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Chapter 11

Papua New Guinea

11.1 Climate Summary

11.1.1 Current Climate

- Annual and half-year air temperatures at Port Moresby and Kavieng have been warming since 1943 and 1962 respectively. Minimum air temperature trends are stronger than maximum air temperature trends.
- Warm temperature extremes have increased and cool temperature extremes have decreased at both sites. All temperature trends are consistent with global warming.
- At Kavieng, there has been a decrease in the number of days with rainfall since 1957. The remaining annual, half-year and extreme rainfall trends show little change at Kavieng and Port Moresby.
- Tropical cyclones affect the Southern Hemisphere portion of Papau New Guinea, mainly between November and April. An average of 15 cyclones per decade developed within or crossed the Papua New Guinea Exclusive Economic Zone (EEZ) between the 1969/70 and 2010/11 seasons. Eleven of the 43 tropical cyclones (26%) between the 1981/82 and 2010/11 seasons were severe events (Category 3 or stronger) in the Papua New Guinea EEZ. Available data are not suitable for assessing long-term trends.
- Wind-waves around Papua New Guinea are typically not large, with markedly different behaviour on the north and south coasts. Waves are seasonally influenced by the trade winds, the West Pacific Monsoon (WPM) and location of the Inter-Tropical Convergence Zone (ITCZ), and display variability on interannual time scales with the El Niño–Southern Oscillation (ENSO). Available data are not suitable for assessing long-term trends.

11.1.2 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*);
- Average rainfall is projected to increase in most areas (*medium confidence*), along with more extreme rain events (*high confidence*);
- Droughts are projected to decline in frequency (*medium 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
- No changes in waves along the Coral Sea coast of Papua New Guinea are projected *(low confidence)*. On the northern coasts, December–March wave heights and periods are projected to decrease *(low confidence)*.

11.2 Data Availability

There are currently 39 operational meteorological stations in Papua New Guinea. Multiple observations within a 24-hour period are taken at 18 stations: four synoptic stations in Momase, two in the Highlands, six in the Southern region and six in the New Guinea Islands. In addition, there are three single observation climate stations and 18 single observation rainfall stations. The primary climate station, Port Moresby Weather Office, is located at Jacksons Airport near Port Moresby. Rainfall data for Port Moresby are available from 1890, and are largely complete from 1905.

Air temperature data are available from 1939. Madang, Wewak, Misima, Kavieng and Momote have more than 50 years of rainfall data. Port Moresby rainfall data from 1945 and air temperature data from 1943, and Kavieng (an island to the north-east) rainfall data from 1957 and air temperature from 1962 have been used in this report. Even though recent temperature data are patchy, both temperature and rainfall records are homogeneous. Additional information on historical climate trends in the Papua New Guinea 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.

11.3 Seasonal Cycles

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

11.3.1 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 Papua New Guinea shows strong spatial variability. On the south coast (e.g. south of Port Moresby), waves are predominantly directed from the south-east throughout the year, but display strong seasonal variability of magnitude with the Southern Hemisphere trade winds and monsoon winds. During June–September, mean waves are largest (seasonal mean height around 1.4 m) (Table 11.1), consisting of trade wind generated waves from the south-east, and a small component of swell propagated from storm events in the Tasman Sea and in the south. During the wetter months of December–March, mean waves reach a minimum (seasonal mean height around 0.8 m) (Figure 11.1) and are directed from the south with some locally generated monsoonal westerly waves. Waves larger than 2.3 m (99th percentile) at Port Moresby occur predominantly during the dry months, usually directed from the south, with some large westerly and south-westerly waves observed during the monsoon season. The height of a 1-in-50 year wave event near Port Moresby is calculated to be 4.1 m.

On the northern coast (e.g. Kavieng), waves are characterised by variability of trade winds and monsoon systems. During December–March, waves near Kavieng have slightly higher magnitude (mean height around 1.4 m) and a longer period (around 9.3 s) than the annual mean (Table 11.1). These waves consist of local monsoon-generated westerly waves, and north-easterly swell generated by trade winds and northern Pacific extra-tropical storms. During June–September, the observed easterly waves are typically generated locally by trade winds with north-easterly swell, and are smaller (mean height around 0.9 m) and of shorter period (about 7.3 s) than the annual mean (Figure 11.2). Waves larger than 2.0 m (99th percentile) occur in December–March from the north-west to north-east due to tropical storms. Some large easterly and north-easterly waves are seen in the dry months. The height of a 1-in-50 year wave event at Kavieng is calculated to be 3.0 m.

No suitable dataset is available to assess long-term historical trends in the Papua New Guinea wave climate, but interannual variability may be assessed in the hindcast record. The wind-wave climate displays strong interannual variability on the north coast of Papua New Guinea (near Kavieng), varying strongly with the El Niño–Southern Oscillation (ENSO). Wave power is much greater during La Niña years than El Niño years in June–September, with waves more strongly directed from the east in both December–March and June–September, associated with increased trade wind strength and changed monsoonal influence in the wet season. The ENSO variability of wave climate on the south coast (e.g. near Port Moresby) is less prominent.

Table 11.1: Mean wave height, period and direction from which the waves are travelling around Papua New Guinea 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 11.5.6 – Wind-driven waves, and Tables 11.7 and 11.8). A compass relating number of degrees to cardinal points (direction) is shown.

		Hindcast Reference Data (1979–2009), Port Moresby	Climate Model Simulations (1986–2005), Coral Sea region	Hindcast Reference Data (1979–2009), Kavieng	Climate Model Simulations (1986–2005), North coast region
Wave Height (metres)	December–March	0.8 (0.3–1.5)	0.4 (0.3–0.6)	1.4 (1.0–1.9)	1.1 (0.9–1.3)
	June–September	1.4 (0.7–2.1)	0.8 (0.5–1.0)	0.9 (0.5–1.4)	0.8 (0.5–1.1)
Wave Period (seconds)	December–March	6.9 (4.7–9.5)	5.9 (4.7–7.1)	9.3 (7.5–11.2)	8.2 (7.2–9.2)
	June–September	6.7 (5.2–8.3)	5.7 (5.0–6.4)	7.3 (5.5–9.3)	5.6 (4.8–6.7)
Wave Direction (degrees clockwise from North)	December–March	180 (140–270)	160 (150–210)	30 (0–50)	30 (10–50)
	June–September	160 (150–170)	150 (145–160)	60 (20–90)	110 (60–160)

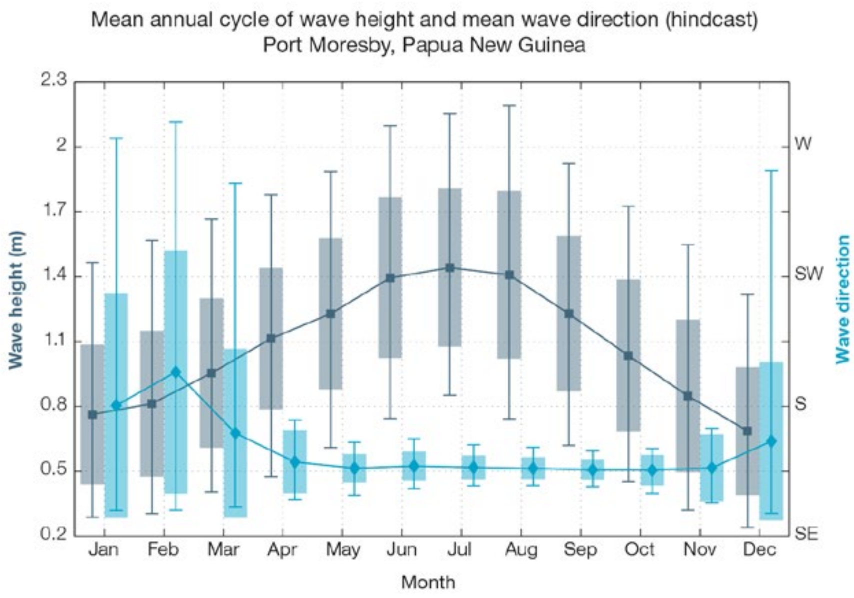

Figure 11.1: Mean annual cycle of wave height (grey) and mean wave direction (blue) at Port Moresby in hindcast data (1979–2009). To give an indication of interannual variability of the monthly means of the hindcast data, shaded boxes show 1 standard deviation around the monthly means, and error bars show the 5–95% range. The direction from which the waves are travelling is shown (not the direction towards which they are travelling).

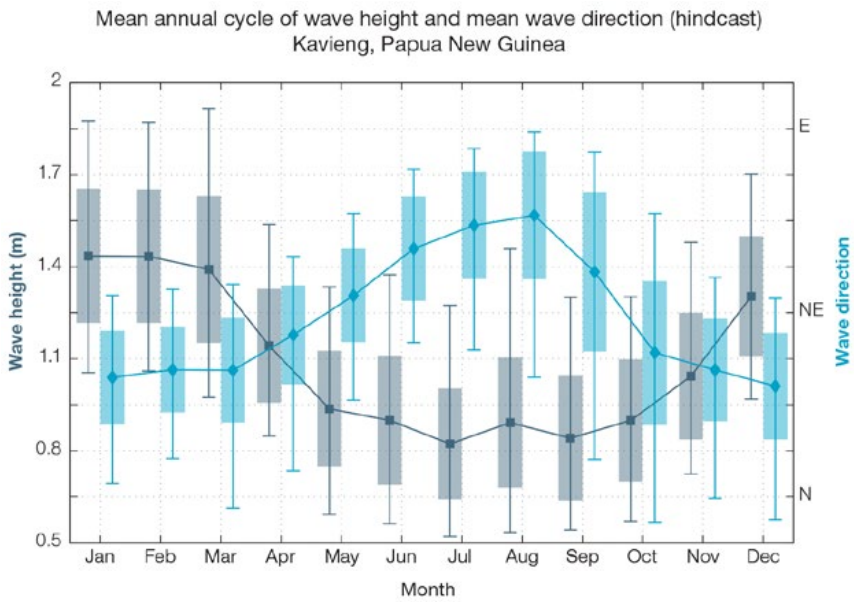

Figure 11.2: Mean annual cycle of wave height (grey) and mean wave direction (blue) at Kavieng in hindcast data (1979–2009). To give an indication of interannual variability of the monthly means of the hindcast data, shaded boxes show 1 standard deviation around the monthly means, and error bars show the 5–95% range. The direction from which the waves are travelling is shown (not the direction towards which they are travelling).

11.4 Observed Trends

11.4.1 Air Temperature

Annual and Half-year Mean Air Temperature

Trends in annual and half-year mean air temperatures at Port Moresby and Kavieng from 1943 and 1962 respectively are positive and shown in Figure 11.3, Figure 11.4 and Table 11.2 (where data are available). Minimum temperature trends are stronger than maximum temperature trends at Port Moresby.

Extreme Air Temperature

Warming trends are also evident in the extreme indices (Table 11.3). The annual number of Warm Days and Warm Nights has significantly increased (5% level) at Port Moresby and Kavieng (Figure 11.5). There have also been significant decreases in the annual number of Cool Days and Cool Nights at both sites (Figure 11.5). Trends in night-time extreme temperatures are stronger than day-time extremes at Port Moresby.

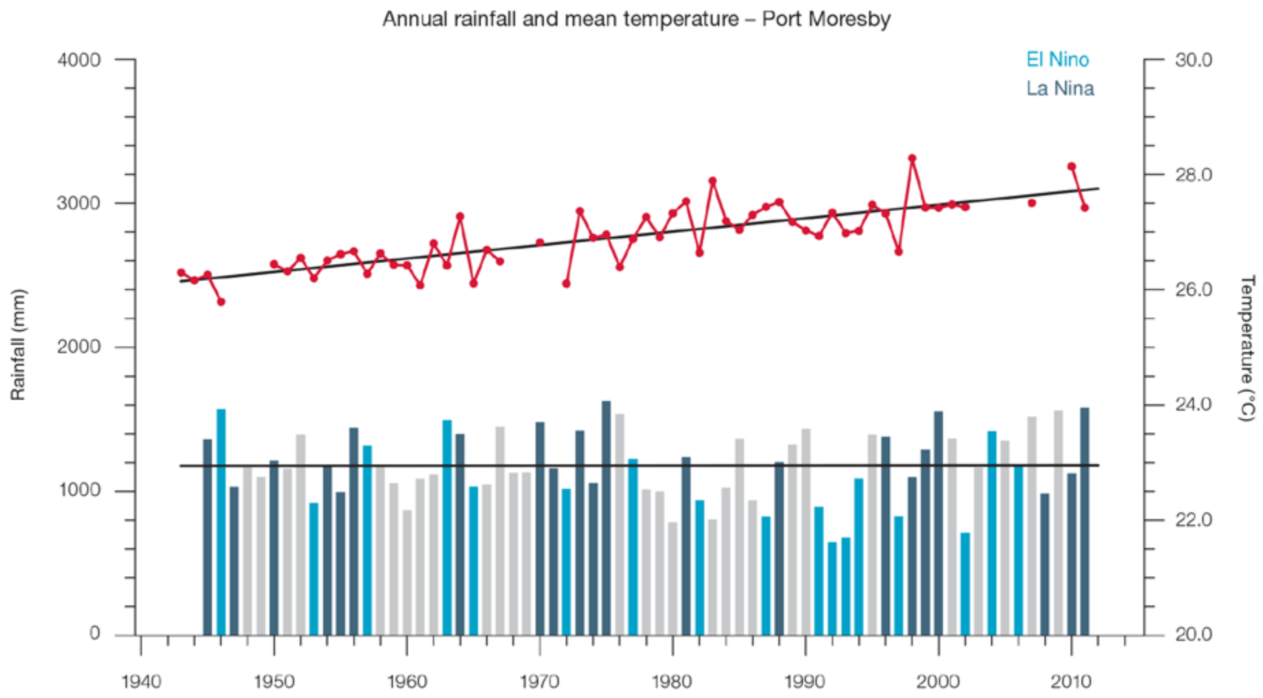

Figure 11.3: Observed time series of annual average values of mean air temperature (red dots and line) and total rainfall (bars) at Port Moresby. Light blue, dark blue and grey bars denote El Niño, La Niña and neutral years respectively. Solid black trend lines indicate a least squares fit.

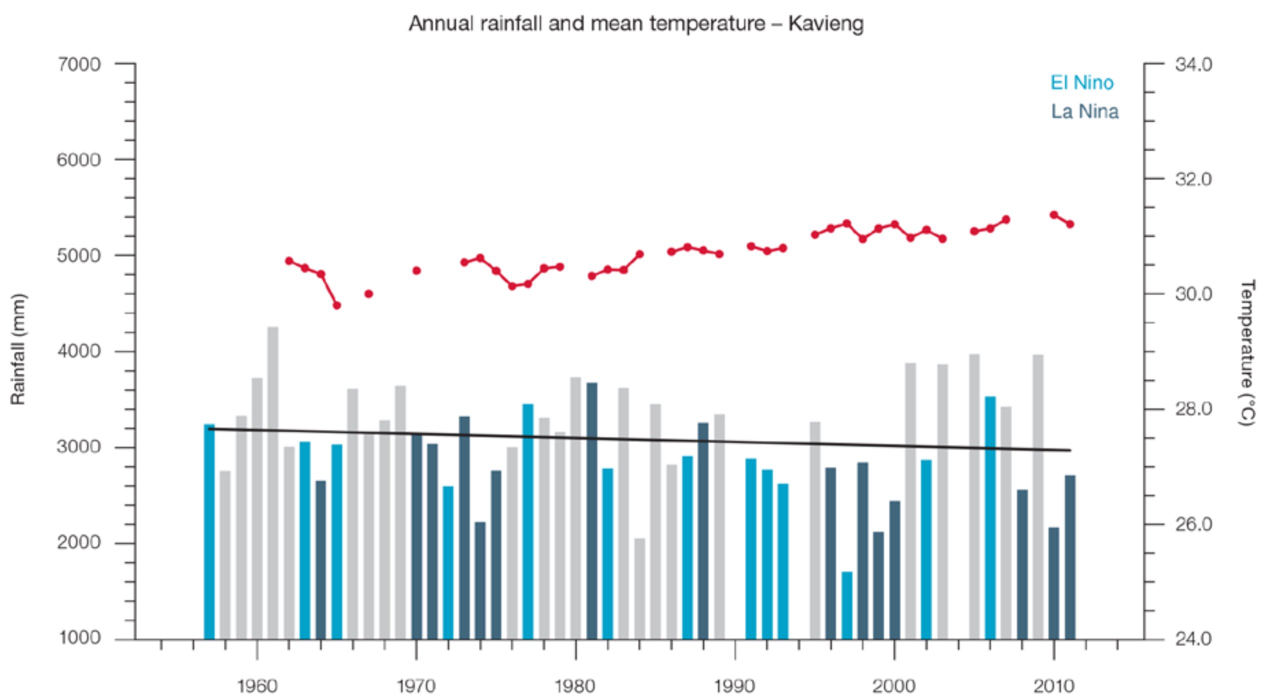

Figure 11.4: Observed time series of annual average values of mean air temperature (red dots and line) and total rainfall (bars) at Kavieng. Light blue, dark blue and grey bars denote El Niño, La Niña and neutral years respectively. Solid black trend lines indicate a least squares fit. The trend line for mean temperature is not presented as more than 20% of the record is missing.

Table 11.2: Annual and seasonal trends in air temperature and rainfall at Port Moresby (top) and Kavieng (bottom). The 95% confidence intervals are shown in brackets. Values for trends significant at the 5% level are shown in **boldface**. A dash (-) indicates insufficient data for calculating trends.

Port Moresby	**Tmax (°C/10yrs)**	**Tmin (°C/10yrs)**	**Tmean (°C/10yrs)**	**Total Rain (mm/10yrs)**
		1943–2011		**1945–2011**
Annual	**+0.13** (+0.07, +0.19)	**+0.30** (+0.10, +0.46)	**+0.22** (+0.10, +0.32)	+5.3 (-39.3, +45.6
Nov–Apr	**+0.16** (+0.09, +0.22)	**+0.31** (+0.27, +0.36)	**+0.24** (+0.19, +0.28)	+1.8 (-31.6, +32.7)
May–Oct	**+0.11** (+0.05, +0.18)	**+0.27** (+0.10, +0.45)	**+0.20** (+0.09, +0.30)	+1.1 (-14.0, +15.8)

Kavieng	**Tmax (°C/10yrs)**	**Tmin (°C/10yrs)**	**Tmean (°C/10yrs)**	**Total Rain (mm/10yrs)**
		1962–2011		**1957–2011**
Annual	-	**+0.43** (+0.37, +0.47)	-	-56.4 (-148.5, +52.2)
Nov–Apr	-	**+0.38** (+0.29, +0.47)	-	-57.5 (-142.8, +8.3)
May–Oct	**+0.23** (+0.14, +0.33)	**+0.41** (+0.36, +0.47)	-	+7.2 (-59.4, +66.7)

Table 11.3: Annual trends in air temperature and rainfall extremes at Port Moresby (left) and Kavieng (right). The 95% confidence intervals are shown in brackets. Values for trends significant at the 5% level are shown in **boldface**.

	Port Moresby	**Kavieng**
TEMPERATURE	**(1943–2011)**	**(1962–2011)**
Warm Days (days/decade)	**+4.02** (+2.21, +6.24)	**+21.97** (+12.36, +28.63)
Warm Nights (days/decade)	**+9.69** (+7.74, +12.06)	**+15.96** (+10.81, +20.88)
Cool Days (days/decade)	**-7.08** (-11.24, -2.87)	**-14.45** (-18.80, -8.21)
Cool Nights (days/decade)	**-19.7** (-28.34, -9.68)	**-20.93** (-31.34, -11.16)
RAINFALL	**(1945–2011)**	**(1957–2011)**
Rain Days ≥ 1 mm (days/decade)	-0.93 (-3.75, +1.86)	**-6.29** (-11.23, -1.97)
Very Wet Day rainfall (mm/decade)	+10.48 (-15.68, +33.57)	-4.49 (-58.06, 49.82)
Consecutive Dry Days (days/decade)	+1.11 (-1.25, +3.53)	+0.36 (0.00, +1.04)
Max 1-day rainfall (mm/decade)	+1.31 (-3.78, +6.86)	-1.71 (-8.56, +2.87)

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

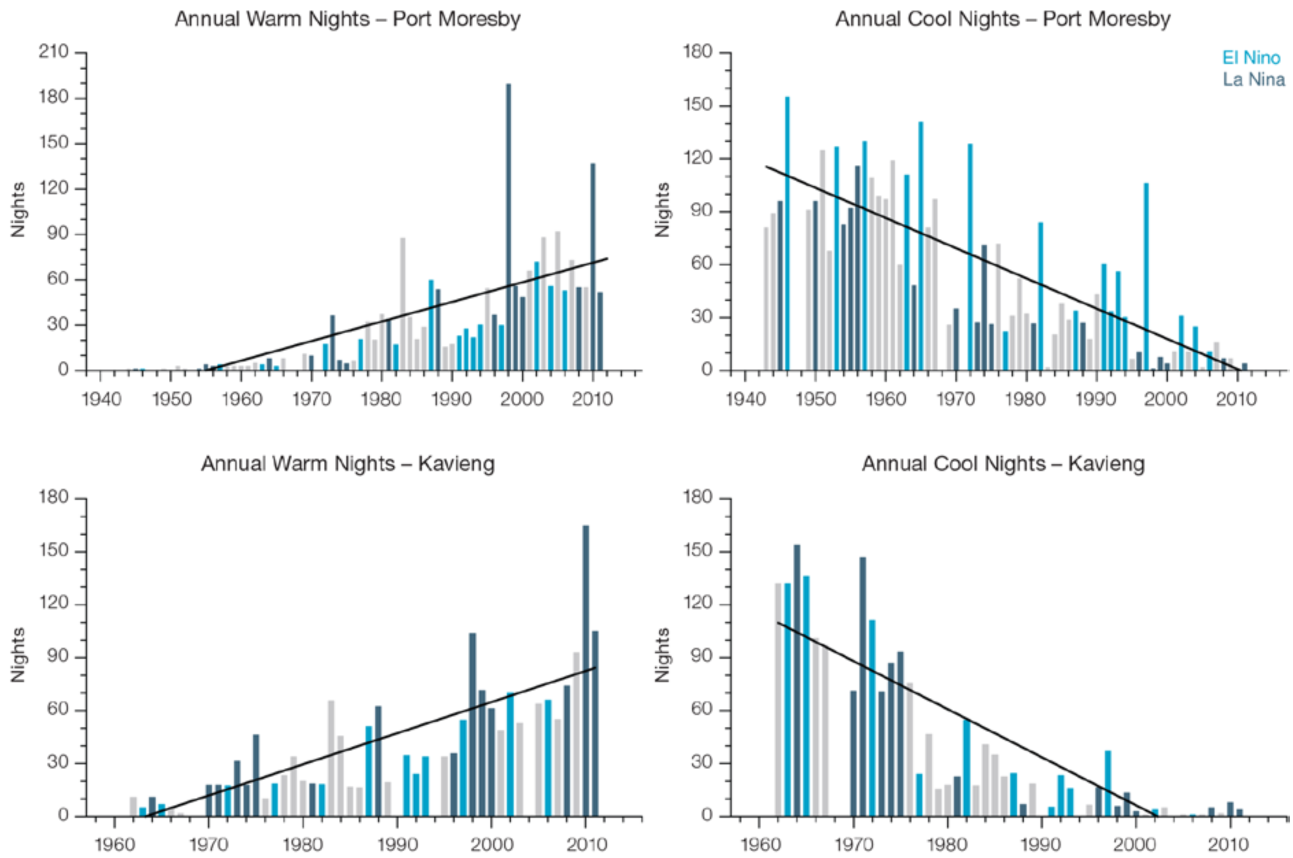

Figure 11.5: Observed time series of annual total number of Warm Nights and Cool Nights at Port Moresby (top) and Kavieng (bottom). Light blue, dark blue and grey columns denote El Niño, La Niña and ENSO neutral years respectively Solid line indicates least squares fit.

11.4.2 Rainfall

Total Rainfall

Notable interannual variability associated with the ENSO is evident in the observed rainfall records for Port Moresby since 1945 (Figure 11.3) and Kavieng since 1947 (Figure 11.4). Trends in annual and seasonal rainfall presented in Table 11.2, Figures 11.3 and 11.4 are not statistically significant at the 5% level, and show little change at Port Moresby and Kavieng.

Daily Rainfall

Daily rainfall trends for Port Moresby and Kavieng are presented in Table 11.3. Figure 11.6 shows trends in annual Consecutive Dry Days and Rain Days ≥ 1 mm (days with rainfall) at both sites. At Kavieng the annual Rain Days ≥ 1 mm has decreased (trend is statistically significant), however no significant trend is present in the other rainfall indices.

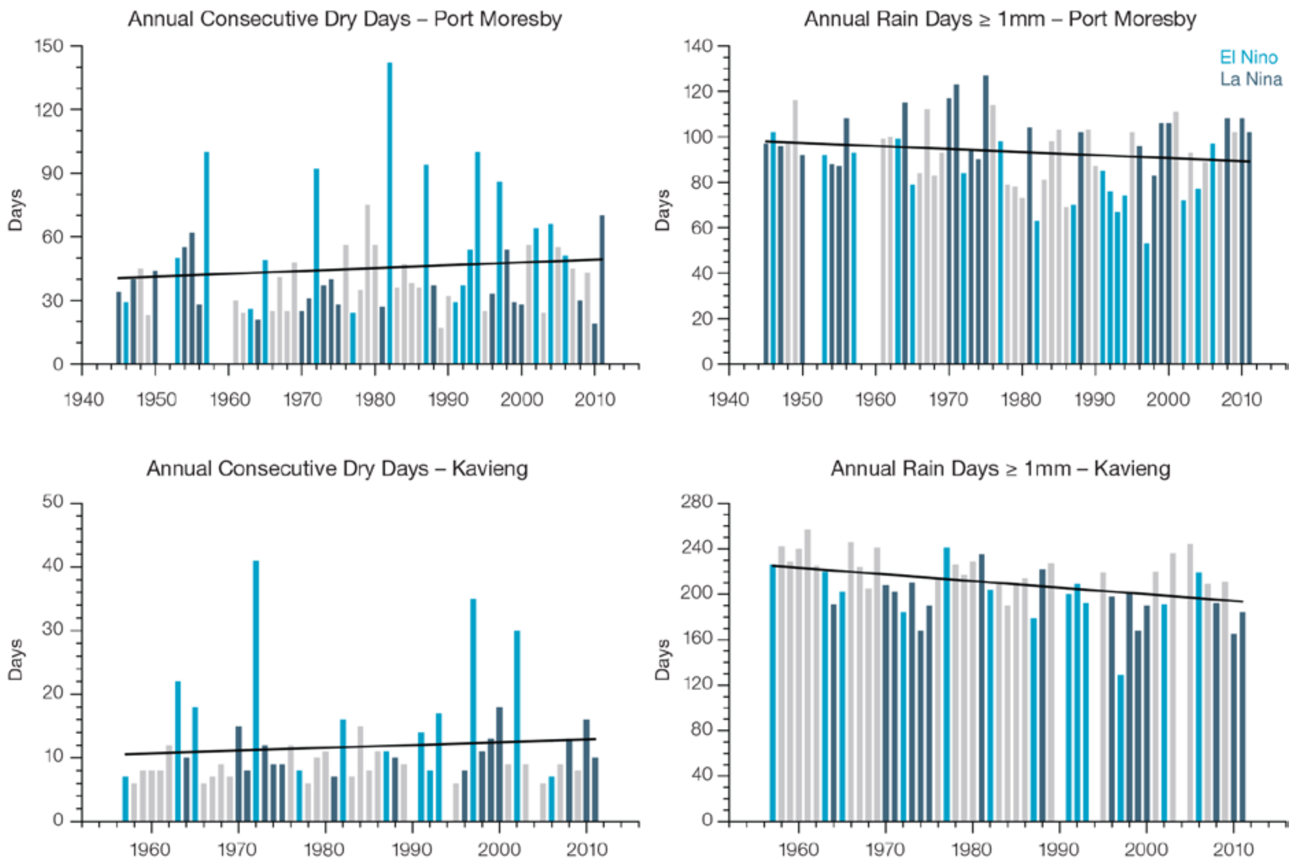

Figure 11.6: Observed time series of annual Consecutive Dry Days and Rain Days ≥ 1 mm at Port Moresby (top) and Kavieng (bottom). Annual and Kavieng (bottom right panel). Light blue, dark blue and grey columns denote El Niño, La Niña and ENSO neutral years respectively. Solid line indicates least squares fit.

11.4.3 Tropical Cyclones

When tropical cyclones affect Papua New Guinea 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 seasons, 64 tropical cyclones developed within or crossed the Papua New Guinea EEZ (Figure 11.7). This represents an average of 15 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 Papua New Guinea in this report (Australian Bureau of Meteorology and CSIRO, 2014) compared to Australian Bureau of Meteorology and CSIRO (2011).

The differences between tropical cyclone average occurrence in El Niño, La Niña and neutral years are not statistically significant. Eleven of the 43 tropical cyclones (26%) between the 1981/82 and 2010/11 seasons were severe events (Category 3 or stronger) in the Papua New Guinea 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 and equal to 34 knots) before and/or after tropical cyclone formation.

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

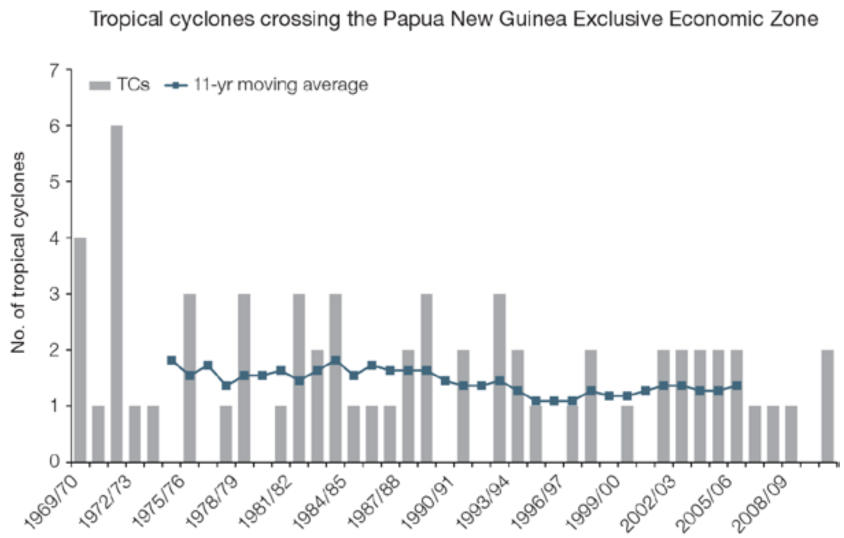

Figure 11.7: Time series of the observed number of tropical cyclones developing within and crossing the Papua New Guinea EEZ per season. The 11-year moving average is in blue.

11.5 Climate Projections

The performance of the available CMIP5 GCMs 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 Papua New Guinea 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 simulate climate more accurately than the best CMIP3 models, and there are fewer poorly-performing models used here than there were in the CMIP3 models used in Australian Bureau of Meteorology and CSIRO 2011. For Papua New Guinea, the two most serious model errors are (1) that the simulated rainfall in the present day is too high over land, perhaps due to biases in the WPM; and (2) the simulated relationship between the ENSO and Papua New Guinea rainfall does not fully match observations. These errors affect the confidence we have in the model projections. 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).

It is important to realise that the models used give different projections under the same scenario. This means there is not a single projected future for Papua New Guinea, but rather a range of possible futures for each emissions scenario. This range is described below.

11.5.1 Temperature

Further warming is expected over Papua New Guinea (Figure 11.8, Table 11.6). Under all RCPs, the warming is up to 1.1°C by 2030, relative to 1995, but after 2030 there is a growing difference in warming between each RCP. For example, in Papua New Guinea by 2090, a warming of 2.1– 4.2°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. Dynamical downscaling of climate models (Australian Bureau of Meteorology and CSIRO, 2011, Volume 1, Chapter 7) suggests that temperature rises may be about 0.4°C greater over land than over ocean in this area.

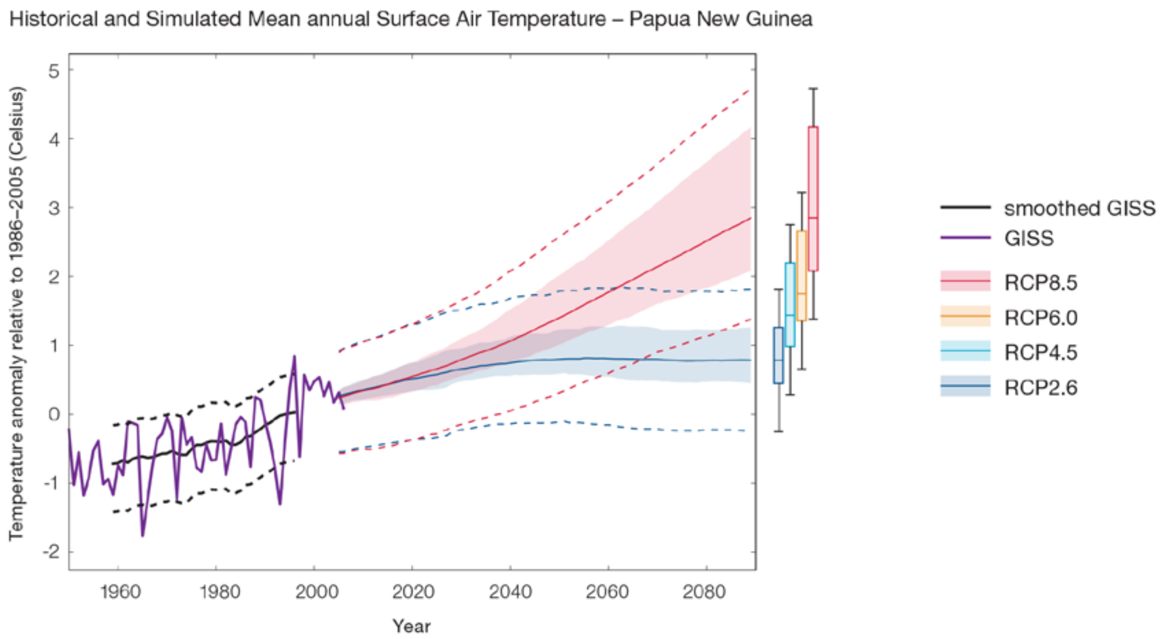

Figure 11.8: Historical and simulated surface air temperature time series for the region surrounding Papua New Guinea. The graph shows the anomaly (from the base period 1986–2005) in surface air temperature from observations (the GISS dataset, in purple), and for the CMIP5 models under the very high (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 magnitude of the model average temperature change shown in Table 11.6 because:

- The new models do not match temperature changes in the recent past in Papua New Guinea as well as in other places, possibly due to problems with the observed records or biases with the models noted below;
- There is a large bias in sea-surface temperature in the nearby western equatorial Pacific; and
- There is a bias in the simulation of the WPM, affecting the uncertainty the projections of rainfall but also temperature.

11.5.2 Rainfall

The long-term average rainfall is projected to increase in most areas of Papua New Guinea in almost all models. The increase is greater for the higher emissions scenarios, especially towards the end of the century (Figure 11.9, Table 11.6). Almost all models project an increase in rainfall in both the May–October and November–April seasons. The year-to-year rainfall variability over Papua New Guinea is much larger than the projected change, except in the upper range of models in the highest emissions scenario by 2090. There will still be wet and dry years and decades due to natural variability, but most models show that the long-term average is expected to be wetter. The effect of climate change on average rainfall may not be obvious in the short or medium term due to natural variability. Dynamical downscaling of CMIP3 climate models (Australian Bureau of Meteorology and CSIRO, 2011, Volume 1, Chapter 7) suggests that there may be large spatial variation in rainfall changes across Papua New Guinea that is not resolved by coarse GCMs. Specifically, CCAM indicates that increases greater than the regional average are possible on northern-facing slopes in both May–October and November–April seasons. Conversely, CCAM indicates that increases less than the regional average or even decreases are possible in some highlands and southern-facing slope regions. These spatial patterns relate to the effects of mountains and the position within the monsoon flow.

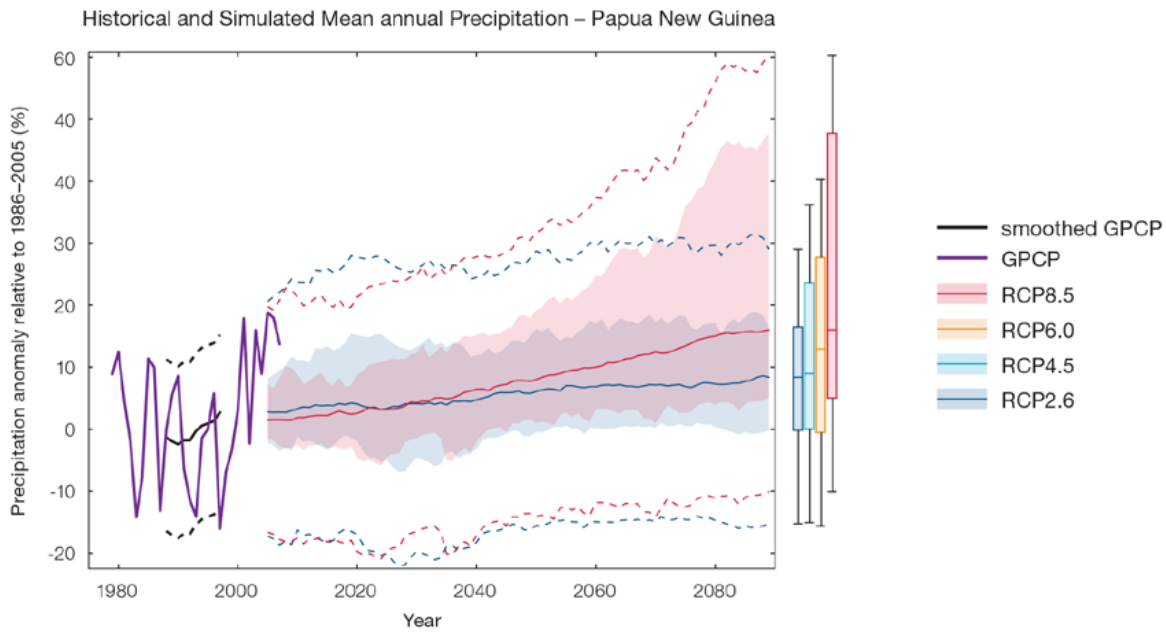

Figure 11.9: Historical and simulated annual average rainfall time series for the region surrounding Papua New Guinea. The graph shows the anomaly (from the base period 1986–2005) in rainfall from observations (the GPCP dataset, in purple), and for the CMIP5 models under the very high (RCP8.5, in red) 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 general agreement between models that rainfall will increase in most areas. However, biases in the nearby sea-surface temperatures of the western equatorial Pacific, in the WPM and in the adjacent SPCZ and ITCZ regions, lowers the confidence in the models of the magnitude of the projected changes. The 5–95th percentile range of projected values from CMIP5 climate models is large, for example in Papua New Guinea North, under RCP8.5 the range is -2– +12% by 2030 and 5–48% by 2090.

There is *medium confidence* that the long-term rainfall will increase in many locations within Papua New Guinea because:

- The majority of CMIP3 and CMIP5 models agree that the rainfall in the WPM and the ITCZ will increase under a warmer climate;
- There are well-understood physical reasons why a warmer climate will lead to increased rainfall in the ITCZ region; and
- The majority of models project that rainfall in the adjacent SPCZ region will increase.

There is *medium confidence* in the model average rainfall change shown in Table 11.6 because:

- 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;
- The new CMIP5 models broadly simulate the influence from the key features such as the ITCZ, but have some uncertainty and biases, similar to the old CMIP3 models;
- The CMIP5 models are similar to the previous CMIP3 models in overestimating the present average rainfall of Papua New Guinea; and
- The future behaviour of the ENSO is unclear, and the ENSO strongly influences year-to-year rainfall variability.

11.5.3 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 0.6°C by 2030 under RCP2.6 and by 0.8°C under RCP8.5. By 2090, the projected temperature of the 1-in-20-year hot day is expected to decrease by 0.8°C for RCP2.6 and increase by 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. 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 Papua New Guinea 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 described in Australian Bureau of Meteorology and CSIRO (2011). Some improvements have been applied for this report (Chapter 1), so the results are slightly different to those in Australian Bureau of Meteorology and CSIRO (2011). By 2030, the current 1-in-20-year daily rainfall amount is projected to increase by approximately 14 mm under RCP2.6 and 12 mm under RCP8.5. By 2090, it is projected to increase by approximately 21 mm for RCP2.6 and by 55 mm for RCP8.5. By 2090, the majority of models project the current 1-in-20-year daily rainfall event will become, on average, a 1-in-7 year event for RCP2.6 and a 1-in-4 year event for RCP8.5.

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); and
- Increases in extreme rainfall in the Pacific are projected in all available climate models.

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 CCAM downscaling 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 (Chapter 1) are described in terms of changes in proportion of time in drought, frequency and duration by 2090 for RCP2.6 and RCP 8.5 emissions scenarios.

For Papua New Guinea, the overall proportion of time spent in drought is expected to decrease in most locations under all scenarios (Figure 11.10). Under RCP8.5, the frequency and duration of drought in all categories is projected to decrease. Under RCP2.6 the frequency of mild drought is projected to increase slightly, while the frequency of severe and extreme drought is projected to decrease slightly. The duration of mild drought events is projected to remain stable, while the duration of events in all categories is projected to decrease slightly under RCP2.6.

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

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

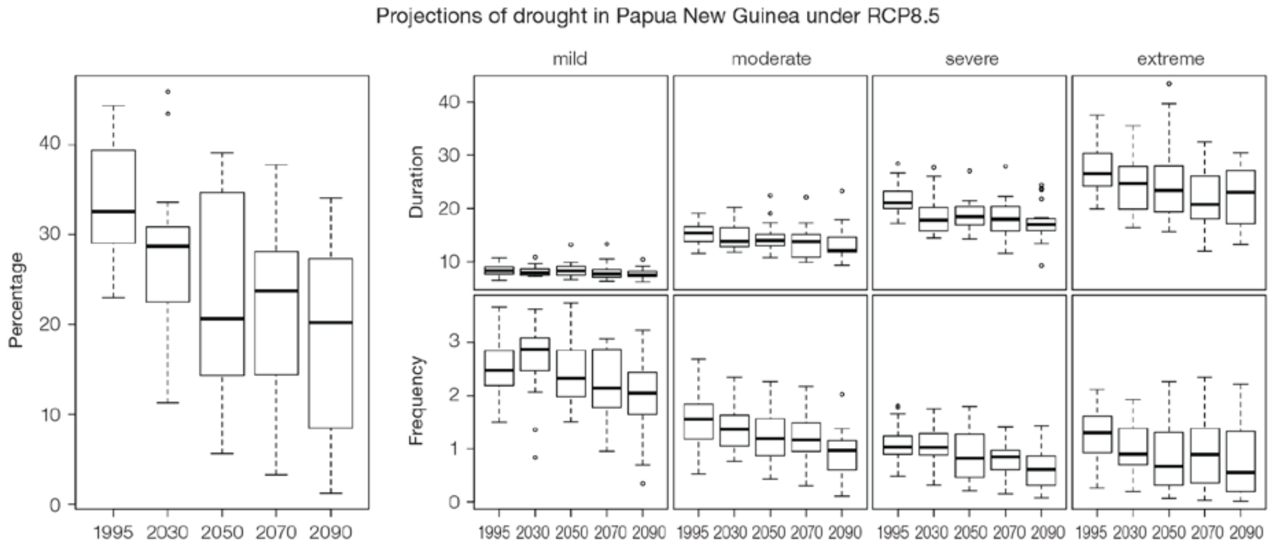

Figure 11.10: Box-plots showing percent of time in moderate, severe or extreme drought (left hand side), and average drought duration and frequency for the different categories of drought (mild, moderate, severe and extreme) for Papua New Guinea. These are shown for 20-year periods centred on 1995, 2030, 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

The level of consistency between studies projecting a decrease in the frequency of tropical cyclones by the end of the 21st century has increased since (2011). The magnitude of the decrease varies from 6% to 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.

Papua New Guinea

The projection is for a decrease in cyclone genesis (formation) frequency for the south-west basin (Figure 11.11 and Table 11.4). However the confidence level for this projection is medium. The GCMs show inconsistent results across 22 models for changes in cyclone frequency for the south-west basin. These models were selected based upon the availability of data (GPI, GPI-M, Tippett) or on the ability of those models to reproduce a current-climate tropical cyclone climatology with annual tropical cyclone numbers within ±50% of observed (CDD and OWZ) (Chapter 1). A little over a half of projected changes indicate a decrease in genesis frequency. About half of the projected changes, based on these methods, vary between a 15%–35% decrease in genesis frequency. The three empirical techniques assess changes in the main atmospheric ingredients known to be necessary for cyclone formation. About two-thirds of models suggest the conditions for cyclone formation will become less favourable in this region, with about one third of projected changes being for a decrease in genesis frequency of between 5–30%. These projections are consistent with those of Australian Bureau of Meteorology and CSIRO (2011).

Table 11.4: Projected percentage change in cyclone frequency in the south-west basin (0–40°S; 130°E–170°E). 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	-11	-11	-62	-17	
access13	11	2	-36	24	
bcccsm11	1	-2	-28		-21
canesm2	24	13	-51	28	
ccsm4				-86	4
cnrm_cm5	-3	-5	-26	-4	-26
csiro_mk36	0	-9	-29	-21	12
fgoals_g2	13	8	-5		
fgoals_s2	3	-3	-40		
gfdl-esm2m				17	26
gfdl_cm3	24	17	-4		-19
gfdl_esm2g				-21	3
gisse2r	4	-2	-30		
hadgem2_es	2	-4	-63		
inm	3	3	-16		
ipslcm5alr	4	-1	-29		
ipslcm5blr				-35	
miroc5				-27	-24
mirocesm	-44	-50	-30		
mpim	-4	-7	-47		
mricgcm3	-5	-9	-38		
noresm1m	0	-6	-30	-39	
MMM	1	-4	-33	-16	-6
N increase	0.7	0.3	0.0	0.3	0.5

11.5.4 Coral Reefs and Ocean Acidification

As atmospheric CO_2 concentrations continue to rise, oceans will warm and continue to acidify (*high confidence*). These changes will impact the health and viability of marine ecosystems, including coral reefs that provide many key ecosystem services. 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

Ocean acidification is expressed in terms of aragonite saturation state (Chapter 1). In Papua New Guinea the aragonite saturation state has declined from about 4.5 in the late 18th century to an observed value of about 3.9±0.1 by 2000 (Kuchinke et al., in press). 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

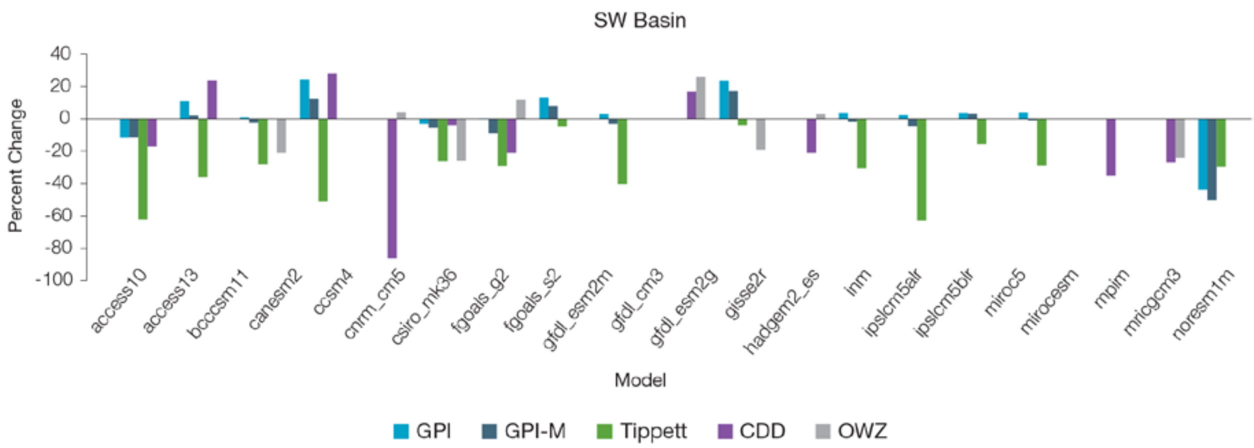

Figure 11.11: Projected percentage change in cyclone frequency in the south-west basin (data from Table 11.4).

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 11.12), suggesting that conditions remain adequate for healthy coral 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.

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 Papua New Guinea 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 adequately resolved. Importantly, the coral bleaching risk calculation does not account for 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 SST changes (Table 11.5). 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 period of severe bleaching risk (referred to as a risk event) will last 8.4 weeks (with a minimum duration of 1.6 weeks and a maximum duration of 5.3 months) and the average time between two risks will be 1.8 years (with the minimum recurrence of 2.8 months and a maximum recurrence of 6.5 years). If severe bleaching events occur more often than once every five years, the long-term viability of coral reef ecosystems becomes threatened.

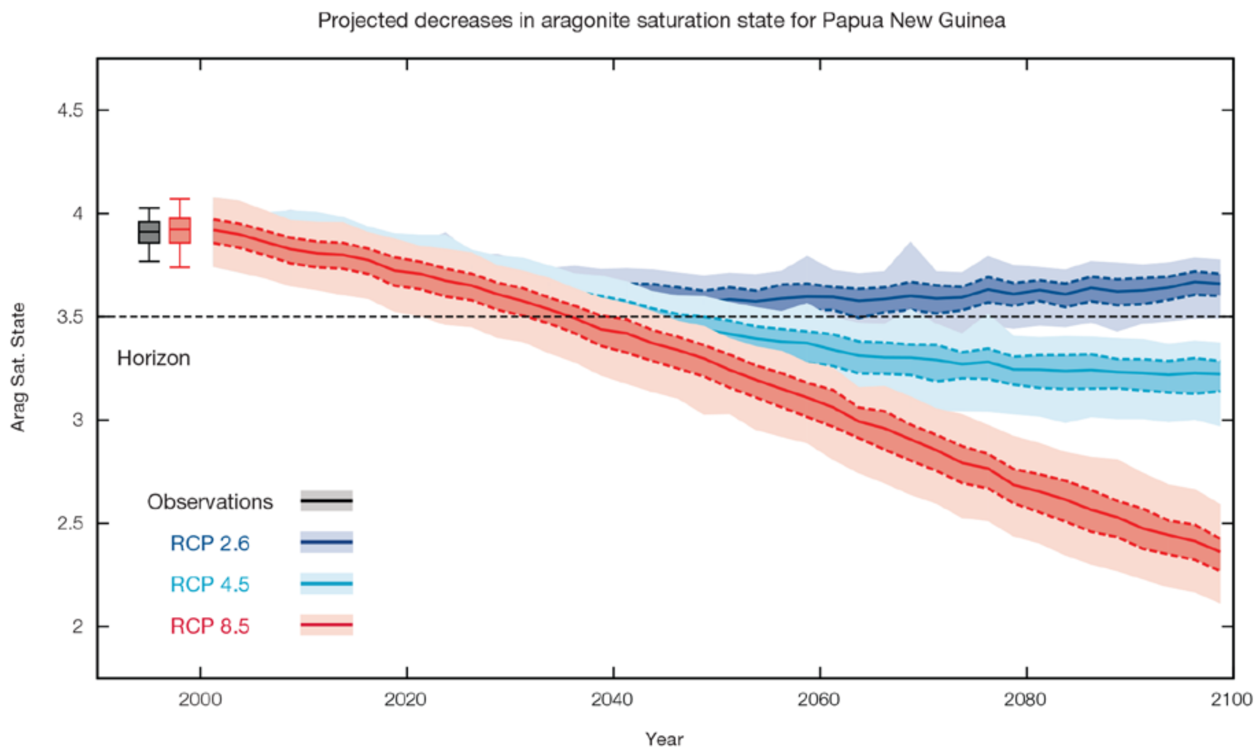

Figure 11.12: Projected decreases in aragonite saturation state in Papua New Guinea from CMIP5 models under RCP2.6, 4.5 and 8.5. Shown are the median values (solid lines), the interquartile range (dashed lines), and 5% and 95% percentiles (light shading). The horizontal line represents the transition to marginal conditions for coral reef health (from Guinotte et al., 2003).

Table 11.5: Projected changes in severe coral bleaching risk for the Papua New Guinea EEZ for increases in SST relative to 1982–1999.

Temperature change [1]	Recurrence interval [2]	Duration of the risk event [3]
Change in observed mean	30 years	6.6 weeks
+0.25°C	29.1 years (29.0 years – 29.2 years)	6.8 weeks (6.7 weeks – 6.8 weeks)
+0.5°C	22.3 years (19 years – 25.6 years)	6.1 weeks (5.0 weeks – 7.3 weeks)
+0.75°C	6.7 years (1.7 years – 13.9 years)	7.0 weeks (2.9 weeks – 2.8 months)
+1.0°C	1.8 years (2.8 months – 6.5 years)	8.4 weeks (1.6 weeks – 5.3 months)
+1.5°C	6.6 months (1.5 months – 1.9 years)	3.7 months (1.8 weeks –1.4 years)
+2.0°C	4.2 months (1.6 months – 9.2 months)	11.4 months (1.5 months – 4.0 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.

11.5.5 Sea Level

Mean sea level is projected to continue to rise over the course of the 21st century under all RCP emissions scenarios. There is very *high confidence* in the direction of change. The CMIP5 models simulate a rise of between approximately 7–17 cm by 2030 (very similar values for different RCPs), with increases of 41–87 cm by 2090 under the RCP8.5 (Figure 11.13 and Table 11.6). 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 23 cm (5–95% range, after removal of the seasonal signal; see dashed lines in Figure 11.13a) and it is likely that a similar range will continue through the 21st century.

The projected changes in wave climate are spatially variable along the Papua New Guinea coast.

On Papua New Guinea's Coral Sea coast, there is no statistically significant projected future change in wave properties *(low confidence)* (Table 11.7). Suggested changes include a slight decrease in wave height (Figure 11.14) and period in December–March with variable direction, while during June–September there may be less variability in period and direction, with a slight clockwise rotation.

On Papua New Guinea's north coast, projected changes in wave properties include a decrease in wave height (significant under RCP8.5 by 2090) (Figure 11.15), accompanied by a slight decrease in wave period and possible anticlockwise rotation (more northerly waves) during December–March consistent with a weakening trade wind contribution *(low confidence)* (Table 11.8). During June–September, projected changes in wave climate are small and not significant *(low confidence)*, including a clockwise rotation toward the south. These features are characteristic of a decrease in strength of the north-easterly trade winds. A decrease in larger waves is suggested *(low confidence)*.

There is *low confidence* in projected changes in the Papua New Guinea 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 are larger than the projected wave changes, which further reduces confidence in projections.

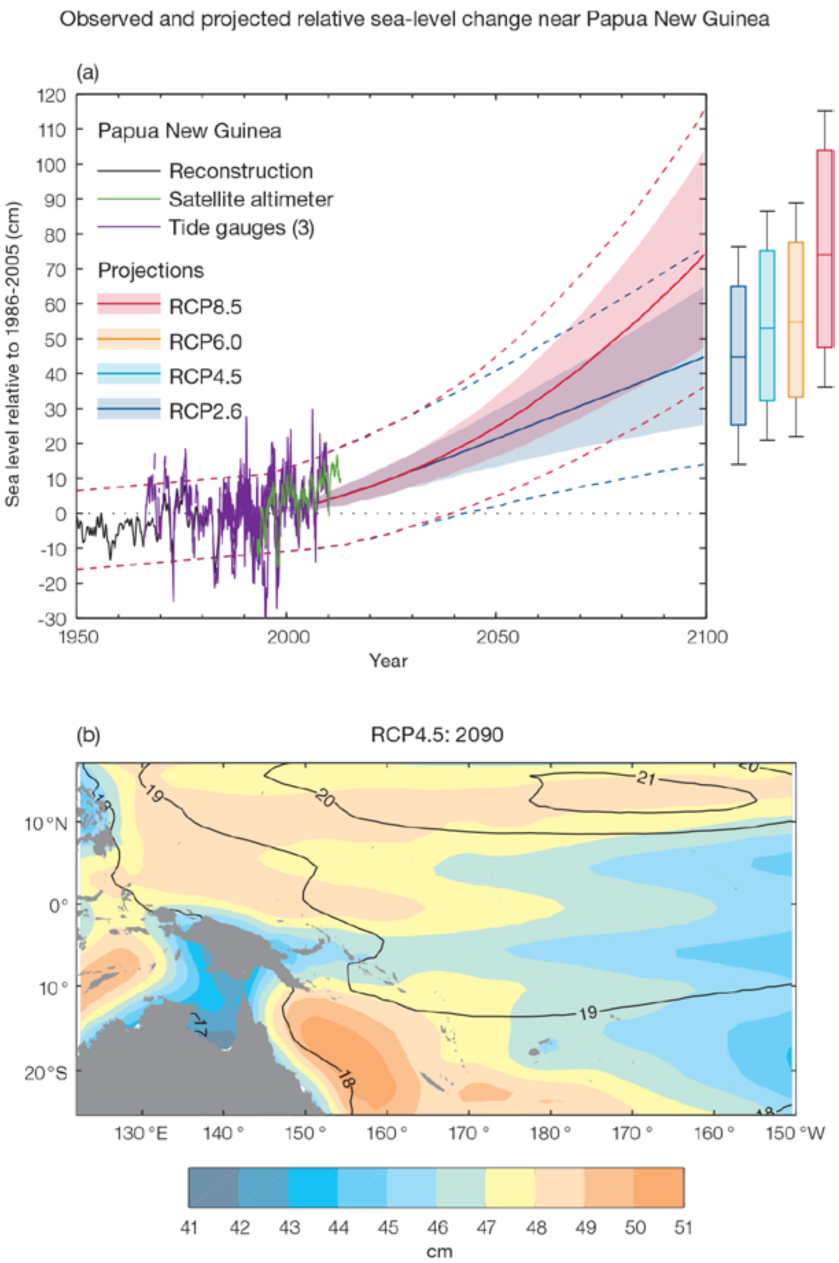

Figure 11.13: (a) The observed tide-gauge records of relative sea-level (since the late 1970s) are indicated in purple, and the satellite record (since 1993) in green. The gridded (reconstructed) sea level data at Papua New Guinea (since 1950) is shown in black. Multi-model mean projections from 1995–2100 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).

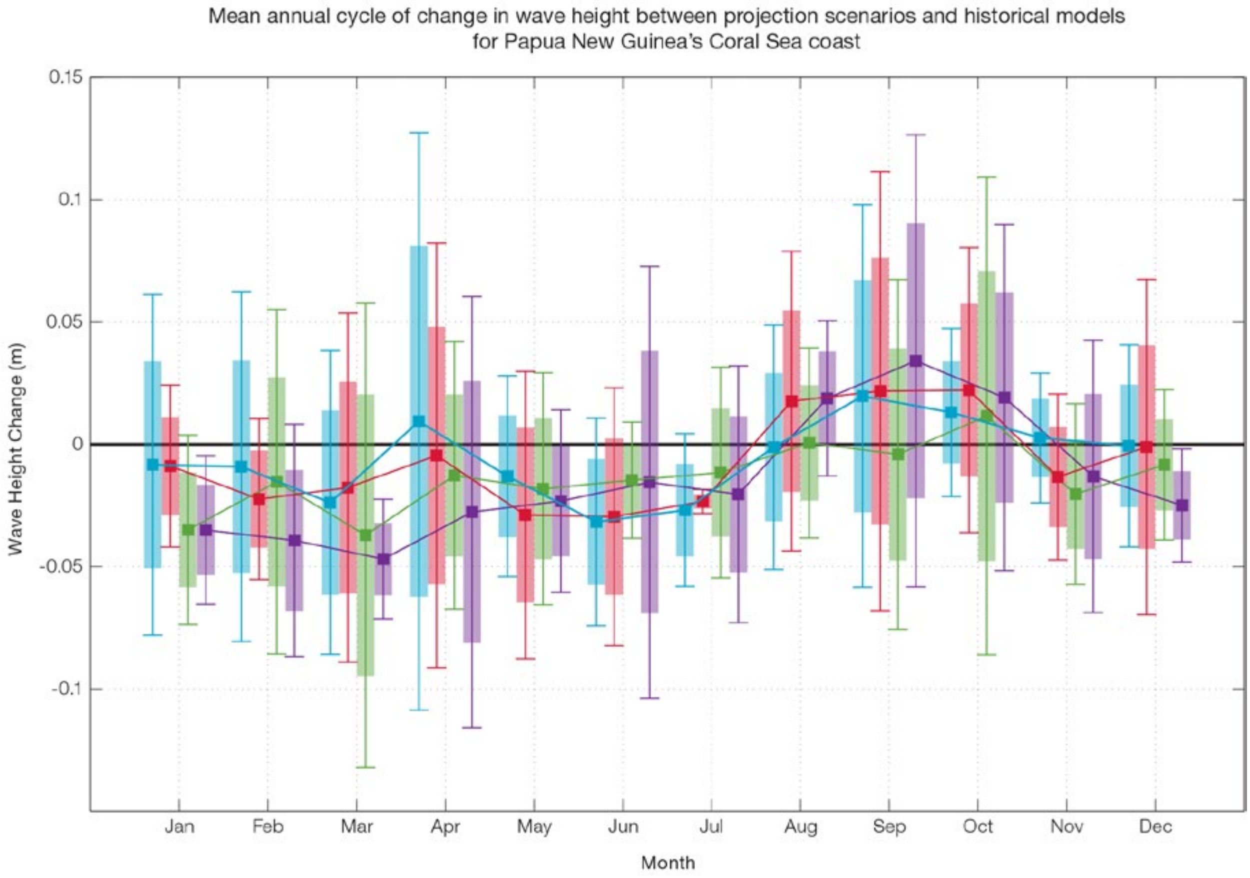

Figure 11.14: Projected mean annual cycle of change in wave height for 2035 and 2090 under RCP4.5 and 8.5 emissions scenarios and mean of historical models on Papua New Guinea's Coral Sea coast. Shaded boxes show 1 standard deviation of models' means around the ensemble means, and error bars show the 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).

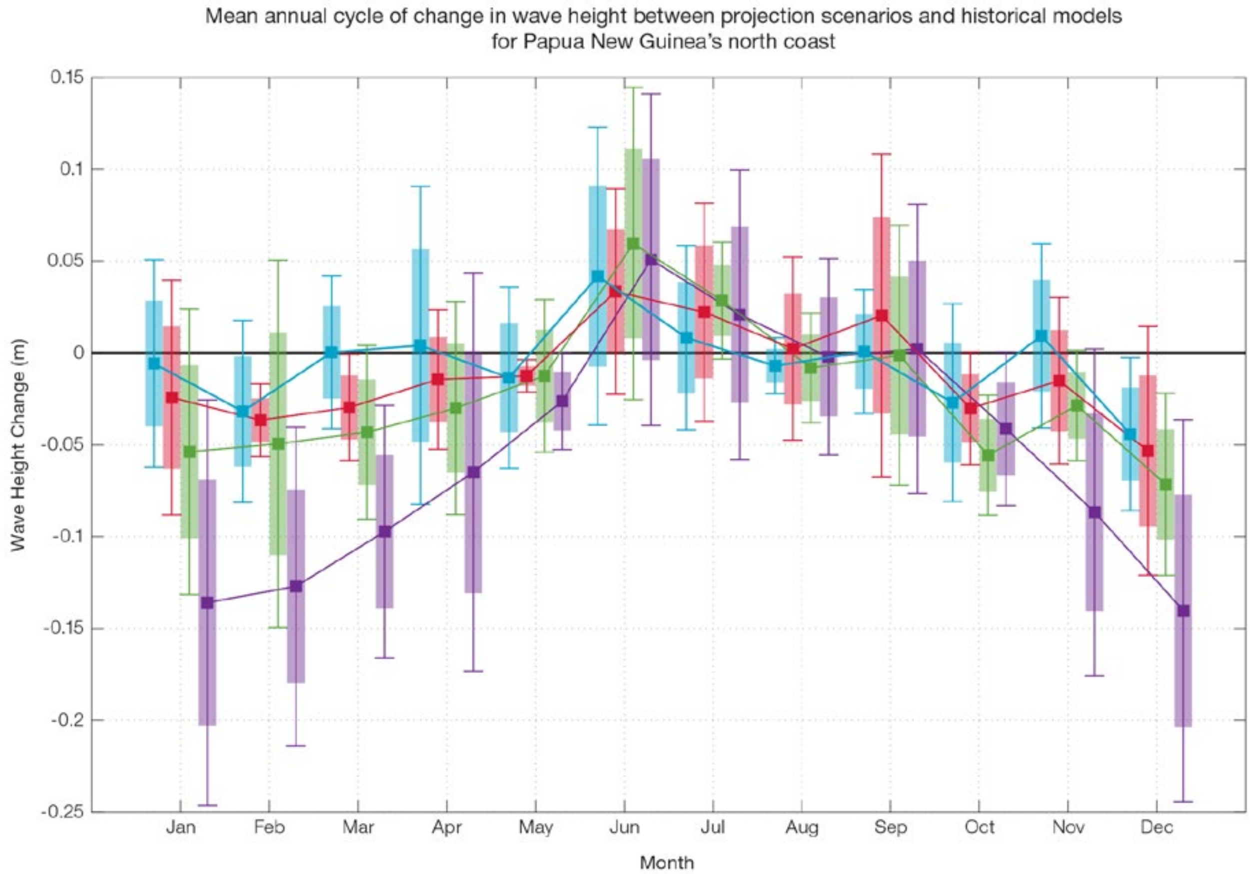

Figure 11.15: Projected mean annual cycle of change in wave height for 2035 and 2090 under RCP4.5 and 8.5 emissions scenarios and mean of historical models on Papua New Guinea's North coast. Shaded boxes show 1 standard deviation of models' means around the ensemble means, and error bars show the 5–95% 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).

11.5.7 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. There is *medium confidence* that mean rainfall will increase, and *medium confidence* in a decrease in drought frequency.

Tables 11.6, 11.7 and 11.8 summarise the quantified 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 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 11.6: Projected changes in the annual and seasonal mean climate for Papua New Guinea 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 (0.6–1.2)	0.8 (0.5–1.3)	0.8 (0.4–1.3)	*Medium*
		0.7 (0.4–1)	1 (0.8–1.5)	1.3 (0.9–1.9)	1.4 (1–2.2)	
		0.6 (0.5–0.9)	1 (0.7–1.4)	1.4 (1.1–2)	1.8 (1.4–2.7)	
		0.8 (0.5–1.1)	1.4 (1–2)	2.2 (1.6–3.2)	2.9 (2.1–4.2)	
Maximum temperature (°C)	1-in-20 year event	0.6 (0.3–0.8)	0.7 (0.4–1.1)	0.7 (0.4–1.1)	0.8 (0.4–1)	*Medium*
		0.6 (0.2–0.9)	0.9 (0.5–1.3)	1.2 (0.7–1.7)	1.4 (0.9–2)	
		NA (NA–NA)	NA (NA–NA)	NA (NA–NA)	NA (NA–NA)	
		0.8 (0.5–1.1)	1.5 (0.9–2)	2.3 (1.5–3.3)	3 (2–4.3)	
Minimum temperature (°C)	1-in-20 year event	0.6 (0.3–0.9)	0.7 (0.2–1.1)	0.8 (0.4–1.1)	0.8 (0.2–1.1)	*Medium*
		0.6 (0.2–0.9)	1 (0.6–1.3)	1.2 (0.7–1.6)	1.4 (0.9–1.8)	
		NA (NA–NA)	NA (NA–NA)	NA (NA–NA)	NA (NA–NA)	
		0.8 (0.4–1.3)	1.5 (1–2.1)	2.3 (1.6–3.4)	3.2 (2.2–4.3)	
Total rainfall (%)	Annual	4 (-5–13)	6 (-1–15)	7 (0–18)	8 (0–16)	*Medium*
		5 (-4–13)	6 (0–14)	8 (0–21)	9 (0–24)	
		5 (-2–11)	7 (0–14)	10 (0–24)	13 (-1–28)	
		4 (-2–12)	8 (2–18)	12 (2–28)	16 (5–48)	
Total rainfall (%)	Nov-Apr	4 (-9–16)	6 (-3–14)	6 (-1–15)	8 (-2–16)	*Medium*
		4 (-6–13)	5 (-3–13)	8 (-3–20)	8 (-2–18)	
		5 (-3–14)	7 (-2–15)	9 (-2–22)	11 (-4–23)	
		3 (-2–9)	7 (-2–18)	11 (-2–25)	14 (-1–35)	
Total rainfall (%)	May-Oct	4 (-4–11)	5 (-2–14)	8 (1–20)	8 (1–18)	*Medium*
		5 (-5–14)	7 (-4–19)	9 (1–27)	9 (-1–31)	
		4 (-2–9)	8 (-1–18)	10 (-1–27)	14 (-2–35)	
		5 (-1–14)	8 (-1–22)	13 (2–36)	18 (-2–51)	
Aragonite saturation state (Ω_{ar})	Annual	-0.3 (-0.6–0.0)	-0.4 (-0.7–-0.1)	-0.4 (-0.7–-0.1)	-0.3 (-0.6–0.0)	*Medium*
		-0.3 (-0.6–-0.1)	-0.5 (-0.8–-0.3)	-0.7 (-0.9–-0.4)	-0.7 (-1.0–-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–-1.2)	
Mean sea level (cm)	Annual	12 (8–17)	22 (14–30)	31 (19–44)	41 (24–58)	*Medium*
		12 (7–17)	22 (14–31)	34 (22–47)	47 (29–66)	
		12 (7–16)	22 (14–29)	34 (21–46)	48 (30–67)	
		13 (8–17)	25 (17–34)	42 (28–57)	63 (41–87)	

Table 11.7: Projected average changes in wave height, period and direction for Papua New Guinea Coral Sea coast 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 (-0.1–0.1)	-0.0 (-0.2–0.1) -0.0 (-0.2–0.1)	*Low*
	June–September	0.0 (-0.2–0.2) 0.0 (-0.2–0.2)	0.0 (-0.2–0.1) 0.0 (-0.2 –0.2)	*Low*
Wave period change (s)	December–March	-0.1(-1.0–0.8) -0.1 (-1.0–0.9)	-0.2 (-0.9–0.6) -0.2 (-1,0–0.7)	*Low*
	June–September	-0.1 (-0.4–0.3) -0.0 (-0.4–0.3)	-0.1 (-0.4–0.3) -0.0 (-0.4–0.3)	*Low*
Wave direction change (° clockwise)	December–March	+0 (-30–30) 0 (-30–30)	0 (-30–30) 0 (-30–30)	*Low*
	June–September	0 (-10–10) 0 (-5–10)	0 (-5–5) 0 (-5–10)	*Low*

Table 11.8: Projected average changes in wave height, period and direction for Papua New Guinea North Coast 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 (-0.2–0.1) -0.0 (-0.2–0.1)	-0.1 (-0.2–0.1) -0.1 (-0.2–0.0)	*Low*
	June–September	0.0 (-0.3–0.3) +0.0 (-0.3–0.3)	+0.0 (-0.2–0.3) +0.0 (-0.2 –0.3)	*Low*
Wave period change (s)	December–March	-0.0(-0.9–0.8) -0.1 (-1.0–0.8)	-0.1 (-1.0–0.8) -0.2 (-1.2–0.7)	*Low*
	June–September	-0.0 (-0.8–0.7) -0.1 (-0.9–0.8)	-0.1 (-0.9–0.7) -0.2 (-1.1–0.7)	*Low*
Wave direction change (° clockwise)	December–March	0 (-10–10) 0 (-10–10)	-0 (-10–10) -0 (-10–10)	*Low*
	June–September	+0 (-40–70) 0 (-40–70)	+0 (-30–60) +10 (-50–70)	*Low*

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