# Niutao Harbour Climate Risk and Vulnerability Assessment

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# I. Introduction

1. The Tuvalu Outer Island Maritime Infrastructure Project (OIMIP) is a joint-funded effort by the Asian Development Bank (ADB) and the Government of Tuvalu. This project proposes construction of harbours at three islands – Nukulaelae, Nanumaga, and Niutao. Previously, a detailed CRVA was done for the Nukulaelae project but a thorough assessment was not done for the other sub-projects proposed at that time for Nanumaga and Niutao, which were more flexible designs (Cardno, 2016).
2. This report is the Climate Vulnerability Risk Assessment (CRVA) for the Niutao Harbour based on the project's Detailed Design Report (Cardno, 2017) and Feasibility Study Report (Cardno, 2018). The CRVA aims to ensure that climate change risks, including risks from extreme weather events are fully considered in the design options of the Niutao Harbour, and clearly identify adaptation and disaster risk reduction strategies for managing risks to the project.

## Project Information

**Project:** Outer Island Maritime Infrastructure Project

**Location:** Niutao, Tuvalu

**Sector:** Transportation

**Sub-sector:** Water transport (non-urban)

**Themes:** Inclusive economic growth; environmentally sustainable growth; regional integration

3. **Project Description:** The Outer Island Maritime Infrastructure Project (OIMIP) aims to: (i) rehabilitate and improve maritime infrastructure in selected outer islands of Tuvalu, and (ii) improve safety, efficiency, and sustainability of maritime transportation between the outer islands and Funafuti, the main island and seat of the capital. Additionally, this project will enhance the capacity of relevant government agencies, including the Department of Marine and Port Services, to operate and maintain facilities.
4. The proposed harbour on Niutao is intended to address connectivity and safety challenges experienced on outer islands which constrain economic and social development. Due to its dispersed geography and inadequate transportation infrastructure, Niutao as the other outer islands of Tuvalu face unique challenges. The outer islands rely on sea transportation for people and cargo. The two inter-island vessels linking the outer islands with the capital and international port on Funafuti arrive only every one or two weeks on inter-island round voyages and there are no direct services to Funafuti. Unloading boats involves significant dangers even in normal conditions of wind and swell and can become impossible when sea conditions are rough. The proposed harbour for the work boats serving the inter-island will improve connectivity and access for passengers and for cargo to and from the island of Niutao.
5. Figure 1 illustrates the location of the project site. The project is located on Niutao (circled in red). The site of the harbour would be on the northeast coast. Figure 2 provides a closer look at the island of Niutao and the placement of the harbour on the island. Figure 3 shows an overhead of the design.


Figure 1. Map of Tuvalu and its relative location in the Pacific Ocean (Cardno, 2017)


Figure 2. Harbour location on Niutao (Cardno, 2017)


Figure 3. Niutao Harbour Location (Cardno, 2017)

## Project Context

6. Tuvalu is the smallest by population and one of the most remote member countries of the ADB. The country is comprised of six coralline atolls (Nanumea, Nui, Nukufetau, Funafuti, Nukulaelae, Vaitupu) and three table reef islands (Nanumaga, Niutao and Niulakita), stretched over 680 kilometers (km) in the Pacific. Only Funafuti has a large, sheltered lagoon with a deep water entrance. Tuvalu's closest neighbour is Fiji, located 1,100 km away. The population of just 10,100 people (as of June 2016) is spread across nine islands, concentrated on Funafuti. Increasingly, people from the outer islands have migrated either to the largest island Funafuti or to Fiji, Australia or New Zealand and beyond, due to limited economic opportunities, leaving the outer islands sparsely populated. Access to the wider world is limited for many people in Tuvalu generally and even more so for residents of Niutao and other outer islands. International flights arrive and depart only three times a week from Suva, Fiji, to the capital in Funafuti and a commercial cargo ship arrives from Fiji once every three weeks.

7. There are a myriad of transportation challenges facing Tuvalu. The only transportation between Funafuti and the outer islands is through government inter-island ships carrying passengers and goods. The government's shipping service only owns two ships that are in continuous operation. Due to this low capacity, boats only reach each island every two to three weeks. Additionally, the outer islands lack proper docking facilities for government ships. Therefore, cargo and passengers must be transferred to the shore on small workboats, which requires passage through the channels leading to the islands and in several cases such as Niutao, landing on a ramp on the beach. The transfer process is hazardous for passengers and goods and is suspended when the sea is rough or after dark. Under dangerous conditions, the inter-island ships may also be delayed, which limits operational efficiency.

8. Due to these limitations, economic growth and development of the outer islands is stifled by the lack of connectivity. In response, the government is committed to improving the transportation network, as outlined in the National Strategy for Sustainable Development – TeKakeega III and the Infrastructure Strategic Investment Plan 2011-2015. As a part of this effort, the Government of Tuvalu has asked the Asian Development Bank (ADB) for assistance in improving its outer island maritime facilities. The proposed project includes two components:

    - Rehabilitating and improving maritime infrastructure in selected outer islands of Tuvalu, some of which were damaged in tropical cyclone Pam in 2015; and
    - Improving safety, efficiency, and sustainability of maritime transportation between the outer islands and Funafuti.

9. Niutao lies east of Nanumea and Nanumaga and about 348 km northwest of Funafuti. The table reef is comprised of a single island approximately 2.5 km long and 1.1 km wide, oriented east to west. Inland, there are a raised large lagoon and a smaller lagoon with brackish water connected by subterranean passages to the sea. The island is surrounded by a fringing reef that supports diverse marine ecosystems that provide food and economic value to Tuvalu (Cardno, 2016). Niutao has more live coral cover than other islands involved in this project (Sewell, 2017).

10. With a population of nearly 700 people, Niutao makes up 6.5% of the total population of Tuvalu. Niutao has experienced a decrease in the resident population of 15.1% between 2002 and 2012. The population of Niutao lives in two villages on the western side of the island: Kulia and Teava. There are more women (52%) than men on Niutao (which is opposite to the national trend where men account for 51% of the population). Most residents rely on subsistence activities for their livelihood, including fishing, raising livestock and fishing. Based on the 2012 Island Profile, only 98 people (23%) of the Niutao population over 15 years old were employed mainly through government work as nurses, teachers and Island Kaupule employees (Initial Environmental Examination, 2018). While there is no significant commercial fishing based on Niutao, the surrounding waters support the Niutao population and form part of the region fished by fleets based in Funafuti.

11. Currently, the small work boats transferring cargo and passengers from inter-island vessels access Niutao through a dredged channel in the outer reef on the western side of the island and unload on a ramp on the beach. Local fishing boats also face challenging conditions entering and leaving the channels, due to a combination of wave height, the small vessel size, and unsheltered landing areas. The project at Niutao aims to build a harbour and wharf for the small work boats transferring goods and passengers from the inter-island vessels to the shore that incorporates climate proofing features. In doing so, transportation safety and efficiency will be improved, and the proposed infrastructure will be designed to be resilient to climate change and withstand climate-induced impacts and extreme weather events. The overall project aims to achieve the following:

    - Contribute to economic development including fisheries;
    - Improve livelihoods and safety conditions in the outer islands; and
    - Reduce migration from outer islands to the capital of Funafuti, which has contributed to overcrowding, pollution, and spread of diseases (Cardno, 2016)

12. Due to human activity and tropical cyclones, the project site is vulnerable to coastal erosion. In 1994-1995, a concrete beach ramp was built near Muli Channel; this structure contributed to severe erosion of the beaches of up to 1.4 km away, affecting 20% of the island's foreshore around the

northeastern corner and western side of the island. It was so destructive that it was removed completely in 2006 (Sewell, 2017). As a result, proposed harbour (see the Feasibility Report) is located away from the vulnerable north west corner of the island near the main village. Include a note Construction of project structures such as protective breakwaters may reduce erosion or alter hydrodynamics in the area, reflecting waves or creating greater current velocities in localized areas (Cardno, 2016). In addition to having impacts on local marine ecosystems, these changes may put additional strain on the wharf and associated structures. Recognizing these risks, the current proposed harbour has been sited to minimize such impacts by locating the facility in the northeast, away from the more vulnerable northwest corner of Niutao.

13. The entire country of Tuvalu is widely recognized as one of the most vulnerable countries in the world to the impacts of climate change, including extreme weather events due to its resident's dependence on ocean resources for their livelihoods, high exposure to climate hazards, and low adaptive capacity. It is also uniformly low, the highest points being only about 4m above sea level. The high level of vulnerability of Niutao is consistent with that of Tuvalu as a whole.

14. Residents of Tuvalu depend on fisheries for their sustenance – the major source of income for the Government being fishing licenses for overseas fishing fleets using mother ships anchored in the Funafuti lagoon - and climate change could contribute to local species extinction of more than half of the fish and invertebrate species currently present (Asch, Cheung, & Reygondeau, 2018). While there is no significant commercial fishing based on Niutao, the surrounding waters support the Niutao population and form part of the region fished by fleets based in Funafuti . While there is no significant commercial fishing based on Niutao, the surrounding waters support the Niutao population and form part of the region fished by fleets based in Funafuti.

15. Coral reefs play a critical role in protecting Niutao and all coastal areas and communities in the region from hazards, such as wave runup, overtopping, flooding and erosion. Due to the low-lying nature of the islands and their fundamental structures as coral islands, they are dependent on continued coral reef health for the supply of sediment on which the islands are built and for wave protection that reefs provide from ocean swell and extreme cyclonic waves (Quataert, Storlazzi, van Rooijen, Cheriton, & van Dongeren, 2015). As reefs degrade, Niutao will likely become more exposed to climate change-induced sea level rise and changing wave climate, which may result in more frequent or extreme coastal flooding on the island. It could also have repercussions for the protection of the harbour infrastructure itself,. Wave runup increases with narrower flat reefs, steeper fore reef, and lower-friction reefs, and it also increases with higher offshore wave levels. Coral bleaching, a main outcome of climate change, kills reefs and may result in lower friction on the coral surface, which is one of the inhibitors of wave runup (Quataert, Storlazzi, van Rooijen, Cheriton, & van Dongeren, 2015). Since climate change will have significant negative impacts on corals, determining ways to promote and establish reef adaptation and restoration will help mitigate coastal hazards on Niutao and other tropical islands.

16. Consequently, this CRVA considers the integration of climate change factors into the specific design elements of the proposed Niutao Harbour within the context of the broader climate change vulnerability of the island. The long term structural integrity of the reef will be critical for the success of the project. Should protective reefs become damaged beyond a critical threshold, the broader livelihoods of Niutao residents will suffer due to potential inundation of the island and chronic coastal erosion, together with reduced availability of nearshore fisheries. The proposed project will contribute to the well-being and stable livelihoods of current residents as broader issues of sustainability are addressed.

17. This CRVA focuses on ensuring that the function of the new Niutao Harbour meets its service objectives in the face of climate change and disasters through integration of climate change and disaster risk reduction factors into the design of the harbour and associated infrastructure.

## Niutao Harbour Design Summary

The design used for this analysis is the Feasibility Study Report prepared by Cardno (Cardno, 2018). This report indicates the key components of the design, siting, and context. The project has a design life of 50 years.

18. The site selected for the project is on the northeast coast. Due to the narrow width of the reef flat at this point, the wave environment at the structures is high but no better site was found. Other parts of the island have more severe wave environments.

19. Specifics of the proposed design are provided in the project's Detailed Design Report including initial design drawings. Key design aspects for the Niutao Harbour, as specified in the Detailed Design Report, include:

    - Excavation of a new sea access channel;
    - Demolition, land clearing, stockpiling of dredged spoil, and earthworks;
    - Construction of channel side protection and basin back walls;
    - Construction of wharf for the loading and unloading of work boats;
    - Construction of an approach jetty;
    - Construction of sea walls;
    - Construction of a boat ramp;
    - Construction of a passenger terminal building, septic tank, water tank;
    - Construction of a warehouse building and water tank; and
    - Installation of appropriate navigation aids.

20. The design includes a segment on land with a road, warehouse, etc. and marine works including a concrete wharf and sidewall elements. Sidewalls are intended to reduce operating wave and current climate for improved navigation (Cardno, 2017). Additionally, a flexmat boat ramp will provide direct boat access from the dredged channel to shore. This option provides flexibility for the ramp to change with the shape of the beach and minimize future costs. A visualization of the proposed design is shown in Figure 4

Figure 4. Visualization of Niutao Harbour design (Cardno, 2017)

# II. Climate Risk Management

## Climate Risk Management Process

21. ADB's Midterm Review Strategy 2020 commits to increase support for climate adaptation and resilience in project design and implementation. Accordingly, since 2014, ADB requires that all investment projects at risk of incurring climate impacts consider climate risk and adaptation measures (ADB, 2014). In designing and building a harbour on Niutao, it is required that climate vulnerability and adaptation options be investigated.

22. ADB's Climate Risk Management Framework aims to reduce risk by identifying climate risks to the project and incorporating corresponding adaptation measures into project design (ADB, 2014). Phases include:

    a) **Climate risk screening**, which includes a preliminary screening. If the project is identified to be medium or high risk, a subsequent detailed screening is undertaken using an appropriate tool, such as AWARE. This stage aims to identify whether the project may be vulnerable to climate change hazards and whether further analysis is required.

    b) **Climate Risk and Vulnerability Assessment (CRVA),** is required for projects that are identified as medium- or high-risk during the climate risk screening phase. The CRVA aims to quantify risks and identify adaptation options that can be integrated into project design.

    c) Technical and economic evaluation of adaptation options.

    d) **Identification of adaptation options,** and incorporation into project design.

    e) Monitoring and reporting the level of risk and climate-proofing measures.

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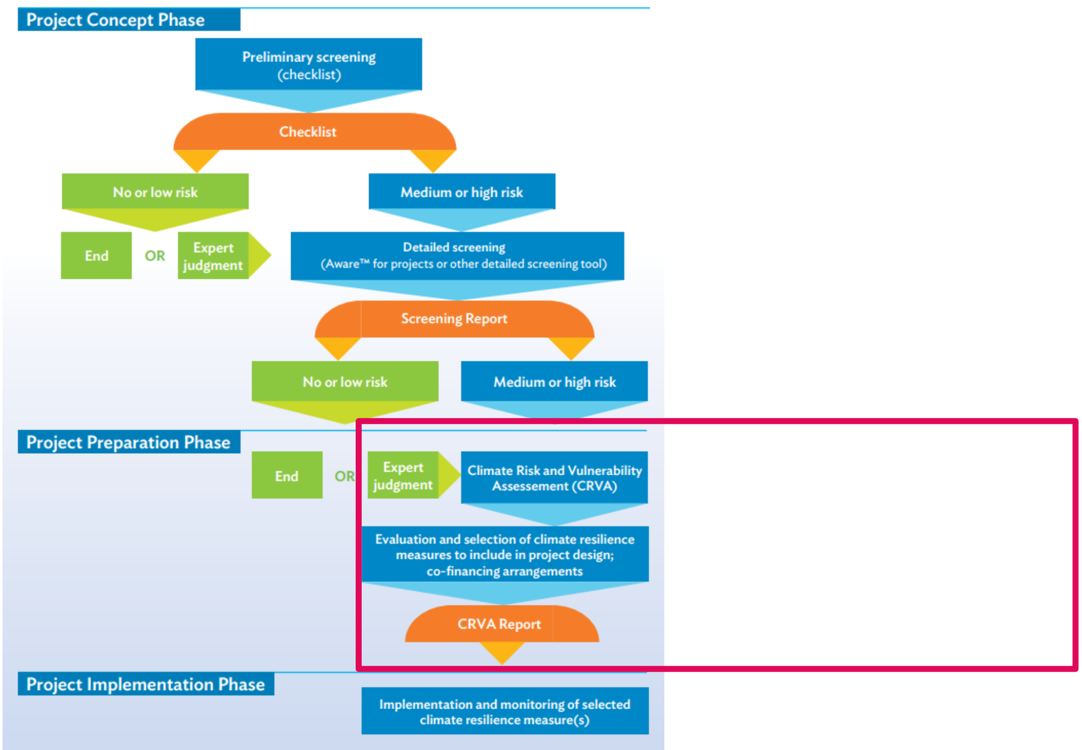


Figure 5. ADB Climate Risk Management Framework and current project phase, as indicated by red box (ADB, 2014).

## Climate Risk Screening

23. The first stage in the Climate Risk Management Framework is to screen the project in order to identify whether it may be vulnerable to climate change hazards. Using the AWARE tool, a climate risk screening was undertaken for the Outer Island Maritime Infrastructure Project that determined that the project is high risk, as shown in Figure 6. The highest sources of risk include sea level rise, wind speed increase, and offshore Category 1 and above storms (the areas where risk spikes into the red zone). All other areas presented low risk. The full screening report is found in Appendix A.

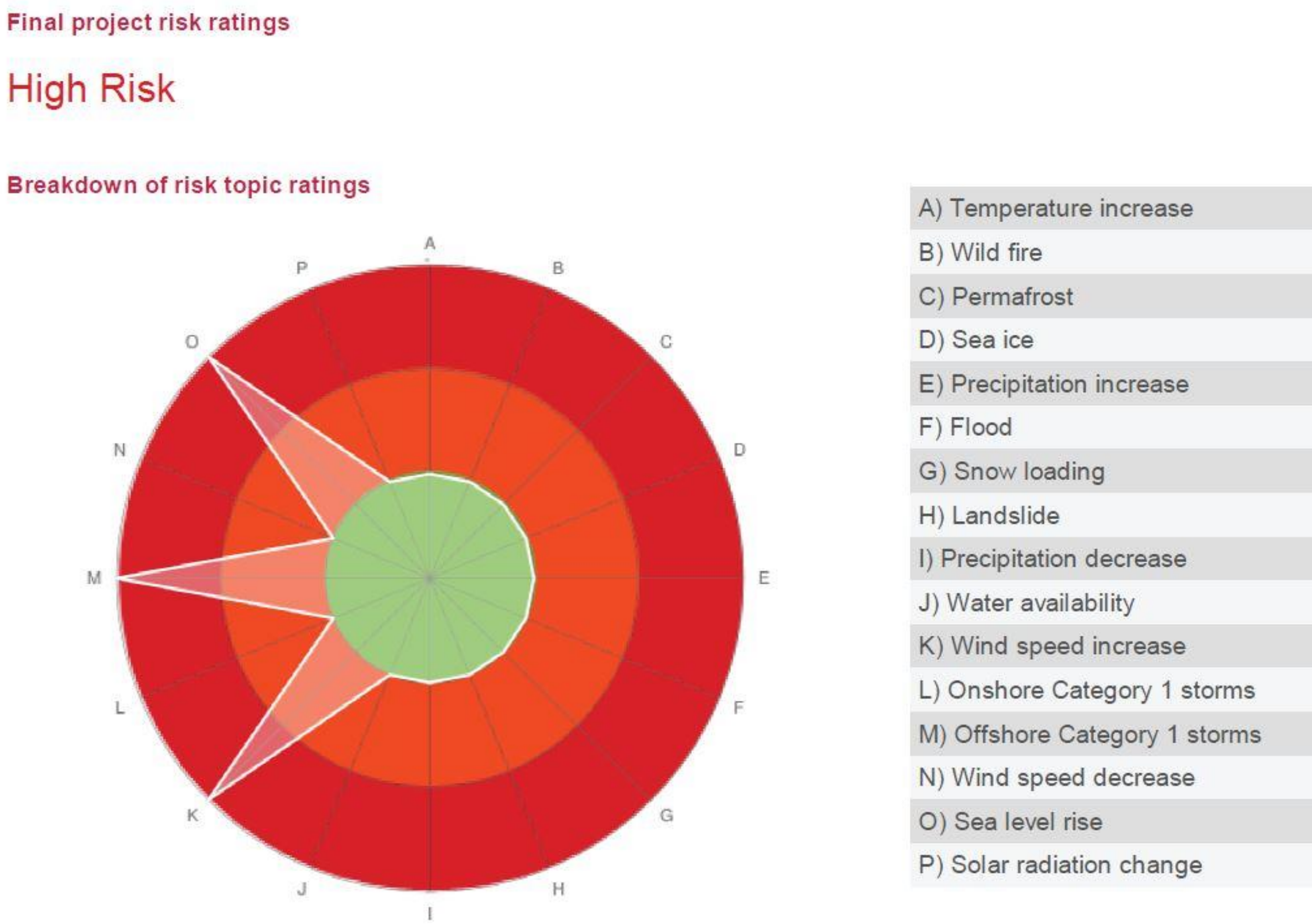


Figure 6. Project climate risk rating based on AWARE tool screening.

## Climate Risk and Vulnerability Assessment

### 1.1.1 Purpose of the CRVA

24. The “High risk” result of the risk screening triggered the requirement for a CRVA, which is the focus of this document. As per the ADB Climate Risk Management Framework, this document assesses climate change risks to the project and recommends a set of adaptation options to mitigate these risks.

25. The purpose of the CRVA is to:

   a. Assess climate change risks to and vulnerabilities of the project;

   b. Identify associated adaptation strategies to manage the identified risks; and

   c. Ensure that climate change is integrated into the project design options being assessed.

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### 1.1.2 Structure of CRVA

26. This CRVA document includes::

**Section III:** Climate Change Overview, including historical climate change and relevant climate change projections

**Section IV:** Climate Risk and Vulnerability Assessment

**Section V:** Recommendations

Section VI: References

Section VII: Appendices

27. The climate change drivers considered throughout this report are drawn from studies published on projected changes specifically for Tuvalu, supplemented by regional assessments. Following consultation with the Project Team, and based on recent CRVAs undertaken in the Pacific (ICF, 2017; Cardno 2016) the climate change drivers are divided into primary climate drivers and secondary climate drivers.

28. The primary climate change drivers are:

- Mean sea-level
- Wind climate
- Wave climate
- Ocean acidification

29. The secondary climate change drivers are:

- Ocean temperature
- Air temperature
- Rainfall and runoff

# III. Climate Change Overview for Niutao

## Literature Review

30. To describe current and future conditions on Niutao, this study uses the Australian Bureau of Meteorology (BoM) and Commonwealth Scientific and Industrial Research Organization (CSIRO) 2011 Country Report on Tuvalu and the Climate Change in the Pacific: Scientific Assessment and New Research (2014) Country Report, both completed under the Australian-supported Pacific Climate Change Science Program (PCCSP). It should be noted that BoM and CSIRO (2014) tends to project greater changes than BoM and CSIRO (2011), probably because of the use of RCPs and CMIP5 models, and updated projections based on IPCC 2013. The PCCSP information is supplemented by a literature review of more recent publications.

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## Climate Change Scenario Selection

31. The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC, 2014) developed climate change projections for various representative concentration pathways (RCPs) based on different greenhouse gas (GHG) emission scenarios. The scenarios are:

- RCP2.6 – stringent GHG mitigation scenario, stabilization at 400 ppm by 2100 (lower than today);
- RCP4.5 – intermediate GHG emissions, stabilization at 538 ppm of CO2 by 2100;
- RCP6.0 – intermediate GHG emissions, stabilization at 670 ppm by 2100; and
- RCP8.5 – very high GHG emissions, little mitigation, reaching 936 ppm by 2100.

32. The BoM and CSIRO (2011) report uses climate projections from up to 18 global climate models from the Coupled Model Intercomparison Project Phase 3 (CMIP3), for three emission scenarios and three 20-year periods centered at 2030, 2055, and 2090 (BoM and CSIRO, 2011). The BoM and CSIRO (2014) report uses updated data from CMIP5-based global climate model projections and the IPCC 2013 reports (BoM and CSIRO, 2014). Also, this report provides projections for four future 20-year periods centered at 2030, 2050, 2070, and 2090 and uses the four RCP scenarios, consistent with IPCC. The models chosen reproduce important features of the current climate and, therefore, they plausibly represent the range of possible future scenarios.

33. The CRVA conducted by Cardno used RCP6.0 based on assumptions regarding future global GHG emission reductions (Cardno, 2016). However, this Niutao CRVA-uses RCP8.5, as a more conservative approach encouraged by ADB for high risk locations, although not required[1]. The RCP8.5 scenario is aligned with the trends of observed emissions (Kotamarthi, Mearns, Hayhoe, Castro, & Wuebble, 2016). It is considered prudent risk management practice to consider higher GHG emission scenarios or "worst case", consequently the RCP8.5 is most appropriate for assessing climate risk for Niutao Harbour.

34. The project has a 50-year design life – or to 2068. Climate change projections are commonly produced for 2030, 2050, 2070 and 2100 time horizons. Consequently, to most closely align with the 2068 project design lifetime, projections to 2070 are adopted in this report; in instances where projections for specific climate stressors to 2070 are not available, the next later time horizon is referenced to err on the side of caution.

## Dominant Climatic Features of the Province

35. The overall climatic features of Niutao are consistent with those of islands throughout Tuvalu. While spread out across roughly 1 million km$^2$, the islands of Tuvalu all lie within the Southern South Pacific Convergence Zone, with Niutao lying more to the north (Figure 7), and experience similar climate conditions. While noting these variations, climate trend information and climate projections for Tuvalu as a whole provide a reasonable proxy for conditions on Niutao. Specific factors that are distinct for Niutao are addressed to the extent data is available.

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[1] Email correspondence, Charles Rodgers,19th March, 2018.

36. Tuvalu has a tropical marine climate with high humidity and mostly uniform temperatures ranging from 26-32 °C. From 1942 to 2005, average annual rainfall was 2875 mm per year, and dry spells and droughts are relatively uncommon. However, average annual rainfall varies from 3500 mm per year in the southern islands of Tuvalu to 2700 mm per year in the northern islands including Niutao.

37. The meteorological and oceanographic climate in Tuvalu is driven by strong intra- and inter-annual cycles, such as the El Niño Southern Oscillation (ENSO) and seasonal variations. The interaction with the Pacific Ocean currents plays an important role in shaping climate. Year-to-year climate variations throughout the Southwest Pacific are driven by ENSO. Funafuti experiences wetter, warmer conditions in El Niño years and drier, cooler conditions during La Niña years (BoM and CSIRO, 2011). Projections for how climate change will impact the frequency and intensity of these inter-annual cycles is uncertain. Future changes in El Niño occurrence could have far-ranging, cross-sectoral impacts. Cai et al. (2014) presents evidence for a doubling in the occurrence of El Niño events in response to future climate change due to surface warming over the eastern Pacific and increased convection over surrounding oceans.

38. Additionally, seasonal variations are critical for Tuvalu. The year is divided into a distinct wet and dry season – the wet season runs from November to April with winds from the west and northwest, and the dry season runs from May to October when the lighter southeast trade winds dominate.

39. The consistency of climate patterns throughout Tuvalu is a result of the large-scale patterns across the Pacific which influence the climate. The South Pacific Convergence Zone (southern blue shading in Figure 7) is a band of heavy rainfall extending from near the Solomon Islands to east of the Cook Islands. It is strongest in the Southern Hemisphere wet season. The Intertropical Convergence Zone (northern blue shading) stretches across the Pacific located in the northern Hemisphere above the equator and is strongest in the Northern Hemisphere during the wet season. The West Pacific Monsoon (eastern part of the Monsoon on the map) is driven by large differences in temperature between the land and the ocean. It moves north to mainland Asia during the Northern Hemisphere summer and south to Australia in the Southern Hemisphere summer.

40. Hence, the seasonal arrival of the Monsoon brings a switch from relatively dry to very wet conditions. The seasonal cycle observed in Tuvalu is driven by the strength of the South Pacific Convergence Zone and the West Pacific Monsoon. The West Pacific Monsoon can also bring high rainfall to Tuvalu during the wet season (BoM and CSIRO, 2011; Cardno, 2016).

41. Figure 7 shows the average positions of the main features related to regional climate in November to April. The yellow arrows show near surface winds, while the blue shading represents the bands of rainfall or convergence zones, the dashed red oval shows the West Pacific Warm Pool which comprises some of the warmest open ocean waters on Earth, and the red circled H represents typical positions of moving high pressure systems for this time of year. These features affect the regional pattern and seasonal cycle in rainfall, winds, tropical cyclone tracks, ocean currents, nutrients and many other aspects of the environment.

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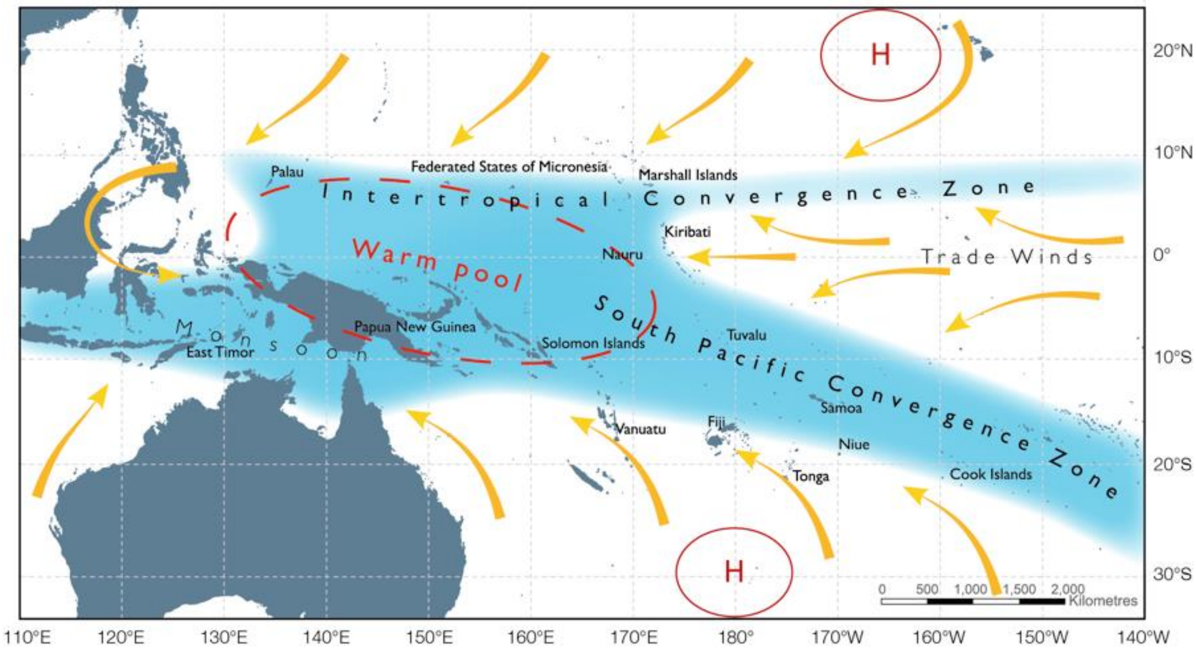


Figure 7. Dominant climatic features of the PCCSP region (including Tuvalu) in November to April (Australian BoM and CSIRO, 2011)

42. Tuvalu is particularly vulnerable to tropical cyclones, which routinely threaten the islands. In 2015, tropical cyclone Pam caused flooding and erosion on the west coasts of several islands, which left maritime infrastructure damaged (Cardno, 2017). A ramp in Nanumaga that was used for loading and unloading cargo from ships was washed away and, on Niutao and Niu, channels were impacted by carried sediment (Cardno, 2016).

43. The following sections provide more detailed descriptions of the climate drivers in the region, including the primary drivers (mean sea-level, wind climate, wave climate, and ocean acidification) and secondary drivers (sea surface temperature, air temperature, and rainfall and runoff). Where specific observations or projections for Niutao are not available, information regarding climate drivers for Tuvalu as a whole are applied as a reasonable proxy for island-specific information.

# Primary Drivers

## 1.1.3 Mean Sea-Level

### 1.1.3.1 Current Conditions

44. Earlier studies, focused on the area near Funafuti, estimated relative sea level rise at 2 (+/-) 1 mm per year from 1950-2001 (Church, White, & Hunter, 2006). However, the Australian Bureau of Meteorology used satellite altimeter data from 1993-2010 to show sea level rise at about 5 mm per year, which is greater than the global average of 3.2 (+/-) 0.4 mm per year (see Figure 8) (BoM and CSIRO, 2011). This analysis indicates that the rate of sea level rise is relatively consistent throughout Tuvalu, including Niutao. Therefore in the absence of specific observations for Niutao this assessment relies of the BoM / CSIRO data.

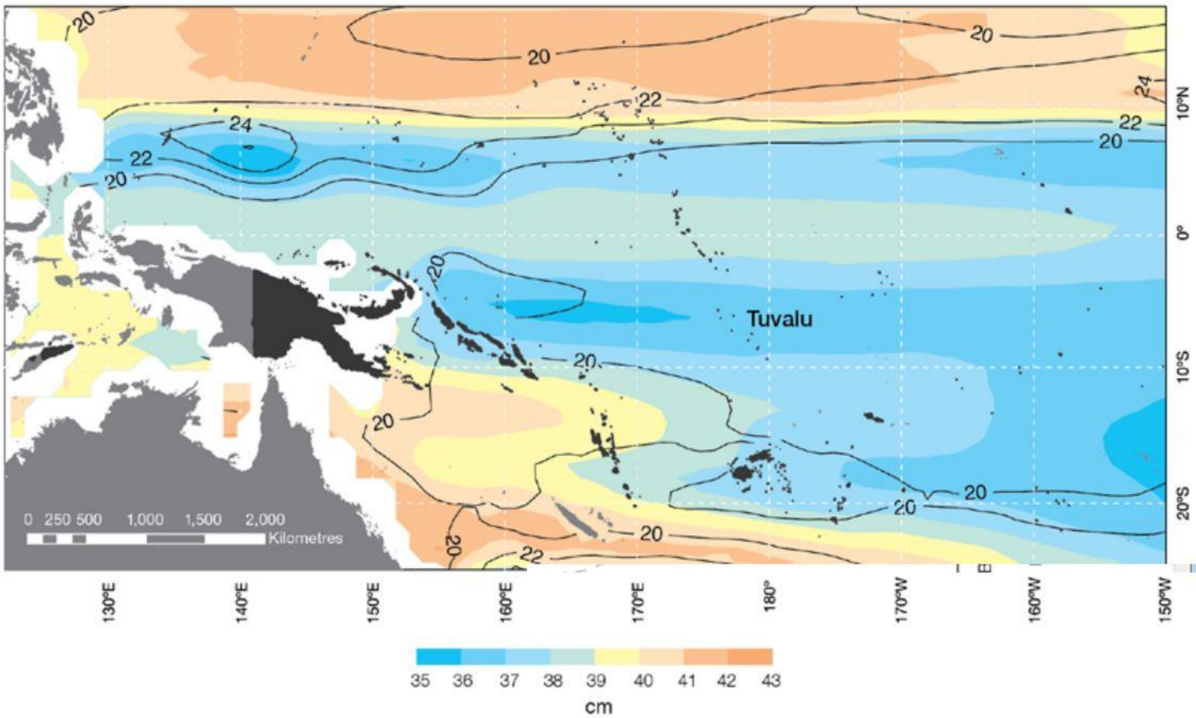


Figure 8. Regional distribution of the rate of sea-level rise, as measured by satellite altimeters from January 1993 to December 2010 (BoM and CSIRO, 2011).

45. Sea level rise changes are partially due to year-to-year and decadal-to-decadal climate variability. From 1993 to 2010, Tuvalu's inter-annual sea-level variability was about 26 cm (5 to 95% confidence range around long-term trends) not considering seasonal variability (BoM and CSIRO, 2011). Church et al. (2006) found that inter-annual variability can be as large as 45 cm due to ENSO. In La Niña years, sea levels tend to be higher due to warmer ocean temperatures, while during El Niño years the seasonal contribution to extreme sea levels is low (BoM and CSIRO, 2011).

46. According to the Feasibility Study conducted for Niutao, the tide planes for Tuvalu are as follows (Cardno, 2018):

Table 1. Tidal levels (Cardno, 2018)

| Tidal Plane | Water Level (m to Lowest Astronomical Tide) | Water Level (m to MSL) |
|---|---|---|
| **Highest Astronomical Tide (HAT)** | 2.422 | 1.263 |
| **Mean High Water Spring (MHWS)** | 1.980 | 0.821 |
| **Mean High Water Neap (MHWN)** | 1.492 | 0.333 |
| **Mean Sea Level (MSL)** | 1.159 | 0 |
| **Mean Low Water Neap (MLWN)** | 0.827 | -0.332 |
| **Mean Low Water Spring (MLWS)** | 0.338 | -0.821 |
| **Lowest Astronomical Tide** | 0.000 | -1.159 |

47. 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 Tuvalu are shown in Figure 9. The ten highest sea level events on record are shown and coded to indicate where in the ENSO phases each occurred (BoM and CSIRO, 2011). Inter-annual variability of sea level will lead to periods of higher and lower regional sea levels.

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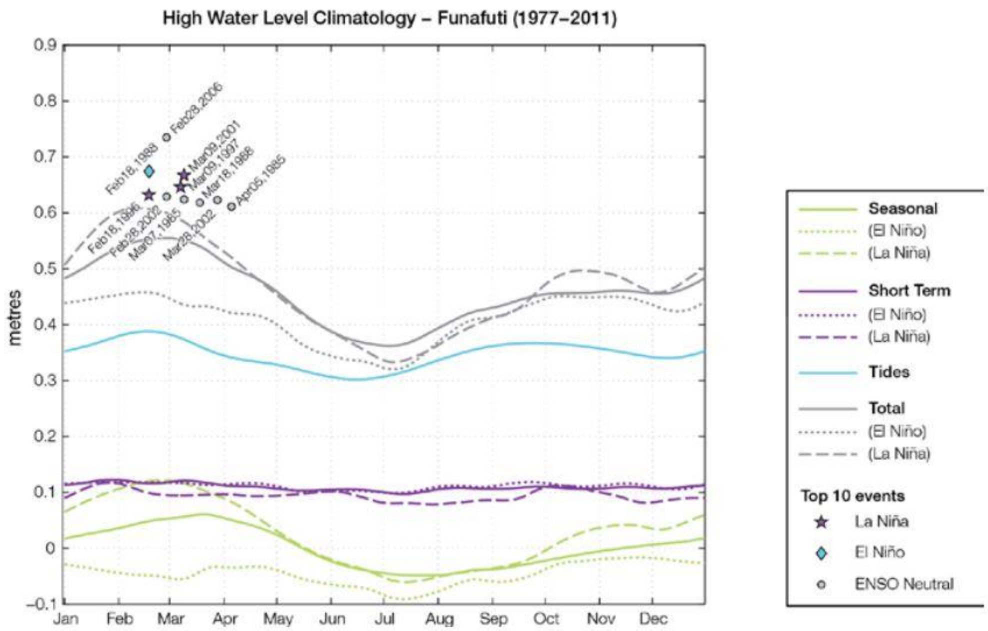


Figure 9: Annual cycle of high waters relative to Mean Higher High Water (MHHW) due to seasonal and inter-annual cycles (BoM and CSIRO, 2011).

48. Despite sea level rise at Funafuti of 3.9 ± 0.4 mm yr-1 since 1971, total land area in Tuvalu has expanded by 73.5 ha (2.9%) (Kench, Ford, & Owen, 2018). These findings challenge existing narratives about islands in the Pacific disappearing due to sea level rise. The Tuvaluan islands have remained above sea level during the post glacial era through a process of coral island building. However, under RCP8.5, or even RCP 6.0, the rate of sea level rise is projected to increase over historic levels that may outpace the natural ability of reefs to grow at such rates and factors such as increased acidification and ocean temperatures may reduce the rate of coral growth.  Under these conditions it is unclear whether islands would be able to adjust and recover (Kench, Ford, & Owen, 2018)

#### 1.1.3.2 Future Scenarios

49. Throughout the 21st century, mean sea level is expected to continue to rise, and the rate of this rise is expected to accelerate. IPCC reported global average sea level rise to be 1.7 mm per year from 1901 to 2010, which culminates in approximately 0.19 m of relative sea level rise (IPCC, 2014). Yet, between 1993 and 2010, sea levels rose 3.2 mm/year on average, which indicates an increasing rate of sea level rise (IPCC, 2014). The IPCC AR5 reports a "*likely*"[2] sea-level rise of 52-98 cm by 2100 for the RCP8.5 scenario (IPCC, 2014). The BoM and CSIRO Tuvalu country report summarizes the range of sea level rise (SLR) relative to 1990, projecting an increase of 5-15 cm by 2030, and 20-60 cm by 2090 under IPCC 4th Assessment Report high and medium emissions scenarios (A2 and A1B) (BoM and CSIRO, 2011). However, more recent work by BoM and CSIRO (2014) that used CMIP5 models project an increase of 7-18 cm by 2030 and increases of 39-87 cm by 2090 under RCP8.5 (Figure 10) (BoM and CSIRO, 2014). The significant uncertainty with these

[2] "*Likely*" is characterized as a one-third probability that sea level rise may lie outside of this range (Sriver, Lempert, Wikman-Svahn, & Keller, 2018).

projections is mostly associated with uncertainty about the contributions of Antarctic ice sheet melt, which could accelerate sea level rise beyond current projections (BoM and CSIRO, 2014).

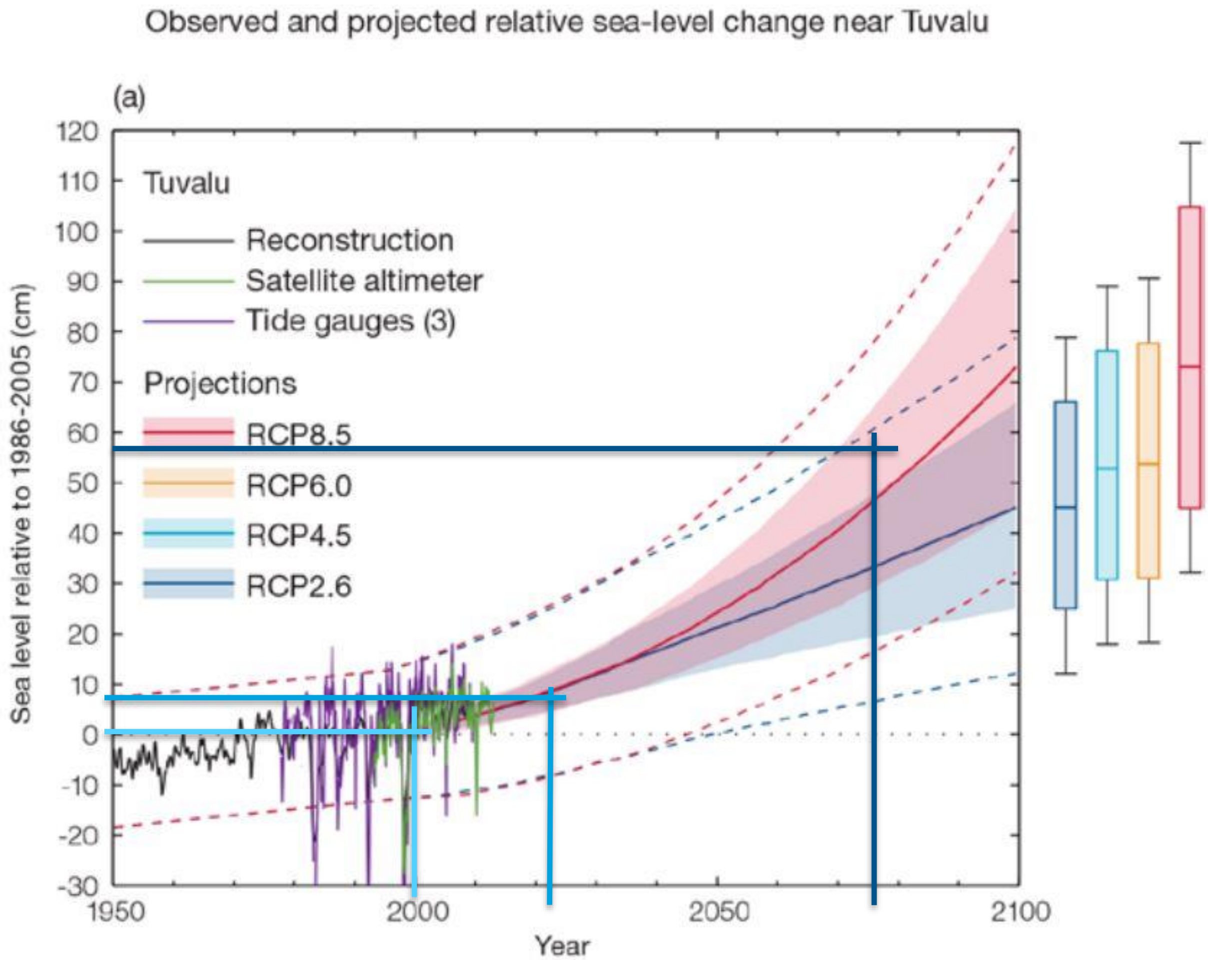


Figure 10. Observed and projected relative sea-level change near Tuvalu. The observed tide-gauge records of relative sea level rise are indicated in purple (since late 1970s), and the satellite record (since 1993) in green. The shaded areas depict the 5 – 95% uncertainty range of model projections, while the dashed lines depict the 5 – 95% uncertainty of interannual variability. The light blue crossing lines depict the upper range of historical MSL (1986 – 2005), the medium blue lines depict the upper range of present day MSL (2018), and the dark blue lines depict the upper range of projected 2070 MSL (BoM and CSIRO, 2014).

50. The Feasibility Study considers a projected 60 cm of sea level rise to incorporate sea-level rise projections into the 50-year design life (Cardno, 2018). This aligns with a rounding up to the nearest 10cm of the upper range of projected change in sea level (RCP 8.5) as shown in Figure 10. This aligns with a rounding up to the nearest 10cm of the upper range of projected change in sea level (RCP 8.5) as shown in Figure 10 (above) of 57 cm by 2070 relative to the baseline period of 1986 – 2005.

51. This level was taken into consideration together with recent higher projections of sea-level rise from NOAA, which indicate that under RCP4.5 and RCP8.5 there is a 73% and 96% chance of exceeding 0.5 m of sea level rise by 2100 (relative to 2000) (NOAA, 2017). The intermediate to

extreme range of projections under RCP8.5 is from 0.57-1.2 m by 2070 (relative to 2000 (see Figure 11) (NOAA, 2017).

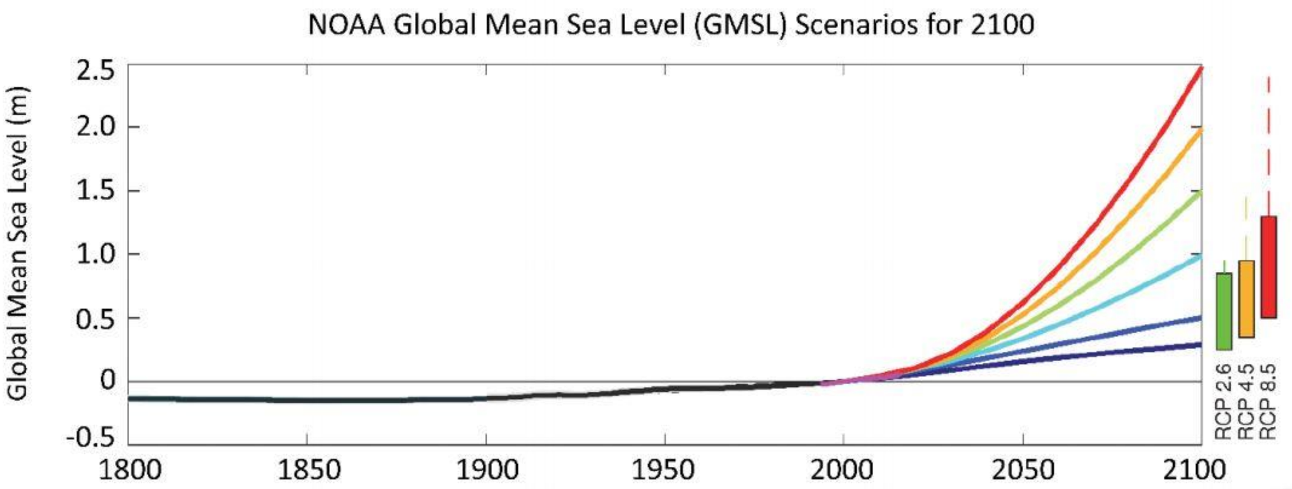


Figure 11. NOAA provided six updated GMSL rise scenarios for 2100 relative to 1800-2015 (NOAA, 2017).

52. NOAA estimates of projected sea level rise are higher, as a sea-level rise projection of 60 cm by 2067 (relative to 2000) approximates to the ‘intermediate’ projections made by NOAA. NOAA (2017) supports the perspective that decision makers should consider the full range of potential outcomes, including high-consequence, low-probability events, when designing long-life infrastructure (NOAA, 2017).

53. It is assumed that the Feasibility Report incorporates 60 cm of sea-level rise based on present-day tidal conditions. Given that sea-level has already risen from the baseline period of 1986 – 2005 (as shown in the light blue lines in Figure 10) there is an additional factor of safety included in taking the baseline year as 2018.

### 1.1.4 Wind Climate, including Tropical Cyclones

#### 1.1.4.1 Current Conditions – Prevailing Winds and Tropical Cyclones

54. Figure 12 shows the wind rose with the direction from which prevailing (non-cyclonic) wind is blowing at the Funafuti Wave buoy. Figure 12 shows that the prevailing easterly winds are generally light and, as such are not as critical to the location of the harbour as cyclonic winds, and ocean swell and storm waves, as outlined below.

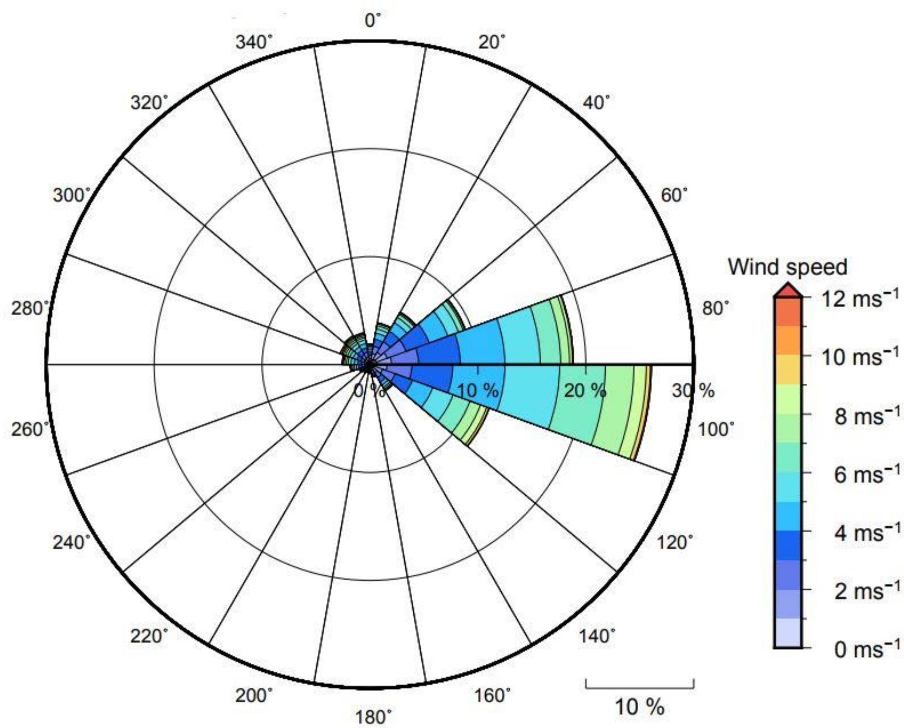


Figure 12. Annual wind rose for Funafuti Wave buoy (Bosserelle, Reddy, & Lal, 2015)

55. Tropical cyclones generate high winds, rainfall, storm surge that can cause inundation on low-lying islands (BoM and CSIRO, 2011). Cyclone activity is concentrated around 10°S and cyclones generally affect Tuvalu between November and April with an average of 8 per decade between 1969 and 2011. This equates to an 80% chance of Tuvalu being affected by a cyclone of Category 1 or higher in a given year.[3] Only three of 24 tropical cyclones that crossed the area during this timeframe were Category 3 or stronger storms, with more frequent storms occurring in El Niño years and fewer in La Niña years. Thus, the inter-annual variability in the number of tropical cyclones is large, ranging from zero to three per season, which makes it difficult to identify future trends (BoM and CSIRO, 2011). Historical tropical cyclone tracks between 1969 and 2016 in the Niutao region are shown in Figure 13 that show that, given the relative proximity of Niutao to the equator, it is relatively less affected by the most severe tropical storms than the Tuvaluan islands further south. The project Feasibility Report analyzed historic cyclone tracks that passed within 1,000km of Niutao to develop a synthetic 'design cyclone' in order to model wind, wave and current parameters for the harbour (Cardo, 2017).

[3] Cyclone or hurricane ratings are based on the Saffir-Simpson Wind Scale. Category 1 is the lowest level; these storms have winds from 74-95 mph, which will produce some damage to homes, break trees, and take out power lines, causing outages that could last several days (NOAA, 2018).

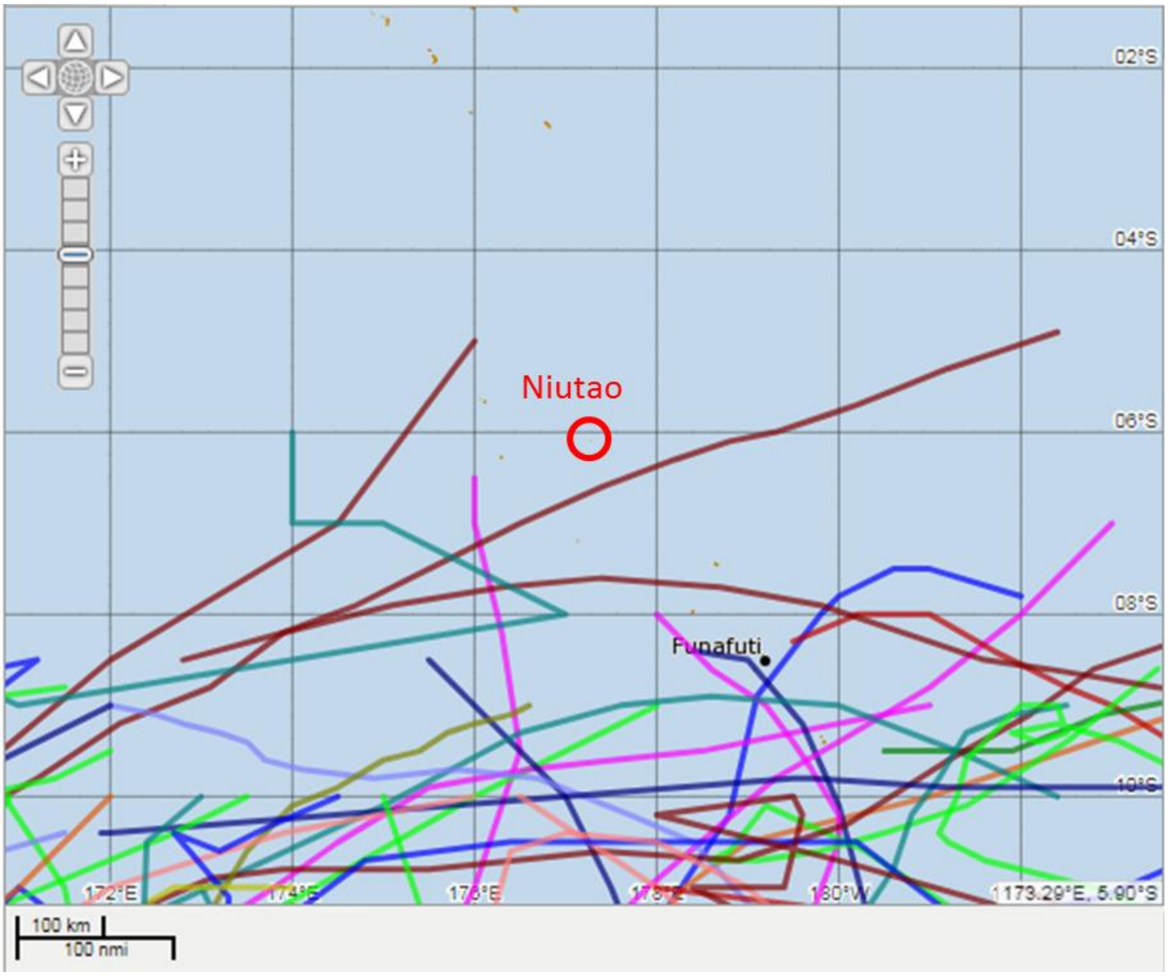


Figure 13. Historical tropical cyclone tracks (1969 – 2016) surrounding Niutao (Australian Bureau of Meteorology, 2018)

#### 1.1.4.2 Future Scenarios – Prevailing Winds and Tropical Cyclones

56. Globally, the strongest tropical cyclones are expected to increase in intensity (Stephens and Ramsay 2014). In the Southwest Pacific, however, simulations vary, with some studies projecting increases in intensity, while other studies indicate no change or decreases (Knutson et al. 2010, Walsh et al. 2012). For example, Leslie et al. (2007) found that the number of tropical cyclones with wind speeds exceeding 30 m/s would double by 2050 in the Southwest Pacific relative to a 1970 to 2000 baseline. However, Walsh et al. (2012) concluded that in the South Pacific, maximum wind speeds are projected to change by -22% to +1% by the end of the century.

57. The frequency of tropical cyclone formation is predicted to decrease in frequency by 10-40% (high confidence) because conditions are expected to become less favorable in the region (BoM and CSIRO, 2014). The vast majority of CMIP3 climate model projections show a decrease in tropical storm formation and there is moderate confidence in these changes. However, despite the projected decrease in cyclone numbers, five of six CCAM simulations show that there could be an increase in the most severe cyclone events (BoM and CSIRO, 2011). However, models agree that cyclone intensity may increase due to increased mean maximum wind speeds of 2-11% globally and increased rainfall of 20% within 100 km of the cyclone center (BoM and CSIRO, 2014). As with

the previous assessment, it is recommended that the assessment assume no change in frequency due to the modeling projections that likelihood will decrease (Cardno, 2016).

58. The Pacific Climate Change Science Program (PCCSP) Projections Builder provides insights into potential future changes in seasonal mean wind speeds for Tuvalu. Mean Wind speeds are projected to change a maximum of -7.4% to +9% under RCP 4.5 and -7.6% to +26.1% under RCP 8.5 by 2070 (see Table 2). The maximum consensus scenario – when the most number of Global Climate Models provide similar results (Whetton, Hennessy, Clarke, McInnes, & Kent, 2012) – estimate changes of -1.1% to +2.2% under RCP 4.5 and from -1.9% to +7.1% under RCP 8.5 by 2070. However, overall consensus on the model projections is low for these scenarios.

Table 2. Projected percentage changes in Tuvalu mean wind speed by 2070 under RCP 4.5 and 8.5 relative to a 1980 to 1999 baseline (PCCSP Climate Futures)

| RCP | Scenario | Dec.-Feb. (DJF) | Mar.-May (MAM) | Jun.-Aug. (JJA) | Sep.-Nov. (SON) | Nov.-Apr. (NDJFMA) | May-Oct. (MJJASO) |
|---|---|---|---|---|---|---|---|
| 4.5 | Max. ↓ | -5.6% | -7.4% | -4.9% | -4.4% | -4.6% | -6.3% |
| | Max. ↑ | 0.7% | 5.3% | 1.5% | 9% | 2.6% | 5.1% |
| | Max. Consensus | 1.6% | -1.1% | 0.3% | 2.2% | -0.6% | 2.0% |
| 8.5 | Max. ↓ | -3.2% | -0.5% | 0.2% | -2.6% | -3.2% | -0.3% |
| | Max. ↑ | 26.1% | 16.5% | -7.6% | 5.7% | 20.1% | -1.7% |
| | Max. Consensus | -0.4% | -0.7% | 5.2% | 6.9% | -1.9% | 7.1% |

59. All structures will be designed for basic wind speeds of 60 m/s, which meets the standard outlined in Section B1.2 of the National Building Code for Tuvalu (Cardno, 2016).

## 1.1.5 Wave Climate

### 1.1.5.1 Current Conditions

60. In Tuvalu, wave climate is dependent on regional and local wind climates including those from ENSO, trade winds, tropical cyclones, and storms. Offshore noncyclonic wave climate is predominantly driven by the south-east trade winds and long period south-westerly swell waves from the Southern Pacific Ocean. Nearshore wave climate differs significantly from offshore wave climate, as waves attenuate as they travel across the reef. The further the wave travels from the reef edge, more attenuation will occur (Cardno, 2017).

61. Historic (hindcast) modelled deep-water wave data was analyzed using the WaveWatch III™ global wind and wave model for a location north-east of Nuitao between 1979-209 (Cardno, 2017). The results of this analysis, shown in Figure 14, highlights that the offshore non-cyclonic wave climate is dominated by the combination of south-east trade winds and long period south-westerly swell waves from the Southern Ocean.

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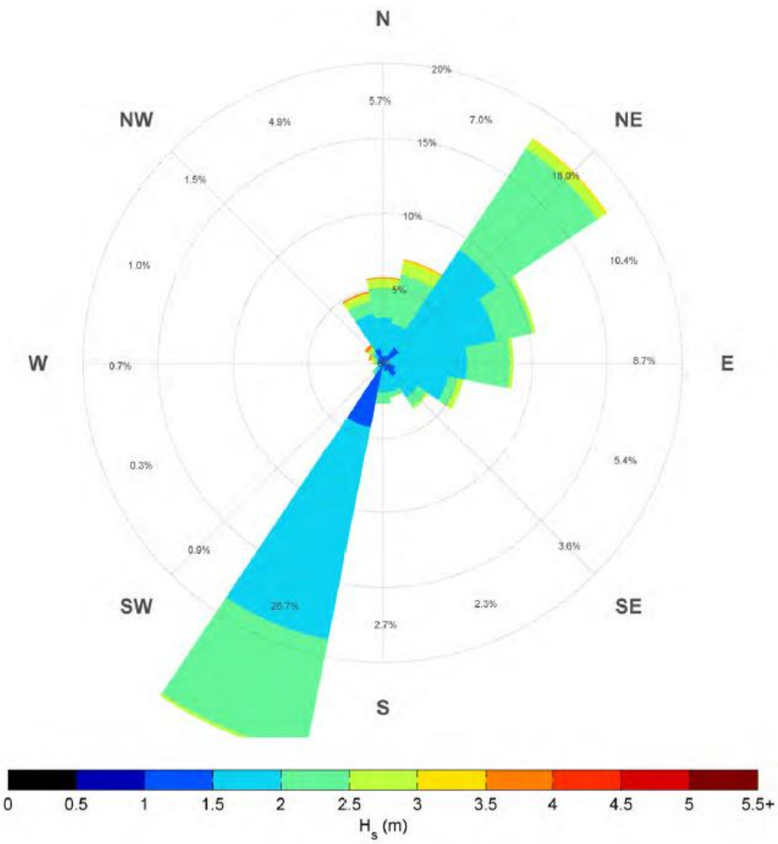


Figure 14. Modelled hindcast offshore wave climate for closest location to Niutao (Lon 177.00º, Lat 6.0°) (Cardno, 2017)

62. Additionally, waves change month-to-month and year-to-year climate oscillations. Typically these variations are smaller than seasonal changes (Bosserelle, Reddy, & Lal, 2015). Inter-annual variability of wave height is 4.7% at Funafuti while average Pacific variability is 7% (Bosserelle, Reddy, & Lal, 2015). Figure 15 shows annual wave height, wave period, and direction ranging between calm and large wave events.

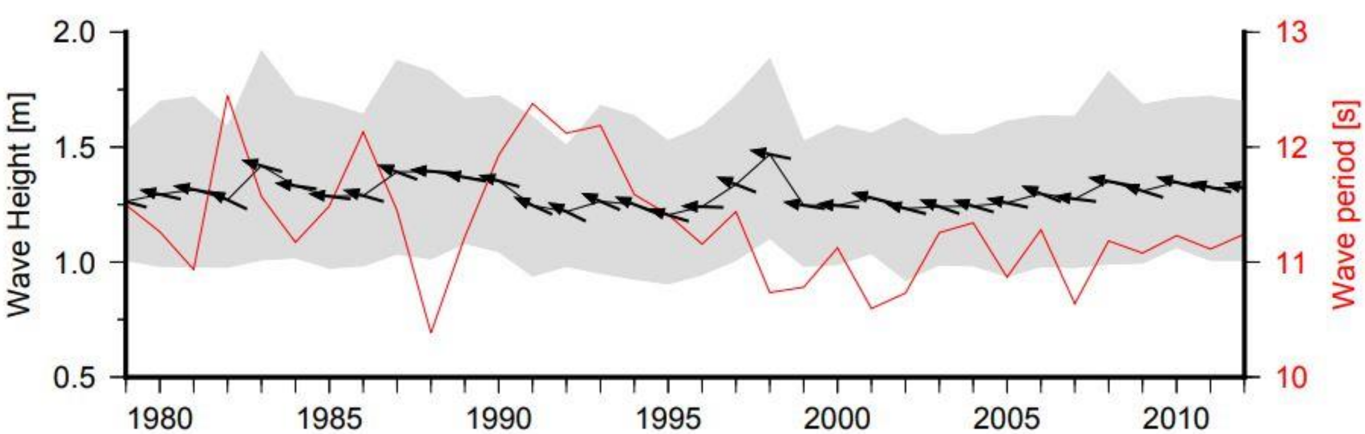


Figure 15. Annual wave height (black line), wave period (red line) and wave direction (arrows) and the grey zone represents the range between calm period and large wave events (10% lowest to 10% highest) (Bosserelle, Reddy, & Lal, 2015)

63. Large wave events occur which can cause erosion and inundation along the shorelines of the islands. Large waves are categorized as those that exceed the 90th percentile of wave height and they are typically the largest event expected each month (Bosserelle, Reddy, & Lal, 2015). These large waves pose the largest risk for those engaging in water-related activities or shipping (Bosserelle, Reddy, & Lal, 2015). Coastal inundation and erosion occur during the perigean spring tides or “king tides” (Bosserelle, Reddy, & Lal, 2015). Severe waves, with a threshold of 2.1 m at Funafuti, are even more severe and less common, occurring less than 1% of the time, the equivalent of 4 days in a year (Bosserelle, Reddy, & Lal, 2015). During severe waves, coastal erosion and inundation may occur and water activities are hazardous. Large and severe waves are generated by cyclones, distant extra tropical storms and fresh trade winds.

64. An analysis of extreme events at Funafuti found that 269 wave events reached or exceeded a 1.94 m threshold for severe waves. Since 1979, all of the 30 largest events exceeded 2 m in wave height and the largest event in 1990 exceeded 4 m (Bosserelle, Reddy, & Lal, 2015). As recently reported, cyclone events can generate wave heights between 3 and 4 meters in Tuvalu (Kench, Ford, & Owen, 2018).

65. The proposed Niutao Harbour is located on the northwestern shoreline, away from southeast trade winds which frequently cause wave conditions. However, the project would be exposed to cyclonic winds and waves, which are more severe (Cardno, 2016). The structures must be designed to withstand wind and wave forces and maintenance should take the implications of these stressors into account (Cardno, 2016). Also, it is important to consider the usability of the facilities given expected wave conditions, although transfers of people and supplies and other boating activities are likely to stop during a cyclone (Cardno, 2016).

#### 1.1.5.2 Future Conditions

66. During December to March, a small decrease in wave height is projected with a possible but non-significant decrease in wave period, and a small clockwise rotation in mean wave direction toward the east, with a suggested increase in waves from the north also, associated with cyclones, in 2090 under the RCP4.5 and RCP8.5 scenarios. No change is projected in the larger storm waves. June to September theirs is not a statistically significant change projected. Non-significant changes include increased wave height, although there is low confidence in projected changes in the Tuvalu wind-wave climate. Wave climate depends on ENSO and the projections for ENSO are low confidence and the difference between simulated and observed wave data can be larger than projected wave changes. All references (BoM and CSIRO, 2014).

Table 3. Wave projections summary for Tuvalu from 1986-2005 baseline, where blue text represents RCP4.5 and red text represents RCP8.5 (BoM and CSIRO, 2014).

| Variable | Season | 2035 | 2090 | Confidence Level |
|---|---|---|---|---|
| **Wave height change (m)** | December-March (wet season) | -0.0 (-0.1 to 0.1)<br>-0.0 (-0.2 to 0.1) | -0.1 (-0.2 to 0.0)<br>-0.1 (-0.2 to 0.0) | Low |
| | June-September (dry season) | +0.0 (-0.2 to 0.2)<br>+0.0 (-0.2 to 0.2) | +0.0 (-0.2 to 0.3)<br>+0.1 (-0.2 to 0.3) | Low |

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| | | | | |
|---|---|---|---|---|
| **Wave period change (s)** | December-March (wet season) | -0.0 (-1.1 to 1.2)<br>-0.1 (-1.2 to 1.1) | -0.1 (-1.4 to 1.4)<br>-0.1 (-1.6 to 1.4) | Low |
| | June-September (dry season) | +0.0 (-1.1 to 1.1)<br>+0.0 (-1.1 to 1.4) | +0.0 (-1.3 to 1.4)<br>0.0 (-1.4 to 1.4) | Low |
| **Wave direction change (°clockwise)** | December-March (wet season) | +0 (-20 to +20)<br>+0 (-20 to +20) | +0 (-20 to +20)<br>+0 (-20 to +20) | Low |
| | June-September (dry season) | +0 (-10 to +10)<br>+0 (-10 to +10) | +0 (-10 to +10)<br>+0 (-10 to +10) | Low |

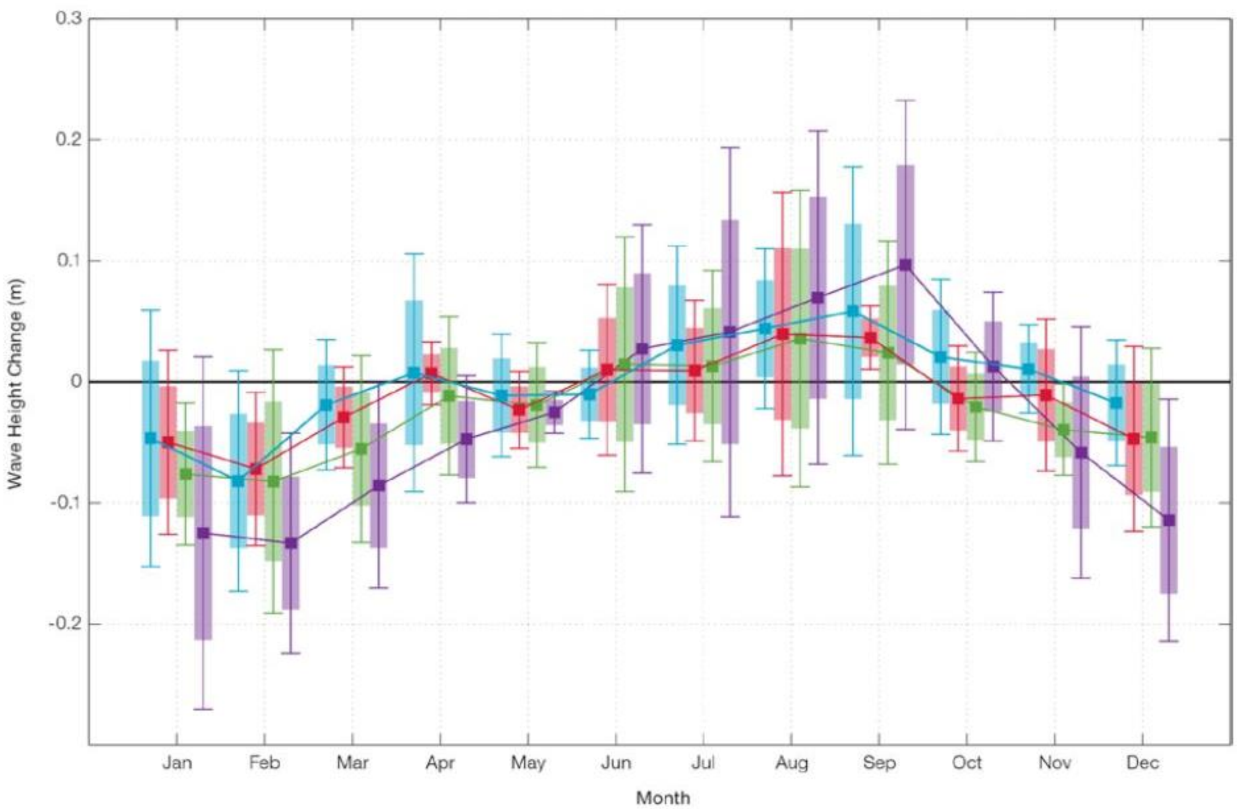


Figure 16. Mean annual cycle of change in wave height between projection scenarios and historical models in Tuvalu. Blue represents RCP4.5 in 2035, red represents RCP8.5 in 2035, green represents RCP4.5 in 20290, and purple represents RCP8.5 in 2090. Shaded boxes represent one standard deviation from the model ensemble mean, and error bars represent the 5 to 95% range (BoM and CSIRO, 2014).

67. Spring wave heights are projected to decrease and the height of waves in the summer could increase, although the confidence in these projections is low (BoM and CSIRO, 2014). Given the low levels of confidence and small projected changes in mean wave height, these do not provide enough actionable information for the CRVA.

68. Globally, average tropical cyclone intensity is projected to experience a 2 to 11% increase and the number of tropical cyclones is projected to experience a 6 to 34% decrease by 2100 relative to a 1946 to 2007 baseline (Knutson, et al., 2010). For the South Pacific, maximum cyclone intensity is projected to increase by 5-10% while the total number of severe tropical cyclones is projected to decrease by 2100 (Walsh, McInnes, & McBride, 2012).

## 1.1.6 Ocean acidification

69. Oceans have been, and are projected to continue to, acidify due to increased atmospheric carbon dioxide concentrations and ocean absorption of carbon dioxide (BoM and CSIRO, 2014). This is of particular concern to Tuvalu, given the important role reefs play at mitigating wave impact to islands. If reefs are negatively impacted by climate change, the project would be exposed to more intense wave action. This section describes current and projected future ocean acidification conditions.

### 1.1.6.1 Current Conditions

70. The Pacific region has an abundance of coral reefs, which indicates that the chemistry of the water contributes to optimal coral growth and healthy reef ecosystems. Aragonite saturation state is used as a proxy for coral reef growth rate and it is projected to decrease as atmospheric carbon dioxide concentrations increase. Guinotte et al (2003) suggests that seawater aragonite saturation states above 4 are optimal for coral growth and development; values from 3.5 to 4 are adequate for coral growth; values between 3 and 3.5 are marginal; and values below 3 are extremely marginal. In the Tuvalu region, the aragonite saturation state in the water has declined from 4.5 in the late 18th century to an observed value of about 4.0 (+/-) by 2000 (BoM and CSIRO, 2014; Guinotte, Buddemeier, & Kleypas, 2003).

71. In the Eastern Pacific, coral reefs are facing climate stressors and the impacts are being studied to gain insight into how systems elsewhere will respond to climate change. Reef systems have shown evidence of thermal stress and stress due to carbon dioxide inputs where the reef stops growing and reef structures are lost (Manzello, Eakin, & Glynn, 2016). After experiencing a 2-3 °C thermal anomaly for more than 2 months, and at aragonite saturation states expected to become more common in the future, reef systems can be lost completely (Manzello, Eakin, & Glynn, 2016). When experiencing thermal stress or acidification in isolation, coral is resilient. However, the combined impact has dire impacts on reef structures (Manzello, Eakin, & Glynn, 2016).

### 1.1.6.2 Future Scenarios

72. Warming ocean temperatures and acidification as atmospheric CO2 concentrations continue to rise and these changes will impact the health and viability of marine ecosystems, including coral reefs that provide many key ecosystem services upon which people depend (BoM and CSIRO, 2014). The ocean is expected to continue to acidify due to increased atmospheric carbon dioxide concentrations throughout the 21st century. By 2030, marginal conditions (3.5) will be reached under RCP 8.5 and 4.5 (BoM and CSIRO, 2014). Under RCP8.5 the aragonite saturation state continues to decline after 2030 to a degree that will likely make it impossible for coral reefs to grow (<3.0) (BoM and CSIRO, 2014). BoM and CSIRO (2011) projected that, by 2060, annual maximum aragonite saturation state is expected to drop below 3.5 (BoM and CSIRO, 2011). To consider a worst-case scenario, it is recommended that this project use a 2070 aragonite saturation range between 2.8-3.0 Ωar (see (see Figure 17). The impact of acidification on reef ecosystem health is

likely to be compounded by other stressors including coral bleaching, storm damage and fishing pressure (BoM and CSIRO, 2014).

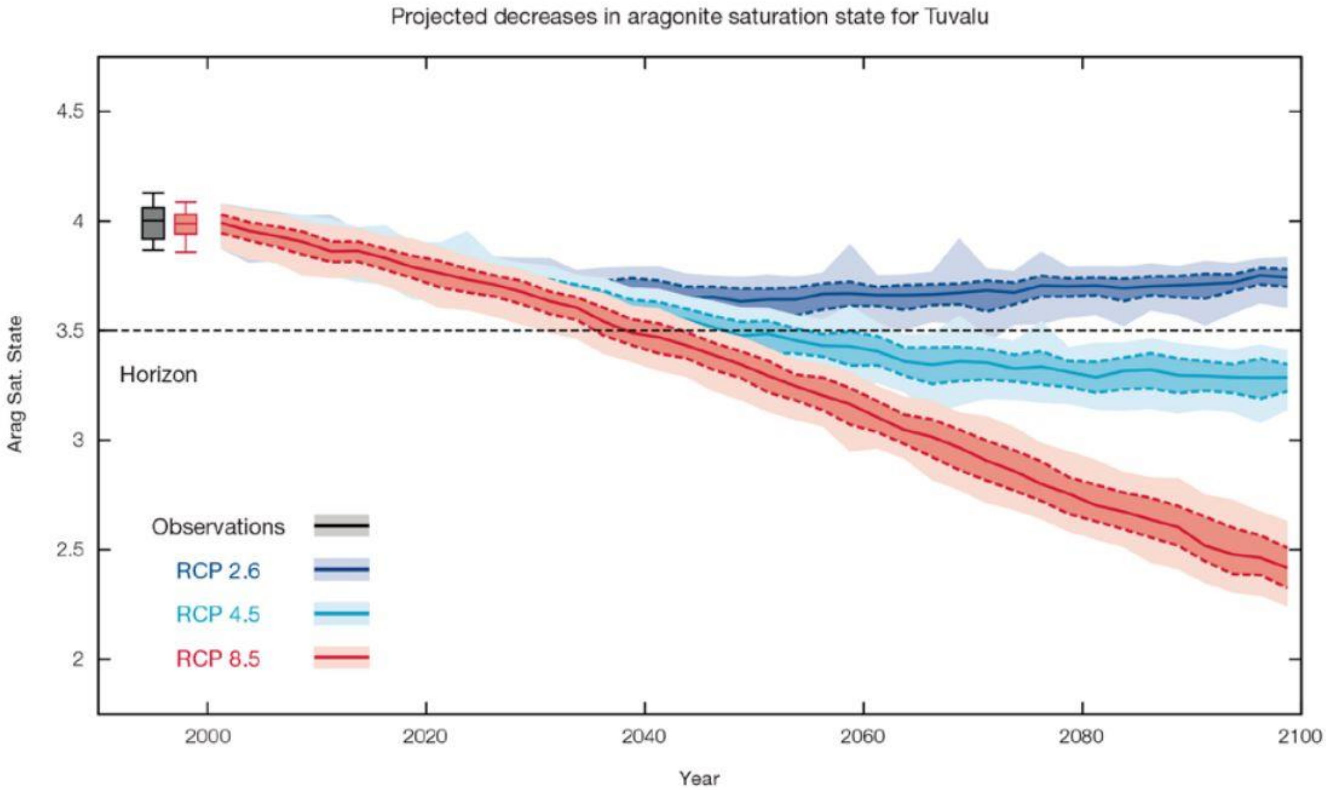


Figure 17. Projected decreases in aragonite saturation state in Tuvalu for CMIP5 models under RCP2.6, 4.5 and 8.5 (BoM and CSIRO, 2014).

## Secondary Climate Change Drivers

73. In addition to the primary climate change drivers outlined in the previous section that are the most critical climate change factors to ensure climate proofing of the Niutao Harbour, three secondary drivers are identified: sea surface temperature, air temperature, and rainfall/runoff. These factors may also impact the project throughout its lifetime but to a lesser degree than the primary drivers. There are nine operational meteorological stations in Tuvalu. Single rainfall observations are collected in Niutao and four other stations; multiple observations within a 24-hour period are taken at four stations (Nanumea, Nui, Funafuti and Niulakita). The Funafuti station has the longest record, with rainfall data available from 1927 and air temperature data from 1933. (BoM and CSIRO 2011). This assessment relies on BoM and CSIRO data as primary sources for this assessment.

### 1.1.7 Sea surface temperature

74. Sea surface temperatures have been rising and are projected to continue to increase in the future (BoM and CSIRO, 2014). This section describes current and projected future sea surface temperature conditions.

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#### 1.1.7.1 Current Conditions

75. Around Tuvalu, water temperatures have risen gradually since the 1950s but at an increasing rate. The rate has been approximately 0.13 °C per decade since the 1970s. Figure 18 shows the sea-surface temperature changes 1950-2000 from three different sea surface temperature datasets. Natural variability may play a large role in sea surface temperature at the regional scale, which makes it difficult to identify long-term trends (BoM and CSIRO, 2011).

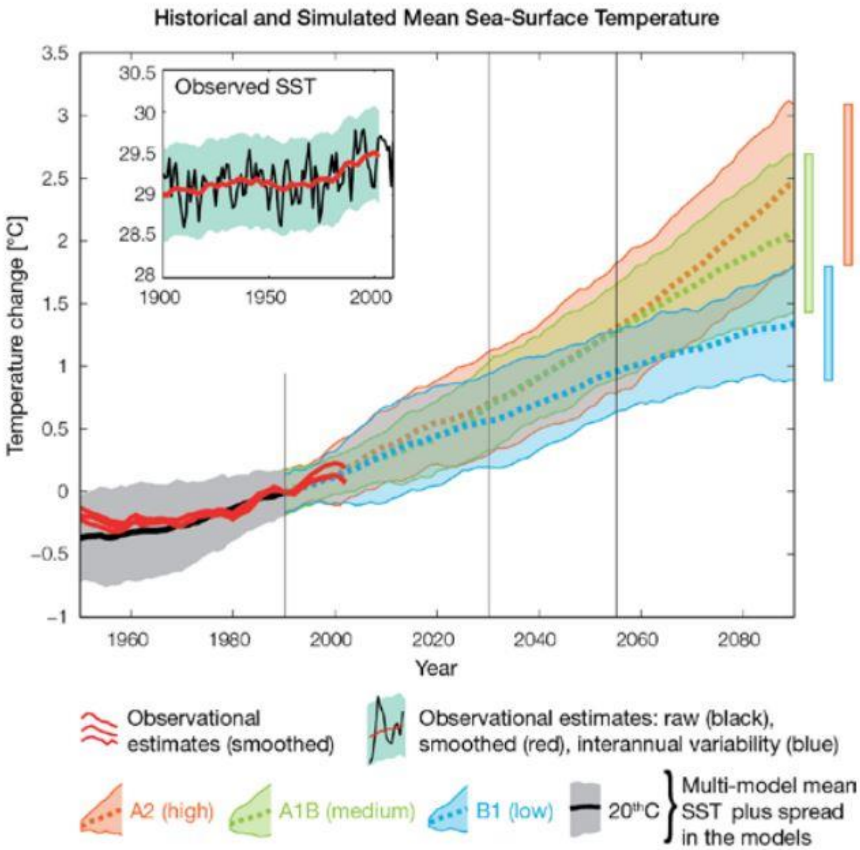


Figure 18. Historical climate from 1950 to 2000 and simulated historical and future climate for annual mean sea-surface temperature around Tuvalu, based on CMIP3 models (BoM and CSIRO, 2011)

#### 1.1.7.2 Future Scenarios

76. Warming oceans increase the risk of coral bleaching and, as a result, potentially change the species composition of the reef and could reduce the structural integrity of the reef. The changes and duration of bleaching risk has been quantified based on projected sea-surface temperature (SST) changes. The trend shows that the frequency of such events may decrease while the duration of risk may increase. If severe bleaching events occur more often than once every five years, the long-term viability of coral reef ecosystems becomes threatened (BoM and CSIRO, 2014).

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Table 4. The impacts of increasing sea surface temperature on coral bleaching risk for the Tuvalu region

| Temperature Change[4] | Recurrence interval[5] | Duration of the risk event[6] |
|---|---|---|
| **Change in observed mean** | 0 | 0 |
| **+0.25°C** | 30 years | 4.2 weeks |
| **+0.5°C** | 19.1 years (14.6 years – 24.6 years) | 7.0 weeks (5.2 weeks – 9.0 weeks) |
| **+0.75°C** | 4.3 years (6.7 months – 10.3 years) | 8.7 weeks (2.4 weeks – 4.3 months) |
| **+1°C** | 1.3 years (0.9 months – 4.6 years) | 10.5 weeks (1.4 weeks – 7.7 months) |
| **+1.5°C** | 6.8 months (0.8 months – 2.3 years) | 5.8 months (1.7 weeks – 2.1 years) |
| **+2°C** | 2.9 months (0.8 months – 6.6 months) | 8.4 months (3.3 weeks – 6.6 years) |

77. In the Pacific, SST is closely related to surface air temperatures, therefore projected changes in air temperature can be used to approximate projected changes in SST. Based on this information, it is recommended that an increase of 2.1°C in mean SST by 2070 be considered for this analysis as a conservative worst case scenario (BoM and CSIRO, 2014).

## 1.1.8 Air temperature

78. Air temperature has been rising in Tuvalu and is projected to continue to rise (BoM and CSIRO, 2014). This section describes current and projected future temperature conditions.

### 1.1.8.1 Current Conditions

79. Tuvalu experiences a tropical marine climate with consistent temperatures ranging from 26-32°C and high humidity. Annual and May-October mean and maximum air temperatures at Funafuti have increased over the period 1933 to 2011 (BoM and CSIRO, 2014). The frequency of cool temperature extremes at night have decreased while warm temperature extremes have increased. However, minimum temperature and November-April trends show little change.

[4] This refers to projected SST anomalies above the mean for 1982-1999.
[5] Recurrence is the mean time between severe coral bleaching risk events. The minimum and maximum range is shown in brackets.
[6] Duration refers to the period of time where coral are exposed to the risk of severe bleaching. The minimum and maximum range is shown in brackets.

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Table 5. Annual and half-year trends in air temperature (Tmax, Tmin, Tmean) and rainfall at Funafuti (BoM and CSIRO, 2014)

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

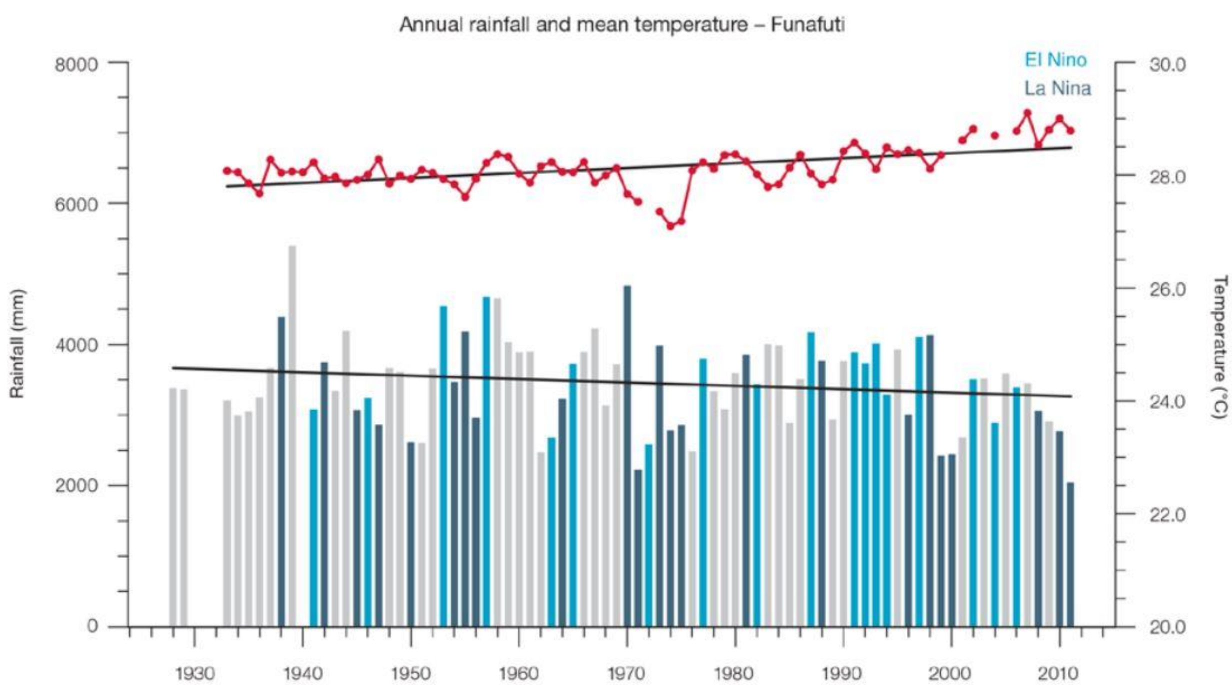


Figure 19. Observed time series of annual average values of mean temperature (red dots and line) and total rainfall (bars) at Funafuti. Light blue indicates El Niño, dark blue are La Niña, and grey bars are neutral years. Solid black trend lines indicate a least squares fit (BoM and CSIRO, 2014).

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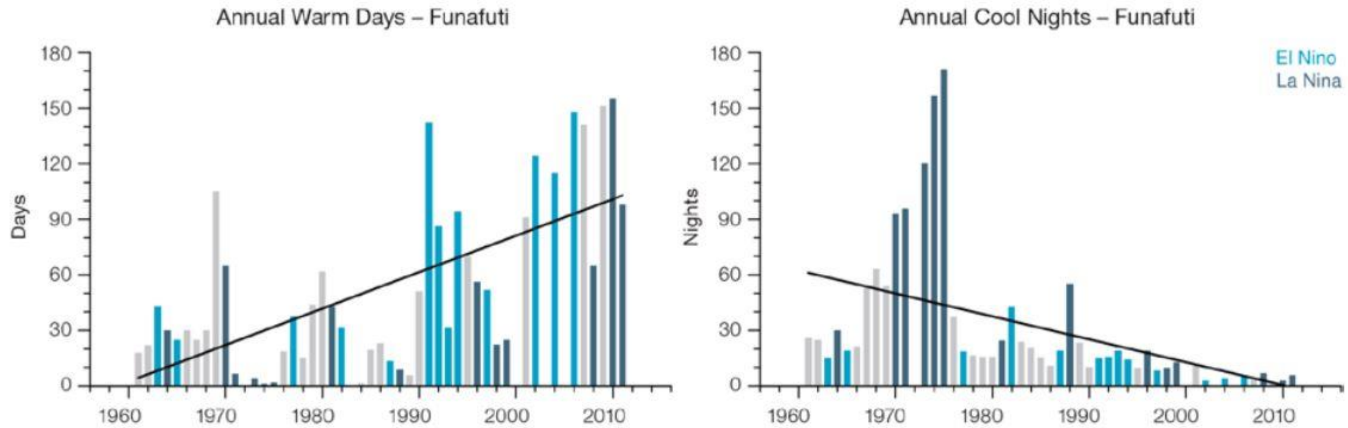


Figure 20. Observed time series of annual total number of warm nights[7] and cool nights[8] at Funafuti (BoM and CSIRO, 2014).

### 1.1.8.2 Future Scenarios

80. Inter-annual variability in surface air temperature and sea-surface temperature is strongly influenced by ENSO in the current climate around Tuvalu. Projections of ENSO activity is inconsistent and whether this inter-annual variability will change in the future is not clear, although ENSO is expected to continue to be a strong influence (BoM and CSIRO, 2011).

81. There is a link between air temperature and sea-surface temperature and the changes are expected to occur at a similar rate of warming for sea surface temperature. There is very high confidence that air temperature is projected to continue increasing through the 21st century due to rising greenhouse gas concentrations. All CMIP3 models agree on this direction of change. By 2030, the majority of CMIP3 models show a slight increase of less than 1 °C in annual and seasonal mean temperature. After 2030, there is a greater difference in warming between scenarios. By 2090, a warming of 0.4-1.3 °C is projected for RCP2.6 and warming of more than 2.5 °C for the A2 (high) scenario (BoM and CSIRO, 2014; BoM and CSIRO, 2011). Relatively extreme years are often due to natural variability but there is projected to be more warm years and decades on average in a warmer climate (BoM and CSIRO, 2014).

82. Table 6 shows the projected change in surface air temperature by 2070 under RCP4.5 and RCP8.5. However, consensus of the models is low to moderate for these scenarios.

Table 6. Projected percentage changes in Tuvalu surface temperature changes by 2070 under RCP4.5 and RCP8.5 relative to a 1980 to 1999 baseline (PCCSP Climate Futures)

| RCP | Scenario | Dec.-Feb. (DJF) | Mar.-May (MAM) | Jun.-Aug. (JJA) | Sep.-Nov. (SON) | Nov.-Apr. (NDJFMA) | May-Oct. (MJJASO) |
|---|---|---|---|---|---|---|---|
| 4.5 | Min. ↑ | 0.88% | 0.89% | 0.91% | 0.83% | 0.88% | 0.88% |
| | Max. ↑ | 2.1% | 2.26% | 2.46% | 2.24% | 2.15% | 2.39% |

[7] Warm days indicate the number of days with maximum temperature greater than the 90th percentile for the base period 1971-2000.
[8] Cool nights indicate the number of days with minimum temperature less than the 10th percentile for the base period 1971-2000.

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Max. Consensus | 1.38% | 1.45% | 1.44% | 1.32% | 1.39% | 1.4% |
| **8.5** | Min. ↑ | 1.58% | 1.47% | 1.53% | 1.62% | 1.51% | 1.58% |
| | Max. ↑ | 3.18% | 3.28% | 3.45% | 3.36% | 3.19% | 3.44% |
| | Max. Consensus | 1.98% | 2.01% | 1.93% | 1.83% | 1.98% | 1.88% |

83. By 2070, annual mean surface air temperature is projected to increase by up to 2.1 °C; 1-in-20-year maximum temperature is projected to increase by up to 2.2°C; and 1-in-20-year minimum temperature is projected to increase by up to 2.2 °C, based on the upper bound of the 95% confidence interval for high emissions scenario (RCP8.5) projections (see Table 7).

Table 7. Projected change in annual air temperature under four emissions scenarios; RCP2.6 (very low emissions, dark blue), RCP4.5 (low emissions, light blue), RCP6 (medium emissions, orange) and RCP8.5 (very high emissions, red) (BoM and CSIRO, 2014)

| Variable | Season | 2030 | 2050 | 2070 | 2090 | Confidence |
|---|---|---|---|---|---|---|
| **Surface air temperature (°C)** | Annual | 0.6 (0.5–0.9) | 0.8 (0.5–1.2) | 0.8 (0.5–1.2) | 0.8 (0.4–1.3) | Medium |
| | | 0.7 (0.5–1) | 1 (0.7–1.4) | 1.3 (0.9–1.8) | 1.4 (1–2.1) | |
| | | 0.6 (0.4–0.9) | 0.9 (0.6–1.4) | 1.3 (0.9–2) | 1.7 (1.1–2.6) | |
| | | 0.8 (0.5–1) | 1.4 (1–1.9) | 2.1 (1.5–3.1) | 2.8 (2–4) | |
| **Maximum temperature (°C)** | 1-in-20 year event | 0.5 (-0.1–0.8) | 0.7 (0.1–1.1) | 0.7 (-0.1–1.1) | 0.7 (-0.1–1.1) | Medium |
| | | 0.6 (-0.1–0.9) | 0.9 (0.1–1.3) | 1.2 (0.4–1.8) | 1.3 (0.6–2) | |
| | | NA (NA–NA) | NA (NA–NA) | NA (NA–NA) | NA (NA–NA) | |
| | | 0.7 (0.1–1.1) | 1.4 (0.5–2) | 2.2 (0.7–3.1) | 2.9 (1.4–4.2) | |
| **Minimum temperature (°C)** | 1-in-20 year event | 0.6 (0.3–0.8) | 0.7 (0.2–1) | 0.8 (0.4–1) | 0.8 (0.4–0.9) | Medium |
| | | 0.6 (0.4–0.8) | 0.9 (0.5–1.3) | 1.1 (0.8–1.5) | 1.3 (1–1.9) | |
| | | NA (NA–NA) | NA (NA–NA) | NA (NA–NA) | NA (NA–NA) | |
| | | 0.8 (0.4–1) | 1.5 (1–2.1) | 2.2 (1.6–3.3) | 3 (2.2–4) | |

84. The combination of increases in atmospheric $CO_2$ concentrations, temperature, and humidity impact the dissolution of $CO_2$ and chlorides into concrete, thereby impacts the corrosion rate. Under the A1F1 emissions scenario, relative to 2000 levels, carbonation-induced damage risk probability is projected to increase by 0.5% by 2070 in coastal areas (excluding tidal and splash zones)[9]and chloride-induced corrosion damage probability is projected to increase to 13% by 2070 in splash and tidal zones[10].

[9] This refers to Australian Concrete Code AS3600 exposure classification B2, which represents coastal areas excluding tidal and splash zones
[10] This refers to Australian Concrete Code AS3600 exposure classification C2, which represents surfaces of members in splash and tidal zones

### 1.1.9 Rainfall

85. Annual and seasonal rainfall trends for Funafuti and Nanumea for the period 1950 to 2009 are not statistically significant (BoM and CSIRO, 2011).

#### 1.1.9.1 Current Conditions

86. Throughout Tuvalu, inter-annual variability changes significantly, primarily because of ENSO. However, since 1927, annual and half-year rainfall trends show little change at Funafuti. There is no significant trend in daily rainfall due to the large year-to-year variability (BoM and CSIRO, 2014).

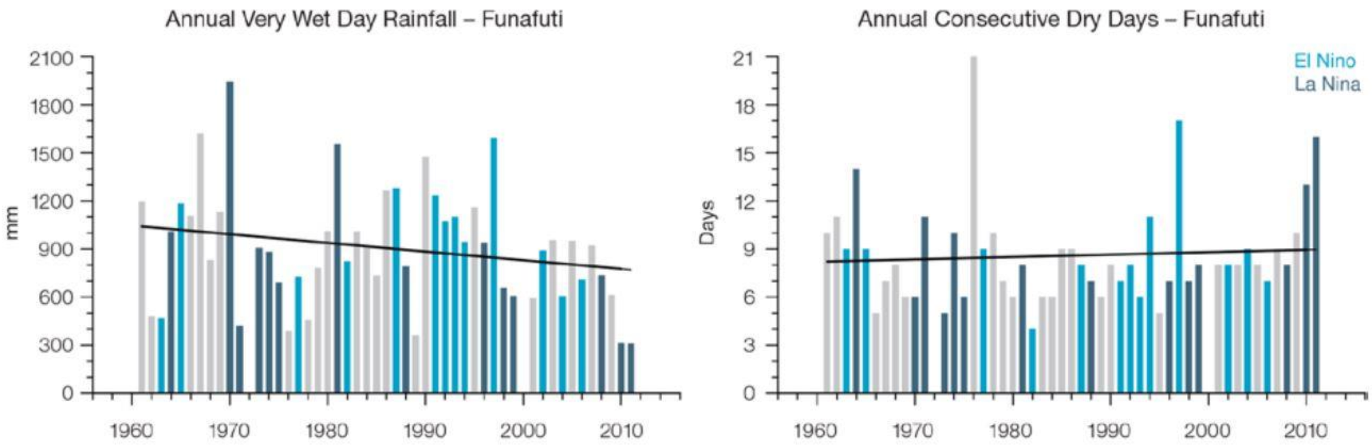


Figure 21. Observed time series of annual total values of Very Wet Days[11] and Consecutive Dry Days[12] at Funafuti (BoM and CSIRO, 2014).

87. Rainfall is linked to ENSO cycles and the shifting position of the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ). In Tuvalu, La Niña seasons in 2010-2011 and 2011-2012 resulted in severe drought conditions (Taylor, McGregor, & Dawson, 2016).

Table 8. Conditions experienced during El Niño and La Niña years (Taylor, McGregor, & Dawson, 2016)

| | El Niño | Extreme El Niño | La Niña |
|---|---|---|---|
| **Tuvalu** | Wet<br>⬇ Sea level | Wet<br>⬇ Sea level | Dry<br>⬆ Sea level |

#### 1.1.9.2 Future Scenarios

88. Throughout the 21st century, wet season (November-April), dry season (May-October), and annual average rainfall are projected to increase. There is high confidence that rainfall will increase because physical arguments indicate that rainfall will increase in the equatorial Pacific in a warmer climate and almost all of the CMIP3 models agree on this direction of change by 2090. Most of the

[11] Very Wet Days are those where the amount of rain in a year where daily rainfall is greater than the 95th percentile for the reference period 1971-2000.

[12] Consecutive Dry Days are the maximum number of consecutive days in a year with rainfall less than 1 mm (0.039 inches).

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CMIP3 models represent small changes (-5% to 5%) in wet season, dry season and annual mean rainfall by 2030. However, by 2090, the majority show increases of greater than 5%, with up to a third showing large increases over 5% under the high (A2) emissions scenario. Inter-annual variability in rainfall over Tuvalu is strongly influenced by ENSO in the current climate but, since there are not consistent projections of future ENSO activity, it is not possible to determine whether inter-annual variability will change in the future. All references (BoM and CSIRO, 2011).

89. The CMIP5 models show a range of projected average annual rainfall change from an increase to a decrease. The range is greater in higher emissions scenarios. Tuvalu is in a region where rain is projected to increase to the north and have little change or even a decrease to the south. Also, the seasonality of rainfall contributes to variability. These contrast with the findings of the Australian Bureau of Meteorology and CSIRO (2011), which reported an increase in rainfall in all seasons (BoM and CSIRO, 2014).

90. Year-to-year rainfall variability is generally larger than the projected change in Tuvalu, except for those with the largest end of century projections. There is no strong agreement as to the direction of change in the models and some show little change. The range of projections is quite large (5-95th percentile range for models), ranging from -1 to +9% by 2030 and -26 to +31% by 2090. All references (BoM and CSIRO, 2014). There is low confidence in these projections.

## Summary of Climate Change Scenarios

Table 9. Summary of climate change scenarios recommended for integration into project design (see previous sections for detailed rationale)

| Variable | Description | Recommendation |
|---|---|---|
| **Primary Drivers** | | |
| Mean Sea-Level | Rise above mean sea-level (1986-2005 baseline)<br><br>Rise above current (2018) mean sea-level | 60 cm<br><br>50 cm |
| Wave Climate | Wave height change (m) | No change |
| Wind Climate | Change relative to current wind speeds | No change |
| Ocean Acidification | Aragonite saturation range | Between 2.8-3.0 Ωar |
| **Secondary Drivers** | | |
| Sea surface temperature | Rise above current sea surface temperature | + 2.1°C |
| Air temperature | Rise above current air temperature | + 2.2 °C |

| Variable | Description | Recommendation |
|---|---|---|
| Rainfall | Change in rainfall volume relative to current conditions | No change |

# IV. Climate Risk and Vulnerability Assessment

## Introduction

91. No CRVA was done for Niutao under the previous phase of the project because a different design was being considered that was temporary and more flexible.

92. Risk management is the process of defining and analyzing risks to facilitate subsequent decision making on the appropriate course of action to optimally mitigate these risks. The ADB was an early adopter of risk-based approaches to assessing and adapting to climate change impacts. This CRVA aims to reduce risk resulting from climate change to ADB investments.

93. The CRVA aims to identify how the designs may be vulnerable to climate hazards and how these hazards may impede progress towards reaching project goals. Additionally, the CRVA identifies adaptation and disaster risk reduction measures that should be considered to reduce/manage identified risks. This project considers primary climate stressors (sea level rise, wind and wave climates, and ocean acidification) over the 50-year design lifetime of the project, which makes climate projections for 2070 most relevant.

94. The key design elements were used to identify vulnerabilities to climate hazards, and develop risk management measures.

- ➢ Fixed breakwater structures
- ➢ Flexmat
- ➢ Channel
- ➢ Onshore facility

95. Risk is evaluated based on the likelihood and consequence of a given event, as described in Table 10 and

96. Table 11. The two factors combine to form a risk matrix, which rates event based on the both likelihood and consequence, and shown in

97. Table 12.

Table 10. Levels of risk likelihood assuming risk is not mitigated

| Level | Description | Frequency | Likelihood |
|---|---|---|---|
| L1 | Almost Certain | Multiple times per year | Over 99% |
| L2 | Likely | Once per year or every few years | 70-99% |
| L3 | Possible | Once in 25 years | 50-70% |

| | | | |
|---|---|---|---|
| L4 | Unlikely | Once in 25 to 50 years | 10-50% |
| L5 | Rare | Unlikely over the next 50 years | <10% |

Table 11. Levels of risk consequence

| Level | Description | Consequence |
|---|---|---|
| C1 | Negligible | Insignificant impact |
| C2 | Minor | Low impact, localized |
| C3 | Moderate | Medium impact, potentially reversible |
| C4 | Major | Significant long-term impact, potentially irreversible |
| C5 | Extreme | Major, irreversible impact |

Table 12. Risk assessment matrix

| | | Consequence | | | | |
|---|---|---|---|---|---|---|
| | | C1 | C2 | C3 | C4 | C5 |
| Likelihood | L1 | Low | Moderate | High | Extreme | Extreme |
| | L2 | Low | Moderate | Moderate | High | Extreme |
| | L3 | Low | Low | Moderate | High | Extreme |
| | L4 | Low | Low | Moderate | Moderate | High |
| | L5 | Low | Low | Low | Moderate | Moderate |

## Success Criteria

98. To evaluate climate risks, Success Criteria describing an effective wharf were developed by the Project Team, described in Table 13.

Table 13. Success criteria for Niutao Harbour

| Topic | Sub-topic | Criteria for Success |
|---|---|---|
| Robustness | Provision of Service | The time during which climate shocks and stresses prevent the use of the harbour is minimal. It is suitable for use for inter-island transport and to support fishing in all tidal states, considering current and projected sea-level rise. |
| | Functionality | The harbour meets local needs over the course of its lifetime. It is capable of berthing design vessels. It provides flexibility for a variety of vessel sizes and users (i.e. cargo, passengers). |
| | Service provision | The harbour is able to support emergency use during extended disaster periods, and immediately post-disaster caused by extreme events, such as cyclones. |

| | | |
|---|---|---|
| | during disaster response | |
| **Flexibility** | | The harbour is adaptable to future changes in climate, is flexible to accommodate changes in shipping technologies and cargo transport, and does not preclude further adaptation as conditions and performance measurement demonstrate need. |

99. To enable the application of these success criteria in rating the level of consequence that each climate risk could have on the project, a matrix of consequence by success criteria was developed. As illustrated in Table 14, each consequence level was defined for each success criterion. This table was applied in rating consequence in the Risk Assessment, as described in the following section.

Table 14: Description of levels of consequence for each success criterion

| | Robustness | | | Flexibility |
|---|---|---|---|---|
| | **Service Provision** | **Functionality** | **Service Provision During Disaster Response** | |
| **Extreme** | Major, long-term, irreversible impact on ability to provide services | Total and permanent loss or damage, replacement required | Harbour is never able to meet community needs during disaster periods | Major, irreversible impact permanently prohibiting the asset from adapting |
| **Major** | Major, long-term, potentially irreversible disruption to services | Major, potentially irreversible damage of the wharf, significant repairs required | Harbour is rarely able to meet community needs during disaster periods | Major impact potentially permanently prohibiting the asset from adapting |
| **Moderate** | Disruption to services for a short, but important period | Moderate damage of the wharf repairs required | Harbour is only sometimes able to meet community needs during disaster periods | Impact reducing the asset's ability to adapt |
| **Minor** | Brief disruption of a service provision of less than 1 week but more than 1 day | Minor damage to wharf monitoring required to ensure it does not worsen | Harbour typically is able to meet community needs during disaster periods | Impact potentially reducing the asset's ability to adapt |

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| | Robustness | | | Flexibility |
|---|---|---|---|---|
| | Service Provision | Functionality | Service Provision During Disaster Response | |
| Negligible | Brief disruption of a service provision of less than 1 day | Negligible damage | Sufficient capacity to meet community needs during disaster periods | Adaptable; can accommodate changes in user needs |

## Climate Change Impacts on Structural Integrity

100. Per AS 5334-2013, climate change vulnerability is defined as the "degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change including climate variability and extremes".

101. As described in the previous section, the primary climate change hazards identified include mean sea-level, wind climate, wave climate, and ocean acidification. Secondary climate change hazards include sea surface temperature, air temperature, and rainfall and runoff. These shocks and stresses may affect the condition of the harbour and structure itself, and thereby directly affect the project's ability to meet the success criteria discussed above (service provision, functionality, disaster response, financial, public safety, adaptability).

102. The extent to which these shocks and stresseswill affect the harbour is a function of both the severity and frequency of the climate hazards (the level of climate shocks and stresses to which the facility is exposed and how often these shocks and stresses occurs), and the thresholds for those conditions that the structure can be expected to withstand (the sensitivity of the project to that exposure).

103. Failure mechanisms for the harbour are considered below in order to identify how those elements that may be vulnerable to climate change hazards will respond given future projected conditions.

- Sea-level rise may result in **regular tidal overtopping** of the structure, including where it connects to the land;
- The combined effect of sea-level rise and increased swell wave heights results in more **regular wave overtopping** of the breakwater structures;
- Ocean acidification and ocean temperature increase may compromise the **structural integrity of the protective coral reefs**, thereby increasing wave energy to the breakwater structures;
- Changes in mean wind direction, seasonal peak wind gusts, and winds during cyclones may impact any **wind-sensitive structures** built on the harbour;
- The combined effect of sea level rise and increased swell wave heights may result in **erosion and inundation** of the land-based facilities;

- Sea level rise and changes in wave direction and energy mobilize **additional volumes of sediment, resulting in enhanced siltation** of the channel.

# Risk Assessment

## Methodology

105. The climate change scenarios summarized in Section 2 were applied to the key design elements of the current Niutao Harbour project based on the likelihood/consequence scales shown in Table 15.

## Risk Assessment Findings

106. The results of the risk assessment are presented in Table 15. These are based on a combination of identified current climate risks, climate change projections (used to assess the likelihood of each risk), the success criteria and consequence/success matrix depicted in Table 14 (used to assess the consequence of each risk), and the risk assessment matrix (Table 12). *The risk assessment is undertaken assuming that no climate change factors are integrated into the harbour design.*

Table 15. Risk assessment results, where L represents likelihood, C represents consequence, and R represents resulting risk.

| Variable | Risk/Impact | Risk Category | | |
|---|---|---|---|---|
| **Primary** | | **L** | **C** | **R** |
| Sea-Level Rise | SLR renders the harbour unusable | 4 | 5 | H |
| | SLR increases frequency of tidal overtopping of the structure | 3 | 4 | H |
| Wind Climate | Changes in mean wind direction, seasonal peak wind gusts, and winds during cyclones impact the operating procedures of the harbour | 4 | 3 | M |
| | Changes in mean wind direction, seasonal peak wind gusts, and winds during cyclones impact the wind-sensitive structures built on the harbour | 4 | 3 | M |
| Wave Climate | SLR plus increased wave heights result in regular wave overtopping of the breakwater structures | 2 | 5 | E |
| | SLR plus increased wave heights cause erosion and inundation that damages the land-based facilities | 2 | 5 | E |
| | Changes in wave direction plus SLR mobilize additional volumes of sediment, resulting in enhanced siltation of the channel | 2 | 5 | E |
| Ocean Acidification | Ocean acidification compromises the structural integrity of protective coral reefs, thereby increasing wave energy to the breakwater structures | 1 | 5 | E |
| **Secondary** | | **L** | **C** | **R** |
| Sea surface temperature | Increased sea surface temperature diminishes structural integrity of temperature-sensitive components of harbour | 5 | 1 | L |
| | Increased sea surface temperature damages coral ecosystems, reducing the structural integrity of the reef and increasing exposure to wave action | 2 | 5 | E |

| | | | | |
|---|---|---|---|---|
| Air temperature | Extreme heat diminishes structural integrity of temperature-sensitive components of wharf | 5 | 1 | L |
| Rainfall and runoff | Increased rainfall results in erosion which destabilizes onshore facilities | 5 | 3 | L |

## Climate Risk Management Response

107. The adaptation and disaster risk reduction measures recommended for incorporation into the harbour design, based on their effectiveness to mitigate identified risks are outlined in Table 16.

Table 16 Summary of Climate Risk Reponses

| Design Element | Recommended Management Response |
|---|---|
| **Fixed breakwater structures** | Incorporate predicted sea level rise, and wind and wave parameters into breakwater design including raising breakwater crest by 500mm.<br>Enhance concrete specifications to accommodate enhanced ocean acidification, include including increasing cover thickness, improving concrete quality, and using coatings and barriers (Stewart, Peng, & Wang, 2012). |
| **Flexmat** | The design of the flexmat should allow landward and upward relocation as the coastline evolves in response to higher sea levels, and changed wave and current conditions. |
| **Channel** | No immediate adaptive measures are required for the channel, given that sea level rise will increase the depth for vessel movements, assuming that there is not increased sedimentation<br>Northerly winds and waves created by cyclones may lead to sedimentation and require maintenance dredging. |
| **Onshore facility** | Incorporate predicted sea level rise, and wind and wave parameters into onshore facility design by ensuring sufficient setback from the shoreline of critical infrastructure, and ensuring structures confirm to current wind-loading parameters. |
| **Piling** | Incorporate predicted sea level rise, and wind and wave parameters into piling design to ensure structural integrity of approach trestle structure through: 1) reduced span between piles and; 2) increase the pile boring costs due to increased loads on the piles. |

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108. High-level cost estimates of integrating the climate-proofing elements as outlined in Table 16 are approximately US$1.4m. The majority of budget (approximately $1.1m) will be required for adapting the fixed breakwater structures through crest raising (and resultant increase in foundation widths) and enhancing concrete specifications to integrate ocean acidification. Additional costs (approximately $0.3m) will be needed to re-engineer the piling of the approach trestle structure. There are only minimal additional costs associated with a higher level platform onshore and it is therefore not included in as an estimate of additional climate change costs.

109. Importantly, in addition to the climate-proofing budget elements of the project, it is recognized that a critical function of the harbour is disaster-risk reduction. The breakwaters are needed for two reasons - to ensure resilience so the island is not left without access after a cyclone and to minimise damage to the beach. Without proper breakwater protection, any channel through the reef will potentially result in damage to the jetty and ramp and worse, destruction of the beach as has happened in the past. Consequently, the full cost of the breakwater structures should be considered necessary for disaster risk reduction. The cost for the breakwater structures (north and south sea walls and approximately half of the wharf concrete structure) is US$1,35 million as determined from the priced bill of quantities of the detailed design.

110. To manage the potential for changes in risk over time, it is recommended that control measures be implemented post-construction, namely: operational strengthening a system for monitoring and evaluation. Monitoring and evaluation should include tracking climatic and environmental conditions, and monitoring the condition of the harbor facility and structures. This provides the opportunity for adaptive management –- implementing adjustments to management practices or evaluating the need for project redesign to accommodate changing conditions. Aspects of monitoring and evaluation should include the following.

- Ongoing monitoring of extreme wind and wave conditions should be conducted, and a disaster contingency management plan for the harbour should be developed for these periods.
- Sedimentation of the channel should be monitored; should increased sediment transport due to sea level rise and increased wave action induce excess sedimentation, a plan to reduce sedimentation should be implemented
- The project's structural integrity should be routinely inspected to ensure that increases in ocean acidification and sea surface temperature do not cause secondary impacts due to reduced structural integrity of protective coral reefs. Should there be significant reductions in coral cover and increases in coral mortality, this may trigger a redesign of the project.

# V. Recommendations

111. The preliminary design of the wharf currently accounts for 500 mm of SLR into "the design of all structures." It is assumed that the tidal datums used in the preliminary design onto which the 500 mm of SLR is added reflect present-day sea-levels. If so, this approximates to the upper SLR projections (RCP8.5) for 2070 from BoM and CSIRO (2014). It is recommended that during detailed design, design levels be against the tidal datums used in the preliminary design.

112. Importantly, the CRVA has highlighted the potential risks to the project in the long-term (mid-century through to 2070) from the compounding impacts of climate change on fringing reefs from SLR, ocean acidification, and ocean temperatures. The detailed design should be cognizant of the

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potential for design enhancements in the longer term should these climate change impacts exceed upper projections and as a result compromise the ability of the fringing reefs to provide the current levels of protection from oceanic conditions.

113. During the detailed design phase, further consideration of climate change factors outlined in the report should be undertaken to ensure the full integration of potential climate risks into structural design and ongoing operations.

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# VII. Appendices

**Appendix A. Aware for Projects Initial Risk Screening**

# 01

## Introduction

This report summarises results from a climate risk screening exercise. The project information and location(s) are detailed in Section 02 of this report.

The screening is based on the Aware$^{TM}$ geographic data set, compiled from the latest scientific information on current climate and related hazards together with projected changes for the future where available. These data are combined with the project's sensitivities to climate variables, returning information on the current and potential future risks that could influence its design and planning.

## Project Information

| | |
|---|---|
| PROJECT NAME: | Outer Island Port Development Project |
| SUB PROJECT: | 1 |
| REFERENCE: | Outer Island Port Development Project |
| SECTOR: | Rural transport infrastructure |
| SUB SECTOR: | Ports - coastal |
| DESCRIPTION: | Construct port facilities in outer islandds of Tuvalu |

# 02

## Chosen Locations

1) Tuvalu
2) Tuvalu
3) Offshore
4) Offshore

# 03

## Project Risk Ratings

Below you will find the overall risk level for the project together with a radar chart presenting the level of risk associated with each individual risk topic analysed in Aware$^{TM}$. Projects with a final "High risk" rating are always recommended for further more detailed climate risk analyses.

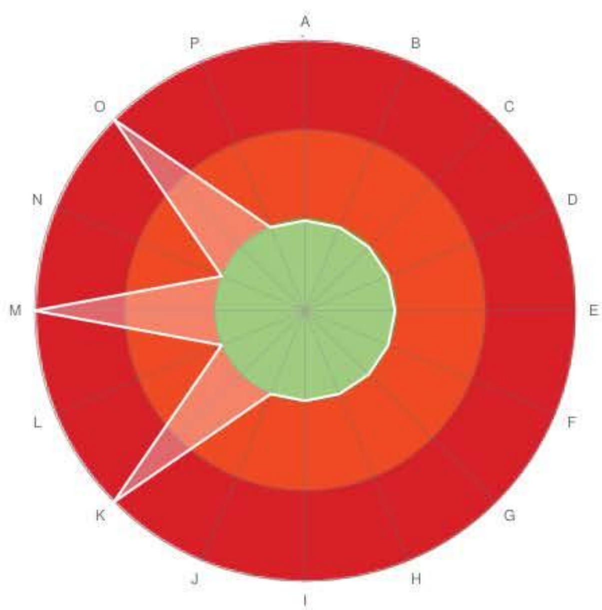
The radar chart provides an overview of which individual risks are most significant. This should be used in conjunction with the final rating to determine whether the project as a whole, or its individual components, should be assessed in further detail. The red band (outer circle) suggests a higher level of risk in relation to a risk topic. The green band (inner circle) suggests a lower level of risk in relation to a risk topic.

In the remaining sections of this report more detailed commentary is provided. Information is given on existing and possible future climate conditions and associated hazards. A number of questions are provided to help stimulate a conversation with project designers in order to determine how they would manage current and future climate change risks at the design stage. Links are provided to recent case studies, relevant data portals and other technical resources for further research.

### Final project risk ratings

## High Risk

### Breakdown of risk topic ratings




| |
|---|
| A) Temperature increase |
| B) Wild fire |
| C) Permafrost |
| D) Sea ice |
| E) Precipitation increase |
| F) Flood |
| G) Snow loading |
| H) Landslide |
| I) Precipitation decrease |
| J) Water availability |
| K) Wind speed increase |
| L) Onshore Category 1 storms |
| M) Offshore Category 1 storms |
| N) Wind speed decrease |
| O) Sea level rise |
| P) Solar radiation change |

04

HIGH RISK

## WIND SPEED INCREASE

Would an increase in average and maximum wind speed require modifications to the design of the project in order to successfully provide the expected services over its lifetime?

**Chosen Answer**

Yes - a lot.

Major modifications may be required to the design of the project if wind speed increases.

## ACCLIMATISE COMMENTARY

### 1. What does this mean for the design of my project?

• There is a potential for an increase in incidences where current design standards will not be sufficient. See "Critical thresholds" in the "Help and glossary" section for further details on how a changing climate can impact on critical thresholds and design standards.

• The design, operational and maintenance standards should be reviewed - take into consideration current impacts of increasing wind speed as well as potential future changes.

### 2. How could stronger winds affect the project even without future climate change?

• The design and operation of certain infrastructure (e.g. wind turbines) is determined by the prevailing climatic wind conditions.
• Given the energy in the wind is the cube of wind speed, a small change in the wind climate can have substantial consequences for the wind energy available.
• Similarly, small changes could have dramatic consequences for wind related hazards e.g. wind storm damage.
• If our data suggests that there is an existing risk of tropical storms in the region, it will be highlighted elsewhere in the report.

### 3. What does the science say could happen in the future?

• Climate change could alter the geographic distribution and/or the seasonal variability of the wind resource.
• Climate model projections remain uncertain and it appears unlikely that mean wind speeds will change by more than the current inter-annual variability.
• Changes in extreme wind speeds associated with extra-tropical and tropical storm are similarly uncertain. However, there have been studies that suggest fewer but more intense events. Stronger storms bring with them an increases risk of coastal storm surge, coastal erosion, wind damage and flooding.
• Given future uncertainty it is advisable to carefully assess past wind speed in the region, bearing in mind that it could change in the future. The UNEP Solar and Wind Energy Resource Assessment SWERA provides a useful global overview of wind information.

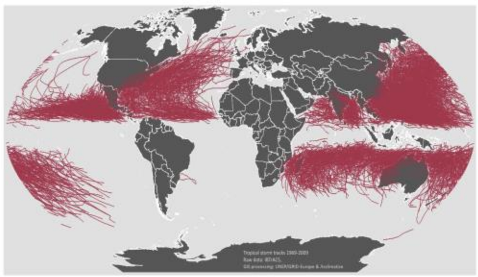
### 4. What next?

1. See the section "Further reading" in "Help and glossary" at the end of this report which lists a selection of resources that provide further information on a changing climate.
2. Click here or here for the latest news and information relating to wind and climate change.

## 05
**HIGH RISK**

## OFFSHORE CATEGORY 1 STORMS

### ACCLIMATISE COMMENTARY



• Our data suggest that the project is located in a region which has experienced Category 1 storms in the recent past. A high exposure in Aware means that between 1968 and 2009 there have been at least one Category 1 storm in the region. This is based on post-processed data from UNEP/ GRID-Europe.
• On the Saffir-Simpson Hurricane Scale a category 1 storm is characterised by sustained winds in excess of 119 km/hr (33 m/s).
• Even this least intense storm can still produce plenty of damage and be life threatening.
• These regions may also susceptible to lower intensity but more frequent tropical storms as well as less frequent higher-intensity storms.
• Up to date information on storm risk worldwide is widely available online, for example UNEP / UNISDR's Global Risk Data Platform.

**1. What the science says could happen in the future and what does this mean for the design of my project?**

• Climate change is projected to influence the frequency and intensity of tropical storms.
• Existing engineering designs may not take into consideration the impact of climate change on the risks from tropical or extra tropical storms. See "Critical thresholds" in the "Help & glossary" section for further details on how a changing climate can impact on critical thresholds and design standards.
• If coastal surges and high winds are identified as a potential problem for the project, it is recommended that a more localised and in-depth assessment is carried out. This information can then be used to inform the project design process if necessary.

**2. As a starting point you may wish to consider the following questions:**

**Q1** Would the expected performance and maintenance of the project be impaired by hazards associated with tropical storms e.g. storm surges and strong winds?
**Q2** Are there any plans to integrate climate change factors into a storm risk assessment for the project?
**Q3** Will the project include continuity plans which make provision for continued successful operation in the event of storm damage?

**3. What next?**

• See the section "Further reading" in "Help and glossary" at the end of this report which lists a selection of resources that provide further information on a changing climate.
• Click here or here for the latest news and information relating to storms and climate change.

☐ I have acknowledged the risks highlighted in this section.

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06
HIGH RISK

SEA LEVEL RISE

ACCLIMATISE COMMENTARY

**1. What does this mean for the design of my project?**

• There is a potential for an increase in incidences where current design standards will not be sufficient. See "Critical thresholds" in the "Help and glossary" section for further details on how a changing climate can impact on critical thresholds and design standards.

• The design, operational and maintenance standards should be reviewed - take into consideration current impacts of inundation from the sea as well as potential future changes.

**2. How could sea level rise affect the project even without future climate change?**

• Low lying coastal regions are particularly prone to local tropical cyclones, mid-latitude storms and associated storm surges.
• Erosion of the coastline can exacerbate 'coastal squeeze', putting pressure on natural sea defences, such as salt marshes and mangroves as well as man-made structures.
• Up to date information on coastal storm and flood risk worldwide is available online, for example UNEP / UNISDR's Global Risk Data Platform.

**3. What does the science say could happen by 2100?**

• Some recent research suggests that global sea levels could be 0.75 to 1.9m higher by the end of the century.
• Local changes in ocean density/dynamics and land movements can also add to, or lessen, the effects of sea level rise at a given location.
• Sea level rise has the potential to accelerate the rate of coastal erosion. Changes in erosion regimes also impact the rate of sedimentation in other areas, particularly in estuarine and other tidal settings. This could provide problems with access to existing ports and jetties.
• In tropical regions, increasing ocean acidification and temperatures can lead to coral reef bleaching and destruction. Such reefs can provide a natural barrier to coastal inundation and erosion.
• In addition, sea level rise could cause saline intrusion into aquifers, further depleting useable water resources.
• Local sea level rise in combination with storm surge and wave height poses a hazard to offshore fixed assets, such as oil and gas platforms.

If you want to know more about projected changes for the project location across a range of sea level rise scenarios, please refer to: The University of Arizona's Sea Level Rise Map.

**4. What next?**

1. See the section "Further reading" in "Help and glossary" at the end of this report which lists a selection of resources that provide further information on a changing climate.
2. Click here or here for the latest news and information relating to sea level and climate change.

☐ I have acknowledged the risks highlighted in this section.

07

LOW RISK

## TEMPERATURE INCREASE

Would an increase in temperature require modifications to the design of the project in order to successfully provide the expected services over its lifetime?

**Chosen Answer**

No - modifications are not required.

The design of the project would be unaffected by increases in temperature.

### ACCLIMATISE COMMENTARY

**1. What does this mean for the design of my project?**

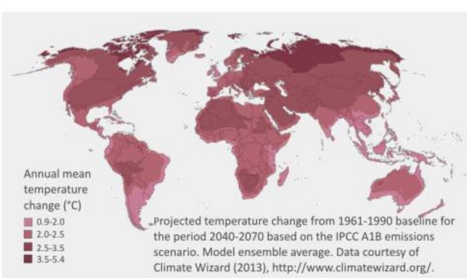
• Even though you have suggested that project designs would not be sensitive to rising temperatures, it is worth considering existing temperature related hazards in the region where the project is planned.
• There is a potential for an increase in incidences where current design standards will not be sufficient. See "Critical thresholds" in the "Help and glossary" section for further details on how a changing climate can impact on critical thresholds and design standards.

• The design, operational and maintenance standards should be reviewed - take into consideration current impacts of high temperatures as well as potential future changes.

**2. How could current high temperatures affect the project even without future climate change?**

• Heatwaves put stress on buildings and other infrastructure, including roads and other transport links. In cities, the 'urban heat island' can increase the risk of heat related deaths.
• Warm weather can raise surface water temperatures of reservoirs used for industrial cooling. In addition, this could impact local eco-systems, improving the growing conditions for algae and potentially harmful micro-organisms in water courses.
• Heatwaves can have an impact on agricultural productivity and growing seasons.
• High temperatures can have implications for energy security. Peak energy demand due to demand for cooling can exceed incremental increases on base load in addition to the risk of line outages and blackouts.
• Human health can be affected by warmer periods. For example, urban air quality and disease transmission (e.g. malaria and dengue fever) can be impacted by higher air temperatures.
• Wildfire risk is elevated during prolonged warm periods that dry fuels, promoting easier ignition and faster spread.
• Permafrost and glacial melt regimes as impacted by warm periods.
• If our data suggests that there are existing hazards associated with high temperatures in the region, they will be highlighted elsewhere in the report. This may include existing wildfire risks as well as areas potentially impacted by permafrost and glacial melt.

**3. What does the science say could happen by the 2050s?**



Projected temperature change from 1961-1990 baseline for the period 2040-2070 based on the IPCC A1B emissions scenario. Model ensemble average. Data courtesy of Climate Wizard (2013), http://www.climatewizard.org/.

• Climate model projections do not agree that seasonal temperature will increase beyond 2 °C in the project location.
• If you want to know more about projected changes in the project location across a range of GCMs and emissions scenarios please refer to The Nature Conservancy's Climate Wizard for detailed maps and Environment Canada's Canadian Climate Change Scenarios Network for scatter plots of expected changes.

## 4. What next?

1. See the section "Further reading" in "Help and glossary" at the end of this report which lists a selection of resources that provide further information on a changing climate.
2. Click here or here for the latest news and information relating to temperature and climate change.

I have acknowledged the risks highlighted in this section.

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08
LOW RISK

## PRECIPITATION INCREASE

Would an increase in precipitation require modifications to the design of the project in order to successfully provide the expected services over its lifetime?

**Chosen Answer**

No - modifications are not required.

The design of the project would be unaffected by increases in precipitation.

### ACCLIMATISE COMMENTARY

**1. What does this mean for the design of my project?**

• Even though you have suggested that designs would not be affected by increased precipitation, it is worth considering existing precipitation related hazards in the region where the project is planned.

**2. How could current heavy precipitation affect the project even without future climate change?**

• Seasonal runoff may lead to erosion and siltation of water courses, lakes and reservoirs.
• Flooding and precipitation induced landslide events.
• In colder regions, seasonal snow falls could lead to overloading structures and avalanche risk.
• If our data suggests that there are existing hazards associated with heavy precipitation in the region, they will be highlighted elsewhere in the report. This may include existing flood and landslide risks.

**3. What does the science say could happen by the 2050s?**

• Climate model projections do not agree that seasonal precipitation will increase in the project location which could indicate a relatively high degree of uncertainty (see the section "Model agreement and uncertainty" in "Help and glossary" at the end of this report). On the other hand, this could also mean precipitation patterns are not expected to change or may even decrease (see elsewhere in the report for more details of projections related to precipitation decrease).
• If you want to know more about projected changes in the project location across a range of GCMs and emissions scenarios please refer to The Nature Conservancy's Climate Wizard for detailed maps and Environment Canada's Canadian Climate Change Scenarios Network for scatter plots of expected changes.

**4. What next?**

1. See the section "Further reading" in "Help and glossary" at the end of this report which lists a selection of resources that provide further information on a changing climate.
2. Click here or here for the latest news and information relating to water and climate change.

I have acknowledged the risks highlighted in this section.

09
LOW RISK

## PRECIPITATION DECREASE

Would a decrease in precipitation require modifications to the design of the project in order to successfully provide the expected services over its lifetime?

**Chosen Answer**

No - modifications are not required.

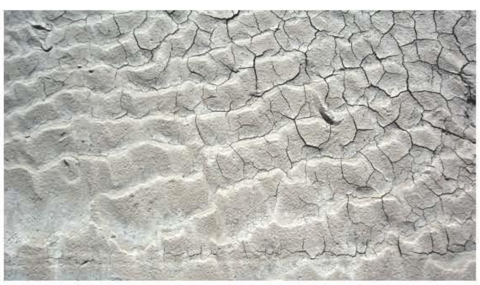
The design of the project would be unaffected by decreases in precipitation.

## ACCLIMATISE COMMENTARY

### 1. What does this mean for the design of my project?

• Even though you have suggested that designs would not be affected by a decrease in precipitation, it is worth considering existing precipitation related hazards in the region where the project is planned.

### 2. How could current heavy precipitation affect the project even without future climate change?



• Decreased seasonal runoff may exacerbate pressures on water availability, accessibility and quality.
• Variability of river runoff may be affected such that extremely low runoff events (i.e. drought) may occur much more frequently.
• Pollutants from industry that would be adequately diluted could now could become more concentrated.
• Increased risk of drought conditions could lead to accelerated land degradation, expanding desertification and more dust storms.
• If our data suggests that there are existing hazards associated with decreased precipitation in the region, they will be highlighted elsewhere in the report. This may include water availability and wildfire.

### 3. What does the science say could happen by the 2050s?

• Climate model projections do not agree that seasonal precipitation will decrease in the project location which could indicate a relatively high degree of uncertainty (see the section "Model agreement and uncertainty" in "Help and glossary" at the end of this report). On the other hand, this could also mean precipitation patterns are not expected to change or may even increase (see elsewhere in the report for more details of projections related to precipitation increase).
• If you want to know more about projected changes in the project location across a range of GCMs and emissions scenarios please refer to The Nature Conservancy's Climate Wizard for detailed maps and Environment Canada's Canadian Climate Change Scenarios Network for scatter plots of expected changes.

### 4. What next?

1. See the section "Further reading" in "Help and glossary" at the end of this report which lists a selection of resources that provide further information on a changing climate.
2. Click here or here for the latest news and information relating to water and climate change.

I have acknowledged the risks highlighted in this section.

10

The sections above detail all High and Medium risks from Aware[TM]. Selected Low risks are also detailed. Local conditions, however, can be highly variable, so if you have any concerns related to risks not detailed in this report, it is recommended that you investigate these further using more site-specific information or through discussions with the project designers.

## HELP AND GLOSSARY:

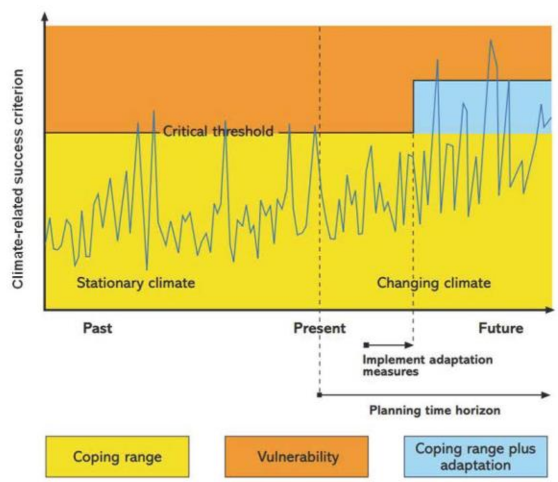
### Model agreement and uncertainty:

Although climate models are constantly being improved, they are not good enough to predict future climate conditions with a degree of confidence which would allow precise adaptation decisions to be made. Outputs from different climate models often differ, presenting a range of possible climate futures to consider, and ultimately a wide range of possible actions to take. In Aware, climate projections are described as having potentially higher degree of uncertainty when less than 14 out of 16 GCMs agree on the direction and / or a pre-defined magnitude of change.

Even with improvements in climate modelling, uncertainties will remain. It is likely that not all the climate statistics of relevance to the design, planning and operations of a project's assets and infrastructure will be available from climate model outputs. The outputs are typically provided as long-term averages, e.g. changes in average monthly mean temperature or precipitation. However, decisions on asset integrity and safety may be based on short-term statistics or extreme values, such as the maximum expected 10 minute wind speed, or the 1-in-10 year rainfall event. In such cases, project designers or engineers should be working to identify climate-related thresholds for the project (see "Critical thresholds" section below) and evaluate whether existing climate trends are threatening to exceed them on an unacceptably frequent basis. Climate models can then be used to make sensible assumptions on potential changes to climate variables of relevance to the project or to obtain estimates of upper and lower bounds for the future which can be used to test the robustness of adaptation options.

**The key objective in the face of uncertainty** is therefore to define and implement design changes (adaptation options) which both provide a benefit in the current climate as well as resilience to the range of potential changes in future climate.

### Critical thresholds:

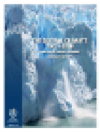



**The relationship between a critical threshold and a climate change related success criterion for a project. [Source: Willows, R.I. and Connell, R.K. (Eds.) (2003). *Climate adaptation: Risk, uncertainty and decision-making*. UKCIP Technical Report, UKCIP, Oxford].**

A key issue to consider when assessing and prioritising climate change risks is the critical thresholds or sensitivities for the operational, environmental and social performance of a project. Critical thresholds are the boundaries between 'tolerable' and 'intolerable' levels of risk. In the diagram above, it can be seen how acceptable breaches in a critical threshold in today's climate may become more frequent and unacceptable in a future climate.

Climate change scenarios can be used to see if these thresholds are more likely to be exceeded in the future. The simplest example is the height of a flood defence. When water heights are above this threshold, the site will flood. The flood defence height is the horizontal line labelled 'critical threshold'. Looking at the climate trend (in this case it would be sea level or the height of a river) – shown by the blue jagged line – it can be seen that the blue line has a gradual upward trend because of climate change. This means that the critical threshold is crossed more often in the future – because sea levels are rising and winter river flows may be getting larger. So, to cope with this change, adaptation is needed – in this case, one adaptation measure is to increase the height of the flood defence.

**Further reading:**

| | |
|---|---|
|  | Report detailing changes in global climate:<br>The Global Climate 2001 - 2010 (PDF) |
|  | IPCC report on climate-related disasters and opportunities for managing risks:<br>Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) |
|  | IPCC report on impacts, adaptation and vulnerability:<br>Working Group II Report "Impacts, Adaptation and Vulnerability" |
|  | IFC report on climate-related risks material to financial institutions:<br>Climate Risk and Financial Institutions. Challenges and Opportunities. |

**Aware data resolution:**

The proprietary Aware data set operates at a resolution of 0.5 x 0.5 decimal degrees (approximately 50 km x 50 km at the equator). These proprietary data represent millions of global data points, compiled from environmental data and the latest scientific information on current climate / weather related hazards together with potential changes in the future. Future risk outcomes are based on projections data from the near- to mid-term time horizons (2020s or 2050s, depending on the hazard and its data availability).

Global climate model output, from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007), were downscaled to a 0.5 degree grid.

[Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor: The WCRP CMIP3 multi-model dataset: A new era in climate change research, Bulletin of the American Meteorological Society, 88, 1383-1394, 2007]

**Aware data application:**

In some instances Risk Topic ratings are only based on Aware data, including:
- Flood
- Permafrost
- Landslides

**Country level risk ratings:**

These are generated from the data points within a country's borders. For single locations, site-specific data are used, and for multiple locations or countries, composite data across the portfolio of locations are used.

**Glossary of terms used in report**

"Climate model projections agree": defined as more than 14 out of 16 GCMs agreeing on the magnitude (e.g. temperature warming of 2 °C) and / or direction of change (e.g. seasonal precipitation).
"Climate model projections do not agree": defined as 14 or fewer out of 16 GCMs agreeing on the magnitude (e.g. temperature warming of 2 °C) and / or direction of change (e.g. seasonal precipitation).
"Significant proportion": defined as at least 25% of locations when multiple locations are selected.
"Large proportion": defined as at least 75% of locations when multiple locations are selected.

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The above thresholds are used as a means of providing a project-wide risk score where a project may be spread across multiple locations. This requires more than one individual location to be at risk to begin signifying whether there is a risk at the overall project level. However, it is always recommended that individual locations are analysed separately for more accurate, site-specific risk screening. The overall risk score for the project (high, medium or low) is based on a count of high risk topic scores. A project scores overall high risk if greater than or equal to 3 individual risk topics score high. A project scores overall medium risk if between 1 and 2 individual risk topics score high. A project scores overall low risk if none of the individual risk topics score high.

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