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# Decision support tools for climate-resilient coastal development: A case study from the Cook Islands Pacific Adaptation to Climate Change (PACC) project

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# Decision support tools for climate-resilient coastal development: A case study from the Cook Islands Pacific Adaptation to Climate Change (PACC) project

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The report was reviewed by Netatua Pelesikoti and Espen Ronneberg of SPREP.

# EXECUTIVE SUMMARY

In the Cook Islands, the Pacific Adaptation to Climate Change (PACC) project focuses on coastal zone management on Mangaia Island. The project is helping to 'climate-proof' coastal development, and to develop an integrated coastal management policy and plan for Mangaia.

The study reported here was developed under the PACC project to demonstrate the combined use of modelling, a climate tool – the Cook Islands Coastal Calculator – and community knowledge to quantify the risk of coastal inundation to property and infrastructure in the village of Oneroa now and under future climate scenarios, and to incorporate this information into community decision making and planning for 'climate-proof' development. The study was led by a team of technical experts from the Secretariat of the Pacific Community (SPC)'s Applied Geoscience and Technology Division (SOPAC) and New Zealand's National Institute of Water and Atmospheric Research (NIWA), with assistance from the Cook Islands Ministry of Infrastructure and Planning (MOIP).

To develop the information needed to inform the Oneroa community on inundation, and how this may change with climate change, the following steps were carried out:

- Modelling of offshore wave and water level conditions;
- Assessment of climate change, and how this might influence wave and water level conditions;
- Selection of appropriate extreme event and climate change scenarios;
- Collection of reef and shoreline data (to feed into the Cook Islands Coastal Calculator);
- Deriving wave run-up levels for Oneroa village (using the Cook Islands Coastal Calculator).

The final step brought together the Oneroa community to review the information and identify appropriate adaptation options to reduce the climate risk to the coastal community and its infrastructure.

## Modelling offshore wave and water level conditions

In the Cook Islands, coastal inundation tends to occur either during tropical cyclones, or when large swell, which has travelled across the ocean, reaches the Cook Islands. The most severe inundation usually occurs when this coincides with high seas, due to tides and other sea fluctuations. To understand and assess inundation of coastal land in the Cook Islands, it is necessary to understand these wave conditions, how likely they are to occur with different sea levels, and how these two parameters influence wave set-up, wave run-up, overtopping and overwashing at the shoreline. Climate change is an additional factor that also needs to be taken into account, for example, sea level rise and other climate change effects, such as changes in intensity and frequency of cyclone conditions.

The first step involved modelling these wave and water level conditions in order to generate joint probability combinations (i.e. likelihood of co-occurrence) for these two parameters, i.e. extreme swell waves and high seas, and cyclone waves and high seas. For swell wave conditions, a global wave hindcast model was used, while for cyclone conditions a cyclone statistical model was built to simulate thousands of years of cyclone events. Joint probability methods were then used to calculate the likelihood of high sea levels (tide + mean level of the sea fluctuations + storm surge) and large swell or cyclone waves occurring at the same time.

## Climate change influences

The main climate change-related factors that could influence the occurrence or severity of coastal flooding in the Cook Islands relate to changes in mean sea level, changes in the frequency or intensity of cyclone events, and changes in swell wave conditions, specifically extreme swell events. This step involved assessing current understanding on these climate change impacts, and the influence these changes might have on shoreline wave and water levels.

## Selecting appropriate extreme event and climate change scenarios

For development decisions that could be affected by coastal hazards (waves and water levels and associated inundation), the following need to be considered:

- What is the potential timeframe or design life of my decision?
- How extreme an event should I consider (i.e. what average recurrence interval event should I use)?
- What sea level rise scenario should I use?
- How sensitive is my decision (what are the potential costs or impacts during the lifetime of the decision) to:
  - Different sea level rises than that assumed, and what happens if resulting sea level rise is greater than I have assumed?
  - Possible changes in cyclone occurrence and intensity?
  - Possible changes in the heights of extreme swell wave conditions?
- What happens beyond the lifetime of my decision?

This step was designed to answer these questions, for consideration of cyclone inundation risk at Oneroa. The process combined climate data and science with community decision making to reach the best informed decisions. Decision making was done within a community meeting that brought together the team of technical experts, staff from MOIP, and the Oneroa community.

## Collection of reef and shoreline data

The cyclone and swell wave and water level conditions modelled need to be translated to shoreline wave and water level conditions in order to be useful for coastal design and engineering. To do this, we also need information on nearshore bathymetry and topography (reef and shoreline profiles, with data related to land levels), and wave and water level calibration data. This information is then used to calibrate the Cook Islands Coastal Calculator.

The field data collection activities were conducted between December 2010 and February 2011 by SOPAC with assistance from MOIP.

## Deriving wave run-up levels for Oneroa village

The Cook Islands Coastal Calculator provides the link between the modelled wave conditions and the coastal inundation that might be expected to occur under different future scenarios. The Calculator is a Microsoft Excel based engineering spreadsheet. It simulates inundation based on information on the 'drivers' of inundation (waves and water levels at the shoreline, wave run-up and overtopping), how these will change over the next 100 years due to possible climate change and sea level rise, and how these drivers interact with the reef and shoreline characteristics at a particular location.

Defining zones of potential wave run-up under cyclone and swell events was done using the Cook Islands Coastal Calculator, and also community knowledge of past cyclone inundation events within historical memory of the Oneroa community, which helped to verify the performance of the Calculator.

Based on community decisions around acceptible levels of risk, the Calcuator was used to derive cyclone wave run-up levels for the following:

- Present day (2010) levels for 50 and 100 year average recurrence interval (ARI) events;
- 2030s level for a 50 year ARI event (i.e., a cyclone event that will *possibly* occur over the next 25 years/1 generation) with a mean sea level rise of 0.15 m (baseline) and 0.3 m (high);
- 2060s level for a 50 year ARI event (i.e. a cyclone event that will *likely* occur over the next 50 years/2 generations) with a mean sea level rise of 0.4 m (baseline) and 0.75 m (high);
- 2060s level for a 100 year ARI event (i.e. a cyclone event that will *possibly* occur over the next 50 years/2 generations) with a mean sea level rise of 0.4 m (baseline) and 0.75 m (high).

Using the run-up levels calculated using the Cook Islands Coastal Calculator for the 2030s and 2060s and consideration of the historical cyclone run-up levels, the figure below gives suggested coastal hazard lines for the period up to the 2030s (green line) and for the period up to the 2060s (red line). These lines represent:

- Green line: a possible chance of wave run-up due to a 50 year ARI cyclone event reaching this level over the period from the present to the 2030s;
- Red line: a possible chance of wave run-up due to a 100 year ARI cyclone event reaching this level over the period from the present to the 2060s.

Final cyclone hazard lines developed for the 2030s and 2060s for Oneroa village, Mangaia, Cook Islands.

## Identifying adaptation options

Using the indicative cyclone run-up levels developed, the historical cyclone run-up levels, and assessment of how these run-up levels may change due to sea level rise and changes in cyclone characteristics, the community identified the facilities at risk along the Oneroa frontage.

Activities that increased the risk of inundation to the village frontage during cyclone events were also identified. These included increasing the width of the channel at the wharf (or any other channels over the fringing reef); cutting roads down through the makatea to the shoreline; and removing vegetation between the road and the shoreline.

For Oneroa village to adapt to the effects that climate change will have on inundation risk, it was agreed by the community to take an approach that prevents any further village infrastructure being constructed in areas that will potentially be affected by cyclone run-up that is likely or possible to occur over the next two generations; and to progressively implement key risk reduction and adaptation options identified as part of the Mangaia Island Administration annual planning and operational activities.

# ABBREVIATIONS

**AR4** Fourth Assessment Report of the Intergovernmental Panel for Climate Change

**ARI** Average recurrence interval

**CDF** Cumulative distribution function

**DEM** Digital elevation map

**ENSO** El Niño Southern Oscillation

**IPCC** Intergovernmental Panel for Climate Change

**MLOS** Mean level of the sea

**MOIP** Cook Islands Ministry of Infrastructure and Planning

**NIWA** National Institute of Water and Atmospheric Research (New Zealand)

**PACC** Pacific Adaptation to Climate Change [programme/project]

**SOPAC** Applied Geoscience and Technology Division (of the Secretariat of the Pacific Community)

# 1. INTRODUCTION

The Pacific Adaptation to Climate Change (PACC) programme is the largest climate change adaptation initiative in the Pacific region, with projects in 14 countries and territories. PACC has three main areas of activity: practical demonstrations of adaptation measures; driving the mainstreaming of climate risks into national development planning and activities; and sharing knowledge in order to build adaptive capacity. The goal of the programme is to reduce vulnerability and to increase adaptive capacity to the adverse effects of climate change in three key climate-sensitive development sectors: coastal zone management, food security and food production, and water resources management. The programme began in 2009 and is scheduled to end in December 2014.

In the Cook Islands, the PACC project focuses on coastal zone management on Mangaia Island. Mangaia is the southernmost and second largest of the Cook Islands, and has a population of about 570 people. The project is helping to 'climate-proof' coastal development, and to develop an integrated coastal management policy and plan for Mangaia.

Property and infrastructure located in the coastal areas of the Cook Islands are extremely vulnerable to coastal inundation, and this will be exacerbated by climate change. Most coastal inundation in the Cook Islands occurs either during tropical cyclones or periods when large swell, which has travelled across the ocean, reaches the Cook Islands. If one of these events coincides with high sea level due to tide or other sea fluctuations, coastal inundation usually occurs.

Understanding extreme water levels and wave conditions, how likely they are to occur together during cyclone and swell events, and how these influence wave set-up, wave run-up, overtopping and overwashing at the shoreline is fundamental in understanding and assessing inundation of land areas in the Cook Islands, and how this may change with sea level rise and other climate change effects (such as changes in intensity and frequency of cyclone conditions).

This study was developed under the PACC project, to demonstrate the combined use of modelling, a new climate tool – the Cook Islands Coastal Calculator – and community knowledge to quantify the risk to property and infrastructure in the village of Oneroa now and under future scenarios, and to incorporate this information into community decision making and planning for 'climate-proof' development.

The study was led by a team of technical experts from the Secretariat of the Pacific Community (SPC)'s Applied Geoscience and Technology Division (SOPAC) and the New Zealand National Institute of Water and Atmospheric Research (NIWA), with assistance from the Cook Islands Ministry of Infrastructure and Planning (MOIP). The study aimed to:

- Develop baseline information necessary to support a risk-based approach to climate change adaptation in the coastal zone of Mangaia Island;
- Assess how climate change and sea level rise will impact on the frequency, magnitude and extent of coastal inundation along the village/harbour and airport shorelines of Mangaia Island;
- Provide a sound, objective and evidence-based framework for developing climate change adaptation strategies for Mangaia; and
- Demonstrate an approach that is scalable and can be transferred and applied to other coastal areas in the Cook Islands (or indeed other Pacific Islands).

This report summarises the process involved in developing the information to support coastal adaptation and risk reduction decision making in the coastal zone of Mangaia. The study aimed at informing the inhabitants of Oneroa on inundation, and how this may change with climate change.

A main project output was the development of the Cook Islands Coastal Calculator, which is a Microsoft Excel based engineering spreadsheet that can be used to provide information on waves and water levels at the shoreline, wave run-up and overtopping. The Calculator is briefly described in Section 6. Information on the cross-shore shape of the local reef profile is needed to use the Calculator. These data were collected at Mangaia by the SOPAC team as part of the study (Section 5).

The basic process adopted for carrying out the study is summarised as a number of steps in Figure 1.

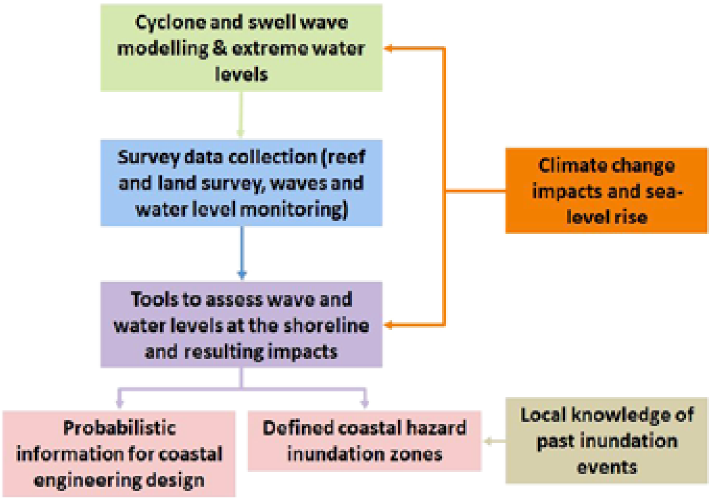



Figure 1. Basic process adopted for the Mangaia study.

The process within each component of Figure 1 is outlined in further detail in the following sections of this report, with further detail contained in the supporting outputs produced as part of the project:

- Single beam bathymetric survey of Mangaia, Cook Islands (Kumar et al., 2012);
- Topographic data acquisition survey in Mangaia, Cook Islands (Damlamian et al., 2012);
- Cook Island Coastal Calculator tool (Version 1.23);
- Cook Islands Coastal Calculator: User Manual (Ramsay, 2012);
- Coastal hazard areas, Oneroa village, Mangaia, Cook Islands (Ramsay, 2012).

## 2. MODELLING OFFSHORE WAVE AND WATER LEVEL CONDITIONS

In the Cook Islands, coastal inundation tends to occur either during tropical cyclones, or when large swell, which has travelled across the ocean, reaches the Cook Islands. For inundation, this usually coincides with high seas, due to tides and other sea fluctuations.

To understand and assess inundation of coastal land in the Cook Islands, it is necessary to understand these wave conditions, how likely they are to occur with different sea levels, and how these two parameters influence wave set-up, wave run-up, overtopping and overwashing at the shoreline. Climate change is an additional factor that also needs to be taken into account, for example, sea level rise and other climate change effects, such as changes in intensity and frequency of cyclone conditions.

This section describes the process of modelling these wave and water level conditions in order to generate joint probability combinations (i.e. likelihood of co-occurrence) for these two parameters, i.e. extreme swell waves and high seas, and cyclone waves and high seas. The processes are summarised in Figures 2 and 3, for swell waves and cyclones, respectively.

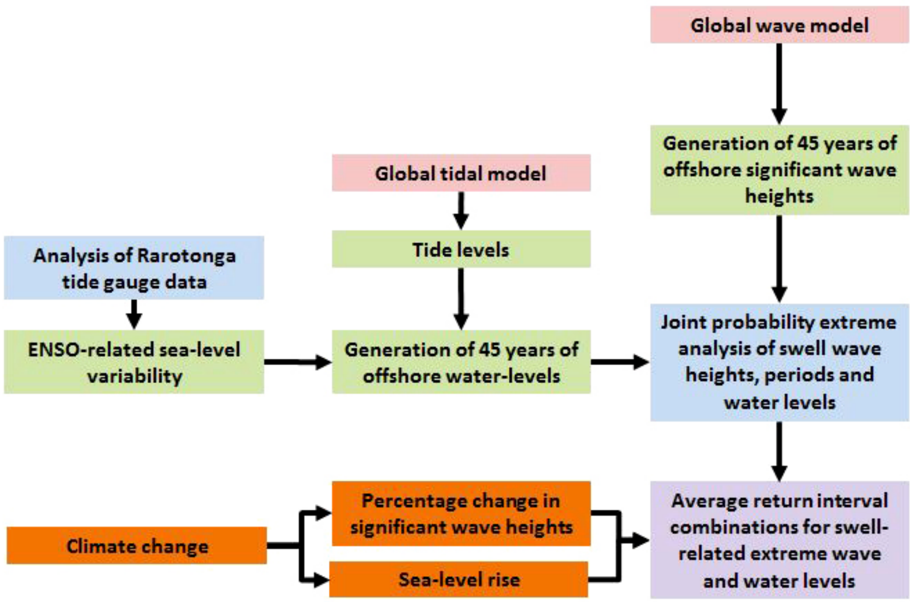



Figure 2. Summary of the process used to derive offshore extreme swell wave/high water level joint probabilities.

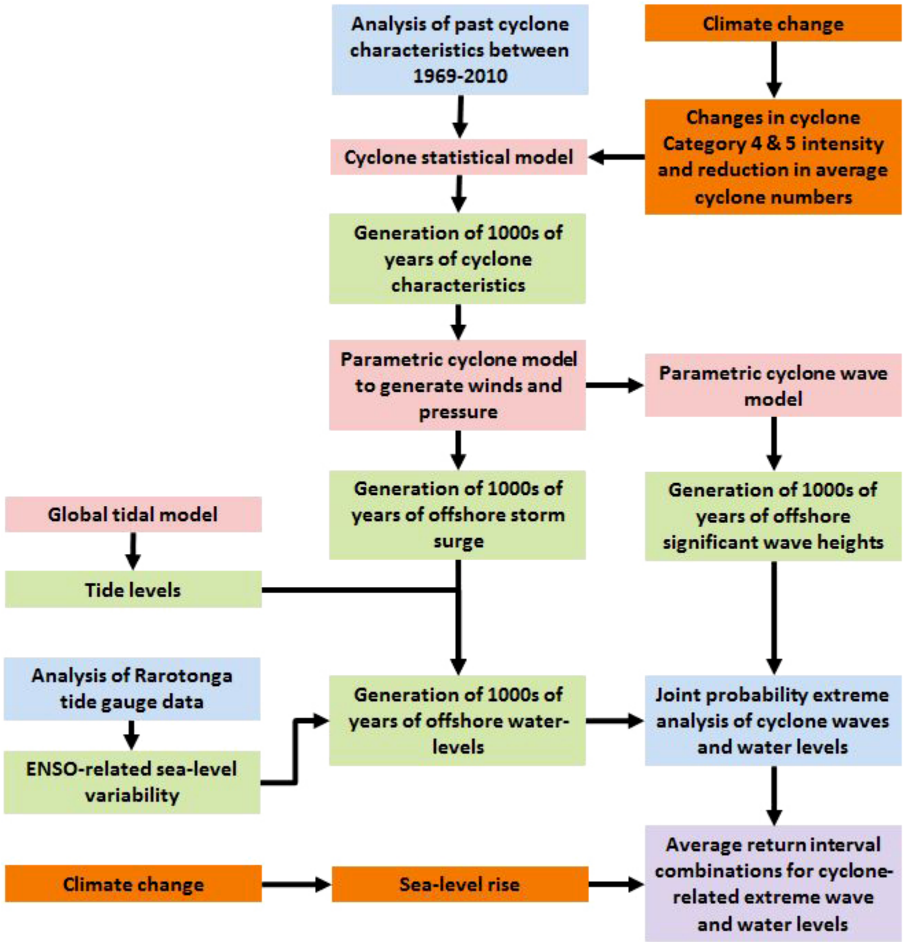



Figure 3. Summary of the process used to derive cyclone wave/high water level joint probabilities.

## 2.1. Swell wave conditions

For swell wave conditions:

1. A global wave hindcast model (Figure 4) was used and forced by wind and sea-surface pressure outputs from the ERA-40 reanalysed dataset from the European Centre for Medium-Range Weather Forecasts at 1.125 x 1.125 degree resolution in latitude/longitude (developed as part of NIWA's Waves And Storm surge Prediction (WASP) project, http://www.niwa.co.nz/our-science/coasts (Gorman et al., 2010, 2011)).
2. The 45 years of data provided a long enough record to assess offshore extreme swell conditions around each island in the Cook Islands. The wave climate at each location was filtered to only include wave conditions from within an appropriate directional sector for the corresponding exposure of each section of each island's coastline. In total, extreme swell conditions were extracted for 75 locations around the 15 islands in the Cook Islands.
3. A global tidal model was used to derive tidal water level variation for the same 45-year period for each of the Cook Islands (Egbert et al., 1994; Egbert and Erofeeva, 2002).
4. Mean level of the sea fluctuations due to climate variability such as El Niño Southern Oscillation (ENSO) was assessed by analysing 18 years of sea level record from the sea level gauge at Rarotonga and assumed to be representative for the entire Cook Islands.
5. Joint probability methods (Hawkes et al., 2002) were then used to calculate the likelihood of high sea levels (tide + mean level of the sea fluctuations) and large swell waves occurring at the same time. For swell waves it was assumed that wave conditions (wave height and period) and sea level were independent of each other.

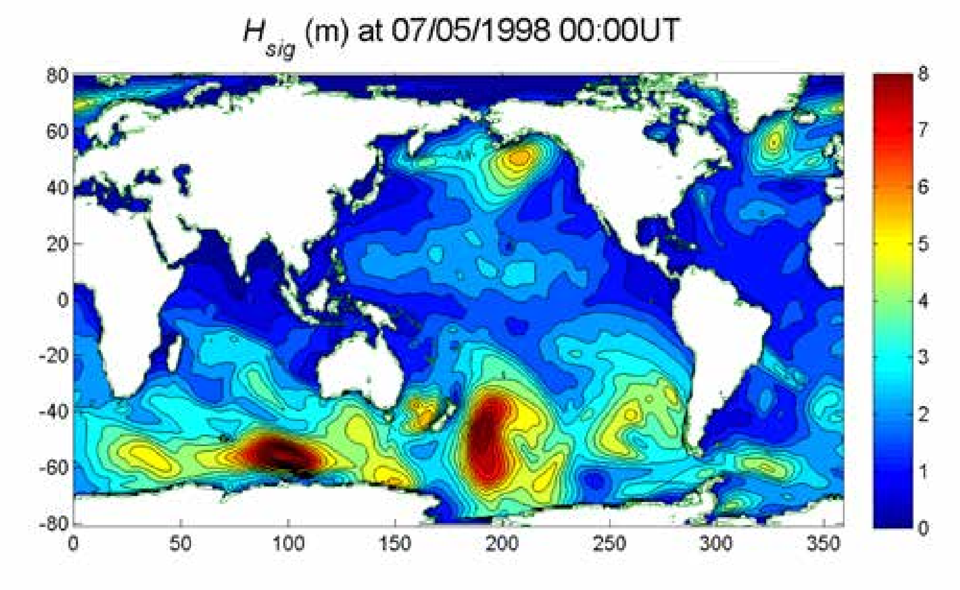



Figure 4. Significant wave height from the global wave model used for one particular date and time. The model output is for 7 May 1998 at 00:00 UT. It shows a large storm system to the east of New Zealand and swell propagating from it up towards the Cook Islands.

## 2.2. Cyclone conditions

Unfortunately in areas that experience cyclones, extreme cyclone wave height conditions cannot be directly calculated from the hindcast dataset above due to the relatively coarse spatial resolution of the model, and to do so would tend to underpredict extreme cyclone wave conditions.

For cyclone wave conditions, a cyclone statistical model was built to simulate thousands of years of cyclone events. The model follows similar approaches in the literature (e.g. Hall and Jewson, 2007; Rumpf et al., 2010), and was built by statistical sampling observations of cyclone tracks and key characteristics since satellite monitoring commenced in 1969 (Figure 5).

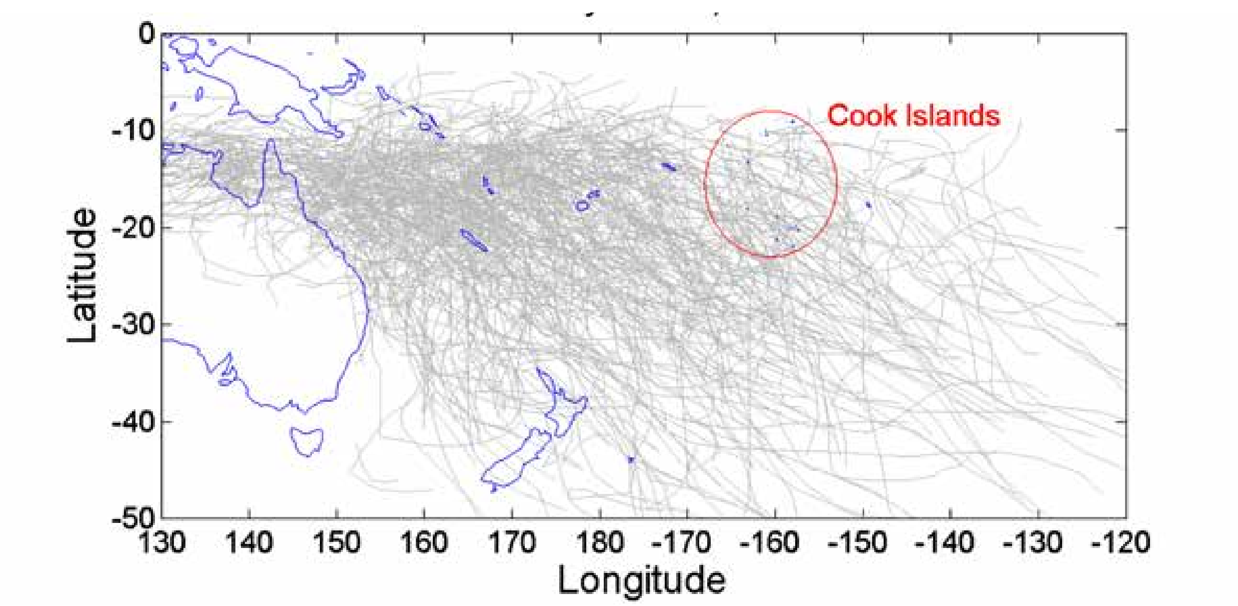



Figure 5. Cyclone tracks in the South Pacific since 1969.

The basic sequence of steps to build the model was:

1. Sample historically observed cyclone 6-hourly locations, and fit a kernel smoothing function to model the likelihood of an observation at a particular location. Randomly sample from the kernel model at the historic observation rate to simulate future cyclone observations. Figure 6 shows an example of how the statistical cyclone model is able to generate cyclone observations with the same occurrence likelihood and spatial patterns as the satellite observations. But whereas the satellite observation dataset is only 43 years long, the statistical cyclone model can be run to simulate cyclones over thousands of years, building up a thorough picture of the cyclone-related hazard at any offshore location.
2. Fit empirical cumulative distribution functions (CDFs) to the five key cyclone parameters: propagation speed and direction, central pressure, maximum wind speed and radius to maximum wind.
3. For each simulated cyclone observation, randomly sample the five key cyclone parameters from the fitted CDFs. Figure 7 compares the CDFs of the cyclone observations with a model simulation. The model gives a good representation of the statistical distribution for all five of the key cyclone parameters. The model parameters were sampled from joint distributions, for example the central pressure is direction dependent, and maximum sustained wind speed is central pressure dependent. The red and green circles in Figure 7 are examples of random variable selections from the CDFs during two model simulations. Thousands of years' worth of cyclones were then simulated by randomly sampling the joint distributions many thousands of times.
4. The cyclone model can be 'tweaked' to simulate possible climate change effects on cyclones, for example, a 10% increase in central pressure intensity for category 4 and 5 cyclones.
5. Having simulated thousands of years' worth of cyclones, the associated wave and inverse-barometer storm-surge conditions were calculated for each cyclone, using the Ross (Ross, 1976) wave parametric model (e.g. Figure 8) and the Holland (Holland, 1980) parametric model. This provided thousands of years' worth of simulated cyclone wave and storm surge conditions, for each island in the Cook Islands group.
6. A Monte Carlo sampling technique was used to generate offshore storm tide levels for each of the Cook Islands, using the tide level variability, climate-related variability in the mean-level-of-the-sea (MLOS) using the approach summarised in the previous section, and the storm surge levels derived from the cyclone model.
7. As with the swell wave conditions, a joint probability analysis (Hawkes et al., 2002) was conducted to calculate the likelihood associated with a range of cyclone-related storm tides and wave heights that could occur together.

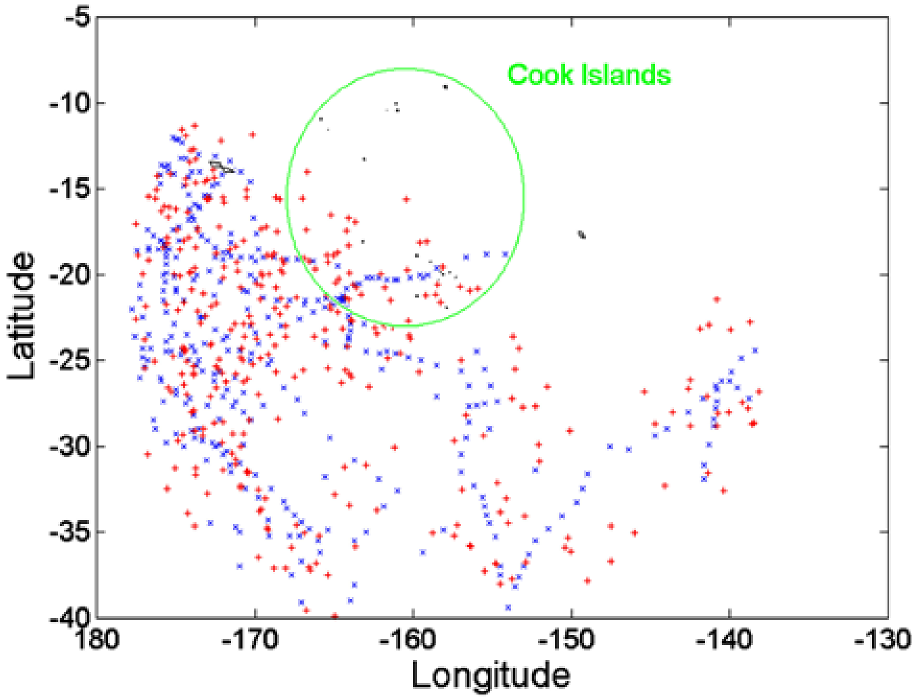



Figure 6. Observed 6-hourly cyclone locations during strong La Niña phases (blue), and a matching number of random cyclone model locations (red).

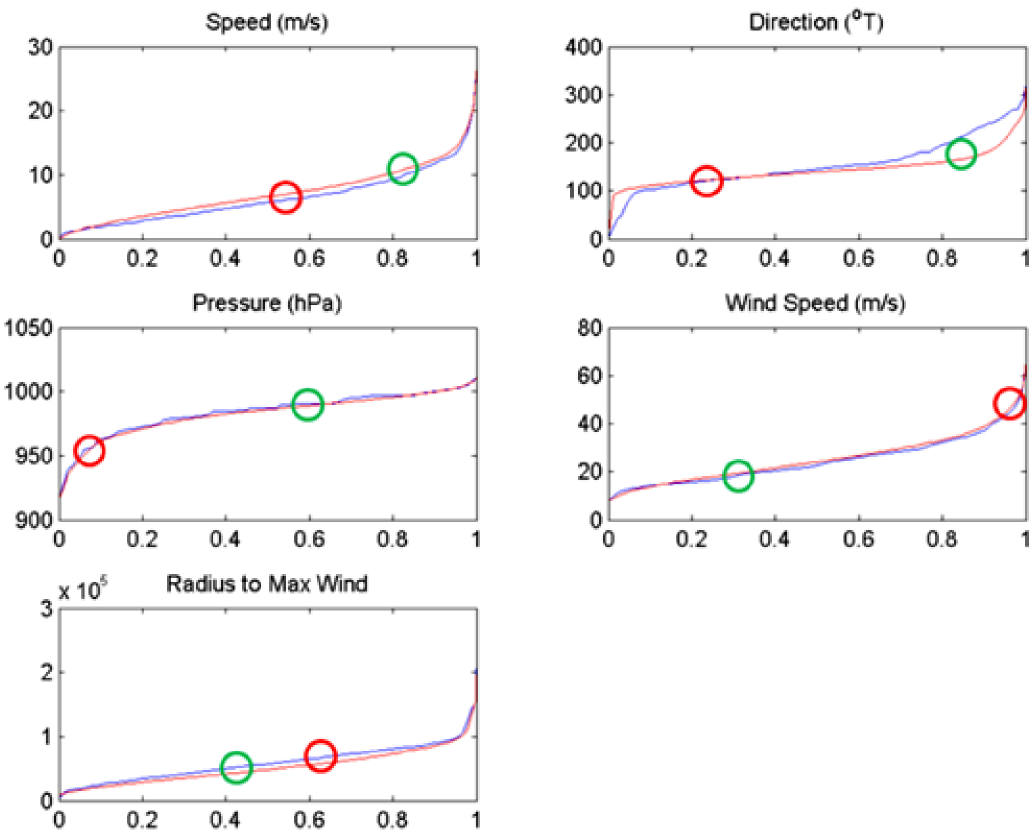



Figure 7. Cumulative distribution functions (CDFs) for the five key cyclone parameters. Observed from the satellite data (blue) and modelled (red).

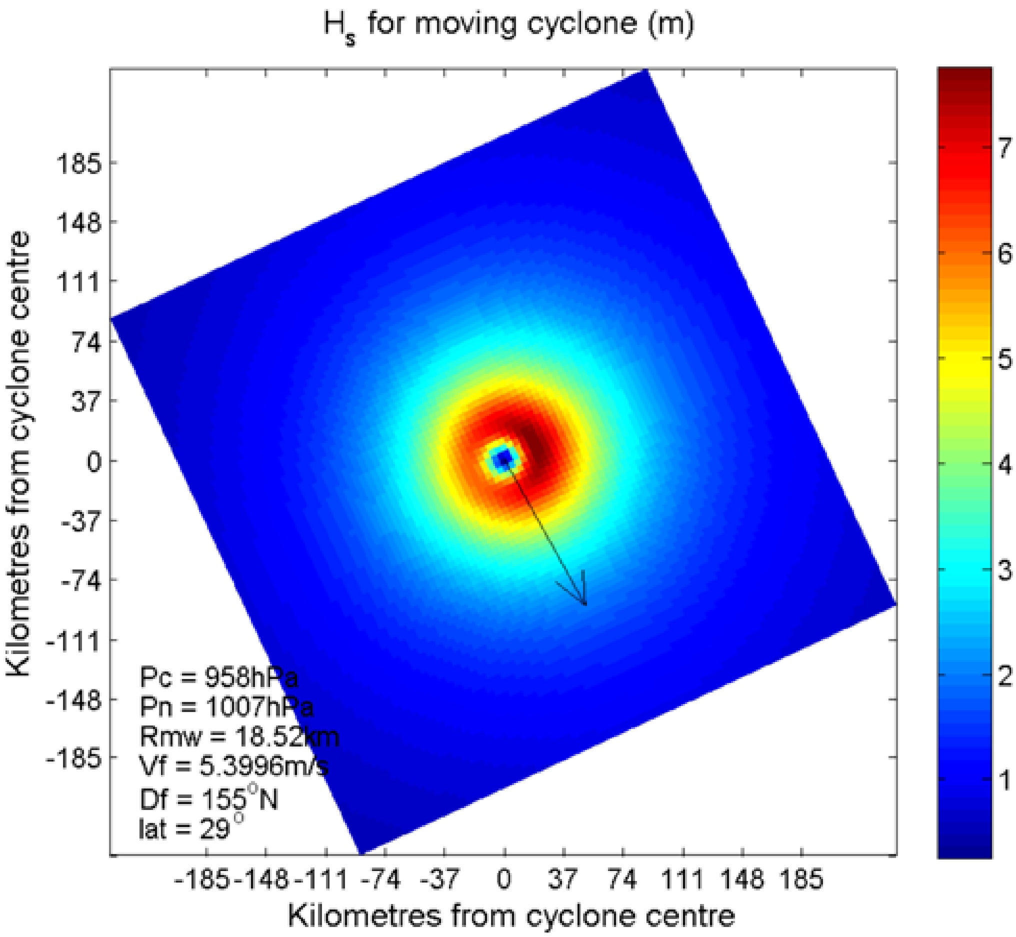



Figure 8. Example of significant wave height distribution predicted using the Ross (1976) wave parametric model.

Figure 9 shows the joint probability analyses for present-day conditions at Mangaia, for both swell and cyclone conditions. This shows how the wave hindcast model underpredicts the extreme wave heights compared to the statistical cyclone model.

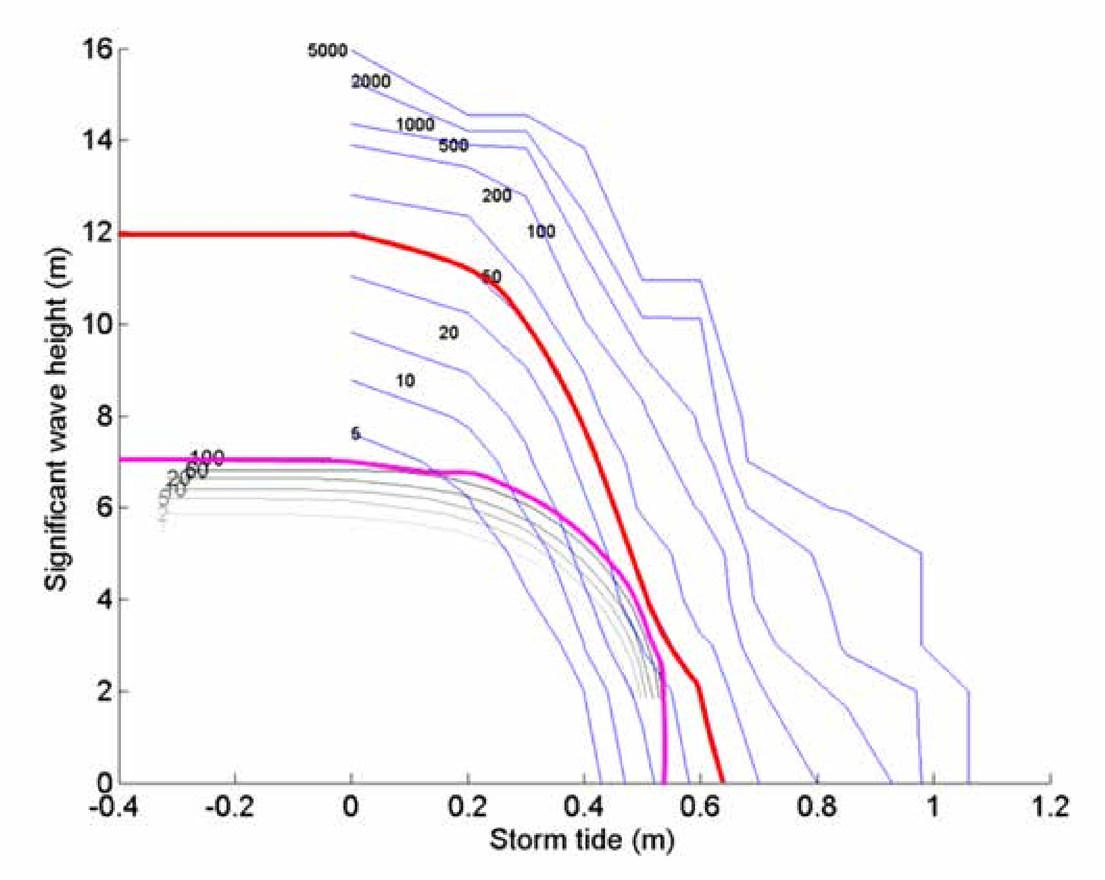



Figure 9. Significant wave height and storm tide joint probability contours offshore of Oneroa village, Mangaia, for both extreme swell and cyclone conditions. The storm tide levels are relative to mean level of the sea. The 1% annual exceedance probability (equivalent to the 1 in 100 year average recurrence interval) curves are marked by the pink curve (swell) and red curve (cyclones).

# 3. CLIMATE CHANGE INFLUENCES

The main climate change-related factors that could influence the occurrence or severity of coastal flooding in the Cook Islands relate to:

- Changes in mean sea level;
- Changes in the frequency or intensity of cyclone events;
- Changes in swell wave conditions, specifically extreme swell events.

This section summarises current understanding on these climate change impacts, and the influence these changes might have on shoreline wave and water levels.

## 3.1. Changes in mean sea level

Over the 20th century global mean sea level increased by on average 0.17 ± 0.05 m (1.7 ± 0.5 mm/year). In the most recent analysis, Church and White (2011) show the global-average trend up to 2009 rose slightly from 1.7 ± 0.2 mm/year (starting from 1900) up to 1.9 ± 0.4 mm/year (starting from 1961). The mean sea level trend at Rarotonga between 1993 and 2010 recorded by the SEAFRAME sea level gauge is currently 4.8 mm/year (Bureau of Meteorology, 2011), but the rate varies from month to month due to the relatively short period of the record.

Sea levels will continue to rise over the 21st century and beyond. The basic range of projected global mean level rise estimated in the Intergovernmental Panel for Climate Change Fourth Assessment Report (AR4) is for a rise of 0.18 to 0.59 m with potentially an additional 0.1 to 0.2 m in the upper estimates due to additional ice sheet discharge if contributions to sea level rise were to grow linearly with global temperature change for each emission scenario (Figure 10). It was also clearly stated that larger contributions from the Greenland and West Antarctic ice sheets over this century could not be ruled out. Subsequently, the increasing component of present-day sea level rise due to ice sheet losses has led to a number of more recent estimates of sea level rise over the 21st century (Figure 11).

The assessment process contained within the Cook Islands Coastal Calculator enables the following sea level rise scenarios to be used:

- Any of the six IPCC AR4 scenarios, with any user-defined additional ice sheet discharge for any decade from the 2020s to the 2120s.
- Any user-defined sea level rise scenario for any decade from the 2020s to the 2120s based on a user-defined sea level rise by 2100.

Guidance for selecting a sea level rise scenario to be used, given the considerable range in future sea level rise projections, is provided in Section 4.

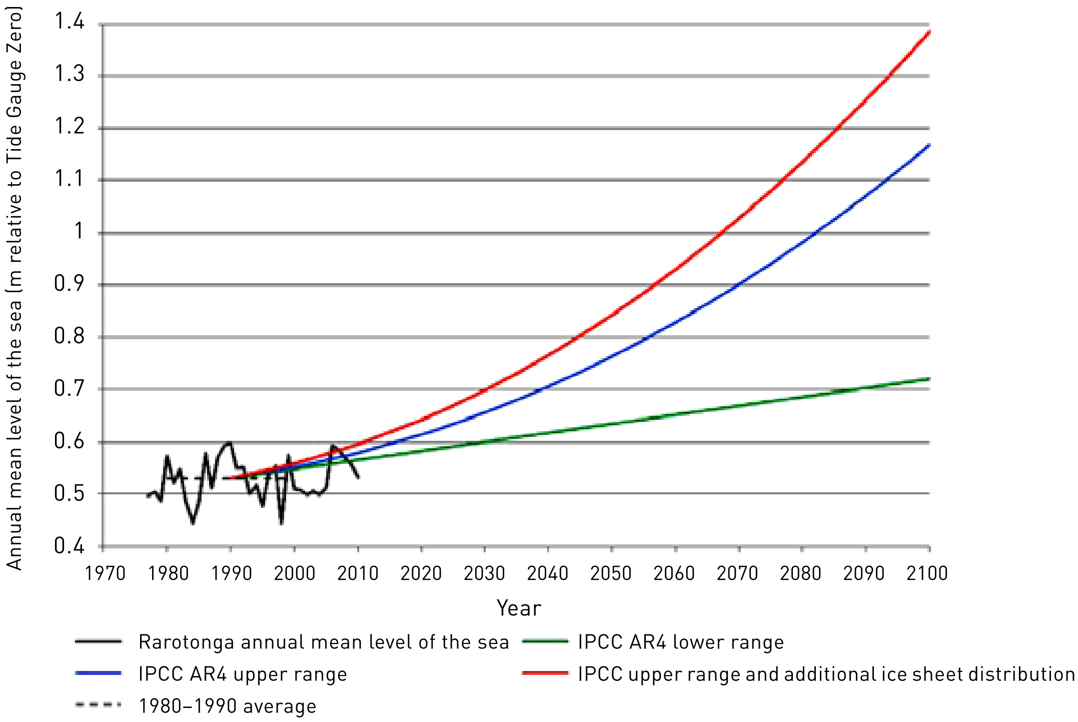



Figure 10. Annual mean level of the sea measured at Rarotonga since 1977, and the range in IPCC AR4 sea level projections to 2100.

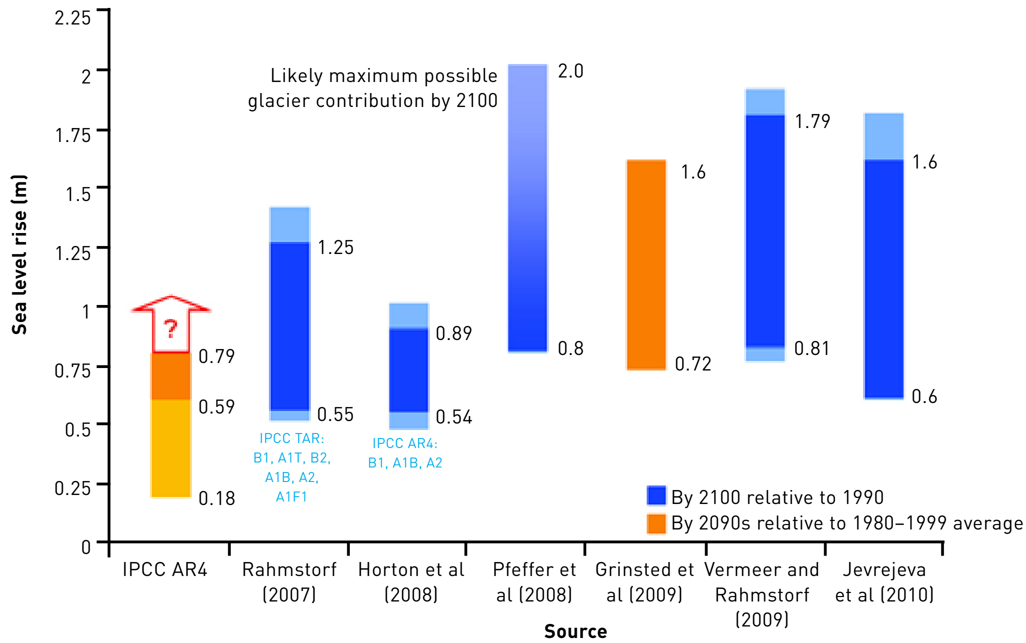



Figure 11. Summary of a selection of sea level rise estimates for 2090s/2100 from recent science publications. The dark blue bars show the range of projections for the various emission scenarios used. The light blue bars show the upper and lower error margins.

## 3.2. Changes in the frequency or intensity of cyclone events

The South Pacific region currently experiences on average nine cyclone events each year. However, the number of cyclone events in the Cook Islands very much depends on El Niño conditions.

Given the dominant influence of interannual fluctuations (particularly ENSO) on cyclone and track characteristics, there is no clear evidence at present of any recent changes in cyclone characteristics due to climate change.

Whether there will be changes in tropical cyclone characteristics in the future is also not clear, again as changes are likely to be compared to interannual and interdecadal variability. ENSO will likely continue to have a much more significant influence on cyclone temporal patterns than gradual and long-term climate change. However, at a global level:

- Frequency of cyclones will either decrease or stay the same (with some indication of a decline in number in the Southern Hemisphere);
- The most severe category 4 and 5 cyclones may become more intense but there is uncertainty at present if this will occur in the South Pacific;
- The severity of heavy rainfall will increase during cyclones.

The modelling conducted in Section 2 assessed the sensitivity of the offshore wave and water level joint probabilities for the following:

- Present day with the following ENSO characteristics (Figure 12):
  - All ENSO phases;
  - El Niño phases only;
  - La Niña phases only;
  - Neutral ENSO conditions only.
- For the above four ENSO phases with the following climate change scenarios (Figure 13):
  - 10% increase in the intensity of category 4 and 5 cyclones.
  - 10% increase in the intensity of category 4 and 5 cyclones and 10% reduction in the average number of cyclones.
  - 20% increase in the intensity of category 4 and 5 cyclones and 20% reduction in the average number of cyclones.

Figures 12 and 13 show that ENSO variability has a much greater influence on extreme waves and water levels experienced at Mangaia than potential future moderate changes in either the intensity or frequency of cyclone events.

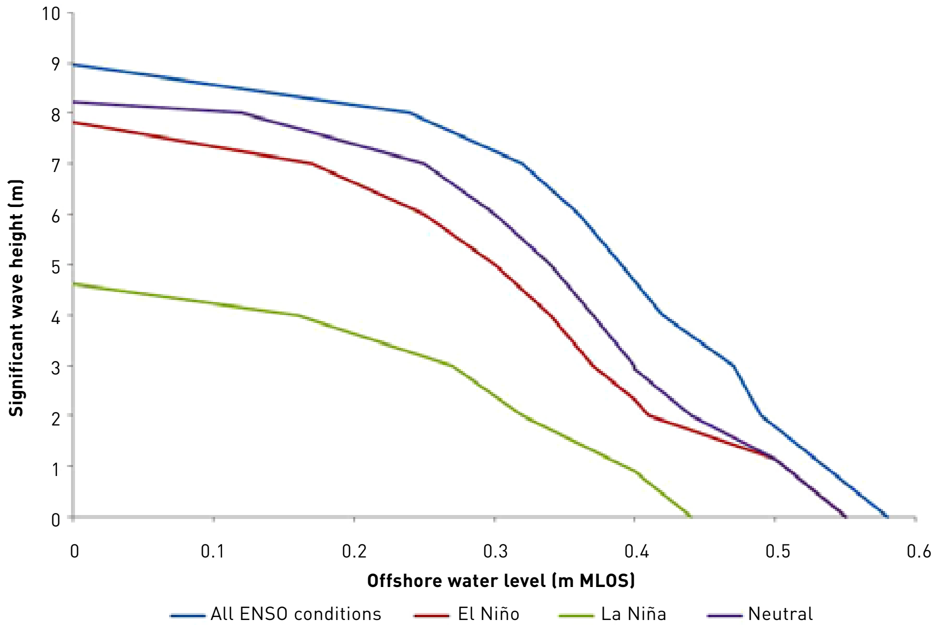



Figure 12. Present wave/water levels joint occurrences for Mangaia for an average recurrence interval of 10 years for different ENSO conditions.

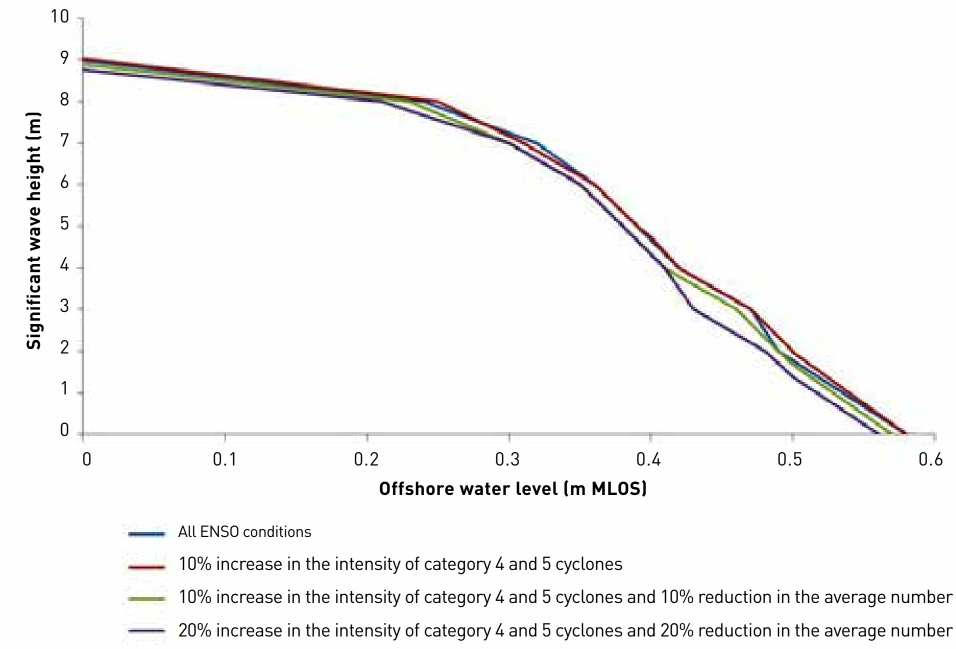



Figure 13. Future wave/water level joint occurrences for Mangaia for an average recurrence interval of 10 years for three different cyclone scenarios.

## 3.3. Changes in swell wave conditions

Seasonal effects and the influence of ENSO on tradewinds and hence wave conditions in the south-west Pacific are well established, with higher significant wave heights observed during El Niño periods in the Cook Islands. However, there is little information on any longer term current trends in swell wave conditions in the vicinity of the Cook Islands. Nor is there any significant current guidance on how extreme swell wave conditions may change in the future, albeit some indication (e.g. Mori et al., 2010) that in the vicinity of the Cook Islands the average significant wave height could increase by up to around 0.1 m by the end of this century.

To assess the sensitivity of potential future changes in swell wave conditions, the assessment process enables present-day extreme swell wave heights to be reduced or increased by 10% or 20%.

# 4. SELECTING APPROPRIATE EXTREME EVENT AND CLIMATE CHANGE SCENARIOS

Making development decisions today for land-use changes, infrastructure, residential property or any other community facility that will be in place for more than a decade requires climate change to be considered within a risk-based decision making framework.

For decisions that could be affected by coastal hazards (waves and water levels and associated inundation), the following need to be considered:

- What is the potential timeframe or design life of my decision?
- How extreme an event should I consider (i.e. what average recurrence interval event should I use)?
- What sea level rise scenario should I use?
- How sensitive is my decision (what are the potential costs or impacts during the lifetime of the decision) to:
  - Different sea level rises than that assumed, and what happens if resulting sea level rise is greater than I have assumed?
  - Possible changes in cyclone occurrence and intensity?
  - Possible changes in the heights of extreme swell wave conditions?
- What happens beyond the lifetime of my decision?

This section describes the process for selecting appropriate scenarios, and the decisions made, for consideration of cyclone inundation risk at Oneroa. The process combines climate data and science with community decision making to reach the best informed decisions. Decision making was done within a community meeting that brought together the team of technical experts, staff from MOIP, and the Oneroa community.

## 4.1. Timeframes

During the community meeting in Oneroa, the typical timeframes or design lives of various community facilities and government infrastructure were discussed (summarised in Table 1). This led to the decision by the community that incorporating climate change into the majority of village decision making should focus on likely changes over the next one to two generations (25 and 50 years).

However, longer timeframes may need to be considered for some major decisions, for example the location of an airport, which are essentially permanent in terms of their location, have limited or no future adaptation options (e.g. are difficult to relocate in the future), and would have catastrophic impacts on the socio-economic well-being of the community if the facility was lost.

Table 1. Typical functional design lives for some Oneroa infrastructure.

| Infrastructure | Considered functional design life |
|---|---|
| Wharf/harbour structures | <30 years |
| Residential homes | 30 years |
| Village hall | 30 years |
| School/hospital | 30 years |
| Administration buildings | 50 years |
| Church | 100 years |
| All government structures (design code) | 50 years |

## 4.2. Severity of cyclone or swell event

Selection of the severity of a cyclone or swell event to accommodate also depends on the nature of the decision and the impact that such an event would have. Table 2 summarises the likelihood of a range of extreme events with particular average recurrence interval (ARI) occurring within a range of different time horizons (with a description of the likelihood given below the table). For example, for a 50 year time period:

- A cyclone event with an ARI of 50 years has on average a 64% chance of occurring, in other words it is *likely* to happen over this time period;
- A cyclone event with an ARI of 10 years has on average a 99% chance of occurring, in other words it is *almost certain* to happen over this time period.

During the community discussions, the Oneroa community considered that an event that was *possible* to occur over the particular timeframe would be suitable for most community decisions:

- For a 25 year timeframe, an event with an ARI of 50 years (40% chance of occurring over this period);
- For a 50 year timeframe, an event with an ARI of 100 years (39% chance of occurring over this period).

Table 2. Likelihood of an extreme event occurring within a given time horizon (e.g. design life).

| Average recurrence interval of event (years) | Design life – time horizon (years) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2 | 5 | 10 | 25 | 50 | 100 | 200 | 500 | 1000 |
| 2 | 75% | 97% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| 5 | 36% | 67% | 89% | 100% | 100% | 100% | 100% | 100% | 100% |
| 10 | 19% | 41% | 65% | 93% | 99% | 100% | 100% | 100% | 100% |
| 50 | 4% | 10% | 18% | 40% | 64% | 87% | 98% | 100% | 100% |
| 100 | 2% | 5% | 10% | 22% | 39% | 63% | 87% | 99% | 100% |
| 200 | 1% | 2% | 5% | 12% | 22% | 39% | 63% | 92% | 100% |
| 500 | <1% | 1% | 2% | 5% | 10% | 18% | 33% | 63% | 100% |

| Rating | Percentage chance that an event with a given average return interval will occur within the design life |
|---|---|
| Almost certain | >85% |
| Likely | 60–84% |
| Possible | 36–59% |
| Unlikely | 16–35% |
| Rare | <15% |

## 4.3. Sea level rise scenario

There is still considerable uncertainty over the magnitude of sea level rise over the next century and beyond (see Section 3). Deciding on an appropriate sea level rise amount to accommodate for a particular decision is a pragmatic decision based on a balance between the level of risk that is willing to be accommodated and the associated costs of addressing that level of risk. Essentially it comes down to a balanced consideration between the following.

- The possibility of a particular sea level being reached within the planning timeframe or design life. For example, over the next 100 years there is a possibility that mean sea levels could rise by 2 m but it is much less likely than sea levels rising by 1 m. However, we cannot say for certain whether a 0.8 m rise is more or less likely than a 1 m rise over this time period.
- The associated consequences and potential adaptation costs. For example the consequences of a 2 m rise in sea level are in most cases likely to be much greater than a 1 m rise in sea level, likewise the costs of accommodating a 2 m rise in mean sea level would be much greater than a 1 m rise.
- How any residual risks would be managed for any consequences if sea level rise occurs at a quicker rate than that accommodated.

Table 3 provides suggested sea level rise amounts to be accommodated for coastal development, infrastructure and hazard planning activities. For each timeframe two levels are given:

- A baseline sea level to be used in most decisions. This is based on a sea level rise of 0.8 m by 2100;
- A higher level amount which may need to be considered for special case decisions (based on a 1.5 m rise in sea level by 2100) where:
  - The consequences resulting from a higher sea level than accounted for over the timeframe is unacceptable;
  - The decision is essentially permanent, e.g. location of major new development or infrastructure where relocation would not be a feasible option, future adaptation options are limited, or where future adaptation options would be required and would require substantial investment.

### Table 3. Suggested sea level rise allowances relative to 2010 for development planning and infrastructure design. Values are rounded up to the nearest 0.05 m

| Tolerance of risk | Mean sea level rise scenario | Usage in decision making | Lifetime of decision/infrastructure design life: | | | |
|---|---|---|---|---|---|---|
| | | | 1 generation | 2 generations | 3 generations | 4 generations |
| | | | 25 years | 50 years | 75 years | 100 years |
| | | | 2030–2039 | 2060–2069 | 2080–2089 | 2110–2120 |
| Normal | Baseline | Most decisions | 0.15 m | 0.4 m | 0.6 m | 1.05 m |
| Low | High | Special cases | 0.3 m | 0.75 m | 1.4 m | 1.9 m |

The rates suggested above are higher than presented by the IPCC, but reflect that many of the decisions to be made will relate to long-term land-use planning, essential infrastructure and disaster risk reduction. However, for the rates over the next one to two generations (shown in Figure 14) the difference between the two rates can be considered in terms of timing, for example:

- Sea levels reached under the 'baseline' scenario assumed above within one generation would be reached 10 years earlier under the 'high' scenario;
- Sea levels reached under the 'baseline' scenario assumed above within two generations would be reached 20 years earlier under the 'high' scenario.

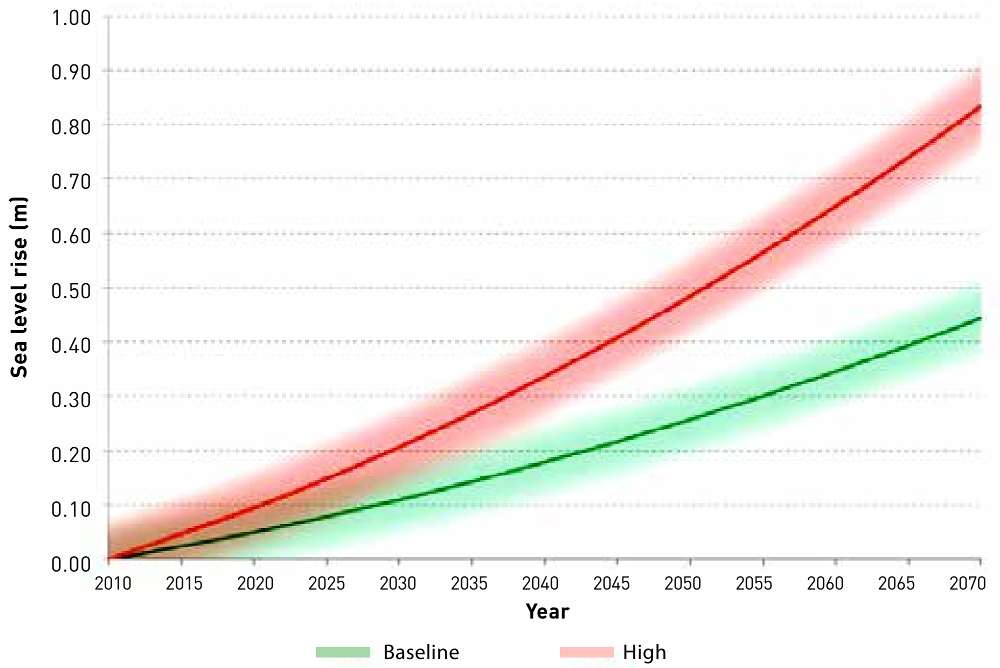



Figure 14. Suggested sea level rise scenarios for the next one to two generations. The shaded area indicates the approximate potential year to year variability in annual mean sea level due to interannual variability (for example ENSO influences).

# 5. REEF AND SHORELINE DATA

The cyclone and swell wave and water level conditions modelled in Section 2 need to be translated to shoreline wave and water level conditions in order to be useful for coastal design and engineering. To do this, we also need information on nearshore bathymetry and topography (reef and shoreline profiles, with data related to land levels), and wave and water level calibration data. This information is then used to calibrate parameters within the Cook Islands Coastal Calculator.

This section describes the collection of this information. The field data collection activities were conducted between December 2010 and February 2011 by SOPAC with assistance from MOIP, and are described in detail in the associated reports (Kumar et al., 2012; Damlamian et al., 2012).

The basic components of wave conditions and water level over a fringing reef are shown in Figure 15.

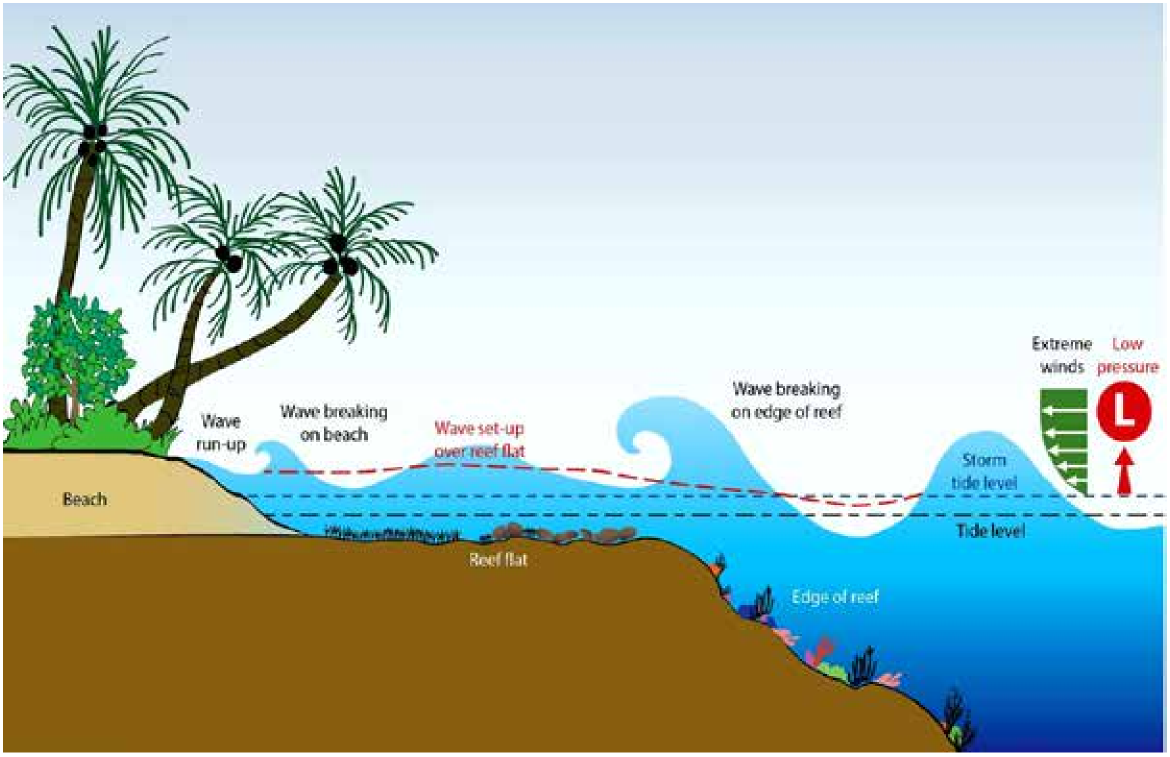



Figure 15. Basic components of wave and water levels over a fringing reef.

To derive shoreline wave and water level conditions and associated wave run-up and overtopping using the Cook Islands Coastal Calculator, the following information is required:

| | | |
|---|---|---|
| The average slope of the reef edge down to 15–20 m water depth | ⇨ | Influences wave breaking at the reef crest and hence wave set-up levels and reef flat wave heights |
| Reef crest level | ⇨ | Influences wave breaking at the reef crest and hence wave set-up levels |
| Reef flat levels | ⇨ | Influences wave heights over the reef flat |
| Reef flat characteristics | ⇨ | Influences wave heights over the reef flat |
| Beach/shoreline slope | ⇨ | Influences wave run-up level at the shoreline |
| Beach/shoreline characteristics | ⇨ | Influences wave run-up level at the shoreline |
| Shoreline seawall characteristics (crest height, revetment slope, armour material etc.) | ⇨ | Influences wave run-up and/or wave overtopping of the structure |

## 5.1. Deriving reef and shoreline profiles

The reef and shoreline information required by the Cook Island Coastal Calculator were derived as follows (summarised in Figure 16):

1. Using a combination of boat-mounted echo sounder, real-time kinetic global positions survey equipment and an electronic theodolite, over 97,000 spot heights were collected at the pilot study site at Oneroa Village on Mangaia. These spot heights are all relative to the mean level of the sea[1].
2. The spot height information was used to create a digital elevation map (DEM) of the Oneroa village frontage from around 100 m water depth offshore (relative to mean level of the sea) to a height above mean level of the sea of 16–17 m.
3. Cross-section profiles were defined at various locations along the Oneroa village frontage.
4. Cross-section information for each profile was extracted from the DEM and used as input for the Cook Islands Coastal Calculator.

Note: application of the Cook Islands Coastal Calculator does not necessarily require the level of detail undertaken during the PACC project. To apply the Calculator may only require some basic site-specific cross-shore profile measurements to be collected, but this will depend on the particular site.

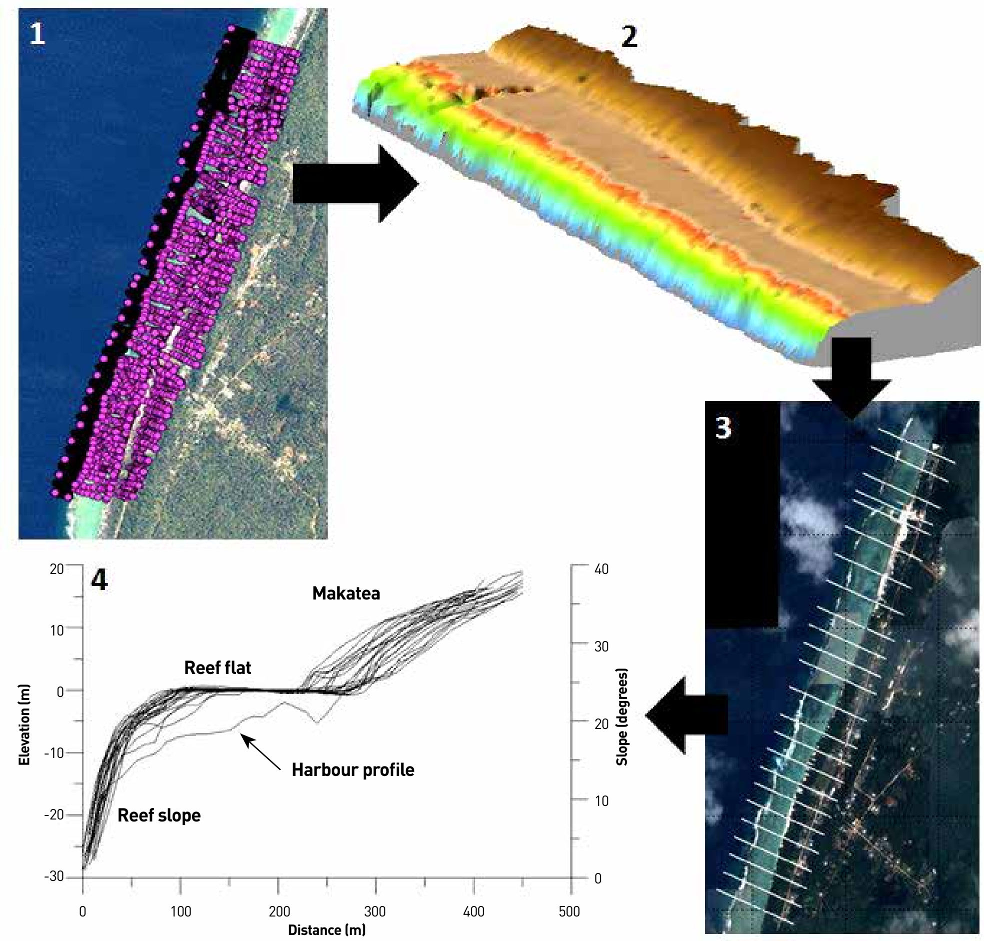



Figure 16. Summary of the process of transforming the survey information into input information for the Cook Islands Coastal Calculator. Part 1 shows the 97,292 survey points collected along the village frontage, part 2 the resulting DEM, part 3 the location of the cross-section profiles, and part 4 the cross-sections for each profile.

[1] The mean level of the sea at Mangaia was based on 3 months of sea level recordings conducted between December 2010 and February 2011.

## 5.2. Reef flat wave heights and water levels

Sea level recorders and a current meter were deployed from December 2010 to February 2011 at a location just to the north of the Oneroa Landing at Oneroa village on the reef slope seaward off the location of wave breaking, at the reef crest, and towards the landward edge of the reef flat (Figure 17). These wave and water level data were required to:

1. Derive the key tidal constituents to construct an astronomical tide time-series at Mangaia as part of the wave and water level joint probability assessment outlined in Section 2;
2. Define mean level of the sea at Mangaia and relate it back to the longer period of measurement from the SEAFRAME water level gauge at Rarotonga;
3. Calibrate the wave set-up and wave transformation formula contained within the Cook Islands Coastal Calculator.

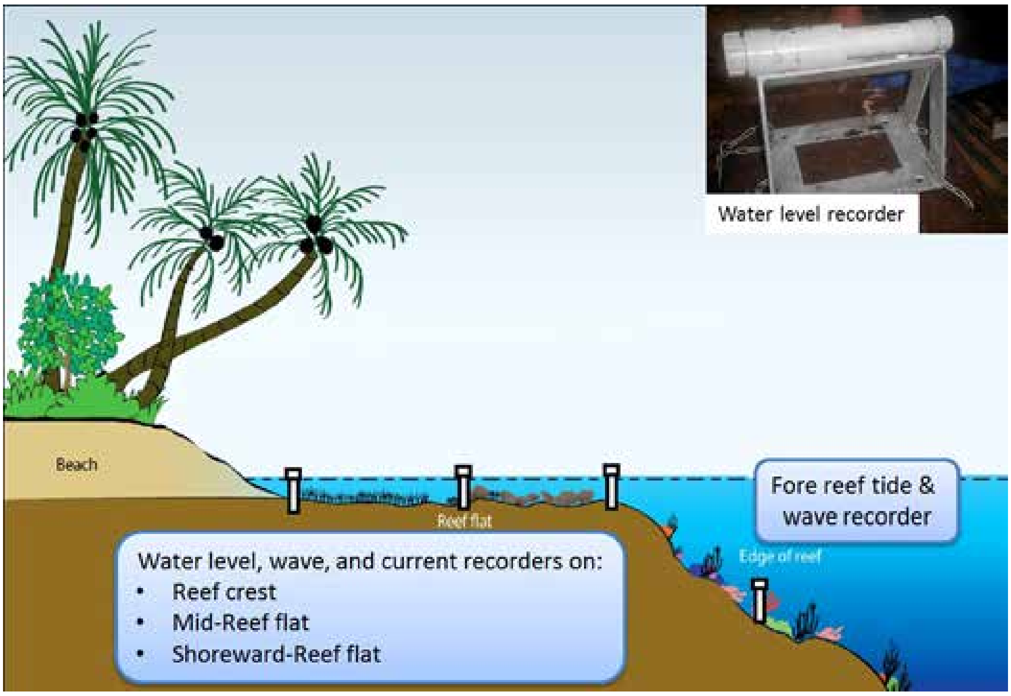



Figure 17. Locations of the water level and wave-recording locations across the fringing reef at Oneroa.

### 5.2.1. Mean level of the sea at Mangaia

The mean sea level (MSL) was defined over the 3 month period (December 2010 to February 2011) and is shown in Figure 18 relative to the benchmark (IPA) used for the static GPS base station for the topographic and bathymetric survey.

This enabled mean level of the sea at Mangaia to be related to mean level of the sea as measured by the SEAFRAME sea level gauge at Rarotonga over the same 3-month period. In turn this enabled the mean level of the sea for the baseline years used in the assessment for future sea level rise scenarios (1980–1999, 2000 and 2010) to be derived for Mangaia based on the average mean level of the sea at Rarotonga over these three periods (Table 4).

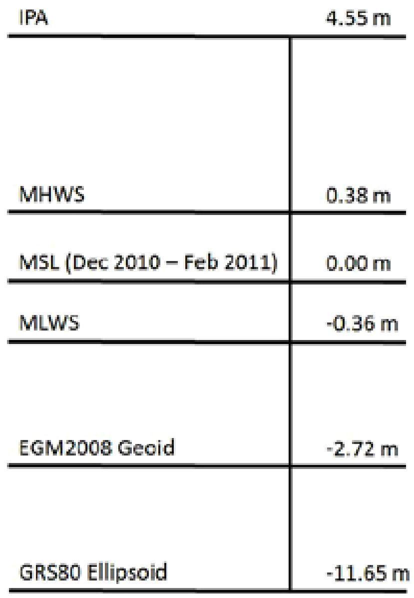



Figure 18. Relationship between mean sea level, MSL (December 2010 to February 2011) and other datums at Mangaia.

Table 4. Average mean level of the sea measured at Rarotonga and measured and derived at Mangaia

| Period | Mean level of the sea at Rarotonga (m Tide staff zero) | Mean sea level at Mangaia (m MSL Dec 2010–Feb 2011) |
|---|---|---|
| December 2010–February 2011 | 0.6139 | 0.000 |
| 2010 | 0.5319 | –0.082 |
| 2000 | 0.5098 | –0.104 |
| 1980–1999 | 0.5306 | –0.083 |

## 5.2.2. Reef flat wave and water level calibration

Wave and water level information collected offshore of the reef edge, at the reef crest and on the reef flat was used to ensure that wave set-up levels simulated in the Cook Islands Coastal Calculator was similar to those measured for the range of offshore significant wave heights experienced during the 3-month field programme. The comparison between measured wave set-up levels at the reef crest and reef flat and those simulated by the calculator for the range of offshore wave conditions is shown in Figure 19.

The key factor influencing wave set-up is the reef profile (Gourlay, 1997) which accounts for the roughness, permeability, and shape of the reef and is dependent on where waves break on the reef (reef edge or reef rim). The reef profile factor parameters derived by Gourlay (1997) resulted in a reasonable comparison between the measured and simulated wave set-up levels and it was decided to use these as published within the calculator.

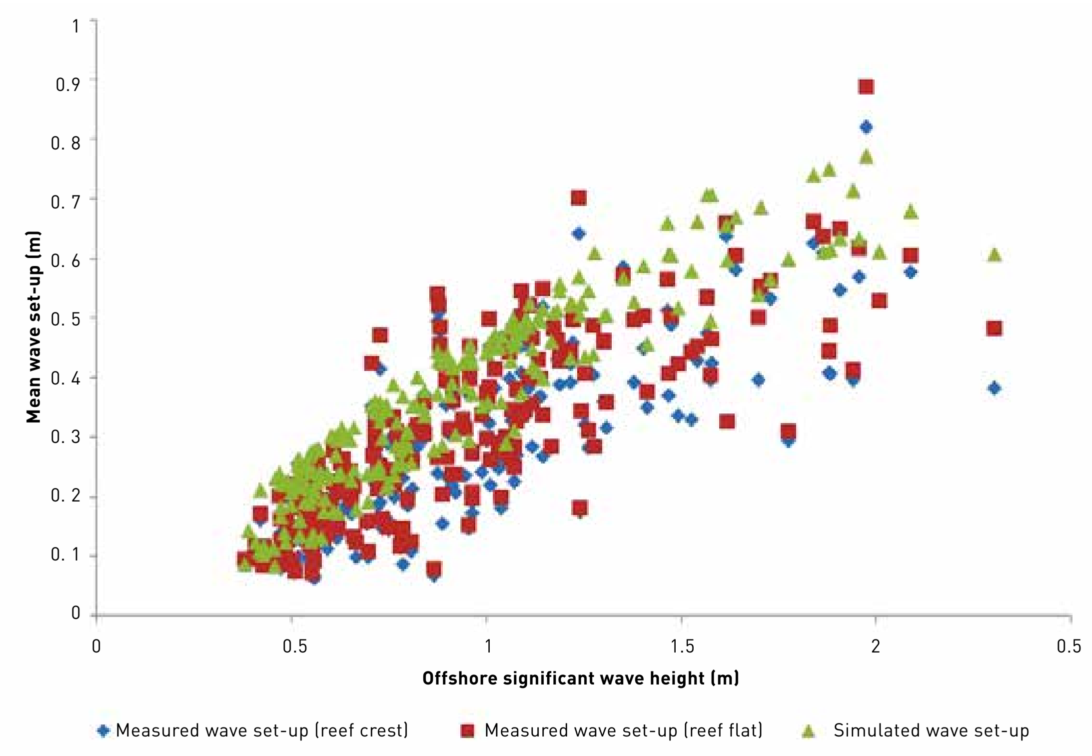



Figure 19. Comparison between measured and simulated (Gourlay, 1997) mean wave set-up levels off the coast of Oneroa village.

# 6. THE COOK ISLANDS COASTAL CALCULATOR

## 6.1. Overview of the Calculator

The Cook Islands Coastal Calculator provides the link between the modelled wave conditions and the coastal inundation that might be expected to occur under different future scenarios. It simulates inundation based on information on the 'drivers' of inundation (waves and water levels at the shoreline, wave run-up and overtopping), and how these will change over the next 100 years due to possible climate change and sea level rise changes.

The Calculator contains information from a number of models:

- Cyclone statistical model – to simulate cyclone parameters such as location, central pressure, propagation speed and direction (developed specifically for this project following similar approaches, e.g. Hall and Jewson, 2007; Rumpf et al., 2010);
- Storm surge model – to convert cyclone parameters into storm surge (Holland, 1980);
- Wave parametric model – to convert cyclone parameters into wave height and period (Ross, 1976);
- Wave hindcast model developed as part of NIWA's Waves And Storm surge Prediction (WASP) project, http://www.niwa.co.nz/our-science/coasts (Gorman et al., 2010; Gorman and Bell, 2011);
- Joint-probability models for waves and sea levels (Hawkes et al., 2002);
- Wave run-up model for fringing reefs (Gourlay 1996a,b).

The Calculator was developed for the PACC demonstration project in Mangaia, however it has application beyond this project. Its purpose is to:

- Act as a database for:
  - Extreme offshore swell significant wave height and water level joint probability combinations (1 to 150 year average recurrence intervals) around each of the 15 Cook Islands (75 locations in total).
  - Extreme offshore cyclone significant wave height and water level joint probability combinations for each island for the following scenarios:
    - Present day conditions;
    - Future conditions with a 10% increase in the intensity of category 4 and 5 cyclones but no change in the average annual number of cyclones;
    - Future conditions with a 10% increase in the intensity of category 4 and 5 cyclones and a 10% reduction in the average annual number of cyclones;
    - Future conditions with a 20% increase in the intensity of category 4 and 5 cyclones and a 20% reduction in the average annual number of cyclones;
    - For each of the above scenarios cyclone significant wave height and water level joint probability combinations for all ENSO conditions, and for El Niño conditions, La Niña and neutral conditions.
  - Annual Mean Level of the Sea (MLOS) data from the University of Hawaii and SEAFRAME tide gauges at Rarotonga from 1977 to present.
  - 5%, central estimates and 95% range of sea level rise for the six emission scenarios used by the IPCC AR4 and allowance for additional ice sheet discharge based on IPCC AR4 guidance.
- Enable site-specific calculations to be made, and comparison between, present day and potential future (based on defined climate change scenarios and timeframes) values of extreme cyclone and swell event conditions for:
  - Storm tide levels;
  - Wave set-up levels over the fringing reef flat;
  - Wave heights at the shoreline;
  - Wave run-up levels on beaches or sloping seawalls;
  - Wave overtopping volumes for a range of different seawall types.

## 6.2. Calculator structure

The Cook Islands Coastal Calculator is a Microsoft Excel spreadsheet. Due to the size of the spreadsheet it will only work in Microsoft Excel version 2010.

The Calculator is arranged into a number of spreadsheet pages:

| Page | Information |
|---|---|
| Introduction | Contains general information about the Cook Islands Coastal Calculator including version number and details of changes to the calculator |
| Datums | Page to define the vertical datums used in the calculator and for the outer islands their relationship to mean sea levels at Rarotonga |
| Climate change scenario | Page to define basic information such as island location, baseline year and the particular sea level rise scenarios to be used in the assessment |
| Calculator | Page to input specific information on the location (reef and shoreline information) and to display the results |
| Help | Help page with information to assist in the application of the calculator |
| Lookup tables | Hidden page: Contains all the look up tables for the drop down menu boxes in the calculator |
| Reef processes | Hidden page: Contains all the equations used to calculate coastal processes over the reef flat and shoreline |
| Cyclone | Hidden page: Contains all the cyclone wave/water level joint probability tables for each island for the present day and for each of the future cyclone scenarios |
| Swell | Hidden page: Contains all the swell wave/water level joint probability tables for 75 locations in total, around the 15 Cook Islands (4–7 locations for each) |

## 6.3. How to use the Calculator

Depending on the particular assessment, the user needs to make some selections or enter information associated with:

- The particular island;
- Vertical datum being used;
- The baseline year;
- The future timeframe for comparison;
- The particular sea level rise scenario;
- Local physical (reef flat and shoreline) characteristics of the location under investigation.

Figure 20 summarises the process of using the calculator for different assessments.

The information on the particular scenario/location under investigation is required to be input into two pages of the spreadsheet:

- Climate change page;
- Calculator page.

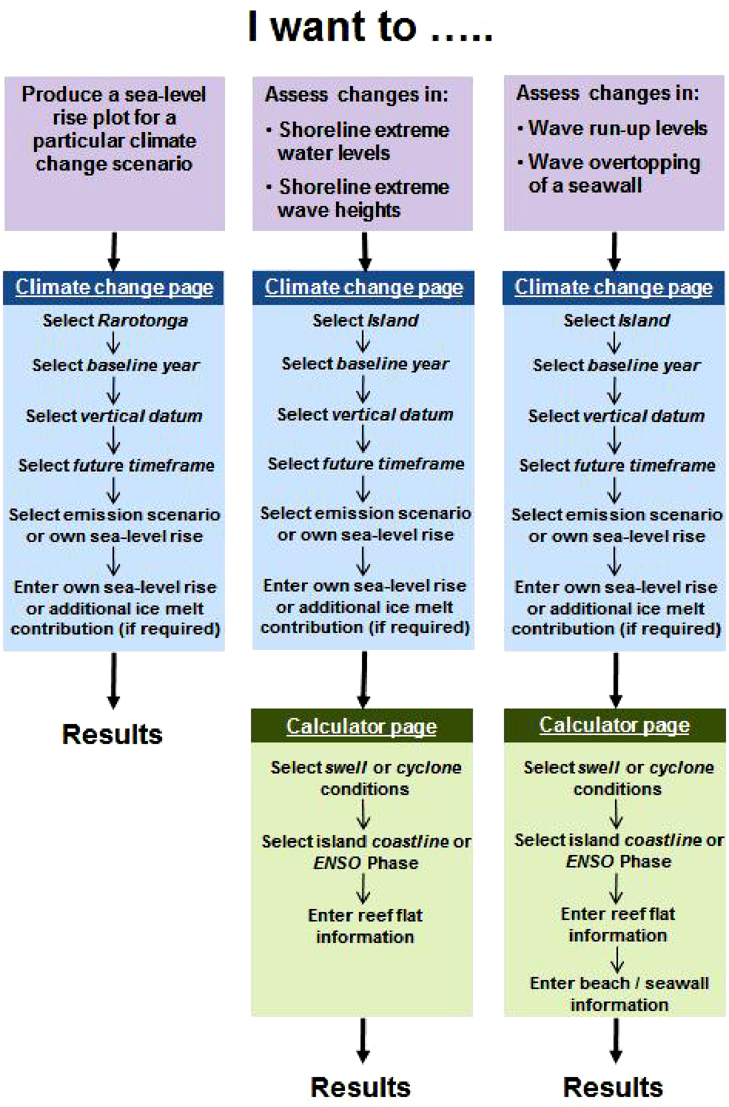



Figure 20. Flowchart for using the Cook Islands Coastal Calculator.

## 6.4. Limitations of the Calculator

Wave and water level processes over fringing reef systems and at the shoreline are extremely complex. The Cook Islands Coastal Calculator takes a simplified approach to simulating the processes of wave breaking, wave set-up, wave transformation, wave-run-up and overtopping based on various empirical equations.

Results from the Calculator should be treated as indicative only and used in the context of the limitations of the underlying empirical equations which are derived from the following literature:

- Reef edge wave breaking, wave set-up and wave transformation: Gourlay (1996, 1997) and Sheppard et al. (2005);
- Shoreline wave run-up and overtopping: Hedges and Mase (2004); Gourlay (1997); Holman (1986); HR Wallingford (1999); Mase (1989); Pullen et al. (2007) and Stockdon et al. (2006).

The Calculator should only be used in the following situations:

- Fringing reef ocean-side environments without any significant lagoon between the reef edge and shoreline
- Where the reef flat and shoreline is relatively homogeneous alongshore (i.e. it is a profile model and does not account for alongshore influences).

Furthermore the Calculator can only calculate wave run-up on a plain beach. It cannot assess how wave run-up would then inundate land behind the beach.

# 7. DERIVING WAVE RUN-UP LEVELS FOR ONEROA VILLAGE

## 7.1. Introduction

The process of defining zones of potential wave run-up under cyclone and swell events was developed using the Cook Islands Coastal Calculator, and also using community knowledge of past cyclone inundation events within historical memory of the Oneroa community.

Before the meetings in Mangaia, the Cook Islands Coastal Calculator was used to define an initial run-up level which was then used as part of the discussion with the Oneroa community. This was based on consideration of run-up levels at the location of Profile 6 (Figure 21) for average recurrence intervals (ARIs) of 10, 50 and 100 years for:

- Present day;
- With a sea level rise of 0.79 m;
- With a sea level rise of 0.79 m and with cyclone changes of: (1) 10% increase in category 4 and 5 intensity, (2) 10% increase in category 4 and 5 intensity and 10% reduction in the average annual number of cyclones, and (3) 20% increase in category 4 and 5 intensity and 20% reduction in the average annual number of cyclones.

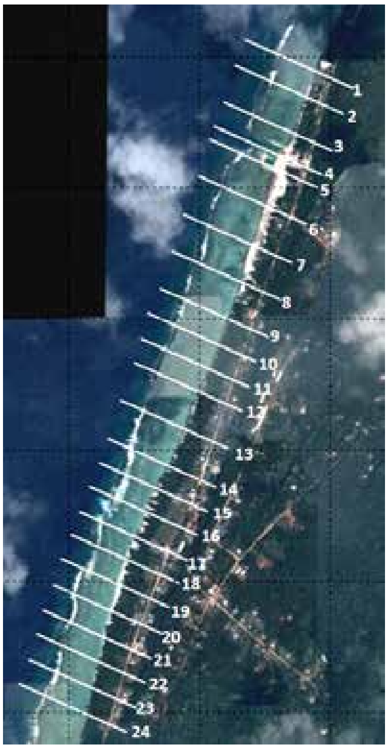
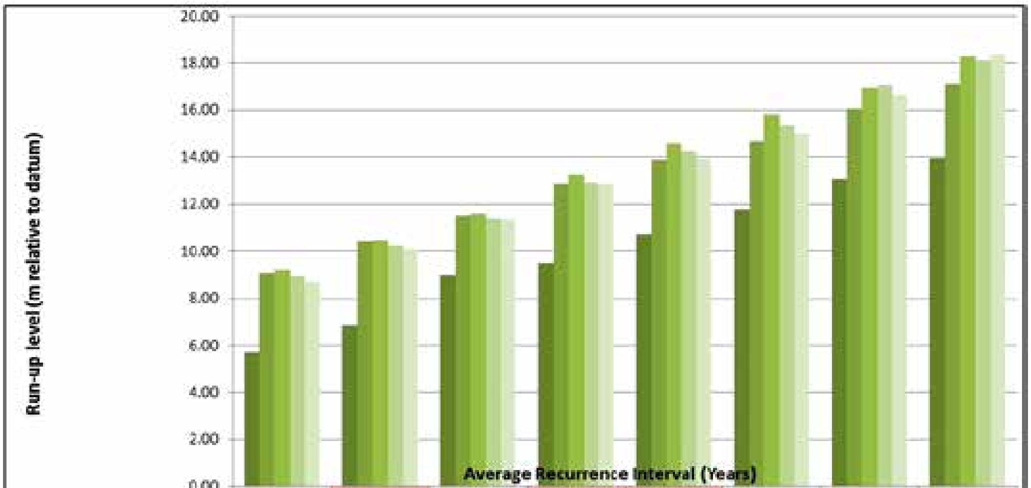



Figure 21. Profile locations along the Oneroa village frontage.

The output from the Cook Islands Coastal Calculator is shown in Figure 22 with the results for the 10, 50 and 100 year ARIs shown for the present and future scenarios in the red shaded columns.




| | 5.0 | 10.0 | 20.0 | 50.0 | 100.0 | 200.0 | 500.0 | 1,000.0 |
|---|---|---|---|---|---|---|---|---|
| Present | 5.71 | 6.82 | 8.96 | 9.48 | 10.72 | 11.76 | 13.05 | 13.95 |
| 2090s SLR | 9.11 | 10.43 | 11.53 | 12.87 | 13.85 | 14.68 | 16.06 | 17.11 |
| 2090s SLR +10%Int 0% Nu | 9.20 | 10.46 | 11.61 | 13.26 | 14.59 | 15.80 | 16.95 | 18.27 |
| 2090s SLR +10%Int -10% Nu | 8.94 | 10.25 | 11.41 | 12.91 | 14.25 | 15.31 | 17.06 | 18.12 |
| 2090s SLR +20%Int -20% Nu | 8.69 | 10.11 | 11.36 | 12.86 | 13.89 | 15.00 | 16.68 | 18.37 |

Figure 22. Output from the Coastal Calculator for cyclone wave run-up levels for the present day and for 2090s at the location of Profile 6. Run-up levels are relative to the mean level of the sea recorded between December 2010 and February 2011.

These levels were then interpolated on to the spot height topography information collected during the field surveys (see Figure 16) and contours for the 10, 50 and 100 year ARI run-up levels extended along the Oneroa village frontage. The result (Figure 23) was then used as the basis for discussions during the community meeting.

Figure 23. Draft 10, 50 and 100 year ARI cyclone run-up levels derived for the Oneroa village frontage. The 10 year ARI run-up level is shown in yellow, the 50 year ARI in orange and the 100 year ARI in red. The run-up levels were produced by version 1.17 of the Cook Islands Coastal Calculator which has subsequently been updated.

## 7.2. Historical cyclone run-up levels

During the meeting, the Oneroa community discussed cyclone events that had affected the village in living memory. Three cyclone events were identified where wave run-up had reached the village:

- 1944 cyclone (31 January 1944);
- Cyclone Sally in late December/early January 1987;
- Cyclone Meena in February 2005.

Based on the memory of the meeting participants, approximate run-up levels along the village frontage were recorded in GIS, and are shown in Figure 24. These run-up levels were used to ensure the Cook Island Coastal Calculator was providing similar run-up levels. A comparison between the observed events and the final 50 and 100 year ARI run-up levels (see next section) is shown in Figure 25.

Figure 24. Cyclone wave run-up levels observed during Cyclones Meena, Sally and in 1944 along the Oneroa village frontage. Blue = Cyclone Sally, green = Cyclone Meena, purple = 1944 cyclone.

Figure 25. Comparison between observed cyclone run-up levels and run-up levels derived for ARIs of 50 and 100 years from the Cook Island Coastal Calculator. Orange = 50 year ARI run-up level, red = 100 year ARI run-up level, blue = Cyclone Sally, green = Cyclone Meena, purple = 1944 cyclone.

## 7.3. Applying the Cook Islands Coastal Calculator to derive cyclone run-up levels for Oneroa

The Cook Islands Coastal Cacluator was used to derive cyclone wave run-up levels for the following:

- Present day (2010) levels for 50 and 100 year ARI events;
- 2030s level for 50 year ARI event (i.e., a cyclone event that will *possibly* occur over the next 25 years/1 generation) with a mean sea level rise of 0.15 m (baseline) and 0.3 m (high);
- 2060s level for 50 year ARI event (i.e. a cyclone event that will *likely* occur over the next 50 years/2 generations) with a mean sea level rise of 0.4 m (baseline) and 0.75 m (high);
- 2060s level for 100 year ARI event (i.e. a cyclone event that will *possibly* occur over the next 50 years/2 generations) with a mean sea level rise of 0.4 m (baseline) and 0.75 m (high).

These run-up levels were calculated for each of the profiles shown in Figure 21 with the exception of Profiles 1 and 2 (due to the vertical seawall in front of the Mangaia Villas) and Profile 4 (harbour channel).

During the initial application of the Calculator it was apparent that run-up at each profile was very heavily dependent on: (1) the elevation of the reef crest, and (2) the slope of the shoreline, and hence very dependent on the specific location of the particular cross-section used. Based on initial comparisons with the observed cyclone run-up levels, the following were subsequently implemented.

- Reef crest levels were set as the median value over a number of profiles over a length of the Oneroa frontage: Profiles 3–8, excluding Profile 4; 9 to 17; and 18 to 24.
- The slope of the limestone platform for each profile was taken as between the 4 m and 10 m contours (over which the majority of the run-up occurs).
- Beachrock at the shoreline with an average top elevation of 1.5 m relative to mean sea level measured between December 2010 and February 2011 was assumed to occur at Profiles 5 to 8.

## 7.4. Present and future run-up levels

Once run-up levels at each profile were calculated, these were then digitised into lines of equal run-up all along the Oneroa frontage in GIS based on interpolated topographic contours from the topographic survey information. The resulting cyclone-related run-up levels for the present day for average recurrence intervals of 50 years and 100 years are shown in Figure 26 and in Figures 27–29 for the 2030s (50 year ARI), 2060s (50 year ARI) and 2060s (100 year ARI), respectively. This suggests that, due to the effect of sea level rise by the 2030s, what is currently a 100 year ARI run-up level will be approximarely a 50 year ARI run-up level.

Figure 26. Cyclone-related run-up levels for the present day for ARIs of 50 and 100 years. Orange = 50 year ARI, red = 100 year ARI.

Figure 27. Comparison between 50 year ARI cyclone-related run-up levels for the present day and 2030s. Green = present day, orange = 2030s with baseline sea level rise (0.15 m relative to 2010), red = 2030s high sea level rise (0.3 m relative to 2010).

Figure 28. Comparison beteen 50 year ARI cyclone-related run-up levels for the present day and 2060s. Green = present day, orange = 2060s with baseline sea level rise (0.4 m relative to 2010), red = 2060s with high sea level rise (0.75 m relative to 2010).

Figure 29. Comparison between 100 year ARI cyclone-related run-up levels for the present day and 2060s. Green = present day, orange = 2060s with baseline sea level rise (0.4 m relative to 2010), red = 2060s with high sea level rise (0.75 m relative to 2010).

## 7.5. Hazard lines for village planning

The run-up lines derived above need to be treated as indicative and it is important that they are not used in isolation to inform village planning and emergency management. As mentioned, the run-up calculations are extremely sensitive to the slope of the reef and shoreline. The effect of this can be seen in and around the sports field and

Mangaia administration offices (Figure 30). The slopes between the 4 m and 10 m contours of the profiles to both the north (Profile 14) and south (Profile 18) of the playing fields are relatively shallow (less than 1 in 10) compared to other profiles used along this part of the village, resulting in lower run-up levels for both the calculated 50 and 100 year ARI run-up levels than was observed during the 1944 cyclone. This is a limit of the simplifications within the Cook Islands Coastal Calculator, of what are extremely complex hydrodynamic processes, and shows the importance of selecting the profile loactions carefully to match key inundation pathways, and using multiple sources of information to derive coastal hazard lines, in this case community knowledge of past cyclone events.

Figure 30. Comparison between 50 and 100 year ARI levels and the 1944 cyclone run-up levels at the centre of Oneroa village. Orange = 50 year ARI cyclone run-up level, red = 100 year ARI cyclone run-up level, purple = indicative run-up level observed during the 1944 cyclone.

Using the run-up levels calculated using the Cook Islands Coastal Calculator for the 2030s and 2060s *and* consideration of the historical cyclone run-up levels, Figure 31 provides suggested coastal hazard lines for the period up to the 2030s (green line) and for the period up to the 2060s (red line). These lines represent:

- Green line: a possible chance of wave run-up due to a 50 year ARI cyclone event reaching this level over the period from the present to the 2030s;
- Red line: a possible chance of wave run-up due to a 100 year ARI cyclone event reaching this level over the period from the present to the 2060s.

Figure 31. Final cyclone hazard lines developed for the 2030s and 2060s for Oneroa village, Mangaia, Cook Islands. The lines indicate a possible chance of wave run-up due to a 50 year ARI cyclone event reaching this level over the period from the present to the 2030s (green line) and a possible chance of wave run-up due to a 100 year ARI cyclone event reaching this level over the period from the present to the 2060s (red line).

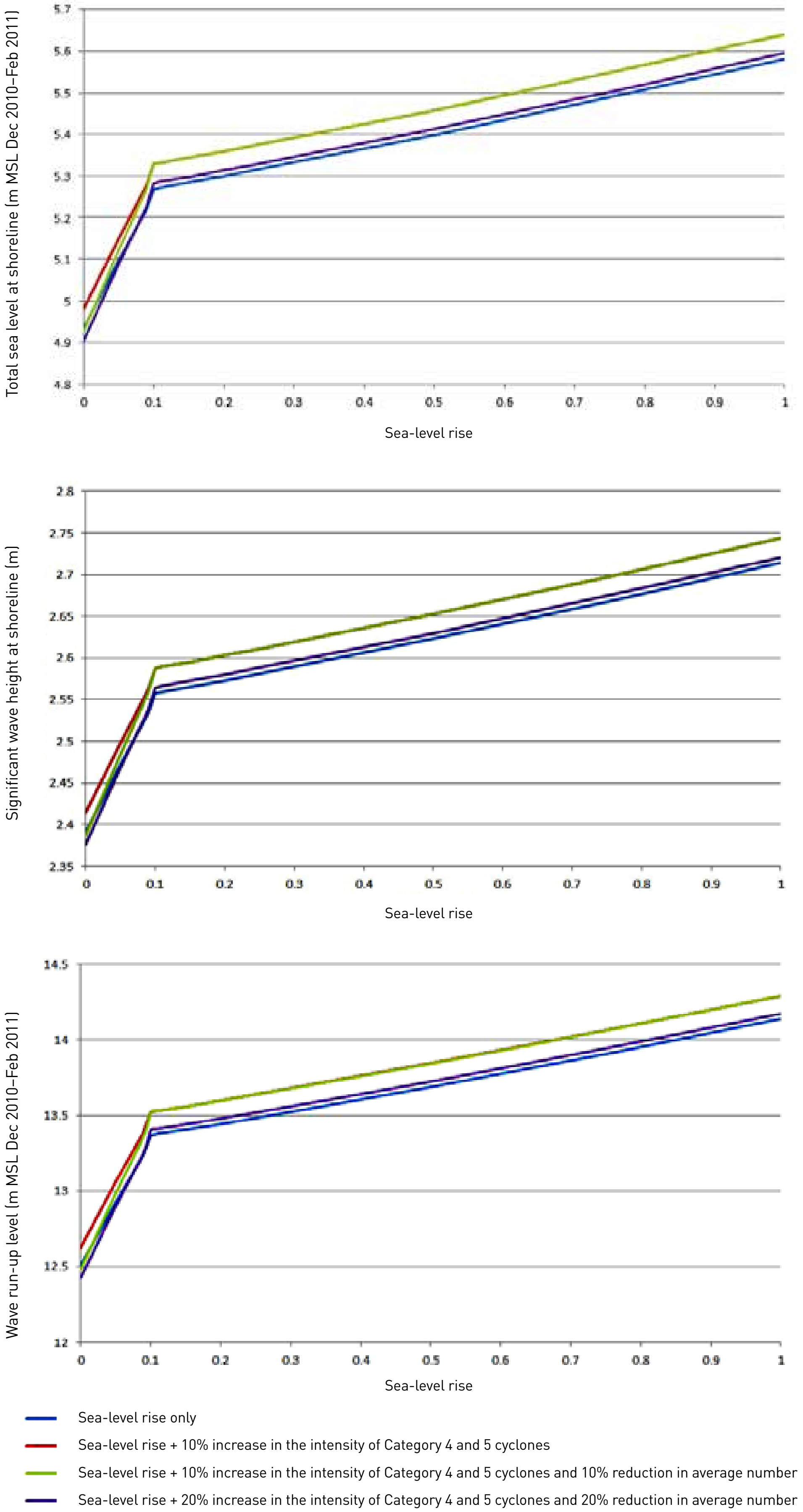



Figure 32. Effect of sea level rise on 50 year ARI shoreline water level (top), significant wave height (middle) and wave run-up (bottom) at the location of Profile 16.

## 7.6. Sensitivity of the run-up results to potential cyclone changes

The Cook Island Coastal Calculator can be used to assess the sensitivity of shoreline processes (extreme water levels and wave heights at the shoreline, wave overtopping and run-up) to changes in sea level and potential changes in cyclone occurrence and intensity (based on the cyclone scenarios used). Using Profile 16 (Figure 21) with 50 year ARI cyclone conditions as an example, Figure 32 shows the effect of sea level rise and cyclone changes on extreme water level and significant wave heights at the shoreline and subsequent run-up at Oneroa village, with Figure 33 the relative difference in cyclone run-up levels between different phases of ENSO and changing cyclone characteristics.

This suggests that for ARIs of typical interest (e.g. up to 100 years), changing cyclone characteristics over this century are unlikely to have a significant impact on shoreline processes at Mangaia, relative to the influence that climate variability has on cyclone occurrence in the Southern Cook Islands, and that sea level rise has on wave conditions from deep water over the fringing reef to the shoreline.

Changing cyclone characteristics only really begin to have a significant influence at much higher ARIs.

Figure 32 also suggests that due to the influence that wave-set up has on extreme water levels at the shoreline, the rate of rise in extreme water levels (and hence run-up) is approximately two-fifths the rate of rise of sea level based on the assumption that there are no changes to the present elevation of the reef crest and reef.

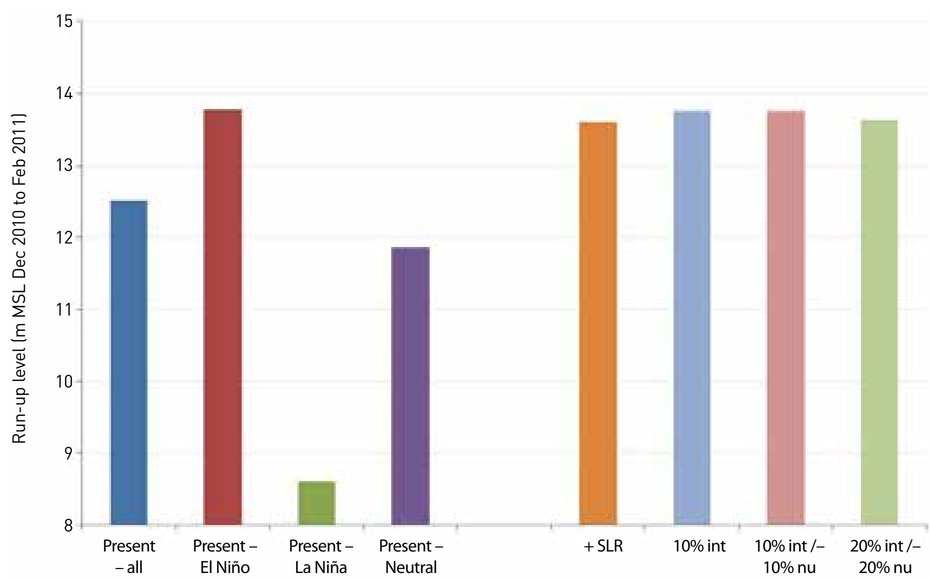



Figure 33. Comparison between ENSO influences on wave run-up and influence of changing cyclone characteristics. The four bars on the left side show present run-up levels for a 50 year ARI cyclone considering all cyclones, and only cyclones during El Niño, La Niña and neutral phases. The four bars on the right side show corresponding run-up levels for all cyclones with 0.40 m of sea level rise, with sea level rise + a 10% increase in intensity of category 4 and 5 cyclones (10% int), with sea level rise + 10% increase in intensity of category 4 and 5 cyclone and 10% reduction in annual average number (10% int /10% nu), and with sea level rise + 20% increase in intensity of category 4 and 5 cyclone and 20% reduction in annual average number (20% int /20% nu).

# 8. IDENTIFYING ADAPTATION OPTIONS

Using the indicative cyclone run-up levels developed, the past historical cyclone run-up levels, and assessment of how these run-up levels may change due to sea level rise and changes in cyclone characteristics, the community identified the facilities at risk along the Oneroa frontage (Figure 34).

Activities that increased the risk of inundation to the village frontage during cyclone events were also identified. These included:

- Increasing the width of the channel at the wharf (or any other channels over the fringing reef);
- Cutting roads down through the makatea to the shoreline;
- Removing vegetation between the road and the shoreline.

For Oneroa village to adapt to the effects that climate change will have on inundation risk, it was agreed by the community to take an approach that:

- Prevents any further village infrastructure being constructed in areas that will potentially be affected by cyclone run-up that is likely or possible to occur over the next two generations;
- Progressively implements key risk reduction and adaptation options as part of the Mangaia Island Administration annual planning and operational activities.


Figure 34. Community facilities and residential property identified as being at risk from cyclone-related inundation by the Oneroa community.

Based on this, a range of risk reduction and adaptation options were identified by the Oneroa community (Table 5).

### Table 5. Risk reduction and adaptation options identified by the Oneroa community

| Key risk reduction/adaptation options |
|---|
| • Improve existing and provision of new evacuation routes inland from the village<br>• Limit any further new roads down to the shoreline along the village frontage<br>• Encourage landowners not to build new residential property on the seaward side of the road<br>• Encourage the planting of natural vegetation between the road and the shoreline |
| **Occasionally required/longer term risk reduction/adaptation options** |
| • Rebuild houses with raised floor levels (e.g. on piled foundations) during any renovations where they are built in areas that could potentially be inundated<br>• Progressively over time move further inland any essential infrastructure or residential property at high risk of damage from inundating waves |
| **Rarely required risk reduction/adaptation options** |
| • If structural measures (e.g. seawalls or boundary walls) were ever deemed necessary to protect infrastructure or property, to have these located as close to the level of the first makatea bench rather than at the shoreline |

Figure 35. Examples of more appropriate 'seawall' structures for the Oneroa frontage. Left: The wall is located close to the level of the road and will provide much more protection to the road than a similar sized structure located at or close to the shoreline. Right: the wall around the church – even if wave run-up reaches the wall, the wall will prevent water entering the churchyard if the openings are blocked up.

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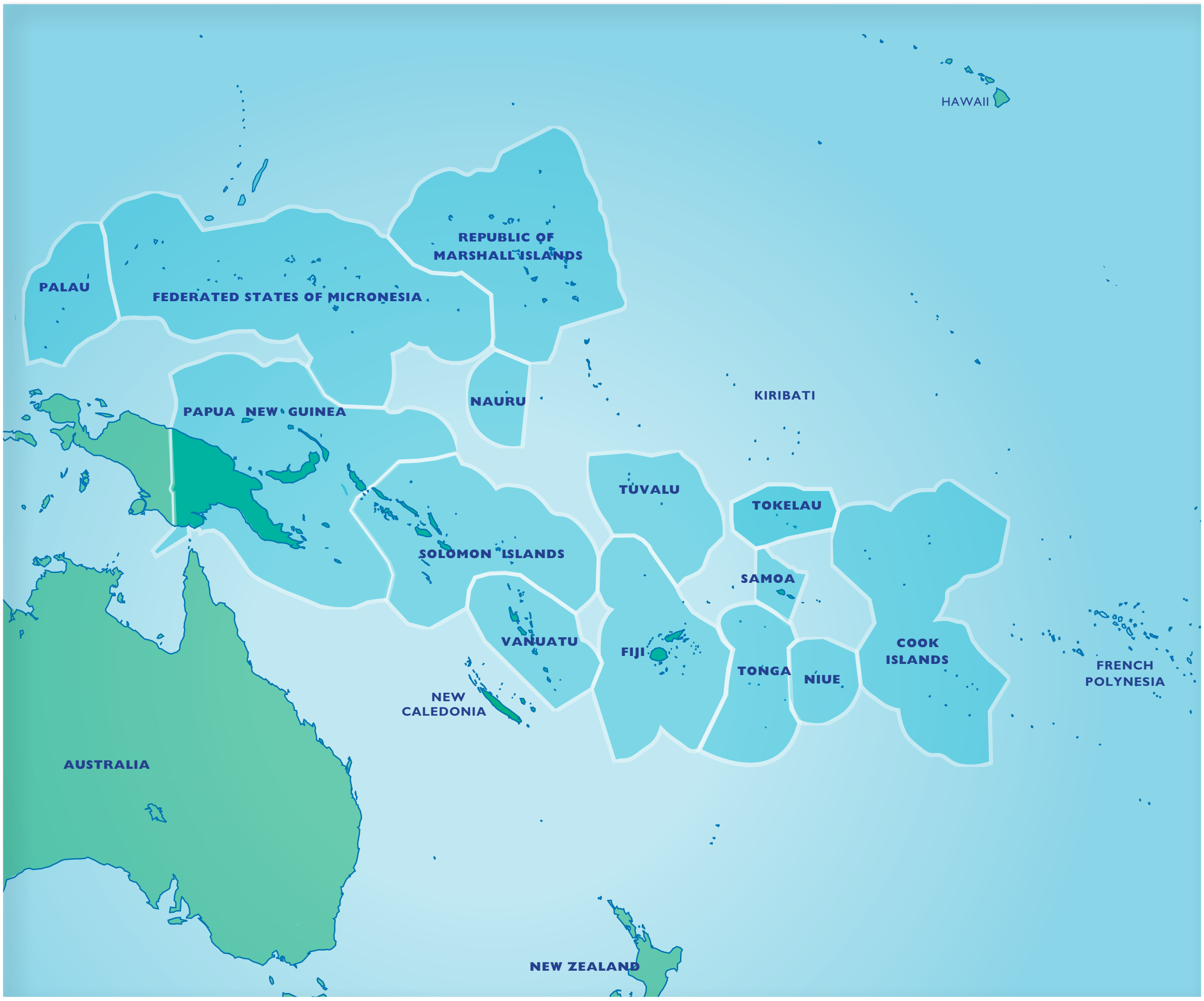


PACC – building adaptation capacity in 14 Pacific island countries and territories

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The PACC programme is funded by the Global Environment Facility (GEF)'s Special Climate Change Fund (SCCF) and the Australian Government with support from the United Nations Institute for Training and Research (UNITAR) Climate Change Capacity Development (C3D+). The Secretariat of the Pacific Regional Environment Programme (SPREP) is the implementing agency, with technical and implementing support from the United Nations Development Programme (UNDP).

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