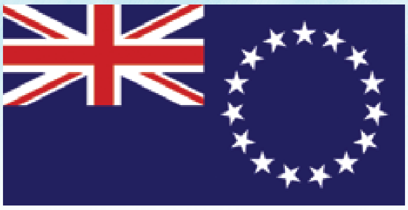


Rarotonga

Chapter 2
Cook Islands

The contributions of Arona Ngari, Maarametua Vaiimene, David Maihia and Nitoro Bates from the Cook Islands Meteorological Service and Pasha Carruthers from the National Enviroment Service are gratefully acknowledged

Introduction

This chapter provides a brief description of the Cook Islands, its past and present climate as well as projections for the future. The climate observation network and the availability of atmospheric and oceanic data records are outlined. Seasonal cycles are described, and the influences of large-scale climate features (e.g. the South Pacific Convergence Zone) and patterns of climate variability (e.g. the El Niño-Southern Oscillation) are analysed and discussed. Observed trends and analysis of air temperature, rainfall, extreme events (including tropical cyclones), sea-surface temperature, ocean acidification, sea level and extreme sea level are presented. Projections for air and sea-surface temperature, rainfall, extreme events, ocean acidification and sea level for the 21st century are provided. These projections are presented along with confidence levels based on expert judgement by Pacific Climate Change Science Program (PCCSP) scientists. The chapter concludes with summary tables of projections for the Northern Cook Islands and the Southern Cook Islands (Tables 2.4 and 2.5). Important background information including an explanation of methods and models is provided in Chapter 1. For definitions of other terms refer to the Glossary.

2.1 Climate Summary

2.1.1 Current Climate

- In the Northern Cook Islands temperatures are fairly constant throughout the year, while in the Southern Cook Islands there is a difference of around 4°C between the warmest and coolest months.
- The wet season in the Cook Islands is usually from late November to April or May but is longer in the Southern Cook Islands.
- Year-to-year rainfall variations are high in both the Northern and Southern Cook Islands, and much of this is due to the El Niño-Southern Oscillation, particularly in the wet season. El Niño years tend to be drier and La Niña years wetter than normal.
- Warming trends are evident in annual and seasonal mean air temperatures at Rarotonga for the period 1950–2009.
- Annual and seasonal rainfall trends for Rarotonga and Penrhyn for the period 1950–2009 are not statistically significant.
- The sea-level rise measured by satellite altimeters since 1993 is about 4 mm per year.
- On average Rarotonga experiences 11 tropical cyclones per decade, with most occurring between November and April. The high interannual variability in tropical cyclone numbers makes it difficult to identify any long-term trends in frequency.

2.1.2 Future Climate

Over the course of the 21st century:

- Surface air temperature and sea-surface temperature are projected to continue to increase (*very high* confidence).
- Annual and seasonal mean rainfall is projected to increase (*low* confidence)
- The intensity and frequency of days of extreme heat are projected to increase (*very high* confidence).
- The intensity and frequency of days of extreme rainfall are projected to increase (*high* confidence).
- The incidence of drought is projected to decrease (*moderate* confidence).
- Tropical cyclone numbers are projected to decline in the south-east Pacific Ocean basin (0–40ºS, 170ºE–130ºW) (*moderate* confidence).
- Ocean acidification is projected to continue (*very high* confidence).
- Mean sea-level rise is projected to continue (*very high* confidence).

2.2 Country Description

The Cook Islands consist of 15 islands spread over 2.2 million km^2 in the South Pacific between 9°S–22°S and 157°–166°W (Cook Islands First National Communication under the UNFCCC, 2000). The Cook Islands are divided geographically into the Northern Group and the Southern Group. The Northern Group consists of six low-lying atolls (most of which are about one to two metres above mean sea level), while the Southern Group comprises nine elevated islands, including volcanic islands and raised atolls. The Cook Islands has an Exclusive Economic Zone of 1.8 million km^2 of which only 237 km^2 is land area. Te Manga (652 m above sea level) on Rarotonga is the highest peak in the Cook Islands (Cook Islands Country Profile, SOPAC, 2000).

Rarotonga is also home to the capital, Avarua and the majority of the Cook Islands' resident population of 11 500 (2010 estimate) (Cook Islands Statistics Office, 2010).

The largest economic sector is tourism which has brought significant revenue and development to both Rarotonga and Aitutaki. Other sources of revenue in the Cook Islands are financial services, black pearl exports, fisheries and agriculture (Cook Islands Country Profile, SOPAC, 2000).

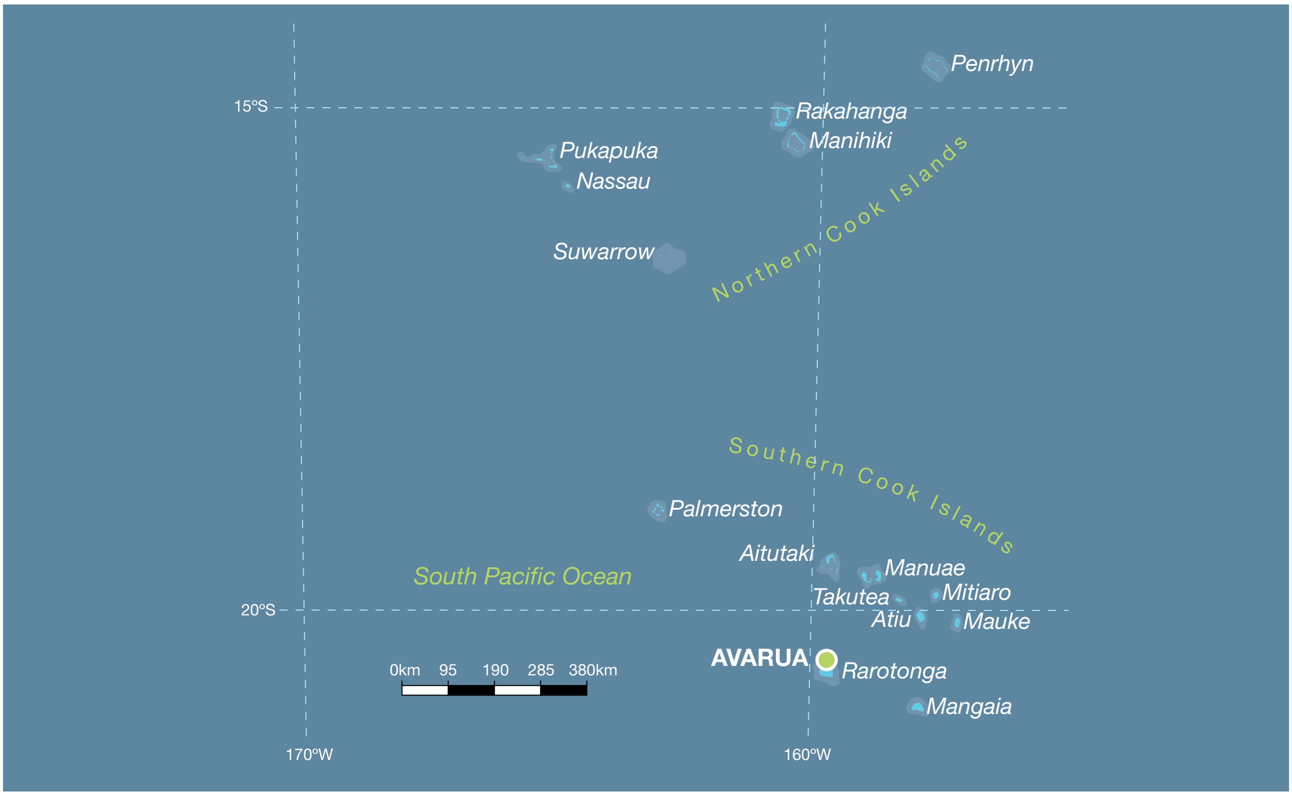


Figure 2.1: Cook Islands

2.3 Data Availability

The Cook Islands Meteorological Service is responsible for monitoring weather and climate in the Cook Islands. It currently operates six automatic weather stations on three islands in the Southern Cook Islands (Mangaia, Mauke, Aitutaki) and three islands in the Northern Cook Islands (Pukapuka, Penryhn, Manihiki).

Good quality historical meteorological data exist for six stations until the mid-1990s when manual observations were replaced by automatic weather stations. Since the mid-1990s observations have been sporadic, with the exception of Rarotonga and Penrhyn, the main observation stations in the Southern and Northern Groups respectively. Multiple observations within a 24-hour period are conducted at both stations. The Rarotonga climate station is located at Nikao, near the western end of the Rarotonga International Airport runway, on the north-western side of the island. Data are available here from 1899 to present for rainfall and 1907 to present for air temperature. For Penrhyn, rainfall data are available from 1937 to present and air temperature data from 1950 to 1995. Data from 1950 have been used for both sites. Both records are homogeneous and more than 95% complete (up to 1995 for temperature at Penrhyn).

Oceanographic records do not cover such a long time period. Monthly-averaged sea-level data are available from the late 1970s at Rarotonga (1977–2001 and 2001– present) and since 1993 with an acoustic gauge at Rarotonga. A global positioning system instrument to estimate vertical land motion was deployed at Rarotonga in 2001 and will provide valuable direct estimates of local vertical land motion in future years. Monthly-averaged sea-level data are available from 1977–present at Penrhyn. Both satellite (from 1993) and in situ sea-level data (1950–2009; termed reconstructed sea level; Volume 1, Section 2.2.2.2) are available on a global 1° x 1° grid.

Long-term locally-monitored sea-surface temperature data are unavailable for the Cook Islands, so large-scale gridded sea-surface temperature datasets have been used (HadISST, HadSST2, ERSST and Kaplan Extended SST V2; Volume 1, Table 2.3).

Measuring evaporation, Cook Islands Meteorological Service

2.4 Seasonal Cycles

Seasonal temperatures differ greatly between Rarotonga in the Southern Group and Penrhyn in the Northern Group (Figure 2.2). Being close to the equator Penrhyn has fairly constant temperatures throughout the year, with average maxima around 30ºC and average minima around 26ºC. In Rarotonga the monthly average temperatures peak in March and are about 4ºC warmer than the winter months (June-September). The colder winter temperatures are due to weaker solar radiation and the influence of colder air from higher latitudes in winter. At both stations, sea-surface temperature changes with the season in the same way as air temperature, and there is a strong linkage between sea-surface temperature and air temperature on the small islands.

Rainfall follows similar seasonal patterns at the two sites. The wet season is from late November to April or May but persists by approximately one month longer at Rarotonga. The South Pacific Convergence Zone (SPCZ) is very important for rainfall in the Cook Islands. The SPCZ is centred close to or over the Southern Cook Islands from November to May. This is when the SPCZ is most active and furthest south. From November to March the SPCZ is wide and strong enough for the Northern Cook Islands to also receive significant rainfall.

The driest months of the year in the Cook Islands are from June to October. In this season, the SPCZ is mostly weak and inactive over the Cook Islands, although occasionally convection and rainfall occur. The Southern Group is also affected by rain systems from the sub- and extra-tropics, such as cold fronts, especially in winter.

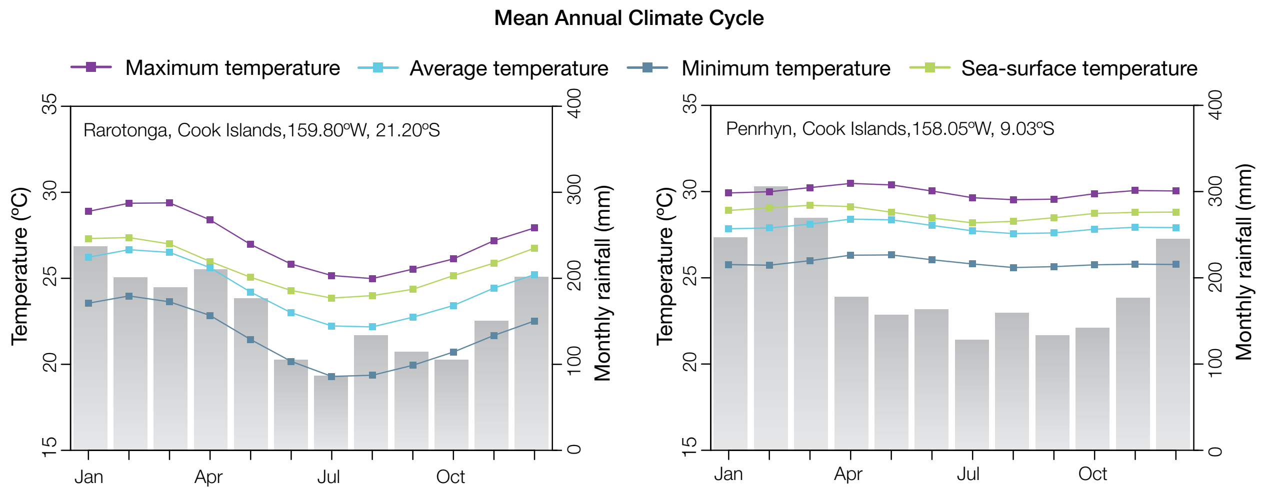


Figure 2.2: Mean annual cycle of rainfall (grey bars) and daily maximum, minimum and mean air temperatures at Rarotonga (left) and at Penrhyn (right), and local sea-surface temperatures derived from the HadISST dataset (Volume 1, Table 2.3).

2.5 Climate Variability

Year-to-year rainfall variations are high in both the Northern and Southern Groups, and much of this is due to the El Niño-Southern Oscillation (ENSO), particularly in the wet season. This is substantiated by the significant correlations between wet and dry season rainfall and ENSO indices. ENSO also affects maximum and minimum air temperatures. ENSO has opposite effects on Penrhyn compared to Rarotonga, which is partly caused by the position and strength of the SPCZ. During an El Niño event rainfall decreases in Rarotonga as the SPCZ moves away to the north-east, an effect that is stronger in the wet season. Temperatures also decrease in Rarotonga during an El Niño event as the waters around the Southern Cook Islands cool. In Penrhyn, however, an El Niño usually brings wetter conditions as the SPCZ moves over the Northern Group. Ocean temperatures warm in this region during an El Niño so air temperatures also warm. At Penrhyn the effect of ENSO appears to be stronger on maximum temperatures than minimum air temperatures, whereas in Rarotonga minimum air temperatures are more strongly affected by ENSO. In both the Southern and Northern Groups the influence of ENSO is greatest in the wet season. ENSO Modoki events (Volume 1, Section 3.4.1) also affect rainfall at both sites, more in the wet than the dry season, with similar influences but to a lesser degree than canonical ENSO events. Wet season air temperatures are also affected by ENSO Modoki events.

The only other significant correlations between climate indices and interannual climate variations found in the Cook Islands (Tables 2.1 and 2.2) are the weak relationship between the Interdecadal Pacific Oscillation and the maximum air temperatures at Rarotonga, and the effect of the Southern Annular Mode on wet season minimum air temperatures in Penrhyn. This suggests the Southern Annular Mode is related to the position of sub-tropical high pressure systems so that only in some years is there a relationship with the temperatures in the Northern Group, whereas these high pressure systems influence the Southern Group in all years. Most of the interannual climate variability in the Cook Islands related to large-scale climate variability seems therefore to come from ENSO, with the SPCZ playing an important role in bringing about this variability.

Table 2.1: Correlation coefficients between indices of key large-scale patterns of climate variability and minimum and maximum temperatures (Tmin and Tmax) and rainfall at Rarotonga. Only correlation coefficients that are statistically significant at the 95% level are shown.

Climate feature/index		Dry season (May-October)			Wet season (November-April)		
		Tmin	Tmax	Rain	Tmin	Tmax	Rain
ENSO	Niño3.4	-0.70	-0.42	-0.35			-0.52
	Southern Oscillation Index	0.67	0.42	0.24	0.33	0.27	0.49
Interdecadal Pacific Oscillation Index						-0.25	
Southern Annular Mode Index							
ENSO Modoki Index						-0.25	-0.21
Number of years of data		77	79	108	78	78	108

Table 2.2: Correlation coefficients between indices of key large-scale patterns of climate variability and minimum and maximum temperatures (Tmin and Tmax) and rainfall at Penrhyn. Only correlation coefficients that are statistically significant at the 95% level are shown.

Climate feature/index		Dry season (May-October)			Wet season (November-April)		
		Tmin	Tmax	Rain	Tmin	Tmax	Rain
ENSO	Niño3.4		0.73		0.45	0.85	0.63
	Southern Oscillation Index		-0.74	-0.28		-0.71	-0.72
Interdecadal Pacific Oscillation Index							
Southern Annular Mode Index					0.40		
ENSO Modoki Index				0.30	0.35	0.54	0.40
Number of years of data		46	46	70	44	45	70

2.6 Observed Trends

2.6.1 Air Temperature

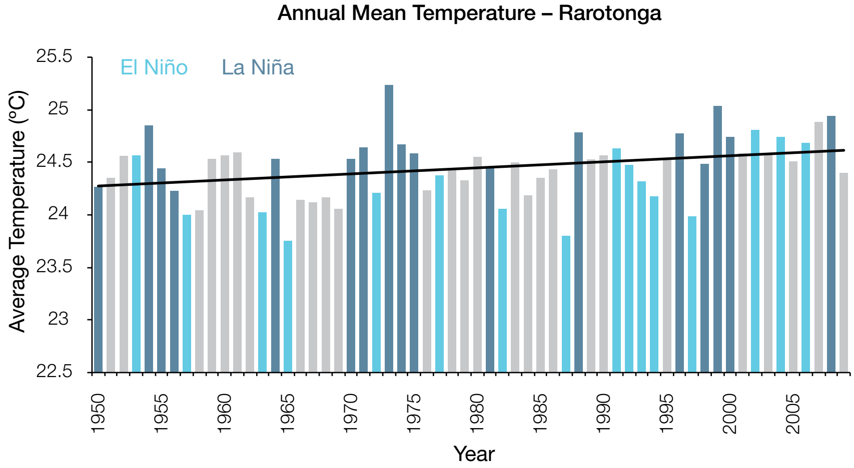
Warming trends (Figure 2.3 top) of similar magnitude have been identified in both annual and seasonal mean air temperatures at Rarotonga for the period 1950–2009. Annual and seasonal minimum air temperature trends are greater than those observed for maximum air temperatures at Rarotonga (Table 2.3). Figure 2.3 (bottom) shows that for the period 1950–1995 there was no trend in annual mean air temperature at Penrhyn. Data are not available for the period 1996–2009.

2.6.2 Rainfall

Annual and seasonal rainfall trends for Rarotonga and Penrhyn for the period 1950–2009 are not statistically significant (Table 2.3 and Figure 2.4).

2.6.3 Extreme Events

Tropical cyclone season in the Cook Islands is 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 2009/10 seasons, the centre of 47 tropical cyclones passed within approximately 400 km of Rarotonga. This represents an average of 11 cyclones per decade. Tropical cyclones were most frequent in El Niño years (15 cyclones per decade) and least frequent in La Niña years (six cyclones per decade). The neutral year average is 11 per decade. The interannual variability in the number of tropical cyclones in the vicinity of Rarotonga is large, ranging from zero in some cyclone seasons to six in the 2005/06 cyclone season (Figure 2.5). This high variability makes it difficult to identify any long-term trends in frequency.



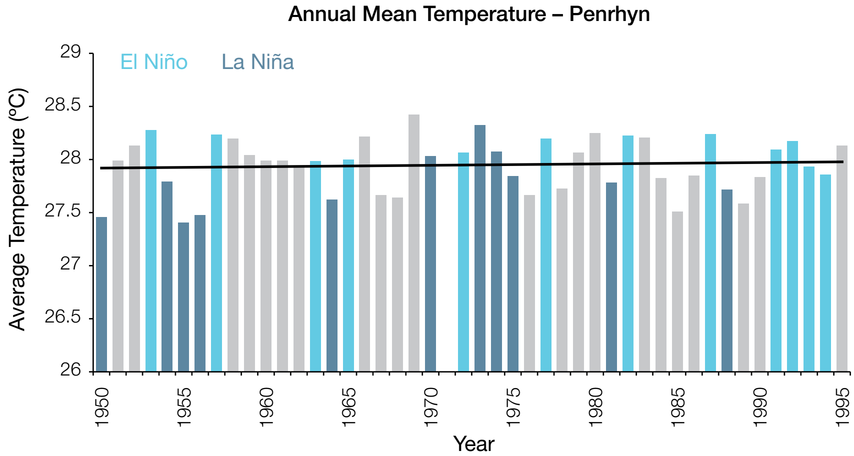
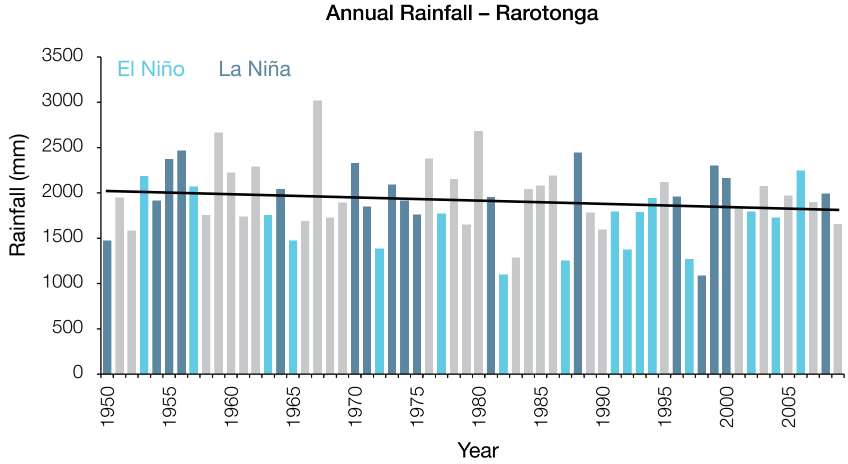


Figure 2.3: Annual mean air temperature for Rarotonga (top) and Penrhyn (bottom). Light blue, dark blue and grey bars denote El Niño, La Niña and neutral years respectively.

Table 2.3: Annual and seasonal trends in maximum, minimum and mean air temperature (Tmax, Tmin and Tmean) and rainfall at Rarotonga (and rainfall only at Penrhyn) for the period 1950–2009. Asterisks indicate significance at the 95% level. Persistence is taken into account in the assessment of significance as in Power and Kociuba (in press). The statistical significance of the air temperature trends is not assessed.

	Rarotonga Tmax (°C per 10 yrs)	Rarotonga Tmin (°C per 10 yrs)	Rarotonga Tmean (°C per 10 yrs)	Rarotonga Rain (mm per 10 yrs)	Penrhyn Rain (mm per 10 yrs)
Annual	+0.05	+0.07	+0.06	-35	+137
Wet season	+0.05	+0.08	+0.06	-28	+69
Dry season	+0.04	+0.08	+0.06	-13	+29



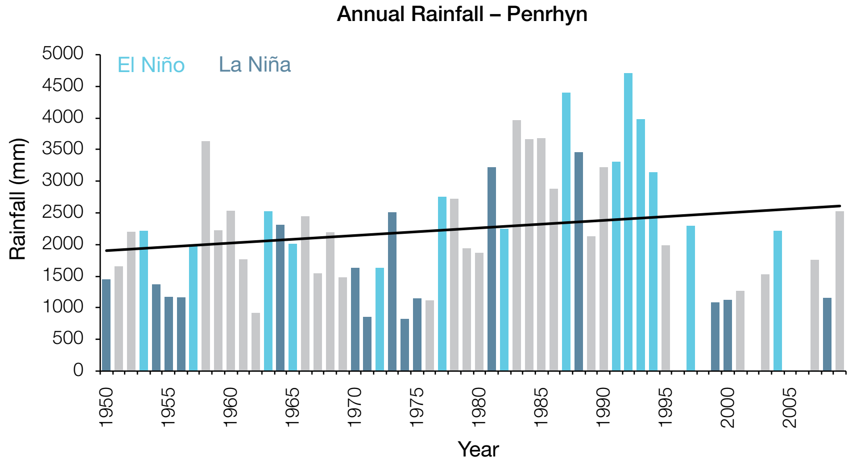


Figure 2.4: Annual rainfall at Rarotonga (top) and Penrhyn (bottom). Light blue, dark blue and grey bars denote El Niño, La Niña and neutral years respectively.

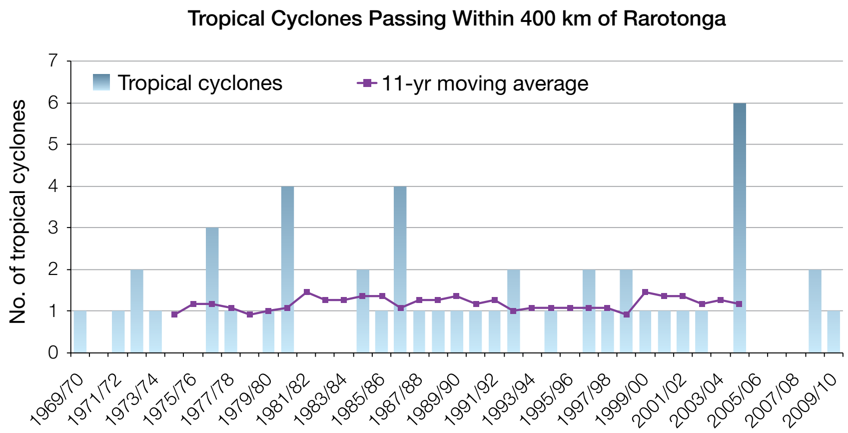


Figure 2.5: Tropical cyclones passing within 400 km of Rarotonga per season. The 11-year moving average is in purple.

2.6.4 Sea-Surface Temperature

Historical changes in sea-surface temperature around the Cook Islands are consistent with the broad-scale changes for the wider PCCSP region. Water temperatures remained relatively constant from the 1950s to the late 1980s. This was followed by a period of more rapid warming (approximately 0.12°C per decade for 1970–present). At these regional scales, natural variability plays a large role in determining sea-surface temperature making it difficult to identify long-term trends. Figure 2.8 shows the 1950–2000 sea-surface temperature changes (relative to a reference year of 1990) from three large-scale, sea-surface temperature gridded datasets (HadSST2, ERSST and Kaplan Extended SST V2; Volume 1, Table 2.3).

2.6.5 Ocean Acidification

Based the large-scale distribution of coral reefs across the Pacific and the seawater chemistry, Guinotte et al. (2003) suggested that seawater aragonite saturation states above 4 were optimal for coral growth and for the development of healthy reef ecosystems, with values from 3.5 to 4 adequate for coral growth, and values between 3 and 3.5 marginal. Coral reef ecosystems were not found at seawater aragonite saturation states below 3 and these conditions were classified as extremely marginal for supporting coral growth.

In the Cook Islands region, the aragonite saturation state has declined from about 4.5 in the late 18th century to an observed value of about 4.1 ± 0.2 by 2000.

2.6.6 Sea Level

Monthly averages of the historical tide gauge, satellite (since 1993) and gridded sea-level (since 1950) data that are co-located have similar variability after 1993 and indicate year-to-year variability in sea levels of about 19 cm (estimated 5–95% range) after removal of the seasonal cycle (Figure 2.10). The sea-level rise near the Cook Islands, measured by satellite altimeters (Figure 2.6) since 1993, is about 4 mm per year, similar to the global average of 3.2 ± 0.4 mm per year. This rise is partly linked to a pattern related to climate variability from year to year and decade to decade (Figure 2.10).

2.6.7 Extreme Sea-Level Events

The annual climatology of the highest daily sea levels has been evaluated using hourly tide gauge measurements at Avarua, Rarotonga and Penrhyn (Tongareva) Atoll (Figure 2.7). Maximum tides tend to occur between March and April at Rarotonga and February and March at Penrhyn. These higher tides and short-term raised water levels combine to produce the highest likelihood of extreme water levels between January and April, peaking in March, at both locations. Seasonal water levels tend to be lower during La Niña years at Penrhyn, but generally higher during La Niña years at Rarotonga. Despite the generally lower seasonal component during El Niño years, the higher short-term components during December-April in El Niño years at Rarotonga result in a tendency for higher water levels during these periods (Volume 1, Section 3.6.3 and Figures 3.20 and 3.21). Seven of the 10 highest water levels recorded occurred during an El Niño at both locations and these events tend to cluster between the months of November to March, especially at Rarotonga. Many of these 10 highest recorded water levels are significantly higher than the total (combined) high water level climatology (grey lines in Figures 2.7). Indeed the five highest sea-level events at Rarotonga and four events at Penrhyn (including the top three) were associated with named tropical cyclones. These results strongly indicate that extreme sea-level events in the Cook Islands are more often associated with tropical cyclones or high wave events than with tides or interannual sea level variability.

Regional Distribution of the Rate of Sea-Level Rise

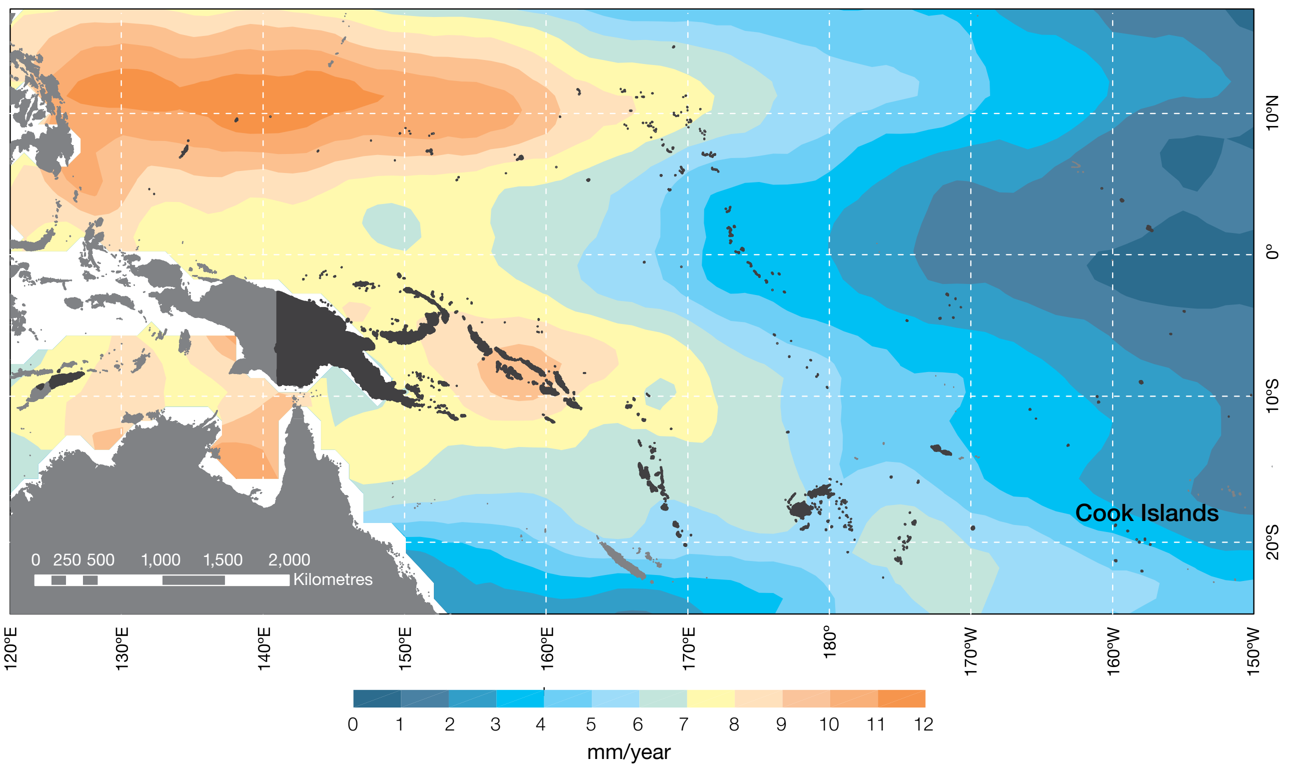


Figure 2.6: The regional distribution of the rate of sea-level rise measured by satellite altimeters from January 1993 to December 2010, with the location of Cook Islands indicated. Further detail about the regional distribution of sea-level rise is provided in Volume 1, Section 3.6.3.2.

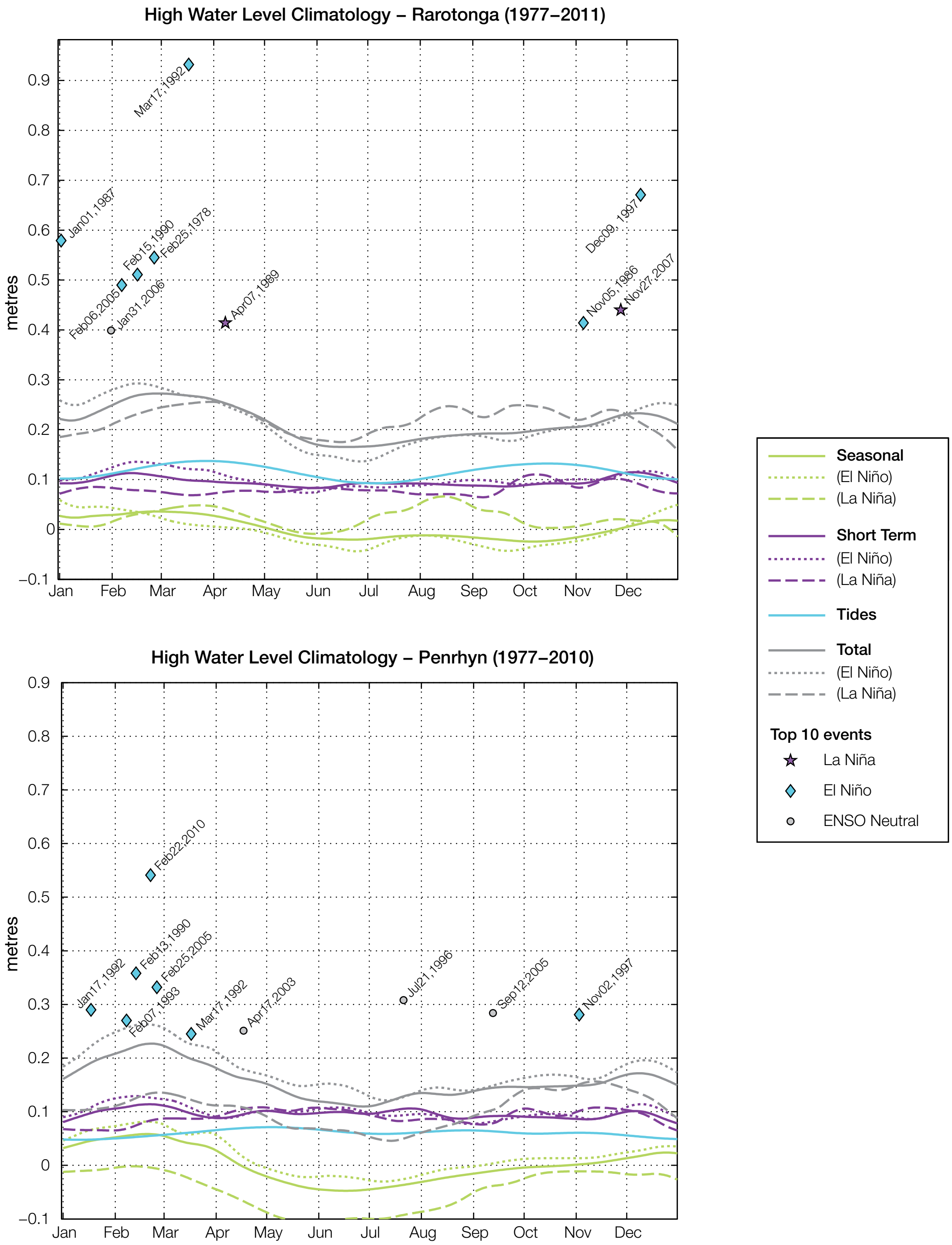


Figure 2.7: The annual cycle of high waters relative to Mean Higher High Water (MHHW) due to tides, short-term fluctuations (most likely associated with storms) and seasonal variations for Rarotonga (top) and Penryhn (bottom). The tides and short-term fluctuations are respectively the 95% exceedence levels of the astronomical high tides relative to MHHW and the short-term sea level anomaly fluctuations. Components computed only for El Niño and La Niña years are shown by dotted and dashed lines, and grey lines are the sum of the tide, short-term and seasonal components. The 10 highest sea level events in the record relative to MHHW are shown, and coded to indicate the phase of ENSO at the time of the extreme event.

2.7 Climate Projections

Climate projections have been derived from up to 18 global climate models from the CMIP3 database, for up to three emissions scenarios (B1 (low), A1B (medium) and A2 (high)) and three 20-year periods centred on 2030, 2055 and 2090, relative to 1990. These models were selected based on their ability to reproduce important features of the current climate (Volume 1, Section 5.2.3), so projections from each of the models may be considered a plausible representation of the future climate. This means there is not one single projected future for the Cook Islands, but rather a range of possible futures. The full range of these futures is discussed in the following sections.

These projections do not represent a value specific to any actual location, such as a town or city in the Cook Islands. Instead, they refer to an average change over the broad geographic region encompassing the Cook Islands and the surrounding ocean. Projections refer to the entire Cook Islands unless otherwise stated. In some instances, given that there are some differences between the climate of the Northern and Southern Cook Islands (Section 2.4), projections are given separately for these two regions (Figure 1.1 shows the region boundaries). Section 1.7 provides important information about interpreting climate model projections.

2.7.1 Temperature

Surface air temperature and sea-surface temperature are projected to continue to increase over the course of the 21st century. There is *very high* confidence in this direction of change because:

- Warming is physically consistent with rising greenhouse gas concentrations.
- All CMIP3 models agree on this direction of change.

The majority of CMIP3 models simulate a slight increase (< 1°C) in annual and seasonal mean surface air temperature by 2030, however by 2090 under the A2 (high) emissions scenario increases of greater than 2.5°C are simulated by almost all models (Tables 2.4 and 2.5). Given the close relationship between surface air temperature and sea-surface temperature, a similar (or slightly weaker) rate of warming is projected for the surface ocean (Figure 2.8). There is *moderate* confidence in this range and distribution of possible futures because:

- There is generally some discrepancy between modelled and observed temperature trends over the past 50 years in the vicinity of the Cook Islands, although this may be partly due to limited observational records (Figure 2.8).

Interannual variability in surface air temperature and sea-surface temperature over the Cook Islands is strongly influenced by ENSO in the current climate (Section 2.5). As there is no consistency in projections of future ENSO activity (Volume 1, Section 6.4.1), it is not possible to determine whether interannual variability in temperature will change in the future. However, it is expected that ENSO will continue to be an important source of variability for the Cook Islands.

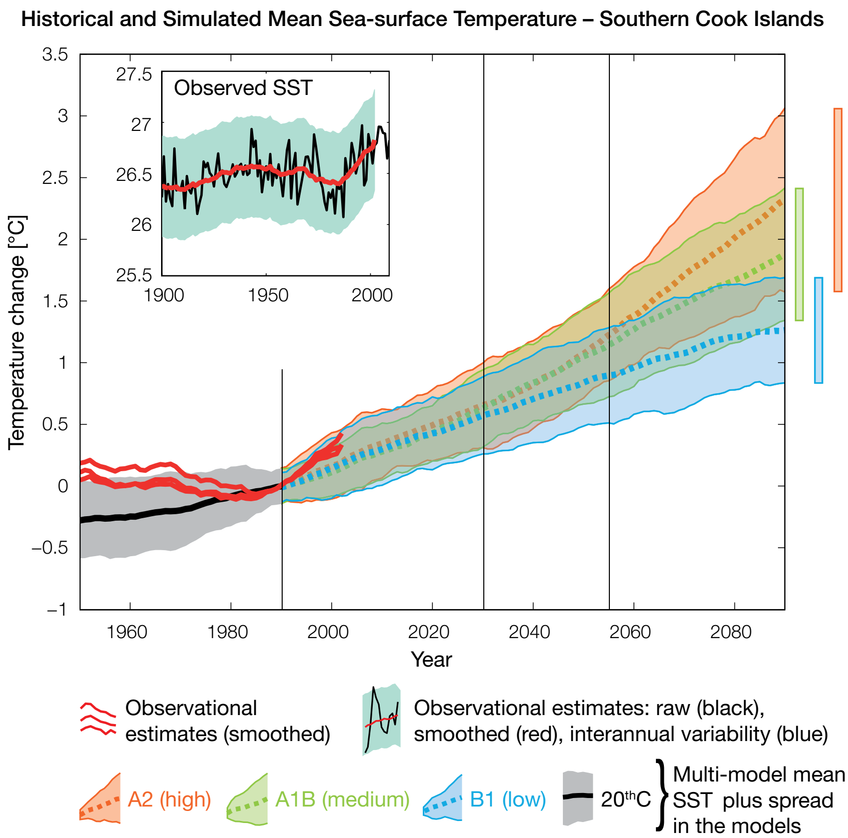


Figure 2.8: Historical climate (from 1950 onwards) and simulated historical and future climate for annual mean sea-surface temperature (SST) over the region surrounding the Southern Cook Islands, for the CMIP3 models. Shading represents approximately 95% of the range of model projections (twice the inter-model standard deviation), while the solid lines represent the smoothed (20-year running average) multi-model mean temperature. Projections are calculated relative to the 1980–1999 period (which is why there is a decline in the inter-model standard deviation around 1990). Observational estimates in the main figure (red lines) are derived from the HadSST2, ERSST and Kaplan Extended SST V2 datasets (Volume 1, Section 2.2.2). Annual average (black) and 20-year running average (red) HadSST2 data is also shown inset. Projections for the Northern Cook Islands closely resemble those for the south and are therefore not shown.

2.7.2 Rainfall

Wet season (November-April), dry season (May-October), and annual average rainfall is projected to increase over the course of the 21st century. There is *moderate* confidence in this direction of change because:

- An increase in rainfall is consistent with the projected likely increase in the intensity of the South Pacific Convergence Zone (SPCZ) (Volume 1, Section 6.4.5) which has a large influence on rainfall in the Cook Islands.
- The majority of CMIP3 models agree on this direction of change by 2090.

The majority of CMIP3 models simulate little change (-5% to 5%) in rainfall by 2030, however by 2090 the majority simulate an increase (>5%) in wet season, dry season and annual rainfall, with up to a third simulating a large increase (>15%) for the Northern Cook Islands under the A2 (high) emissions scenario (Table 2.4 and 2.5). There is *low* confidence in this range and distribution of possible futures because:

- In simulations of the current climate, the CMIP3 models generally do not locate the SPCZ in the correct location relative to the Cook Islands (Brown et al., 2011).
- The CMIP3 models are unable to resolve many of the physical processes involved in producing rainfall. As a consequence, they do not simulate rainfall as well as other variables such as temperature (Volume 1, Chapter 5).

Interannual variability in rainfall over the Cook Islands is strongly influenced by ENSO in the current climate, particularly via its influence on the movement of the SPCZ (Section 2.5). As there is no consistency in projections of future ENSO activity (Volume 1, Section 6.4.1), it is not possible to determine whether interannual variability in rainfall will change in the future.

2.7.3 Extremes

Temperature

The intensity and frequency of days of extreme heat are projected to increase over the course of the 21st century. There is *very high* confidence in this direction of change because:

- An increase in the intensity and frequency of days of extreme heat is physically consistent with rising greenhouse gas concentrations.
- All CMIP3 models agree on the direction of change for both intensity and frequency.

For both the Northern and Southern Cook Islands, the majority of CMIP3 models simulate an increase of approximately 1°C in the temperature experienced on the 1-in-20-year hot day by 2055 under the B1 (low) emissions scenario, with an increase of over 2.5°C simulated by the majority of models by 2090 under the A2 (high) emissions scenario (Tables 2.4 and 2.5). There is *low* confidence in this range and distribution of possible futures because:

- In simulations of the current climate, the CMIP3 models tend to underestimate the intensity and frequency of days of extreme heat (Volume 1, Section 5.2.4).
- Smaller increases in the frequency of days of extreme heat are projected by the CCAM 60 km simulations.

Rainfall

The intensity and frequency of days of extreme rainfall are projected to increase over the course of the 21st century. There is *high* confidence in this direction of change because:

- An increase in the frequency and intensity of extreme rainfall is consistent with larger-scale projections, based on the physical argument that the atmosphere is able to hold more water vapour in a warmer climate (Allen and Ingram, 2002; IPCC, 2007). It is also consistent with the projected likely increase in SPCZ intensity (Volume 1, Section 6.4.5).
- Almost all of the CMIP3 models agree on this direction of change for both intensity and frequency.

For the Northern Cook Islands, the majority of CMIP3 models simulate an increase of at least 20 mm in the amount of rain received on the 1-in-20-year wet day by 2055 under the B1 (low) emissions scenario, with an increase of at least 30 mm simulated by the majority of models by 2090 under the A2 (high) emissions scenario. In the Southern Cook Islands, the majority of CMIP3 models project this increase to be at least 10 mm for the 1-in-20-year wet day by 2055, under the B1 (low) emissions scenario, and 20 mm by 2090 under the A2 (high) emissions scenario. The majority of models project, by 2055 under the B1 (low) emissions scenario, that the current 1-in-20-year extreme rainfall event will occur, on average, four times every year in the Northern Cook Islands and three times every year in the Southern Cook Islands. By 2090, under the A2 (high) emissions scenario, the projected frequency remains relatively unchanged in the Northern Cook Islands, and increases to three to four times every year over the Southern Cook Islands. There is *low* confidence in this range and distribution of possible futures because:

- In simulations of the current climate, the CMIP3 models tend to underestimate the intensity and frequency of extreme rainfall (Volume 1, Section 5.2.4), and generally do not locate the SPCZ in the correct location relative to the Cook Islands (Brown et al., 2011).
- The CMIP3 models are unable to resolve many of the physical processes involved in producing extreme rainfall.

Drought

The incidence of drought is projected to decrease over the course of the 21st century. There is *moderate* confidence in this direction of change because:

- A decrease in drought is consistent with projections of increased rainfall (Section 2.7.2).
- The majority of models agree on this direction of change for most drought categories.

For the Northern and Southern Cook Islands, the majority of CMIP3 models project that mild drought will occur approximately seven to eight times every 20 years in 2030 under all emissions scenarios, decreasing to six to seven times by 2090. The frequency of moderate drought is projected to remain stable at once to twice every 20 years in the Southern Cook Islands, while in the north it is expected to decrease from twice every 20 years in 2030, to once to twice by 2090. The majority of CMIP3 models project that severe droughts will occur approximately once every 20 years across all time periods and scenarios in both the north and south. There is *low* confidence in this range and distribution of possible futures because:

- There is only low confidence in the range of rainfall projections (Section 2.7.2), which directly influences projections of future drought conditions.

Tropical Cyclones

Tropical cyclone numbers are projected to decline in the south-east Pacific Ocean basin (0–40ºS, 170ºE– 130ºW) over the course of the 21st century. There is *moderate* confidence in this direction of change because:

- Many studies suggest a decline in tropical cyclone frequency globally (Knutson et al., 2010).
- Tropical cyclone numbers decline in the south-east Pacific Ocean in the majority assessment techniques.

Based on the direct detection methodologies (Curvature Vorticity Parameter (CVP) and the CSIRO Direct Detection Scheme (CDD) described in Volume 1, Section 4.8.2), 65% of projections show no change or a decrease in tropical cyclone formation when applied to the CMIP3 climate models for which suitable output is available (Volume 1, Appendix 1, Table A2). When these techniques are applied to CCAM, 100% of projections show a decrease in tropical cyclone formation. In addition, the Genesis Potential Index (GPI) empirical technique suggests that conditions for tropical cyclone formation will become less favourable in the south-east Pacific Ocean basin, for all analysed CMIP3 models. There is *moderate* confidence in this range and distribution of possible futures because:

- In simulations of the current climate, the CVP, CDD and GPI methods capture the frequency of tropical cyclone activity reasonably well (Volume 1, Section 5.4).

Despite this projected reduction in total tropical cyclone numbers, five of the six CCAM 60 km simulations show an increase in the proportion of the most severe cyclones. Most models also indicate a reduction in tropical cyclone wind hazard north of 20ºS latitude and regions of increased hazard south of 20ºS latitude. This increase in wind hazard coincides with a poleward shift in the latitude at which tropical cyclones are most intense.

2.7.4 Ocean Acidification

The acidification of the ocean will continue to increase over the course of the 21st century. There is *very high* confidence in this projection as the rate of ocean acidification is driven primarily by the increasing oceanic uptake of carbon dioxide, in response to rising atmospheric carbon dioxide concentrations.

Projections from all analysed CMIP3 models indicate that the annual maximum aragonite saturation state will reach values below 3.5 by about 2050 in the Southern Cook Islands and 2065 in the Northern Cook Islands. The aragonite saturation will continue to decline thereafter (Figure 2.9; Tables 2.4 and 2.5). There is *moderate* confidence in this range and distribution of possible futures because the projections are based on climate models without an explicit representation of the carbon cycle and with relatively low resolution and known regional biases.

The impact of acidification change on the health of reef ecosystems is likely to be compounded by other stressors including coral bleaching, storm damage and fishing pressure.

2.7.5 Sea Level

Mean sea level is projected to continue to rise over the course of the 21st century. There is *very high* confidence in this direction of change because:

- Sea-level rise is a physically consistent response to increasing ocean and atmospheric temperatures, due to thermal expansion of the water and the melting of glaciers and ice caps.
- Projections arising from all CMIP3 models agree on this direction of change.

The CMIP3 models simulate a rise of between approximately 5–15 cm by 2030, with increases of 20–60 cm indicated by 2090 under the higher emissions scenarios (i.e. A1B (medium) and A2 (high); Figure 2.10; Tables 2.4 and 2.5). There is *moderate* confidence in this range and distribution of possible futures because:

- There is significant uncertainty surrounding ice-sheet contributions to sea-level rise and a larger rise than that projected above cannot be excluded (Meehl et al., 2007b).

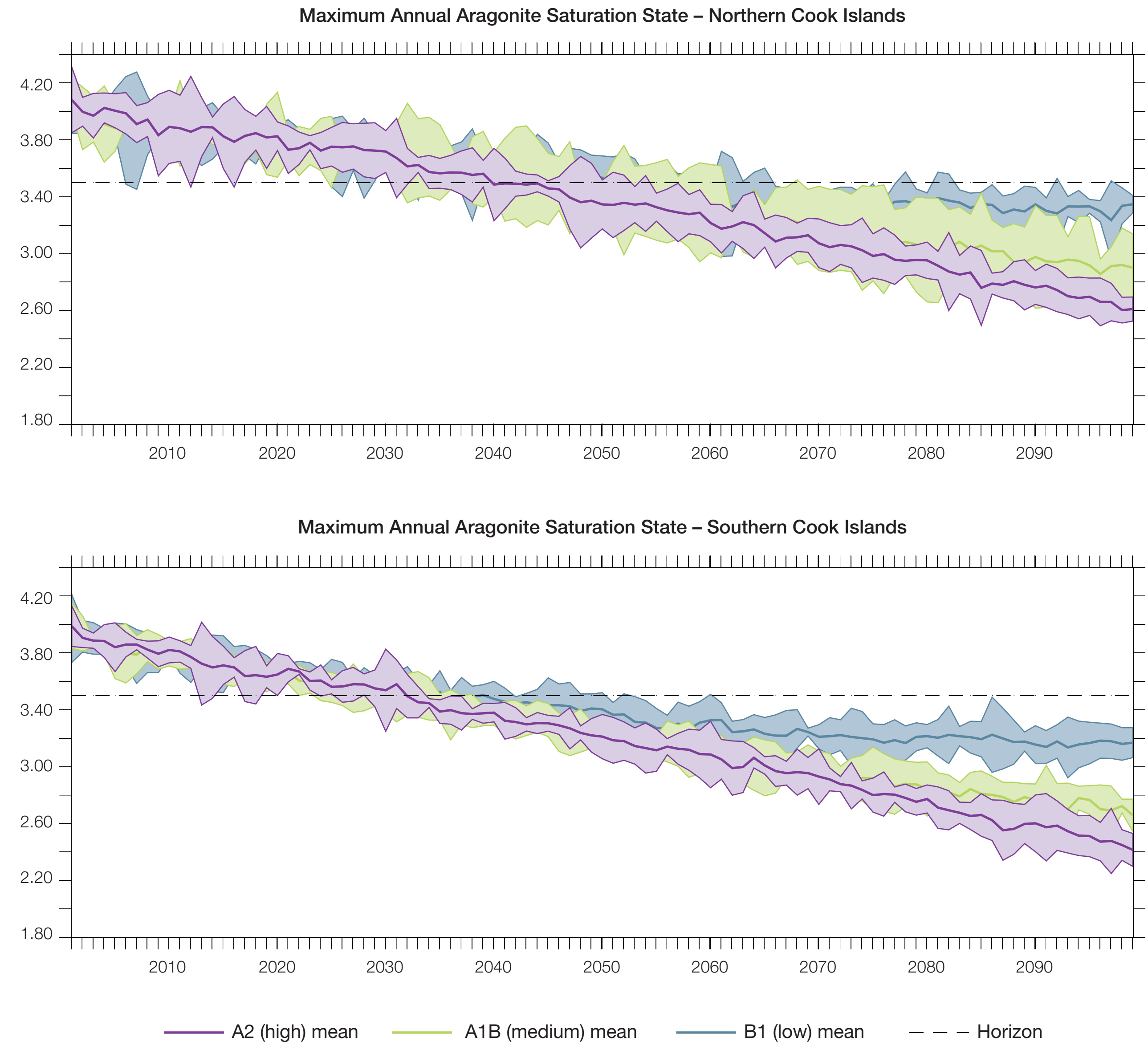


Figure 2.9: Multi-model projections, and their associated uncertainty (shaded area represents two standard deviations), of the maximum annual aragonite saturation state in the sea surface waters of the Northern Cook Islands (top) and the Southern Cook Islands (bottom) under the different emissions scenarios. The dashed black line represents an aragonite saturation state of 3.5.

However, adequate understanding of the processes is currently too limited to provide a best estimate or an upper bound (IPCC, 2007).

- Globally, since the early 1990s, sea level has been rising near the upper end of the above projections. During the 21st century, some studies (using semi-empirical models) project faster rates of sea-level rise.

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 19 cm (5–95% range, after removal of the seasonal signal; see dashed lines in Figure 2.10 (a)) and it is likely that a similar range will continue through the 21st century. In addition, winds and waves associated with weather phenomena will continue to lead to extreme sea-level events.

In addition to the regional variations in sea level associated with ocean and mass changes, there are ongoing changes in relative sea level associated with changes in surface loading over the last glacial cycle (glacial isostatic adjustment) and local tectonic motions. The glacial isostatic motions are relatively small for the PCCSP region.

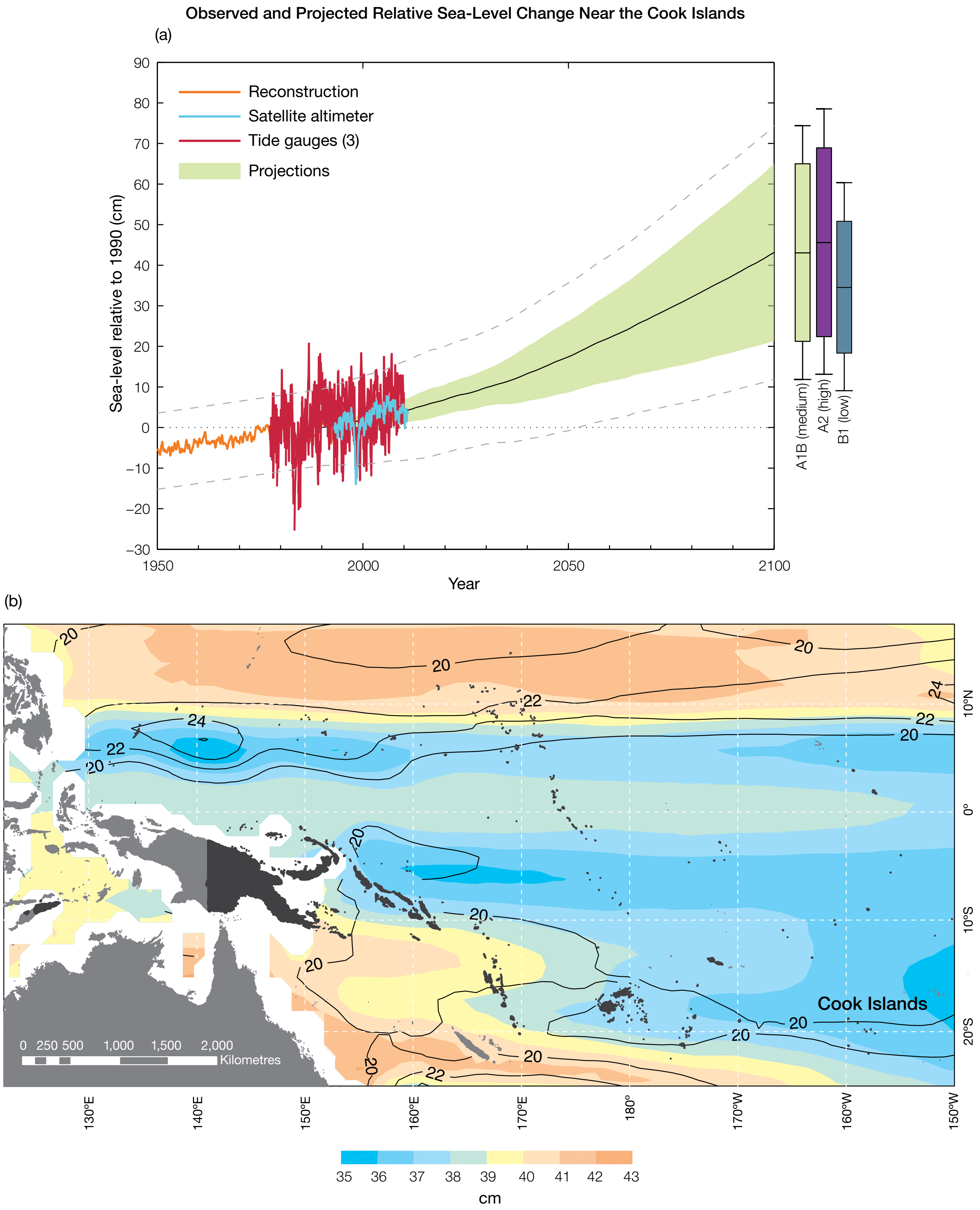


Figure 2.10: Observed and projected relative sea-level change near the Cook Islands. (a) The observed in situ relative sea-level records (since the late 1970s) are indicated in red, with the satellite record (since 1993) in light blue. The gridded (reconstructed) sea level data at the Cook Islands (since 1950, from Church and White (in press)) is shown in orange. The projections for the A1B (medium) emissions scenario (5–95% uncertainty range) are shown by the green shaded region from 1990–2100. The range of projections for the B1 (low), A1B (medium) and A2 (high) emissions scenarios 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% range about the long-term trends) and indicate that individual monthly averages of sea level can be above or below longer-term averages. (b) The projections for the A1B (medium) emissions scenario for the average over 2081–2100 relative to 1981–2000 are indicated by the shading, with the estimated uncertainty in the projections indicated by the contours (in cm).

2.7.6 Projections Summary

The projections presented in Section 2.7 are summarised in Table 2.4 (Northern Cook Islands) and Table 2.5 (Southern Cook Islands). For detailed information regarding the various uncertainties associated with the table values, refer to the preceding text in Sections 2.7 and 1.7, in addition to Chapters 5 and 6 in Volume 1. When interpreting the differences between projections for the B1 (low), A1B (medium) and A2 (high) emissions scenarios, it is also important to consider the emissions pathways associated with each scenario (Volume 1, Figure 4.1) and the fact that a slightly different subset of models was available for each (Volume 1, Appendix 1).

Table 2.4: Projected change in the annual and seasonal mean climate for the Northern Cook Islands, under the B1 (low; blue), A1B (medium; green) and A2 (high; purple) emissions scenarios. Projections are given for three 20-year periods centred on 2030 (2020–2039), 2055 (2046–2065) and 2090 (2080–2099), relative to 1990 (1980–1999). Values represent the multi-model mean change ± twice the inter-model standard deviation (representing approximately 95% of the range of model projections), except for sea level where the estimated mean change and the 5–95% range are given (as they are derived directly from the Intergovernmental Panel on Climate Change Fourth Assessment Report values). The confidence (Section 1.7.2) associated with the range and distribution of the projections is also given (indicated by the standard deviation and multi-model mean, respectively). See Volume 1, Appendix 1, for a complete listing of CMIP3 models used to derive these projections.

Variable	Season	2030	2055	2090	Confidence
Surface air temperature (°C)	Annual	+0.6 ± 0.4 +0.8 ± 0.4 +0.7 ± 0.2	+1.1 ± 0.4 +1.4 ± 0.5 +1.4 ± 0.4	+1.5 ± 0.6 +2.2 ± 0.8 +2.6 ± 0.6	Moderate
Maximum temperature (°C)	1-in-20-year event	N/A	+1.0 ± 0.6 +1.4 ± 0.6 +1.5 ± 0.5	+1.3 ± 0.7 +2.0 ± 1.1 +2.6 ± 1.3	Low
Minimum temperature (°C)	1-in-20-year event	N/A	+1.3 ± 1.7 +1.6 ± 1.6 +1.4 ± 1.9	+1.7 ± 1.7 +1.9 ± 1.8 +2.3 ± 1.9	Low
Total rainfall (%)*	Annual	+3 ± 8 +4 ± 9 +3 ± 13	+5 ± 12 +6 ± 25 +6 ± 26	+6 ± 22 +8 ± 33 +9 ± 37	Low
Wet season rainfall (%)*	November-April	+4 ± 9 +4 ± 9 +3 ± 9	+5 ± 11 +6 ± 19 +5 ± 19	+6 ± 19 +8 ± 31 +8 ± 31	Low
Dry season rainfall (%)*	May-October	+4 ± 14 +5 ± 13 +5 ± 19	+6 ± 15 +7 ± 35 +8 ± 38	+6 ± 28 +9 ± 42 +10 ± 51	Low
Sea-surface temperature (°C)	Annual	+0.6 ± 0.3 +0.7 ± 0.4 +0.7 ± 0.4	+0.9 ± 0.4 +1.2 ± 0.5 +1.3 ± 0.6	+1.3 ± 0.5 +2.0 ± 0.8 +2.3 ± 0.8	Moderate
Aragonite saturation state (Ωar)	Annual maximum	+3.6 ± 0.2 +3.6 ± 0.2 +3.6 ± 0.1	+3.4 ± 0.2 +3.3 ± 0.2 +3.3 ± 0.2	+3.3 ± 0.1 +2.9 ± 0.3 +2.7 ± 0.1	Moderate
Mean sea level (cm)	Annual	+10 (5–15) +10 (5–15) +10 (4–15)	+18 (10–26) +20 (10–30) +19 (10–29)	+31 (17–45) +38 (19–56) +38 (19–58)	Moderate

*The MIROC3.2(medres) and MIROC3.2(hires) models were eliminated in calculating the rainfall projections, due to their inability to accurately simulate present-day activity of the South Pacific Convergence Zone (Volume 1, Section 5.5.1).

Table 2.5: Projected change in the annual and seasonal mean climate for the Southern Cook Islands, under the B1 (low; blue), A1B (medium; green) and A2 (high; purple) emissions scenarios. Projections are given for three 20-year periods centred on 2030 (2020–2039), 2055 (2046–2065) and 2090 (2080–2099), relative to 1990 (1980–1999). Values represent the multi-model mean change ± twice the inter-model standard deviation (representing approximately 95% of the range of model projections), except for sea level where the estimated mean change and the 5–95% range are given (as they are derived directly from the Intergovernmental Panel on Climate Change Fourth Assessment Report values). The confidence (Section 1.7.2) associated with the range and distribution of the projections is also given (indicated by the standard deviation and multi-model mean, respectively). See Volume 1, Appendix 1, for a complete listing of CMIP3 models used to derive these projections.

Variable	Season	2030	2055	2090	Confidence
Surface air temperature (°C)	Annual	+0.6 ± 0.4 +0.7 ± 0.4 +0.7 ± 0.3	+1.0 ± 0.5 +1.3 ± 0.6 +1.3 ± 0.4	+1.3 ± 0.6 +2.0 ± 0.8 +2.5 ± 0.7	Moderate
Maximum temperature (°C)	1-in-20-year event	N/A	+1.0 ± 0.6 +1.4 ± 0.6 +1.5 ± 0.6	+1.2 ± 0.8 +2.0 ± 0.9 +2.5 ± 1.3	Low
Minimum temperature (°C)	1-in-20-year event	N/A	+1.1 ± 1.6 +1.4 ± 1.6 +1.3 ± 1.6	+1.4 ± 1.5 +2.9 ± 1.8 +2.0 ± 1.9	Low
Total rainfall (%)*	Annual	+1 ± 11 +3 ± 10 +5 ± 9	+2 ± 8 +3 ± 13 +5 ± 11	+5 ± 14 +6 ± 13 +8 ± 24	Low
Wet season rainfall (%)*	November-April	+1 ± 11 +3 ± 11 +3 ± 9	+3 ± 11 +3 ± 13 +5 ± 14	+5 ± 19 +7 ± 15 +10 ± 23	Low
Dry season rainfall (%)*	May-October	+1 ± 15 +5 ± 15 +7 ± 12	+2 ± 12 +4 ± 17 +5 ± 15	+5 ± 13 +6 ± 22 +6 ± 34	Low
Sea-surface temperature (°C)	Annual	+0.6 ± 0.3 +0.6 ± 0.3 +0.7 ± 0.3	+0.9 ± 0.4 +1.1 ± 0.4 +1.2 ± 0.4	+1.3 ± 0.4 +1.9 ± 0.5 +2.3 ± 0.7	Moderate
Aragonite saturation state (Ωar)	Annual maximum	+3.5 ± 0.1 +3.5 ± 0.1 +3.5 ± 0.1	+3.3 ± 0.1 +3.1 ± 0.1 +3.1 ± 0.1	+3.1 ± 0.1 +2.7 ± 0.1 +2.5 ± 0.1	Moderate
Mean sea level (cm)	Annual	+10 (5–15) +10 (5–15) +10 (4–15)	+18 (10–26) +20 (10–30) +19 (10–29)	+31 (17–45) +38 (19–56) +38 (19–58)	Moderate

*The MIROC3.2(medres) and MIROC3.2(hires) models were eliminated in calculating the rainfall projections, due to their inability to accurately simulate present-day activity of the South Pacific Convergence Zone (Volume 1, Section 5.5.1).