean change. N increase is the proportion of models (for the individual projection method) projecting an increase in cyclone formation.

Model	GPI change	GPI-M change	Tippett	CDD	OWZ
access10	5	-22	-54	-23	
access13	-26	-26	-36	-10	
bcccsm11	-3	-1	-28		-5
canesm2	-7	-13	-49	-6	
ccsm4				-78	-5
cnrm_cm5	-4	-5	-26	8	7
csiro_mk36	-16	-13	-33	-26	-27
fgoals_g2	6	-8	-40		
fgoals_s2	-15	-20	-48		
gfdl_esm2m				-48	-36
gfdl_cm3	-1	-5	-25		-11
gfdl_esm2g				-18	-36
gisse2r	17	16	-6		
hadgem2_es	-8	-11	-51		
Inm	-3	-3	-30		
ipslcm5alr	-13	-19	-43		
ipslcm5blr				7	
miroc5				-43	-22
mirocesm	-40	-38	46		
mpim	-26	-19	-41		
mricgcm3	-8	-10	-28		
noresm1m	-36	-40	-59	-80	
MMM	-11	-14	-32	-29	-17
N increase	0.2	0.1	0.1	0.2	0.125

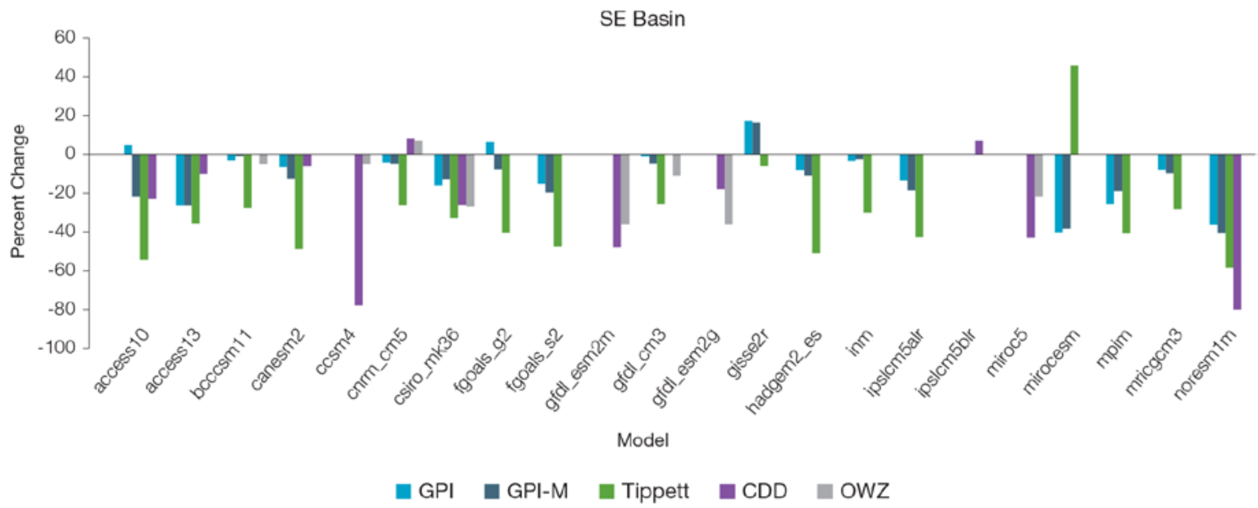

Figure 15.10: Projected percentage change in cyclone frequency in the south-east basin (data from Table 15.4).

15.5.4 Coral Reefs and Ocean Acidification

As atmospheric CO_2 concentrations continue to rise, oceans will warm and continue to acidify. These changes will impact the health and viability of marine ecosystems, including coral reefs that provide many key ecosystem services (*high confidence*). These impacts are also likely to be compounded by other stressors such as storm damage, fishing pressure and other human impacts.

The projections for future ocean acidification and coral bleaching use three RCPs (2.6, 4.5, and 8.5).

Ocean Acidification

In Tuvalu the aragonite saturation state has declined from about 4.5 in the late 18th century to an observed value of about 4.0±0.1 by 2000 (Kuchinke et al., 2014). All models show that the aragonite saturation state, a proxy for coral reef growth rate, will continue to decrease as atmospheric CO_2 concentrations increase (*very high confidence*). Projections from CMIP5 models indicate that under RCPs 8.5 and 4.5 the median aragonite saturation state will transition to marginal conditions (3.5) around 2030. In RCP8.5 the aragonite saturation state continues to strongly decline thereafter to values where coral reefs have not historically been found (< 3.0). Under RCP4.5 the aragonite saturation plateaus around 3.2 i.e. marginal conditions for healthy coral reefs. While under RCP2.6 the median aragonite saturation state never falls below 3.5, and increases slightly toward the end of the century (Figure 15.11) suggesting that the conditions remains adequate for healthy corals reefs. There is *medium confidence* in this range and distribution of possible futures because the projections are based on climate models that do not resolve the reef scale that can play a role in modulating large-scale changes. The impacts of ocean acidification are also likely to affect the entire marine ecosystem impacting the key ecosystem services provided by reefs.

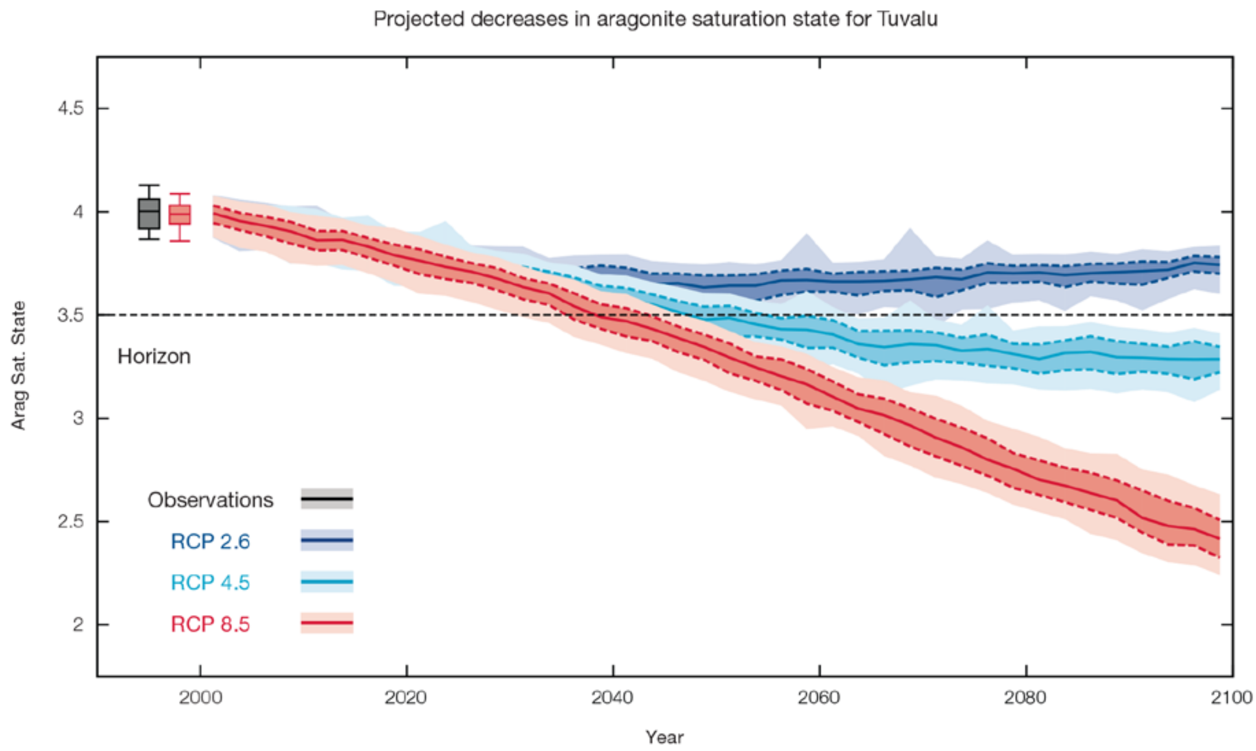

Figure 15.11: Projected decreases in aragonite saturation state in Tuvalu from CMIP5 models under RCP2.6, 4.5 and 8.5. Shown are the median values (solid lines), the interquartile range (dashed lines), and 5% and 95% percentiles (light shading). The horizontal line represents the transition to marginal conditions for coral reef health (from Guinotte et al., 2003).

Coral Bleaching Risk

As the ocean warms, the risk of coral bleaching increases (*very high confidence*). There is *medium confidence* in the projected rate of change for Tuvalu because there is *medium confidence* in the rate of change of SST, and the changes at the reef scale (which can play a role in modulating large-scale changes) are not resolved. Importantly, the coral bleaching risk calculation does not account the impact of other potential stressors (Chapter 1).

The changes in the frequency (or recurrence) and duration of severe bleaching risk are quantified for different projected sea-surface temperature (SST) changes (Table 15.5). Overall there is a decrease in the time between two periods of elevated risk and an increase in the duration of the elevated risk. For example, under a long-term mean increase of 1°C (relative to 1982–1999 period), the average severe bleaching risk event will last 10.5 weeks (with a minimum duration of 1.4 weeks and a maximum duration of 7.7 months) and the average time between two risks will be 1.3 years (with the minimum recurrence of 0.9 months and a maximum recurrence of 4.6 years). If severe bleaching events occur more often than once every five years, the long-term viability of coral reef ecosystems becomes threatened.

15.5.5 Sea Level

Mean sea level is projected to continue to rise over the course of the 21st century. There is *very high confidence* in the direction of change. The CMIP5 models simulate a rise of between approximately 7–18 cm by 2030 (very similar values for different RCPs), with increases of 39–87 cm by 2090 under the RCP8.5 (Figure 15.12 and Table 15.6). There is *medium confidence* in the range mainly because there is still uncertainty associated with projections of the Antarctic ice sheet contribution. Interannual variability of sea level will lead to periods of lower and higher regional sea levels. In the past, this interannual variability has been about 26 cm (5–95% range, after removal of the seasonal signal, see dashed lines in Figure 15.12 (a) and it is likely that a similar range will continue through the 21st century.

Table 15.5: The impacts of increasing SST on severe coral bleaching risk for the Tuvalu EEZ.

Temperature change [1]	Recurrence interval [2]	Duration of the risk event [3]
Change in observed mean	0	0
+0.25°C	30 years	4.2 weeks
+0.5°C	19.1 years (14.6 years – 24.6 years)	7.0 weeks (5.2weeks – 9.0 weeks)
+0.75°C	4.3 years (6.7 months – 10.3 years)	8.7 weeks (2.4 weeks – 4.3 months)
+1°C	1.3 years (0.9 months – 4.6 years)	10.5 weeks (1.4 weeks – 7.7months)
+1.5°C	6.8 months (0.8 months – 2.3 years)	5.8 months (1.7 weeks – 2.1 years)
+2°C	2.9 months (0.8 months – 6.6 months)	8.4 months (3.3 weeks – 6.6 years)

[1] This refers to projected SST anomalies above the mean for 1982–1999.

[2] Recurrence is the mean time between severe coral bleaching risk events. Range (min – max) shown in brackets.

[3] Duration refers to the period of time where coral are exposed to the risk of severe bleaching. Range (min – max) shown in brackets.

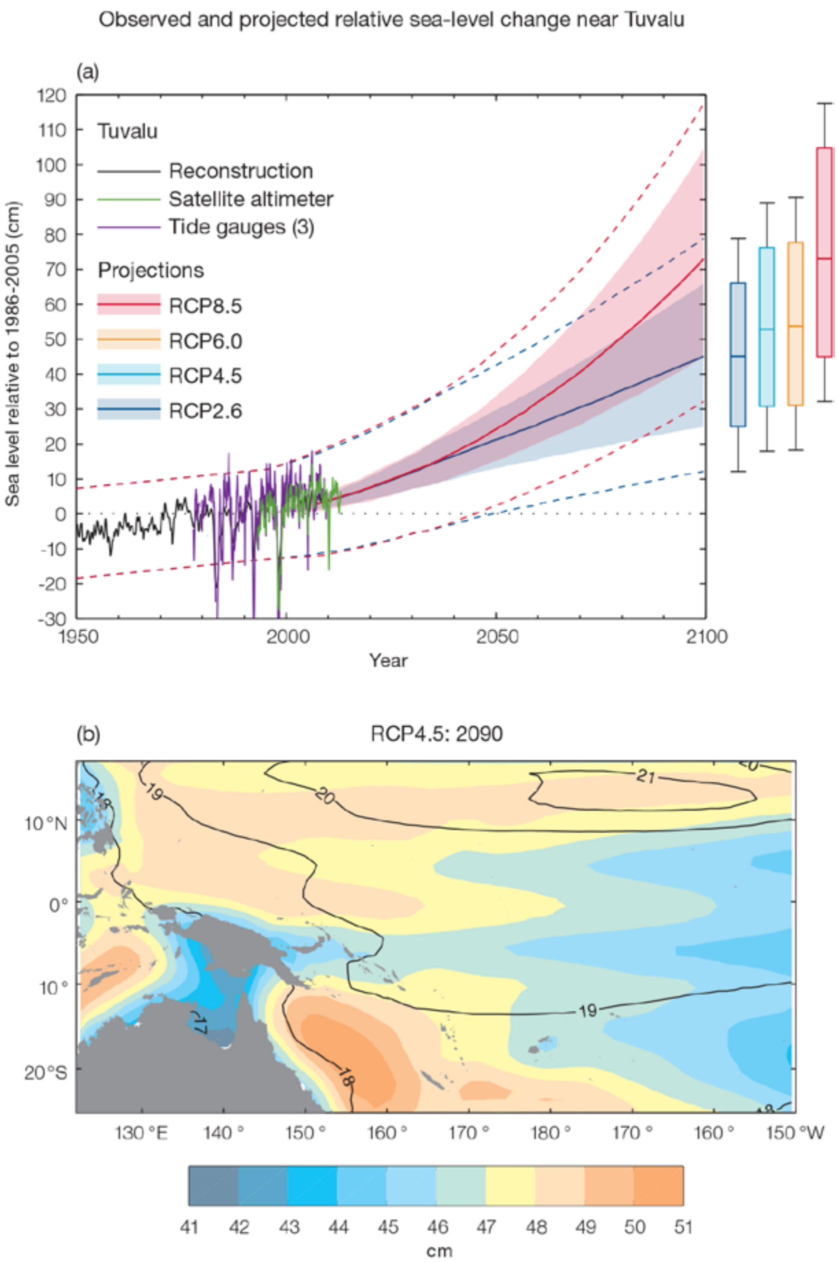

Figure 15.12: (a) The observed tide-gauge records of relative sea-level (since the late 1970s) are indicated in purple, and the satellite record (since 1993) in green. The gridded (reconstructed) sea level data at Tuvalu (since 1950) is shown in black. Multi-model mean projections from 1995–2100 are given for the RCP8.5 (red solid line) and RCP2.6 emissions scenarios (blue solid line), with the 5–95% uncertainty range shown by the red and blue shaded regions. The ranges of projections for four emission scenarios (RCPs 2.6, 4.5, 6.0 and 8.5) by 2100 are also shown by the bars on the right. The dashed lines are an estimate of interannual variability in sea level (5–95% uncertainty range about the projections) and indicate that individual monthly averages of sea level can be above or below longer-term averages.

(b) The regional distribution of projected sea level rise under the RCP4.5 emissions scenario for 2081–2100 relative to 1986–2005. Mean projected changes are indicated by the shading, and the estimated uncertainty in the projections is indicated by the contours (in cm).

15.5.6 Wind-driven Waves

During December–March, a small decrease in wave height is projected (significant in December, February and March in 2090 under RCP8.5, January in 2090 under RCP4.5 and February in 2035 under RCP8.5) (Figure 15.13), with a possible but non-significant decrease in wave period, and a small clockwise rotation in mean wave direction toward the east, with a suggested increase in waves from the north also, associated with cyclones, in 2090 under the RCP8.5 scenario *(low confidence)* (Table 15.7). No change is projected in the larger storm waves *(low confidence)*.

In June–September, there are no statistically significant projected changes in wave properties *(low confidence)* (Table 15.7). Non-significant changes include an increase in wave height. An increase in the height of larger waves is suggested *(low confidence)*.

There is *low confidence* in projected changes in the Tuvalu wind-wave climate because:

- Projected changes in wave climate are dependent on confidence of projected changes in the ENSO, which is low; and
- The difference between simulated and observed (hindcast) wave data can be larger than the projected wave changes, which further reduces our confidence in projections.

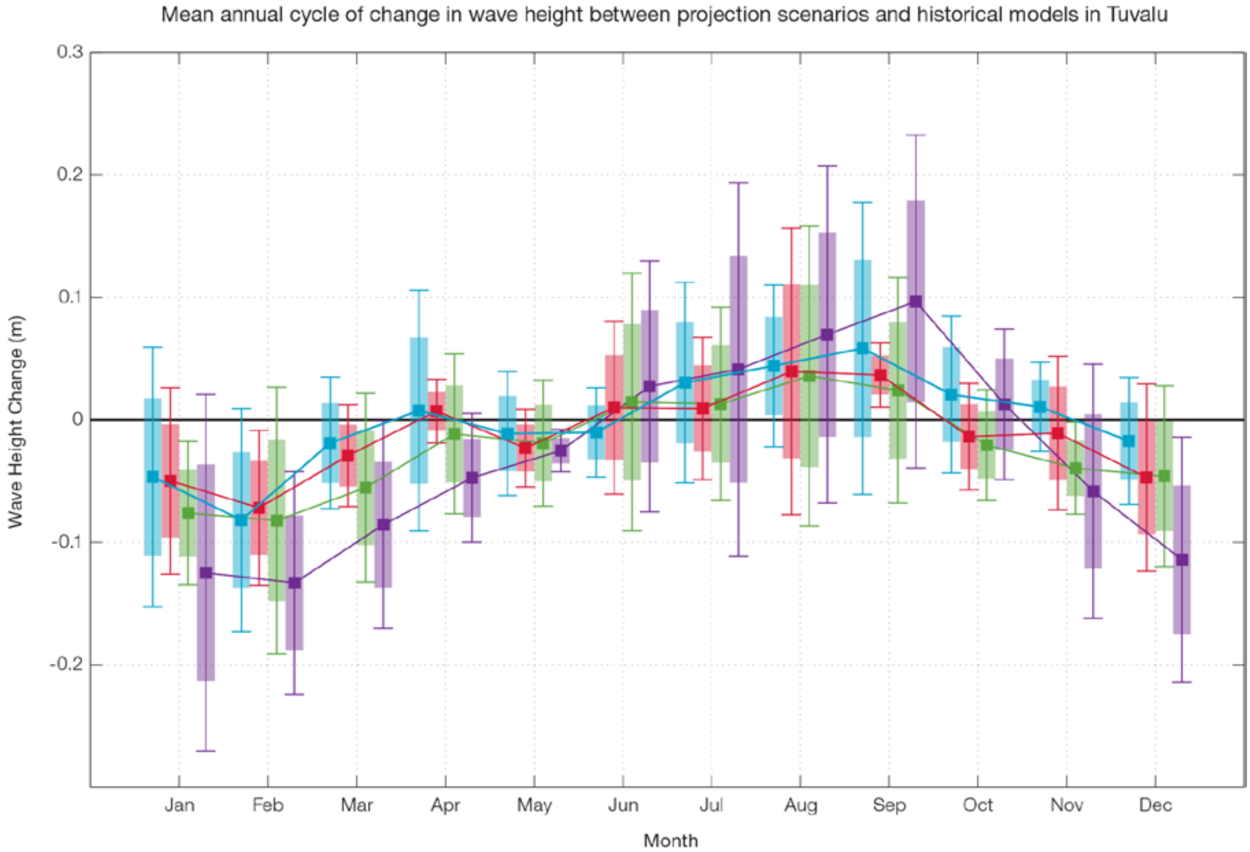

Figure 15.13: Mean annual cycle of change in wave height between projection scenarios and mean of historical models in Tuvalu. This panel shows a small decrease in wave heights in the wet season months (statistically significant in 2090 RCP8.5 (very high emissions) in December, February and March, in January in 2090 under RCP4.5 and February in 2035 under RCP8.5, very high emissions), with no statistically significant change in the dry season months but a suggested increase in wave heights. Shaded boxes show 1 standard deviation of models' means around the ensemble means, and error bars show the 5–95% range inferred from the standard deviation. Colours represent RCP scenarios and time periods: blue 2035 RCP4.5 (low emissions), red 2035 RCP8.5 (very high emissions), green 2090 RCP4.5 (low emissions), purple 2090 RCP8.5 (very high emissions).

15.5.7 Projections Summary

There is *very high confidence* in the direction of long-term change in a number of key climate variables, namely an increase in mean and extremely high temperatures, sea level and ocean acidification. There is *high confidence* that the frequency and intensity of extreme rainfall will increase. However, it is unclear whether average annual rainfall and drought frequency will increase, decrease or stay similar to the current climate.

Tables 15.6 and 15.7 quantify the mean changes and ranges of uncertainty for a number of variables, years and emissions scenarios. A number of factors are considered in assessing confidence, i.e. the type, amount, quality and consistency of evidence (e.g. mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement, following the IPCC guidelines (Mastrandrea et al., 2010). Confidence ratings in the projected magnitude of mean change are generally lower than those for the direction of change (see paragraph above) because magnitude of change is more difficult to assess. For example, there is *very high confidence* that temperature will increase, but *medium confidence* in the magnitude of mean change.

Table 15.6: Projected changes in the annual and seasonal mean climate for Tuvalu under four emissions scenarios; RCP2.6 (very low emissions, in dark blue), RCP4.5 (low emissions, in light blue), RCP6 (medium emissions, in orange) and RCP8.5 (very high emissions, in red). Projected changes are given for four 20-year periods centred on 2030, 2050, 2070 and 2090, relative to a 20-year period centred on 1995. Values represent the multi-model mean change, with the 5–95% range of uncertainty in brackets. Confidence in the magnitude of change is expressed as *high*, *medium* or *low*. Surface air temperatures in the Pacific are closely related to sea-surface temperatures (SST), so the projected changes to air temperature given in this table can be used as a guide to the expected changes to SST. (See also Section 1.5.2). 'NA' indicates where data are not available.

Variable	Season	2030	2050	2070	2090	Confidence (magnitude of change)
Surface air temperature (°C)	Annual	0.6 (0.5–0.9)	0.8 (0.5–1.2)	0.8 (0.5–1.2)	0.8 (0.4–1.3)	*Medium*
		0.7 (0.5–1)	1 (0.7–1.4)	1.3 (0.9–1.8)	1.4 (1–2.1)	
		0.6 (0.4–0.9)	0.9 (0.6–1.4)	1.3 (0.9–2)	1.7 (1.1–2.6)	
		0.8 (0.5–1)	1.4 (1–1.9)	2.1 (1.5–3.1)	2.8 (2–4)	
Maximum temperature (°C)	1-in-20 year event	0.5 (-0.1–0.8)	0.7 (0.1–1.1)	0.7 (-0.1–1.1)	0.7 (-0.1–1.1)	*Medium*
		0.6 (-0.1–0.9)	0.9 (0.1–1.3)	1.2 (0.4–1.8)	1.3 (0.6–2)	
		NA (NA–NA)	NA (NA–NA)	NA (NA–NA)	NA (NA–NA)	
		0.7 (0.1–1.1)	1.4 (0.5–2)	2.2 (0.7–3.1)	2.9 (1.4–4.2)	
Minimum temperature (°C)	1-in-20 year event	0.6 (0.3–0.8)	0.7 (0.2–1)	0.8 (0.4–1)	0.8 (0.4–0.9)	*Medium*
		0.6 (0.4–0.8)	0.9 (0.5–1.3)	1.1 (0.8–1.5)	1.3 (1–1.9)	
		NA (NA–NA)	NA (NA–NA)	NA (NA–NA)	NA (NA–NA)	
		0.8 (0.4–1)	1.5 (1–2.1)	2.2 (1.6–3.3)	3 (2.2–4)	
Total rainfall (%)	Annual	2 (-2–5)	3 (-6–11)	3 (-10–12)	5 (-4–12)	*Low*
		4 (-2–12)	3 (-3–10)	6 (-5–15)	4 (-8–18)	
		4 (-4–10)	3 (-6–8)	1 (-10–8)	-1 (-20–13)	
		4 (-1–9)	3 (-11–17)	6 (-15–28)	6 (-26–31)	
Total rainfall (%)	Nov-Apr	2 (-5–7)	3 (-6–10)	4 (-10–13)	6 (-6–15)	*Low*
		4 (-3–11)	3 (-7–11)	6 (-4–14)	4 (-10–15)	
		4 (-4–10)	4 (-8–11)	1 (-13–11)	2 (-21–15)	
		4 (-4–10)	4 (-16–16)	7 (-18–24)	8 (-25–36)	
Total rainfall (%)	May-Oct	3 (-2–8)	2 (-5–14)	2 (-8–14)	4 (-2–17)	*Low*
		3 (-1–13)	4 (-3–15)	5 (-3–21)	4 (-7–19)	
		5 (-3–16)	3 (-4–15)	0 (-9–10)	-3 (-18–8)	
		3 (-1–11)	3 (-9–17)	4 (-15–30)	3 (-26–24)	
Aragonite saturation state (Ωar)	Annual	-0.3 (-0.6–0.0)	-0.4 (-0.7–0.0)	-0.4 (-0.7–0.0)	-0.3 (-0.7–0.0)	*Medium*
		-0.3 (-0.7–0.0)	-0.5 (-0.9–-0.2)	-0.7 (-1.0–-0.4)	-0.7 (-1.1–-0.4)	
		NA (NA–NA)	NA (NA–NA)	NA (NA–NA)	NA (NA–NA)	
		-0.4 (-0.7–-0.1)	-0.7 (-1.0–-0.4)	-1.1 (-1.4–-0.8)	-1.5 (-1.8–-1.1)	
Mean sea level (cm)	Annual	12 (7–17)	21 (13–30)	31 (19–44)	41 (23–59)	*Medium*
		12 (7–17)	22 (13–31)	34 (20–48)	47 (28–67)	
		12 (7–16)	21 (13–29)	33 (20–47)	48 (28–67)	
		12 (7–18)	24 (16–34)	41 (26–57)	62 (39–87)	

Waves Projections Summary

Table 15.7: Projected average changes in wave height, period and direction in Tuvalu for December–March and June–September for RCP4.5 (low emissions, in blue) and RCP8.5 (very high emissions, in red), for two 20-year periods (2026–2045 and 2081–2100), relative to a 1986–2005 historical period. The values in brackets represent the 5th to 95th percentile range of uncertainty.

Variable	Season	2035	2090	Confidence (range)
Wave height change (m)	December–March	-0.0 (-0.1–0.1) -0.0 (-0.2–0.1)	-0.1 (-0.2–0.0) -0 1 (-0.2–-0.0)	*Low*
	June–September	+0.0 (-0.2–0.2) +0.0 (-0.2–0.2)	+0.0 (-0.2–0.3) +0.1 (-0.2–0.3)	*Low*
Wave period change (s)	December–March	-0.0 (-1.1–1.2) -0.1 (-1.2–1.1)	-0.1 (-1.4–1.4) -0.1 (-1.6–1.4)	*Low*
	June–September	+0.0 (-1.1–1.1) +0.0 (-1.1–1.4)	+0.0 (-1.3–1.4) 0.0 (-1.4–1.4)	*Low*
Wave direction change (° clockwise)	December–March	+0 (-20–20) 0 (-20–20)	0 (-20–20) +0 (-20–20)	*Low*
	June–September	+0 (-10–10) 0 (-10–10)	+0 (-10–10) +0 (-10–10)	*Low*

Wind-wave variables parameters are calculated for a 20-year period centred on 2035.