Tuvalu National Adaptation Plan: Climate Impact, Vulnerability & Risk Assessment

Hazard Assessment: Final Report

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Executive Summary

Context

Tuvalu has nine islands: five coral atolls, three table reef islands and one atoll/reef island. The landmass of only 25.3 km^2 is spread over an Exclusive Economic Zone (EEZ) of 749,790 km^2. The population is about 11,500, of which 60 % live on the main (capital) island of Funafuti. The land mass is entirely low lying with the latest reported, highest (natural) elevation level at 6.54 metres above sea level. Communities are reliant on subsistence agriculture and fisheries which also underpin a large part of the national economy.

The purpose of this report is to summarise the findings of the assessment of the key climate hazards impacting Tuvalu over current and future (multi-decadal) climate change timescales, in particular as relates to six priority sectors, viz: agriculture, fisheries, water, health, coastal development/infrastructure and disaster management. More specifically, this assessment is intended to provide science-based evidence to inform an integrated Climate Impact, Vulnerability and Risk Assessment (CIVRA) as part of the development of the new National Adaptation Plan (NAP) for Tuvalu funded by the Green Climate Fund (GCF). The key audience for this report is the Secretariat of the Pacific Environment Program (SPREP), as the designated GCF-Implementation Entity for the Tuvalu NAP project, and the Government of Tuvalu through the mechanism of the Tuvalu NAP Country Team. It is however expected the report also has broader utility for other key stakeholders and users of the data and information as might require technical insights around better understanding and reporting of Tuvalu's current and future climate.

Whereas coastal inundation is already an issue due to high tides, storm-surges and sea level rise, other key hazards have also been identified as having material impacts on the priority and related cross-cutting sectors and systems for Tuvalu; both now and into the future, with the hazard extent dictated by the various global greenhouse gas emissions scenarios. Existing and future climate vulnerabilities and exposure exacerbate the risks and associated challenges faced by communities, thereby dictating the need for an appropriate adaptation response as part of the new NAP.

Climate averages

Tuvalu's climate is tropical, with minimum temperatures around 25 °C, maximum temperatures around 31 °C, a wet season from December to March, and a dry season from April to November. The annual-average rainfall is 3,400 mm in the south islands and 2,900 mm in the north.

Ocean temperature, as measured at the Tuvalu tide-gauge in Funafuti lagoon from 1993 to 2021, ranges from 29 °C to 30 °C, exhibiting unique bimodal peaks around 30 °C in November/December and April/May. From the 1980s to 2000s, the average duration of marine heat waves was 5–16 days.

Tuvalu is vulnerable to cyclone-generated winds, storm surges and swells (typically from the east), as well as spring tides. Over the period 1971 to 2021, an average of twelve cyclones per decade passed within the Tuvalu EEZ, though none directly impacted the islands.

Climate variability

Climate variability in the western tropical Pacific is significantly influenced by the El Niño Southern Oscillation (ENSO). This is a natural, large-scale ocean-atmosphere circulation that affects temperature, rainfall, and tropical cyclones in the region. Sea surface temperature north-east of Tuvalu is warmer than normal during an El Niño event, cooler than normal during a La Niña event, and close to normal in a neutral year. This affects the position and strength of the South Pacific Convergence Zone (SPCZ) which is another large-scale climate feature characterised by a band of heavy rainfall and cyclone activity. During El Niño events, the SPCZ tends to move north-east, so Tuvalu gets more rainfall and more cyclones. During La Niña events, the SPCZ tends to move south-west, so Tuvalu gets less rainfall and fewer cyclones. Historically, El Niño events occur every 3–5 years and typically last 6–24 months, while La Niña events occur every 3–7 years and half of them have lasted 24–36 months.

Climate variable	La Niña	El Niño
Rainfall	Drier	Wetter
Drought	More	Less
Tropical cyclones	Less	More
Sea surface temperature	Cooler	Warmer
Sea level	Lower	No effect

Historical and current climate trends

Climate change due to increases in greenhouse gas concentrations has contributed to changes in temperature, rainfall, sea level and ocean chemistry.

Since 1951, minimum temperatures have increased by 0.20 °C per decade, maximum temperatures have increased by 0.17 °C per decade, and hot days (temperature above the 90th percentile for 1961–1990) have increased by 29 days per decade. Since 1951, annual total rainfall has varied from 2000 to 4800 mm at Funafuti, though there has been no significant trend. The annual maximum daily rainfall amount varies from around 100 to 350 mm/day, with no statistically significant trend.

While there is no trend in meteorological drought (measured by the Standardised Precipitation Index) between 1951 to 2022, a statistically significant increase in consecutive dry days (0.36 days/decade) has been observed in Funafuti (1951–2020).

Sea level has risen near Tuvalu by about 4.5 mm per year since 1993, above the global average of 3.2–4.2 mm per year. In Funafuti, the mean annual wave height has remained unchanged since 1979.

During 1982–2022, sea surface temperatures (SSTs) increased by 0.22 °C per decade. Marine heatwave (MHW) duration increased significantly in the 2010s over most of the Pacific to 8–20 days. Oceanic pH measurements since 1988 showed that the tropical Pacific Ocean became 12 % more acidic.

There has been no significant change in the number of tropical cyclones since 1981. An intensification of the easterly trade winds in the tropics. Substantial wave runup can be generated either by nearby tropical storms and cyclones both in the vicinity or even more remote from Tuvalu leading to significant impacts for the coastlines of Tuvalu.

Projected climate changes

Projected changes in climate have been estimated over the coming decades for Tuvalu for low and high greenhouse gas emissions pathways, based on simulations from global climate models. These changes are summarised in Table 18-1.

Figure 1-1: Overview of projected climate changes for Tuvalu.

Annual-average temperature is projected to increase 0.7 °C by 2030, relative to the average for 1986–2005, regardless of the emissions pathway. By 2050, the increase is 0.8 °C for low emissions and 1.4 °C for high emissions. By 2070, the increase is 0.8 °C for low emissions and 2.1 °C for high emissions. This means more extremely hot days.

Annual-average rainfall is projected to increase 4 % by 2030 and 3 % by 2050, for both low and high emissions, relative to the average for 1986–2005.

Extreme daily rainfall events are projected to become more intense. For example, a 200 mm/day extreme rainfall event occurring once every 30 years during 1970–2000 may occur once on average every 18 years by 2070–2100 for low emissions, and once on average every 2 years for high emissions.

Drought duration is projected to decline in future across all three drought categories (moderate, severe, extreme). A general decrease in the frequency of moderate and severe droughts is projected. Little change in drought intensity is projected.

Given Tuvalu is located on the northern boundary of the tropical cyclone (TC) formation region for the Southern Hemisphere, TCs making landfall in Tuvalu are rare, and are not usually in the severe category. However, associated impacts such as storm surge from remotely occurring TCs can have a large influence on coastal inundation. On the balance of evidence, TCs and associated impacts affecting Tuvalu are projected to become less frequent but more intense in future.

Annual-average sea level is projected to increase 13 cm by 2030, relative to the average for 1986–2005. By 2050, the rise is 22 cm for low emissions and 27 cm for high emissions. Under present sea levels ~6.9 km^2 (~27.2%) of land area inundate once every 5-year across all of Tuvalu. By 2060 under high emissions (SSP5-8.5), this value almost doubles to ~13.5 km^2 (~53.1%) for an ARI of 100 years. However, some islands are more likely to experience flooding than others.

In Funafuti, the frequency of MHWs increases from less than 10 days/year during a 20-year period centred on 1995 to around 130 days/year by 2050 (low warming model/low emissions) up to 360 days per year (high warming model/high emissions). This will have implications for marine ecosystems and coral bleaching. Annual severe bleaching conditions (Degree heating weeks > 8), where there is no break in this destructive event for the coral to recover, are projected to occur on average within the Tuvalu EEZ by around 2060 (for low emissions; SSP1-2.6), and by around by 2035 (for very high emissions; SSP5-8.5)

Ocean acidification is projected to continue. Under a high emissions scenario, aragonite saturation states may fall below 3 by 2060, a level where coral reefs in Tuvalu may not only stop growing but start to get smaller, as they dissolve faster than they are built. However, if emissions follow a low scenario, consistent with the Paris Agreement target of keeping global warming well below 2 °C, then the aragonite saturation state may start to recover after 2060.

By 2050, ocean pH around Tuvalu is projected to decline 0.05 units for a low emissions scenario and 0.12 units for a high emissions scenario, which represents an increase in the acidity of the ocean.

There may be more extreme El Niños and more extreme La Niñas in future, causing greater climate variability and extreme events.

Confidence, limitations and uncertainties

Where possible, confidence ratings are provided for each climate projection. This is based on the Intergovernmental Panel on Climate Change (IPCC) framework that assesses the amount of scientific evidence and the degree of agreement between different lines of evidence. For example, limited evidence and low agreement leads to low confidence, while robust evidence and high agreement leads to high confidence.

Global climate models have limitations. Their coarse resolution (about 200 km between data points) is adequate for simulating large-scale climate features but inadequate for regional and local climate features. Statistical and/or dynamical downscaling is required for better representation of regional and local climate features, especially extreme weather events. Climate projections over the next decade are strongly influenced by natural variability, which is hard to predict. This is an active area of research.

Uncertainties in climate projections are due to different emissions pathways, different regional climate responses simulated by climate models for each pathway, and natural climate variability from days to years. Where possible these uncertainties are quantified. The median (50th percentile) change is usually given along with an uncertainty estimate, often defined by the 10-90 percentile range, e.g. a median temperature change of 2 °C (uncertainty range 1-3 °C).

Changes outside these ranges are possible but hard to quantify. For example, larger and irreversible tipping points may be triggered with modest global warming, such as thawing of Boreal permafrost, collapse of the overturning circulation in the north Atlantic Ocean, and rapid disintegration of the Greenland and Antarctic ice sheets.

The magnitude and direction of projected change reported for climate variables affecting Tuvalu for 2030 and 2050 (low and high emissions), relative to 1995 observed climate may increase or decrease the related consequences in future (assuming no adaptation).

Impacts and hazard ratings

This assessment is focussed on the materiality of climate hazards impacting six priority sectors for the Tuvalu NAP both now and into the future: fisheries, agriculture, coastal development and infrastructure, health, water and disaster risk management. Infrastructure includes transport, waste management, energy, telecommunications. These sectors are systematically interconnected, so in practice there can be cascading and compounding impacts across multiple interdependent sectors and systems; and thereby material to the risks informing the design and priorities of the NAP. A discussion of sectoral impacts affected by climate hazards, drawn from the scientific literature and from anecdotal information and feedback provided through key in-country stakeholder consultation, is summarised in

Table 1-2.

Based on an assessment of climate hazards, exposure, vulnerability and related impacts currently experienced in Tuvalu, each hazard has been assigned a rating (Table 0-3

Table 1-3). Currently, sea level and droughts are given a ‘very high’ impact rating, while the other climate hazards have a medium or high rating (Table 0-3

Table 1-3). These may, or may not, change under projected climate conditions. For example, the projected decrease in droughts by 2050 is expected to reduce the impact rating from high to medium. The projected increase in sea level by 2050 is likely to raise the impact rating from very high to extreme for low emissions and very extreme for high emissions. The impact ratings will also increase for marine heatwaves and extreme rainfall. The rating for cyclones does not change in future because the projected decrease in frequency and increase in intensity have high uncertainty and low confidence. The future hazard ratings do not explicitly consider sectoral/system interdependencies; however such interdependencies are considered once the integrated risk ratings are separately and subsequently estimated for the CIVRA project.

Knowledge gaps and research priorities

The estimate climate hazard ratings (Table 0-3) are a primary line of science-based evidence from this assessment, including both quantitative data/metrics and associated qualitative data and information, informing the overall integrated risk ratings for the CIVRA as part of the Tuvalu NAP (n.b. risk ratings reported separately). This assessment is based for the most part on existing, readily accessible data that is scientifically robust and/or anecdotal inforation that is appropriately validated through formal and systematically structured key stakeholder engagemenht.

It follows the assessment has provided a compelling line of evidence to inform the intergated risk assessment and associated NAP design for Tuvalu. However it has also revealed a number of relevant knowledge gaps and informed the following list of research priorities for future reference and planning as might enhance the overall scientific understanding of Tuvalu’s future climate:

- Ongoing digitisation, quality control, monitoring and analysis of historical climate data observations.
- Detection and attribution of historical trends.
- Projections based on analysis of the latest archive of global climate model (GCM) data (currently CMIP6).
- Pacific downscaled climate projections based on best available CORDEX domain, GCMs, downscaling methods and standards to improve local detail/reliability at a spatial and temporal scale relevant to decision-making for ocean temperature, ENSO variability, extreme sea level, extreme rainfall, cyclones, extreme heat, drought and marine heatwaves.
- Tipping points relevant to the Pacific, including so-called ‘low likelihood-hyigh consequence’ events.
- Better information about historical links between climate hazards and impacts, particularly as relates to climate extremes and acute shocks to the economy, to inform computationally robust 'damage functions' that can be used in future risk and associated ‘loss and damage’ assessments.
- Co-design and co-development of communication products with local end-users of the CIVRA to inform policy development, planning, capacity development and associated decision-making.

There is an opportunity to address these issues at a regional level in the western tropical pacific in an updated version of the Pacific Climate Change Research Roadmap (currently in preparation under direction of the Pacific Meteorological Council and the Pacific Climate Change Centre).

Table 1-1 Historical climate (20-years centred on 1995) and projected climate change for 20-year periods centred on 2030 and 2050, relative to a 20-year period centred on 1995. Changes are based on simulations from CMIP5 global climate models (GCMs) for low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenarios. However, changes in extreme wind speed and marine heat waves are based on CMIP6 GCMs for low (SSP1-2.6) and high (SSP5-8.5) emissions scenarios. For some variables, the Tuvalu EEZ region is assessed, rather than Funafuti, as indicated. Confidence ratings are based on the IPCC framework (Mastrandrea et al, 2010) involving an assessment of the amount of evidence and the degree of agreement between lines of evidence.

Funafuti		Projected change			
20-years centred on 1995		2030	2050	2050	
			Low emissions RCP2.6	Very high emissions RCP8.5	Confidence
	ATMOSPHERIC VARIABLES				
Min 26 °C Max 31 °C	Annual average temperature (°C)	+0.7 (0.4 to 1.0)	+0.8 (0.5 to 1.2)	+1.4 (1.0 to 1.9)	high
12 (0 to 31)	Hot days (days > 33 °C) [a]		+181 (140 to 222)	+264 (140 to 331)	high
3460 mm	Annual average rainfall (%)	+4 (-4 to +12)	+3 (-6 to +11)	+3 (-11 to +17)	medium
134 (119 to 160) mm/day	Annual maximum daily rainfall (mm/day)		+12 (-17 to 39)	+15 (-15 to 65)	medium
	Average drought intensity (more negative = more intense)	Slight increase	No data	Slight increase	medium
1.2 per 20 years	Average drought frequency (per 20 years)	Slight decrease	No data	Slight decrease	medium
~17 months	Average drought duration (months)	Slight decrease	No data	Slight decrease	medium
~30 (20-39) m/s	Tropical cyclone windspeed (m/s)			Increase	low
12 per decade	Tropical cyclone frequency (%)			Decrease	low
	OCEAN VARIABLES				
0m	Annual average sea level (m)	+0.13 (0.09 to 0.17)	+0.22 (0.17 to 0.29)	+0.27 (0.19 to 0.37)	high
11 km^2	Extreme sea level proxy: 50-yr ARI Tuvalu flooded area (km^2)[b]	No data	~16 (2060; SSP2-4.5)	~16.5 (2060)	high
28.6-29.5 °C	Sea surface temperature (°C) over EEZ [c, f]	+0.7 (-0.6 to 1.7)	+0.9 (-0.5 to 2.1)	+1.3 (0.0 to 2.5)	high
~ 10 days/ yr	Marine heatwave frequency (days/year) [c,f]	110-290	130-340	220-360	high
0 days/ 20 yr	Coral bleaching days (per 20 years) [d,f]	No data	169-2934	1652-6460	high
~8.08 (8.1-8.07)	Annual average ocean pH over EEZ (c,e)	8.02 (7.99-8.04)	8.0 (7.99-8.02)	7.95 (7.93-7.96)	high
~4.1 (4.0-4.2)	Annual average aragonite saturation (c,e)	3.77 (3.51-4.06)	3.69 (3.53-4.01)	3.4 (3.18-3.70)	high

[a] number of days over the 95th percentile of 1985-2014 daily temperatures [b] data source .[c] Future values are reported, not changes. [d] Exceed coral bleaching Alert level 2 at Niutao. [e] Baseline figures are estimated from

Table 1-2 Climate related hazards affecting sectors in Tuvalu.

Climate Hazard	Fisheries and marine resources	Agriculture	Coastal development and infrastructure	Disaster Management and emergency response	Health	Water resources
Annual average temperature	Fish storage in boats and while processing	Crop suitability. Crop disease			Vector borne disease	
Extreme temperature	Fish storage at port and on vessel. Fishers' and fish processors heat stress and workforce productivity.	Crop stress Farm-worker heat-stress Pig and chicken heat-stress	Health of outside workers for general maintenance and installations. Melting of Road tar. High energy demand for air conditioning may cause black outs. May require more solar/battery back-up. Increased demand for replacement parts and equipment. Black outs may cut telecoms.	Increased demand for communal air-conditioned refuges to escape heat.	Heat stress increases hospital and health centre admissions from heat stroke. Power outages may affect sewage pumping facilities. Food-borne disease due to inadequate cooling. Labour productivity Mental/ psychosocial disorders	High water demand for domestic and agricultural use for stock watering and irrigation.
Annual average rainfall		Crop suitability. Water for livestock.			Vector borne disease.	Availability/ storage
Extreme rainfall	Nutrient and sediment Runoff into coastal areas.	Limited farm access due to flooding. Damage to some crops. Increased disease pressure.	Flood risk depends on road design and flood mitigation e.g. drainage. Extreme rain can result in flooding of Funafuti airport runway. Flooding of electricity infrastructure may cause blackouts. Flood related black outs may cut telecoms. Require functioning gutters and rooves to collect water to water tanks.	Require flood early warning systems, evacuation centres, and post-flood impact assessments.	Water quality affects health, sanitation and hygiene. Post-flood trauma may affect mental health.	Flooding can overwhelm drains, with overflow of septic tanks, affecting ground water quality.

Drought	Invasive seaweed e.g. *Sargassum polycystum* has been observed during drought events.	Crop stress e.g. reduced yield from Pulaka (Giant swamp Taro). Loss of cultural livelihood.	Towers caking with salt, with no rainfall to wash salt away, can also affect telecoms. Water supply from household water tanks becomes inadequate.	RO capacity. Reliance on trucks to deliver RO water. Supply of RO water to outer islands.		Water Shortage. Reliance on RO water.
Extreme windspeed	More days too windy for fishing (<20 knots) Relevant to both lagoon and off-reef/FAD pelagic fishery. When very windy more fishing in the lagoon.	Crop damage.	Large waves and storm surges causing overtopping of barriers Disruption of air and sea transport Wind-damage to infrastructure can cause blackouts. Blackouts, wind-borne debris and fallen trees may cut telecoms. Towers caking with salt from sea spray can affect telecoms.	Deaths, injuries, damage and disruption in general. Post cyclone impact assessments can inform climate-resilient recovery.	Injuries due to airborne debris and building collapse during cyclones.	Ocean overtopping of barriers can cause salt-water contamination of groundwater.
Sea level rise, extreme sea level (inc waves and TC impacts)	Coral reefs provide less defence against storm surge and tsunami. Sea-Turtle nests and Mangroves may be inundated.	Saltwater inundation affects Pulaka pits.	Infrastructure, houses, roads and bridges affected. Underground copper wiring becoming corroded with inundation, with upgrading to fibre-optic cable expensive.	Need barriers and land reclamation to reduce inundation risk.	Mental health issues due to inundation of property, and loss of livelihood & income, internal and external relocation.	Contamination of freshwater lens.
Ocean temperature and marine heatwave	Changing distribution of Tuna fisheries ($). Coral bleaching. Sea-Turtle gender. Fish kills.		Coral bleaching/die-back/reef erosion.		Ciguatera- links to SST unclear. More study needed.	
Ocean pH	Fisheries, reef and aquatic ecosystem viability, productivity, and diversity.		Marine infrastructure e.g. fixings such as nails, rivets, bolts etc. Coral bleaching/die-back/reef erosion reducing island protection.			
Aragonite saturation	Coral formation and reef integrity, shells, and fish skeletons.		Coral integrity, lagoon protection			

Table 1-3 Climate hazard assessment for Tuvalu, based on current and future climate hazards (Table 18-1) for 2030 and 2050 for low and high emissions scenarios, noting current vulnerabilities and exposure based on the TVAR , Chapter 2 of this report (L), or in-country (IC) missions. Colours are aligned to the consequence rating scale below. SST is sea surface temperature and MHW is marine heatwave.

Low	Medium	High	Very high	Extreme	Very Extreme	Unclear

Sector/Theme	Source	Current vulnerability and exposure	Current hazard ratings	Climate hazard ratings		
				2030	2050	
				Low/high	Low	High
Fisheries: ocean	L	National revenue is strongly dependent on offshore fish catches and licences	SST	Unclear	Low	Very Extreme
Fisheries: coastal	T*, L	Household consumption is strongly dependent on inshore fisheries productivity and marine biodiversity	SST	High	Very high	Extreme
	T	Invasive species affect marine biodiversity and ecosystem health (e.g. Crown of thorns seastars).				
	L	Food and fish are vulnerable to spoiling post-harvest on very hot days due to lack of suitable cold storage	Extreme temperature	Very high	Extreme	Very Extreme
	T	Invasive species affecting land crabs etc. (e.g. yellow crazy ants)	Temperature	High	High	High
	T, L	Maritime saftey and fishing activity for coastal fishers can be affected and/or weather / waves too rough	Wind speed	Medium	High	Very high
	L	Fish being processed may spoil in the heat without refrigeration, affecting potential sale value and suitability for consumption	Extreme temperature	Very high	Extreme	Very Extreme
	T	Declining ecosystem health of coastal marine habitat such as coral reefs and lagoons	MHW	Very high	Extreme	Very Extreme
			Ocean acidification	Very high	Extreme	Very Extreme
	T	Low resilience of marine food sources observed in past droughts (Nukulaelae) maybe due to high temperatures and low water flushing through the lagoon impacting water quality	Drought	High	High	High
	L, T	Nutrient runoff, pollution and wastewater degrades water quality in lagoons	Extreme rainfall	Unclear	Very high	Extreme
	L	Sea turtle gender affected by sand temperature (air temperature and SST)	Sand temperature	Unclear	Unclear	Unclear
	L	Sargassum polycystum infestation of reefs and lagoons due to high nutrient levels near densely populated areas (mainly in Funafuti)	Wind Rainfall	Unclear	Unclear	Unclear
Agriculture	T	High exposure of agriculture in low lying coastal areas with reducing reslience to coastal inundation, declining or poor soil quality for farming with salt water intrusion and storm surge (Vaitupu in particular).	Extreme sea level	Very high	Extreme	Very Extreme

		Low resilience of crops to salt water leading to declining or limited crop diversity (Niutao, Nui). Crops can become inundated with saline water from wave overtopping				
	T	Poor soil quality and exposure of crops to salinity from groundwater intrusion	Extreme sea level			
	L	Livestock (pigs) are vulnerable to heat stress	Extreme temperature			
	T, L	Crops have shown low resilience to droughts in the past	Drought			
	T	Crops have shown low resilience to floods causing recrurrent crop failure	Extreme rainfall			
	T	Low resilience of crops to tropical cyclone winds and waves e.g. breadfruit dropping, tree damage etc	Cyclones			
Coastal infrastructure and ecosystems	T*, L	With high exposure in low lying coastal areas, and limited coastal protection, shorelines are retreating due to coastal inundation and erosion (Nanumea and Nanumaga in particular). Exposure to salt water due to coastal inundation causes decline in shoreline vegetation health and cover.	Extreme sea level			
	L	Asphalt road surfaces/ airport runways are poorly maintained and exposed to coastal inundation/erosion, e.g. pot holes (Funafuti and Vaitupu)	Extreme sea level			
			Extreme rainfall			
			Extreme temperature			
	L, IC	Water, electricity and other infrastructure subject to surface flooding, coastal inundation and groundwater intrusion	Extreme rainfall			
			Extreme sea level			
	L	Inadequate marine resource (natural infrastructure) conservation including coral / coastal protection, also to waves generated by remote severe cyclones.	Ocean acidification			
			Marine heatwaves			
			Cyclones			
Health	L, IC	Heat stress occurs where there are buildings with inadequate cooling,lack of communal 'green space'/natural shade and at outdoor worksites without protection from the sun; compounded during power outages	Extreme temperature			
	L	Limited capacity to cope with heat related morbidity, diabetes, and heat related mental health issues				
	L	Food safety issues where adequate refrigeration is limited or not available				
	T	Lack of refrigeration for timely and effective transportation and storage of medical supplies				
	T	Changes to coastal fisheries production may affect availability of fresh food quality and quantity	SST			
	IC	Incidence of Cigateurra poisoning	SST			
	T	Exposure to vector borne disease (Chikungunya, dengue and lymphatic filariasis)	Temperature			
			Rainfall			

	T	Exposure to water borne diseases due to poor water quality, availability and environmental health and sanitation, especially during floods	Extreme rainfall			
	L	Flood related water borne disease and sanitation issues due to limited water treatment and sewage treatment plants				
	L	High exposure to inundation, loss and damage in low lying coastal areas, affecting mental health	Extreme sea level			
	T	Low resilience of health infrastructure to inundation				
	L	Communities affected by lack of access to potable quality water and reduced water for agriculture, contributing to water/food stress and physical (sanitation-related) and mental health issues	Drought			
Water	L, IC	Water demand increases under extreme heat conditions	Extreme temperature			
	T	Salt water intrusion affects ground water quality, affecting potable water supply	Extreme sea level			
	L, T	Increasing pressure on water resources occurs during drought due to limited access to water treatment equipment, inadequate household and communal water tank capacity, leaking or faulty household water tanks, and inadequate public water supply system and services	Drought			
	L	Drainage affected during flooding events leading to reduced water quality, excessive run-off, damage to infrastructure and loss of public amenity	Extreme rainfall			
	T*	Limited ability to capture water in household water tanks due to land availability and cost of purchasing and maintaining water tanks	Rainfall			
Disaster risk management	T	Lack of cyclone-proof and extreme climate-resilient housing, e.g cyclone straps, poorly fixed roofing materials	Cyclones Extreme rainfall			
	T	Limited access to post-disaster building reconstruction services, including shipping and transporation being affected by waves generated by remote severe cyclones.	Cyclones			
	T*	Limited or no access to adequately sized and located climate-resilient evacuation centres (Vaitupu, Nui and Nukufetau) (Top TIVA priority)	Cyclones Extreme sea level			
	T, IC	High exposure to coastal inundation in low lying areas affects power supply, ctelecommunications and evacuation centres	Extreme sea level			
	L, IC	Inundation and damage to roads and airports and other public infrastructre affecting transport and other critical support services	Extreme rainfall			

*denotes vulnerability issue with the highest frequency of total responses across all islands, according to TVAR

Chapter 1 Introduction

The purpose of this report is to summarise the findings of the assessment of the key climate hazards impacting Tuvalu over current and future (multi-decadal) climate change timescales, in particular as relates to six priority sectors, viz: agriculture, fisheries, water, health, coastal development/infrastructure and disaster management. More specifically, this assessment is intended to provide science-based evidence to inform an integrated Climate Impact, Vulnerability and Risk Assessment (CIVRA) as part of the development of the new National Adaptation Plan (NAP) for Tuvalu funded by the Green Climate Fund (GCF).

The report follows a standardised, step-wise methodological approach to hazard-based materiality and impact assessments for the Pacific, consistent with guidance materials from the IPCC and associate peer-reviewed literature. This includes an enironmental scan of relevant 'open source' (published and/or otherwise reliablae and accessible) data and information, in-country face-to-face inception meetings and consultations with key stakeholders, and further ancillary engagements with related projects, initiatives and assessments. For the most part the assessment is also based on existing, readily accessible data, information, analytics and metrics from the peer-reviewed literature and/or anecdotal data and information that are otherwise deemed to be scientifically robust and/or otherwise appropriately validated through formal and systematically structured key stakeholder consultation.

The key audience for this report is the Secretariat of the Pacific Environment Program (SPREP), as the designated GCF-Implementation Entity for the Tuvalu NAP project, and the Government of Tuvalu through the mechanism of the Tuvalu NAP Country Team. It is however expected the report also has broader utility for other key stakeholders and users of the data and information as might require technical insights around better understanding and reporting of Tuvalu's current and future climate.

Background

Tuvalu is a Polynesian nation, located between the latitude of 5° and 10° south and longitude of 176° and 180° in the South Pacific Ocean (Figure 1-1). Tuvalu's nearest neighbouring states (more than 1,000 km away) are Kiribati to the north and Fiji to the South, while the nearest major (developed nation) market is New Zealand, 3,500 km away [1]. The relatively small landmass of Tuvalu, alongside its isolated location, scattered population and limited transport services between the outer islands, poses major logistical challenges for local communities and the economy.

Tuvalu consists of five coral atolls (Nanumea, Nui, Nukufetau, Funafuti, Nukulaelae), and three table reef islands (Nanumaga, Niutao, Niulakita) with one composite (coralline atoll/table reef) island (Vaitupu) (Figure 1-1; inset).

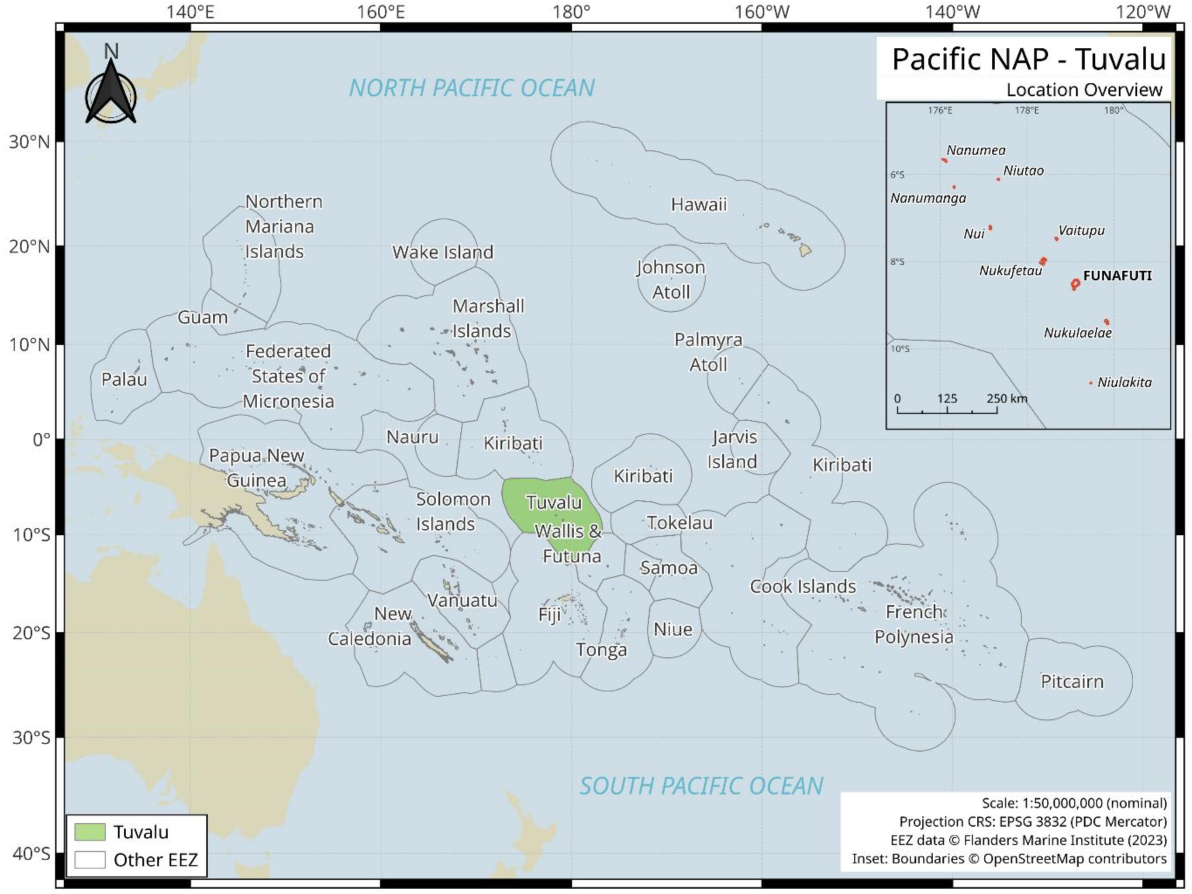


Figure 1-1. Tuvalu Exclusive Economic Zone (green) and the surrounding western tropical Pacific Exclusive Economic Zones (EEZ). Inset shows Tuvalu islands and atolls.

Geomorphology and geography

The country’s nine islands have a landmass of only 25.3 km^2 above mean high water spring (MHWS) [2] in an Exclusive Economic Zone (EEZ) of 749,790 km^2 (Figure 1-2). The islands in most places are less than 75 meters wide, which provides limited space for development. The islands are made up of young, poorly developed, infertile sandy or gravel coralline soil, which is relatively poor quality, so there has been limited agricultural development [1]. All of the islands are extremely low-lying, with the highest natural (non-anthropogenic) elevation being 6.5 m above mean sea level (MSL) on Niulakita and Nanumaga, associated with the ocean-side storm berm landforms of the islands [2].

Fongafale is the largest of Funafuti's islets (Figure 1-2). It is a long narrow sliver of land, 12 kilometres long and between 10 and 400 metres wide, with the South Pacific Ocean and reef on the east and the predominately reef-protected lagoon on the west. Funafuti International Airport runs from northeast to southwest on the widest part of the island, with the village and administrative centre of Vaiaku on the lagoon side. The country’s tide gauge is found on the northern arm of the main atoll, the Tengako peninsula (Figure 1-2).

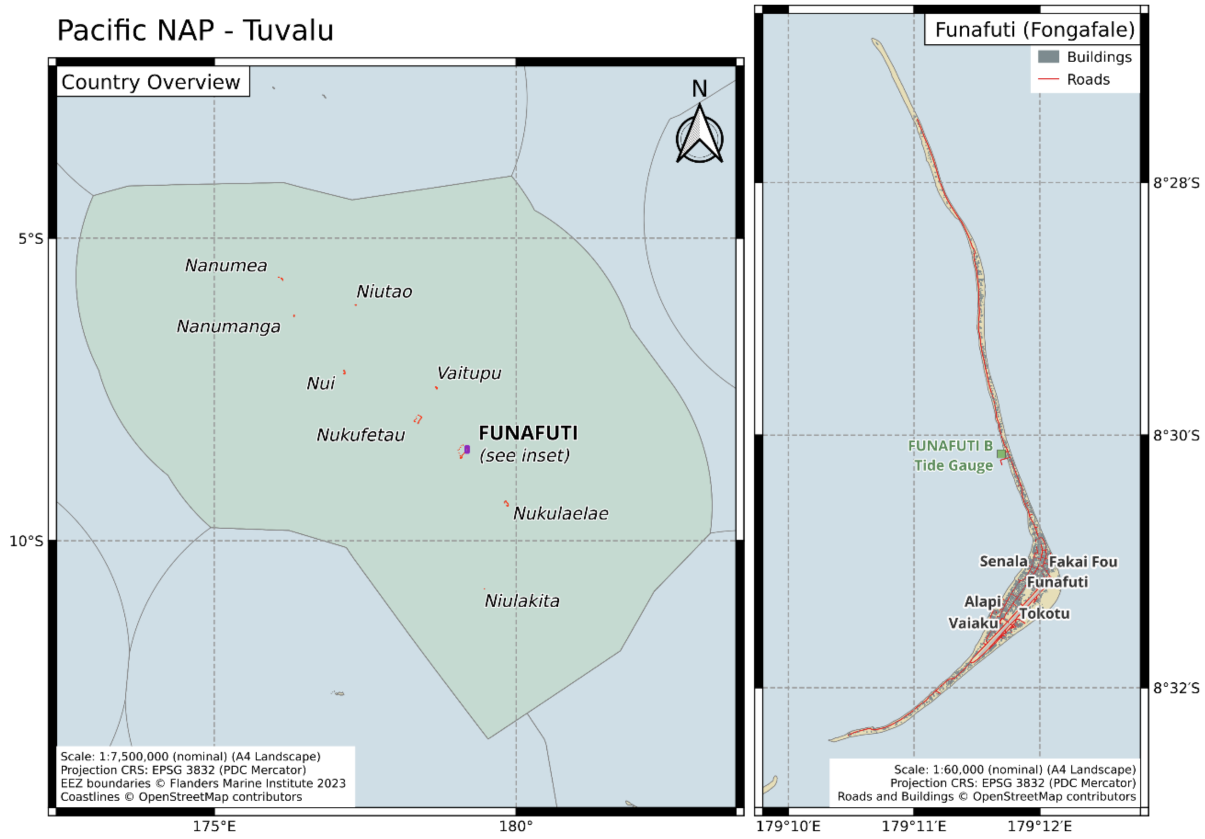


Figure 1-2 Tuvalu islands and atolls, located across the EEZ, with Fongafale Islet of Funafuti shown in the right panel. Funafuti B tide gauge is indicated by green square.

Inter-island transport is already impacted by ongoing maintenance and down-time of boats, plus frequent poor weather making sea transport high risk, at the same time as high demand from communities.

Climate overview

Tuvalu is located within the South Pacific Convergence Zone (SPCZ) and the Intertropical Convergence Zone (ITCZ), both of which are bands of frequent heavy rainfall extending from near the equator (Figure 1-3)[3]. The SPCZ is the dominant influence on the regional weather and climate [4]. In the central tropical Pacific Ocean, easterly winds help to moderate the heat and humidity associated with the warm ocean close to the equator. Contributing to climate variability, three main climate processes operate across the tropical Pacific [3]: the Madden-Julian Oscillation (MJO) [5, 6], El Niño Southern Oscillation (ENSO) [7] and Interdecadal Pacific Oscillation [8]. Extreme weather events such as heatwaves, droughts and floods, resulting from climate variability, can cause considerable economic loss and damage for Tuvalu.

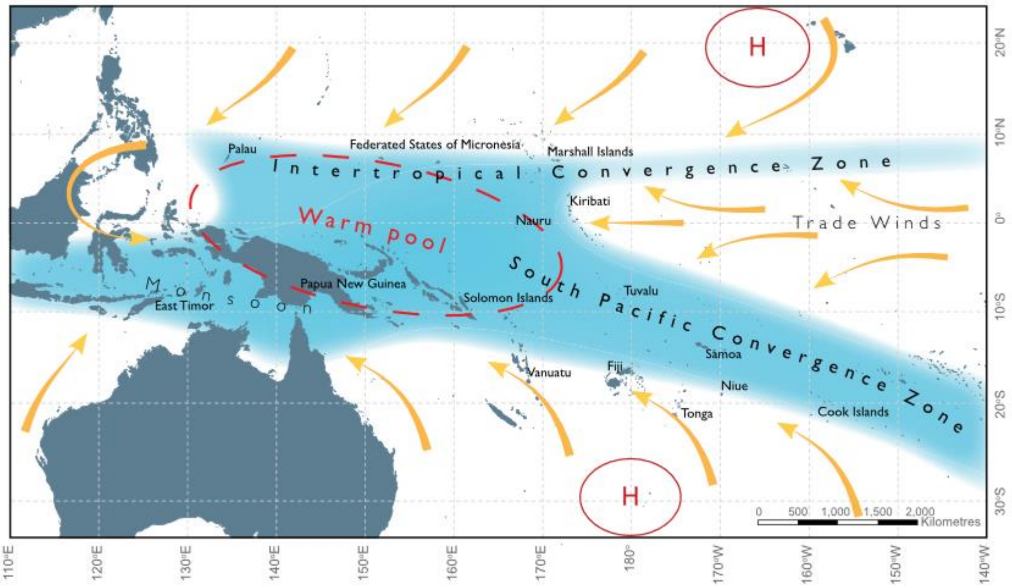


Figure 1-3 Schematic representation of major climatic features and drivers in the western tropical Pacific. The Intertropical Convergence Zone (ITCZ), South Pacific Convergence Zone (SPCZ) and West Pacific Monsoon are characteristic features where convective activities such as tropical cyclones and thunderstorms are frequently spawned. (Source: [3])

Socio-economic status

Tuvalu is a Polynesian island nation located in the Pacific Ocean, midway between Hawaii and Australia, with a population of around 11,500 population in 2024, based on the latest UN estimates [9]. In 2022, the Gross domestic product (GDP) for Tuvalu was nearly US$60 million ([10]. The economy of Tuvalu is constrained by its remoteness and lack of economies of scale. Government revenues largely come from fishing licences [11] and direct grants from international donors (government donors as well as from the Asian Development Bank). Tuvalu has hardly any tourism. It has no tour guides, tour operators or organised activities and no cruise ships visit.

Funafuti atoll is home to around, approximately 60 % of the country's people and is also where the country's hospital, primary school, university campus, radio station, main port, international airport and most businesses and government offices are located [1]. The outer islands are for the most part populated at relatively low density compared to Funafuti, and with reasonably abundant and healthy natural resources, although key infrastructure and services are somewhat limited by comparison. Risks to cultural heritage and social cohesiveness are becoming evident due to a net increase in the population density of Funafuti (returning citizens from abroad plus migration from outer islands).

Fish and fisheries contribute significantly to the economies, livelihoods, food security and income of Pacific Island countries and territories, including Tuvalu [12]. Located in the east of the main equatorial tuna fishing grounds, Tuvalu's EEZ supports substantial purse seine and longline fisheries [1]. Tuvalu's economy has been termed 'tuna-dependent' with tuna access fees being US$25.6 million per year, equivalent to 54 % of government revenue [11]. Longline and pole-and-line fishing also occurs, making relatively minor contributions to these economies compared with purse-seine fishing [11]. The value of fishery production in Tuvalu increased between 2007 and 2014 [12] (Figure 1-4). In the five countries that gained the most over the period (Tokelau, Cook Islands, Kiribati, Tuvalu, and Nauru), this was largely due to an "El Niño bonus". In the five that declined the most, the reasons were more diverse and include the decline of locally based longlining (American Samoa, Samoa), the decline of pearl farming (French Polynesia), and an "El Niño penalty" (Solomon Islands) [12].

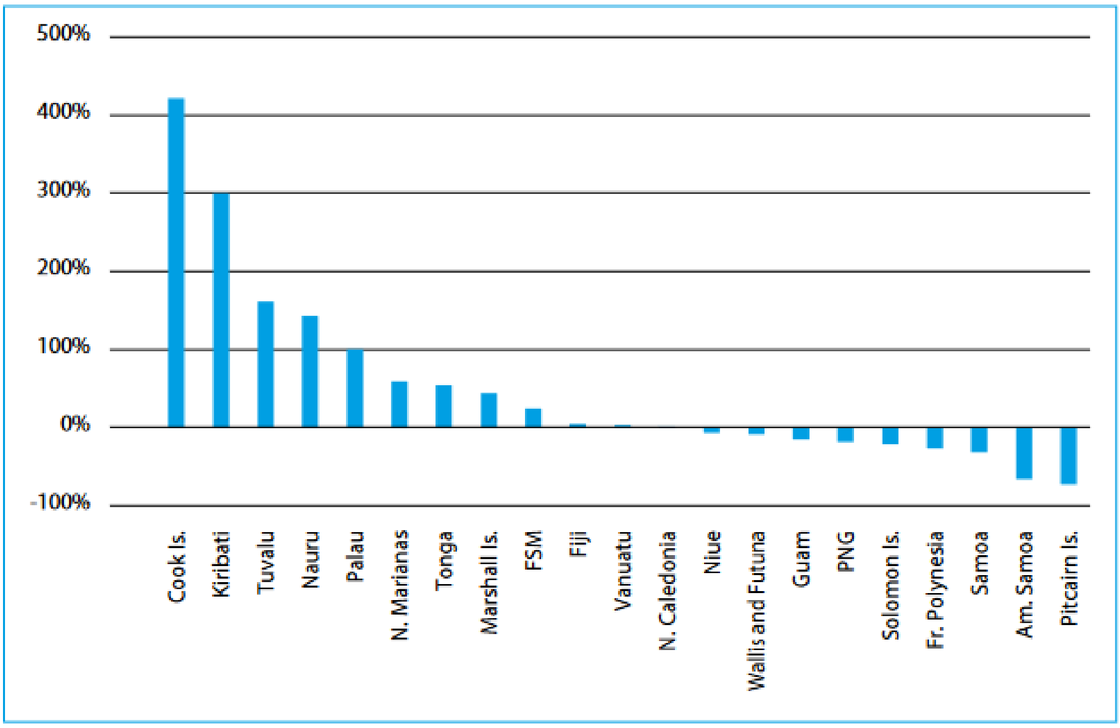


Figure 1-4 Changes in the Real Value of Fisheries and Aquaculture Production, 2007–2014 (Source [12]).

Coastal subsistence and commercial fisheries also contribute to the food security, livelihoods and cultures of Pacific Island countries and territories. Approximately 75% of households in Tuvalu participate in some kind of fishing, with the vast majority undertaking subsistence fishing (FAO, 2024). As of 2014, the production volume of coastal subsidence fisheries (1,135 t; USD$1,120,287) was greater than coastal commercial fisheries (300 t; USD$747 851). A 2016 report compared fish consumption across 16 Pacific Island countries and Territories, indicating Tuvalu has the highest annual per capita fish consumption after Kiribati and Tokelau [12], with this largely sourced from subsistence fisheries [13]. For those engaged in subsistence fishing, men mostly fish from canoes or boats while women glean and collect on reef flats [14].

According to the World Bank and ADB (2021) [15], Tuvalu's biodiversity faces extreme pressure, with loss of some fish, coral, bird and terrestrial species. Tuvalu relies heavily on subsistence agriculture and fisheries, however agricultural productivity is limited due to land availability and over-fishing in various locations. Having a high dependence on these natural resources, which are exposed to climate change impacts, threatens food and water security and economic livelihoods. This exposure is further exacerbated by limited ecological, socio-economic and technological capacities [16].

Tuvalu's agricultural sector is characterized by a harsh physical environment, poor soil quality and small land area. This is intensified by very high population density, especially on the island of Funafuti, declining outer island population, lack of interest in traditional farming and limited local market access [1].

There is a long-term threat from increasing frequency and magnitude of coastal inundation and storm-surge/wave-driven flooding due to projected sea level rise (SLR). 'Climate' migration of some local communities has already occurred, with permanent relocation to higher ground within and beyond Tuvalu. Anthropogenic sea-level rise (SLR) is predicted to impact, and, in many cases, displace, a large proportion of the population via inundation and heightened SLR-related hazards.

With the global coastal population projected to surpass one billion people this century, SLR might be among the most costly and permanent future consequences of climate change [17]. This climate-exposed population is being problematically positioned to speak for an entire planet under threat [18]. Geographic isolation and economic vulnerabilities, including dependence on foreign aid (e.g. the proposed UNFCCC loss and damage fund), exacerbates the challenges faced by communities, who will need increasing support to adapt to the changing climate.

As a remote and import-dependent nation, Tuvalu's competitiveness is restricted. As international air service is limited, shipping is crucial for Tuvalu's economic and social development. In the absence of domestic air services, Tuvalu relies solely on inter-island vessels for the movement of its people and goods around the nine Islands and connecting people with the key social services available in Funafuti. The government-owned and operated ships service the outer islands and intermittently Fiji. Therefore, each island has access to these ships once in 2-3 weeks. The costs associated with shipping services and maintaining the conditions of the vessels has been a major expenditure outlay for the national budget [1].

The runway of Funafuti International Airport (FUN) is located at the widest part of Fongafale (about 650m), covers around one third of the whole island, and plays a key role in connecting Tuvalu to the region. Unlike most other Pacific Island Countries, which predominantly rely on their airports for bringing tourists into their countries, FUN is Tuvalu's strategic lifeline. Tourism accounts for roughly half of all arrivals, however, given the shortage of work opportunities in Tuvalu there is a significant migrant work culture reliant on air-services to reach work destinations. Travel for education, health and family connections are also common [1].

Access to infrastructure such as water tanks has been inequitable in the past [19]. Housing structures lack functioning gutters and pipes to channel the water into the water tanks. On Funafuti, where average household size is larger than the outer islands, water shortage becomes a major issue as there is not enough water tanks per household nor is there any physical space to put additional tanks onsite (K. Morioka Pers. Comm). Projects aimed at increasing water capacity are being initiated to repair water tanks as shown in the photograph [16]. Through this initiative, the tanks have been installed at nurseries, near home gardens, a clinic, village halls, and schools in Nanumea, where storage capacity has been increased by 400 m^3.

According to a 2020 report, [20] there are only two Reverse Osmosis (RO) desalination plants that are fully operational - one $10m^3$/day plant and one $100m^3$/day plant. These plants are insufficient to meet the water demand of the country. One of the two plants is portable and can be deployed to outer islands in case of drought or in water emergency crisis. However, this is inadequate to supply freshwater to the nine islands. As of 2020, there was a new $300m^3$/day RO unit purchased by the Government of Tuvalu and stored in Funafuti waiting to be installed. The installation is pending technical assistance from the RO supplier, Suez Company. Once this assistance is acquired, installation of the unit was planned to commence in Funafuti. In the past, two smaller plants were also installed in other parts of the group, Vaitupu and Nanumaga (both 30 m^3/d). Recent reporting by the Public Works Department (PWD) recommends a new $20m^3$/day desalination plant [20].

Tuvalu's Renewable Energy Master Plan 2012-2020 articulates Government's vision to enhance energy security by reducing its dependence on imported fuel for power generation and achieving 100 percent renewable energy for all its power generation by the end of 2020 and increase energy efficiency in Funafuti by 30 percent [1].

Recent national initiatives

Two recent donor-funded national initiatives, Tuvalu completed an integrated vulnerability analysis (IVA) have provided highly relevant data, information and both sectoral and local community insights for informing this assessment:

Tuvalu IVA (TIVA):

In 2018-2021, Tuvalu completed an IVA for all nine islands [21]. The initial phase of the IVA was supported by the Global NAP Network via the International Institute for Sustainable Development. Drawing on the IVA framework for atoll islands, the Tuvalu IVA (TIVA; https://www.tuvaluiva.com/) is based on a sustainable livelihoods approach that combines the assessment of vulnerability to both climate change and disasters. Vulnerability was identified and assessed across seven human security sectors and five livelihood assets, producing a total of 35 intersecting components.

The aggregation of the sub-national-level TIVA data provides a broad national picture of vulnerability, including:

- Vulnerability issues vary considerably between islands, localities and groups (men, women and youths).
- The most frequently cited vulnerability issues were: inadequate household water tank capacity, declining/retreating shoreline due to coastal erosion, limited to no access to adequately sized and safely located evaluation centre that is safe from storm surge and cyclones and declining inshore marine food source quantity yield (fisheries and invertebrates).
- Nearly all of the islands expressed concerns about the need for long-term coastal protection measures that are fit-for-purpose, durable and appropriate for local conditions.
- Majority of the islands identified the need for greater financial support from the national government to fund adaptation and resilience building initiatives.
- Underlying social, economic and environmental issues, such as lack of basic income and housing, and inadequate waste management services, emerged as ongoing challenges for some islands. If these issues are not addressed, they may exacerbate the community's vulnerability to climate hazards and impacts.

Emerging themes from the focus group discussions were:

- The need for greater community awareness of available government services and funding opportunities for climate change adaptation.
- The need for better policy planning and coordination to manage environmental resources to address issues such as overfishing, pollution and sand extraction.
- The importance of providing social protection for households on low incomes to address inequity issues.
- The need for investments in scientific and technical research to assess the appropriateness and feasibility of long-term adaptation strategies.

Tuvalu Coastal Adaptation Project (TCAP):

TCAP (https://opm.gem.spc.int/tcap/home) [22] offers highly interactive access to key national-scale datasets including high resolution Digital Elevation Models (DEMs), inundation hazard and risk products as well as shoreline change layers and high-resolution imageries spanning over the last half a century. Tuvalu's increased risk to coastal inundation is highlighted, with the knowledge providing decision makers with ready-made risk products to support the development of short- to long-term effective adaptation strategies. This open-source dashboard is designed as a living platform enabling the integration of new datasets by government [22].

It follows this hazard assessment for the Tuvalu NAP CIVRA project leverages substantially off the outcomes of these two key initiatives, particularly in terms of i) the current vulnerability and associated adaptative capacity of local communities to the physical hazards and impacts of climate change (TIVA) and ii) the hazards and impacts from sea level rise, extreme sea levels and coastal inundation (TCAP).

Scope of this climate hazard assessment

This report is divided into 2 sections:

- Section 1 - Tuvalu's climate, climate trends and projections: The first section includes some background information about the data that was sourced in production of this report, and the confidence and limitations that is understood around climate projections. Chapter 3 through to Chapter 11 describe Tuvalu's average temperature, extreme temperature, average rainfall, extreme rainfall, drought, wind, sea level rise, ocean warming and ocean acidification.
- Section 2 - Observed and projected sectoral impacts: presents sectoral impacts associated with different hazards under both current and future climate conditions. Hazard prioritisation is covered in Chapter 13 and knowledge gaps and research priorities are noted in Chapter 14, followed by a glossary (Chapter 15).

As previously stated, this assessment is focussed on the materiality of climate hazards impacting six priority sectors for the Tuvalu NAP both now and into the future: fisheries, agriculture, coastal development and infrastructure, health, water and disaster risk management. For the purposes of this assessment infrastructure includes transport, waste management, energy, telecommunications and associated systematic interdependencies. In practice there can be cascading and compounding impacts across multiple interdependent sectors and systems, and these interdependencies and related impacts are material to the risks informing the design and priorities of the NAP. For example, a storm causing extreme winds, sea swell and heavy rain during a high tide can cause major damage and disruption to critical infrastructure such as transport, energy and telecommunications. This in turn has consequences for coastal communities, agriculture, health and disaster risk management. The level of impact also depends on local exposure and vulnerability (see Chapter 3 on Data and Methods for a discussion of compound hazards).

While Traditional Knowledge (TK) is considered an important additional line of evidence to inform climate change risk and adaptation planning in Tuvalu (e.g. several outer islands having 'Special Protected Areas' (marine reserves) that have local community adoption of sustainably managed traditional fishing methods), a detailed analysis of TK is out of scope for this report.

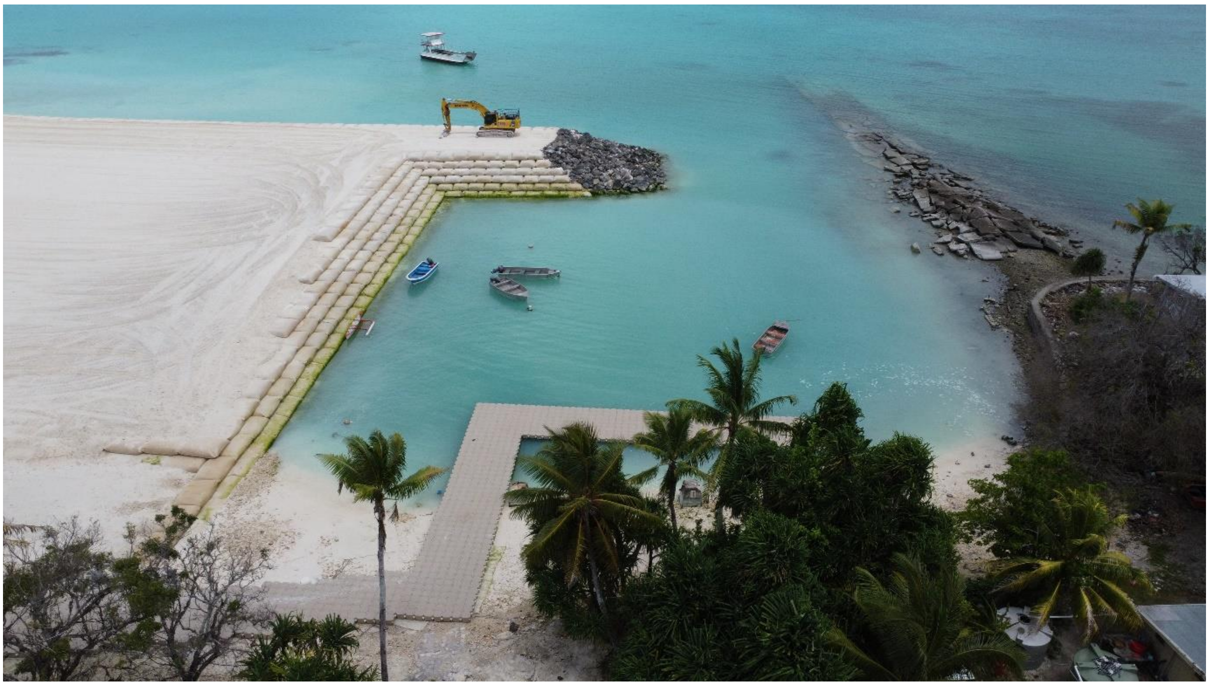
References

1. Government of Tuvalu, *Tuvalu: Follow-up of the Implementation of the Instanbul Programme of Action for the Least Developed Countries* 2019; Available from: https://www.un.org/ldc5/sites/www.un.org.ldc5/files/tuvalu_instanbul_report_post_dcc_191219revise.pdf.
2. Wandres, M., A. Espejo, T. Sovea, S. Tetoa, F. Malologa, A. Webb, J. Lewis, G. Lee, and H. Damlamian, A national ‐ scale coastal flood hazard assessment for the atoll nation of Tuvalu. *Earth's Future,* 2024. 12(4): p. e2023EF003924.

3. Chand, S., S. Power, K. Walsh, and Coauthors, Climate processes and drivers in the Pacific and global warming: a review for informing Pacific planning agencies. *Climatic Change,* 2023. 176(5) DOI: 10.1007/s10584-022-03467-z.
4. Brown, J.R., M. Lengaigne, B.R. Lintner, M.J. Widlansky, K.v.d. Wiel, C. Dutheil, B.K. Linsley, A.J. Matthews, and J. Renwick, South Pacific Convergence Zone dynamics, variability and impacts in a changing climate. *Nat. Rev. Earth Environ.,* 2020. 1: p. 530–543 DOI: 10.1038/s43017-020-0078-2.
5. Madden, R.A. and P.R. Julian, Description of global-scale circulation cells in the tropics with a 40-50 day period. *Journal of the Atmospheric Sciences,* 1972. 29(6): p. 1109-1123.
6. Zhang, C., Madden‐julian oscillation. *Reviews of Geophysics,* 2005. 43(2).
7. Trenberth, K.E., *ENSO in the Global Climate System* Ch *Chapter 1* in *El Niño Southern Oscillation in a Changing Climate*, M.J. McPhaden, A. Santoso, and W. Cai, Editors. 2020, American Geophysical Union p. 21-37.
8. Power, S., T. Casey, C. Folland, A. Colman, and V. Mehta, Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics,* 1999. 15(5): p. 319-324 DOI: 10.1007/s003820050284.
9. Worldometer, *Tuvalu population*. 2024 Elaboration of data by United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects: The 2022 Revision. ; Available from: www.Worldometers.info.
10. World Bank Group, *GDP (current US$)- Tuvalu*. 2024; Available from: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=TV.
11. Bell, J.D., I. Senina, T. Adams, O. Aumont, B. Calmettes, S. Clark, M. Dessert, M. Gehlen, T. Gorgues, and J. Hampton, Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature sustainability,* 2021. 4(10): p. 900-910.
12. Gillett, R., *Fisheries in the economies of the Pacific island countries and territories*. 2016 Pacific Community (SPC); Available from: https://www.spc.int/sites/default/files/wordpresscontent/wp-content/uploads/2016/11/Gillett_16_Benefish-fisheries-in-economies-of-pacific-countries.pdf
13. Bell, J.D., M. Kronen, A. Vunisea, W.J. Nash, G. Keeble, A. Demmke, S. Pontifex, and S. Andréfouët, Planning the use of fish for food security in the Pacific. *Marine Policy,* 2009. 33(1): p. 64-76.
14. FAO, *Fishery and Aquaculture Country Profiles. Tuvalu, 2014. Country Profile Fact Sheets. Updated Apr 10, 2018* Accessed 2024: Rome; Available from: https://www.fao.org/fishery/en/facp/tuv?lang=en.
15. World Bank and ADB *Tuvalu Country Risk Profile. The World Bank Group and the Asian Development Bank.* 2021; Available from: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/511991468183560800/tuvalu-country-risk-profile.
16. Nyman, N., *Mid-term Evaluation of the Tuvalu NAPA-1 and NAPA-1+ Project. Annex VIII – Evaluation Report of the Baseline Project*. 2013 GREEN CLIMATE FUND FUNDING PROPOSAL; Available from: https://www.adaptation-undp.org/sites/default/files/resources/evalutation_report_of_the_baseline_project_0.pdf
17. Hauer, M.E., E. Fussell, V. Mueller, M. Burkett, M. Call, K. Abel, R. McLeman, and D. Wrathall, Sea-level rise and human migration. *Nature Reviews Earth Environment,* 2020. 1(1): p. 28-39.
18. Farbotko, C. and H. Lazrus, The first climate refugees? Contesting global narratives of climate change in Tuvalu. *Global Environmental Change,* 2012. 22(2): p. 382-390 DOI: https://doi.org/10.1016/j.gloenvcha.2011.11.014.
19. Baarsch, F. and L.M.N. Berg, The Significance of contextual vulnerability in effective adaptation to Climate Change on Tuvalu. *Climate Change in the Asia-Pacific Region,* 2015: p. 301-317.

20. Government of Tuvalu and Pacific Community (SPC), *ASSESSMENT REPORT: EXISTING DESALINATION UNITS IN TUVALU*. 2020 Pacific Community (SPC); Available from: http://ccprojects.gsd.spc.int/wp-content/uploads/2021/03/Assessment-on-all-existing-RO-Plants-in-Tuvalu-Final.pdf
21. Government of Tuvalu, *Tuvalu Integrated Vulnerability Assessment Report – Funafuti community, Funafuti. Government of Tuvalu and NAP Global Network/International Institute for Sustainable Development (IISD).* 2020; Available from: https://napglobalnetwork.org/wp-content/uploads/2021/01/napgn-en-2020-Tuvalu-IVA-report-Amatuku-Islet.pdf.
22. SPC, *Tuvalu Coastal Adaptation Project*. 2023; Available from: https://opm.gem.spc.int/tcap/risk.

Section 1 TUVALU’S CLIMATE, CLIMATE TRENDS AND PROJECTIONS



Chapter 2 Data, confidence, limitations and uncertainties around climate projections

Data

Each climate variable is assessed separately. The variables are average temperature, extreme temperature, average rainfall, extreme rainfall, drought, tropical cyclones and extreme wind, sea level rise and coastal inundation, ocean warming, and ocean acidification.

The average climate, recent trends, variability and future projections are presented. Projections are calculated for 20-years centred on 2030 and 20-years centred on 2050. In most cases, the projections are presented as changes relative to a historical reference period, e.g. 1986-2005 (used in the IPCC 5th Assessment Report) or 1995-2014 (used in the IPCC 6th Assessment Report).

Historical climate data

For assessment of historical temperature in the Tuvalu region, we use five global observed datasets: HadCRUT5 (1850–2020; [1]), Berkeley Earth (1850–2019; [2]), NOAA GlobalTemp (1880–2019; [3]), Cowtan and Way (1850–2019;[4]) and GISTEMP (1880–2019; [5]).

For rainfall, we use the CMAP and GPCP gridded gauge-satellite monthly precipitation datasets available from 1979 [6] and ERA5 grided reanalysis rainfall data from 1979-2020 ([7]). For drought, ERA5 rainfall data are bias-corrected using data from nearby climate stations.

For sea surface temperature we use OISST v2.1 [8].

For tropical cyclones we use IBTrACS; [9] and ERA5 reanalysis wind data [7] verified by the TAO and TRITON buoy network [10].

Gridded datasets use records from weather stations, satellite data and other sources, then fill in any gaps in space and time using data interpolation methods. Therefore, the changes and trends from these gridded datasets generally agree with those from the underlying weather stations (see [11]) but are not exactly the same. Early periods include fewer weather observations with fewer supplementary data sources to draw upon, so these rely more heavily on interpolation across time and space and are therefore less reliable.

Future climate data

Ongoing increases in greenhouse gases will lead to further global warming and regional climate change. There are three main sources of uncertainty in regional climate projections:

1. Greenhouse gas emissions and atmospheric concentration pathways, based on assumptions about socio-economic change, technological change, energy and land use.
2. Regional climate responses to a given concentration pathway, based on computer simulations from climate models.
3. Natural climate variability due to local weather systems and large-scale processes such as the El Niño Southern Oscillation.

The main greenhouse gases are water vapour, carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs). Future greenhouse gas emissions pathways range from low to high. These pathways are used in carbon cycle models to estimate atmospheric greenhouse gas concentrations, after allowing for uptake by the oceans and land. Representative Concentration Pathways (RCPs) used in the IPCC Fifth Assessment Report are shown in Figure 2-1. These are often termed low (RCP2.6), medium (RCP4.5), medium-high (RCP6.0), and high (RCP8.5) pathways. An updated set of Shared Socio-economic Pathways (SSPs) were used in the IPCC Sixth Assessment Report: low (SSP1-2.6), medium (SSP2-4.5), medium-high (SSP3-7.0), and high (SSP5-8.5).

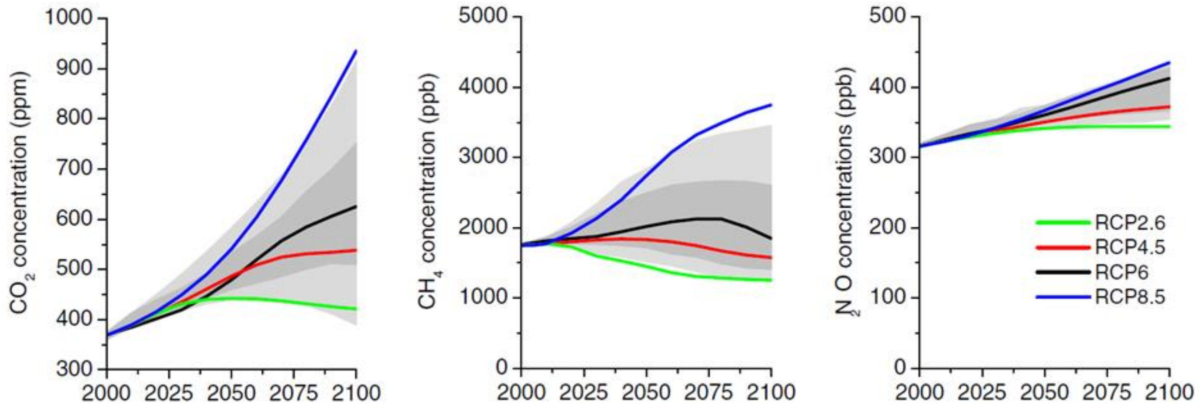


Figure 2-1: Greenhouse gas concentration pathways used in the IPCC Fifth Assessment Report. The gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Grey area indicates the 98th and 90th percentiles (light/dark grey). Source: van Vuuren et al (2012).

RCPs can be compared in terms of CO_2 concentrations and global warming by the end of the century:

- RCP2.6 is a low pathway where emissions peak and decline substantially before 2030, with the CO_2 concentration reaching about 420 parts per million (ppm) by 2100[1]. This ambitious pathway requires rapid global decarbonisation, leading to a global warming of 0.9 to 2.4 °C by 2081–2100 relative to the pre-industrial period 1850-1900 [12].
- RCP4.5 is a medium pathway where emissions peak in 2040 and then decline, with the CO_2 concentration reaching 540 ppm by 2100, leading to a global warming of 1.7 to 3.3 °C by 2081–2100 [12].
- RCP6.0 is a medium-high pathway, with the CO_2 concentration reaching about 620 ppm by 2100, leading to a global warming of 2.0 to 3.8 °C by 2081–2100 [12].
- RCP8.5 is a high pathway assuming limited implementation of current policies, with the CO_2 concentration reaching about 940 ppm by 2100, leading to global warming of 3.2 to 5.4 °C by 2081–2100 [12].

Current global emissions reduction policies are projected to lead to a global warming of 2.1°C–3.9°C by 2100 [13]. Another estimate suggests current policies might lead to a global warming of 2.2-3.4 °C by 2100 [14]. CO_2 emissions growth rates most consistent with observations from 2005 to 2020 and data from the International Energy Agency might cause a global warming of 2-3 °C by 2100 [15]. Each of these global warming estimates is similar to the RCP4.5 pathway.

The SSPs are like the RCPs in many ways, but with some small differences such as a different starting point, evolution through time, and mix of gases. The socio-economic assumptions have been summarised as: Sustainability (SSP1), Middle of the Road (SSP2), Regional Rivalry (SSP3), Inequality (SSP4) and Fossil-fuelled Development (SSP5). The SSPs have similar global warming ranges to the relevant RCPs by 2081-2100. SSP1-2.6 is 1.3-2.4 °C, SSP2-4.5 is 2.1-3.5 °C, SSP3-7.0 is 2.8-4.6 °C and SSP5-8.5 is 3.3-5.7 °C [16].

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[1] As of February 2023 CO_2 concentration measured at Manua Loa (NOAA) was reported as 420.3 ppm (https://www.co2.earth/)

Regional climate responses for each pathway have been simulated by global climate models (GCMs). These models represent the climate system in mathematical equations, based on the laws of physics, that are solved on powerful supercomputers. Data are generated for hundreds of climate variables, over hundreds of years, over thousands of points on a grid covering the globe. Each GCM uses slightly different methods for representing key climate features and processes, such as cloud feedback, ice feedback, carbon cycle feedback, convection, and atmospheric chemistry. Different models have different sensitivity to changes in greenhouse gases. Therefore, each GCM has a unique simulation of past and future climates.

This report mostly uses data from the Coupled Model Inter-comparison Project phase 5 (CMIP5) [17] involving 21 climate models for RCP8.5 and RCP4.5, and 17 models for RCP2.6, that have passed evaluation tests [18]. Limited model simulations for RCP6.0 were not used. For some climate variables (extreme temperature, extreme rainfall, extreme windspeed, marine heatwaves and ocean acidification), data from the Coupled Model Inter-comparison Project phase 6 (CMIP6) [19] were used, involving a smaller set of available simulations for SSP1-2.6 and, SSP3-7.0 and SSP5-8.5.

Natural climate variability in space and time is captured in all climate simulations. This includes daily weather variability through to monthly, yearly and decadal variability. Maps and time-series graphs are used to visualise historical and future variability, and statistics are used to quantify variability such as the 10-90 percentile range.

Confidence

Confidence ratings are based on the amount/type of evidence and the level of agreement between lines of evidence, consistent with IPCC guidance [20]. For example, when there is limited evidence and low agreement, the confidence rating is low. In contrast, when there is robust evidence and high agreement, the confidence rating is high (Figure 2-2). For each climate variable in this report, a confidence rating is provided for projected changes, e.g. temperature and sea level projections have high confidence, rainfall projections have medium confidence, and extreme windspeed projections have low confidence.

Confidence ratings may be improved over time through ongoing investment in climate research and innovation, e.g. field measurements, understanding weather/climate processes, reducing climate model biases, finer resolution in dynamical downscaling, and better simulation of extreme weather events.

	Limited evidence	Medium evidence	Robust evidence
Low agreement	Low confidence	Low-medium confidence	Medium confidence
Medium agreement	Low-medium confidence	Medium confidence	Medium-high confidence
High agreement	Medium confidence	Medium-high confidence	High confidence

Figure 2-2 A depiction of evidence and agreement statements and their relationship to confidence. Confidence increases towards the bottom-right corner as suggested by the increasing strength of shading. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence [20].

Limitations of climate models

GCMs have coarse resolution (about 200 km between data points) and can provide useful climate projections over the coming decades at broad scales, e.g. estimates of global warming. Dynamical downscaling involves running a Regional Climate Model (RCM) with finer resolution (10–50 km between data points) over a specific region, rather than over the whole globe. This generally gives better representation of regional weather and climate phenomena, especially over complex terrain such as mountains and coastlines. However, some local weather phenomena such as land-sea breezes, mountain winds, cold fronts and extreme rainfall require a resolution of less than 10 km. This is an active area of research. Another limitation of dynamical downscaling is that the RCM is driven at its boundary by information from a GCM, so the RCM will inherit any biases in the broad-scale climate simulated by the GCM, e.g. too hot/cold or too wet/dry. Therefore, GCMs with small biases are usually chosen for downscaling.

Since dynamically downscaled climate simulations still have biases, statistical downscaling methods are often used to reduce these biases and provide data that have local relevance. The statistical methods range from simple to complex and usually require expert guidance. The numerical precision of these downscaled data should not be confused with accuracy; the downscaled data are plausible, rather than precise.

Uncertainties

As noted above, there are three sources of uncertainty in climate projections: (1) emissions pathways, (2) regional climate responses to a given emissions pathway, and (3) natural climate variability. The range of uncertainty due to each of these factors should be quantified for a particular climate variable.

The uncertainty due to emissions pathways is small prior to 2040, so regional climate projections for the low and high pathways are similar. After 2040, the pathways increasingly diverge so regional climate projections for the low and high pathways become distinctly different. Quantifying the impact of different pathways is policy-relevant, i.e. emission reductions can slow climate change and constrain the impacts.

The uncertainty due to different regional climate responses from up to 50 climate models is usually expressed as a range. The IPCC and research organisations typically provide a 10-90 percentile range or a 5-95 percentile range for each climate variable, e.g. a warming of 2.1-3.5 °C or a rainfall change of –10 to +5 %. Uncertainty in the magnitude and direction of change can be influenced by the number and quality of climate models analysed. A small sample of models (less than 10) and/or inclusion of low-quality models may skew the uncertainty ranges. Best practice favours a large sample of high-quality models. Uncertainty in the direction of change is larger for some climate variables than others. For example, there is low uncertainty regarding the increase in temperature and sea level, but high uncertainty regarding the direction of change in rainfall. The high uncertainty in rainfall affects other variables such as drought and soil moisture.

Natural variability is a major contributor to uncertainties at regional and local scales, especially over the next decade [21]. Figure 2-3 shows that natural variability over the next decade can enhance or offset the long-term trend in annual temperature over Tuvalu. Therefore, historical climate trends over recent decades may be the best choice to inform climate trends for the next decade [22]. Climate model simulations can inform trends beyond the next decade.

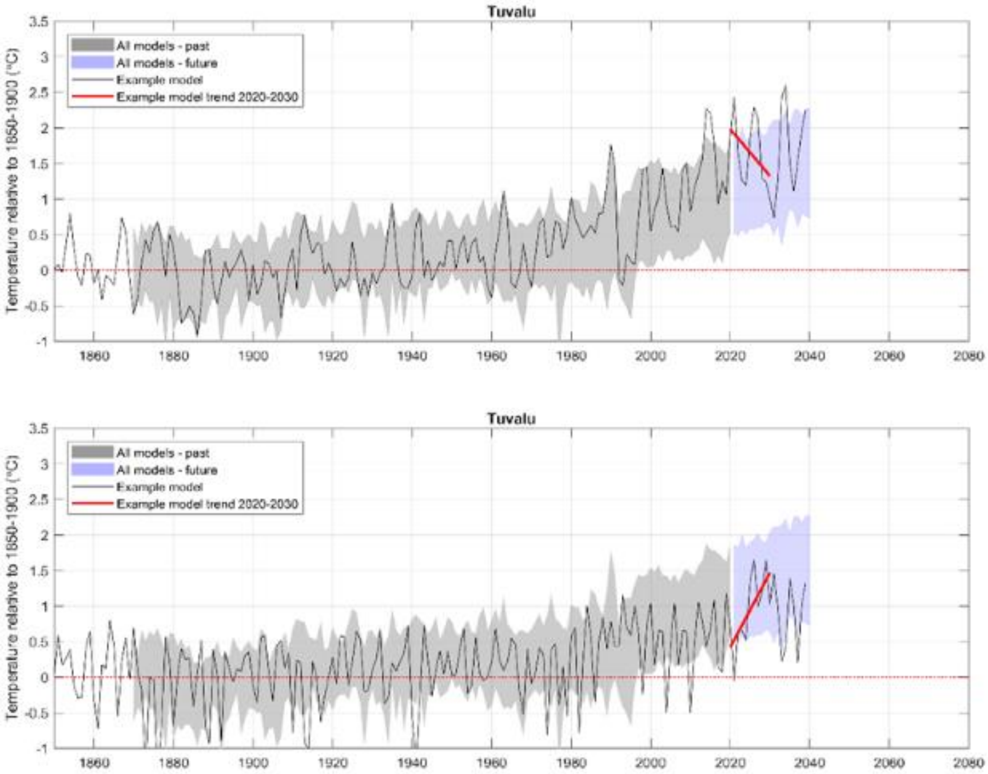

Figure 2-3 Average annual temperature in Tuvalu relative to 1850-1900 (°C) simulated in CMIP5 models, showing the range of all climate models (historical; grey band, future; blue band) and example model simulations (black line) with the linear trend for 2020-2030 marked (red line); top: an example with suppressed warming in 2020-2030 due to climate variability, bottom: an example with enhanced the warming in 2020-2030 due to climate variability [21].

Caveats[2]

ENSO

Changes in the zonal gradients of sea surface temperature (SST) across the equatorial Pacific have major consequences for global climate [23]. It is important to note that there is a large degree of inconsistency among climate models on some aspects of future projections, as well as biases (e.g. [24-27]). For example, observational records appear to show a 'La Niña-like' strengthening of the zonal SST gradient since the 1950's [23] whereas most climate model simulations project 'El Niño-like' changes toward a weaker gradient, which becomes more pronounced in the projections [23, 27], and the discrepancy between modelled and observed trends persists in the latest CMIP6 model simulations [28, 29] as well as an overestimation of ENSO variability [30]. Therefore, caution must be exercised when interpreting climate change projections. Future projections from these models are often used to plan climate mitigation and adaptation at regional scales, which will depend on the future state of the tropical Pacific. Therefore, it is critical to consider the plausible range of future tropical Pacific climate changes using models, observations, and theories, and to understand the broader implications of these changes [23].

Regardless, there is a strong consensus that ENSO variability will continue to dominate regional-scale climate in the future [31, 32], and strongly influence weather-related variables such as drought and rainfall (e.g. [32-34].

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[2] Also see chapter discussions around caveats: Tropical Cyclones and wind, Drought, Sea level rise and coastal inundation, and Ocean warming

Extreme weather events

Extreme weather and climate events often cause major impacts. Projections for some extreme events have low or medium confidence, but high relevance for impact assessment. For adaptation planning, decisions may need to be made in the absence of high confidence projections. To manage expectations and legal liability, it is important that confidence ratings and uncertainties are effectively communicated.

Compound events

The greatest impacts often occur when multiple hazards, exposures and vulnerabilities coincide or occur in close succession, resulting in severe impacts for communities, economies, and ecosystems [35, 36]. These are called compound events [37-39], but they are difficult to quantify routinely within climate projections [40]. Storyline scenarios involving compound events can be used to ''stress test'' systems. For example, a cyclone causing a storm surge, extreme winds and heavy rain during a high tide can cause major damage and disruption. Drought, heatwaves and fires often occur together and cause major damage and disruption. However, the influence of climate change on compound events is a significant knowledge gap and further research is needed [41].

Tipping Points

Parts of the climate system can reach a ‘tipping point’ where change is often abrupt and irreversible on long timescales. Several tipping points may be triggered this century with modest global warming, while others require higher levels of global warming [42]. However, there are deep uncertainties about some of the climate processes that could cause tipping points, e.g. thawing of Boreal permafrost, collapse of the main overturning ocean circulation in the north Atlantic Ocean, and rapid disintegration of the Greenland and Antarctic ice sheets [43]. Further details regarding tipping points and sea level rise are provided in Chapter 9.

References

1. Morice, C.P., J.J. Kennedy, N.A. Rayner, and P.D. Jones, Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *Journal of Geophysical Research: Atmospheres (1984–2012),* 2012. 117(D8).
2. Rohde, R.A. and Z. Hausfather, The Berkeley Earth land/ocean temperature record. *Earth System Science Data Discussions,* 2020. 12(4): p. 3469-3479.
3. Zhang, H., B. Huang, J. Lawrimore, M. Menne, and T. Smith, *NOAA Global Surface Temperature Dataset (NOAAGlobalTemp), Version 5.0. NOAA National Centers for Environmental Information*. 2017.
4. Cowtan, K. and R.G. Way, Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Quarterly Journal of the Royal Meteorological Society,* 2014. 140(683): p. 1935-1944.
5. Lenssen, N.J., G.A. Schmidt, J.E. Hansen, M.J. Menne, A. Persin, R. Ruedy, and D. Zyss, Improvements in the GISTEMP uncertainty model. *Journal of Geophysical Research: Atmospheres,* 2019. 124(12): p. 6307-6326.
6. Yin, X., A. Gruber, and P. Arkin, Comparison of the GPCP and CMAP merged gauge–satellite monthly precipitation products for the period 1979–2001. *Journal of hydrometeorology,* 2004. 5(6): p. 1207-1222.
7. Hersbach, H., B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz ‐ Sabater, J. Nicolas, C. Peubey, R. Radu, and D. Schepers, The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society,* 2020. 146(730): p. 1999-2049.
8. Huang, B., C. Liu, V. Banzon, E. Freeman, G. Graham, B. Hankins, T. Smith, and H. Zhang, *NOAA 0.25-degree daily optimum interpolation sea surface temperature (OISST), version 2.1*. 2020; Available from: https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.html

9. Knapp, K.R., M.C. Kruk, D.H. Levinson, H.J. Diamond, and C.J. Neumann, The international best track archive for climate stewardship (IBTrACS) unifying tropical cyclone data. *Bulletin of the American Meteorological Society,* 2010. 91(3): p. 363-376.
10. McPhaden, M.J., K. Ando, B. Bourles, H. Freitag, R. Lumpkin, Y. Masumoto, V. Murty, P. Nobre, M. Ravichandran, and J. Vialard, The global tropical moored buoy array. *Proceedings of OceanObs,* 2010. 9: p. 668-682.
11. McGree, S., N. Herold, L. Alexander, S. Schreider, Y. Kuleshov, E. Ene, S. Finaulahi, K. Inape, B. Mackenzie, and H. Malala, Recent changes in mean and extreme temperature and precipitation in the Western Pacific Islands. *Journal of Climate,* 2019. 32(16): p. 4919-4941.
12. IPCC, *The ocean and cryosphere in a changing climate*. 2019; Available from: https://www.ipcc.ch/srocc/chapter/summary-for-policymakers/.
13. Liu, P.R. and A.E. Raftery, Country-based rate of emissions reductions should increase by 80% beyond nationally determined contributions to meet the 2 C target. *Communications Earth Environment,* 2021. 2(1): p. 29.
14. Climate Action Tracker, *2100 Warming Projections: Emissions and expected warming based on pledges and current policies. December 2023.* 2023 Climate Analytics and NewClimate Institute. All rights reserved.; Available from: https://climateactiontracker.org/global/temperatures/.
15. Pielke Jr, R., M.G. Burgess, and J. Ritchie, Plausible 2005-2050 emissions scenarios project between 2 and 3 degrees C of warming by 2100. *Environmental Research Letters,* 2022.
16. IPCC, ed. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. ed. V. Masson-Delmotte, et al. 2021, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, .
17. Taylor, K.E., R.J. Stouffer, and G.A. Meehl, An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society,* 2012. 93(4): p. 485-498.
18. Grose, M.R., J.N. Brown, S. Narsey, J.R. Brown, B.F. Murphy, C. Langlais, A.S. Gupta, A.F. Moise, and D.B. Irving, Assessment of the CMIP5 global climate model simulations of the western tropical Pacific climate system and comparison to CMIP3. *International Journal of Climatology,* 2014.
19. O'Neill, B.C., C. Tebaldi, D.P. Van Vuuren, V. Eyring, P. Friedlingstein, G. Hurtt, R. Knutti, E. Kriegler, J.-F. Lamarque, and J. Lowe, The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geoscientific Model Development,* 2016. 9(9): p. 3461-3482.
20. Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, and P.R. Matschoss, *Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties*. 2010; Available from: https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf.
21. CSIRO and SPREP, *'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for Tuvalu.* . 2021: Final report to the Australia-Pacific Climate Partnership for the Next Generation Climate Projections for the Western Tropical Pacific project. Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP). Melbourne, Australia; Available from: https://www.rccap.org/uploads/files/909d29f7-7cb7-4618-b58b-3ca889669965/Tuvalu%20Country%20Report%20Final.pdf
22. Fiedler, T., A.J. Pitman, K. Mackenzie, N. Wood, C. Jakob, and S.E. Perkins-Kirkpatrick, Business risk and the emergence of climate analytics. *Nature Climate Change,* 2021. 11(2): p. 87-94.
23. Lee, S., M. L'Heureux, A.T. Wittenberg, R. Seager, P.A. O'Gorman, and N.C. Johnson, On the future zonal contrasts of equatorial Pacific climate: Perspectives from Observations, Simulations, and Theories. *Climate Atmospheric Science,* 2022. 5(1): p. 82.

24. Collins, M., S.-I. An, W. Cai, A. Ganachaud, E. Guilyardi, F.-F. Jin, M. Jochum, M. Lengaigne, S. Power, and A. Timmermann, The impact of global warming on the tropical Pacific Ocean and El Niño. *Nature Geoscience,* 2010. 3(6): p. 391-397.
25. Graham, F.S., A.T. Wittenberg, J.N. Brown, S.J. Marsland, and N.J. Holbrook, Understanding the double peaked El Niño in coupled GCMs. *Climate Dynamics,* 2017. 48(5): p. 2045-2063 DOI: 10.1007/s00382-016-3189-1.
26. Power, S., M. Lengaigne, A. Capotondi, M. Khodri, J. Vialard, B. Jebri, E. Guilyardi, S. McGregor, J.-S. Kug, and M. Newman, Decadal climate variability in the tropical Pacific: Characteristics, causes, predictability, and prospects. *Science Advances,* 2021. 374(6563): p. eaay9165.
27. Erickson, N.E. and C.M. Patricola, Future projections of the El Niño—Southern Oscillation and tropical Pacific mean state in CMIP6. *Journal of Geophysical Research: Atmospheres,* 2023. 128(21): p. e2022JD037563.
28. Seager, R., N. Henderson, and M. Cane, Persistent discrepancies between observed and modeled trends in the tropical Pacific Ocean. *Journal of Climate,* 2022. 35(14): p. 4571-4584.
29. Cai, W., A. Santoso, M. Collins, B. Dewitte, C. Karamperidou, J.-S. Kug, M. Lengaigne, M.J. McPhaden, M.F. Stuecker, and A.S. Taschetto, Changing El Niño–Southern oscillation in a warming climate. *Nature Reviews Earth Environment,* 2021. 2(9): p. 628-644.
30. Grose, M.R., S. Narsey, F. Delage, A.J. Dowdy, M. Bador, G. Boschat, C. Chung, J. Kajtar, S. Rauniyar, and M. Freund, Insights from CMIP6 for Australia's future climate. *Earth's Future,* 2020. 8(5): p. e2019EF001469.
31. Power, S., F. Delage, C. Chung, G. Kociuba, and K. Keay, Robust twenty-first-century projections of El Nino and related precipitation variability. *Nature,* 2013. 502(7472): p. 541-545 DOI: 10.1038/nature12580.
32. McPhaden, M.J., A. Santoso, and W. Cai, *Introduction to El Niño Southern Oscillation in a changing climate* Ch in, E.N.S.O.i.a.c. climate, Editor. 2020, American Geophysical Union. p. 1-19.
33. Stevenson, S., B. Fox-Kemper, M. Jochum, R. Neale, C. Deser, and G. Meehl, Will there be a significant change to El Niño in the twenty-first century? *Journal of Climate,* 2012. 25(6): p. 2129-2145.
34. Iese, V., A.S. Kiem, A. Mariner, P. Malsale, T. Tofaeono, D.G. Kirono, V. Round, C. Heady, R. Tigona, and F. Veisa, Historical and future drought impacts in the Pacific islands and atolls. *Climatic Change,* 2021. 166(1): p. 1-24.
35. Sepúlveda, I., P.L.-F. Liu, M. Grigoriu, J.S. Haase, and P. Winckler, Non-Stationary Probabilistic Tsunami Hazard Assessments Compounding Tides and Sea Level Rise. *Earth's Future,* 2022. 10(11): p. e2022EF002965 DOI: https://doi.org/10.1029/2022EF002965.
36. Li, S., T. Wahl, C. Piecuch, S. Dangendorf, P. Thompson, A. Enríquez, and L. Liu, Compounding of Sea-Level Processes During High-Tide Flooding Along the U.S. Coastline. *Journal of Geophysical Research: Oceans,* 2023. 128(8): p. e2023JC019885 DOI: https://doi.org/10.1029/2023JC019885.
37. Zscheischler, J., S. Westra, B.J. Van Den Hurk, S.I. Seneviratne, P.J. Ward, A. Pitman, A. AghaKouchak, D.N. Bresch, M. Leonard, and T. Wahl, Future climate risk from compound events. *Nature climate change,* 2018. 8(6): p. 469-477.
38. Adade, W.P., B.-F. Lea, B. Robbert, H. Marjolijn, C. Donovan, M.-S.J. Issah, J.E. Tom, N.A. Marshall, S. Salma, and M.A. LS, Adaptation to compound climate risks: A systematic global stocktake. *iScience,* 2023. 26(2).
39. Simpson, N.P., P.A. Williams, K.J. Mach, L. Berrang-Ford, R. Biesbroek, M. Haasnoot, A.C. Segnon, D. Campbell, J.I. Musah-Surugu, and E.T. Joe, Adaptation to compound climate risks: A systematic global stocktake. *Iscience,* 2023. 26(2).
40. Simpson, N.P., K.J. Mach, A. Constable, J. Hess, R. Hogarth, M. Howden, J. Lawrence, R.J. Lempert, V. Muccione, and B. Mackey, A framework for complex climate change risk

assessment. *One Earth,* 2021. 4(4): p. 489-501 DOI: https://doi.org/10.1016/j.oneear.2021.03.005.

41. Ridder, N.N., A.M. Ukkola, A.J. Pitman, and S.E. Perkins-Kirkpatrick, Increased occurrence of high impact compound events under climate change. *npj Climate and Atmospheric Science,* 2022. 5(1): p. 3 DOI: 10.1038/s41612-021-00224-4.
42. Armstrong McKay, D.I., A. Staal, J.F. Abrams, R. Winkelmann, B. Sakschewski, S. Loriani, I. Fetzer, S.E. Cornell, J. Rockström, and T.M. Lenton, Exceeding 1.5 C global warming could trigger multiple climate tipping points. *Science Advances,* 2022. 377(6611): p. eabn7950.
43. CSIRO Workshop Report, *Understanding the risks to Australia from global climate tipping points.* . 2024 CSIRO, Australia.; Available from: file:///C:/Users/web167/Downloads/CSIRO_Tipping-Points-Report.pdf.

Chapter 3 Average Temperature

Introduction

Daily historical air temperature records for Nanumea and Funafuti from 1951 were obtained from the Tuvalu Meteorological Service (Niulakita and Nui weather stations have rainfall records only) [1, 2].

Observed temperature

Air temperatures have a small seasonal cycle in Tuvalu, as recorded at Funafuti and Nanumea, with less than 1 °C change in average monthly maximum and minimum temperatures during the year (Figure 3-1). Monthly-average maximum air temperatures over Tuvalu are around 31 °C while minimum temperatures are around 26 °C (Figure 3-1; left). Except for average minimum temperatures at Nanumea for April and June, there has been a clear shift towards warmer average monthly temperatures between the periods of 1961–1990 and 1991–2020 (Figure 3-1; left). Average annual and seasonal temperatures have increased significantly at Funafuti (Figure 3-1; right). May–October temperatures are warming faster than November–April temperatures.

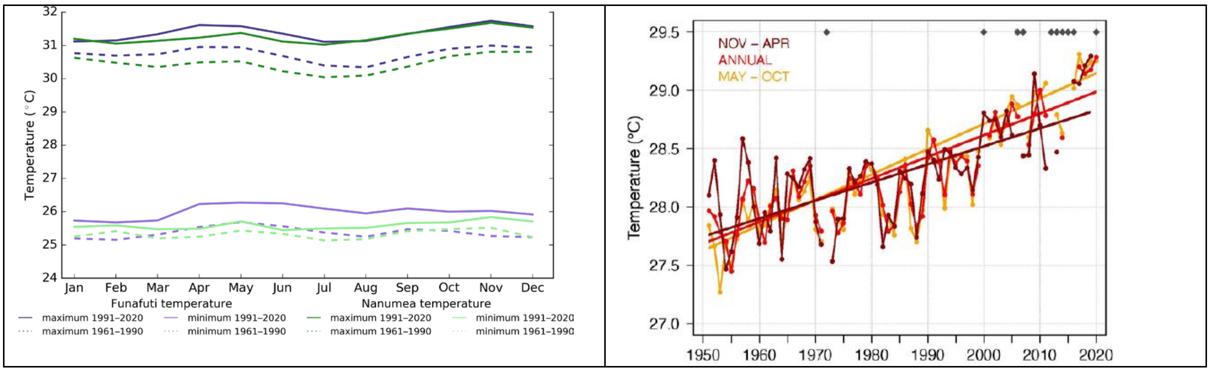


Figure 3-1 Monthly-average maximum and minimum air temperature for Funafuti and Nanumea in Tuvalu, based on data from 1951-2020 (left). Annual November–April and May–October average temperatures for Funafuti. Straight lines indicate linear trends. Diamonds indicate years with insufficient data for one or more variables (right). Source: McGree et al (2022).

The annual-average maximum air temperature has increased 0.17 °C per decade since 1951, while the minimum air temperature has increased 0.21 °C per decade [2].

The cooling degree days index provides a measure of the energy demand needed to cool a building down to 25 °C, with the assumption that air conditioners are generally turned on at this temperature. There has been a very strong increase in the cooling degree index at Funafuti, suggesting the energy needed for cooling has increased significantly since 1951 [2].

El Niño Southern Oscillation and temperature

Being small atoll islands, air temperatures over Tuvalu are strongly linked to the surrounding sea surface temperatures. In El Niño years, minimum air temperatures are typically higher, and conversely, minimum temperatures are typically lower during La Niña years, similarly for maximum air temperatures during the wet season [2].

Projected temperature

Estimates of future climate change are affected by three main sources of uncertainty: (1) greenhouse gas emissions pathways, (2) regional climate responses to each pathway simulated by climate models, and (3) natural climate variability due to factors such as ENSO. Temperature projections for Tuvalu out to 2080 are presented for low (RCP2.6; green) and high (RCP8.5; pink) emissions pathways (Figure 3-2). In the near term (2020-2039) the range of projected temperature change is similar for both emissions pathways, but in the medium term (2040-2059) the pathways begin to separate, and in the long term (2060-2079) the pathways give very different outcomes. The combined range of uncertainty is given by the blue arrow in Figure 3-2. The regional climate response for high emissions (pink arrow) and low emissions (green arrow) includes the range of natural climate variability (black arrow).

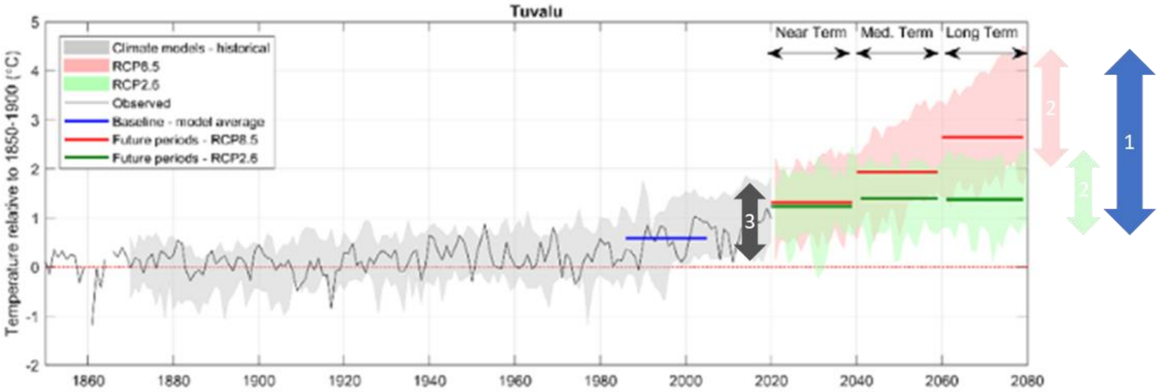
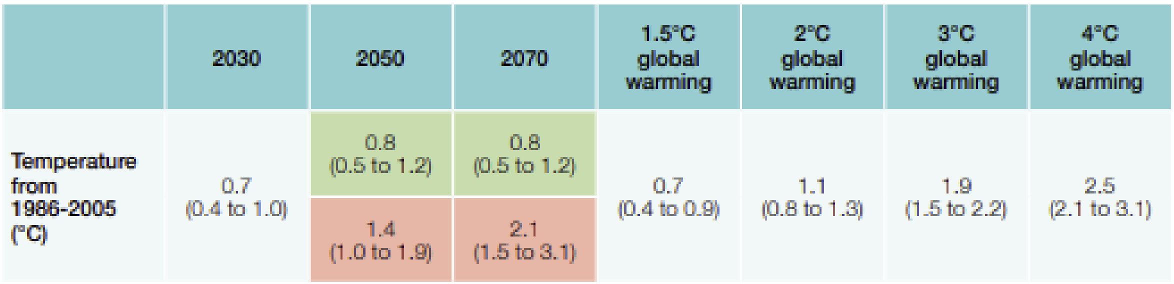


Figure 3-2 Average annual temperature in the Tuvalu region relative to 1850-1900 (°C) derived from observations (Berkeley shown; grey solid line) and simulated in CMIP5 models, showing the range of all models for the past period (grey band), the future under a very high emissions pathway (pink band) and a very low emissions pathway (green band). Thick horizontal lines show the mean of all models in 20-year periods of the baseline 1986-2005 (blue) and future 20-year periods centred on 2030, 2050 and 2070 (RCP8.5; red horizontal lines, RCP2.6; green horizontal lines). (Source [3]).0. The arrows indicate (1) total range of uncertainty, (2) climate response uncertainty due to different emissions pathways, and (3) uncertainty due to natural climate variability.

The projected warming for a 20-year period centred on 2030 (i.e. 2021-2040) is 0.7 °C (uncertainty range 0.4-1.0 °C) relative to a 20-year period centred on 1990 (i.e. 1986-2005), regardless of the emissions pathway. By 2050, the projected warming is 0.8 °C (uncertainty range 0.5-1.2 °C) for low emissions and 1.4 °C (uncertainty range 1.0-1.9 °C) for high emissions. By 2070, it's 0.8 °C (uncertainty range 0.5-1.2 °C) for low emissions and 2.1 °C (uncertainty range 1.5-3.1 °C) for high emissions [3] (Table 3-1).

Table 3-1 Projected change in Tuvalu annual-average temperature and rainfall for 20-year periods centred on 2030, 2050 and 2070, relative to a 20-year period centred on 1990, for low (RCP2.6) and high (RCP8.5) emissions pathways. Median changes are shown with the 10-90 percentile range of uncertainty in brackets. Changes are also shown for different global warming levels. Source: CSIRO and SPREP (2021).



	2030	2050	2070	1.5°C global warming	2°C global warming	3°C global warming	4°C global warming
Temperature from 1986-2005 (°C)	0.7 (0.4 to 1.0)	0.8 (0.5 to 1.2) 1.4 (1.0 to 1.9)	0.8 (0.5 to 1.2) 2.1 (1.5 to 3.1)	0.7 (0.4 to 0.9)	1.1 (0.8 to 1.3)	1.9 (1.5 to 2.2)	2.5 (2.1 to 3.1)

References

1. Bureau of Meteorology, Pacific Climate Change Data Portal 2023.
2. McGree, S., G. Smith, E. Chandler, N. Herold, Z. Begg, Y. Kuleshov, P. Malsale, and M. Ritman, *Climate Change in the Pacific 2022: Historical and Recent Variability, Extremes and Change.* . 2022 Climate and Oceans Support Program in the Pacific. Pacific Community: Suva, Fiji.; Available from: https://library.sprep.org/content/climate-change-pacific-2022-historical-and-recent-variability-extremes-and-change

3. CSIRO and SPREP, *'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for Tuvalu.* . 2021: Final report to the Australia-Pacific Climate Partnership for the Next Generation Climate Projections for the Western Tropical Pacific project. Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP). Melbourne, Australia; Available from: https://www.rccap.org/uploads/files/909d29f7-7cb7-4618-b58b-3ca889669965/Tuvalu%20Country%20Report%20Final.pdf

Chapter 4 Extreme temperature

Introduction

Tuvalu has a tropical climate. Monthly-average maximum air temperatures are around 31 °C while minimum temperatures are around 26 °C [1]. Air temperatures are strongly linked to the surrounding sea surface temperatures. Air and sea temperatures in Tuvalu are typically higher in El Niño years and lower during La Niña years [1].

Extreme temperature explained

Extreme temperatures can be defined in different ways. Frequency, intensity and duration are common metrics. Frequency can be expressed as the number of hours, days or months above or below a specified intensity threshold. The threshold should be considered rare for the given location, e.g. within the bottom/top 1-10 % of recorded events. The bottom 10 % of events sit below the 10th percentile, while the top 10 % of events sit above the 90th percentile. Sometimes, it's simpler to refer to actual temperatures, such as minima below 20 °C or maxima above 35 °C. Events with longer duration often have larger impacts, e.g. a 5-day heatwave with an average maximum temperature over 35 °C.

Observed extreme temperature

In Tuvalu, since 1951, the annual-average number of hot days (maximum temperature above the 90th percentile for 1961-1990) has increased by 29 days per decade, while the number of warm nights (minimum temperature above the 90th percentile for 1961-1990) has increased by 14 days per decade [1]. The annual-average number of cool days (maximum temperature below the 90th percentile for 1961-1990) has decreased by 5 days per decade, while the number of cool nights (minimum temperature below the 90th percentile for 1961-1990) has decreased by 8.5 days per decade (Figure 4-1).

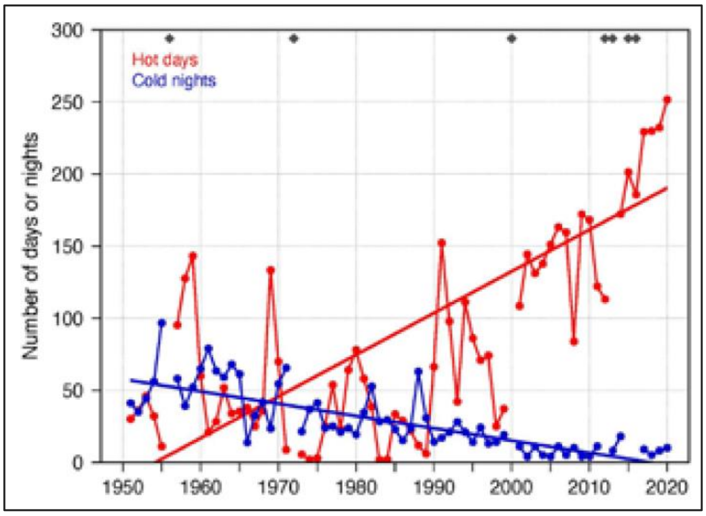


Figure 4-1 Annual number of hot days and cold nights at Funafuti. Straight lines indicate linear trends. Diamonds indicate years with insufficient data for one or both variables.

Projected extreme temperature

Simulated daily maximum temperatures for Tuvalu were analysed from 1950-2100 (Chand et al., (in prep). The simulated historical annual maximum mean temperature is just below 34 °C (33.0°C - 34.6°C) (Figure 4-2). By mid-century (i.e., for the 2040-2060 period), relative to the 1985-2014 period, the mean of annual maximum temperatures increases by 1.8 °C (1.4°C - 2.0°C) under low emissions, 2.1 °C (1.5°C - 2.8°C) under medium emissions and 2.5 °C (1.7°C - 3.5°C) under high emissions (Figure 4-2, left). However, by 2080-2100 annual maximum mean temperatures increase by about 2.2 °C (1.9°C - 2.7 °C)for low emissions, about 3.3 °C (3.0°C - 3.8°C) for medium emissions and about 5.8 °C (4.5°C - 6.8°C) for high emissions (Figure 4-2, right).

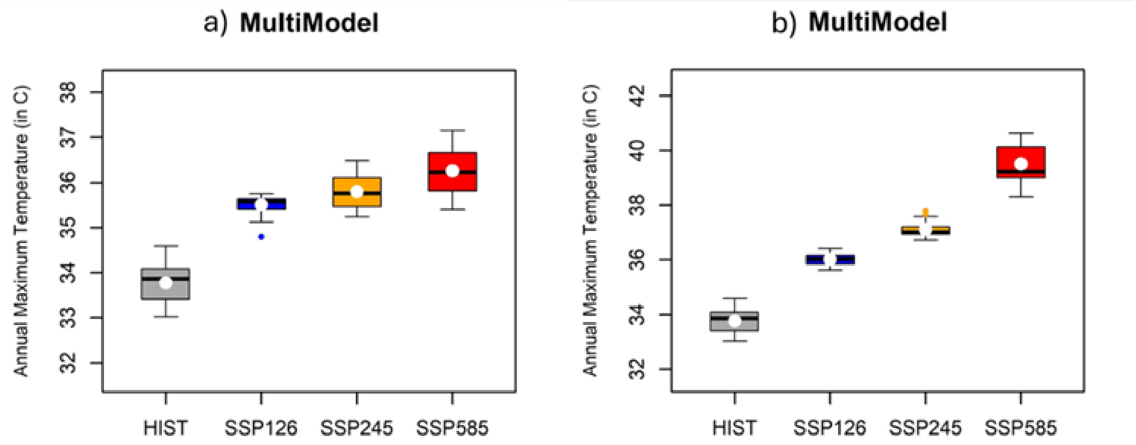


Figure 4-2 Comparison of annual maximum temperature distributions for two periods (1985–2014 and 2040–2060) (left) and (1985–2014 and 2080–2100) (right) for low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways. Results are based on five CMIP6 models. In each box/whisker plot, the central dot/line is the median, the box defines the 25–75th percentile range, and the whiskers define the 10–90th percentile range (Chand et al. in prep).

During 1985-2014, an average of 12 days (0 – 31 days) exceed the 95th percentile. By 2040-2060, this increases by about 181 days (140 – 222 days) for low emissions, 216 days (144 – 261 days) for medium emissions and 264 days (140 – 331 days) for high emissions (Figure 4-3). By the end of the century (2080-2100), the increase is about 235 days (179 – 273 days) for low emissions, 328 days (308 – 339 days) for medium emissions and 353 days (350 – 353 days) for high emissions (Figure 4-3).

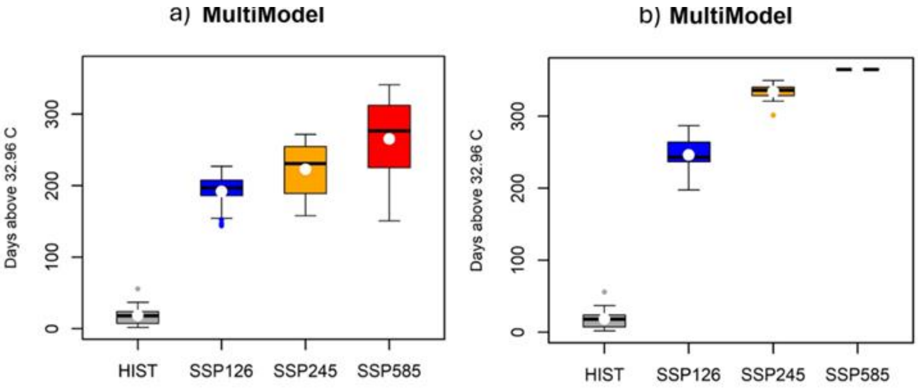


Figure 4-3 Comparison of Funafuti 'hot' days (defined as the number of days over the 95th percentile of 1984-2014 daily temperatures) for periods 1984-2014 (Hist), 2040-2060 (a) and 2080 – 2100 (b) for low (SSP1-2.6), medium (SP2-4.5) and very high (SSP5-8.5) emissions pathways. In each box/whisker plot, the central dot/line is the median, the box defines the 25-75th percentile range, and the whiskers define the 10-90th percentile range.

Extreme annual maximum temperature was also calculated for average return periods of 1-100 years by fitting an extreme value distribution (Figure 4-4). While there are differences between climate model simulations, the general tendency is for extreme temperatures to have shorter return periods in future. For example, the multi-modal mean shows that a 35° C event has a return period of approximately 40 years in the historical climate, but by 2040-2060 and 2080 – 2100 these events may occur every year under all emission scenarios (Figure 4-4).

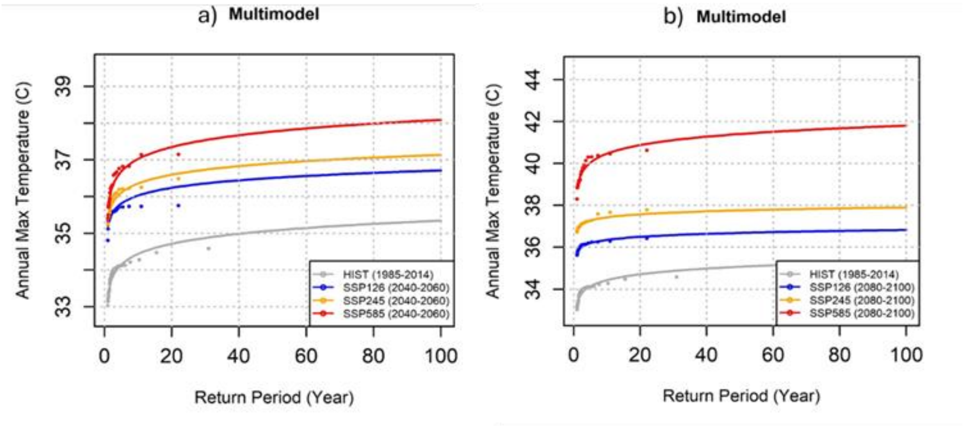


Figure 4-4 Comparison of Funafuti annual maximum daily temperature distributions for return periods of 1-100 years for historical (HIST: 1984-2014) and future (2040-2060 (a) and 2080 – 2100 (b)) timeframes, for low (SSP1-2.6), medium (SP2-4.5) and high (SSP5-8.5) emissions pathways. Results are based on the average of 5 CMIP6 climate models Source (Chand et al, in prep)

References

1. McGree, S., G. Smith, E. Chandler, N. Herold, Z. Begg, Y. Kuleshov, P. Malsale, and M. Ritman, *Climate Change in the Pacific 2022: Historical and Recent Variability, Extremes and Change.* . 2022 Climate and Oceans Support Program in the Pacific. Pacific Community: Suva, Fiji.; Available from: https://library.sprep.org/content/climate-change-pacific-2022-historical-and-recent-variability-extremes-and-change

Chapter 5 Average rainfall

Introduction

Across the Pacific region, rainfall observations made at weather stations show large year-to-year and decade-to-decade variability. However, long-term trends in annual and seasonal rainfall show little change at most locations over the last 70 years [1]. Historical and projected changes in extreme daily rainfall are provided in Chapter 6 on rainfall extremes.

Observed rainfall

Tuvalu has a wet season from December to March and a dry season from April to November. The seasonal cycle is strongly affected by the South Pacific Convergence Zone (SPCZ), which is most intense during the wet season [1]. The percentage of rainfall received at Funafuti and Nanumea during December–March is 43 % (Figure 5-1). Funafuti averages about 3460 mm of rain per year, with 410 mm in January and about 210 mm in June. Nanumea averages around 325 mm in January and almost 160 mm in September.

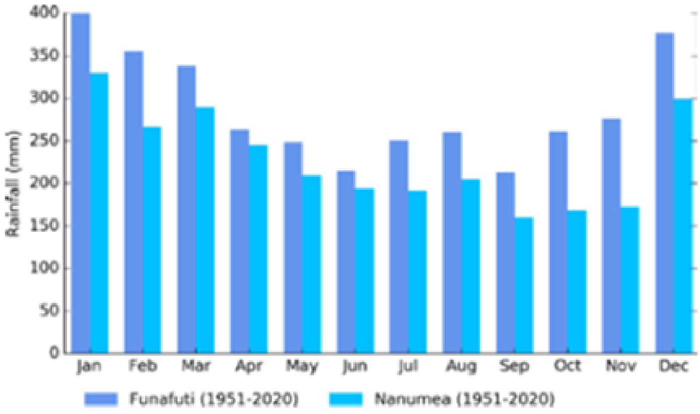


Figure 5-1 Monthly average rainfall at Funafuti and Nanumea in Tuvalu, based on data from 1951-2020. Source: McGree et al (2022).

Trends in annual-total rainfall and annual-maximum 1-day rainfall since 1951 are not statistically significant [1]. Annual rainfall since 1951 has varied from approximately 2000 to 4800 mm, and on average, over half of the days each year experience rain. Over the period 1951–2020 at Funafuti, trends in annual and seasonal rainfall are not statistically significant (Figure 5-2). The number of wet days each year has decreased (2.2 days/decade), though this trend is not statistically significant [1]. A statistically significant increase in consecutive dry days (0.36 days/decade) has been observed in Funafuti (1951–2020) [2], with longer dry spells and droughts being typically experienced during La Niña years [1] (Figure 5-2).

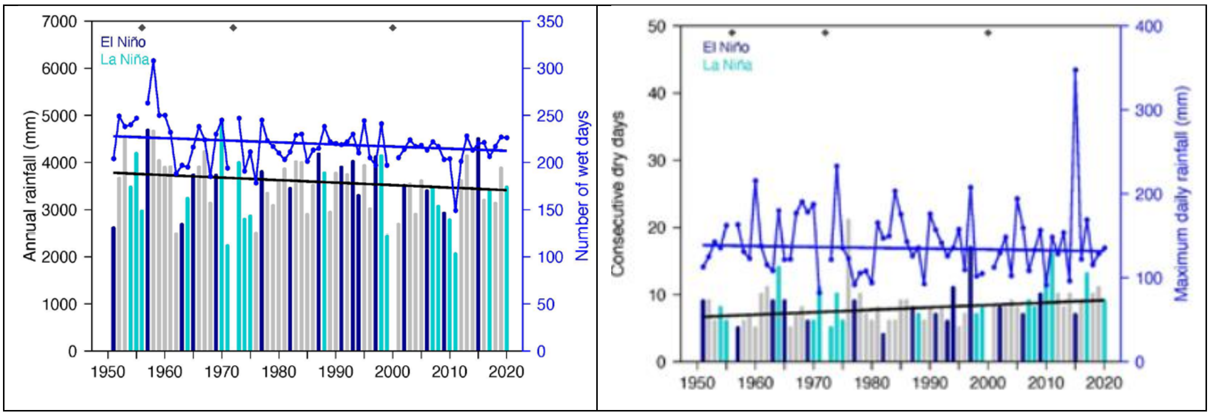


Figure 5-2 Annual rainfall (bar graph) and number of wet days (where rainfall is at least 1 mm; line graph) at Funafuti (left). Annual longest run of consecutive dry days (bar graph) and maximum daily rainfall (line graph) at Funafuti (right). Straight black (blue) lines indicate linear trends corresponding to colour of axis. Criteria for statistical significance were not met for determining linear trends at Funafuti. Diamonds indicate years with insufficient data for one or both variables [1].

Rainfall Variability

Seasonal rainfall variability in Funafuti is not as strongly pronounced as in some other Pacific Island Countries, with rainfall averages between 200 and 400 mm each month of the year. This is attributed to the location of Tuvalu near the West Pacific Warm Pool, where thunderstorm activity occurs all year round. Tuvalu's wet season is affected by the movement and strength of the SPCZ. The West Pacific Monsoon (WPM) can also bring heavy rainfall to Tuvalu during the wet season. Tuvalu's rainfall varies considerably from year to year due to ENSO and SPCZ displacement [3].

ENSO is a large-scale ocean-atmosphere circulation that influences rainfall and tropical cyclones in the tropical Pacific region. The sea surface temperature northeast of Tuvalu is warmer than normal during an El Niño event, and cooler than normal during a La Niña event [4]. This affects the position and strength of the SPCZ. During El Niño, the SPCZ tends to move northeast, producing more rainfall over Tuvalu. During La Niña, the SPCZ tends to move southwest, so Tuvalu has less rainfall [1] (Figure 5-3).

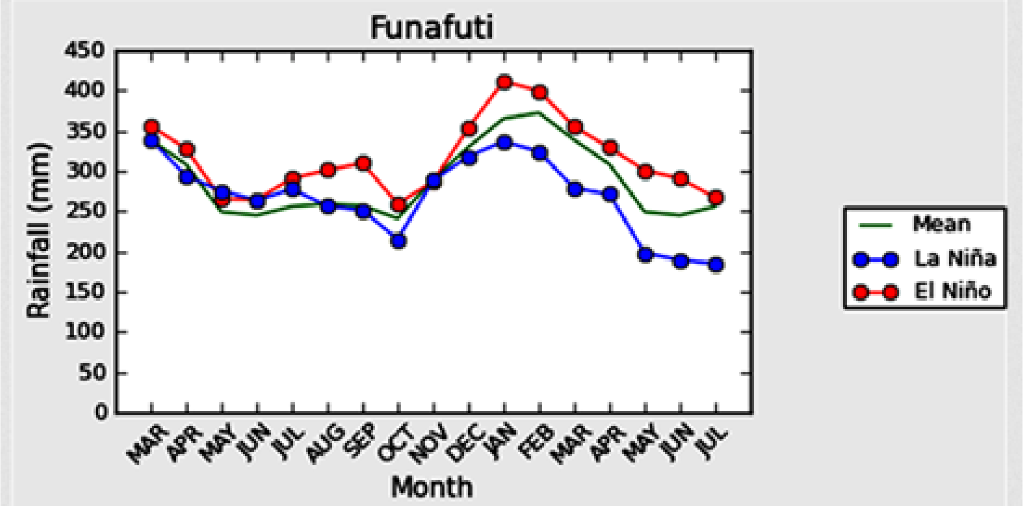


Figure 5-3 Average monthly rainfall for Funafuti, Tuvalu, for El Niño (blue) and La Niña (red) years, along with the mean (green). Data retrieved through the WMO Global Producing Centre (GPC) for long-range forecast portal at http://poama.bom.gov.au/experimantal/pasap/index.shtml [3].

Projected rainfall

For Tuvalu, the projected change in annual average rainfall for a 20-year period centred on 2030 is +4 % (uncertainty range –4 to +12 %) relative to a 20-year period centred on 1995, regardless of the emissions pathway. By 2050, the projected change is +3 % (uncertainty range –6 to +11 %) for low emissions and +3 % (uncertainty range –11 to +17 %) for high emissions (Figure 5-4). By 2070, it’s +3% (uncertainty range –10 to +12 %) for low emissions and +6 % (uncertainty range –15 to +28 %) for high emissions (Figure 5-4 & Table 5-1) [5]. In terms of global warming levels, the projected change in annual average rainfall is +3 % for 1.5 °C global warming, +5 % for 2.0 °C global warming, +7 % for 3.0 °C global warming, and +11 % for 4.0 °C global warming, with increasing ranges of uncertainty [5].

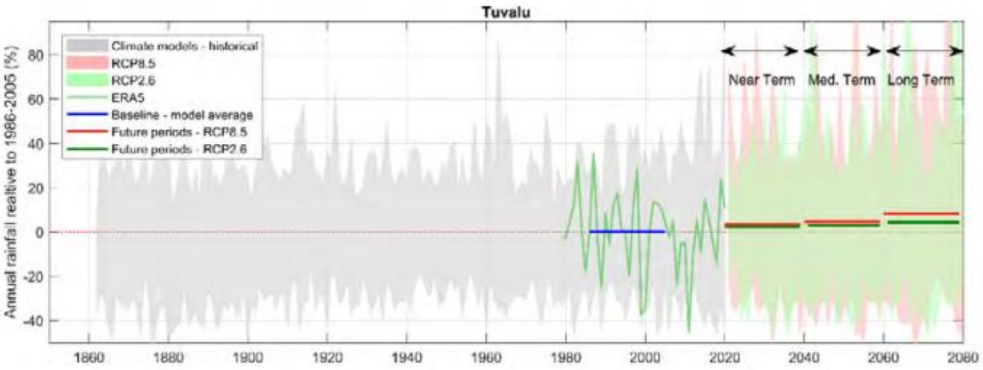
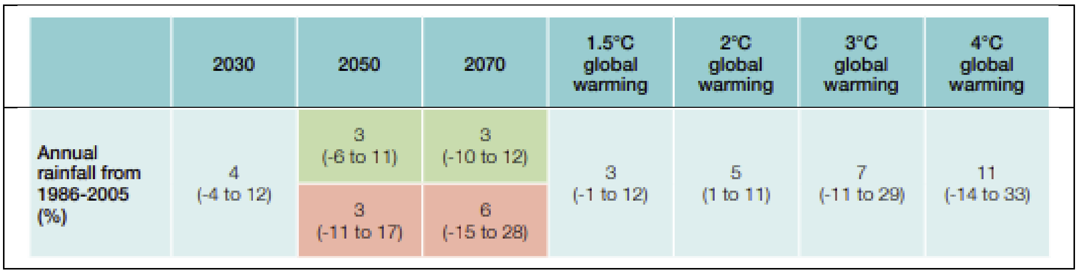


Figure 5-4 Average annual rainfall anomalies (%) for Tuvalu relative to the 1986-2005 baseline in ERA5 historical climate data (dark green line) and in CMIP5 climate model data. Simulations from up to 40 models are shown for the historical period (grey), and for the future, under a high emissions pathway (RCP8.5, pink band) and a low emissions pathway (RCP2.6, green band). Thick lines show the average of all models for 20-year periods centred on 1995 (blue), 2030, 2050 and 2070 (RCP8.5; red lines, RCP2.6; green lines). Source: [5]

Table 5-1 Projected change in Tuvalu annual-average rainfall for 20-year periods centred on 2030, 2050 and 2070, relative to a 20-year period centred on 1990, for low (RCP2.6 green) and high (RCP8.5 pink) emissions pathways. Median changes are shown with the 10-90 percentile range of uncertainty in brackets. Changes are also shown for different global warming levels. Source: [5]



	2030	2050	2070	1.5°C global warming	2°C global warming	3°C global warming	4°C global warming
Annual rainfall from 1986-2005 (%)	4 (-4 to 12)	3 (-6 to 11) 3 (-11 to 17)	3 (-10 to 12) 6 (-15 to 28)	3 (-1 to 12)	5 (1 to 11)	7 (-11 to 29)	11 (-14 to 33)

References

1. McGree, S., G. Smith, E. Chandler, N. Herold, Z. Begg, Y. Kuleshov, P. Malsale, and M. Ritman, *Climate Change in the Pacific 2022: Historical and Recent Variability, Extremes and Change.* . 2022 Climate and Oceans Support Program in the Pacific. Pacific Community: Suva, Fiji.; Available from: https://library.sprep.org/content/climate-change-pacific-2022-historical-and-recent-variability-extremes-and-change
2. McGree, S., M. Kruk, J.J. Marra, E. Chandler, H. Diamond, and E. Lutu-McMoore, *Atmosphere*. Pacific Climate Change Monitor: 2021., ed. Marra et al. (Eds.). 2022: The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC).
3. Kuleshov, Y., S. McGree, D. Jones, A. Charles, A. Cottrill, B. Prakash, T. Atalifo, S. Nihmei, F. Seuseu, and S.K. Lagomauitumua, Extreme weather and climate events and their impacts on island countries in the Western Pacific: cyclones, floods and droughts. *Atmospheric Climate Sciences,* 2014. 4(05): p. 803.

4. Dhage, L. and M.J. Widlansky, Assessment of 21st century changing sea surface temperature, rainfall, and sea surface height patterns in the tropical Pacific Islands using CMIP6 greenhouse warming projections. *Earth's Future,* 2022(e2021EF002524) DOI: 10.1029/2021EF002524.
5. CSIRO and SPREP, *'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for Tuvalu.* . 2021: Final report to the Australia-Pacific Climate Partnership for the Next Generation Climate Projections for the Western Tropical Pacific project. Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP). Melbourne, Australia; Available from: https://www.rccap.org/uploads/files/909d29f7-7cb7-4618-b58b-3ca889669965/Tuvalu%20Country%20Report%20Final.pdf

Chapter 6 Extreme rainfall

Introduction

Extreme rainfall is strongly affected by the SPCZ, which is most intense during the wet season [1]. This can cause flooding, injuries deaths, erosion, water quality, food security, disruption and damage.

Extreme rainfall explained

Frequency, intensity and duration are common metrics for defining extreme rainfall. Frequency can be expressed as the number of hours, days or months above or below a specified intensity threshold. The threshold should be considered rare for the given location e.g., within the bottom/top 1-10 % of recorded events. For example, the bottom 10 % of events sit below the 10th percentile, while the top 10 % of events sit above the 90th percentile. The annual maximum daily rainfall event occurs once per year, but events with higher intensity might only occur once in 10 years or more. The average return period is the average time between events of the same intensity, e.g. a 1-in-10-year event. These concepts are used below.

Observed extreme rainfall

The annual maximum daily rainfall amount varies from around 100-350 mm/day (Figure 6-1). This amount has decreased slightly (-1 mm/decade) since 1951, but the trend is not statistically significant [1]. The tropical cyclone contribution of 1-day, 2-day and 3-day rainfall to annual maximum rainfall in Tuvalu is 19 %, 21 % and 22 %, respectively [2], so about 80 % of the extreme rainfall comes from non-cyclone weather systems.

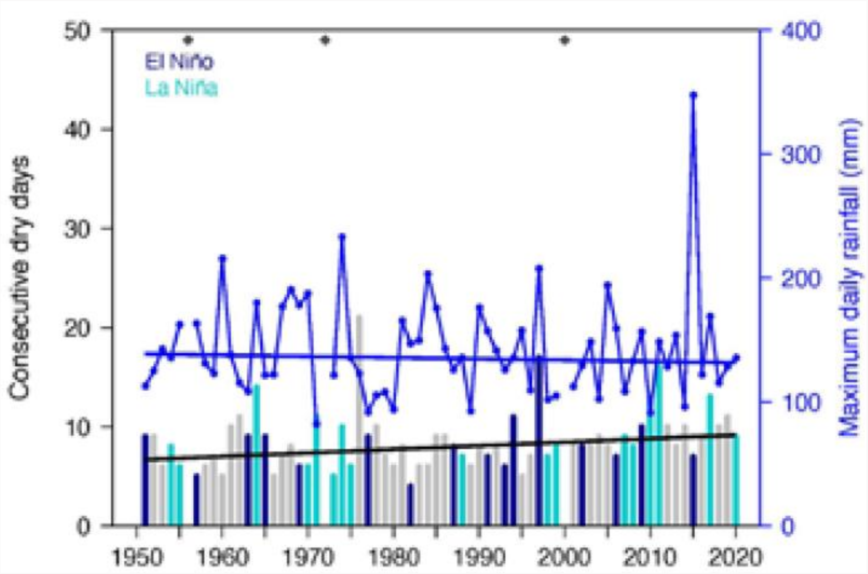


Figure 6-1 Annual maximum daily rainfall and consecutive dry days at Funafuti from 1951-2020. Source [1]

Extreme rainfall variability

During El Niño events, the SPCZ tends to move northeast, resulting in warmer sea surface temperatures, heavier rainfall and more tropical cyclones, with the opposite during La Niña events [3]. See the Glossary for a definition of ENSO.

Projected extreme rainfall

Simulated daily rainfall data for Tuvalu were analysed from 1950-2100 (Chand et al., (in prep). with large interannual variability being superimposed on a slightly increasing trend (not shown). Simulations of annual maximum rainfall intensity averages 133.9 (119 to 160) mm/day for the 1985-2014 period. By mid-century (i.e., for the 2040-2060 period) this increases to 146.0 (117 to 173) mm/day (9 % increase) under low emissions, 143.5 (127 to 163) mm/day (7 % increase) under medium emissions and 148.4 (119 to 200) mm/day (a 11 % increase) under high emissions (Figure 6-2, left). By the end of the century (2080-2100), relative to 1985-2014, annual maximum rainfall intensity increases to 149 (130 to 160) mm/day (11 % increase) for low emissions, 156.6 (126 to 187) mm/day (17 % increase) for medium emissions and 171.7 (126 to 217) mm/day (28 % increase) for high emissions. Figure 6-2, right).

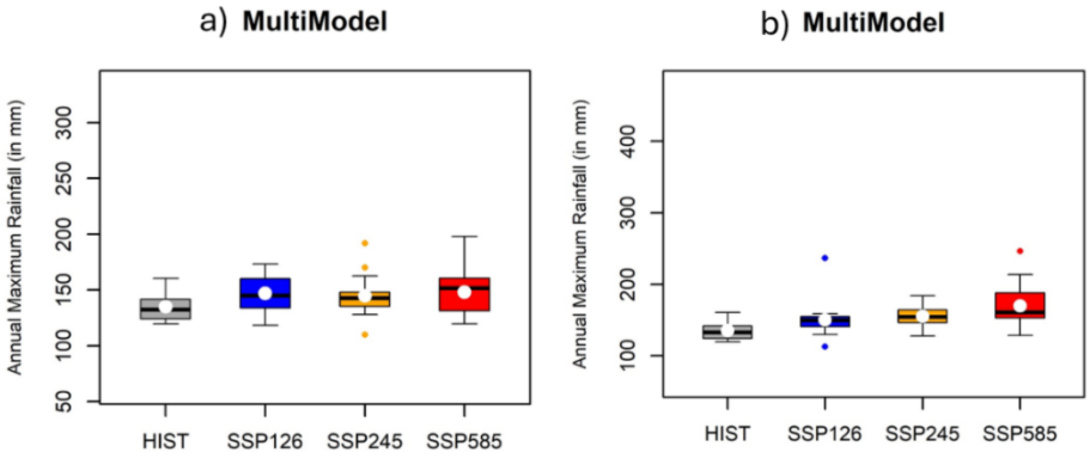


Figure 6-2 Comparison of Funafuti annual maximum daily rainfall distributions for two periods 1985-2014, 2040-2060 (panel a) and 2080-2100 (panel b) for low (SSP1-2.6), medium (SP2-4.5) and high (SSP5-8.5) emissions pathways. Five CMIP6 models were assessed. In each box/whisker plot, the central dot/line is the median, the box defines the 25-75th percentile range, and the whiskers define the 10-90th percentile range. Source (Chand, (in prep)).

For the 1985-2014 period, 18.7 days on average sit above the 95th percentile threshold. By mid-century (2040-2060), this increases to 21.4 days (+14 %) for low emissions, 20.8 days (+11 %) for medium emissions and 21.4 days (+14 %) for high emissions (Figure 6-3, left). By the end of the century (2080-2100), this increases to 20.4 days (+9 %) for low emissions, 23 days (+23 %) for medium emissions and 24.2 days (+29 %) for high emissions (Figure 6-3, right).

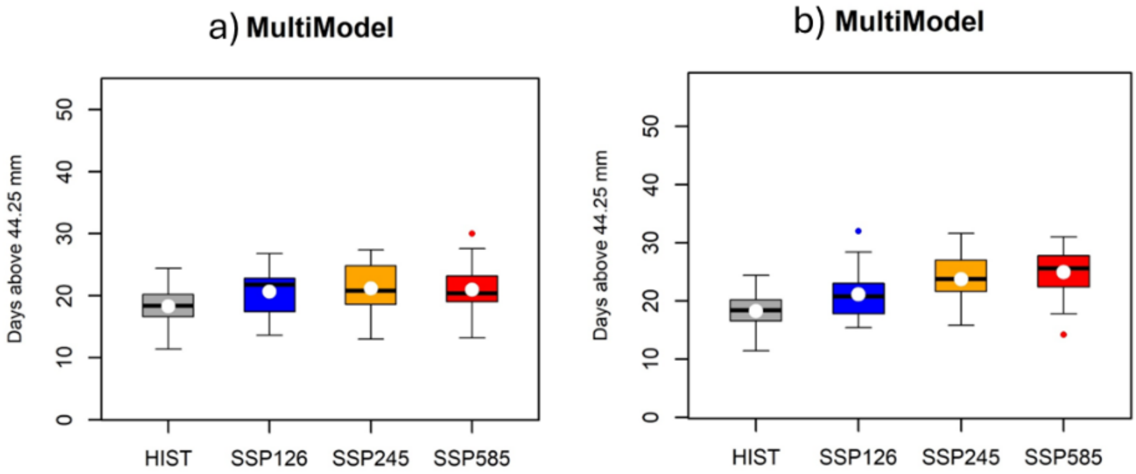


Figure 6-3 Comparison of the average number of days per year when daily rainfall is above the 95th percentile for periods 1985-2014, 2040-2060 (a) and 2080 – 2100 (b) for low (SSP1-2.6), medium (SP2-4.5) and high (SSP5-8.5) emissions pathways. The 95th percentile (shown on the y-axis) is obtained from five CMIP6 models. In each box/whisker plot, the

central dot/line is the median, the box defines the 25-75th percentile range, and the whiskers define the 10-90th percentile range. Source [4].

Extreme daily rainfall intensity was also calculated for average return periods of 1-100 years by fitting an extreme value distribution (Figure 6-4). While there are differences between climate model simulations, the general tendency is for extreme rainfall events to occur with higher frequency in future. For example, the multi model mean shows a 175 mm/day event with a return period of 80 years in the historical climate, but by 2040-2060 these events may occur every 12 years for low and medium emissions, and every 8 years for high emissions (Figure 6-4). By the end of the century (2080-2100), the return period is further shortened with values of about 8.2 years for low emissions, 5.5 years for medium emissions and 3.6 years for high emissions (Figure 6-4). Furthermore, a projected increase in the frequency of extreme ENSO events may also influence extreme rainfall scenarios [5, 6].

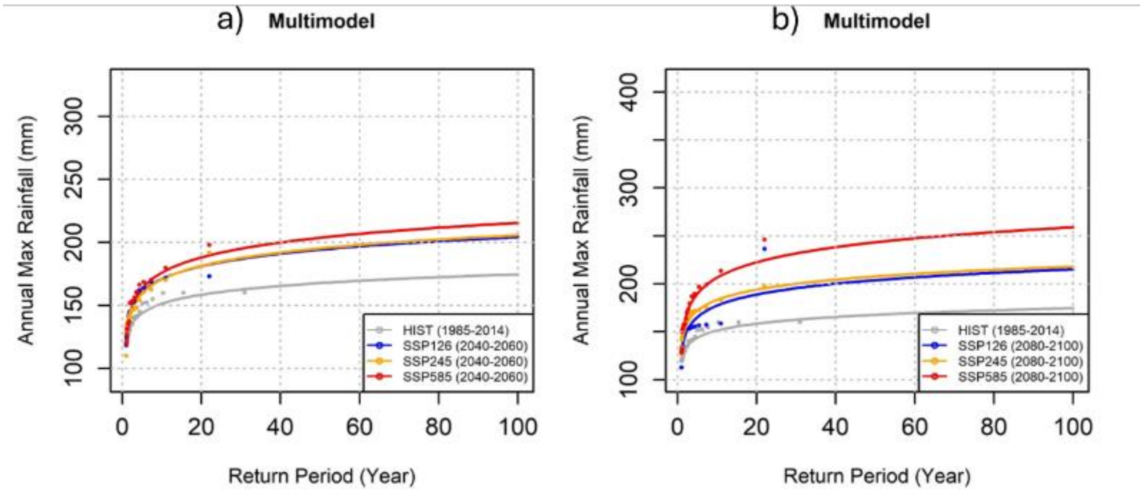


Figure 6-4 Comparison of Funafuti annual maximum daily rainfall distributions for return periods of 1-100 years for historical (HIST: 1984-2014) and future (2040-2060 (a) and 2080 – 2100 (b)) timeframes, for low (SSP1-2.6), medium (SP2-4.5) and very high (SSP5-8.5) emissions pathways. Five CMIP6 models were assessed. Source [4].

References

1. McGree, S., G. Smith, E. Chandler, N. Herold, Z. Begg, Y. Kuleshov, P. Malsale, and M. Ritman, *Climate Change in the Pacific 2022: Historical and Recent Variability, Extremes and Change.* . 2022 Climate and Oceans Support Program in the Pacific. Pacific Community: Suva, Fiji.; Available from: https://library.sprep.org/content/climate-change-pacific-2022-historical-and-recent-variability-extremes-and-change
2. Deo, A., S.S. Chand, H. Ramsay, N.J. Holbrook, S. McGree, A. Magee, S. Bell, M. Titimaea, A. Haruhiru, and P. Malsale, Tropical cyclone contribution to extreme rainfall over southwest Pacific Island nations. *Climate Dynamics,* 2021. 56: p. 3967-3993.
3. Epu, K. and H. Vivae, *Climate, Climate Variability and Change in Tuvalu*. 2011: Tuvalu Meteorological Service. ; Available from: https://www.pacificclimatechangescience.org/wp-content/uploads/2013/10/14.Tuvalu-GH-Poster.pdf.
4. Chand, S. and et al., Projected change in extreme temperature, extreme rainfall and tropical cyclones for Tuvalu. . (in prep).
5. Cai, W., S. Borlace, M. Lengaigne, P. van Rensch, M. Collins, G. Vecchi, A. Timmermann, A. Santoso, M.J. McPhaden, and L. Wu, Increasing frequency of extreme El Nino events due to greenhouse warming. *Nature Climate Change,* 2014. 4(2): p. 111-116.

6. Cai, W., G. Wang, A. Santoso, M.J. McPhaden, L. Wu, F.-F. Jin, A. Timmermann, M. Collins, G. Vecchi, and M. Lengaigne, Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change,* 2015. 5(2): p. 132-137.

Chapter 7 Drought

Introduction

In general, drought refers to a lack of rainfall over an extended period, usually more than a few months, resulting in a water shortage for some activities, groups, sectors, and related natural resources (including marine and terrestrial biodiversity) [1]. Historical droughts in other Pacific Island countries (excluding Nauru) have been described in a review by Iese et al. [2]. The impacts of drought vary significantly depending on (i) the type of drought (e.g. meteorological drought or agricultural drought); (ii) the location (e.g. high islands versus atolls); (iii) socio-economic conditions in the location affected by drought; and (iv) cultural attitudes towards the causes of drought.

Drought definitions and indicators

There are different drought definitions and indicators that are appropriate to different purposes [3]:

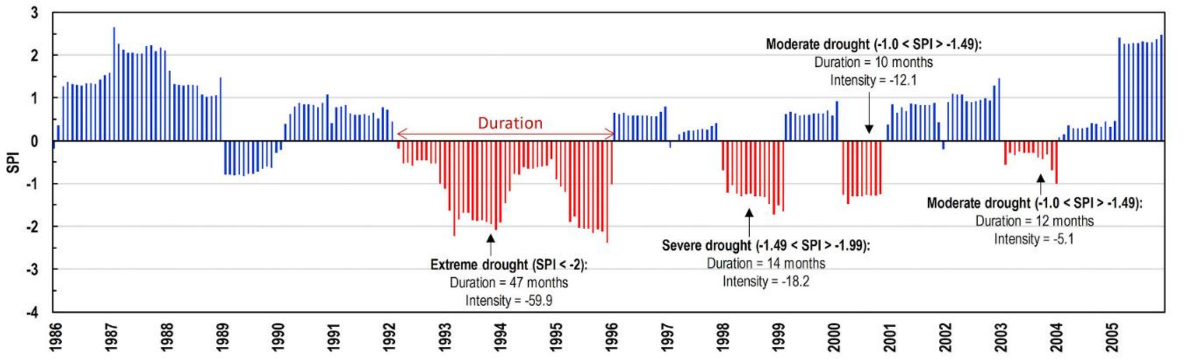
- Meteorological drought (below normal rainfall) (used in this assessment)
- Agricultural drought (below normal water storage in the soil)
- Hydrological drought (below normal water availability in streams, lakes, and groundwater)

Indicators commonly employed for declaring drought include the Standardised Precipitation Index (SPI) [4] or rainfall percentiles [2, 5], though there are many other methods that also account for factors such as evapotranspiration [6], soil moisture, or crop productivity [7].

Standardised Precipitation Index (SPI)

Rainfall anomalies, preferably normalised by standard deviation, are often used to represent drought [8]. The SPI is a widely used indicator for drought, including by the Tuvalu Meteorological Department, and is endorsed as the world standard for determining meteorological drought by the World Meteorological Organization [3]. The SPI is a statistical indicator comparing the total precipitation received at a particular location during a period of months with the long-term rainfall distribution for the same period at that location. The SPI is calculated monthly for a moving window of n months, where n indicates the rainfall accumulation period, which is typically 1, 3, 6, 9, 12, 24 or 48 months denoted as SPI-1, SPI-3, etc. [9]. The concept which underpins the SPI is that it allows quite different rainfall regimes to be expressed in relative terms, i.e. drier than usual relative to what is expected at the time of year for the particular location [10]. Positive SPI values indicate greater than median precipitation and negative values indicate less than median precipitation [9].

A drought event is declared any time the SPI is continuously (over at least 3 months) negative and reaches an intensity of -1.0 or less at some time during each event (see Figure 7-1). The drought begins when the SPI first falls below zero and ends with the first positive value of SPI following a value of -1.0 or less [4]. The drought intensity is the average of cumulative SPI from all events for the drought period. The SPI has been used to assess droughts in the Pacific [11].



Drought category	SPI value
Near normal	-0.99 to 0
Minor Drought	Less than or equal to -1.0
Moderate drought	-1.0 to -1.5
Severe drought	-1.5 to -2.0
Extreme drought	Less than -2.0

Figure 7-1 Example illustration of a Standardised Precipitation Index (SPI) time series and the associated drought events for the period 1986–2005 [12]. In this 20-year period, the SAMPLE site experiences four droughts (with a mean duration of 28.3 months, and intensity per event of -31.8). There are two moderate droughts (with a mean duration of 11 months, and intensity per event of -8.6), one severe drought, and one extreme drought. The site experiences 19.5 % time in extreme drought. Drought categories based on SPI are also indicated [4] noting the ranges in the table differ slightly from the example graph.

Since the SPI can be calculated over different rainfall accumulation periods, different SPIs allow for estimating different potential impacts of a meteorological drought. For example, soil moisture conditions respond to precipitation anomalies on a relatively short scale such as 3 to 6 months whereas groundwater, streamflow and reservoir storage reflect the longer-term precipitation anomalies (12 months and above).

Observed droughts

Using bias corrected ERA5 precipitation data [13, 14], SPI was calculated relative to 3-month and 12-month rainfall accumulations[3] for Funafuti for the period 1951-2023 (Figure 7-2; top). Across the same period, the NINO 3.4 index is also shown (Figure 7-2; bottom). La Niña is declared when the Niño 3.4 index reaches - 0.4 °C [16]. There were 32 SPI-3 and 11 SPI-12 drought events recorded in the period 1950-2023.

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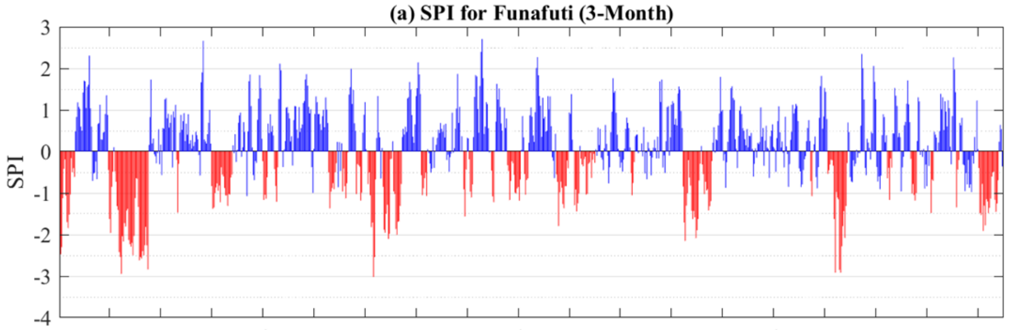
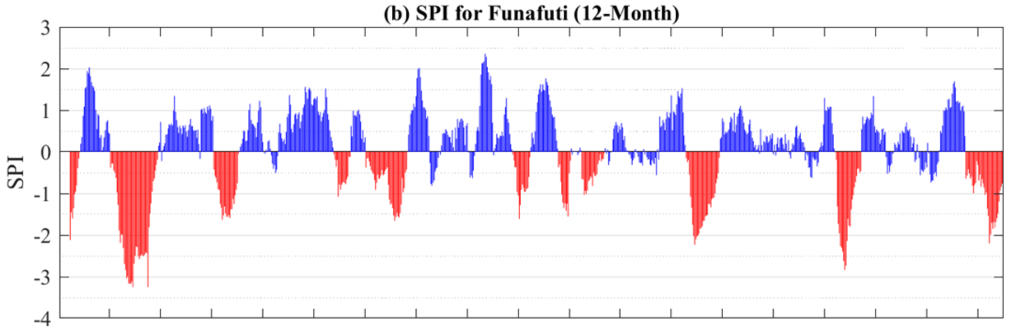
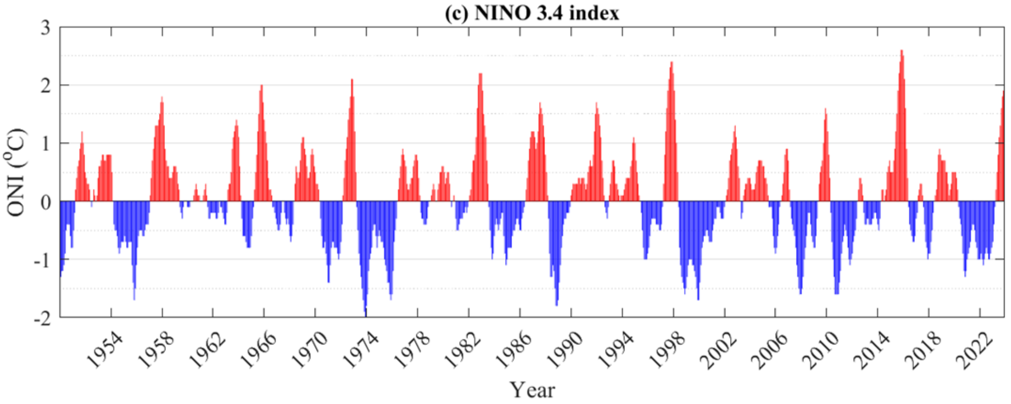
[3] For countries with good water storage on land, a 12-month accumulation is more appropriate e.g. 15. Kirono, D.G.C. and D.M. Kent, Assessment of rainfall and potential evaporation from global climate models and its implications for Australian regional drought projection. *International Journal of Climatology,* 2011. 31(9): p. 1295-1308 DOI: 10.1002/joc.2165.. For the case of Tuvalu, streams, groundwater, and reservoirs are absent, hence, SPI-3 has been used to reflect drought events. Short-term water shortages are frequent issues over the island country (Personal communication) and therefore, the use of SPI-3 would appropriately reflect precipitation anomalies at this timescale.



(a) SPI for Funafuti (3-Month)



(b) SPI for Funafuti (12-Month)



(c) NINO 3.4 index

Figure 7-2 SPI plot for Tuvalu over (a) 3-month and (b) 12-month accumulation periods for the 1950 to 2023 period. The 3-monthly running average of the Oceanic Nino 3.4 index (ONI: Trenberth, 2001) is also shown (c) – Source Deo et al., 2024.

It has been found that drought intensity (DI) has been decreasing for both SPI-3 and -12 between successive events for the 1950 – 2023 period. The trend in drought duration (DD) is mixed: it is decreasing for SPI-3 but increasing for SPI-12. DF has been found to be decreasing over the years for SPI-3 (Figure 10-3) and -12. However, these trends in DI, DD and DF are not statistically significant at the 95 % confidence level (Deo et al 2024). . No statistically significant trend was also found between 1981–2010 and 1951–1980 [6].

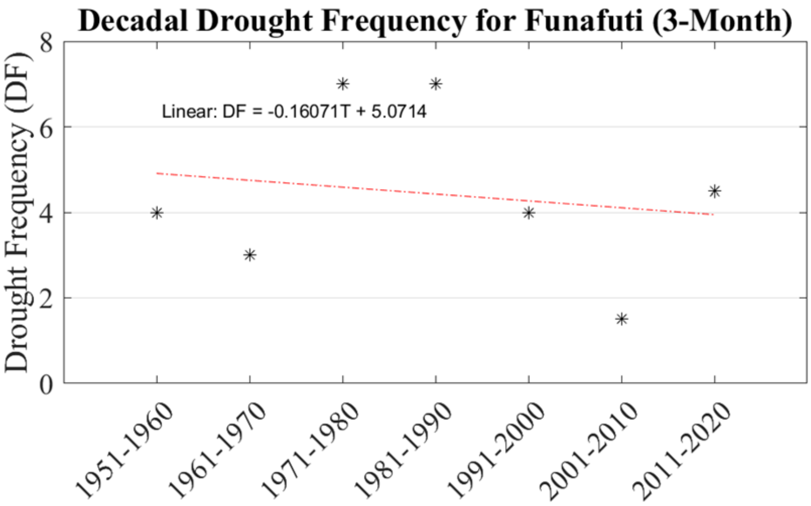


Figure 7-3 Linear regression of decadal drought frequency (SPI with 3-month accumulation period) over Tuvalu for the 1951 – 2020 period. The trend is not statistically significant at the 95% confidence level.

El Niño Southern Oscillation and drought

Variations in ocean temperatures drive changes in atmospheric circulation patterns leading to widespread and persistent changes in air temperatures, rainfall, cyclones, and sea level. ENSO is an ocean-atmosphere interaction influencing drought occurrence in the Pacific region, including Tuvalu [6]. During an El Niño event, wetter conditions are usually experienced in Tuvalu, while La Niña events tend to bring drier conditions (Figure 7-4) [17].

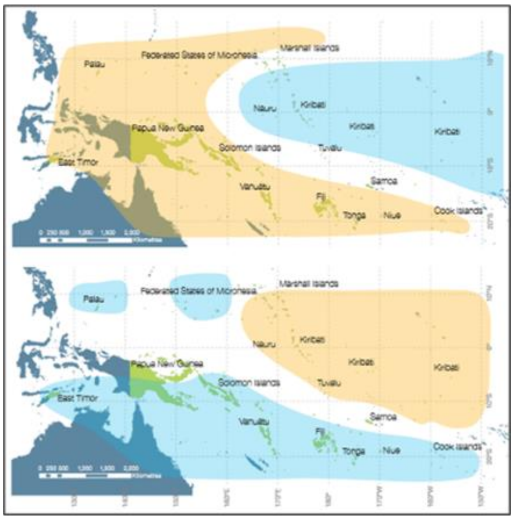
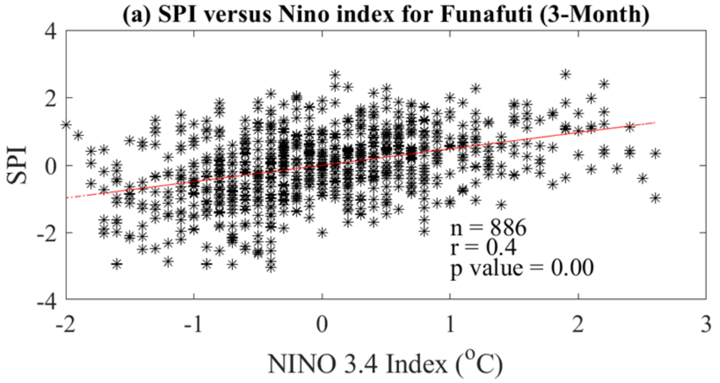


Figure 7-4 Typical changes to rainfall patterns during El Niño (top) and La Niña (bottom) events in the western tropical Pacific (blue shading, wetter than average; yellow shading, drier than average) [17].

Figure 7-2 shows that drought is associated with the La Niña phase of ENSO. Of the 16 La Niña events occurring in the period from 1951-2023, only 3 were not associated with drought (1995, 2006, 2018). Drought intensity (DI) is also correlated with the ENSO intensity across the period Figure 7-5.


(a) SPI versus Nino index for Funafuti (3-Month)

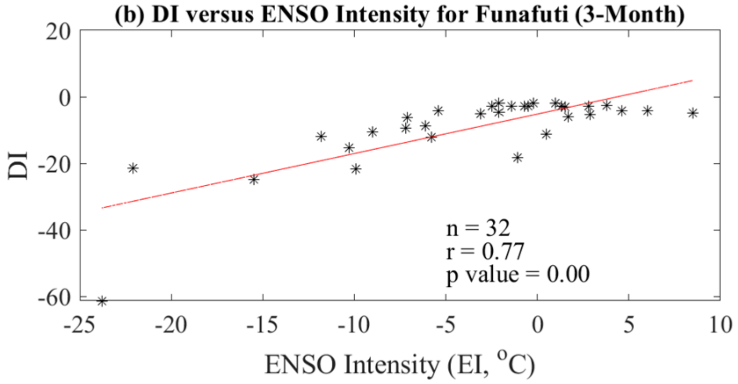

(b) DI versus ENSO Intensity for Funafuti (3-Month)

Figure 7-5 a) Linear regression of SPI against ONI. This includes all the SPI and ONI values as shown in Figure 1 a and b respectively and not just the values corresponding to the 32 drought events. (b) Linear regression of drought intensity (DI) against ENSO intensity (EI) for the 32 drought events. Each EI value is the sum of the corresponding ONI values for each drought event, which is like how DI is computed. These are for the 3-month accumulation period and note, the trends are not statistically significant at the 95% confidence level.

Projected drought

Ongoing increases in greenhouse gas emissions are projected to cause further climate change [18]. Climate model simulations of future SPI drought are presented for the current climate (20 years centred on 1995) and future 20-year periods out to 2090 under a high greenhouse gas emission scenario (RCP8.5) (Figure 7-6). The characteristics of drought are represented by three measures, following [12]:

- Drought duration: the average length (in months) of an event in a selected 20-year period.
- Drought frequency: the number of droughts in a selected 20-year period.
- Drought intensity per event: the average of cumulative SPI from all events for the selected 20-year period. The more negative the value, the more intense the event.

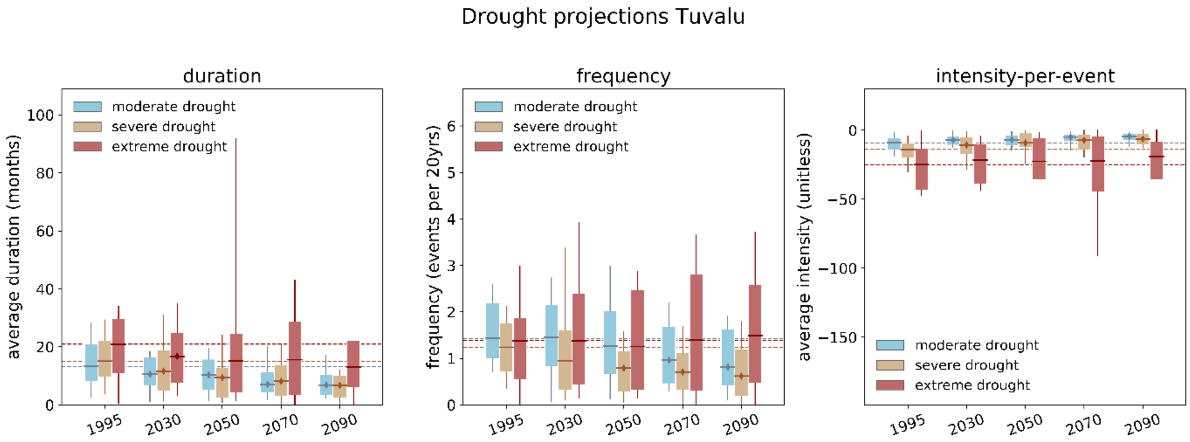


Figure 7-6 Tuvalu average of drought duration (top), frequency (middle) and intensity (bottom) in the reference period (20 years centred on 1995) and future periods (20-years centred on 2030, 2050, 2070, 2090) for a high greenhouse gas emission pathway (RCP8.5). Different drought categories (moderate, severe, and extreme) are given. Drought duration is in months, frequency is in "number of events per period," while intensity is unitless (NB: the more negative the value the more intense the event). Results from 34 climate model simulations are shown as the median (50th percentile), 10th and 90th percentile (bars) and minimum and maximum values (whiskers). The dashed lines show the multi-model median for the baseline period for each drought category [2, 12]. SPI is calculated monthly with the value for each month representing the rainfall anomaly over the past 12 months [12].

Drought duration is projected to decline across all drought categories (Figure 7-6). A general decrease in the frequency of moderate and severe droughts is projected. Little change in drought intensity is projected. This is consistent with the projected increase in average rainfall (Chapter 5).

The drought projections in Figure 7-6 are based on the SPI, which does not include the effect of projected increases in evapotranspiration. Therefore SPI-based drought projections may be conservative as increasing temperature, which affects evapotranspiration, is not considered.

Furthermore, increased variability in rainfall may result in the increasing severity and likelihood of both flooding and droughts [19]. This is consistent with projected increases in extreme La Niña and El Niño events due to climate change [20-22]. Thus, the projected changes in ENSO extremes in the tropical Pacific could have significant impacts on Tuvalu's weather patterns and coastal communities.

Caveats

Despite no trend in drought-related rainfall deficiencies, droughts are becoming hotter due to global warming associated with increases in greenhouse gas emissions [8]. Over Tuvalu, maximum air temperatures have increased 0.17 °C per decade since 1951, while minimum air temperatures have increased 0.21 °C per decade. The annual-average number of hot days (maximum temperature above the 90th percentile of the 1961-1990 period) has increased by 29 per decade, while the number of warm nights (minimum temperature above the 90th percentile for 1961-1990) has increased by 14 per decade [11].

Changes in the zonal gradients of sea surface temperature (SST) across the equatorial Pacific have major consequences for global climate [23]. It is important to note that there is a large degree of inconsistency among climate models on some aspects of future projections [23], as well as biases (e.g. [24-27]). See Chapter 4 for a more detailed explanation.

References

1. CSIRO and BoM, *Climate Change in Australia Technical Report*. 2015 CSIRO Marine and Atmospheric Research and Bureau of Meteorology (CAWCR) and the Department of the

Environment: Melbourne, Australia; Available from: URL: http://climatechangeinaustralia.com.au/.

2. Iese, V., A.S. Kiem, A. Mariner, P. Malsale, T. Tofaeono, D.G. Kirono, V. Round, C. Heady, R. Tigona, and F. Veisa, Historical and future drought impacts in the Pacific islands and atolls. *Climatic Change,* 2021. 166(1): p. 1-24.
3. WMO and GWP, *Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2.* Ch in *Handbook of drought indicators and indices*, M. Svoboda and B.A. Fuchs, Editors. 2016, World Meteorological Organization (WMO) and Global Water Partnership (GWP): Geneva.
4. McKee, T.B., N.J. Doesken, and J. Kleist. The relationship of drought frequency and duration to time scales. in *Proceedings of the 8th Conference on Applied Climatology*. 1993: Boston, MA, USA.
5. BoM, *Drought, rainfall deficiencies and water availability. 2023. Australian Bureau of Meteorology.* 2023; Available from: http://www.bom.gov.au/climate/drought/drought.shtm.
6. McGree, S., S. Schreider, and Y. Kuleshov, Trends and variability in droughts in the Pacific Islands and Northeast Australia. *Journal of Climate,* 2016. 29(23): p. 8377-8397.
7. Sivakumar, M.V., *Agricultural drought—WMO perspectives*. 2011 World Meteorological Organization: Geneva, Switzerland.
8. Dai, A., Drought under global warming: a review. *WIREs Climate Change,* 2011. 2: p. 45-65.
9. Edwards, D.C. and T.B. McKee, *Characteristics of 20 th century drought in the United States at multiple time scales*. Vol. 97. 1997: Colorado State University Fort Collins.
10. Parry, S., J. Hannaford, C. Prudhomme, B. Lloyd-Hughes, and J. Williamson, *Objective drought and high flow catalogues for Europe*. 2011; Available from: https://nora.nerc.ac.uk/id/eprint/15044/1/WATCH_technical_report_33_Objective_Drought_and_High_Flow_Catalogues_for_Europe.pdf (Accessed 6/4/2023).
11. McGree, S., G. Smith, E. Chandler, N. Herold, Z. Begg, Y. Kuleshov, P. Malsale, and M. Ritman, *Climate Change in the Pacific 2022: Historical and Recent Variability, Extremes and Change.* . 2022 Climate and Oceans Support Program in the Pacific. Pacific Community: Suva, Fiji.; Available from: https://library.sprep.org/content/climate-change-pacific-2022-historical-and-recent-variability-extremes-and-change
12. Kirono, D.G., V. Round, C. Heady, F.H. Chiew, and S. Osbrough, Drought projections for Australia: Updated results and analysis of model simulations. *Weather Climate Extremes,* 2020. 30: p. 100280.
13. Hersbach, H., B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz ‐ Sabater, J. Nicolas, C. Peubey, R. Radu, and D. Schepers, The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society,* 2020. 146(730): p. 1999-2049.
14. Biswas, S., S.S. Chand, A.J. Dowdy, W. Wright, C. Foale, X. Zhao, and A. Deo, Statistical calibration of long-term reanalysis data for Australian fire weather conditions. *Journal of Applied Meteorology and Climatology,* 2022.
15. Kirono, D.G.C. and D.M. Kent, Assessment of rainfall and potential evaporation from global climate models and its implications for Australian regional drought projection. *International Journal of Climatology,* 2011. 31(9): p. 1295-1308 DOI: 10.1002/joc.2165.
16. Trenberth, K.E. and D.P. Stepaniak, Indices of el Niño evolution. *Journal of climate,* 2001. 14(8): p. 1697-1701.
17. Australian Bureau of Meteorology and CSIRO, *PACCSAP factsheet: Large-scale climate features in the western tropical Pacific*. 2014 Bom and CSIRO; Available from: https://www.pacificclimatechangescience.org/wp-content/uploads/2015/11/PACCSAP-factsheet_Large-Scale-Climate-Features.pdf (Accessed 10/4/2023).

18. IPCC, *Summary for Policymakers. Synthesis of IPCC Sixth Assessment Report.* . 2023 IPCC: Geneva, Switzerland; Available from: https://www.ipcc.ch/report/ar6/syr/ (Accessed 23/3/2023).
19. Dhage, L. and M.J. Widlansky, Assessment of 21st century changing sea surface temperature, rainfall, and sea surface height patterns in the tropical Pacific Islands using CMIP6 greenhouse warming projections. *Earth's Future,* 2022(e2021EF002524) DOI: 10.1029/2021EF002524.
20. Cai, W., S. Borlace, M. Lengaigne, P. van Rensch, M. Collins, G. Vecchi, A. Timmermann, A. Santoso, M.J. McPhaden, and L. Wu, Increasing frequency of extreme El Nino events due to greenhouse warming. *Nature Climate Change,* 2014. 4(2): p. 111-116.
21. Cai, W., G. Wang, B. Dewitte, L. Wu, A. Santoso, K. Takahashi, Y. Yang, A. Carréric, and M.J. McPhaden, Increased variability of eastern Pacific El Niño under greenhouse warming. *Nature,* 2018. 564(7735): p. 201-206.
22. Cai, W., G. Wang, A. Santoso, M.J. McPhaden, L. Wu, F.-F. Jin, A. Timmermann, M. Collins, G. Vecchi, and M. Lengaigne, Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change,* 2015. 5(2): p. 132-137.
23. Lee, S., M. L'Heureux, A.T. Wittenberg, R. Seager, P.A. O'Gorman, and N.C. Johnson, On the future zonal contrasts of equatorial Pacific climate: Perspectives from Observations, Simulations, and Theories. *Climate Atmospheric Science,* 2022. 5(1): p. 82.
24. Collins, M., S.-I. An, W. Cai, A. Ganachaud, E. Guilyardi, F.-F. Jin, M. Jochum, M. Lengaigne, S. Power, and A. Timmermann, The impact of global warming on the tropical Pacific Ocean and El Niño. *Nature Geoscience,* 2010. 3(6): p. 391-397.
25. Graham, F.S., A.T. Wittenberg, J.N. Brown, S.J. Marsland, and N.J. Holbrook, Understanding the double peaked El Niño in coupled GCMs. *Climate Dynamics,* 2017. 48(5): p. 2045-2063 DOI: 10.1007/s00382-016-3189-1.
26. Power, S., M. Lengaigne, A. Capotondi, M. Khodri, J. Vialard, B. Jebri, E. Guilyardi, S. McGregor, J.-S. Kug, and M. Newman, Decadal climate variability in the tropical Pacific: Characteristics, causes, predictability, and prospects. *Science Advances,* 2021. 374(6563): p. eaay9165.
27. Erickson, N.E. and C.M. Patricola, Future projections of the El Niño—Southern Oscillation and tropical Pacific mean state in CMIP6. *Journal of Geophysical Research: Atmospheres,* 2023. 128(21): p. e2022JD037563.

Chapter 8 Tropical cyclones and extreme wind

Introduction

Tropical cyclones (TCs) are one of the costliest natural hazards impacting communities in Pacific Island Countries due to their high exposure and vulnerability, which limits adaptive capacity [1]. Impacts come directly and indirectly from strong winds, extreme rainfall and storm surge, depending on TC intensity, location/tracks and speed of movement [2].

TC definition

Tropical cyclones are rapidly rotating storms that originate over tropical oceans with sea surface temperatures (SST) that are typically above 25.5 °C, and at least 5° of latitude away from the equator where there is sufficient Coriolis force to create rotation. TCs are typically around 500 km wide, but can vary considerably [3].

In the Australian and the South Pacific Ocean basins, a weather system is classified as a TC when it has a 10-minute sustained mean wind speed of at least 17.5 metres per second (m/s). In these basins, TCs are classified into five categories (Table 8-1): Category 1 (weakest) to Category 5 (strongest). Systems that reach Category 3 and above are often referred to as severe TCs.

Southern Hemisphere TCs usually form in the South Pacific Convergence Zone (SPCZ; Figure 8-1) region and propagate southeast. Consequently, island countries that lie along or poleward of the SPCZ can experience TCs more often than those that lie equatorward or farther east [4, 5]. Given Tuvalu is located on the northern boundary of the TC formation region for the Southern Hemisphere [4], TCs making landfall in Tuvalu are fewer, and are not usually in the severe category.

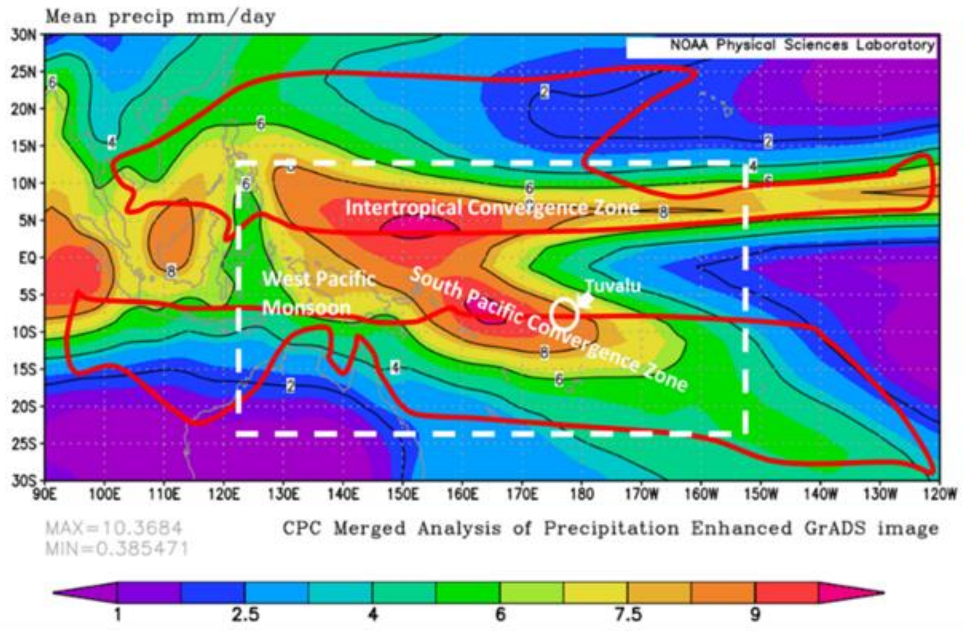


Figure 8-1 The average locations of the South Pacific Convergence Zone, the Intertropical Convergence Zone, and the West Pacific Monsoon in the tropical Pacific region, defined using the mean daily precipitation over the period 1979-2020 (colour shadings and black contours). Mean TC formation regions (enclosed within red contours) for the summer-months (July-September in the northwest Pacific, and January-March in the southwest Pacific) are derived using the information from Tory et al. (2020) [4]. Dashed white box encloses Pacific Island nations. Location of Tuvalu is indicated (white circle).

Table 8-1 The Australian/Fiji TC intensity scale is used to classify TCs from categories 1 to 5 [6]. Maximum mean wind refers to 10-minute sustained wind speed. Note that the TC wind speed used for analyses are in m/s rather than km/hr or knots.

Category	Typical effects	Maximum Wind		
		km/hr	m/s	kts
1	Damaging winds. Negligible house damage. Damage to some crops and trees. Boats may drag moorings.	63–88	17.5–24.4	34.0–47.5
2	Destructive winds. Minor house damage. Significant damage to signs and trees. Heavy damage to some crops. Risk of power failure. Small boats may break moorings.	89–117	24.7–32.5	48.1–63.2
3	Very destructive winds. Some roof and structural damage. Some caravans destroyed. Power failures are likely.	118–159	32.8–44.2	63.7–85.9
4	Significant roofing loss and structural damage. Many caravans destroyed and blown away. Dangerous airborne debris. Widespread power failures.	160–200	44.4–55.6	86.4–108.0
5	Extremely dangerous with widespread destruction	Greater than 200	Greater than 55.6	Greater than 108.0

Observed tropical cyclones

Tropical cyclones usually affect Tuvalu during the southern hemisphere tropical cyclone season, which is from November to April, but also occasionally occur outside the tropical cyclone season [7]. A total of 59 TCs from the SPEArTC database were identified within the Tuvalu EEZ that either developed or passed the zone between the 1970/71 and 2021/22 TC seasons (Figure 8-2). This represents an average of 11.6 cyclones per decade for Tuvalu.

Interannual variability in the number of tropical cyclones in the Tuvalu EEZ is large, ranging from zero in some seasons to four in 1993/04, 2004/05 and 2019/20. The high interannual variability is primarily due to the El Niño Southern Oscillation (ENSO) phenomenon where TCs are most frequent in El Niño years (e.g., ~6 cyclones per decade based on the 1970/71-2021/22 climatology), followed by neutral years (~4.6 cyclones per decade) and least frequent in La Niña years (1.2 cyclones per decade) (Figure 8-2). Note this large variability and the small number of tropical cyclones occurring within the Tuvalu EEZ make reliable identification of long-term trends in frequency and intensity difficult.

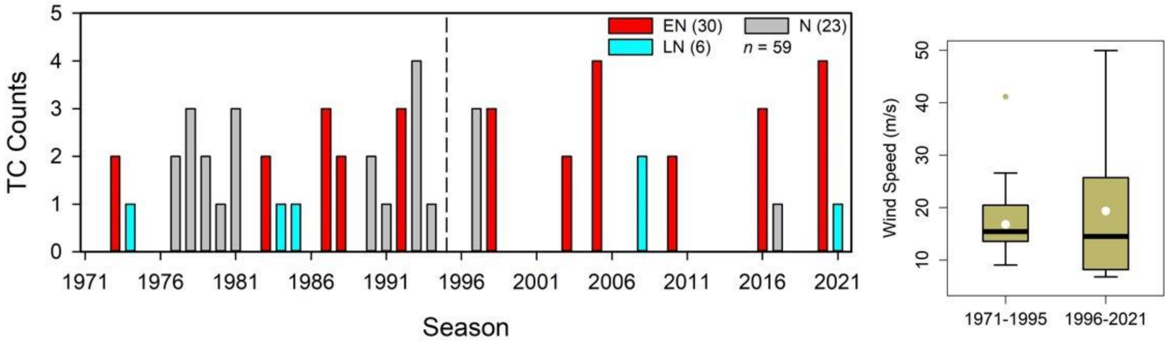


Figure 8-2 Number of tropical cyclones passing within the Tuvalu EEZ per season. Each season is defined by the ENSO status, with red being an El Niño year, blue a La Niña year and grey showing neutral ENSO years (total TC counts for each category are indicated brackets). TC data are from the International Best Track Archive for Climate Stewardship (IBTrACS; [8]). Also presented (right panel) are the wind speed distributions as boxplots for two 25-year periods (1971-1995 and 1996-2021). The black line within the boxplot represents the median, the white dot represents the mean, the box is the 25-75th percentile range, and the whiskers represent the 5-95th percentile range. Since TCs are spread over the two calendar years a second year is used here to designate a season.

Comparing TC frequency and intensity for the two 25-year historical climatological periods (i.e., 1970/71-1995/96 and 1996/97-2021/22), we note an average of 13.6 TCs/decade occurred in the earlier 1971-1995 period and around 9.6 TCs/decade in the latter 1996-2021 period; this difference is not statistically significant at the 95 % significance level. It is not clear whether this reduced frequency over the two periods is due to a direct impact of climate change or a result of natural climate variability given past decades have also been dominated by La Niña events that often account for relatively low TCs numbers over Tuvalu compared with El Niño and neutral events. Moreover, the mean TC wind speed shows ~10.6 % increase between the two periods (not statistically significant, Figure 8-2 right panel); 16.8 m/s (1970/71-1995/96) compared with 18.6 m/s (1996/97-2021/22). It is important to note that majority of TCs occurring during the latter period were associated with El Niño events where TCs can undergo increased intensity (e.g., [9]).

These findings align with some other studies for the broader Pacific region where there is clear evidence that the total number of TCs affecting the Pacific have declined historically, – but the frequency of proportion (i.e., the ratio between number of severe TCs and total TCs), as well as mean TC intensity, have increased e.g. [10].

El Niño Southern Oscillation and tropical cyclones.

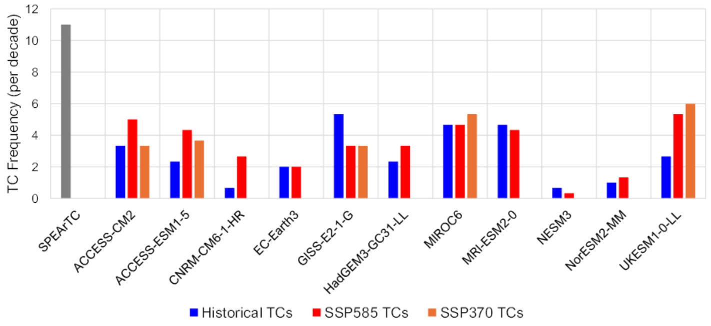
As discussed above, ENSO phenomena substantially modulate TC activity over Tuvalu [11]:

- Generally higher TC-induced impacts are present during El Niño due to increased frequency and intensity of TCs over Tuvalu.
- Impacts are further enhanced during positive phase of the IPO, which favour occurrence of more El Niño events and also contribute to higher sea-level over Tuvalu (compared to the negative phase).
- During La Niña, TCs are relatively infrequent and less intense. However, higher sea-level (as opposed to during El Niño) can elevate impacts of storm surge and coastal inundation in an event of a cyclone.
- More frequent occurrence of TCs (including severe TCs) during El Niño are also associated with higher impacts of destructive waves.

Tropical cyclone Projections

Here we used models from the latest generation of the Coupled Model Intercomparison Project Phase 6 (CMIP6) [12] to assess projected changes in TC frequency and intensity for Tuvalu under the two emission scenarios: SSP3-7.0 (high emission scenario) and SSP5-8.5 (very high emission scenario). Note due to inherent limitations in CMIP6 models (such as coarse resolution, parametrization issues etc.), projections of TC frequency and intensity are substantially underestimated for Tuvalu. Therefore, our confidence in these local-area projections is low and so care must be exercised when interpreting the results in the context of global warming.

There is also a large inconsistency between models in projecting changes in TC frequency for mid-century (2036-2065) and late century (2070-2100), under both SSP3-7.0 and SSP5-8.5 emission scenarios. This is not surprising given inherent challenges of coarse resolution models to simulate TCs at local scales. For mid-century projections, most models project an increase in TC numbers though the increase for all models assessed is not statistically significant at the 95 % significance level (Figure 8-3, top). However, projected changes can vary from approximately 50 % decline to up to a 10 % increase, noting that TC numbers in these models are substantially low compared with observations and so statistics associated with percentage changes can be considerably exaggerated. By the end of the century, more models show a decline in TC numbers. This is also consistent with results from CMIP5 simulations for the broader southwest Pacific region where the consensus is for declining cyclone numbers towards the end of the twenty-first century (e.g., [13]).


(a) Frequency of CMIP6 model-simulated TCs for Tuvalu EEZ: Historical period (1985-2014) and future period (2036-2065) under SSP5-8.5 and SSP3-7.0

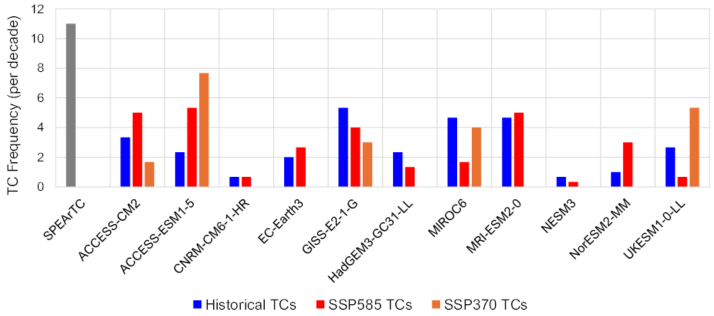

(b) Frequency of CMIP6 model-simulated TCs for Tuvalu EEZ: Historical period (1985-2014) and future period (2071-2100) under SSP5-8.5 and SSP3-7.0

Figure 8-3 Tropical cyclone frequency for Tuvalu in selected CMIP6 models for the historical climate period (1985-2014) and the two future simulations, (a) the mid-century (2036-2065) and (b) late twenty-first century (2070-2100), under SSP3-7.0 and SSP5-8.5 emission scenarios. Note models are chosen to give a representation of a wide range of uncertainties associated with local-area projections.

For countries like Tuvalu where ENSO play a major role in modulating TC frequency (i.e., more TCs during El Niño than La Niña events), it is also important to interpret any future changes in TC numbers in the context of ENSO. Chand et al. (2017) [14] showed that ENSO will continue to be a dominant large-scale climate process influencing natural variability of TCs in future. As per this study, while TC numbers are projected to decrease overall in the broader southwest Pacific, TCs are also projected to become ~20–40 % more frequent in the entire central Pacific region during future-climate El Niño periods compared to present-climate El Niño periods (Figure 8-4, b), and less frequent during future-climate La Niña and neutral periods compared to present-climate La Niña and neutral periods (Figure 8-4, c). Since CMIP6 models project more El Niño-type conditions in the future climate [15], increased TC frequency for Tuvalu - as projected by some CMIP6 models - should also be given careful attention, as opposed a general narrative of declining TC numbers which may be true for the broader Pacific and globally (e.g., [16-18]).

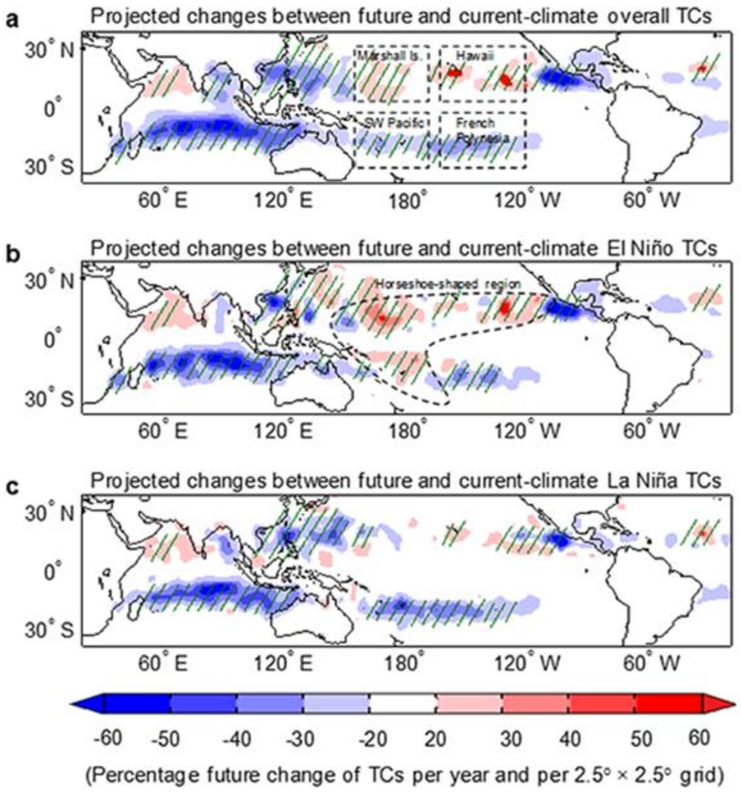


Figure 8-4 Changes in TC frequency for late 21st century (2070-2100) vs late 20th century (1970-2000) overall (top), for El Niño conditions (middle) and La Niña conditions (bottom). Blue indicates decrease while red indicates increase. Projections are derived from 13 CMIP5 global climate models driven by a high emissions pathway (RCP8.5). Source: Chand et al. [14].

Mean TC intensity (represented by white dots in Figure 8-5) within the Tuvalu EEZ is projected to increase slightly for high and very high emissions scenarios. For the high (SSP3-7.0) scenario, mean TC intensity increased by 24 % and 36 % during the mid- and late-century periods, respectively, compared with the historical period. However, for the very high (SSP5-8.5) scenario, there is no significant change in the mean TC intensity, but the number of events with extreme winds have clearly increased for both mid- and late-century simulations (red dots in Figure 8-5).

The return periods of extreme wind speed events are projected to decrease (Figure 8-6). By mid-century, an event that occurred once in 30 years historically (e.g. TC Gavin on 6 March 1997) may occur once in 10 years for the high emissions scenario and once in 20 years for the very high emissions scenario. By late-century, an event that occurred once in 30 years historically may occur once in 20 years for the high emissions scenario and once in 10 years for the very high emissions scenario. The confidence in such changes is low due to uncertainties associated with coarse resolution models and the small sample of models.

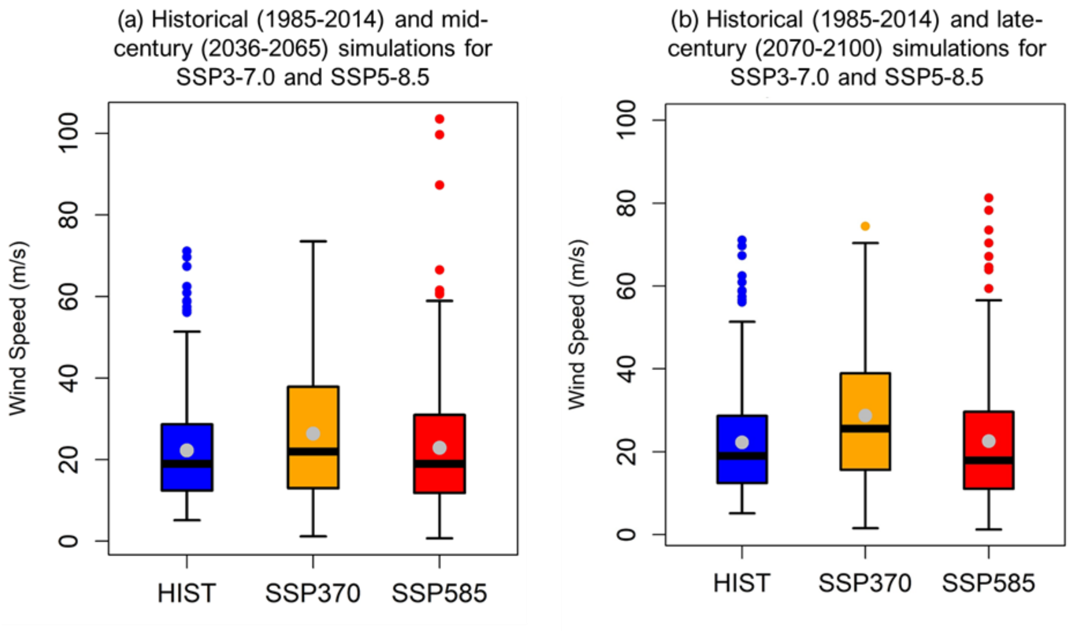


Figure 8-5 Boxplots showing TC wind speed distribution for historical (HIST, 1985-2014) and future climate simulations for (a) mid-century (2036-2065) and (b) late twenty-first century (2070-2100) under SSP3-7.0 and SSP5.8.5 scenarios.

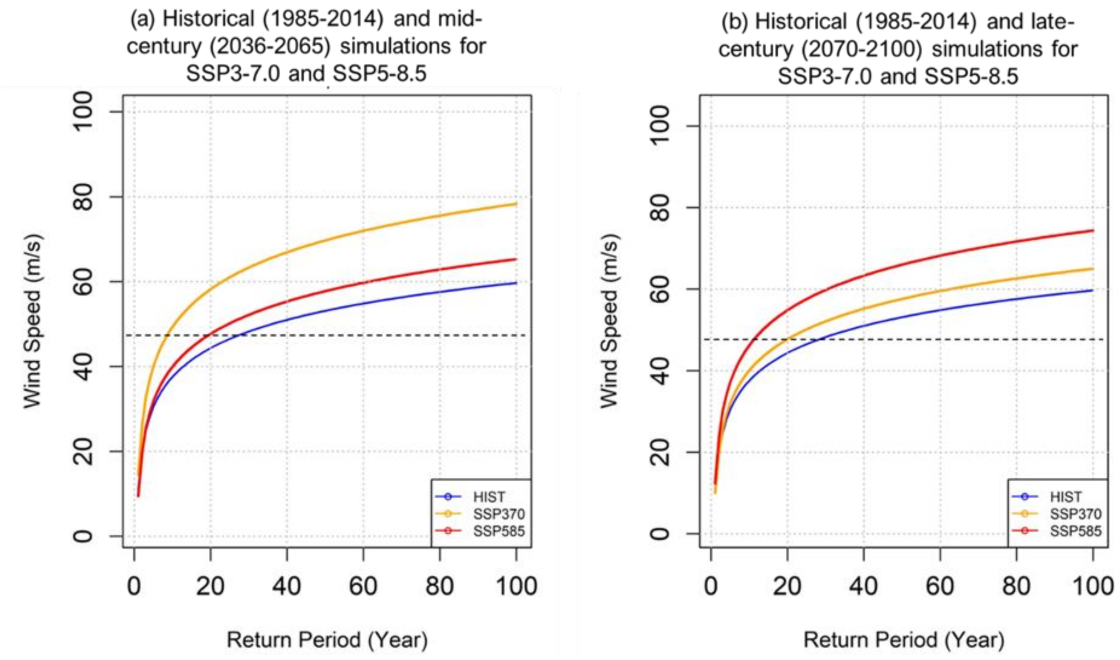


Figure 8-6 Return period curves of TC wind speed for historical (HIST, 1985-2014) and future climate simulations for (a) mid-century (2036-2065) and (b) late-century (2070-2100) under SSP3-7.0 and SSP5.8.5 scenarios. Dotted line represents lower wind speed threshold for Category 4 cyclones (i.e. 44.4 m/s as per Table 11).

We find substantial evidence that TCs are projected to become more frequent (~20- 40%) in the central Pacific region spanning Tuvalu during future El Niño periods compared with present El Niño periods, and less frequent during future La Niña and neutral periods than their present-climate counterparts [14]. These projections have low confidence because global climate model simulations have coarse resolution and the number of CMIP6 models with relevant data is limited [11].

Extreme Winds and Storminess days

Tropical cyclones are among one of many factors that often cause extreme winds over Tuvalu. Other factors may include, but are not limited to, west wind bursts associated with the Madden-Julian Oscillation (MJO, e.g., [19]) and strengthening trade winds (e.g., [20]). Therefore it is worth considering extreme winds due to all factors, not just TCs (in the previous).

Extreme winds over Tuvalu were analysed using five CMIP6 models for the three different emissions pathways (SSP1-2.6, SSP2-4.5 and SSP5-8.5) to determine the extent to which extreme winds may change in future. Since simulated wind data tend to under-estimate historical intensity of extreme winds, the data have been statistically bias-corrected with available observational records (such as those from station data and TAO/TRITON buoys in the tropical Pacific [21]). Care must be exercised when interpreting the following results in the context of future climate change.

Overall, there is a large variability in annual maximum extreme winds within and between models for both mid-century (Figure 8-7) and late-century periods (Figure 8-8), making it difficult to discern any significant trend.

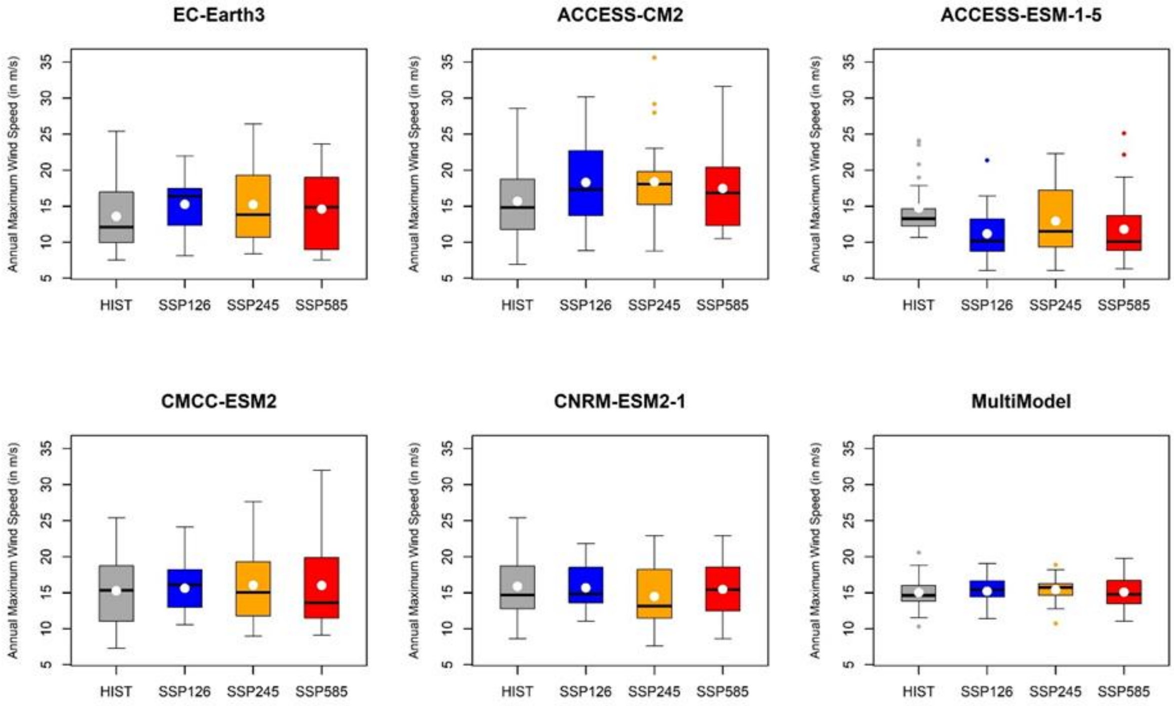


Figure 8-7 Comparison of Tuvalu annual maximum windspeed (m/s) for periods 1985-2014 (Hist) and mid-century 2040-2060 using five CMIP6 models under low (SSP1-2.6), medium (SP2-4.5) and very high (SSP5-8.5) emissions pathways. The multi-model mean is shown in the bottom right panel. In each box/whisker plot, the central dot and line are the mean and median, respectively, and the box defines the 25-75th percentile range, and the whiskers define the 10-90th percentile range.

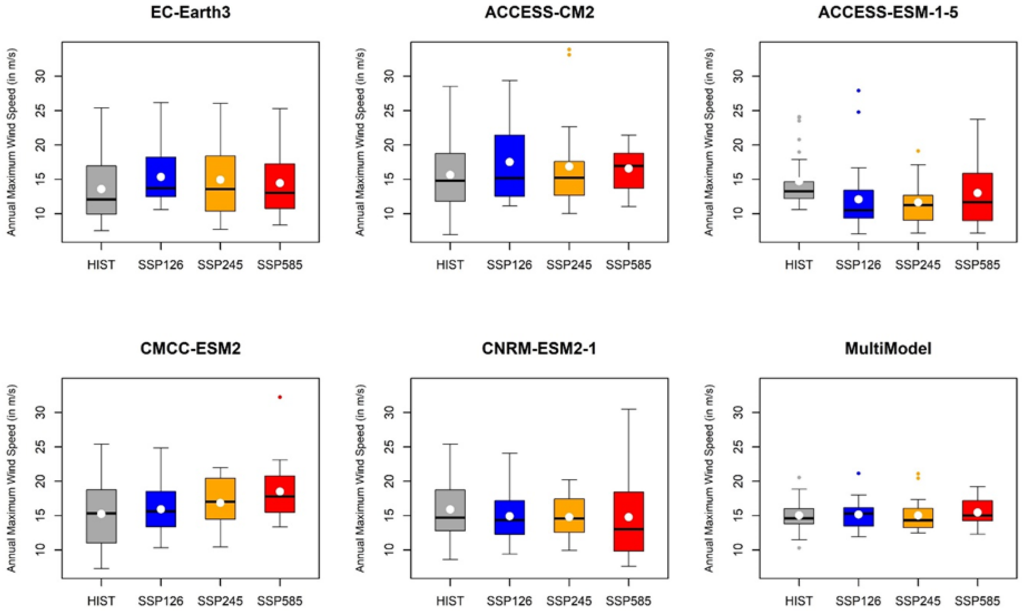


Figure 8-8 Same as Figure 18, but for end of the twenty-first century (2080-2100) simulation.

The number of "storminess days” is relevant to conditions that are unsafe for fishing. This is defined as any day on which the maximum wind speed exceeds the threshold of 20 knots (or 10.29 m/s). Figure 8-9 and Figure 8-10 indicate that the number of unsafe fishing days may increase in future. To put this change into context, the number of unsafe days in present climate is around 4 days per year. This may increase to up to 6 or 7 days by mid-century, and up to 8 days by late-century, under the SSP5-8.5 pathway. While changes in tropical cyclone characteristics is one factor that may be contributing to the increase, it is not clear to what extent other factors such as strengthening trades winds and the MJO-related westerly wind busts are contributing to the changes. Future work is needed to investigate this.

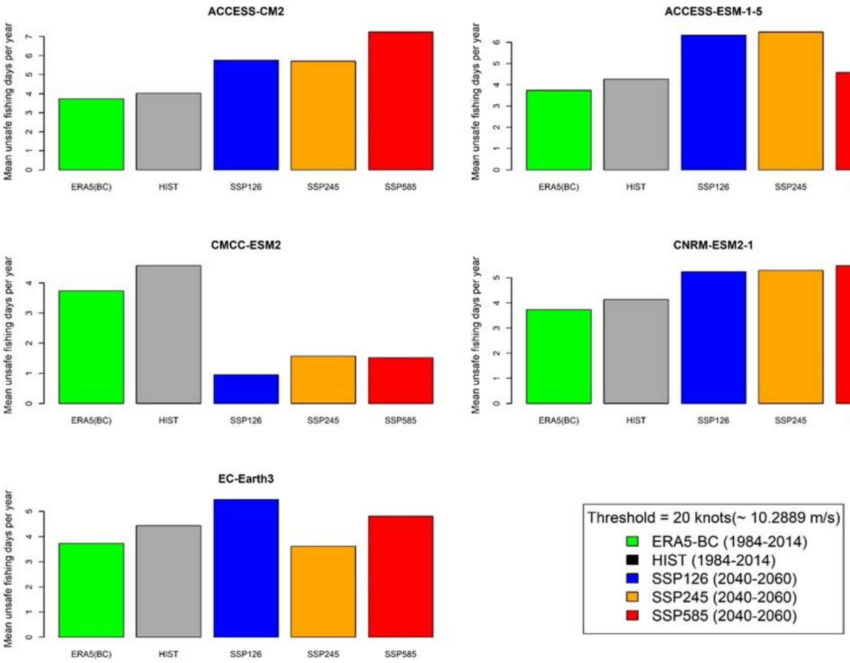


Figure 8-9 Comparison of Tuvalu storminess days distributions for the historical period (1985-2014) and for the period 2040-2060 under low (SSP1-2.6), medium (SP2-4.5) and very high (SSP5-8.5) emissions pathways.

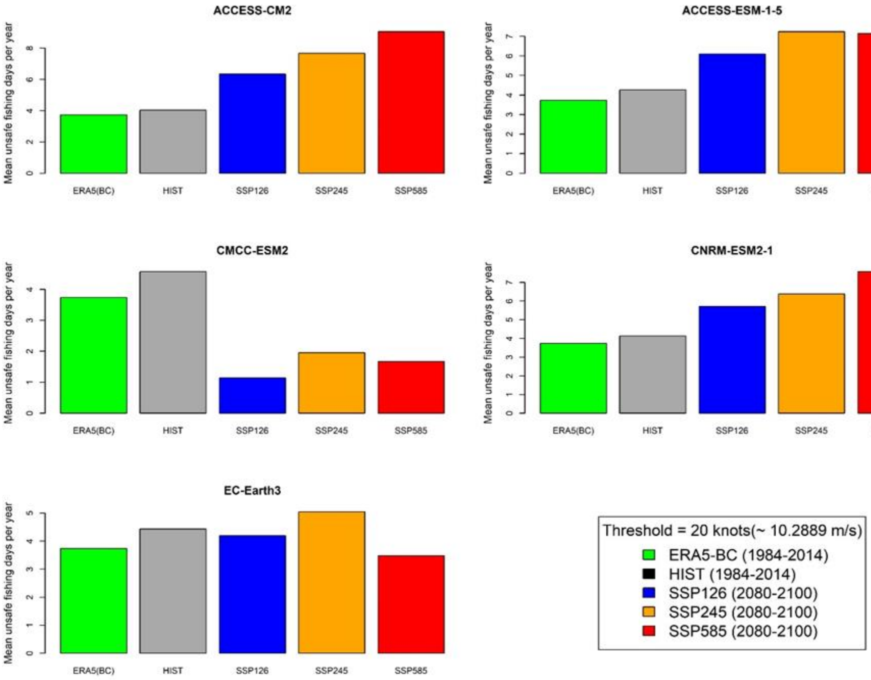


Figure 8-10 Same as Figure 20 but for the period 2080-2100.

Caveats, uncertainties, confidence, and limitations

Care must be exercised when interpreting historical and projected changes in TC frequency and intensity. High interannual variability and the small number of tropical cyclones occurring in the Tuvalu EEZ make reliable identification of long-term trends difficult.

Estimating the future behaviour of TCs in the Pacific presents significant technical challenges. This is primarily due to the complex factors that drive TCs, the limitations of historical data, and the inherent uncertainty associated with climate models' ability to accurately simulate both the frequency and intensity of TCs over multi-decadal timescales. These limitations are further complicated by the presence of large natural variability [7, 22]. However, undertaking analyses using different techniques can add confidence to the projections (e.g. [10, 13]), noting that selection of climate models should account for how well each model can simulate observed TC features. Different or conflicting results can also be reported in different experiments because of the different regional buffers used for analysis. For example, one assessment used the Exclusive Economic Zones, which are typically ~370 km from shorelines [23], while this assessment uses a 500 km buffer.

It is important to assess the level of confidence in TC projections when communicating results, e.g., [17]. The projected increase in rainfall associated with TCs is robust (high confidence) [17]. Some climate models indicate a poleward shift in TC formation, but there is substantial uncertainty and low-medium confidence. CMIP6 climate models still have difficulty with simulations of key ENSO features [15]. Recent research indicates the potential for more uncertainty of ENSO projections in climate models, which has implications for regional TC frequency, especially concerning the observational records appearing to show a "La Niña-like" strengthening of the zonal SST gradient over the past century, whereas most climate model simulations project "El Niño-like" changes toward a weaker gradient [24]. A better understanding of the fundamental mechanisms of both is needed to reduce the uncertainty [17]. Therefore, the projected decrease in TC frequency and increase in TC intensity have low confidence. Further TC research is needed using fine-resolution downscaling of a large sample of CMIP6 climate models.

References

1. Deo, A., S.S. Chand, R.D. McIntosh, B. Prakash, N.J. Holbrook, A. Magee, A. Haruhiru, and P. Malsale, Severe tropical cyclones over southwest Pacific Islands: economic impacts and implications for disaster risk management. *Climatic Change,* 2022. 172(3-4): p. 38.
2. Hoeke, R.K., H. Damlamian, J. Aucan, and M. Wandres, Severe flooding in the atoll nations of Tuvalu and Kiribati triggered by a distant Tropical Cyclone Pam. *Frontiers in Marine Science,* 2021. 7: p. 539646.
3. NOAA. *Tropical Cyclone Structure*. 2023 Available from: https://www.noaa.gov/jetstream/tropical/tropical-cyclone-introduction/tropical-cyclone-structure.
4. Tory, K.J., H. Ye, and G. Brunet, Tropical cyclone formation regions in CMIP5 models: a global performance assessment and projected changes. *Climate Dynamics,* 2020. 55(11-12): p. 3213-3237.
5. Chand, S.S., A. Dowdy, S. Bell, and K. Tory, A review of South Pacific tropical cyclones: impacts of natural climate variability and climate change. *Climate change impacts in the Pacific,* 2020: p. 251-273.
6. Australian Bureau of Meteorology. *"What is a Tropical Cyclone?,"* 2023 Available from: http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/understanding/tc-info/.
7. McGree, S., G. Smith, E. Chandler, N. Herold, Z. Begg, Y. Kuleshov, P. Malsale, and M. Ritman, *Climate Change in the Pacific 2022: Historical and Recent Variability, Extremes and Change.* . 2022 Climate and Oceans Support Program in the Pacific. Pacific Community: Suva, Fiji.; Available from: https://library.sprep.org/content/climate-change-pacific-2022-historical-and-recent-variability-extremes-and-change
8. Knapp, K.R., M.C. Kruk, D.H. Levinson, H.J. Diamond, and C.J. Neumann, The international best track archive for climate stewardship (IBTrACS) unifying tropical cyclone data. *Bulletin of the American Meteorological Society,* 2010. 91(3): p. 363-376.
9. Chand, S.S. and K.J. Walsh, Tropical cyclone activity in the Fiji region: Spatial patterns and relationship to large-scale circulation. *Journal of Climate,* 2009. 22(14): p. 3877-3893.
10. Knutson, T., S.J. Camargo, J.C. Chan, K. Emanuel, C.-H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, and K. Walsh, Tropical cyclones and climate change assessment: Part I: Detection and attribution. *Bulletin of the American Meteorological Society,* 2019. 100(10): p. 1987-2007.
11. Chand, S., A. Deo, L. Webb, M. Grose, G. Gooley, and K. Pearce, *Tropical cyclones and climate change: Implications for Tuvalu*. 2021 CSIRO and SPREP: Melbourne, Australia.
12. O'Neill, B.C., C. Tebaldi, D.P. Van Vuuren, V. Eyring, P. Friedlingstein, G. Hurtt, R. Knutti, E. Kriegler, J.-F. Lamarque, and J. Lowe, The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geoscientific Model Development,* 2016. 9(9): p. 3461-3482.
13. Bell, S.S., S.S. Chand, K.J. Tory, A.J. Dowdy, C. Turville, and H. Ye, Projections of southern hemisphere tropical cyclone track density using CMIP5 models. *Climate Dynamics,* 2019. 52: p. 6065-6079.
14. Chand, S.S., K.J. Tory, H. Ye, and K.J. Walsh, Projected increase in El Niño-driven tropical cyclone frequency in the Pacific. *Nature Climate Change,* 2017. 7(2): p. 123-127.
15. Erickson, N.E. and C.M. Patricola, Future projections of the El Niño—Southern Oscillation and tropical Pacific mean state in CMIP6. *Journal of Geophysical Research: Atmospheres,* 2023. 128(21): p. e2022JD037563.

16. Tory, K.J., S.S. Chand, J.L. McBride, H. Ye, and R. Dare, Projected changes in late-twenty-first-century tropical cyclone frequency in 13 coupled climate models from phase 5 of the Coupled Model Intercomparison Project. *Journal of Climate,* 2013. 26(24): p. 9946-9959.
17. Knutson, T., S.J. Camargo, J.C. Chan, K. Emanuel, C.-H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, and K. Walsh, Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society,* 2020. 101(3): p. E303-E322.
18. Chand, S.S., K.J.E. Walsh, S.J. Camargo, J.P. Kossin, K.J. Tory, M.F. Wehner, J.C.L. Chan, P.J. Klotzbach, A.J. Dowdy, S.S. Bell, H.A. Ramsay, and H. Murakami, Declining tropical cyclone frequency under global warming. *Nature Climate Change,* 2022. 12(7): p. 655-661 DOI: 10.1038/s41558-022-01388-4.
19. Liang, Y., A.V. Fedorov, V. Zeitlin, and P. Haertel, Excitation of the Madden–Julian oscillation in atmospheric adjustment to equatorial heating. *Journal of the Atmospheric Sciences,* 2021. 78(12): p. 3933-3950.
20. Latif, M., T. Bayr, J. Kjellsson, J.F. Lübbecke, T. Martin, H.C. Nnamchi, W. Park, A. Savita, J. Sun, and D. Dommenget, Strengthening atmospheric circulation and trade winds slowed tropical Pacific surface warming. *Communications Earth Environment* 2023. 4(1): p. 249.
21. Hayes, S., L. Mangum, J. Picaut, A. Sumi, and K. Takeuchi, TOGA-TAO: A moored array for real-time measurements in the tropical Pacific Ocean. *Bulletin of the American Meteorological Society,* 1991. 72(3): p. 339-347.
22. CSIRO and SPREP, *Tropical Cyclones and Climate Change: implications for the Western Tropical Pacific.* 2022 Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP): Melbourne, Australia.
23. Kuleshov, Y., R. Fawcett, L. Qi, B. Trewin, D. Jones, J. McBride, and H. Ramsay, Trends in tropical cyclones in the South Indian Ocean and the South Pacific Ocean. *Journal of Geophysical Research: Atmospheres,* 2010. 115(D1).
24. Lee, S., M. L'Heureux, A.T. Wittenberg, R. Seager, P.A. O'Gorman, and N.C. Johnson, On the future zonal contrasts of equatorial Pacific climate: Perspectives from Observations, Simulations, and Theories. *Climate Atmospheric Science,* 2022. 5(1): p. 82.

Chapter 9 Sea Level Rise and Coastal Inundation

Introduction

All of Tuvalu's islands are extremely low-lying, with the LiDAR DEM measurement of highest natural elevation being 6.54 m on Nuilakita [1]. Coastal inundation and groundwater intrusion risks arise due to a combination of factors, including tides, storm surge and waves, interannual sea level variability, and sea level rise (SLR).

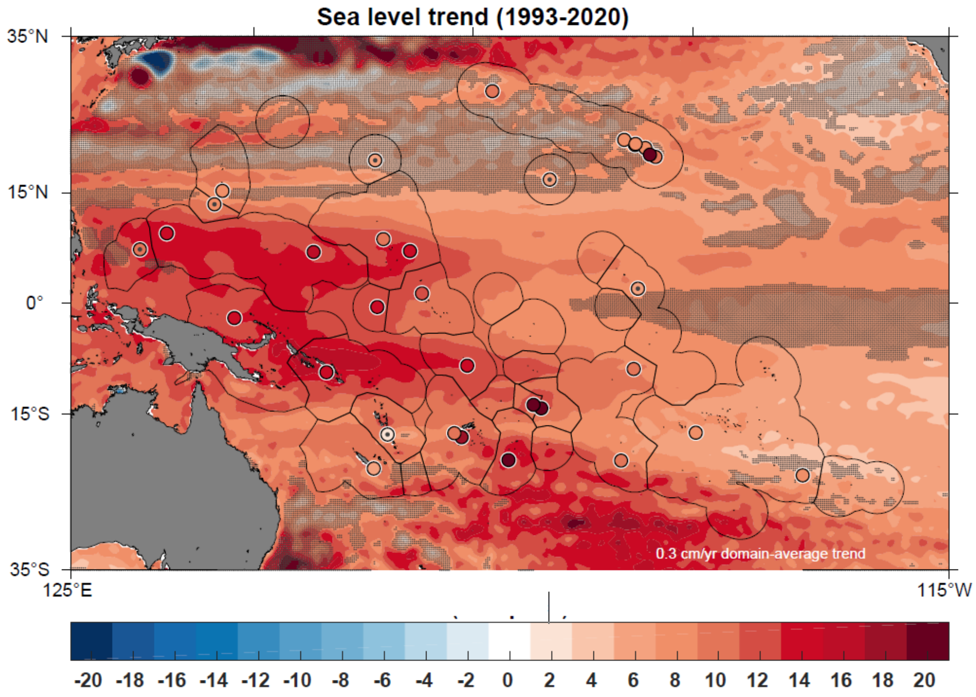
The impacts from coastal inundation depend largely on the exposure and vulnerability of local communities and related infrastructure and commerce/trade. Tuvalu communities are highly exposed because the population of 12,000 live within 1 km of the coast [2, 3].

The Tuvalu Coastal Adaptation Project (TCAP) is implementing measures that reduce exposure to coastal hazards in the three target islands, developing a long term coastal adaptation strategy, building capacity of national and local authorities to better implement adaptation actions, and investing in youth as future stewards of a resilient nation (https://tcap.tv). The physical climate change risks from SLR and storm-surge, coastal inundation and groundwater upwelling are for the most part well understood through the work of the TCAP. It follows that this assessment of hazards and impacts draws primarily from the key findings and outcomes of the TCAP (see TCAP breakout box for more details).

Observations and trends

Sea level

One of the most pressing climate change concerns for Tuvalu is the rise in sea levels and the associated projected shoreline retreat resulting from global warming [4]. Global mean sea level rose 20 cm between 1901-2018 [5, 6] with 15 cm in the past 30 years [7]. Over the western tropical Pacific, sea level rose about 10–15 cm between 1993 and 2020 [8], which is faster than in the central and eastern parts of the tropical Pacific [9] (Figure 9-1; top). Tide gauge measurements indicate a rise of 0.43 cm/year for the period 1992 to 2020 (Figure 9-1; bottom).



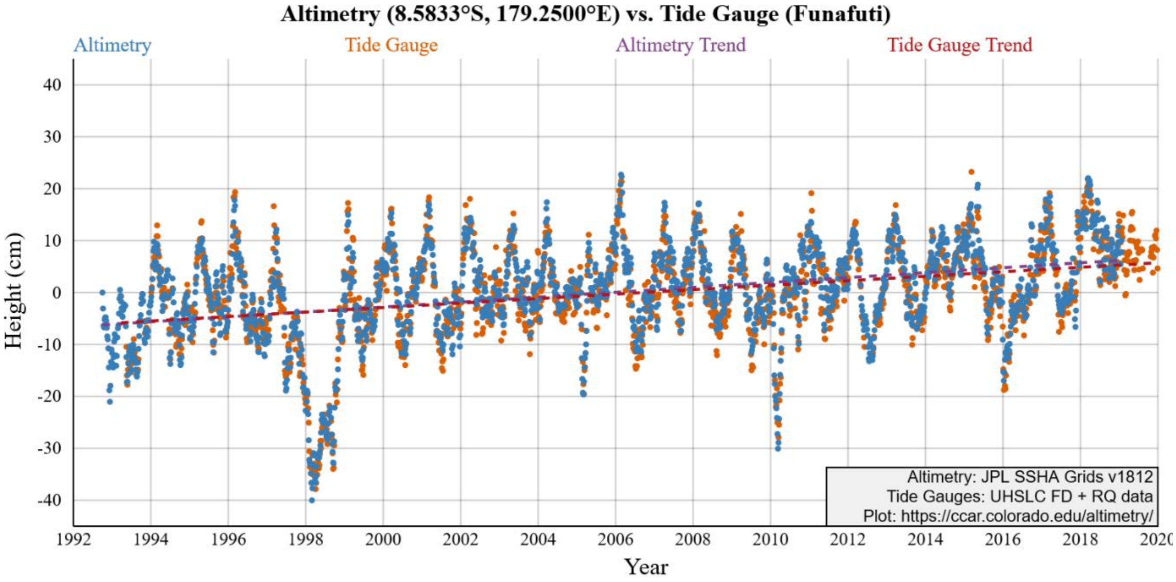


Figure 9-1 Top: Sea surface height (SSH) trends (cm/epoch) from satellite altimetry (shaded contours) and sea level trends from tide gauges (circles) during 1993–2020. Trends that are less than interannual variability, which is determined by the standard deviation of monthly anomalies, are indicated by hatching and circles with dots for the altimetry and tide gauges, respectively. Source: [8] Bottom: Daily SSH data from satellite altimetry and the Funafuti tide gauge measured relative sea level (see Sea Level Explorer Tool (https://ccar.colorado.edu/altimetry/).

Sea level rise is particularly of note for Tuvalu's total land area of 25.3 km^2 (MHWS), because the highest natural points are 6.54 metres above sea level in Niulakita based on recently collected LiDAR data [1][4]. Tuvalu is therefore very vulnerable to coastal inundation, saltwater intrusion, flooding and erosion, particularly in the vicinity of windward sites of the atoll islands [7, 11, 12]. Measurements taken in Fongafale indicate land subsidence at a rate between 1993 and 2023 of 1.4 mm per year [7]; with the rate most likely varying across the archipelago. If subsidence rates increase, SLR impacts will increase accordingly [13].

Elevation (and land area) is being increased in some locations through land reclamation [14, 15]. The Government of Tuvalu's long-term adaptation plan, 'L-TAP', is designed to accommodate the population safely beyond 2100 (beyond the time frame scope of this current assessment), by reclaiming a 3.6 square kilometre footprint on Funafuti [16].

Sea level variability

The tropical Pacific experiences very large internal and decadal sea level variability, which to some degree confounds these regional sea level rise rate differences. Seasonal variations in sea level can occur due to changes in ocean temperature, ocean currents or prevailing pressure and wind patterns. At Funafuti the seasonal range is 0.00 to 0.09 with higher values around March and lower values around September [17]. The year-to-year variations in sea level are closely associated with the El Niño-Southern Oscillation. During El Niño events, sea level around Tuvalu typically drops in January- February-March following the onset of the event in the previous year. Within the

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[4] Human induced increases in elevation extend higher to ~10.48 m but these dredge spoil mounds are not considered stable substrate". 10. FUGRO, *Report of survey airborne LiDAR acquisition across Tuvalu's nine atolls*. 2019 Fugro Document No. TLCS 00.066.006; Available from: https://tcap.tv/news/2021/10/27/lidar-imagery-data-in-tuvalu-an-empowering-tool-against-climate-change-chegj..

observational record, these drops can exceed 20 cm, although there is substantial variability from year-to-year. During La Niña events, sea level in Tuvalu does not exhibit a substantial response [7]. Additionally, the Madden-Julian Oscillation which is more active in the austral summer can create significant sea level variations resulting from wind-stress anomalies, with a larger response found along western coastlines [7, 18].

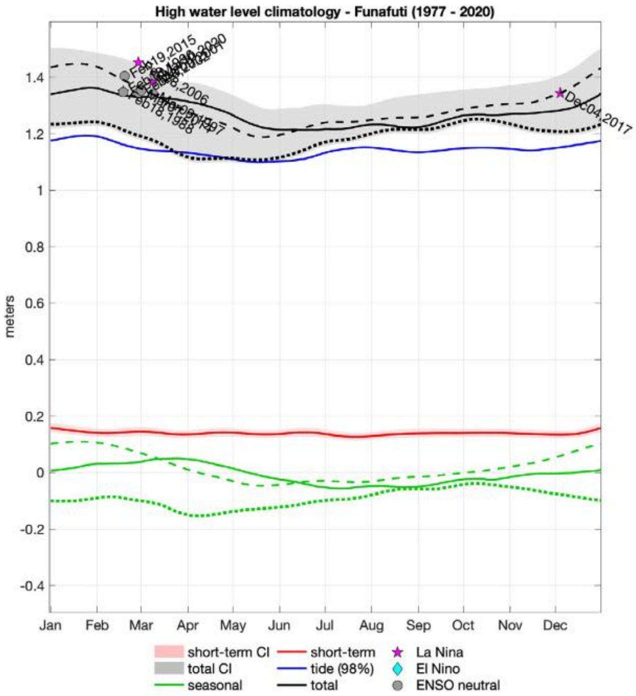

Figure 9-2The annual cycle of high waters relative to mean sea level (MSL) due to tides, short-term fluctuations (most likely associated with storms) and seasonal variations for Funafuti. The tides and short-term fluctuations are respectively the 98% exceedance levels of the astronomical high tides relative and the short-term sea level anomaly fluctuations (both relative to MSL). Components computed only for El Niño and La Niña years are shown by dotted and dashed lines, and black lines are the total (sum of the tide, short-term and seasonal components). Overall confidence intervals (CI) for total water levels are shaded in grey. The 10 highest sea level events in the record relative are shown and coded to indicate the phase of ENSO at the time of the extreme event (Source: [17]).

Extreme sea level and coastal inundation

The annual climatology of the highest daily sea levels has been evaluated from hourly measurements by tide gauges at Funafuti (Figure 15.7). Tides and short-term sea-level fluctuations create a tendency for highest annual water levels to occur during February through March. This is consistent with the timing of most of the top 10 highest sea levels recorded which all occur during these months [19].

'King Tide' events[5] have been estimated at 3.2 m for Tuvalu [20]. The height of King Tide is affected by the combined factors of spring tide, storm surge, climate variability, and, significantly, by the warm-water effect [20]. Fongafale experiences average king tides of 3.2 m and average spring tides of 2.7 m with the terrain profile of Tuvalu drawn to illustrate the relative elevation of mean lower low water, the regular spring tide elevation, and the King Tide threshold [20] (Figure 9-3). On average, there are approximately 1.5 King Tide events every year, the rate corresponding with local observational information.

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[5] National Oceanic and Atmospheric Administration defines King Tide events as those that occur 'once or twice a year'.

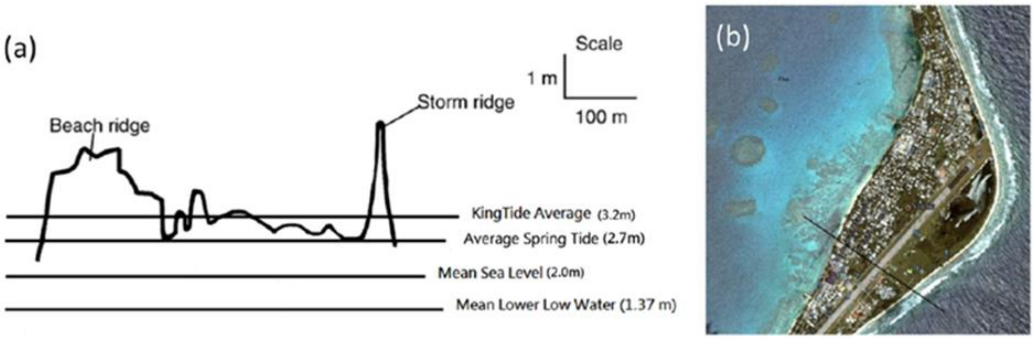

Figure 9-3 Conceptual explanation of coastal geomorphology for interpreting and analysing tidal forcing (a) relative height profiles of key datums for Fongafale, Tuvalu, and (b) Google Maps image of Fongafale, Funafuti. (Source: [20]).

The risk of being inundated is due to a combination of factors, including tides, storm surges, storm waves and interannual sea level variability (due to factors such as ENSO) [7, 21]. Local geomorphology influences the relative contributions of these different factors and how they combine to create extreme sea levels. For example, coastal bathymetry (shape of the seabed), especially the presence of offshore reefs, can influence storm surges and wave-driven contributions (*Figure* 9-4).

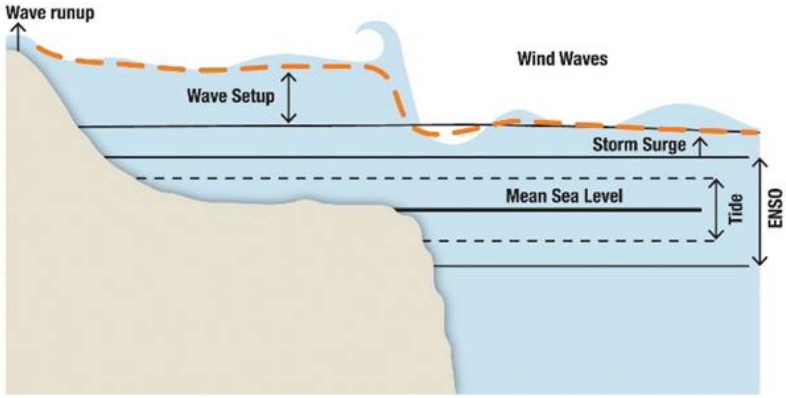

Figure 9-4 Schematic diagram of the contributions of extreme sea levels at the coast for a reef fronted island. The different contributions are tides, storm surge, storm waves and interannual sea level variability. Extreme sea levels are rare and may not always occur due to a tropical cyclone; for instance, if a storm surge happens at low tide, the total water level may not be extreme at the adjacent coastline.

Storm events and waves play important roles in total water level changes on shorter timescales (minutes to days) in Tuvalu. Storms both in the vicinity of Tuvalu or more remote to Tuvalu can lead to significant impacts for the coastlines of Tuvalu. Substantial wave setup and runup can be generated either by nearby tropical storms and cyclones or from wind-waves triggered from distant sources [22]. The compound impacts during extreme weather events are important to appreciate. The impacts of Tropical Cyclone Pam, which affected Tuvalu in 2015, resulted in locally extreme sea levels due to the combination of regional sea-level rise, tides and wind-waves [11, 21, 23].

There are three main wave energy sources affecting Tuvalu - extratropical storms in the Southern Ocean, extratropical storms in the North Pacific, as well as easterly trade winds [24]. Tuvalu's wave conditions are also linked to ENSO, the Pacific Decadal Oscillation, and the Arctic and Antarctic Oscillation [25]. In the past flooding, has occurred during the high spring tides from January to March but in recent years flooding in Tuvalu has also been experienced due to waves from cyclones (TC Pam in 2015 and TC Tino in 2020) and swell waves from distant sources (Adams et al 2023; Hoeke et al 2013).

Offshore reefs cause waves to break offshore and thereby reduce the wave energy (and height) that eventually reaches the coast (Figure 9-4). The dynamic nature of coastal foreshores can result in highly localised changes in response to currents and waves, resulting in both deposition and erosion of sand and other reef-derived materials [26, 27]. So, while mean sea level rise is slow and gradual over time, coastal inundation impacts are already being witnessed regularly throughout Tuvalu on each spring tide [20].

Sea level rise projections and exposure to inundation

Recent studies have demonstrated that wave setup and runup and thus total water level associated with these events can vary depending on the approach of a storm or direction of waves generated remotely [11]. Sea level rise will likely enhance the impact of wave runup in Tuvalu as water levels become higher over the coral reefs, allowing larger waves to reach the shoreline [7, 22]. Future SLR will trigger increases in both the frequency and the severity of episodic flooding with more than 100 days of flooding every year by 2100 [7].

Sea level rise projections

The sea level rise projections for Tuvalu[6] [28] show a median rise of about 0.13 m by 2030 (Table 9-1) compared to a 20-year baseline centred on 1995 (1986–2005), By 2050, the rise is 0.22 m for low emissions (RCP2.6) and 0.27 m for high emissions (RCP8.5). By 2090, the rise is 0.41 m for low emissions and 0.71 m for high emissions (Table 9-1 and Figure 9-5).

Table 9-1 Median sea-level projections for Tuvalu with 5–95% uncertainty range relative to 1986–2005 for RCPs 2.6, 4.5, and 8.5. Units are metres. Source: [28].

20-year periods	RCP2.6		RCP4.5		RCP8.5	
2030	0.13	[0.09–0.17]	0.12	[0.09–0.16]	0.13	[0.09–0.18]
2050	0.22	[0.17–0.29]	0.23	[0.16–0.31]	0.27	[0.19–0.37]
2070	0.32	[0.23–0.43]	0.36	[0.26–0.48]	0.46	[0.32–0.63]
2090	0.41	[0.30–0.56]	0.50	[0.36–0.68]	0.71	[0.50–1.00]

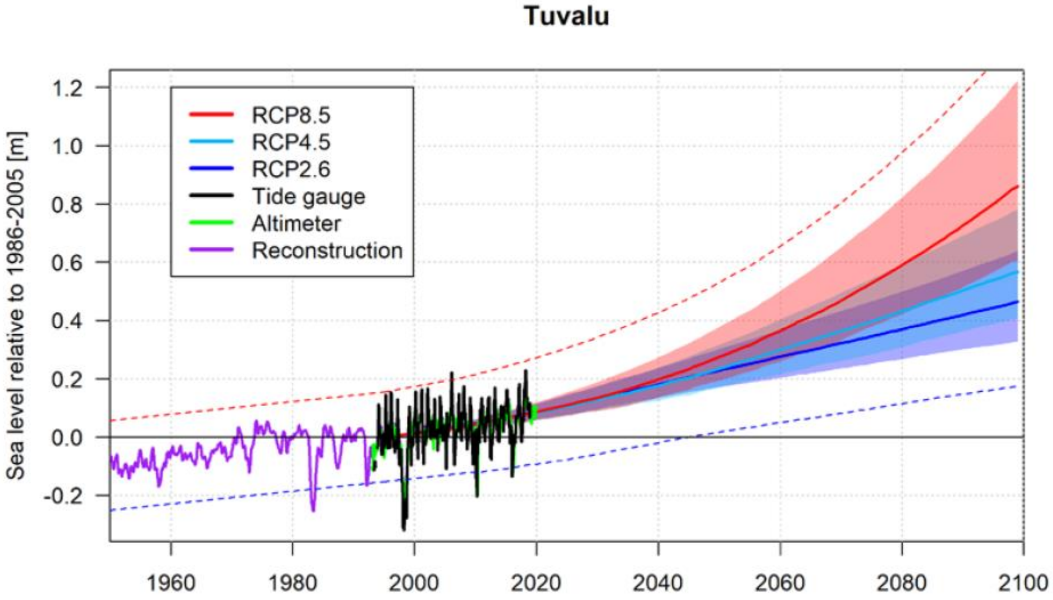

Figure 9-5 Time series of past and future sea level rise. Funafuti tide-gauge records of relative sea level are indicated in black, the satellite record in green, reconstructed sea level data in purple, all are monthly means and referenced to mean sea-level between 1986-2005. Climate-model projections from 1995–2100 are given for three RCPs with the 5–95%

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[6] This is a reassessment of CMIP5-based sea level rise projections, which were published by the IPCC in 2019. Please see Caveats section for discussion of sea level rise tipping points.

uncertainty range shown by the shaded regions. The dashed lines are an estimate of month-to-month variability in sea level (5–95% uncertainty range about the projections and reconstruction) and indicate that individual monthly averages of sea level can be above or below longer-term averages. Source [28]

Adams et al 2023 [7] provide a visual representation of the likely saltwater intrusion and shallow groundwater flooding vulnerability for 2100 using a mean of SSP2-4.5 and SSP5-8.5 for both groundwater recharge and sea level (Figure 9-6 and Figure 9-7).

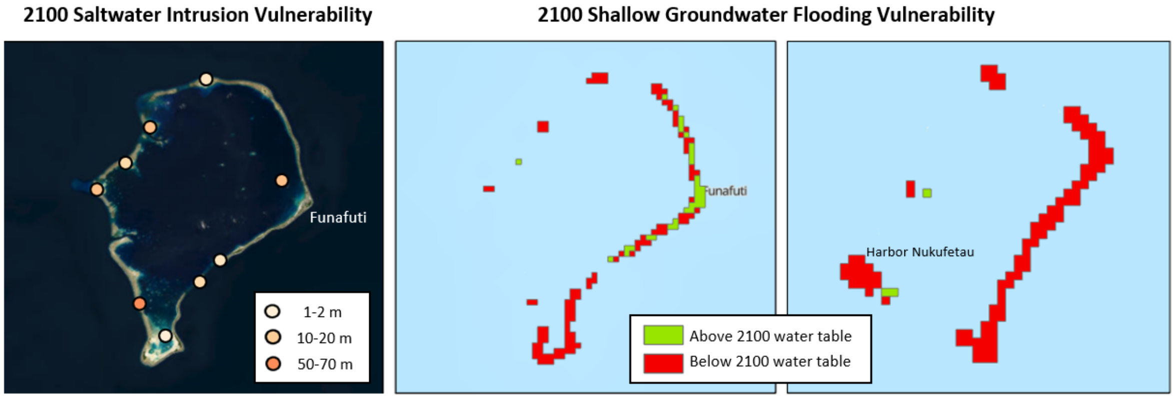


Figure 9-6 Saltwater intrusion and shallow groundwater flooding vulnerability for 2100 for Tuvalu for SSP2-45 (left and SSP5-8.5 (right). Note for saltwater intrusion, calculations are done at the centroid of different watersheds, leading to circles in the nearshore ocean for curved watersheds (e.g. near Funafuti). There is more risk of saltwater intrusion near the southwest part of the island, near Tefonufala Beach. Higher parts of the island near Funafuti display less vulnerability to shallow groundwater flooding (Source: [7].

Figure 9-7 Salt-water intrusion on land in Tuvalu

Coastal inundation projections

A recent study [24] exploring coastal inundation, includes nearshore processes such as wave setup and runup, in addition to tides and sea level, in their modelling. These processes are critical for providing fine-scale projections of coastal inundation for Tuvalu's nine main islands.

Hazard maps were calculated for the present sea level, as well as for sea level rise projections corresponding to different shared socio-economic pathways (SSP2 4.5 and SSP5 8.5) and time horizons (2060 and 2100). Figure 9-8 shows the current return intervals for flooding of Nanumea. By 2100 (SSP2 4.5) many areas presently only flooded once every 50, 100, or even 250 years may flood once every 5 or 10 years (Figure 9-8). While there are differences across the various islands, the overall trends and timelines remain similar. In Funafuti, Nui, Nukufetau, and Vaitupu, current 50-year flooding may occur once every 1 to 5years by 2060 [1].

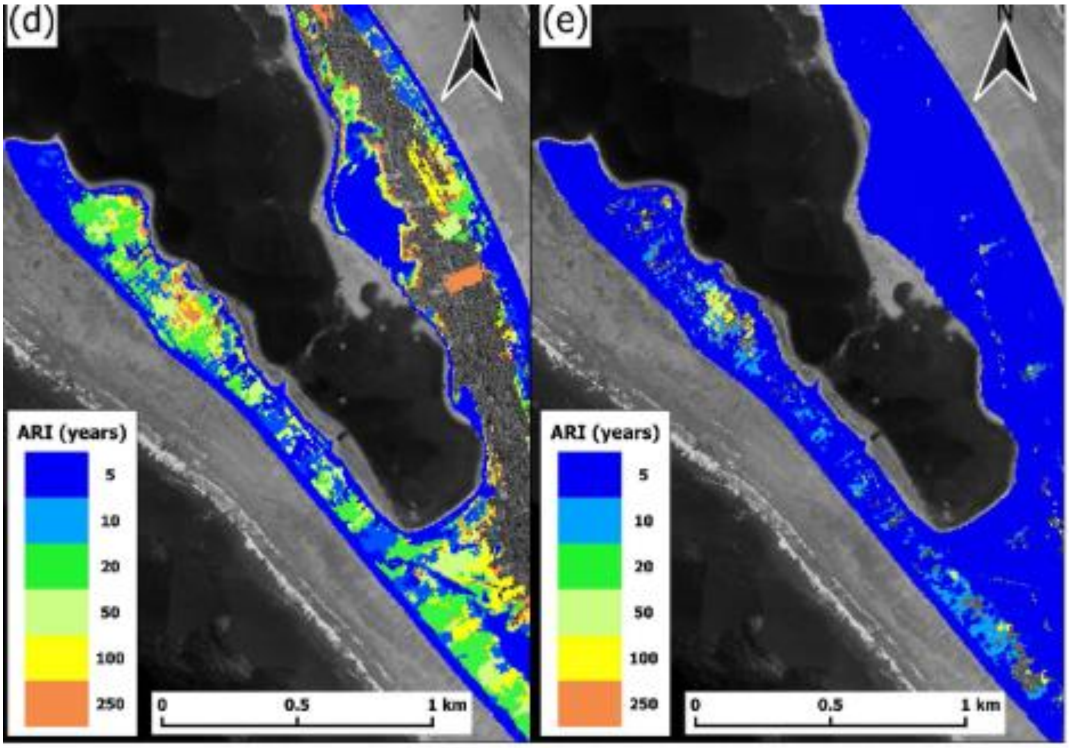


Figure 9-8 Average return intervals (ARI) for flooding in Nanumea under present sea levels (left), and under SSP2 4.5 by the year 2100 (right) (Source [24]).

The flooded area was calculated for each return period and sea level scenario (Figure 10). Under present sea levels ~6.9 km^2 (~27.2%) of land area inundate once every 5-year across all of Tuvalu. By 2060 under high emissions (SSP5-8.5), this value almost doubles to ~13.5 km^2 (~53.1%) for an ARI of 100 years (Figure 9-9). However, some islands are more likely to experience flooding than others (See chapter 2 of this report) [1]. The increase in low, medium and high tide flooding extents flooding also indicate an increase in frequency in Funafuti due to sea level rise alone [7] with detail in their study showing inundation timing under both SSP2-4.5 and SSP5-8.5.

It is noted, projected changes in wave climate are expected to only have minimal effects on inundation levels compared with changes in sea levels. However, as global warming continues, the frequency of tropical cyclones is anticipated to decrease while the intensity of tropical cyclones will increase (e.g., [29, 30]). Whether this will significantly alter the coastal flood hazard in Tuvalu remains subject to further study [1, 24].

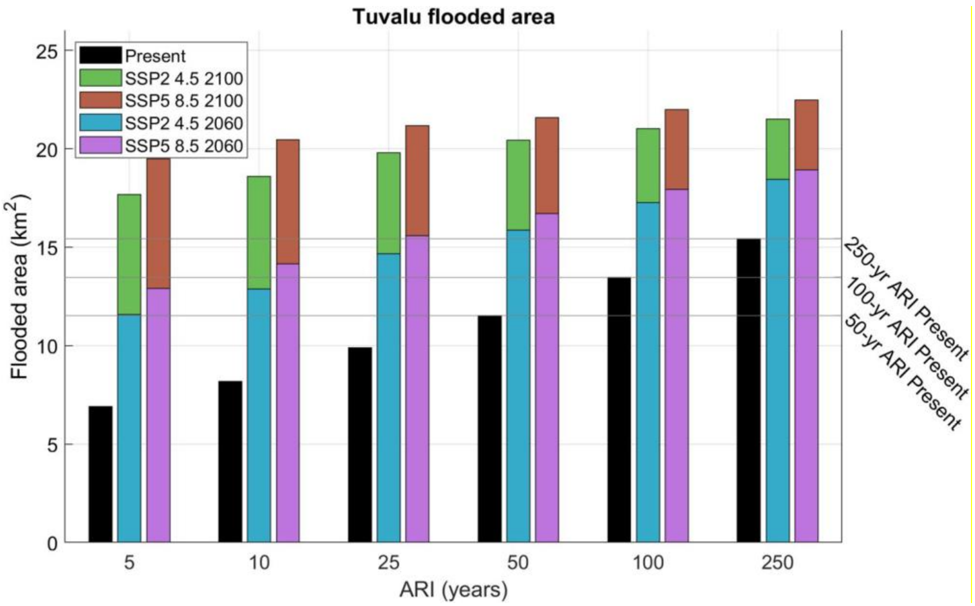


Figure 9-9 Flooded area (km^2) above MHWS across all of Tuvalu for different annual return intervals (ARIs) and sea levels. Colours represent different sea level scenarios. 50-yr ARI, 100-yr ARI, and 250-yr ARI under present sea levels are highlighted by grey lines for comparison. Source: Wandres et al., 2024

Though the projections vary across Tuvalu's islands the overall trends and timelines are similar such that in Funafuti, Nui, Nukufetau, and Vaitupu the present-day 50-year ARI flooding will become more frequent than once every 5 years by 2060 (Figure 9-10). Whereas these projections find that for Nanumaga, Nanumea, Niutao, and Nukulaelae the present day 50-year ARI flooding will occur more than once every 10 years by 2060, even under SSP2 4.5 (Figure 9-10).

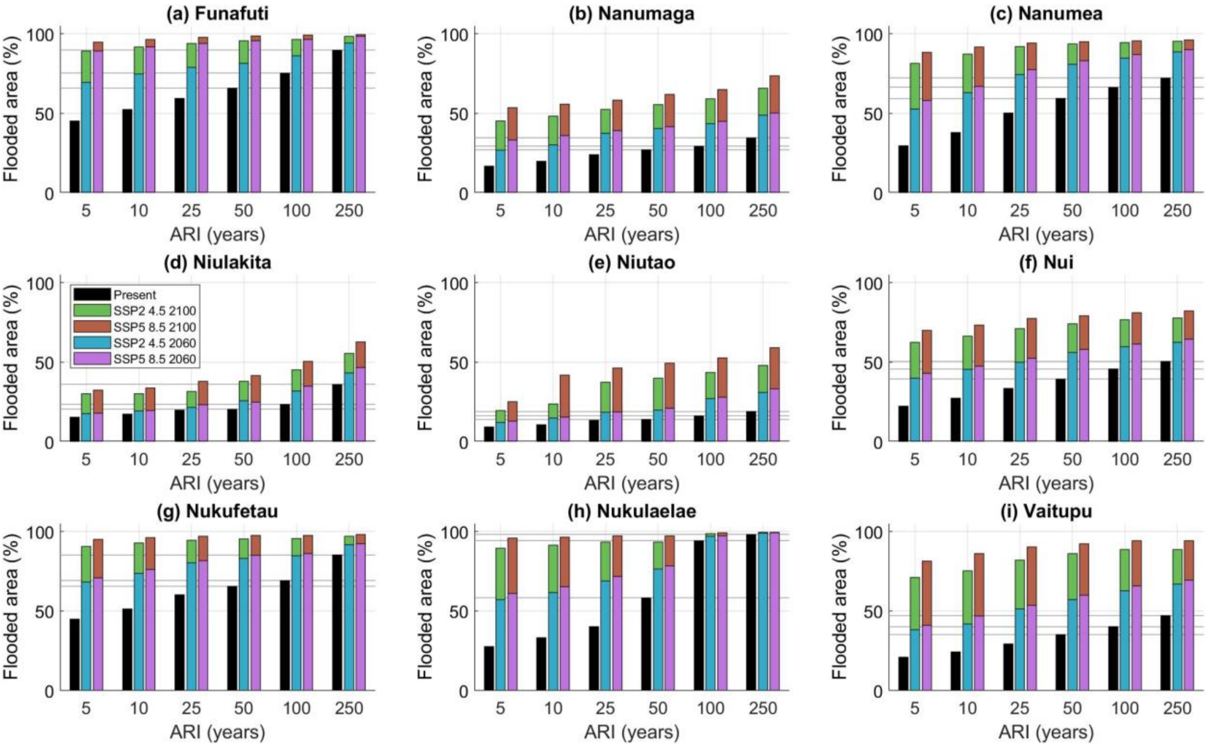


Figure 9-10 Percentage of flooded area (% of land area) above MHWS for different annual return intervals (ARIs) and sea levels for the different islands of Tuvalu. 50-yr ARI, 100-yr ARI, and 250-yr ARI under present sea levels are highlighted by grey lines for comparison. Source: Wandres et al., 2024.

Other factors affecting coastal inundation impacts.

Tsunami risk

Tuvalu's morphology means that tsunami risks present a notable hazard. In 2015, the Global Facility for Disaster Reduction and Recovery (GFDRR) assessed Tuvalu as having a medium hazard level, which means "there is more than a 10 % chance of a potentially damaging tsunami occurring in the next 50 years" [31]. However, the assessment of Tuvalu's tsunami hazard risk level is not informed by sites in Tuvalu itself, see Figure 9-11 below.

An earlier assessment of tsunami risk of southwest Pacific nations [32] pointed out that low-lying atolls such as Tuvalu and Kiribati are likely to be especially vulnerable to tsunamis due to lack of higher ground. However, they also point out that the steep declines into deep ocean may mean there is not a pronounced shoaling effect and so these islands may never experience a large tsunami [32]. Therefore, assessment of Tuvalu's tsunami risk may need to be prioritised for further research efforts to clearly elucidate the associated risks.

Geohazards such as tsunamis are forecast to increase in both severity and frequency as part of climate change impacts since tsunamis are exacerbated by sea level rise (which is responsible for causing dynamic morphological changes of the near- and onshore coastal environment). Recently it was reported that tsunami hazard intensity tends to increase linearly with sea-level rise and the impacts of climate change on tsunami risk require more research [33, 34].

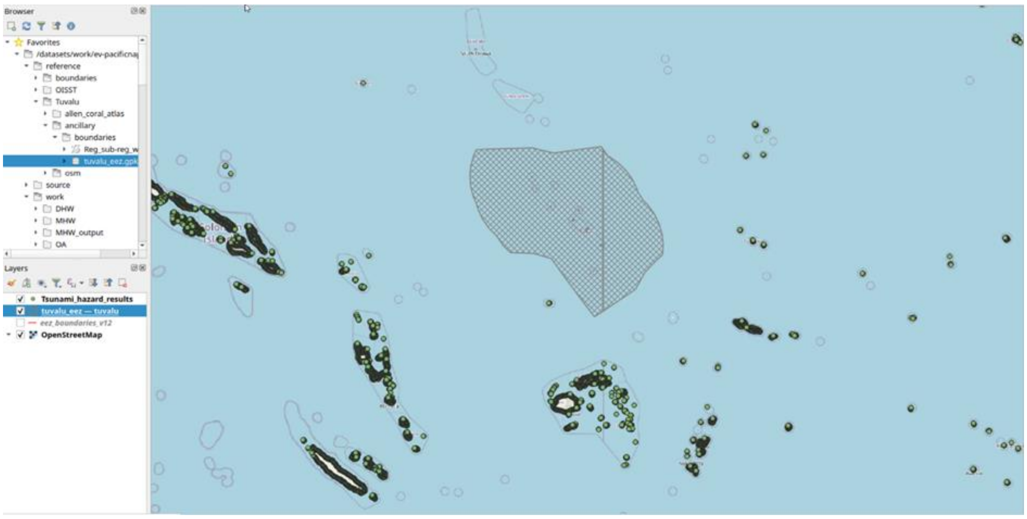


Figure 9-11: Tsunami risk assessment for the Tuvalu area, depicting which sample sites were used noting sample sites were not within the Tuvalu EEZ. Source: https://risk.preventionweb.net/download/Tsunami_hazard_results_g1545.zipavailable

Land reclamation

Several land reclamation projects have been recently completed in Tuvalu in an attempt to mitigate the risk of sea level rise under various climate change scenarios. The impacts of coastal inundation need to be re-assessed once all phases of the reclamation projects are completed and a new digital elevation model (DEM) is produced. The inundation risks may be further reduced because of the final phase in which the reclamation projects complete revegetation of the sites. Planning for long-term sea level rise out to 2100 is being considered under the LTAP initiative [16] (NB: Not in the time-frame scope of this assessment).

Borrow pit remediation through reclamation

One of the projects to address inundation impacts already experienced in Tuvalu was the filling of borrow pits which had been excavated during World War II to build Tuvalu's airstrip. The borrow pit filling project dredged over 250,000 m^3 of sand from the Funafuti lagoon [35]. The borrow pits were tidal and porous, moving waste into the lagoon, degrading the local ecosystem, and triggering human health risks with sanitation concerns – see Figure 9-12. The project to fill the borrow pits removed the sanitation risk and created a further 6 % of useable land [35].

Figure 9-12: Borrow pit filling project at Funafuti (Source: https://www.hallcontracting.com.au/projects/donors-and-international-aid/nukufetau-coastal-works-project)

Nukufetau seawall repair

Tuvalu was affected by wind-waves generated by Cyclone Pam in early 2015 [36] causing considerable flooding [11] and damage to Nukufetau. The island's concrete block seawall was destroyed, resulting in damage to homes and vulnerability to damaging cyclones (Source: https://www.hallcontracting.com.au/projects/donors-and-international-aid/nukufetau-coastal-works-project). Urgent seawall repairs were undertaken with the assistance of UNDP, as well as beach sand replenishment to restore the usable land area. The restoration work used 5 tonne geotextile sand containers (ELCOROCK) filled with local sand to re-establish the Nukufetau seawall [35].

Figure 9-13: Borrow pit filling project at Funafuti (Source: [35])

Funafuti shoreline changes

Land reclamation on Funafuti involved the addition of two strategically placed groynes constructed from 2.5 m^3 geotextile sand containers to retain the dredged beach nourishment sand (115,000 m^3

dredged from the nearby lagoon and pumped to a reclamation area). This created a new recreation area of around 40,000 m^2 with the project works carried out for 55,000 m^2 of coastline [35].

Commentary on island erosion, accretion and sea level rise

Sea level rise is one of the most significant climate hazards for Tuvalu, now and into the future, and adaptation to increasing SLR in order to protect high value coastal resources, critical infrastructure and local communities is an existing and ongoing priority. However, the coastlines of reef islands (i.e. those composed of reef-derived carbonate material), which comprise all the Tuvaluan islands, evolve naturally (changing to varying degrees) over years to decades, as local erosion or accretion occurs. This is due to the interaction of waves, winds, sea level, the calcification rates of reef organisms and subsequent reef growth and associated production of carbonate sediment, some portion of which eventually becomes part of island substrates; more recently human actions, such as land reclamation have also played a large role [37, 38].

Storm surges and waves during inundation events may be both destructive (eroding materials) and constructive (depositing new sediment); reef islands are widely expected to experience increasing erosion pressure due sea level rise this century [39]. There is strong evidence, on the other hand, that (on average) most reef islands globally have ‘kept up’ (i.e. have not experienced net erosion) with past sea level changes (at least over the last two thousand years, see Kench et al 2023 for summary). This is consistent with several independent studies of Tuvalu that show that overall, its islands do not appear to have experienced net loss of land (erosion) over the last several decades (e.g. [40, 41]), despite experiencing the sea level rise over the same period.

To what degree this will continue in future is highly uncertain, however. The projected (accelerated) rates of sea level rise combined with anticipated impacts to reef growth (marine calcification rates) due to ocean acidification and ocean temperature-related coral bleaching may rapidly outstrip reef islands’ natural ability to keep pace with sea level rise, particularly under higher emission scenarios. Also, even if some islands can keep pace with higher-end sea level rise scenarios, it will mean much more frequent inundation events [42].

There is little doubt, however, that individual islands will have highly disparate outcomes – as with many climate impacts, there will be relative winner and loser locations within Tuvalu in terms of increased vs. decreased (net) erosion. Understanding this will be a key part of successful climate adaptation, but it is complex and requires better knowledge and prediction of changes in reef growth and sediment production [38] and improved island geomorphic models [43]. Success will likely depend on implementation of carefully designed mitigation and/or intervention practices (including ecosystem-based approaches, such as that discussed in Toth, et al 2023 [44]) in concert with targeted traditional coastal engineering solutions, such as sediment renourishment or land reclamation where appropriate. This will depend on local managers to be fully cognisant of the principal drivers of coastal evolution in a changing climate [45].

When this is sufficiently understood, there are examples of carefully managed, assisted sediment transport regimes which have intervention have arguably successfully protecting coastal communities from erosion and inundation in low-lying coastal settings, such as the Tweed River and Gold Coast sand bypassing and backpassing systems on the Queensland and NSW border in Australia or the sand engine in the Netherlands which also uses an engineered mega-nourishment system [46]. These are in continental coastlines dominated by longshore transport of significant fluvial (river) sediment sources (significantly different environments from reef islands), however and the solutions they employ rely on intensive monitoring and several decades of prior study. The unique sediment dynamics of reef islands and their vulnerability of to sea level rise require new, integrated adaptation strategies to be developed to avoid critical impacts to the future viability of the islands making up Tuvalu. In particular understanding how the geomorphological impacts of SLR combined with increasing wave energy should be investigated focussed on contrasting issues for table reef islands compared to atoll islands.

Coastlines, and particularly reef islands, are expected to experience more erosion pressure due to compound hazard events (storm surge, sea level rise, coral bleaching, and ocean acidification) as a result of climate change [47]. Factors for future consideration include:

- Monitoring of land vertical movements should be more fully included in future coastal hazard assessment for Tuvalu.
- Using dynamic adaptation pathways planning ensures that appropriate adaptation strategies are used prior to impact thresholds being crossed [48].
- Ultimately, it is important to involve local people in making observations of coastal erosion to collect information about extreme weather erosion impacts.

Caveats

All of the inundation modelling discussed in this report is not able to account for island (or reef) morpho-dynamics (changes in topography/bathymetry) due to natural processes like island erosion/accretion and reef calcification (growth) or degradation due to ocean acidification, ocean warming or coral bleaching impacts [49]. This is important, since in realty significant changes in all of these factors will occur.

There are significant uncertainties about sea level rise and coastal inundation [50]. Table 9-1 quantifies the 5-95 percentile range of uncertainty for sea level rise, but larger values are possible. These ‘low likelihood high impact’ scenarios, can be very confronting and confusing for stakeholders, so it is important to describe the associated confidence ratings and uncertainties [51]. The most relevant sea-level tipping point for Tuvalu is extremely high sea level rise due to rapid ice sheet disintegration [52], but there is high uncertainty about whether, and on what time scale, such changes will occur.

A predictive model included a correlation between global mean surface temperature and Antarctic ice-mass loss, and a projection of global mean surface temperature for a high (RCP8.5) greenhouse gas concentration pathway, giving a median SLR of 1.84 m, and a 95th percentile value of 2.92 m, by the year 2100 relative to the year 2000 [52]. These findings are higher than IPCC (2021) [5] projections for the high (SSP5-8.5) concentration pathway indicating a 'low confidence’ 95th percentile value of 2.3 m by 2100, relative to 1995-2014 (Figure 9-14). More recently an analysis based on physical storylines arrived at a lower value of up to 1.6 m in 2100 and up to 10.4 m by 2300 [53].

Sweet et al (2022) [54] report a range of projections of relative sea level along the contiguous U.S. coastline being 0.6–2.2 m by 2100 relative to 2000. This broad range is driven by uncertainty in the response of the underlying physical processes. “For the low-confidence ice-sheet processes and high emissions pathways, probabilities rise to about 50 %, 20 %, and 10 % of exceeding 1.0 m, 1.5 m, or 2.0 m of global rise by 2100, respectively.” Sweet et al’s high end estimates put a lot of emphasis on a single study (that of DeConto and Pollard 2016 [55]) which was not used in SROCC or AR6 because the Marine Ice Cliff instability (MICI) process was not considered to be a major factor on the time scale of 2100. Similarly the medium confidence projections of AR6 do not include MICI.

While extremely high sea level rise scenarios are relevant for stress-testing and risk screening, they are associated with low confidence and low likelihood, so should be treated with caution. The high uncertainty around these SLR ranges should reduce over the next decade when both marine ice sheet instability and marine ice cliff instability become better understood and incorporated into the models [5]. Furthermore, the high concentration pathway is considered to have low likelihood given recent emissions growth rates and policies [56].

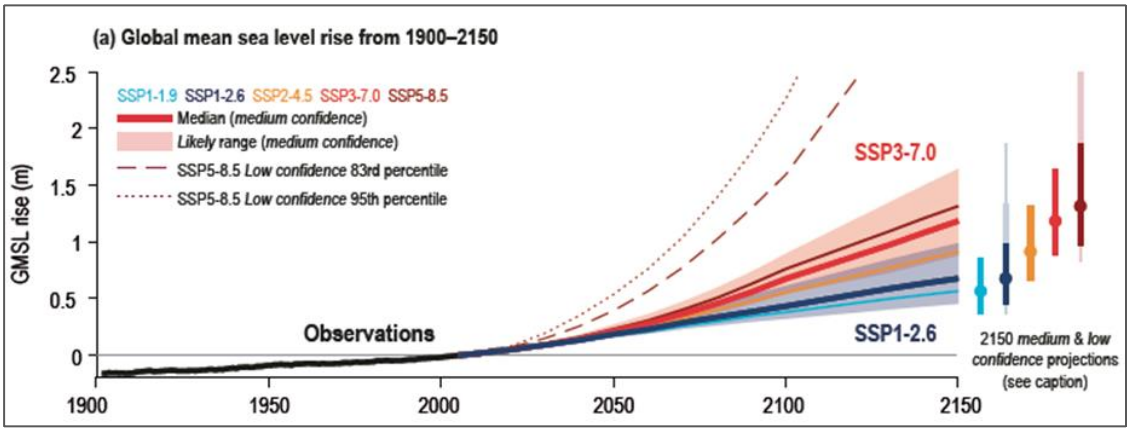


Figure 9-14 Global mean sea level (GMSL) rise on different time scales and under different scenarios. The observed change from 1900 to 2018 (black line) is shown along with projected changes from 2000–2150 relative to a 1995–2014 baseline. Solid lines show median projections. Shaded regions show likely ranges for SSP1-2.6 and SSP3-7.0. Dotted and dashed lines show respectively the 83rd and 95th percentile low confidence projections for SSP5-8.5. Bars at right show likely ranges for SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 in 2150. Lightly shaded thick/thin bars show 17th–83rd/5th–95th percentile low-confidence ranges in 2150 for SSP1-2.6 and SSP5-8.5, based upon projection methods incorporating structured expert judgement and marine ice cliff instability Source: [5] Box TS.4.

References

1. Wandres, M., A. Espejo, T. Sovea, S. Tetoa, F. Malologa, A. Webb, J. Lewis, G. Lee, and H. Damlamian, A national‐scale coastal flood hazard assessment for the atoll nation of Tuvalu. *Earth's Future,* 2024. 12(4): p. e2023EF003924.
2. Andrew, N.L., P. Bright, L. de la Rua, S.J. Teoh, and M. Vickers, Coastal proximity of populations in 22 Pacific Island Countries and Territories. *PLoS One,* 2019. 14(9): p. e0223249.
3. SPC. *Mapping (Coastal)*. 2021 Available from: https://sdd.spc.int/mapping-coastal.
4. Ceccarelli, D.M., *Chapter 32 - Tuvalu*. 2019 Academic Press; Available from: https://www.sciencedirect.com/science/article/pii/B9780081008539000415.
5. IPCC, ed. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. ed. V. Masson-Delmotte, et al. 2021, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, .
6. IPCC, *The ocean and cryosphere in a changing climate*. 2019; Available from: https://www.ipcc.ch/srocc/chapter/summary-for-policymakers/.
7. Adams, K., C. Blackwood, R. Cullather, B. Hamlington, E. Heijkoop, K. Karnauskas, R. Kopp, E. Larour, T. Lee, and R.S. Nerem, Assessment of Sea Level Rise and Associated Impacts for Tuvalu. 2023.
8. Marra, J.J., J.T. Potemra, A. Espejo, N. Fauchereau, A. Genz, V. Hernaman, S. Heron, G. Smith, L. Webb, M.J. Widlansky, P.I. Woodworth-Jefcoats, D. (Eds.), and P.D. 10.5281/zenodo.6965143, *Ocean* Ch *2* in *Pacific Climate Change Monitor: 2021*, Marra et al., Editor. 2022: The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC).
9. Fasullo, J.T. and R.S. Nerem, Altimeter-era emergence of the patterns of forced sea-level rise in climate models and implications for the future. *Proceedings of the National Academy of Sciences,* 2018. 115(51): p. 12944-12949.
10. FUGRO, *Report of survey airborne LiDAR acquisition across Tuvalu's nine atolls*. 2019 Fugro Document No. TLCS 00.066.006; Available from: https://tcap.tv/news/2021/10/27/lidar-imagery-data-in-tuvalu-an-empowering-tool-against-climate-change-chegj.

11. Hoeke, R.K., H. Damlamian, J. Aucan, and M. Wandres, Severe flooding in the atoll nations of Tuvalu and Kiribati triggered by a distant Tropical Cyclone Pam. *Frontiers in Marine Science,* 2021. 7: p. 539646.
12. Islam, S.N., S. Reinstädtler, M.S. Reza, S. Afroze, and A.K. Azad, Climate change versus livelihoods, heritage and ecosystems in small Island states of the Pacific: a case study on Tuvalu. *Environment, Development and Sustainability,* 2023. 25(8): p. 7669-7712 DOI: 10.1007/s10668-022-02367-7.
13. Wu, G., Q. Liu, H. Xu, and J. Wang, Modelling the combined impact of sea level rise, land subsidence, and tropical cyclones in compound flooding of coastal cities. *Ocean & Coastal Management,* 2024. 252: p. 107107 DOI: https://doi.org/10.1016/j.ocecoaman.2024.107107.
14. Farbotko, C., I. Boas, R. Dahm, T. Kitara, T. Lusama, and T. Tanielu, Reclaiming open climate adaptation futures. *Nature Climate Change,* 2023. 13(8): p. 750-751 DOI: 10.1038/s41558-023-01733-1.
15. TCAP. *Tuvalu unveils long-term adaptation plan at COP27, a vision for a safe, climate-resilient future*. 2022 Available from: https://go.nature.com/3r4UEd0.
16. Government of Tuvalu, UNDP, and TCAP. *Government of Tuvalu's long-term adaptation plan (LTAP)*. 2023 Available from: https://tcap.tv/.
17. CSIRO and SPREP, *Extreme Sea Level Climatologies for the Western Tropical Pacific*. 2022 Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP): Melbourne, Australia.
18. Chand, S., S. Power, K. Walsh, and Coauthors, Climate processes and drivers in the Pacific and global warming: a review for informing Pacific planning agencies. *Climatic Change,* 2023. 176(5) DOI: 10.1007/s10584-022-03467-z.
19. Australian Bureau of Meteorology and CSIRO, *Climate Change in the Pacific: Scientific Assessment and New Research. Volume 2: Country Reports*. 2011; Available from: https://www.pacificclimatechange.net/node/5295.
20. Lin, C.-C., C.-R. Ho, and Y.-H. Cheng, Interpreting and analyzing king tide in Tuvalu. *Natural Hazards and Earth System Sciences,* 2014. 14(2): p. 209-217.
21. McInnes, K.L., C.J. White, I.D. Haigh, M.A. Hemer, R.K. Hoeke, N.J. Holbrook, A.S. Kiem, E.C. Oliver, R. Ranasinghe, and K.J. Walsh, Natural hazards in Australia: sea level and coastal extremes. *Climatic Change,* 2016. 139: p. 69-83.
22. Hoeke, R.K., K.L. McInnes, J.C. Kruger, R.J. McNaught, J.R. Hunter, and S.G. Smithers, Widespread inundation of Pacific islands triggered by distant-source wind-waves. *Global and Planetary Change,* 2013. 108: p. 128-138.
23. Kench, P.S., M.R. Ford, and S.D. Owen, Patterns of island change and persistence offer alternate adaptation pathways for atoll nations. *Nature Communications,* 2018. 9(1): p. 605 DOI: 10.1038/s41467-018-02954-1.
24. Wandres, M., A. Espejo, and H. Damlamian, Wave Climate Variability and Trends in Tuvalu Based on a 44-Year High-Resolution Wave Hindcast. *Journal of Geophysical Research: Oceans,* 2023. 128(4): p. e2022JC019523 DOI: https://doi.org/10.1029/2022JC019523.
25. Wandres, M., A. Espejo, and H. Damlamian, Wave climate variability and trends in Tuvalu based on a 44 ‐ year high ‐ resolution wave hindcast. *Journal of Geophysical Research: Oceans,* 2023. 128(4): p. e2022JC019523.
26. Tuck, M.E., M.R. Ford, P.S. Kench, and G. Masselink, Sediment supply dampens the erosive effects of sea-level rise on reef islands. *Scientific Reports,* 2021. 11(1): p. 5523.
27. Kennedy, D.M., K. McInnes, and D. Ierodiaconou, *Understanding coastal erosion on beaches: A guide for managers, policy makers and citizen scientists*. 2019, Deakin University.
28. CSIRO and SPREP, *‘NextGen’ Projections for the Western Tropical Pacific: Current and Future Climate for Tuvalu.* . 2021: Final report to the Australia-Pacific Climate Partnership for the Next Generation Climate Projections for the Western Tropical Pacific project.

Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP). Melbourne, Australia; Available from: https://www.rccap.org/uploads/files/909d29f7-7cb7-4618-b58b-3ca889669965/Tuvalu%20Country%20Report%20Final.pdf

29. Portner, H., D. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, and E. Poloczanska, *IPCC The Ocean and Cryosphere in a Changing Climate Summary for Policmakers. IPCC Spec. Rep. Ocean Cryosph. a Chang. Clim*. 2019 SPM-1-SPM-42. Geneva: IPCC; Available from: https://www.ipcc.ch/srocc/chapter/technical-summary/ts-0-introduction/ipcc-srocc-ts_4/ (Accessed 22/3/2023).
30. Knutson, T., S.J. Camargo, J.C. Chan, K. Emanuel, C.-H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, and K. Walsh, Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society,* 2020. 101(3): p. E303-E322.
31. Think Hazard. 2023; Available from: https://thinkhazard.org/en/report/252-tuvalu/TS
32. Thomas, C., D. Burbidge, and P. Cummins, *A preliminary study into the tsunami hazard faced by southwest Pacific nations*. 2007 Risk Impact Analysis Group, Geoscience Australia; Available from: https://www.researchgate.net/publication/267818809_A_Preliminary_Study_into_the_Tsunami_Hazard_faced_by_Southwest_Pacific_Nations?enrichId=rgreq-79aceabca30a1ecf445d16dd26cd93b7-XXX&enrichSource=Y292ZXJQYWdlOzI2NzgxODgwOTtBUzoxNjI0MzE4NjMxMDc1ODRAMTQxNTczODE4MjUwNw%3D%3D&el=1_x_3&_esc=publicationCoverPdf
33. Alhamid, A.K., M. Akiyama, H. Ishibashi, K. Aoki, S. Koshimura, and D.M. Frangopol, Framework for probabilistic tsunami hazard assessment considering the effects of sea-level rise due to climate change. *Structural Safety,* 2022. 94: p. 102152 DOI: https://doi.org/10.1016/j.strusafe.2021.102152.
34. Weiss, R., T. Dura, and J.L. Irish, Modeling Coastal Environmental Change and the Tsunami Hazard. *Frontiers in Marine Science,* 2022. 9 DOI: 10.3389/fmars.2022.871794.
35. HALL. 2023; Available from: https://www.hallcontracting.com.au/about/news/pacific-islands-project-takes-out-top-gong
36. Wandres, M., A. Espejo, and H. Damlamian, *Hazard assessment for wave-driven inundation in Fongafale, Tuvalu. Geoscience, Energy and Maritime Division, Pacific Community, Suva, Fiji*. 2021.
37. Stoddart, D. and J. Steers, The nature and origin of coral reef islands. *Biology geology of coral reefs,* 1977. 4: p. 59-105.
38. Perry, C., P. Kench, S. Smithers, B. Riegl, H. Yamano, and M. O'Leary, Implications of reef ecosystem change for the stability and maintenance of coral reef islands. *Global Change Biology,* 2011. 17(12): p. 3679-3696.
39. Woodroffe, C.D., Reef-island topography and the vulnerability of atolls to sea-level rise. *Global Planetary Change,* 2008. 62(1-2): p. 77-96.
40. Hisabayashi, M., J. Rogan, and A. Elmes, Quantifying shoreline change in Funafuti Atoll, Tuvalu using a time series of Quickbird, Worldview and Landsat data. *GIScience & Remote Sensing,* 2018. 55(3): p. 307-330 DOI: 10.1080/15481603.2017.1367157.
41. Kench, P., C. Liang, M. Ford, S. Owen, M. Aslam, E. Ryan, T. Turner, E. Beetham, M. Dickson, and W. Stephenson, Reef islands have continually adjusted to environmental change over the past two millennia. *Nature Communications,* 2023. 14(1): p. 508.
42. Storlazzi, C.D., S.B. Gingerich, A. Van Dongeren, O.M. Cheriton, P.W. Swarzenski, E. Quataert, C.I. Voss, D.W. Field, H. Annamalai, and G.A. Piniak, Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science advances,* 2018. 4(4): p. eaap9741.

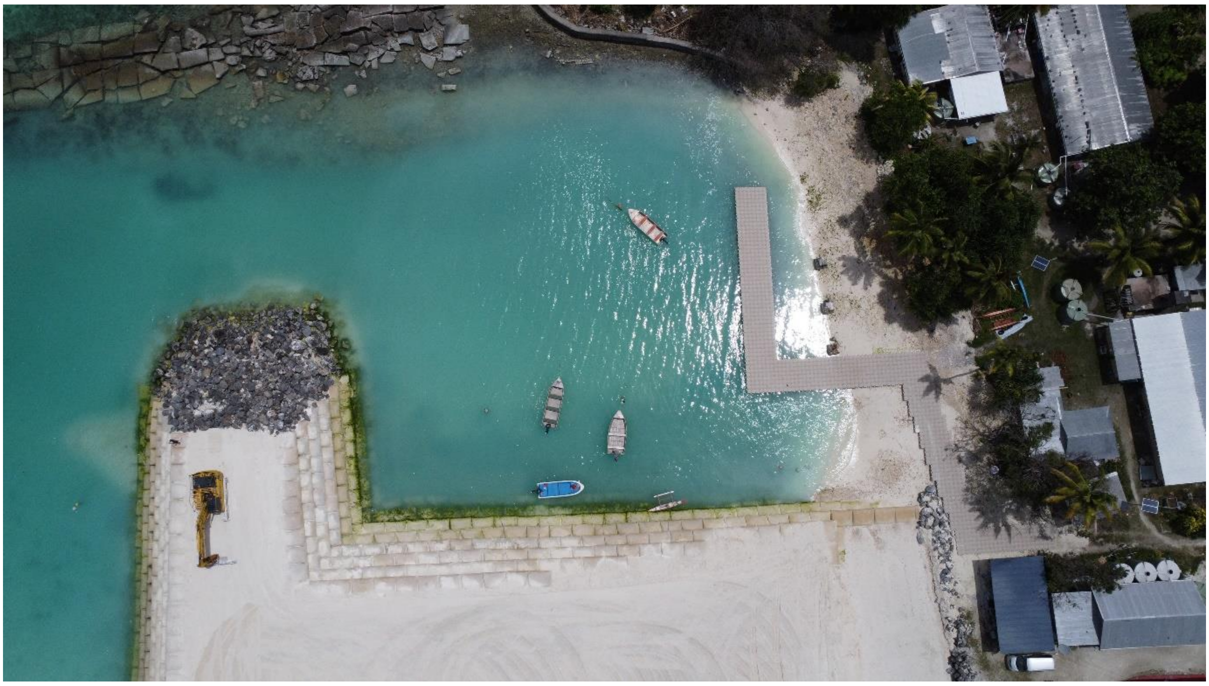
43. Masselink, G., E. Beetham, and P. Kench, Coral reef islands can accrete vertically in response to sea level rise. *Science Advances,* 2020. 6(24): p. eaay3656.
44. Toth, L.T., C.D. Storlazzi, I.B. Kuffner, E. Quataert, J. Reyns, R. McCall, A. Stathakopoulos, Z. Hillis-Starr, N.H. Holloway, and K.A. Ewen, The potential for coral reef restoration to mitigate coastal flooding as sea levels rise. *Nature Communications,* 2023. 14(1): p. 2313.
45. Kennedy, D.M., A review of the vulnerability of low-lying reef island landscapes to climate change and ways forward for sustainable management. *Ocean Coastal Management,* 2024. 249: p. 106984.
46. Ribas, F., L. Portos-Amill, A. Falqués, J. Arriaga, M. Marcos, and G. Ruessink, Impact of mean sea-level rise on the long-term evolution of a mega-nourishment. *Climatic Change,* 2023. 176(5): p. 66 DOI: 10.1007/s10584-023-03503-6.
47. Ridder, N.N., A.M. Ukkola, A.J. Pitman, and S.E. Perkins-Kirkpatrick, Increased occurrence of high impact compound events under climate change. *npj Climate and Atmospheric Science,* 2022. 5(1): p. 3 DOI: 10.1038/s41612-021-00224-4.
48. Ministry for the Environment, *Coastal hazards and climate change guidance.* 2024 Wellington: Ministry for the Environment.; Available from: https://environment.govt.nz/assets/publications/Coastal-hazards-and-climate-change-guidance-2024-ME-1805.pdf.
49. Perry, C.T., K.M. Morgan, I.D. Lange, and R.T. Yarlett, Bleaching-driven reef community shifts drive pulses of increased reef sediment generation. *Royal Society Open Science,* 2020. 7(4): p. 192153.
50. Toimil, A., P. Camus, I.J. Losada, G. Le Cozannet, R.J. Nicholls, D. Idier, and A. Maspataud, Climate change-driven coastal erosion modelling in temperate sandy beaches: Methods and uncertainty treatment. *Earth-Science Reviews,* 2020. 202: p. 103110 DOI: https://doi.org/10.1016/j.earscirev.2020.103110.
51. CSIRO Workshop Report, *Understanding the risks to Australia from global climate tipping points.* . 2024 CSIRO, Australia.; Available from: file:///C:/Users/web167/Downloads/CSIRO_Tipping-Points-Report.pdf.
52. Le Bars, D., S. Drijfhout, and H. De Vries, A high-end sea level rise probabilistic projection including rapid Antarctic ice sheet mass loss. *Environmental Research Letters,* 2017. 12(4): p. 044013.
53. van de Wal, R.S., R.J. Nicholls, D. Behar, K. McInnes, D. Stammer, J.A. Lowe, J.A. Church, R. DeConto, X. Fettweis, and H. Goelzer, A High‐End Estimate of Sea Level Rise for Practitioners. *Earth's future,* 2022. 10(11): p. e2022EF002751.
54. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, and T. Frederikse, *Global and regional sea level rise scenarios for the United States: Updated mean projections and extreme water level probabilities along US coastlines*. 2022: National Oceanic and Atmospheric Administration.
55. DeConto, R.M. and D. Pollard, Contribution of Antarctica to past and future sea-level rise. *Nature,* 2016. 531(7596): p. 591-597.
56. Pielke Jr, R., M.G. Burgess, and J. Ritchie, Plausible 2005-2050 emissions scenarios project between 2 and 3 degrees C of warming by 2100. *Environmental Research Letters,* 2022.

Chapter 10 Ocean warming

Introduction

The global ocean has warmed unabated since 1970 and has taken up more than 90 % of the excess heat in the climate system [1]. Sea surface temperatures (SSTs) were 0.88 °C higher in 2011-2020 than 1850-1900 [2]. Marine heatwaves (MHWs) are episodes of prolonged and anomalously high ocean temperatures [3, 4]. Over the last four decades across the globe, MHW frequency, intensity, and duration have increased [5], and climate projections indicate that this trend is set to continue for decades to come in many regions, including the Pacific.

Ocean warming is largely due to increases in greenhouse gas emissions caused by human activities [2], and various related climate impacts on coastal communities, resources and biodiversity (e.g. species redistribution, coral bleaching, die-back of seagrass and mangroves, algal blooms and fish kills) [6]. These emissions having also resulted in increased ocean acidification (See Chapter 11).



Observed sea surface temperature

Observed average patterns, seasonal cycle, and trends.

Across the Tuvalu region, annual average SSTs range from about 28.6 °C to 29.5 °C from south to north (Figure 10-1, left). Ocean temperature, as measured at the Tuvalu tide-gauge in Funafuti lagoon, ranges from 29 °C to 30 °C for the 1993 to 2021 period, exhibiting unique bimodal peaks around 30 °C in November/December and April/May (Figure 10-1, top right) [7]. Individual monthly temperatures can reach as high as 31.5 °C. Minimum average temperature only dips down to 29 °C in August. Temperatures can be up to 2 °C higher or lower than these averages, although 50 % of observations fall within 1 °C of the average [7].

Satellite-derived SST measurements taken from the NOAA (National Atmospheric and Oceanic Administration) daily Optimum Interpolation Sea Surface Temperature v2-1 dataset[7] (hereafter called OISST v2-1; [8]), have been averaged over the Tuvalu Exclusive Economic Zone, revealing a warming trend of 0.22 °C per decade during 1981-2021 (Figure 10-1, bottom right) [7].

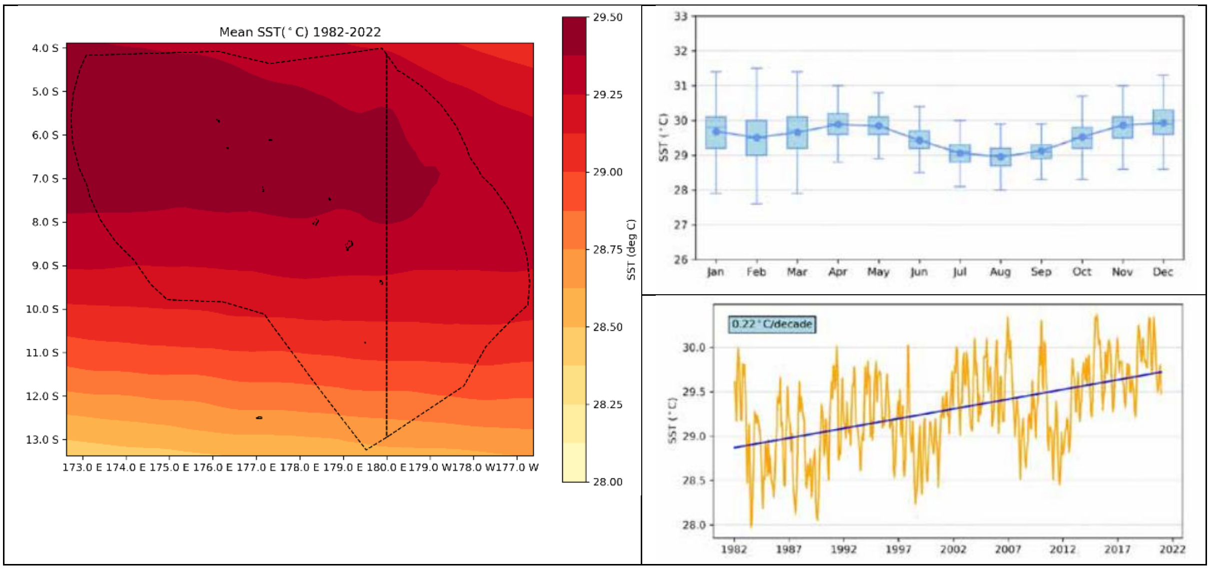


Figure 10-1 (left) Tuvalu annual-average SST (°C) (1982–2022). (Top right) SST (° C) measured at the Funafuti tide gauge (1993–2021), with blue dots showing the monthly average, shaded boxes show the median (middle 50 % of observations) and lines showing the top and bottom 25 % of observations. (Bottom right) SST from satellite measurements averaged across the Tuvalu EEZ, with annual averages shown as the orange line. The blue line shows the linear regression trend [7]. Data source for left and bottom right plots: [8].

SST, ENSO and skipjack tuna catch

The dynamics of many marine fish stocks are linked to multiple scales of climate variability. An important case in point is the large-scale, east-west displacements of skipjack tuna in the equatorial Pacific, which are correlated with ENSO events [9] and lead to large fluctuations in catches from the EEZs of PICTs. SSTs northeast of Tuvalu are usually warmer than normal during an El Niño event, and cooler during a La Niña event (PACCSAP, 2014). This causes large-scale, east-west displacements of skipjack tuna in the equatorial Pacific, and in an El Niño event, the fish can occur in a more westward area following the warm water [10, 11]. Therefore, during La Niña events, the best catches of skipjack tuna are made in the west of the region, whereas during El Niño events fishing is best in the east [11].

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[7] Daily OISST data are constructed by combining observations from different platforms (satellites, ships, buoys, and Argo floats) on a regular 0.25 ° global grid (around 27 km between data points) with interpolation to fill any data gaps. Full-year data are available from 1982–2022. Also see Glossary.

SST Projections

Projected increases in SST for the Tuvalu EEZ region by 2050 range from around 0.9°C for SSP1-2.6, 1.1°C for SSP2-4.5 and 1.3°C for SSP5-8.5, and by 2090 range from around 1.0°C for SSP1-2.6, about 1.6°C for SSP2-4.5 or up to 2.8°C for SSP5-8.5, relative to the average for 1995-2014 (Figure 10-2 and Table 10-1). This translates to average ocean temperatures of over 32.1°C by the end of the century under SSP585, compared to the baseline average of 29.3°C (1995-2014). The spatial patterns of SST in 2030, 2050, 2070 and 2090 for SSP1-2.6 and SSP5-8.5 are shown in Figure 10-3.

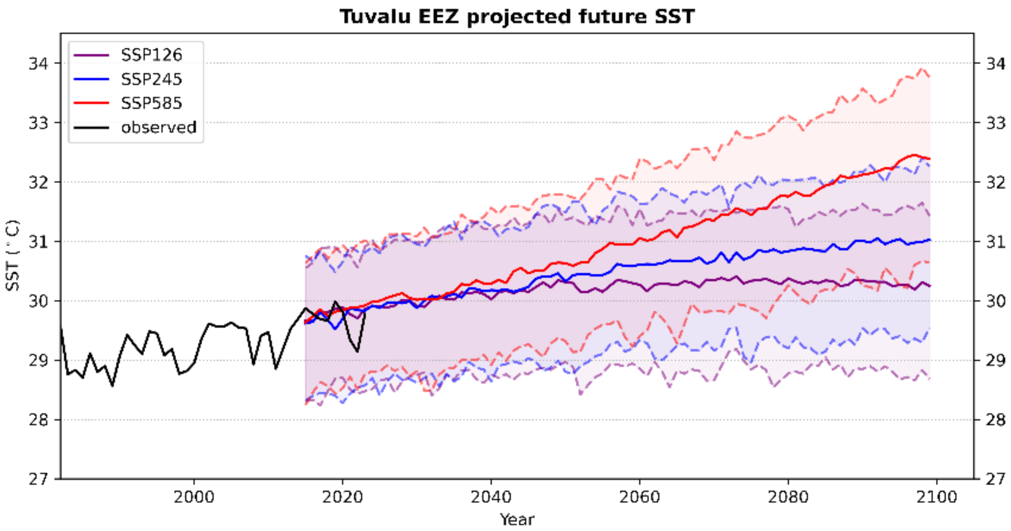


Figure 10-2 Timeseries of projected increase in annual average SST (°C) (2010-2100) for the Tuvalu EEZ from 23 CMIP6 models over three emission scenarios: SSP126, SSP245, and SSP585. Shown are the median values (bold line) and the 10th and 90th percentile under each scenario. OISSTv2.1 observed annual average SST over the Tuvalu EEZ is shown by the solid black line.

Table 10-1: Summary table of the SST changes (°C) for SSP1-2.6 and SSP5-8.5 in Figure 3 relative to a 20-year period centred on the 1995-2014 baseline period.

Time period	Scenario	Mean change (°C)	10th to 90th percentile (°C)
2030 (2021-2040)	SSP1-2.6	0.7	-0.7 to 1.7
	SSP5-8.5	0.8	-0.5 to 1.8
2050 (2041-2060)	SSP1-2.6	0.9	-0.5 to 2.1
	SSP5-8.5	1.3	0.0 to 2.5
2070 (2061-2080)	SSP1-2.6	1.0	-0.5 to 2.2
	SSP5-8.5	2.0	0.5 to 3.3
2090 (2081-2100)	SSP1-2.6	1.0	-0.5 to 2.2
	SSP5-8.5	2.8	1.0 to 4.1

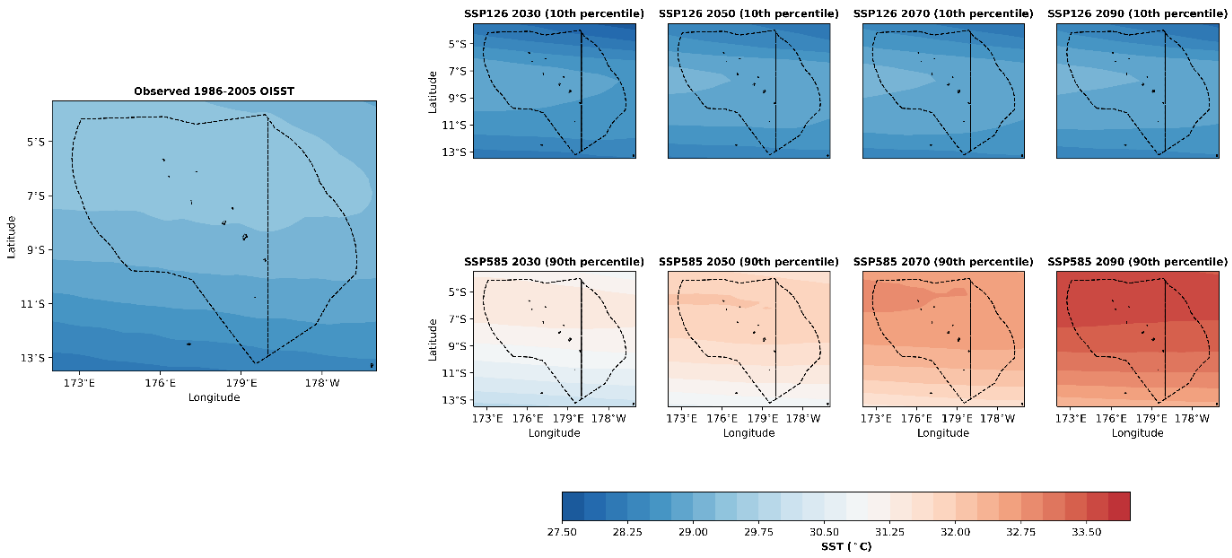


Figure 10-3 (left) Observed 20-yr average Tuvalu SST (°C) (1986-2005; OISSTv2-1), and (right) range of projected SST for the Tuvalu region from 23 CMIP6 models for 2030, 2050, 2070 and 2090 under SSP126 (top) and SSP585 (bottom). To show the potential range of change, the 10th percentile of the SSP126 and the 90th percentile of the SSP585 CMIP6 projections are shown. The Tuvalu Exclusive Economic Zone is shown by the dashed polygon.

Tuna fish catch, SST and ENSO

Across the Pacific Ocean, SST projections suggest a large eastward shift in the location of the edge of the Western Pacific Warm Pool. The Warm Pool is defined by a fixed isotherm, e.g., 28.5 or 29 °C, which is a temperature threshold supporting tuna fisheries. This warming is related to slightly enhanced warming along the equatorial Pacific, and possibly associated with a projected slowdown in the equatorial trade winds [11]. Based on CMIP3 models, the historical area contained within the 29 °C isotherm: 9 Million km^2 (averaged over 1980–2000) expands to 29–33 Million km^2 (model ensemble 90% confidence interval) by 2050 [11]. In addition to the expansion of the warm pool, there may be more extreme El Niños and La Niñas in future [12, 13].

New modelling efforts have been undertaken to better understand the effects of climate change on tuna biomass [11], particularly around distribution within the EEZs and the high seas [11]. There is considerable uncertainty in the timing and magnitude of tuna redistributions in and out of Tuvalu's EEZ, however, the general consensus in climate modelling is that tropical tuna distributions in the Pacific are projected to shift eastwards [9, 11, 14-16] (See Fisheries section in Chapter 2).

Ocean temperature extremes

Introduction

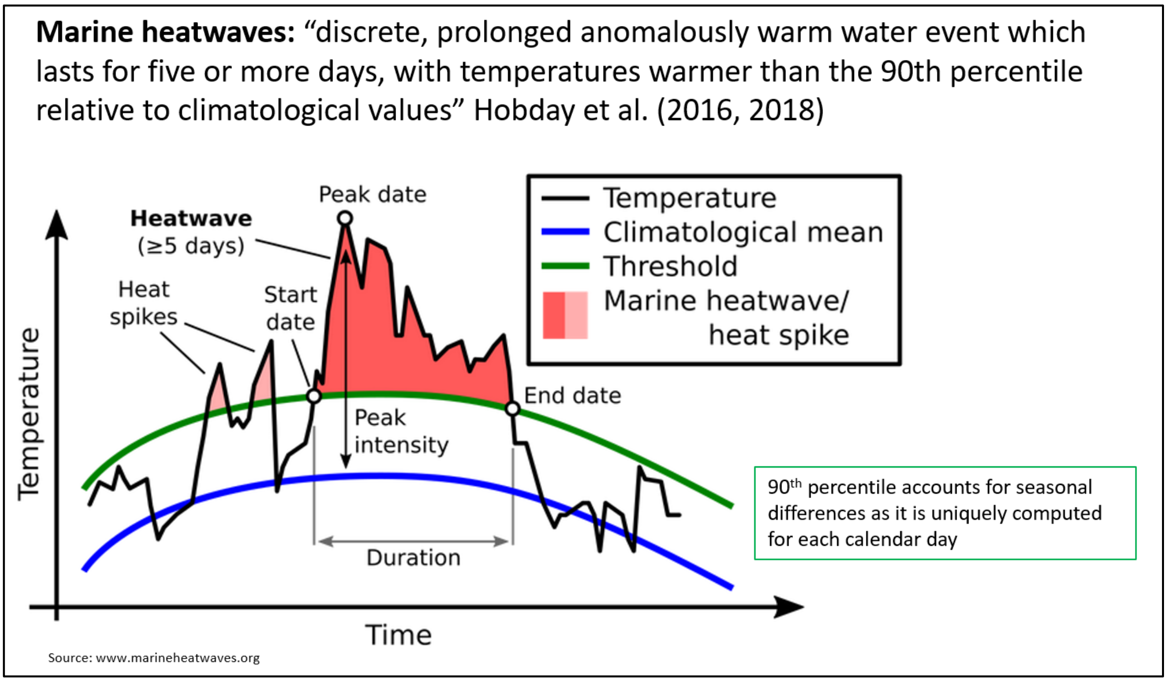
Marine heatwaves (MHWs) are typically caused by either atmosphere-ocean heating or the convergence of heat from changes in ocean currents, which can be modulated by modes of climate variability [17, 18]. MHWs have resulted in substantial impacts to marine ecosystems and the services they provide [19], including biological and socioeconomic consequences [20, 21]. Furthermore, future projections of MHWs through the 21st century are likely to carry severe consequences for marine species and ecosystems [22].

MHWs can have a very different temperature profile (i.e. °C) depending on the seasonal / regional background temperatures. For example, a heatwave occurring in August is unlikely to reach temperatures as high as those occurring in February in Tuvalu. However, there may be other biological processes (e.g., spawning, recruitment, food web relationships) that would still be sensitive to MHWs in August, e.g., [23] MHWs on top of long-term warming in August enables establishment of invasive species where a previously cool August would have killed them off [24].

Marine heatwaves defined

Marine heatwaves are defined as 'discrete, anomalously warm water events which last for five or more days, with SSTs warmer than the 90th percentile relative to climatological values' over a 30-year period [3, 4]:

- 'discrete' implies a well-defined start and end date, and separated from a previous MHW by more than two days;
- 'Anomalously warm' is warmer than the 90th percentile (top 10%) in a 30-yr baseline period; and
- 90th percentile accounts for seasonal differences as it is uniquely computed for each calendar day (Figure 10-4).

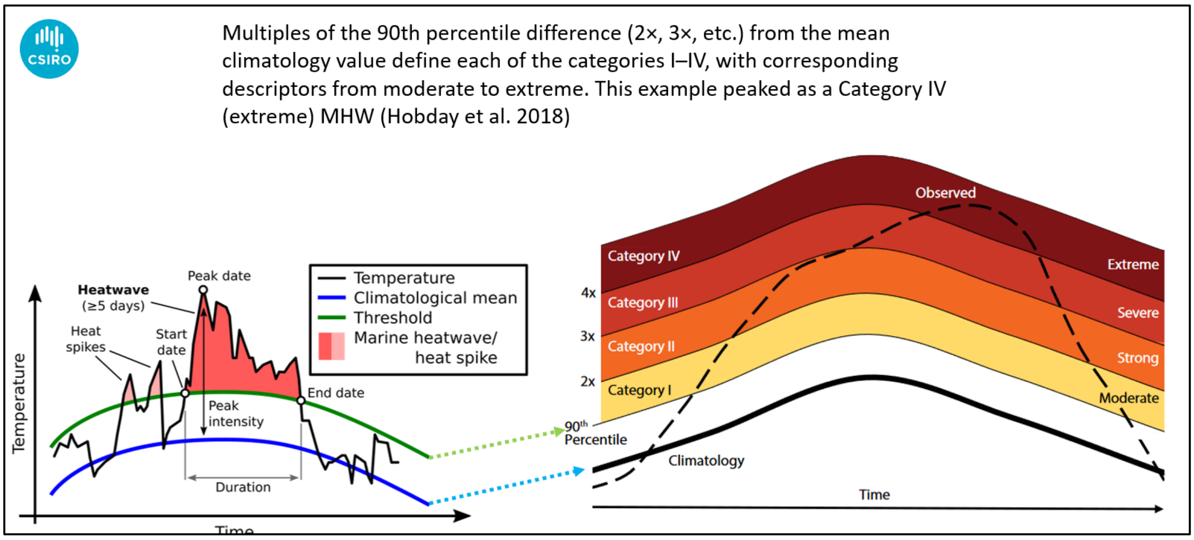


Marine heatwaves: "discrete, prolonged anomalously warm water event which lasts for five or more days, with temperatures warmer than the 90th percentile relative to climatological values" Hobday et al. (2016, 2018)

Source: www.marineheatwaves.org

Figure 10-4 Diagram illustrating MHW definition: SST (°C) timeseries (black line) overlaid on the average SST (blue line) and the 90th percentile threshold (green line). When the SST exceeds the threshold for more than five days, it is defined as a MHW (red shading) [3, 4]. Heat spikes (pink shading) are not classified as a MHW because they are shorter than five days and are separated from the MHW by more than two days.

MHWs are categorised into four intensity categories, defined by multiples of the difference between the mean SST across a defined period and the 90th percentile threshold, i.e., the difference (D) between the blue and green lines in Figure 10-4. Intensity is defined as 'Moderate' (Category I, 1–2xD), 'Strong' (Category II, 2–3xD), 'Severe' (Category III, 3–4×D), and 'Extreme' (Category IV, greater than 4xD) (Figure 10-5) [4].



Multiples of the 90th percentile difference (2×, 3×, etc.) from the mean climatology value define each of the categories I–IV, with corresponding descriptors from moderate to extreme. This example peaked as a Category IV (extreme) MHW (Hobday et al. 2018)

Figure 10-5 Multiples of the 90th percentile difference (2×D, 3×D, etc.) from the mean climatological value define each of the MHW categories I–IV, with corresponding descriptors from moderate to extreme. This example (dashed line) peaked as a Category IV (extreme) MHW [4]

Observed marine heatwave events

Globally, MHWs have become more frequent over the 20th century and into the beginning of the 21st century [5], approximately doubling in frequency and becoming more intense and longer since the 1980s [5, 25]. The probability of occurrence (as well as duration and intensity) of the largest and most impactful MHWs has increased more than 20-fold due to anthropogenic climate change [26].

Observations in the Pacific Islands region indicate that from the 1980s to 2000s, the average duration of MHWs is consistent, with much of the region within the 5- to 16-day range. However, there was a significant increase in event duration in the 2010s, with most of the Pacific Islands region in the 8 to 20+ day range [27].

Timeseries of MHW observations have been assessed for Tuvalu’s atolls and islands. At eight sites of interest, there has been an increasing frequency of MHW’s during 1982–2023, mostly in the moderate to strong category (Figure 10-6).

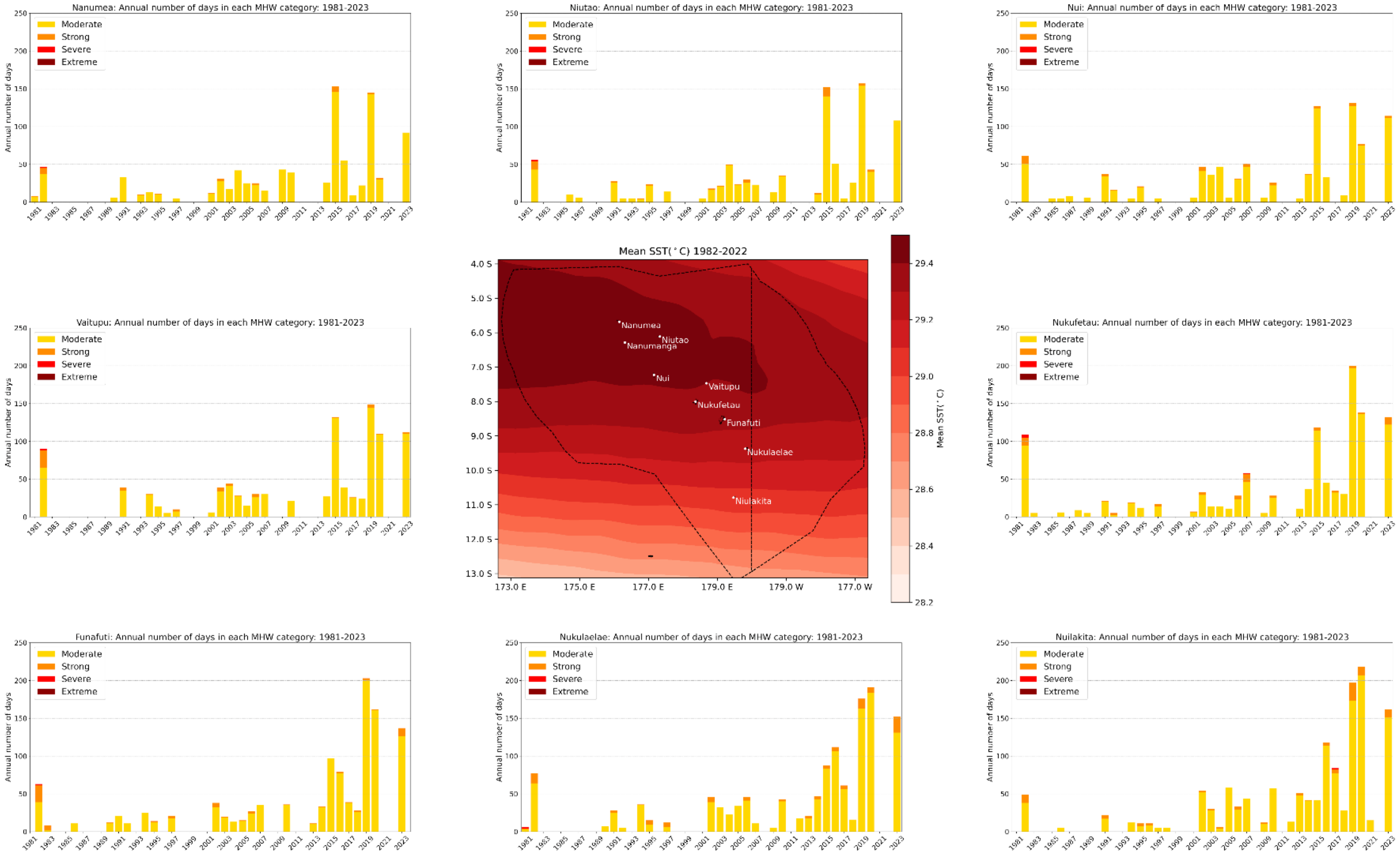
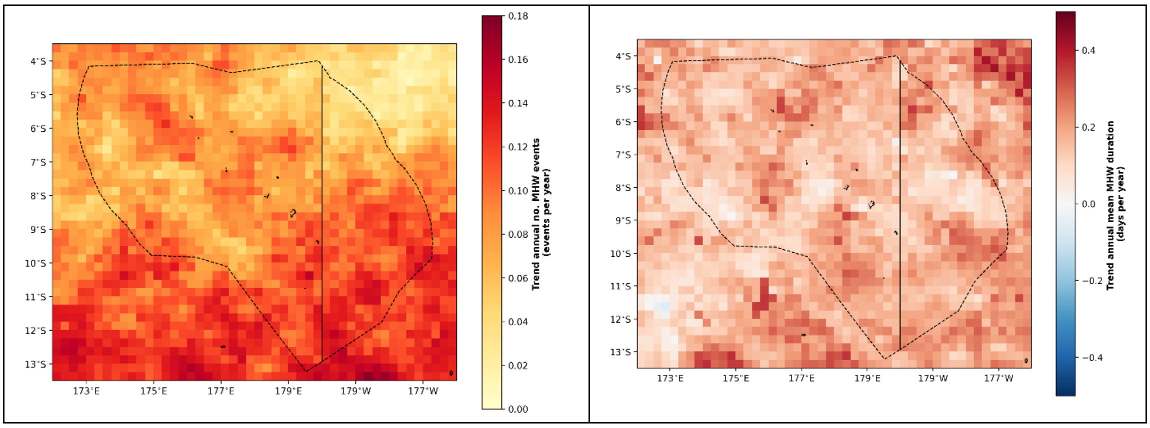


Figure 10-6 Mean SST (°C) (1982-2022) for Tuvalu atolls and islands of interest (central map). For each site, the annual number of MHW days (1982-2023) is shown in each category [3, 4]. Data source: NOAA OISST v2-1 [8]. Spatial analyses of trends in observed MHWs.

Spatial analyses of MHWs occurring in the Tuvalu region for 1982–2019 are presented in Figure 10-7. Note that MHWs are considered as separate events if a period of more than two days elapses since occurrence of a previous MHW [3, 4].

- Increases in annual MHW frequency have occurred across the country, with a greater increase in the south than the north (Figure 10-7, top left).
- Increases in annual MHW duration have occurred, particularly around Nanumea and Niutao, but decreases have occurred in some sites to the west of Nukufetau and Funafuti (Figure 10-7, top right).
- Decreases in annual maximum MHW intensity have occurred, particularly around Funafuti and the ocean north-east of Funafuti (Figure 10-7, bottom left). Area-averages show that there is a weak negative trend in MHW intensity due to a combination of a relatively short observational record and the equatorial region of the Pacific Ocean experiencing a cooler sea-surface temperature phase of the Interdecadal Pacific Oscillation during the early 21st century [6] [8].
- The total number of MHW events over the period 1982-2019 varies across the region, mostly above 60, with more in the north-east (Figure 10-7, bottom right).

Regarding the sites of interest (Figure 10-6), most islands and atolls are equally exposed to MHWs, however with Nukufetau and Niulakita seeing an increase in MHW frequency and duration but little change in mean MHW intensity.



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[8] We expect a large influence on trends across all MHW metrics in this region is due to the length of the record (only 38 years) that is dominated by the interdecadal variability in the Pacific. Specifically, the first 10–15 years of the 21st century was marked by a substantial negative Interdecadal Pacific Oscillation (IPO) phase, which caused cooler-than-usual SSTs across much of the tropical Pacific (e.g. 28. England, M.H., S. McGregor, P. Spence, G.A. Meehl, A. Timmermann, W. Cai, A.S. Gupta, M.J. McPhaden, A. Purich, and A. Santoso, Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nature Climate Change,* 2014. 4(3): p. 222-227.).

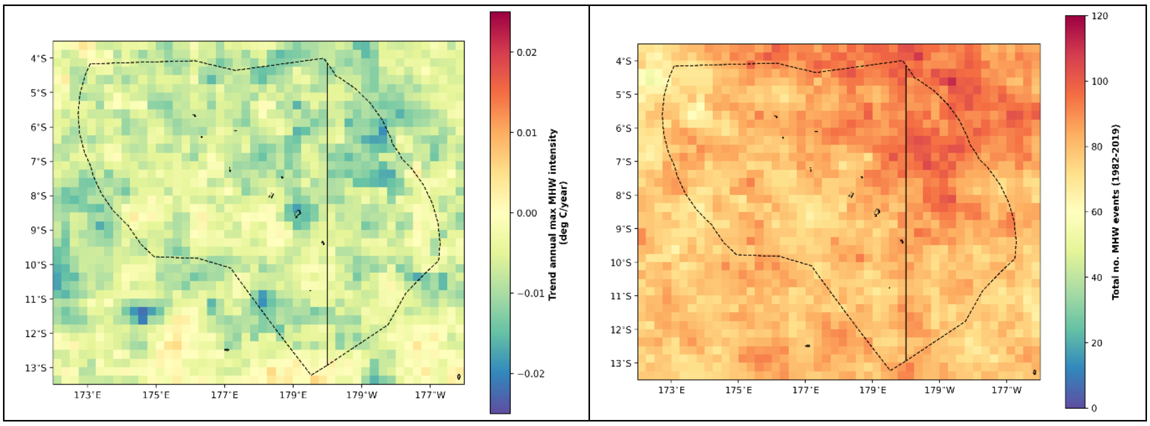

Figure 10-7 Trend (1982–2019) in annual number of MHW events (top left), annual mean MHW duration (top right), annual maximum MHW intensity (bottom left), and total number of MHW events (bottom right). Source data: NOAA OISST v2-1 SST [8].

Marine heatwaves and ENSO

The incidence of MHWs is influenced by the El Niño-Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO), as well as local factors such as circulation patterns and processes that affect air-sea heat fluxes [29]. Climate in and around the Pacific Ocean also displays variability on decadal to interdecadal time scales (e.g. [30, 31]). Much of this variability in the Southern Pacific has been linked to the Interdecadal Pacific Oscillation (IPO, [32]). When the IPO is in a positive phase, SST in the central and eastern Pacific are high, whereas the opposite is true during negative phases of the IPO.

During El Niño events, higher SST, rainfall, and sea level are clearly apparent in the central tropical Pacific [29], including Tuvalu. The opposite tends to occur during La Niña events. MHWs can, however, occur during any ENSO phase, and are often associated with periods of clear skies and more settled conditions, and consequently less wind-driven mixing of the surface ocean, which enhances surface heating.

Projected MHWs

MHWs will continue to increase in frequency, with a likely global increase of 2‑9 times in 2081‑2100 compared with 1995‑2014 under SSP1-2.6, and 3‑15 times under SSP5-8.5, with the largest increases in tropical and Arctic Oceans (Fox-Kemper et al. 2021). A recent study by Holbrook et al. (2022) investigated MHWs in the tropical western and central Pacific Ocean in observations and future projections. Holbrook et al. (2022) showed that under low emissions (SSP1-2.6), 'moderate' intensity MHWs are projected to increase from recent historical (1995–2014) values of 10–50 days per year (dpy) across the region to the equivalent of >100 dpy by the year 2050. Under the high emissions scenario (SSP5-8.5), their study projected 200 dpy of moderate MHW intensities across the region by 2050, with >300 dpy nearer the equator.

Projected MHWs out to the end of the century have been calculated for a lower-warming climate model and a higher-warming climate model, under low and high emissions scenarios, to capture the projected range of change (**Error! Reference source not found.**). 18 CMIP6 models and two SSPs are e mployed in this assessment. Historical OISST v2-1 observations (1995-2014) are indicated by the left bar in each plot, denoted with an 'x'.

Across all sites, the typical number of MHWs is around 10 days per year (1985-2014) (Figure 10-8). By 2050, under the low emissions scenario (SSP1-2.6) low warming model, across all sites, this increases to about 130–150 days per year (Figure 10-8, left). For low emissions and a high warming model, the range is 290-340 days per year. Under the high emissions scenario (SSP5-8.5; Figure 10-8, right) for a low warming model, the range is 220-250 days per year. For high emissions and a high warming model, this increases to about 350-360 days per year, with many days in the 'Strong' and 'Severe' MHW categories (Figure 10-8). By 2090, larger increases in MHWs are projected, more-so in the north. For a low emissions scenario, the number of MHW days is 200-350, with a substantial increase in 'Strong' events (Figure 10-8, left). For a high emissions scenario, the number of MHW days is 310-360 for Funafuti, with a big increase in 'Severe' and 'Extreme' events (Figure 10-8, right). This increase in MHW days is driven by long-term ocean warming.

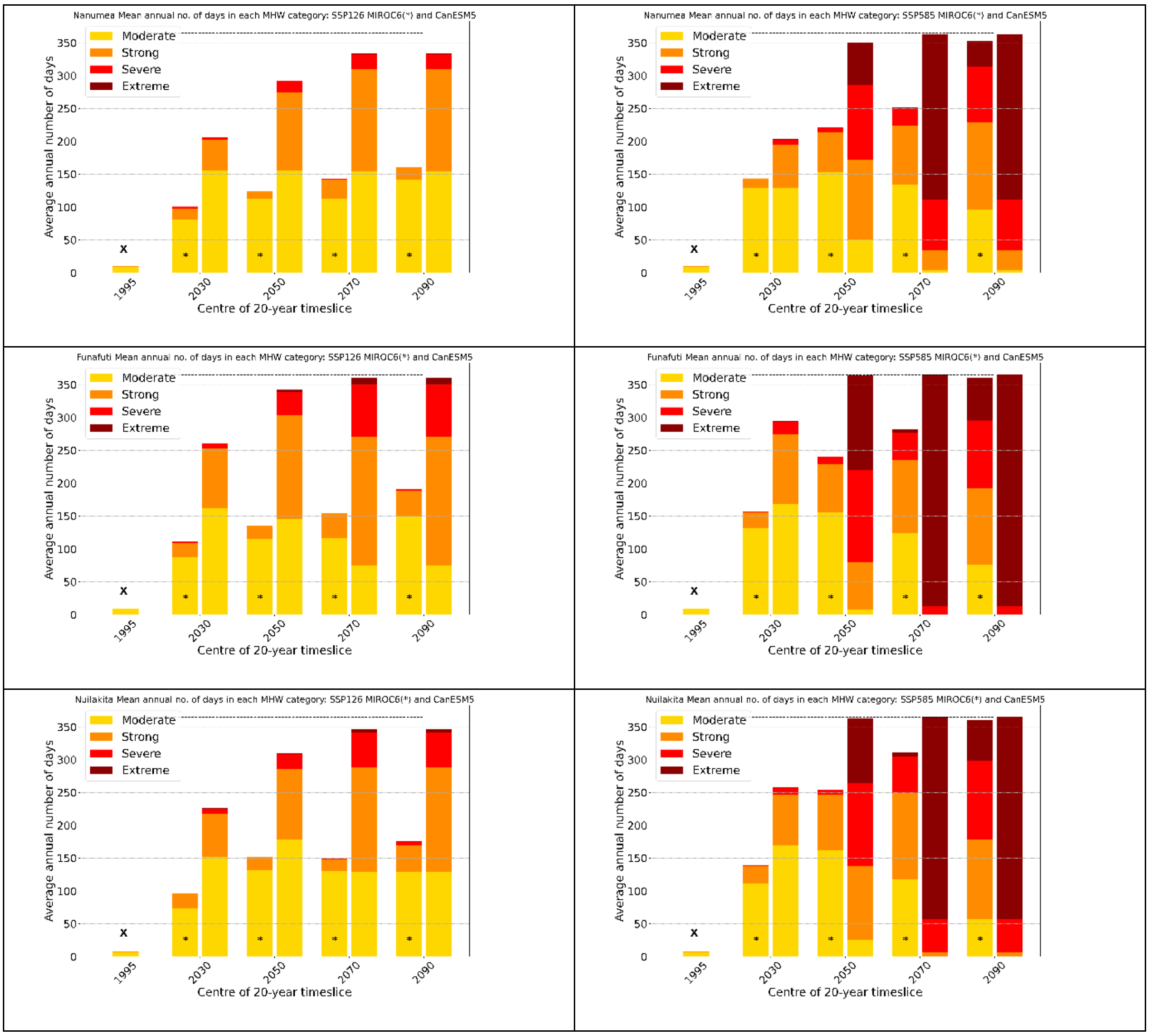

Figure 10-8 Projected average annual number of MHW days for an area-averaged domain encompassing Northern through to Southern atolls of Tuvalu: (top) Nanumea, (middle) Funafuti, and (bottom) Nuilakita. The 'x' above the left bar on each plot indicates that a different dataset (OISST v2-1) was used to determine the historical observed MHW frequency for a 20-year period centred on 1995 (1986–2005), quantified by the bar height. Projected MHWs for 20-year periods centred on 2030, 2050, 2070, and 2090 are plotted for a lower emission scenario (SSP126; left panels) and higher emission scenario (SSP585; right panels) under a low warming model (MIROC6) (*) and a high warming model (CanESM5) based on CMIP6 climate modelling. For all periods, MHWs are categorised: moderate, strong, severe, and extreme [4]). (Data source: OISST v2-1 SST [8]).

Degree heating weeks

Degree heating weeks (DHW) provide a measure of coral stress [33-35]. Corals become stressed when SSTs are warmer than the bleaching threshold (solid blue line in Figure 10-9). This threshold is defined as 1.0 °C above the maximum of the monthly mean (MMM) SST °C (indicated by the dashed blue line in Figure 10-9). Heat stress builds up the longer SST stays above the bleaching threshold. Both the magnitude of threshold exceedance and length of the exceedance are important factors in measuring stress, and thereby DHW.

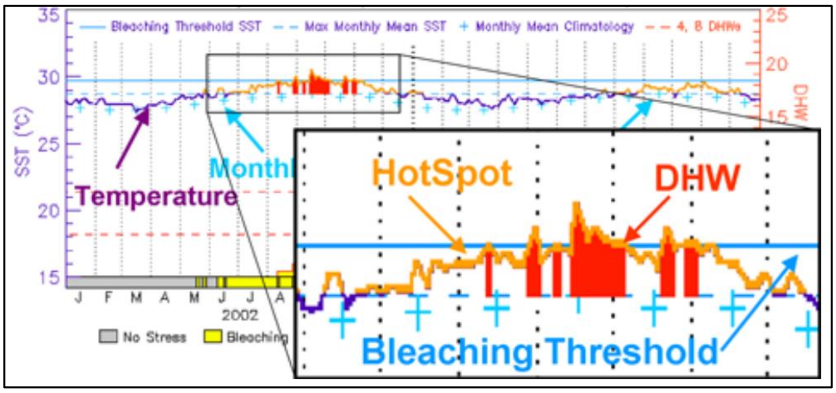

Figure 10-9 Simulated SST (°C) timeseries for a sample site in the Pacific. A HotSpot is included in the DHW calculation when SST reaches or exceeds the bleaching threshold temperature. DHW (red region) is accumulated from HotSpot occurrence as the magnitude of exceedance above the MMM for a period of 12 weeks.

The term 'HotSpot' indicates the extent (in °C) that SST is above the MMM each day. DHW indicates how much heat stress has accumulated[9] and is calculated by summing the HotSpot values, over the previous 12 weeks, whenever the SST reached or exceeded the MMM. It is calculated as a running sum over a 12-week window (i.e., as you advance each day, you lose a day off the start of the 12-week window). The sum is divided by 7 to obtain the unit of '°C-weeks'. In that way, a DHW of 2 is equivalent to one week of HotSpot values persistently at 2 °C (i.e., 2 °C x 7 days/7 =14/7 = 2), or two weeks of HotSpot values persistently at 1 °C (i.e., 1 °C x 14 days/7 =14/7 = 2), etc. (see : https://coralreefwatch.noaa.gov/product/5km/methodology.php#dhw The United States National Oceanic and Atmospheric Administration monitors world SST and releases warnings for bleaching based on DHW (e.g. Figure 10-10).

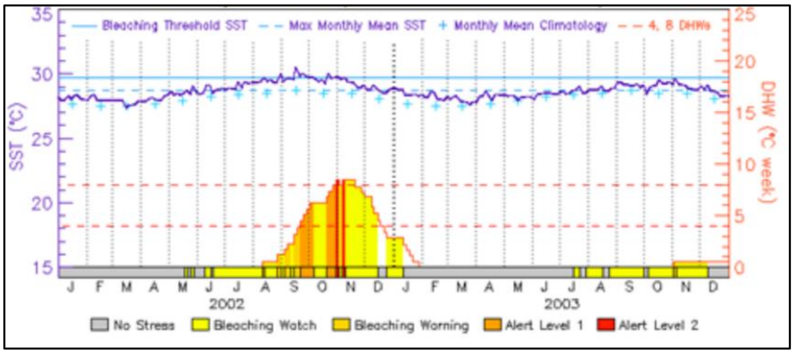

Figure 10-10 DHWs are plotted for a sample site in the Pacific along the bottom of the graph, corresponding to the accumulated threshold exceedance of SST above MMM. The 4-DHW and 8-DHW thresholds are shown as dashed, horizontal red lines. The colours that fill below the DHW line correspond to established satellite bleaching alert levels (see Table 10-2).

'Bleaching Watch' (Table 10-2) means that there is low-level thermal stress present at that location but not of sufficient magnitude to accumulate stress for corals, should they exist in that location. 'Alert Level 1' indicates that DHW is 4-8 and coral bleaching is likely to occur for some species. 'Alert Level 2' indicates DHW is greater than 8, so both widespread bleaching and significant coral

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[9] This anomaly is summed for the preceding 12-week period to produce 'Degree Heating Days' over 12 weeks. Dividing this by seven, can change the unit to 'Degree Heating Weeks' over 12 weeks.

mortality are likely. This scale has been successfully validated across historical observations at eight sites in north-western Pacific Ocean [36].

Table 10-2 Coral bleaching thermal stress levels based on the NOAA Coral Reef Watch warnings (NOAA Coral Reef Watch Daily 5km Satellite Coral Bleaching Heat Stress Bleaching Alert Area Product (Version 3.1))[10]

Stress Level	Definition	Potential Bleaching and Mortality
No Stress	HotSpot <= 0	**No Bleaching**
Bleach Watch	0 < HotSpot < 1	
Bleaching Warning	1 <= HotSpot and 0 < DHW < 4	**Risk of Possible Bleaching**
Bleaching Alert Level 1	1 <= HotSpot and 4 <= DHW < 8	**Risk of Reef-Wide Bleaching**
Bleaching Alert Level 2	1 <= HotSpot and 8 <= DHW < 12	**Risk of Reef-Wide Bleaching with Mortality of Heat-Sensitive Corals**
Bleaching Alert Level 3	1 <= HotSpot and 12 <= DHW < 16	**Risk of Multi-Species Mortality**
Bleaching Alert Level 4	1 <= HotSpot and 16 <= DHW < 20	**Risk of Severe, Multi-Species Mortality (> 50% of corals)**
Bleaching Alert Level 5	1 <= HotSpot and 20 <= DHW	**Risk of Near Complete Mortality (> 80% of corals)**

Increasingly frequent and severe coral bleaching is among the greatest threats to coral reefs posed by climate change. Global climate models project large spatial variation in the timing of annual severe bleaching conditions; a point at which reefs are certain to change and recovery will be limited; in Tuvalu, severe coral bleaching may occur on an annual basis by 2039 under RCP8.5 [37].

Degree Heating Weeks exposure: historical period

For the 20-year historical period centred on 1995, the frequency of DHW greater than 4 are mapped, showing some regional variation (Figure 10-12). Reefs exposed to more than 4 DHW events, indicating 'Risk of Reef-wide Bleaching' (Table 10-2) are located near Niutao and Niulakita. Less exposed reefs can be seen across the rest of Tuvalu. No reefs have experienced DHW greater than 8 during the period 1985-2004, indicating 'Risk of Reef-wide Bleaching with Mortality of Heat-sensitive corals' (Table 10-2).

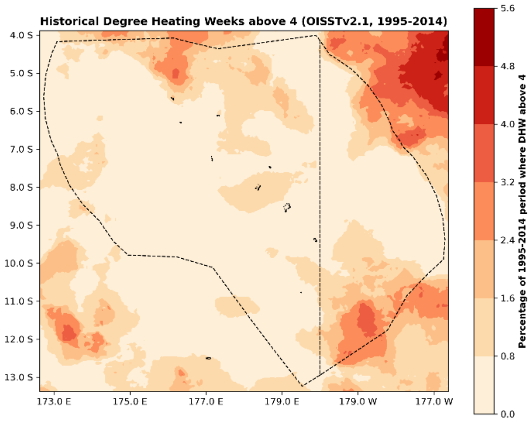

Figure 10-11 Occurrence of Degree Heating Weeks above 4 in the OISST v2.1 data for the Tuvalu region for the historical baseline period 1995-2014. The Tuvalu EEZ is indicated by a dashed polygon.

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[10] On December 15, 2023, NOAA Coral Reef Watch implemented a revised coral bleaching heat stress category system for its Bleaching Alert Area product. Extreme accumulations of coral bleaching heat stress in 2023, in multiple regions of the world, especially in the eastern tropical Pacific Ocean and Greater Caribbean, which were confirmed by in-water observations, necessitated the introduction of additional Bleaching Alert Levels. This development is a refinement of the original system that only used Bleaching Alert Levels 1 and 2. The new Alert Levels 3-5 provide important, added detail, for when the magnitude of extreme heat stress exceeds the threshold of Alert Level 2 conditions. NOAA Coral Reef Watch Revises Heat Stress Category System | ICRI (icriforum.org)

Degree Heating Weeks projections

Regionally, climate model projections for Tuvalu suggest that some areas could experience annual severe bleaching conditions seven or more years later than others. Later bleaching regions are those near the north-west of Tuvalu, namely Nanumea, Nanumanga and Niutao (Figure 10-12). Annual severe bleaching conditions (DHW > 8) are projected to occur on average within the Tuvalu EEZ by around 2060 (for low emissions; SSP1-2.6) (Figure 10-12, left), and by around by 2035 (for very high emissions; SSP5-8.5) (Figure 10-12, right).

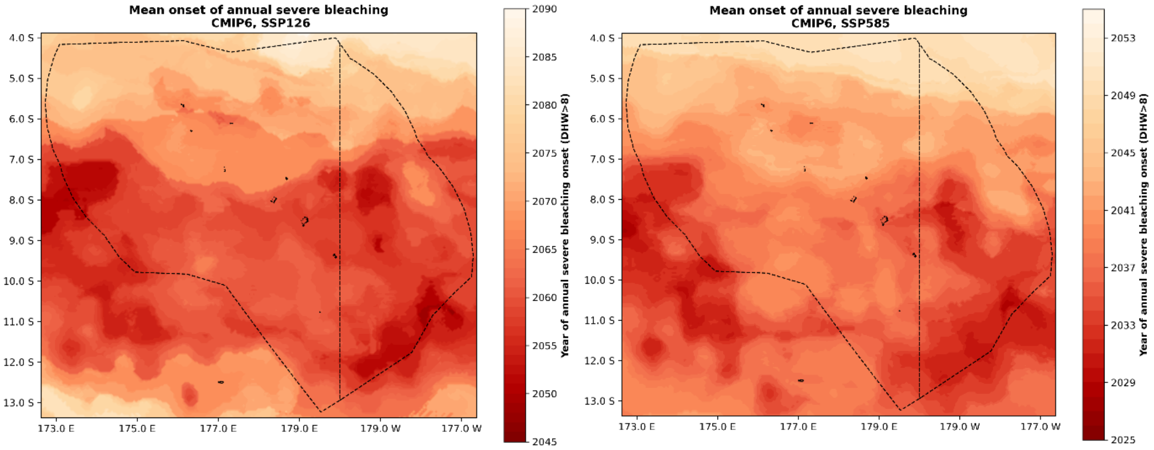


Figure 10-12 Mean onset year of annual severe bleaching (that is, degree heating week events with DHW>8 °C-week each year) for an ensemble of future projections from 14 CMIP6 models under a low warming scenario (SSP1-2.6, left) and a high warming scenario (SSP5-8.5, right). Regional variability of degree heating weeks (DHW) is evident. The severe bleaching level assumes no adaptation to thermal stress. Method here follows Maynard et al. 2018 [38]. NB: DIFFERENT COLOUR SCALE due to the large difference in the years for SSP5-8.5 and SSP1-2.6 (it saturates the scale for the SSP5-8.5 image).

To explore differences in bleaching exposure, DHW time series were compared for two sites Funafuti and Niutao under a low warming climate scenario by 2050. Alert levels are exceeded more frequently in Niutao than Funafuti (Figure 10-13, top). Comparing Nuitao's coral bleaching under low emissions (Figure 10-13, middle) and high emissions (Figure 10-13, bottom) are also explored, where for Alert Level 2, which is not exceeded in the historical period (1995-2014), by 2050, under low emissions and low warming model, it is exceeded once but under high emissions high warming model, it is almost constantly exceeded (Figure 10-13, middle and bottom; Also see Table 10-3).

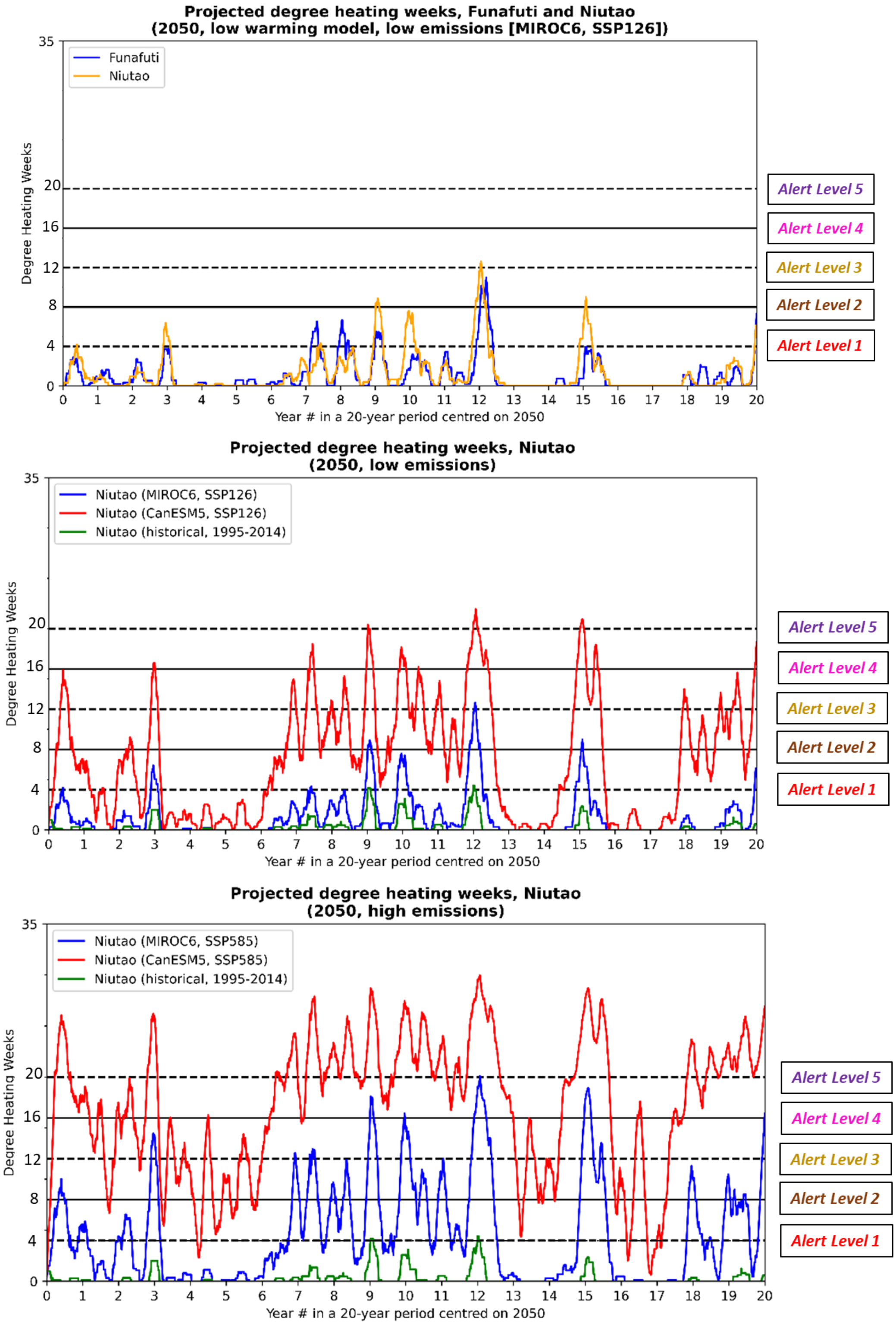


Figure 10-13 Regional variability of degree heating weeks (DHW) based on time series of DHW (°C-week) for a 20-year period centred on 2050 for 'low warming' (MIROC6, SSP126) for Funafuti (blue) and Niutao (orange) (top). ZHIsrorical (1995-2014) period (green), a 20-year period centred on 2050 for 'low emissions' (SSP126, blue) (high and low warming model) for Niutao (middle), and a 20-year period centred on 2050 for 'high emissions' (SSP585, red)) (high and low warming model) for Niutao (bottom). The horizontal lines show the levels at which significant coral bleaching is likely (DHW>4 °C-week), severe bleaching and significant coral mortality is likely (DHW>8 °C-week), multi-species coral mortality is likely (DHW>12 °C-week), severe multi-species coral mortality is likely (DHW>16 °C-week), and near complete coral

mortality is likely (DHW>20 °C-week). These levels assume no adaptation to thermal stress. Method here follows Langlais et al. 2017 [39], and high-frequency spatial and temporal variability based on that in OISST v2-1 SST [8].

Table 10-3 Number of events and days above the DHW thresholds for Bleaching Alert Level 1 (DHW>4 °C-week) and Bleaching Alert Level 2 (DHW>8 °C-week, see Table 10-2) in historical OISST v2-1 SST data, and 20-year projections centred on 2050 for Niutao in both high-warming (CanESM5) and low-warming (MIROC6) models, as well as lower (SSP126) and higher (SSP585) emissions scenarios.

Degree heating week thresholds	Historical data (1995-2014)	Low Emissions (SSP126)		High Emissions (SSP 585)	
		Low warming (MIROC6)	High warming (CanESM5)	Low warming (MIROC6)	High warming (CanESM5)
# of events exceeding Alert level 1	2	8	9	24	5
Days above Alert level 1	48	655	4446	3074	7092
# of events exceeding Alert level 2	0	3	21	21	17
Days above Alert level 2	0	169	2934	1652	6460

Ocean warming caveats

The resolution of the datasets described above does not capture the detailed spatial and temporal temperature fluctuations and ocean chemistry of individual reefs and lagoons. To fully understand how large-scale changes surrounding the lagoon translate to these localised waters, access to high-quality long-term monitoring data is important.

Some of the largest biases found in GCMs are in the western Pacific, meaning that confidence in some climate projections is low compared to other regions. Such biases should be considered when interpreting results from climate model projections for practical applications within a particular region. Important model biases for the Pacific region include sea surface temperatures: West Pacific Warm Pool and equatorial 'cold tongue' can be the wrong shape, and the cold tongue is generally too strong in models [40-42].

It is useful to note the size of the atolls compared to the resolution of the gridded SST data (Figure 10-14). Selecting different sites on the one atoll for comparison will not show any meaningful differences. For sub-atoll assessments, ocean monitoring buoys at the locations can be used to inform or calibrate the data [43].

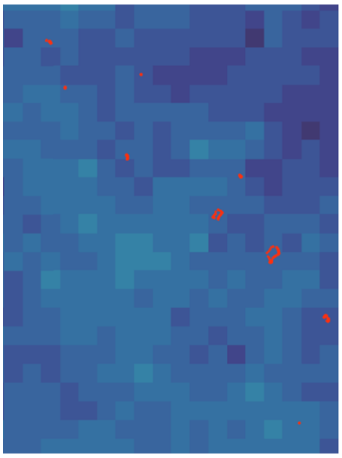


Figure 10-14 NOAA OISST v2-1 grid (0.25 degree or ~ 28 km) [8], showing Tuvalu's atolls (red), noting the relative size of the grid cell from which each SST timeseries and MHW analysis is taken.

Changes in the zonal gradients of sea surface temperature (SST) across the equatorial Pacific such as ENSO have major consequences for global climate [44]. It is important to note that there is a large degree of inconsistency among climate models on some aspects of future projections [44], as well as biases (e.g. [31, 41, 45, 46]). See Chapter 4 for a more detailed explanation.

References

1. IPCC, *The ocean and cryosphere in a changing climate*. 2019; Available from: https://www.ipcc.ch/srocc/chapter/summary-for-policymakers/.
2. IPCC, ed. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. ed. V. Masson-Delmotte, et al. 2021, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, .
3. Hobday, A.J., L.V. Alexander, S.E. Perkins, D.A. Smale, S.C. Straub, E.C. Oliver, J.A. Benthuysen, M.T. Burrows, M.G. Donat, and M. Feng, A hierarchical approach to defining marine heatwaves. *Progress in Oceanography,* 2016. 141: p. 227-238.
4. Hobday, A.J., E.C. Oliver, A.S. Gupta, J.A. Benthuysen, M.T. Burrows, M.G. Donat, N.J. Holbrook, P.J. Moore, M.S. Thomsen, and T. Wernberg, Categorizing and naming marine heatwaves. *Oceanography,* 2018. 31(2): p. 162-173.
5. Oliver, E.C.J., M.G. Donat, M.T. Burrows, P.J. Moore, D.A. Smale, L.V. Alexander, J.A. Benthuysen, M. Feng, A. Sen Gupta, A.J. Hobday, N.J. Holbrook, S.E. Perkins-Kirkpatrick, H.A. Scannell, S.C. Straub, and T. Wernberg, Longer and more frequent marine heatwaves over the past century. *Nature Communications,* 2018. 9(1): p. 1324 DOI: 10.1038/s41467-018-03732-9.
6. Holbrook, N.J., V. Hernaman, S. Koshiba, J. Lako, J.B. Kajtar, P. Amosa, and A. Singh, Impacts of marine heatwaves on tropical western and central Pacific Island nations and their communities. *Global Planetary Change,* 2022. 208: p. 103680.
7. McGree, S., G. Smith, E. Chandler, N. Herold, Z. Begg, Y. Kuleshov, P. Malsale, and M. Ritman, *Climate Change in the Pacific 2022: Historical and Recent Variability, Extremes and Change.* . 2022 Climate and Oceans Support Program in the Pacific. Pacific Community: Suva, Fiji.; Available from: https://library.sprep.org/content/climate-change-pacific-2022-historical-and-recent-variability-extremes-and-change
8. Huang, B., C. Liu, V. Banzon, E. Freeman, G. Graham, B. Hankins, T. Smith, and H. Zhang, *NOAA 0.25-degree daily optimum interpolation sea surface temperature (OISST), version 2.1*. 2020; Available from: https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.html
9. Lehodey, P., J. Hampton, R. Brill, S. Nicol, I. Senina, B. Calmettes, H.-O. Pörtner, L. Bopp, R. Ilyina, and J. Bell, *Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In Bell, J., Johnson, JE, Hobday, AJ (Ed.), Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climae Change* Ch in *Secretariat of the Pacific Community. Noumea New Caledonia.* 2011.
10. Patrick Lehodey, John Hampton, Rich W Brill, Simon Nicol, Inna Senina, Beatriz Calmettes, Hans O Pörtner, Laurent Bopp, Tatiana Ilyina, Johann D Bell, and John Siber, *Vulnerability of oceanic fisheries in the tropical Pacific to climate change* Ch in *Vulnerability of tropical Pacific fisheries and aquaculture to climate change.*, J.D. Bell, J.E. Johnson, and A.J. Hobday, Editors. 2011, SPC: New Caledonia.
11. Bell, J.D., I. Senina, T. Adams, O. Aumont, B. Calmettes, S. Clark, M. Dessert, M. Gehlen, T. Gorgues, and J. Hampton, Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature sustainability,* 2021. 4(10): p. 900-910.
12. Cai, W., G. Wang, A. Santoso, M.J. McPhaden, L. Wu, F.-F. Jin, A. Timmermann, M. Collins, G. Vecchi, and M. Lengaigne, Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change,* 2015. 5(2): p. 132-137.
13. Cai, W., S. Borlace, M. Lengaigne, P. van Rensch, M. Collins, G. Vecchi, A. Timmermann, A. Santoso, M.J. McPhaden, and L. Wu, Increasing frequency of extreme El Nino events due to greenhouse warming. *Nature Climate Change,* 2014. 4(2): p. 111-116.

14. Bell, J.D., C. Reid, M.J. Batty, P. Lehodey, L. Rodwell, A.J. Hobday, J.E. Johnson, and A. Demmke, Effects of climate change on oceanic fisheries in the tropical Pacific: implications for economic development and food security. *Climatic change,* 2013. 119: p. 199-212.
15. Asch, R.G., W.W.L. Cheung, and G. Reygondeau, Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. *Marine Policy,* 2018. 88: p. 285-294 DOI: https://doi.org/10.1016/j.marpol.2017.08.015.
16. Senina, I., P. Lehodey, B. Calmettes, M. Dessert, J. Hampton, N. Smith, T. Gorgues, O. Aumont, M. Lengaigne, and C. Menkes, *Impact of climate change on tropical Pacific tuna and their fisheries in Pacific Islands waters and high seas areas*. 2018 14th Regular Session of the Scientific Committee of the Western Central Pacific Fisheries Commission, WCPFC-SC14; Available from: https://meetings.wcpfc.int/node/10666.
17. Holbrook, N.J., H.A. Scannell, A. Sen Gupta, J.A. Benthuysen, M. Feng, E.C.J. Oliver, L.V. Alexander, M.T. Burrows, M.G. Donat, A.J. Hobday, P.J. Moore, S.E. Perkins-Kirkpatrick, D.A. Smale, S.C. Straub, and T. Wernberg, A global assessment of marine heatwaves and their drivers. *Nature Communications,* 2019. 10(1): p. 2624 DOI: 10.1038/s41467-019-10206-z.
18. Holbrook, N.J., A. Sen Gupta, E.C.J. Oliver, A.J. Hobday, J.A. Benthuysen, H.A. Scannell, D.A. Smale, and T. Wernberg, Keeping pace with marine heatwaves. *Nature Reviews Earth & Environment,* 2020. 1(9): p. 482-493 DOI: 10.1038/s43017-020-0068-4.
19. Smale, D.A., T. Wernberg, E.C. Oliver, M. Thomsen, B.P. Harvey, S.C. Straub, M.T. Burrows, L.V. Alexander, J.A. Benthuysen, and M.G. Donat, Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change,* 2019. 9(4): p. 306-312.
20. Smith, K.E., M.T. Burrows, A.J. Hobday, A. Sen Gupta, P.J. Moore, M. Thomsen, T. Wernberg, and D.A. Smale, Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science Advances,* 2021. 374(6566): p. eabj3593.
21. Smith, K.E., M.T. Burrows, A.J. Hobday, N.G. King, P.J. Moore, A. Sen Gupta, M.S. Thomsen, T. Wernberg, and D.A. Smale, Biological impacts of marine heatwaves. *Annual Review of Marine Science,* 2023. 15: p. 119-145.
22. Oliver, E.C., M.T. Burrows, M.G. Donat, A. Sen Gupta, L.V. Alexander, S.E. Perkins-Kirkpatrick, J.A. Benthuysen, A.J. Hobday, N.J. Holbrook, and P.J. Moore, Projected marine heatwaves in the 21st century and the potential for ecological impact. *Frontiers in Marine Science,* 2019. 6: p. 734.
23. Shanks, A.L., L.K. Rasmuson, J.R. Valley, M.A. Jarvis, C. Salant, D.A. Sutherland, E.I. Lamont, M.A. Hainey, and R.B. Emlet, Marine heat waves, climate change, and failed spawning by coastal invertebrates. *Limnology Oceanography,* 2020. 65(3): p. 627-636.
24. Atkinson, J., N.G. King, S.B. Wilmes, and P.J. Moore, Summer and winter marine heatwaves favor an invasive over native seaweeds. *Journal of Phycology,* 2020. 56(6): p. 1591-1600.
25. Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Adalgeirsdottir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallee, A.B.A. Slangen, and Y. Yu, *Ocean, Cryosphere and Sea Level Change.* Ch in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte, et al., Editors. 2021, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, . p. 1211–1362.
26. Laufkötter, C., J. Zscheischler, and T.L. Frölicher, High-impact marine heatwaves attributable to human-induced global warming. *Science Advances,* 2020. 369(6511): p. 1621-1625.
27. Marra, J.J., G. Gooley, M.-V.V. Johnson, V.W. Keener, M.K. Kruk, S. McGree, J.T. Potemra, and O. Warrick, *Pacific Islands Climate Change Monitor: 2021*. 2022 The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS)

Panel and Pacific Meteorological Council (PMC); Available from: https://www.pacificmet.net/pacific-climate-change-monitor-report.

28. England, M.H., S. McGregor, P. Spence, G.A. Meehl, A. Timmermann, W. Cai, A.S. Gupta, M.J. McPhaden, A. Purich, and A. Santoso, Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nature Climate Change,* 2014. 4(3): p. 222-227.
29. Dhage, L. and M.J. Widlansky, Assessment of 21st century changing sea surface temperature, rainfall, and sea surface height patterns in the tropical Pacific Islands using CMIP6 greenhouse warming projections. *Earth's Future,* 2022(e2021EF002524) DOI: 10.1029/2021EF002524.
30. Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society,* 1997. 78(6): p. 1069-1080.
31. Power, S., M. Lengaigne, A. Capotondi, M. Khodri, J. Vialard, B. Jebri, E. Guilyardi, S. McGregor, J.-S. Kug, and M. Newman, Decadal climate variability in the tropical Pacific: Characteristics, causes, predictability, and prospects. *Science Advances,* 2021. 374(6563): p. eaay9165.
32. Power, S., T. Casey, C. Folland, A. Colman, and V. Mehta, Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics,* 1999. 15(5): p. 319-324 DOI: 10.1007/s003820050284.
33. Skirving, W., B. Marsh, J. De La Cour, G. Liu, A. Harris, E. Maturi, E. Geiger, and C. Eakin, 12, 3856; https://doi.org/10.3390/rs12233856. , CoralTemp and the Coral Reef Watch Coral Bleaching Heat Stress Product Suite Version 3.1. . *Remote Sens.,* 2020. 12: p. 3856 DOI: https://doi.org/10.3390/rs12233856.
34. Liu, G., Skirving WJ, Geiger EF, De La Cour JL, Marsh BL, Heron SF, Tirak KV, Strong AE, and Eakin CM, NOAA Coral Reef Watch's 5km Satellite Coral Bleaching Heat Stress Monitoring Product Suite Version 3 and Four-Month Outlook Version 4. . *Reef Encounter 45,* 2017. 32(1): p. 39-45.
35. NOAA. *Coral Reef Watch Satellite Monitoring and Modeled Outlooks*. 2023 Available from: https://coralreefwatch.noaa.gov/satellite/index.php.
36. Kayanne, H., Validation of degree heating weeks as a coral bleaching index in the northwestern Pacific. *Coral Reefs,* 2017. 36(1): p. 63-70.
37. Van Hooidonk, R., J. Maynard, J. Tamelander, J. Gove, G. Ahmadia, L. Raymundo, G. Williams, S.F. Heron, and S. Planes, Local-scale projections of coral reef futures and implications of the Paris Agreement. *Scientific reports,* 2016. 6(1): p. 1-8.
38. Maynard J, Heron S, van Hooidonk R, and D. Tracey, *Past and projected future impacts of coral bleaching on the reefs of Vanuatu.* . 2018 Secretariat of the Pacific Regional Environment Programme (SPREP), : Apia, Samoa; Available from: https://library.sprep.org/content/past-and-projected-future-impacts-coral-bleaching-reefs-vanuatu.
39. Langlais, C., A. Lenton, S. Heron, C. Evenhuis, A. Sen Gupta, J. Brown, and M. Kuchinke, Coral bleaching pathways under the control of regional temperature variability. *Nature Climate Change,* 2017. 7(11): p. 839-844.
40. Grose, M.R., S. Narsey, F. Delage, A.J. Dowdy, M. Bador, G. Boschat, C. Chung, J. Kajtar, S. Rauniyar, and M. Freund, Insights from CMIP6 for Australia's future climate. *Earth's Future,* 2020. 8(5): p. e2019EF001469.
41. Graham, F.S., A.T. Wittenberg, J.N. Brown, S.J. Marsland, and N.J. Holbrook, Understanding the double peaked El Niño in coupled GCMs. *Climate Dynamics,* 2017. 48(5): p. 2045-2063 DOI: 10.1007/s00382-016-3189-1.
42. Brown, J.N., C. Langlais, and C. Maes, Zonal structure and variability of the Western Pacific dynamic warm pool edge in CMIP5. *Climate Dynamics,* 2014. 42(11): p. 3061-3076 DOI: 10.1007/s00382-013-1931-5.

43. Webb, L.B., V. Hernaman, R. Hoeke, and K. Hennessy, *Ocean Monitoring*. 2023: Explainer prepared for the Vanuatu Meteorology and Geo-hazards Department as part of the Van-KIRAP project. CSIRO, VMGD, SPREP, Melbourne, Australia; Available from: https://www.vanclimatefutures.gov.vu/assets/docs/Ocean%20Monitoring%20Factsheet.pdf .
44. Lee, S., M. L'Heureux, A.T. Wittenberg, R. Seager, P.A. O'Gorman, and N.C. Johnson, On the future zonal contrasts of equatorial Pacific climate: Perspectives from Observations, Simulations, and Theories. *Climate Atmospheric Science,* 2022. 5(1): p. 82.
45. Collins, M., S.-I. An, W. Cai, A. Ganachaud, E. Guilyardi, F.-F. Jin, M. Jochum, M. Lengaigne, S. Power, and A. Timmermann, The impact of global warming on the tropical Pacific Ocean and El Niño. *Nature Geoscience,* 2010. 3(6): p. 391-397.
46. Erickson, N.E. and C.M. Patricola, Future projections of the El Niño—Southern Oscillation and tropical Pacific mean state in CMIP6. *Journal of Geophysical Research: Atmospheres,* 2023. 128(21): p. e2022JD037563.

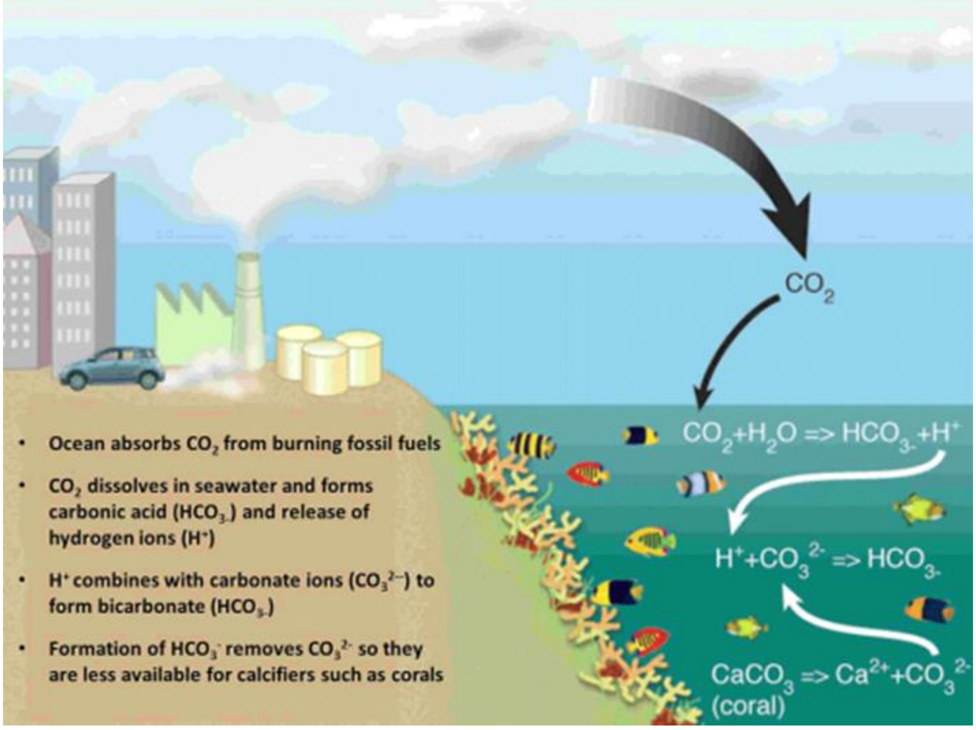
Chapter 11 Ocean acidification

Introduction

Fish provide 50–90 % of animal protein towards the diet of coastal communities across the Pacific islands, with national average fish consumption per person more than 3–4 times the global average. A loss of fisheries productivity and marine aquatic biodiversity would threaten national economies dependent on fisheries resources [1]. Aquaculture commodities in the tropical Pacific that are expected to be most vulnerable to acidification are pearl oysters, shrimp, and marine ornamentals [2]. The key implications of ocean acidification are being addressed through regional and national plans and policies for economic development, food security, and livelihoods [2].

As carbon dioxide (CO_2) concentrations increase in the atmosphere, more CO_2 is available for oceanic uptake, dissolving in the seawater and changing ocean chemistry [3]. This process, termed 'ocean acidification' (OA) [4], results in fewer carbonate ions and more hydrogen ions, therefore increasing acidity (reducing the pH) (Figure 11-1).

In the ocean, carbonate is used (together with calcium) to produce aragonite, which in turn is used in building coral reef structures and by invertebrate organisms to make their skeletons and hard shells [5]. As the availability of aragonite is strongly correlated to ocean pH, if the ocean becomes more acidic it will become difficult for creatures to make their skeletons and shells, and for corals to build and repair reef structures [6].



- **Ocean absorbs CO_2 from burning fossil fuels**
- **CO_2 dissolves in seawater and forms carbonic acid (HCO_{3-}) and release of hydrogen ions (H^+)**
- **H^+ combines with carbonate ions (CO_3^{2-}) to form bicarbonate (HCO_{3-})**
- **Formation of HCO_3^- removes CO_3^{2-} so they are less available for calcifiers such as corals**

Figure 11-1 The process of ocean acidification. Source: modified from Hoegh-Guldberg et al. 2007 [7].

This poses a significant global threat to the long-term viability of corals, shellfish and fish (through impacts on growth, survival of juveniles, recruitment, and food web relationships), coral reefs and associated marine ecosystems, and coastal communities that rely on them for their livelihood and wellbeing. This is a particular hazard impacting the western tropical Pacific, including Tuvalu, with major implications for the fisheries sector [8].

Observed aragonite saturation and pH

Atmospheric CO_2 concentrations have increased 47 % since the pre-industrial era (1750) [9] and 24–33 % of the CO_2 is being absorbed by oceans [2]. Globally, average ocean pH is now 8.1, with the pH of the tropical Pacific Ocean decreasing by 0.06 pH units since the pre-industrial era [2]. In 2022, in the southern section of the Pacific Ocean (latitudes 35 °S to 7 °S), pH is slightly lower, at around 8.05. Observations indicate a decrease of 0.070 in pH in the 1982-2022 period, representing an 18 % increase in acidity. For aragonite saturation for the Pacific Ocean latitude band 35 °S to 7 °S, levels have decreased from around 3.7 in 1982, to below 3.4 in 2022 [10] (Figure 11-2). It is noted that across longitude bands ocean acidification levels vary so levels described in Figure 11-2 cannot be applied to Tuvalu directly. In the western tropical Pacific Warm Pool, trends during the 1985–2016 period show a change on average of −0.0013 per year for pH and −0.0083 per year for the aragonite saturation state [11]. While the projected change in pH seems small, it is important to remember that the pH scale is logarithmic, so the reduction in pH in surface ocean waters that we have already seen actually represents a 30 % increase in acidity.

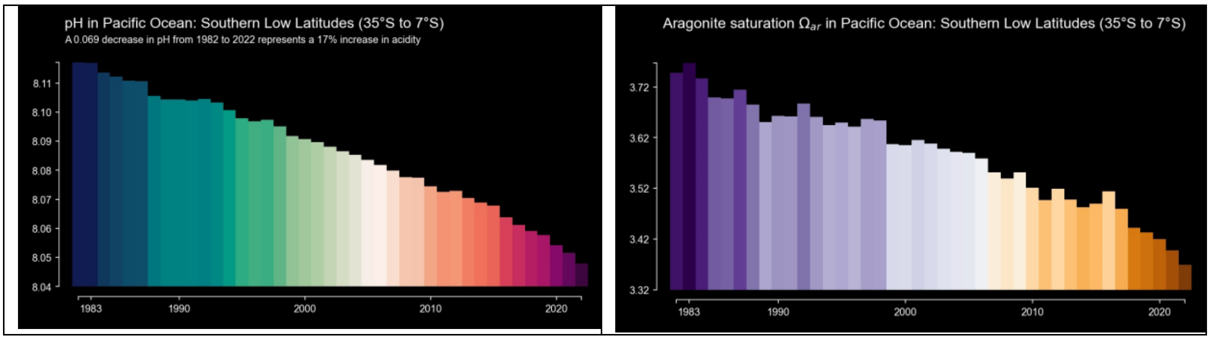


Figure 11-2 pH (left) and aragonite saturation levels (right) in the low latitudes of the Pacific Ocean Basin measured from 1982-2022 [10] https://oceanacidificationstripes.info/c/ph/basin/pacificocean/equatorial7sto7n Data Source: OceanSODA-ETHZ [12].

Importance of the Pacific OA monitoring network

Local OA observations are vital to improve our understanding of natural variability in ocean chemistry at the scale of reefs and coastal communities, and associated responses in a wide range of organisms and ecosystems. The Global Ocean Acidification Observing Network (GOA-ON; http://goa-on.org/) is an international collaborative network which provides a framework for the coordination of methods and resources for making local-scale OA observations.

For example, a series of Sofar Spotter buoys has recently been deployed by the Van-KIRAP project across the Vanuatu archipelago [13]. There is an opportunity for integration of ocean chemistry monitoring instruments into the existing Sofar Spotter buoy coastal network. This would improve our understanding the vulnerability of ocean organisms to changes in OA and enhance the availability of reliable, fine resolution OA data.

Projected aragonite saturation and pH

Projections of future OA conditions under a changing climate are crucial for guiding society's mitigation and adaptation efforts [14]. Under all global CO_2 emission scenarios, a net decrease in pH and aragonite saturation state occurs, with the largest changes associated with the highest atmospheric CO_2. Global-average open-ocean surface pH is projected to decline by 0.08 ± 0.003 (very likely range), 0.17 ± 0.003, 0.27 ± 0.005 and 0.37 ± 0.007 pH units in 2081–2100 relative to 1995–2014, for SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively [15].

For Tuvalu, the projected change in pH by the year 2050 is 0.05 units for a low emissions scenario and 0.12 units for a high emissions scenario (Figure 11-3, bottom). Spatial patterns of projected changes in aragonite saturation state near Tuvalu are shown in Figure 11-4. Larger changes are obvious for the high emissions scenario compared to the low emissions scenario.

For Tuvalu, under a high emission scenario (RCP8.5), aragonite saturation states may fall below 3 by 2060, a level where coral reefs in Tuvalu may not only stop growing but start to get smaller, as they dissolve faster than they are built (Figure 11-3, top & Figure 11-4 for spatial view). However, if emissions follow a low scenario (RCP2.6), consistent with the Paris Agreement target of keeping global warming well below 2 °C, then the aragonite saturation state may start to recover after 2060.

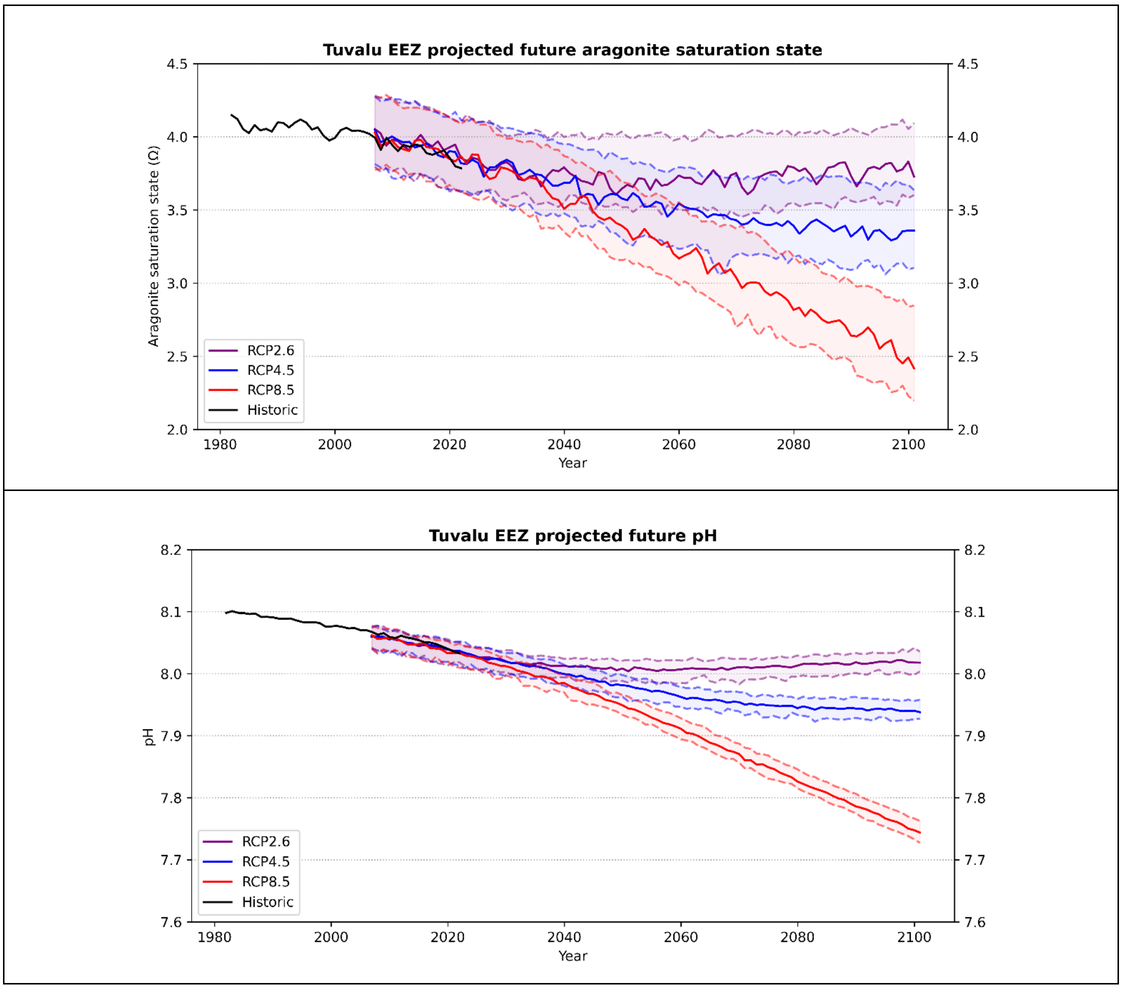


Figure 11-3 Projected decreases in aragonite saturation state (top) and pH (bottom) for the Tuvalu Exclusive Economic Zone (EEZ) from six CMIP5 climate models under three emissions scenarios: RCP2.6, RCP4.5, and RCP8.5. Shown are the median values (bold lines), and the 10th and 90th percentiles (dashed lines and shading). Also shown are historic data (black line) from the OceanSODA-ETHZ dataset from 1982 – 2022.

Table 11-1: Summary table of the median aragonite saturation state for SSP1-2.6 and SSP5-8.5 in Figure 11-3 for 2030 and 2050 climatologies (10th to 90th percentile of model range in brackets; 6 CMIP5 models represented).

Projected climatology	RCP 2.6	RCP 8.5
2030 (2020-2039)	3.79 (3.59 – 4.06)	3.74 (3.51 – 4.01)
2050 (2040-2059)	3.69 (3.53 – 4.01)	3.40 (3.18 – 3.70)

Table 11-2 Summary table of the median pH for SSP1-2.6 and SSP5-8.5 in Figure 11-3 for 2030 and 2050 climatologies (10th to 90th percentile of model range in brackets; 6 CMIP5 models represented).

Projected climatology	RCP 2.6	RCP 8.5
2030 (2020-2039)	8.02 (8.00 – 8.04)	8.01 (7.99 – 8.03)
2050 (2040-2059)	8.01 (7.99 – 8.02)	7.95 (7.93 – 7.96)

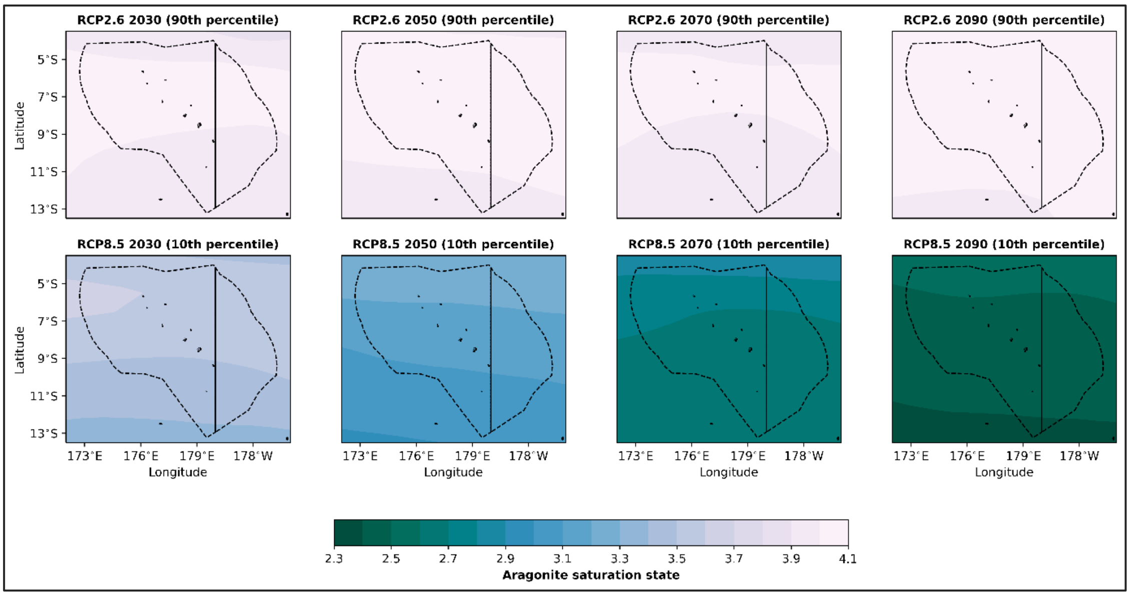


Figure 11-4: Upper and lower projections of aragonite saturation state for the Tuvalu and the Tuvalu Exclusive Economic Zone (marked by the dashed line) from six CMIP5 climate models under emissions scenarios RCP2.6 and RCP8.5 for the years 2030, 2050, 2070 and 2090. Shown are upper projections, given by the 90th percentile of RCP2.6 projections (top row), and lower projections, given by the 10th percentile of RCP8.5 projections (bottom row).

There is very high confidence that the ocean will become more acidic, with a net reduction in pH. There is also high confidence that the rate of OA is, and will continue to be, proportional to the CO_2 emissions. There is medium confidence that long-term viability of corals will be impacted under RCP8.5 and RCP4.5, and that there will be harm to marine ecosystems from the large reduction in pH under RCP8.5 [16, 17].

Caveats

It is difficult to generalise actual responses across organisms and ecosystems to changing ocean chemistry for several reasons:

- Projected changes in aragonite saturation and pH are for the open ocean, and do not account for numerous local processes that modify ocean chemistry, especially on reefs.
- Closely related species can respond differently; most experiments have been conducted under relatively short-term laboratory conditions (although field-based experiments are becoming more widespread); and research has shown greater adaptive capacity in some species compared to others [18].
- Detecting and attributing marine ecosystem responses to ocean acidification and deoxygenation outside of laboratory studies remains challenging because of the strong influence of co-occurring environmental changes on natural systems (IPCC WG2 report page 460, 2022).

References

1. SPC. *Ocean acidification: a tide of challenges for Pacific Islanders*. 2022 Available from: https://www.spc.int/updates/blog/2022/08/ocean-acidification-a-tide-of-challenges-for-pacific-islanders.
2. Johnson, J.E., J.D. Bell, and A.S. Gupta, *Pacific islands ocean acidification vulnerability assessment*. 2015 SPREP Apia, Somoa; Available from: https://www.sprep.org/attachments/Publications/CC/ocean-acidification.pdf.

3. DeVries, T., The Ocean Carbon Cycle. *Annual Review of Environment Resources,* 2022. 47: p. 317-341.
4. Feely, R.A., S.C. Doney, and S.R. Cooley, Ocean acidification: present conditions and future changes in a high-CO_2 world. 2009.
5. Bell, J.D., J.E. Johnson, and A.J. Hobday, *Vulnerability of tropical Pacific fisheries and aquaculture to climate change*. 2011, Noumea, New Caledonia.: Secretariat of the Pacific Community (SPC).
6. Doney, S.C., M. Ruckelshaus, J.E. Duffy, J.P. Barry, F. Chan, C.A. English, H.M. Galindo, J.M. Grebmeier, A.B. Hollowed, and N. Knowlton, Climate change impacts on marine ecosystems. *Marine Science,* 2012. 4.
7. Hoegh-Guldberg, O., P. Mumby, A. Hooten, R. Steneck, P. Greenfield, E. Gomez, C. Harvell, P. Sale, A. Edwards, and K. Caldeira, Coral reefs under rapid climate change and ocean acidification. *Science,* 2007. 318(5857): p. 1737-1742.
8. Marra, J.J., G. Gooley, M.-V.V. Johnson, V.W. Keener, M.K. Kruk, S. McGree, J.T. Potemra, and O. Warrick, *Pacific Islands Climate Change Monitor: 2021*. 2022 The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC); Available from: https://www.pacificmet.net/pacific-climate-change-monitor-report.
9. IPCC, *Summary for Policymakers. Synthesis of IPCC Sixth Assessment Report.* . 2023 IPCC: Geneva, Switzerland; Available from: https://www.ipcc.ch/report/ar6/syr/ (Accessed 23/3/2023).
10. Gruber, N. and L. Gregor, *#OceanAcidificationStripes*. 2023: Website: Institute for Environmental Analytics logoInstitute for Environmental Analytics; Available from: https://oceanacidificationstripes.info/c/ph/basin/globalocean/entirebasin
11. Ishii, M., K.B. Rodgers, H.Y. Inoue, K. Toyama, D. Sasano, N. Kosugi, H. Ono, K. Enyo, T. Nakano, and D. Iudicone, Ocean acidification from below in the tropical Pacific. *Global Biogeochemical Cycles,* 2020. 34(8): p. e2019GB006368.
12. Gregor, L. and N. Gruber, OceanSODA-ETHZ: a global gridded data set of the surface ocean carbonate system for seasonal to decadal studies of ocean acidification. *Earth System Science Data Discussions,* 2021. 13(2): p. 777-808.
13. CSIRO, VMGD, and SPREP, *Ocean monitoring: Sofar Spotter buoys*. 2023; Available from: https://www.vanclimatefutures.gov.vu/assets/docs/Ocean%20Monitoring%20Factsheet.pdf .
14. Jiang, L.q., J. Dunne, B.R. Carter, J.F. Tjiputra, J. Terhaar, J.D. Sharp, A. Olsen, S. Alin, D.C. Bakker, and R.A. Feely, Global surface ocean acidification indicators from 1750 to 2100. *Journal of Advances in Modeling Earth Systems,* 2023. 15(3): p. e2022MS003563.
15. IPCC WG2, *Climate Change 2022: Impacts, Adaptation and Vulnerability.* . 2022 Cambridge University Press, : Cambridge, UK and New York, NY, USA, .
16. IPCC, *Summary for Policymakers. IPCC Sixth Assessment Report from Working Group 2 on Impacts, Adaptation and Vulnerability.* . 2022; Available from: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf.
17. CSIRO and BoM, *Climate Change in Australia Technical Report*. 2015 CSIRO Marine and Atmospheric Research and Bureau of Meteorology (CAWCR) and the Department of the Environment: Melbourne, Australia; Available from: URL: http://climatechangeinaustralia.com.au/.
18. Broadgate, W., U. Riebesell, C. Armstrong, P. Brewer, K. Denman, R. Feely, K. Gao, J.-P. Gattuso, K. Isensee, and J. Kleypas. Ocean acidification summary for policymakers–Third Symposium on the ocean in a high-CO2 world. 2013: International Geosphere-Biosphere Programme.

Section 2 HAZARD-BASED IMPACTS AND RATINGS FOR SECTORS

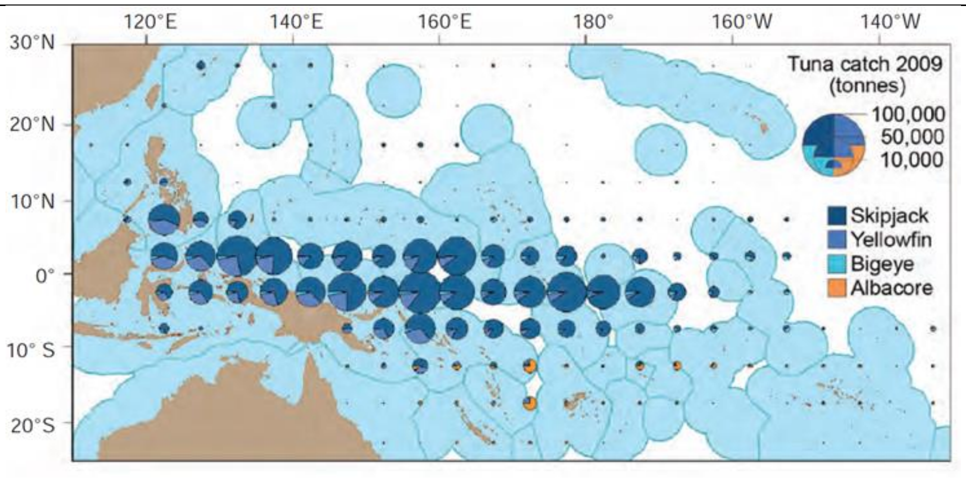
Chapter 12 Fisheries and marine resources

Increasing sea surface temperatures and ocean acidification can affect commercial and subsistence fisheries, including productivity and yield due to changes in distribution, recruitment, growth and abundance. Additionally, degradation of coral reefs and associated critical habitat is also relevant to the sustainability of near-shore coastal fisheries [1]. Impacts associated with each of these climate hazards are described below.

Tuvalu's fisheries sector is divided into two categories; the commercial oceanic fisheries sector, where the majority of government revenue is derived from selling fishing license quota and access to foreign commercial operators; and the coastal fisheries sector, characterised by subsistence, small-scale artisanal fishing for local market sale and consumption. A section on the broader marine resources and coastal biodiversity resources of Tuvalu is also discussed here.

Oceanic Fishing

The four main species that underpin these oceanic fisheries are skipjack tuna *Katsuwonus pelamis*, yellowfin tuna *Thunnus albacares*, bigeye tuna *T. obesus* and South Pacific albacore tuna *T. alalunga* (Figure 12-1; top) [2]. Combined harvests yield more than 1 million tonnes each year, and support fishing operations ranging from industrial fleets to subsistence catches [2]. Each species of tuna has a limited range of ocean temperature within which it occurs [2]. Skipjack tuna, for example, are most abundant in water temperature around 20 to 29 °C, though are found in temperatures slightly outside this range (Figure 12-1; bottom). With warming, locations of suitable foraging and spawning habitat may change, and the availability of tuna species to EEZ and high-seas fisheries may alter [2].



Common name	Species	All occurrences (°C)	Abundant occurrences (°C)
Skipjack	*Katsuwonus pelamis*	17–30	20–29
Yellowfin	*Thunnus albacares*	18–31	20–30
Bigeye	*T. obesus*	11–29	13–27
Albacore	*T. alalunga*	13–25	15–21
Southern bluefin	*T. maccoyii*	10.5–21	17–20

Figure 12-1 Distribution of catches of the four species of tuna that dominate oceanic fisheries in the Western and Central Pacific Ocean in 2009 [2] (top) Range of sea surface temperatures (SSTs) for tuna species targeted by Pacific Island States and Territories) in the Pacific Ocean, together with the SST range where substantial commercial catches are made (abundant occurrences) [3] (bottom).

Sea surface temperature

With SST warming, the location of prime fishing grounds may change, and the productivity and catchability of tuna by surface and longline fisheries may alter [2]. Good fishing grounds could be displaced further eastward along the equator or shift to higher latitudes. Potential negative climate change impacts on fisheries would have flow-on impacts on Tuvalu's ability to generate revenue, contributing to increased economic vulnerability [4].

The projected responses of tuna species targeted by purse-seine fisheries (skipjack, yellowfin, and bigeye) to climate change have been estimated by an ecosystem model (the Spatial Ecosystem and Population Dynamics Model SEAPODYM) informed by four climate models from CMIP5 [5]. For Tuvalu, climate-driven shifts in tuna distributions are projected to have varied consequences for fisheries catch depending on the emissions scenario (RCP4.5 or 8.5). At the Pacific basin-scale, tuna biomass is projected to shift eastwards, with a 12.6 % decrease in biomass in the Western Central Pacific Ocean (considered here as the EEZ of 10 Pacific Islands and Territories) and concurrent 23.3 % increase in biomass in the central Eastern Pacific Ocean by 2050 under RCP8.5

For Tuvalu specifically, by 2050 under RCP4.5 the average purse-seine catch of skipjack, yellowfin, and bigeye tuna is projected to increase by 3.4 %, however under RCP8.5 by 2050 the average catch is projected to decline by 23.4 % [5] (Table 12-1). These projected changes may have economic consequences for Tuvalu's government revenue associated with tuna-fishing access fees. By 2050, revenue is projected to increase by 1.9 % under RCP4.5 or decline by 12.6 % under RCP8.5 [5] (Table 12-1).

Table 12-1 Average projected changes in purse-seine catch (%, tonne and revenue) for Tuvalu for 2050 under RCP4.5 and RCP8.5. Source: [5].

	2050 RCP4.5		2050 RCP8.5	
	Median	Model range	Median	Model range
Catch (% change)	+3.4 %	-4.9 to +19.9 %	- 23.4%	-31.7 to -14.3 %
Catch (tonne)	+2509	-3,585 t to +14,512 t	- 17,088	-23,159 t to -10,448 t
Revenue change (%)	+1.9 %	-2.7 to +10.7 %	- 12.6 %	-17.1 to –7.7 %

There is considerable uncertainty in the timing and magnitude of tuna redistributions in and out of Tuvalu's EEZ, however, the general consensus in climate modelling is that tropical tuna biomass in the Pacific are projected to shift eastwards compared to their current position ([5-9]. To further explore this uncertainty, new work on tuna biomass modelling has been proposed. The existing modelling assumes that each tuna species forms a single stock across the tropical/subtropical Pacific Ocean basin. Evidence is accumulating that this is not the case. Finally when considering the changes reported in Table 12-1, it is understood for the Pacific region there is lower confidence in SST projections; the climate models tend to simulate the wrong shape for the Warm Pool and equatorial 'cold tongue', and the 'cold tongue' is generally too strong in models [10-12] (see Caveats section). Projected changes in ENSO also have significant uncertainty (See Chapter 2).

In addition to the overall warming of the ocean, east-west displacements of skipjack tuna are correlated ENSO [7], leading to large fluctuations in catches from the EEZs of PICTs (Figure 12-2). In a La Niña event, the fish can occur in a more westward area following the warm water [5, 13]. Therefore, during La Niña events, the best catches of skipjack tuna are made in the west of the region, whereas during El Niño events fishing is most efficient in the east [5]. SSTs northeast of

Tuvalu are usually warmer than normal during an El Niño event, and cooler during a La Niña event (PACCSAP, 2014). During El Niño events, higher purse-seine catches are made in the central Pacific, such as Tuvalu.

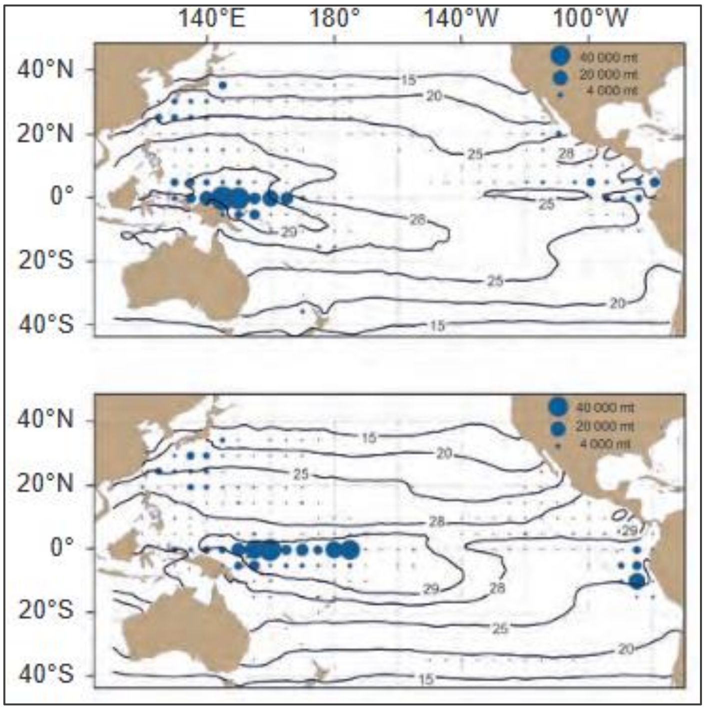


Figure 12-2 Impact of El Niño-Southern Oscillation (ENSO) on skipjack catch distribution and movement in the Western and Central Pacific Ocean. (a) Skipjack tuna catch (tonnes) and mean sea surface temperature (°C) in the tropical Pacific Ocean during the first half of 1989 (La Niña period) (top panel), and in the first half of 1992 (El Niño period) (bottom panel), showing effects of ENSO on the location of the Warm Pool (28–29°C) and distribution of skipjack catch. (source: [13]).

Ocean acidification

The main species of tuna in the tropical Pacific are expected to be sensitive to the projected changes in pH in at least four ways.

1. an increase in carbonic acid in the body fluids (acidosis) is likely to cause lower blood pH levels, potentially affecting fish's metabolic demands [14].
2. the growth and formation of the ear bones (otoliths) of tuna may be susceptible to lower pH because they are composed of aragonite, affecting orientation and hearing, especially during the larval stage [15].
3. the effects of decreased pH on reducing the availability of calcium carbonate can have indirect effects on the distribution and abundance of tuna by changing the availability of species of calcifying phytoplankton and zooplankton within the lower trophic levels of the food webs that support tuna [16].
4. the influence of pH on acoustics in the ocean can affect sound attenuation, reducing the sound absorption coefficient, creating a noisier environment and possibly propagating sound further [17].

Coastal Fishing

Coastal fishery targets tuna using trolling, and / or reef fish using spearfishing, such as unicornfish (*Naso* spp.), surgeonfish (Acanthuris spp.), and parrotfish (Scaridae spp.) [18]. Fish Aggregation Devices (FADs) have also been deployed on Tuvalu's islands to help improve catch for small-scale fishers and divert fishing pressure away from reef resources [18, 19].

Some of the reef fish caught in Tuvalu can consume ciguatoxins via feeding on marine algae under certain environmental conditions. Ciguatera poisoning is caused by the consumption of (primarily) finfish contaminated with ciguatoxins, potent neurotoxins produced by benthic single-cell microalgae. When consumed, ciguatoxins are bio-transformed and can bioaccumulate throughout the food-web via complex pathways. In Tuvalu, ciguatera poisoning can occur throughout the year but is reported to be more prevalent during westerly winds [20]. Ciguatera-derived food insecurity is particularly extreme for small island-nations, where fear of intoxication can lead to fishing restrictions by region, species, or size [21], as well as a reluctance of local communities to consume potentially contaminated fish. Exacerbating these complexities are anthropogenic or natural changes occurring in global marine habitats, e.g., climate change, overfishing, invasive species, and the international seafood trade [21]. Furthermore, increased cropping is impacting sustainability of land-crab resources (important natural resource for harvesting as supplementary food source in outer islands), due to habitat competition.

Aquaculture plays a small role in providing food and income for Tuvaluans. The primary aquaculture species in Tuvalu is milkfish (*Chanos chanos*) farmed in Vaitu, where earthen ponds and stone-walled sea pens either on land or in shallow lagoons are used [22]. Also sea cucumber farming using so-called 'sea-ranching' practices plays a small part in Tuvalu's aquaculture.

SST

Changes to ocean temperatures in conjunction with other climate impacts are expected to directly and indirectly effect the distribution and production of coastal fish and invertebrates [23, 24]. By 2050, coral reef fish biomass is projected to decrease by 20 % under a high emissions scenario [23]. A decrease in coastal fish production threatens food security for Tuvaluans who are dependent on subsidence fishing, and threatens livelihoods for those engaged in commercial coastal fishing.

The relative impacts of ocean warming to coastal fishing sectors remains unclear. For example, trolling and using FADs for coastal pelagic fish and tunas may experience different impacts to fishery productivity and catchability compared to spearfishing and hand collecting on reef flats and lagoons.

Since 2011, Tuvalu has been affected by algal blooms, including a large growth of Sargassum on the main atoll of Funafuti, related to high ocean temperatures [25]. The abundance and diversity of benthic harmful *Gambierdiscus* and *Fukuyoa spp.,* dinoflagellates associated with ciguatera fish poisoning, are found to be temperature dependent, with increases in SST favouring some species over others. In a Caribbean based study, ciguatera risk was also location dependent, with both increased and decreased risk varying across the study region [26]. A 1999 Pacific Islands study, including Tuvalu, indicated strong positive correlations between the annual incidence of ciguatera fish poisoning (1973-1994) and El Niño related SST warming [27]. However, another assessment suggests that waters that remain warm enough for a long enough period can lead to ciguatera, while extended periods where the water remains too hot may depress ciguatera case rates [28]. In summary, global ocean warming will promote the growth of benthic harmful dinoflagellates, except in tropical areas where temperatures may exceed upper thermal tolerances (30-31 °C) [29]. Environmental factors affecting ciguatera are undoubtedly complex [27, 28, 30], and further location specific assessments may be required to understand the effects on ciguatera fish poisoning from ocean warming.

Fresh fish are a perishable commodity, and spoilage begins immediately after harvest, especially in the tropics [31]. Temperature is an extremely important factor influencing growth of micro-organisms, and for inshore coastal fisheries, small boats have limited (if any) cooling facilities. Supply chain logistics including timely post-harvest handling and processing (including salting and drying), wet market wholesale/retail sales, and cold storage facilities, where appropriate, become more critical under higher temperatures in order to maintain appropriate food-safety standards [31].

Increases in air and water temperatures from climate change along with reduced water quality will impact aquaculture species productivity, growth, survival, and disease risk for cultured species [22]. [25]. Likewise, TC-induced storms and extreme sea-levels will impact aquaculture infrastructure such as coastal ponds, and natural habitat for lagoon-based activities such as sea-ranching.

Marine and atmospheric heat waves

Impacts from MHWs have been observed on spawning and recruitment processes in coastal fisheries, for example on the high value Grouper species (G. Gooley Pers comm).

Increased incidence of extreme heat events (heatwaves) may impact the coastal fishery processing sector through pressure on storage facilities, and a reduction in workforce productivity; it will be too hot for work outdoors at certain times of the day and year.

Rainfall

Extreme rainfall can lead to increased nutrient and sediment runoff into coastal regions [32], thereby exacerbating localised water quality problems for the coastal fishery sector, while droughts compounded by high temperatures and periodic storm-water and wastewater run-off into adjacent lagoons have been linked to invasive seaweed (*Sargassum polycystum*) [25].

Wind

Salt spray is increasingly a problem for maintenance of fisheries equipment, and this would be exacerbated through periodic drought events.

Increases in coastal wind speed may result in a reduction in 'safe fishing days', i.e. days with wind speeds below 20 knots for small boats used for coastal fisheries (Chand et al. in prep). Wave buoys have been attached to the FADs on the western side of Funafuti (2018-2021) to assist with planning for safe fishing days outside the lagoon [33]. If there are more 'windy' days pressure on fishing in the lagoon will be increased. Maintenance of these FADs has been noted as a problem in Tuvalu.

The Mariner's tropical cyclone guide [34] offers advice around operating vessels while facing threats from TCs.

Marine resources and coastal biodiversity

The 'Status of Coral Reefs of the World 2020' report [35] indicates that between 2009 and 2018 there was a progressive loss of about 14 % from the world's coral reefs. This was primarily caused by recurring, large-scale bleaching events combined with other local pressures such as coastal development, land-based and marine pollution, unsustainable fishing, and tropical storms. Increasing SSTs and associated MHWs adversely impact coral populations worldwide through increasing thermal bleaching events [36, 37]. Degree Heating Weeks (DHWs) is a metric that quantifies bleaching events, taking account of both the length and magnitude of MHWs [38].

A wide variety of reef habitat types exist in Tuvalu, but reef communities tend to be split between typical high-energy oceanic reef systems and sheltered lagoon communities [39]. The 2010 Tuvalu Marine Life (TML) project estimated the overall cover of living corals at 20 to 30 % across all habitats in Funafuti, Nanumea, and Nukulaelae, while the macroalgal cover was low (5 to 10 %) [39]. Reef fish communities in Tuvalu are typical of Central Pacific reef fish faunas, and their diversity lies approximately halfway on a gradient from the most species rich reefs of the Coral Triangle to the relatively depauperate Eastern Pacific reefs [39]. In the past, declines in coral cover have been documented as a consequence of storms, destructive fishing, crown-of-thorns sea stars (COTS) and other coral predators, and bleaching [40].

Tuvalu is home to the globally threatened Hawksbill turtle which is Critically Endangered on the IUCN Red List and only recorded on the Vaitupu underwater visual census (UVC) survey [41]. The recent BioRAP survey also videoed a young leatherback sea-turtle in the Niutao surveys outside of the actual survey transects (with a shell length of ~50 cm) [41]. Pacific Ocean sub-populations of leatherback sea turtles are Critically Endangered on the IUCN Red List. According to a recent survey [42], Tuvalu has established ten conservation areas on eight of its nine islands. The conservation area in Funafuti was established under formal legislation, with the remainder set up by local communities and managed with their traditional systems. The Island Care project monitors nesting turtles, and a Regional Action Plan on Turtles may be able to detect changes over time in gender balance of turtle eggs.

Exotic pests such as Yellow Crazy Ants, *Anoplolepis gracilipes* (F. Smith) (YCA), have adversely affected both land and coconut crabs, earthworms, turtles, seabirds and other populations in some islands in Tuvalu [43]. Targeted, site-specific research on the biology of the yellow crazy ant within Tuvalu can be used to improve the management outcomes for this species to assist with design of knowledge-based treatment protocols and determine assessment benchmarks [44].

Temperature

Gender in sea turtles is determined by nest-incubation temperature during embryonic development in the egg, with warmer sand temperatures skewing the population’s sex ratios towards predominantly females [45]. Sand temperature is related to air temperature and SST [46]. In the northern Great Barrier Reef, Australia, for example, green turtle rookeries have been producing primarily females for more than two decades and complete feminization of this population is possible in the near future [47]. This gender imbalance could ultimately lead to populations becoming compromised or extinct.

Environmental factors, especially temperature and moisture, play key roles in determining the distribution of YCA species, where it is reported to forage at between 21 °C and 35 °C [48], a relatively wide suitable range. While the predicted distribution may move into lower latitudes that it currently occupies, the Pacific Islands remain a suitable location for this species [49].

Harmful macroalgal blooms associated with high SST affect Tuvalu predominantly on the lagoon side. This includes both blue-green and brown algal blooms [39].

Marine heat waves

MHW frequency, intensity, and duration have been detrimental across the region [37], with devastating impacts on marine ecosystems, including many that provide critical habitat and ecosystem services (e.g., coral reefs). For Tuvalu, the impacts from MHWs are most evident on the inshore coral reefs, lagoons and associated coastal fisheries, and other aquatic biota. The ongoing degradation of coral reef and open-ocean fishing habitats will also adversely impact emerging tourism and recreation-based activities [1].

Future coral bleaching is unlikely to be spatially uniform. Therefore, understanding regional differences will be critical for identifying potential refugia and better targeting adaptation management [50]. For example, a 2021 BioRAP survey conducted across four Tuvalu regions (Funafuti Atoll, Nukulaelae Atoll, Niutao Island and Vaitupu Island) noted that “Coral bleaching was more widespread on Niutao, in the northern part of Tuvalu, with bleached coral making up an average of 31 % of the surveyed coastal substrate. The level of bleaching was greater on the leeward reef compared to the windward reef" [41].

Overfishing is compounding problems related to critical habitat loss, however several outer islands have 'Special Protected Areas' (marine reserves) under local community management that employ TK and sustainable traditional fishing methods. A recent discussion describes specific ways to optimize the utility of TK and ensure it has a realistic role in sustaining Pacific Island communities into the future [51].

Wind

Sargassum (dominated by *Sargassum polycystum*) is a genus of brown algae (up to 2 metres in length) that floats in island-like masses, or mats, and never attaches to the seafloor [52]. These mats can be carried from the open sea to the shore by wind and currents [53].

Increasingly, floating Sargassum mats have resulted in mass beaching events and within 48 hours of beaching the decomposing algae produces the toxic gases - hydrogen sulphide (known as rotten egg gas) and ammonia [54]. Sargassum beaching lowers beach amenity and causes human health risks because acute or chronic exposure to these gases may cause respiratory, cardiac, cognitive or neurological impairments [52, 54]. It can result in mortality of marine fish and crustacea by lowering the water quality because of the high nutrient runoff and low oxygen hypoxic conditions. There is, however, potential to use Sargassum for biogas production or fertiliser [52].

Rainfall

Nutrient run-off during rainfall events is impacting lagoon water quality and stimulating algal blooms of Sargassum including in Funafuti and Nui. The Sargassum covers the reefs and smothers coral; run-off is compounded by piggery waste plus septic tank seepage.

Prolonged lack of rainfall (related to La Niña conditions) was associated with the appearance of Sargassum in Funafuti in 2011 [25].

Extreme sea level events

Extreme sea level events are caused by high tides, storm surges, ocean swell, wind-driven waves and sea level rise. Coral reefs play a critical role in providing natural protection to reef lagoons and resources, shoreline stability, turtle nesting sites, coastal communities and infrastructure. Reefs that are damaged due to combined impacts of MHWs, ocean acidification and sea level rise will provide less protection to adjacent coastlines.

Mangroves rely on saline sediments and are highly effective for reducing coastal erosion, sequestering carbon, and providing nursery grounds for fisheries [1, 7, 37]. On Tuvalu, there are limited mangrove resources, with two species present, *Lumnitzera littorea* (Combretaceae) and *Rhizophora stylosa* (Rhizophoridae) [55. The mangrove ecosystems of Tuvalu were listed as threatened ecosystems in 1986 {Ceccarelli, 2019 #1087. The largest forest of red mangroves (Rhizophora stylosa) covering nearly 28.5 hectares is on Nanumanga, while small patches of mangroves (1.7 hectares) are found on Funafuti and Nui {Ceccarelli, 2019 #1087. The mangrove ecosystems of Tuvalu were listed as threatened ecosystems in 1986 {Ceccarelli, 2019 #1087. The largest forest of red mangroves (Rhizophora stylosa) covering nearly 28.5 hectares is on Nanumanga, while small patches of mangroves (1.7 hectares) are found on Funafuti and Nui {Ceccarelli, 2019 #1087]. Some mangrove planting has been conducted in parts of Tuvalu with mixed success. Some of the failures are likely due to sediment and wave energy conditions which are unsuitable for mangroves, and evenly spaced planting in straight lines would have increased mortality and morbidity of the mangrove seedlings. In other parts of the Pacific and in Australia, new technology involves planting the mangroves into biodegradable mesh that helps stabilise the seedlings while they establish roots [56, 57].

In many Pacific countries, mangroves deliver ecosystem goods and services that are essential to the livelihoods of local people and can enhance resilience to climate change. iTaukei (Indigenous Fijian) communities have sustainably managed mangrove ecosystems over time, demonstrating how traditional knowledge and experience can enable future ecosystem-based adaptation options that are more sustainable and effective [51, 58].

Ocean acidification

The increased acidity of seawater is reducing the saturation state of aragonite, the mineral that calcifying organisms, such as corals, certain plankton, and shellfish, use to build calcium carbonate skeletons [59, 60]. The combined impacts of ocean acidification with other stressors, such as increasing ocean temperatures, have implications for the health of reef ecosystems, including biodiversity, productivity and physical integrity, and longer-term sustainability [61, 62]. For example, OA has been shown to lower the temperatures at which corals bleach [63], potentially reducing the resilience of these environments to natural climate variability and long-term climate change. Increasing OA has the potential to impact fisheries, aquaculture, and overall marine productivity and biodiversity in tourism and coastal development sectors. Coastal protection may be reduced because inshore reefs are likely to deteriorate through the combined effects of coral bleaching and cyclone damage in some locations [64].

Studies suggest aragonite saturation states between 3.5–4.0 are adequate (but not optimal) for coral growth, and values between 3.0–3.5 are marginal [65]. Coral reef ecosystems are not found at aragonite saturation states less than 3 and these conditions are classified as extremely marginal for supporting coral growth, at least in assessing the global average conditions [65, 66].

References

1. Marra, J.J., G. Gooley, M.-V.V. Johnson, V.W. Keener, M.K. Kruk, S. McGree, J.T. Potemra, and O. Warrick, *Pacific Islands Climate Change Monitor: 2021*. 2022 The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC); Available from: https://www.pacificmet.net/pacific-climate-change-monitor-report.
2. Bell, J.D., J.E. Johnson, and A.J. Hobday, *Vulnerability of tropical Pacific fisheries and aquaculture to climate change*. 2011, Noumea, New Caledonia.: Secretariat of the Pacific Community (SPC).
3. Sund, P.N., M. Blackburn, and F. Williams, Tunas and their environment in the Pacific Ocean: a review. *Oceanogr. Mar. Biol. Ann. Rev,* 1981. 19: p. 443-512.
4. Department of Commerce Industry Trade & Environment, *Nauru National Food Systems Pathway, United Nations Food System Summit 2021.* 2021; Available from: https://summitdialogues.org/wp-content/uploads/2021/09/FSS-National-Pathway-Nauru_2021_September_2021_FinalDraft_Approved.pdf.
5. Bell, J.D., I. Senina, T. Adams, O. Aumont, B. Calmettes, S. Clark, M. Dessert, M. Gehlen, T. Gorgues, and J. Hampton, Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature sustainability,* 2021. 4(10): p. 900-910.
6. Bell, J.D., C. Reid, M.J. Batty, P. Lehodey, L. Rodwell, A.J. Hobday, J.E. Johnson, and A. Demmke, Effects of climate change on oceanic fisheries in the tropical Pacific: implications for economic development and food security. *Climatic change,* 2013. 119: p. 199-212.
7. Lehodey, P., J. Hampton, R. Brill, S. Nicol, I. Senina, B. Calmettes, H.-O. Pörtner, L. Bopp, R. Ilyina, and J. Bell, *Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In*

Bell, J., Johnson, JE, Hobday, AJ (Ed.), Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climae Change Ch in *Secretariat of the Pacific Community. Noumea New Caledonia.* 2011.

8. Asch, R.G., W.W.L. Cheung, and G. Reygondeau, Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. *Marine Policy,* 2018. 88: p. 285-294 DOI: https://doi.org/10.1016/j.marpol.2017.08.015.
9. Senina, I., P. Lehodey, B. Calmettes, M. Dessert, J. Hampton, N. Smith, T. Gorgues, O. Aumont, M. Lengaigne, and C. Menkes, *Impact of climate change on tropical Pacific tuna and their fisheries in Pacific Islands waters and high seas areas*. 2018 14th Regular Session of the Scientific Committee of the Western Central Pacific Fisheries Commission, WCPFC-SC14; Available from: https://meetings.wcpfc.int/node/10666.
10. Grose, M.R., S. Narsey, F. Delage, A.J. Dowdy, M. Bador, G. Boschat, C. Chung, J. Kajtar, S. Rauniyar, and M. Freund, Insights from CMIP6 for Australia's future climate. *Earth's Future,* 2020. 8(5): p. e2019EF001469.
11. Graham, F.S., A.T. Wittenberg, J.N. Brown, S.J. Marsland, and N.J. Holbrook, Understanding the double peaked El Niño in coupled GCMs. *Climate Dynamics,* 2017. 48(5): p. 2045-2063 DOI: 10.1007/s00382-016-3189-1.
12. Brown, J.N., C. Langlais, and C. Maes, Zonal structure and variability of the Western Pacific dynamic warm pool edge in CMIP5. *Climate Dynamics,* 2014. 42(11): p. 3061-3076 DOI: 10.1007/s00382-013-1931-5.
13. Patrick Lehodey, John Hampton, Rich W Brill, Simon Nicol, Inna Senina, Beatriz Calmettes, Hans O Pörtner, Laurent Bopp, Tatiana Ilyina, Johann D Bell, and John Siber, *Vulnerability of oceanic fisheries in the tropical Pacific to climate change* Ch in *Vulnerability of tropical Pacific fisheries and aquaculture to climate change.*, J.D. Bell, J.E. Johnson, and A.J. Hobday, Editors. 2011, SPC: New Caledonia.
14. Pörtner, H.O., M. Langenbuch, and A. Reipschläger, Biological impact of elevated ocean CO 2 concentrations: lessons from animal physiology and earth history. *Journal of oceanography,* 2004. 60: p. 705-718.
15. Munday, P.L., D.L. Dixson, J.M. Donelson, G.P. Jones, M.S. Pratchett, G.V. Devitsina, and K.B. Døving, Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *Proceedings of the National Academy of Sciences,* 2009. 106(6): p. 1848-1852.
16. Le Borgne, R., V. Allain, S.P. Griffiths, R.J. Matear, A.D. McKinnon, A.J. Richardson, and J.W. Young, *Vulnerability of open ocean food webs in the tropical Pacific to climate change*. 2011; Available from: https://coastfish.spc.int/component/content/article/412-vulnerability-of-tropical-pacifc-fisheries-and-aquaculture-to-climate-change.html.
17. Ilyina, T., R.E. Zeebe, and P.G. Brewer, Future ocean increasingly transparent to low-frequency sound owing to carbon dioxide emissions. *Nature Geoscience,* 2010. 3(1): p. 18-22.
18. FAO, *Fishery and Aquaculture Country Profiles. Tuvalu, 2014. Country Profile Fact Sheets. Updated Apr 10, 2018* Accessed 2024: Rome; Available from: https://www.fao.org/fishery/en/facp/tuv?lang=en.
19. Preston, G., S. Matelina, and S. Finikaso, Tuvalu Fisheries: Moving into the 21 st century. 2016.
20. Sauni, S., M. Kronen, S. Pinca, L. Sauni, K. Friedman, L. Chapman, and F. Magron, *Tuvalu country report: profile and results from in-country survey work (October–November 2004 and March–April 2005).* . 2008 Pacific Regional Oceanic and Coastal Fisheries Development Programme, Secretariat of the Pacific Community, Noumea, New Caledonia.
21. Loeffler, C.R., L. Tartaglione, M. Friedemann, A. Spielmeyer, O. Kappenstein, and D. Bodi, Ciguatera Mini Review: 21st Century Environmental Challenges and the Interdisciplinary

Research Efforts Rising to Meet Them. *Environmental Research and Public Health,* 2021. 18(6): p. 3027.

22. Pickering, T.D., B. Ponia, C.A. Hair, P.C. Southgate, E.S. Poloczanska, L. Della Patrona, A. Teitelbaum, C.V. Mohan, M.J. Phillips, J.D. Bell, and S. De Silva, *Vulnerability of aquaculture in the tropical Pacific to climate change* Ch in *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change.* , Bell JD, Johnson JE, and Hobday AJ, Editors. 2011, Secretariat of the Pacific Community, : Noumea, New Caledonia.
23. Bell, J.D., A. Ganachaud, P.C. Gehrke, S.P. Griffiths, A.J. Hobday, O. Hoegh-Guldberg, J.E. Johnson, R. Le Borgne, P. Lehodey, and J.M. Lough, Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Climate Change,* 2013. 3(6): p. 591-599.
24. Pratchett, M.S., P.L. Munday, N.A. Graham, M. Kronen, S. Pinca, K. Friedman, T.D. Brewer, J.D. Bell, S.K. Wilson, and J.E. Cinner, *Vulnerability of coastal fisheries in the tropical Pacific to climate change* Ch *6* in. 2011. p. 167-185.
25. De Ramon N'Yeurt, A. and V. Iese, The proliferating brown alga Sargassum polycystum in Tuvalu, South Pacific: assessment of the bloom and applications to local agriculture and sustainable energy. *Journal of Applied Phycology,* 2015. 27: p. 2037-2045.
26. Kibler, S.R., P.A. Tester, K.E. Kunkel, S.K. Moore, and R.W. Litaker, Effects of ocean warming on growth and distribution of dinoflagellates associated with ciguatera fish poisoning in the Caribbean. *Ecological Modelling,* 2015. 316: p. 194-210.
27. Hales, S., P. Weinstein, and A.J. Woodward, Ciguatera (fish poisoning), El Niño, and Pacific sea surface temperatures. *Ecosystem Health,* 1999. 5(1): p. 20-25.
28. Llewellyn, L.E., Revisiting the association between sea surface temperature and the epidemiology of fish poisoning in the South Pacific: Reassessing the link between ciguatera and climate change. *Toxicon,* 2010. 56(5): p. 691-697.
29. Tester, P.A., R.W. Litaker, and E. Berdalet, Climate change and harmful benthic microalgae. *Harmful Algae,* 2020. 91: p. 101655.
30. Soliño, L. and P.R. Costa, Global impact of ciguatoxins and ciguatera fish poisoning on fish, fisheries and consumers. *Environmental Research,* 2020. 182: p. 109111 DOI: https://doi.org/10.1016/j.envres.2020.109111.
31. Ikape, S., Fish spoilage in the tropics: A review. *Octa Journal of Biosciences,* 2017. 5(2).
32. Devlin, M., A. Smith, C.A. Graves, C. Petus, D. Tracey, M. Maniel, E. Hooper, K. Kotra, E. Samie, and D. Loubser, Baseline assessment of coastal water quality, in Vanuatu, South Pacific: Insights gained from in-situ sampling. *Marine Pollution Bulletin,* 2020. 160: p. 111651.
33. SPC. *Climate Risk Early Warning Systems (CREWS) : Inundation forecast system for Tuvalu & Kiribati*. 2023 Available from: https://gem.spc.int/projects/climate-risk-early-warning-systems-crews-inundation-forecast-system-for-tuvalu-kiribati.
34. Flynn, D., *Mariner's Tropical Cyclone Guide*. 2023 National Oceanic and Atmospheric Administration; Available from: https://www.nhc.noaa.gov/marinersguide.pdf.
35. UNEP, *Status of Coral Reefs of the World: 2020 Summary for Policymakers*. 2023 Global Coral Reef Monitoring Network (GCRMN),; Available from: https://gcrmn.net/wp-content/uploads/2022/05/Status-of-Coral-Reefs-of-the-World-2020-Summary-for-Policymakers.pdf.
36. Hoegh-Guldberg, O., S. Andréfouët, K. Fabricius, G. Diaz-Pulido, J.M. Lough, P. Marshall, and M. Pratchett, *Vulnerability of coral reefs in the tropical Pacific to climate change.* 2011 Secretariat of the Pacific Community: Noumea, New Caledonia. .
37. Holbrook, N.J., V. Hernaman, S. Koshiba, J. Lako, J.B. Kajtar, P. Amosa, and A. Singh, Impacts of marine heatwaves on tropical western and central Pacific Island nations and their communities. *Global Planetary Change,* 2022. 208: p. 103680.
38. Donner, S.D., An evaluation of the effect of recent temperature variability on the prediction of coral bleaching events. *Ecological Applications,* 2011. 21(5): p. 1718-1730.

39. Ceccarelli, D.M., *Chapter 32 - Tuvalu*. 2019 Academic Press; Available from: https://www.sciencedirect.com/science/article/pii/B9780081008539000415.

40. Lovell, E., H. Sykes, M. Deiye, L. Wantiez, C. Garrigue, S. Virly, J. Samuelu, A. Solofa, T. Poulasi, and K. Pakoa, Status of Coral Reefs in the South West Pacific: Fiji, Nauru, New Caledonia, Samoa, Solomon Islands, Tuvalu and Vanuatu. *Status of coral reefs of the world,* 2004. 2: p. 337-362.

41. Naikatini, A., T. Elu, K. Falenga, S. Tui, and F. Penivao, *Biodiversity Rapid Assessment Program (BioRAP) of Funafuti Atoll, Nukulaelae Atoll, Niutao Island and Vaitupu Island, Tuvalu - Technical Report. Ridge to Reef Unit, Department of Environment, Vaiaku, Tuvalu*. 2021. p. 136 pp.

42. Ceccarelli, D.M., *Tuvalu* Ch in *World Seas: an Environmental Evaluation*. 2019, Elsevier. p. 699-711.

43. Vaqalo, M., M. Lonalona, S. Panapa, and F. Khan, *Yellow crazy ants and fruit fly surveys in Tuvalu*. 2014 Report to the Secretariat of the Pacific Community (SPC); Available from: http://www.piat.org.nz/uploads/PIAT_content/pdfs/Vaqalo%20et%20al_2014.pdf.

44. Hoffmann, B.D., Integrating biology into invasive species management is a key principle for eradication success: the case of yellow crazy ant Anoplolepis gracilipes in northern Australia. *Bulletin of Entomological Research,* 2015. 105(2): p. 141-151 DOI: 10.1017/S0007485314000662.

45. Standora, E.A. and J.R. Spotila, Temperature dependent sex determination in sea turtles. *Copeia,* 1985: p. 711-722.

46. Fuentes, M., J. Maynard, M. Guinea, I. Bell, P. Werdell, and M.J.E.S.R. Hamann, Proxy indicators of sand temperature help project impacts of global warming on sea turtles in northern Australia. 2009. 9(1): p. 33-40.

47. Jensen, M.P., C.D. Allen, T. Eguchi, I.P. Bell, E.L. LaCasella, W.A. Hilton, C.A.M. Hof, and P.H. Dutton, Environmental Warming and Feminization of One of the Largest Sea Turtle Populations in the World. *Current Biology,* 2018. 28(1): p. 154-+ DOI: 10.1016/j.cub.2017.11.057.

48. Jung, J.-M., S. Jung, M.R. Ahmed, B.-K. Cho, and W.-H. Lee, Invasion risk of the yellow crazy ant (Anoplolepis gracilipes) under the Representative Concentration Pathways 8.5 climate change scenario in South Korea. *Journal of Asia-Pacific Biodiversity,* 2017. 10(4): p. 548-554 DOI: https://doi.org/10.1016/j.japb.2017.08.004.

49. Chen, Y., Global potential distribution of an invasive species, the yellow crazy ant (Anoplolepis gracilipes) under climate change. *Integrative Zoology,* 2008. 3(3): p. 166-175 DOI: https://doi.org/10.1111/j.1749-4877.2008.00095.x.

50. Langlais, C., A. Lenton, S. Heron, C. Evenhuis, A. Sen Gupta, J. Brown, and M. Kuchinke, Coral bleaching pathways under the control of regional temperature variability. *Nature Climate Change,* 2017. 7(11): p. 839-844.

51. Nunn, P.D., R. Kumar, H.M. Barrowman, L. Chambers, L. Fifita, D. Gegeo, C. Gomese, S. McGree, A. Rarai, and K. Cheer, Traditional knowledge for climate resilience in the Pacific Islands. *Wiley Interdisciplinary Reviews: Climate Change,* 2024: p. e882.

52. Antoine De Ramon, N.Y. and V. Iese, The proliferating brown alga Sargassum polycystum in Tuvalu, South Pacific: assessment of the bloom and applications to local agriculture and sustainable energy. *Journal of Applied Phycology,* 2015. 27(5): p. 2037.

53. Louime, C., J. Fortune, and G. Gervais, Sargassum invasion of coastal environments: a growing concern. *American Journal of Environmental Sciences,* 2017. 13(1): p. 58-64.

54. Marx, U.C., J. Roles, and B. Hankamer, Sargassum blooms in the Atlantic Ocean – From a burden to an asset. *Algal Research,* 2021. 54: p. 102188 DOI: https://doi.org/10.1016/j.algal.2021.102188.

55. Woodroffe, C.D., Pacific island mangroves: distribution and environmental settings. *Pacific Science,* 1987. 41: p. 166-185.

56. Perricone, V., M. Mutalipassi, A. Mele, M. Buono, D. Vicinanza, and P. Contestabile, Nature-based and bioinspired solutions for coastal protection: an overview among key ecosystems and a promising pathway for new functional and sustainable designs. *ICES Journal of Marine Science,* 2023. 80(5): p. 1218-1239 DOI: 10.1093/icesjms/fsad080.
57. Schapova, N. *Scientists use 3D-printed biodegradable structures to halt erosion*. 2023 Available from: https://www.abc.net.au/news/2023-03-30/3d-printers-used-to-halt-erosion-with-biodegradable-structures/102155970.
58. Pearson, J., K.E. McNamara, and P.D.J.M.c.c.a.i.t.P.r. Nunn, iTaukei ways of knowing and managing mangroves for ecosystem-based adaptation. 2020: p. 105-127.
59. Johnson, J.E., J.D. Bell, and A.S. Gupta, *Pacific islands ocean acidification vulnerability assessment*. 2015 SPREP Apia, Somoa; Available from: https://www.sprep.org/attachments/Publications/CC/ocean-acidification.pdf.
60. Tesan, M., *Ocean acidification: a tide of challenges for Pacific Islanders*. 2022 SPC; Available from: https://www.spc.int/updates/blog/2022/08/ocean-acidification-a-tide-of-challenges-for-pacific-islanders.
61. Fabricius, K.E., C. Langdon, S. Uthicke, C. Humphrey, S. Noonan, G. De'ath, R. Okazaki, N. Muehllehner, M.S. Glas, and J.M. Lough, Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nature Climate Change,* 2011. 1(3): p. 165-169.
62. Silverman, J., B. Lazar, L. Cao, K. Caldeira, and J. Erez, Coral reefs may start dissolving when atmospheric CO2 doubles. *Geophysical Research Letters,* 2009. 36(5).
63. Anthony, K.R., D.I. Kline, G. Diaz-Pulido, S. Dove, and O. Hoegh-Guldberg, Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences,* 2008. 105(45): p. 17442-17446.
64. Cooley, S.R., H.L. Kite-Powell, and S.C. Doney, Ocean acidification's potential to alter global marine ecosystem services. 2009.
65. Guinotte, J., R. Buddemeier, and J. Kleypas, Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. *Coral reefs,* 2003. 22: p. 551-558.
66. Australian Bureau of Meteorology and CSIRO, *Climate Variability, Extremes and Change in the Western Tropical Pacific: New Science and Updated Country Reports.* 2014 Pacific-Australia Climate Change Science and Adaptation Planning Program, Australian Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation, Melbourne, Australia.; Available from: https://www.pacificclimatechangescience.org/wp-content/uploads/2014/07/PACCSAP_CountryReports2014_Ch1Intro_WEB_140710.pdf

Chapter 13 Agriculture

Land for agriculture in Tuvalu is extremely limited, and soils are extremely poor and crop cultivation of any sort in these environments presents great challenges. Since soils in atolls are predominantly derived from carbonate reef-borne material and are relatively young, they are poorly developed, lack structure and texture and are very porous with poor water holding capacity [1-3]. Availability of good quality compost as soil conditioner is also a problem in Funafuti (not so much on the outer islands).

In contrast, swamp taro pits tend to have comparatively deep, dark, organic rich soils in comparison to surrounding soils. This occurs both due to the natural propensity for organic materials (leaves, husks, etc.) to collect in such depressions but also (and importantly) through the efforts of the farmers who over the years have laboured intensively and applied systematic traditional cultivation practices [3].

Despite the poor growing conditions, for subsistence Tuvalu's temperature and rainfall conditions support fruit trees such as banana, breadfruits, pandanus, coconut trees, and pulaka, or pit-grown giant swamp taro. However, as with much of the Pacific Islands, a decline in domestic subsistence agricultural production has caused an increasing dependence on imported foods [4].

Temperature

Optimal temperature ranges or 'envelopes' can affect suitability for agricultural production of many crop types. Whereas increased average temperatures may result in less optimal growing conditions for some crops, opportunities for introduction of new crop varieties more suited to the changed growing conditions may also emerge. For example, for different root crops, the suitable temperature range varies slightly with different species. For yam 25–30 °C is optimum, whereas for taro it is 25–35 °C, and for cassava it is 25–29 °C but 12–40 °C is tolerated [5].

Increasing air temperature will have negative impacts on crops, including home gardens, and livestock (pigs), and may increase heat stress as well as invasive species, pests and diseases [5]. Higher temperatures can increase fruit flies and coconut scale pests on Nanumaga and Vaitupu and result in more conducive conditions for increased incidence of agricultural pests and diseases more generally.

Throughout the Pacific region, free-range chickens and pigs are an integral part of self-sufficiency. Extreme heat causes stress for livestock [5], with associated increase in water demand. Chickens are less tolerant of excess heat, with the thermal comfort zone of adult pigs being 16-25 °C, young pigs 25-32 °C, and chickens 10-20 °C [5].

Rainfall and drought

Extreme rainfall can reduce access to farms due to flooding. Damage, increased disease incidence, and/or waterlogging can affect some crops [5].

Droughts are an important climate hazard for Tuvalu [6]. For example, between 2010 and 2013, Funafuti (Central Tuvalu) experienced drought for one year (December 2010–December 2011) while Niulakita (Southern Tuvalu) experienced three droughts between February 2010 and June 2013 (Iese et al., 2021).

Through the 2011 drought, coconut, breadfruit, bananas and giant swamp taro (pulaka; a core crop for socio-cultural and food security reasons) [3], wilted and died or became inedible [7]. Prolonged negative impacts of drought on pulaka yield affected traditional staple diets and led to abandonment of pulaka cultivation with potential loss of traditional knowledge [3, 7, 8]. Similarly, over pumping or extraction of groundwater resources to supply human needs also act in a similar fashion to drought, where removal of freshwater is greater than recharge, causing the lens to contract affecting pulaka [3]. Pacific peoples have long depended on island ecosystems to provide healthy diets [9], something that is declining in many islands with the inclusion of more imported (often nutrient-poor) foods in daily diets [4, 10].

Drought also limits water availability for animal husbandry, in particular domestic pig production. Periodic limits on domestic water supplies due to drought mean that potable water for human consumption is prioritised over requirements for livestock. Through drought periods, water from bores, becoming more and more saline over time, is being used for non-potable purposes, e.g. watering pigs [11].

Tropical cyclones

High winds related to TCs can affect crops in Tuvalu. Storm surges during cyclones threaten less salt-water resistant crops (bananas and breadfruit trees) and can destroy pulaka pit plantations [12].

Sea level

Rising sea level is increasing saltwater intrusion into groundwater and surface soils; it has already destroyed 60 % of pulaka pit plantations, and the remaining 40 % are highly sensitive [13]. Tuvalu has a relatively thin freshwater lens that supports taro, planted in excavated ‘pulaka pits’, thereby accessing water from the water table. However, this water has been increasing in salinity, especially during spring tides due to sea water intrusion [14]. While the taro has high tolerance to increased salinity, monitoring the salinity levels will be important as saline soil adversely affects agriculture. Through the 2011 drought period, the pulaka yield was reduced due to prolonged water stress and salt-coated soil caused by high evaporation in the pits [11, 15].

Extreme sea level

Natural perturbations such as wave wash over and/or extreme high water and storm events can contaminate the fresh groundwater lens and therefore the pulaka pits with saline marine water [3]. After waves generated by Tropical Cyclone Pam inundated the Tuvaluan community, evacuees were able to move their pigs, but not their poultry, to safety [16].

References

1. Government of Tuvalu, *Tuvalu: Follow-up of the Implementation of the Instanbul Programme of Action for the Least Developed Countries* 2019; Available from: https://www.un.org/ldc5/sites/www.un.org.ldc5/files/tuvalu_instanbul_report_post_dcc_191219revise.pdf.
2. Yamano, H., H. Kayanne, T. Yamaguchi, Y. Kuwahara, H. Yokoki, H. Shimazaki, and M. Chikamori, Atoll island vulnerability to flooding and inundation revealed by historical reconstruction: Fongafale Islet, Funafuti Atoll, Tuvalu. *Global and Planetary Change,* 2007. 57(3): p. 407-416 DOI: https://doi.org/10.1016/j.gloplacha.2007.02.007.
3. Webb, A., *Assessment of salinity of groundwater in swamp taro (Cyrtosperma chamissonis)“Pulaka” pits in Tuvalu*. 2007 EU EDF8-SOPAC Project report Suva, Fiji, SOPAC.
4. Hughes, R.G. and M. Lawrence, Globalisation, food and health in Pacific Island countries. *Asia Pacific journal of clinical nutrition,* 2005. 14(4): p. 298-305.
5. Taylor, M., A. McGregor, and B. Dawson. Vulnerability of Pacific Island agriculture and forestry to climate change. 2016: SPC.
6. Government of Tuvalu, *Tuvalu Integrated Vulnerability Assessment Report – Funafuti community, Funafuti. Government of Tuvalu and NAP Global Network/International Institute*

for Sustainable Development (IISD). 2020; Available from: https://napglobalnetwork.org/wp-content/uploads/2021/01/napgn-en-2020-Tuvalu-IVA-report-Amatuku-Islet.pdf.

7. Tekinene, M., *An assessment of the impacts of climate change on cultivated pulaka (Cyrtosperma chamissonis) in Tuvalu*. 2014, University of the South Pacific, Fiji.
8. Paeniu, L., *Understanding and predicting drought in Tuvalu*, in *Sustainable Development,* . 2018, The University of the South Pacific, Fiji.
9. Nunn, P.D., R. Kumar, H.M. Barrowman, L. Chambers, L. Fifita, D. Gegeo, C. Gomese, S. McGree, A. Rarai, and K. Cheer, Traditional knowledge for climate resilience in the Pacific Islands. *Wiley Interdisciplinary Reviews: Climate Change,* 2024: p. e882.
10. Sievert, K., M. Lawrence, A. Naika, and P. Baker, Processed foods and nutrition transition in the Pacific: Regional trends, patterns and food system drivers. *Nutrients,* 2019. 11(6): p. 1328.
11. Sinclair, P., F. Atumurirava, and J. Samuela, *Rapid drought assessment Tuvalu 13 October-8 November 2011: SOPAC technical report (PR38)*. 2012: Funafuti, Tuvalu.
12. Tui, S. and B. Fakhruddin, Food for thought: Climate change risk and food (in)security in Tuvalu. *Progress in Disaster Science,* 2022. 16: p. 100255 DOI: https://doi.org/10.1016/j.pdisas.2022.100255.
13. Marra, J.J., G. Gooley, M.-V.V. Johnson, V.W. Keener, M.K. Kruk, S. McGree, J.T. Potemra, and O. Warrick, *Pacific Islands Climate Change Monitor: 2021*. 2022 The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC); Available from: https://www.pacificmet.net/pacific-climate-change-monitor-report.
14. Kumar, L. and S. Taylor, Exposure of coastal built assets in the South Pacific to climate risks. *Nature Climate Change,* 2015. 5(11): p. 992-996.
15. Nyman, N., *Mid-term Evaluation of the Tuvalu NAPA-1 and NAPA-1+ Project. Annex VIII – Evaluation Report of the Baseline Project*. 2013 GREEN CLIMATE FUND FUNDING PROPOSAL; Available from: https://www.adaptation-undp.org/sites/default/files/resources/evalutation_report_of_the_baseline_project_0.pdf
16. Reliefweb, *Nowhere to run. Tuvaluans consider their future after Tropical Cyclone Pam*. 2015 International Federation of Red Cross And Red Crescent Societies; Available from: https://reliefweb.int/report/tuvalu/nowhere-run-tuvaluans-consider-their-future-after-tropical-cyclone-pam.

Chapter 14 Coastal development and infrastructure

Coastal development and infrastructure includes buildings, docks, seawalls, land reclamation, roads and airports, as well as related energy, wastewater management and telecommunication infrastructure. Each provides essential services. In Tuvalu, 66 % of the total asset number and 62 % of the total infrastructure replacement value is located within 100 m of the coast [1]. The entire population of 11,000 lives extremely close to the coast [2, 3].

The TCAP coastal inundation projections include waves and tide as well as mean sea level anomalies, also distinguishing between extreme wave conditions from distant sources versus local tropical cyclones [4]. Different combinations of wave, tide, and sea level anomalies where used to produce nearshore extreme water levels, or proxy Total Water Levels (TWL), for different return intervals to generate probabilistic inundation maps which can be viewed in the TCAP portal (Figure 14-1).

Users of the TCAP portal (https://opm.gem.spc.int/tcap/home) can view the various extreme sea level return periods for the present climate (1999 to 2009), 2060, and 2100 for medium emissions (SSP2-4.5) and high emissions (SSP5-8.5). The portal can display a range of impact types for either Populations or Buildings, e.g. % and number exposed, % damaged, economic damage and annual economic damage.

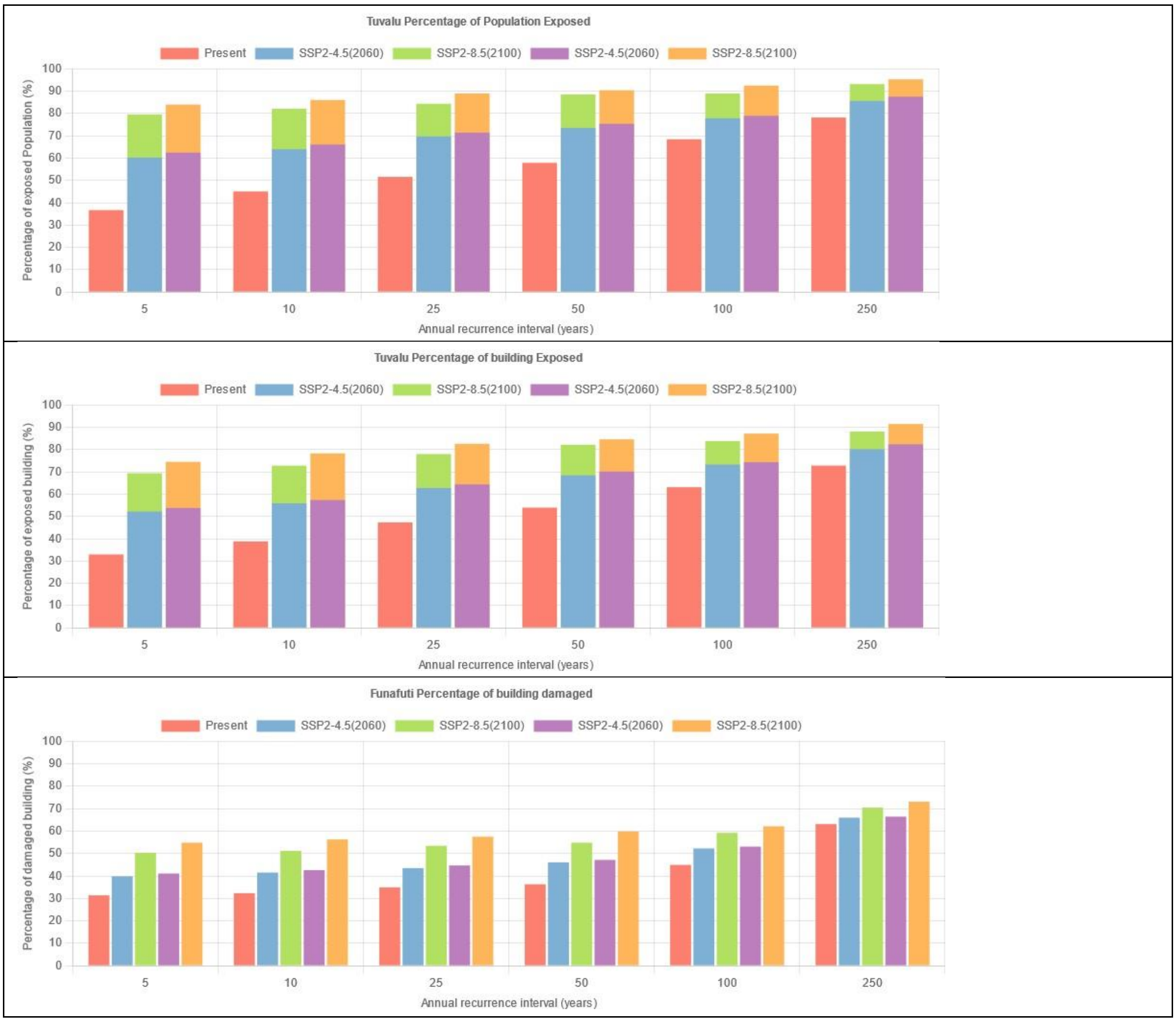


Figure 14-1: TCAP projections of coastal inundation impacts on % of exposed population (top), % of exposed buildings (middle), and % of damaged buildings (Source: [5]).

A newly completed World Bank study [6] comprehensively assessed 29 school buildings located across nine islands, in relation to their exposure to wind (100 %), tsunami (75 %), coastal inundation (79 %), and pluvial flooding (100 %). With projected sea level rise the exposure of schools to tsunami and coastal inundation was reported to increase [6]. Most of the surveyed schools have a high vulnerability to wind due to inadequate roof fixing in terms of their condition, fixing type and spacing/layout. While most buildings have moderate or Low vulnerability to coastal inundation, buildings with timber frames have a high vulnerability rating. There is very low vulnerability to fluvial flooding. About one third of the schools could be unusable at 0.5m of sea level rise, two thirds would be unusable at 1m of sea level rise and almost all would be unusable at 2m of sea level rise [6].

Risk statements and ratings for this study have been estimated for this sector noting that a new Building Code has been recently developed for Tuvalu [7]. This new building code has incorporated new provisions for building design and associated engineering specifications designed to better address disaster risk reduction requirements within a changing climate, and thereby build resilience to future climate for the built environment in Tuvalu.

Tuvalu is heavily reliant on imported petroleum products for transport, electricity generation and household use such as cooking and lighting. The high transport and associated fuel prices and fluctuations impact heavily on businesses and households and undermine growth and food security, especially the most isolated outer islands [8]. Transport, health, water supply, water treatment and telecommunications are critically dependent on reliable and cost-effective electricity supply for services that support communities, government, and business. Intermittent power outages, for various climate and non-climate-related reasons, compound these sectoral impacts, particularly in Funafuti as relates to water supply, essential equipment for health and telecommunications, as well as cooling, refrigeration and other core household services.

Tuvalu’s coastal infrastructure and communities may be affected by coastal inundation and erosion during high tides, storms surges, ocean swell, wind-driven waves and sea level rise. While cyclone frequency is projected to decrease, increasing cyclone intensity would result in larger wind driven waves, storm surges and swell, exacerbated by rising sea levels, leading to increased coastal inundation, beach erosion, and infrastructure damage.

Waves are one of the main causes of coastal flooding and shoreline change in low-lying atoll nations like Tuvalu. Tuvalu's wave climate is dominated by three energy sources: extratropical storms in the Southern Ocean and in the North Pacific; and easterly trade winds [9].

Waste management is a significant issue, particularly with storm water run-off and domestic wastewater (septic tank) leakage to lagoons compounded by SLR. A potential ongoing and longer-term problem exists with e-waste due to increased demand for solar panels and batteries, and for as industrial waste (heavy plant and equipment used for coastal development/land reclamation, such as old barges, excavators, pipes and fittings, de-salination equipment etc.). In addition, issues exist with existing landfill in Funafuti due to periodic burn-off of the piles and related run-off to the lagoon that is impacting water quality.

Extreme Temperature

Asphalt road-pavements are important for transport, and bitumen is a critical component. At high temperatures, bitumen is more fluid; at intermediate temperatures, it is a viscoelastic liquid; and at low temperatures, it is solid [10]. Extreme temperatures will therefore affect asphalt road surface performance [11]. Repairs may be needed more often in a warmer climate.

Extremely hot days and heatwaves increase demand for electricity to run fans, air-conditioners and refrigerators. When demand exceeds electricity supply capacity, black-outs can occur. As previously stated, this has cascading impacts on government services, businesses, telecommunication, health, labour productivity , transport and households. Projected increases in hot days and heatwaves would exacerbate these impacts, particularly as Tuvalu manages ageing energy infrastructure such as in Funafuti (generators, transformers, distribution networks), while transitioning to renewables.

A non-linear relationship between temperature and electricity demand is seen in a recent study undertaken in Vanuatu [12], where temperatures above 32 °C cause a significant increase in demand (Figure 14-2). A similar relationship is likely in Tuvalu. High electricity demand and limited electricity supply can result in failure of the electricity grid (particularly when operational ratings are exceeded for conductors and switching equipment). Blackouts can occur, with compounding impacts on public health and workforce productivity.

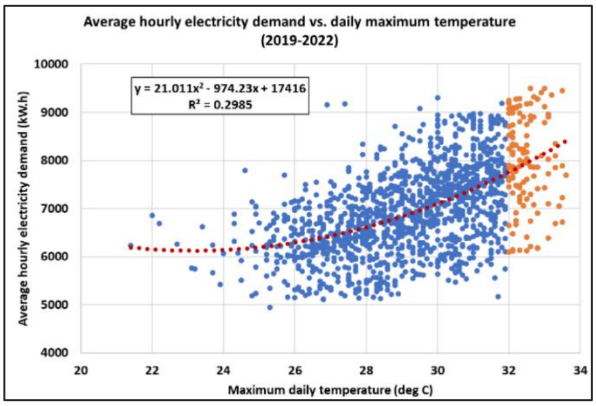


Figure 14-2 Average hourly energy demand (kW/hr) compared to daily maximum temperature in Port Vila, Vanuatu.

Increasing air temperatures will lead to increasing energy demand for fans, air-conditioning and refrigeration [13, 14]. For instance, a 12-hour power outage in Funafuti in Oct 2023 was caused by overloading of a transformer due to extreme heat and, high electricity demand, and no access to spare switch gear to allow for partial shutdown, and with only one spare transformer.

Rainfall

Extreme rainfall over hours to days can cause flooding, with associated infrastructure damage and disruption. This can have implications for disaster risk management, road transport, water quality, food security, community health, income security, aviation and maritime transportation [15].

Heavy rainfall, combined with high tides and rising sea levels, has caused localised flooding and damage to public infrastructure (including the international airport runway on Funafuti), inundation of homes and shops, and damage to flexible pavement surfaces [16, 17]. For example, in December 2023, the airport runway was flooded and flights were cancelled https://www.abc.net.au/news/2023-12-16/australians-stuck-in-tuvalu-flights-cancelled-fiji-airways/103237676

Flooding can force sediment and debris into drainage systems, affecting associated water quality and water-borne diseases. The existence of a good drainage system is crucial [18].

Extreme sea level

With a mean elevation of 1.55 m above mean sea level (1.37 m above mean high water spring), more than 25 % of Tuvalu's land area is inundated once every 5 years and more than 50 % of land area floods once every 100 years [19]. This has strong implications for coastal development and infrastructure. For example, flooding of electricity infrastructure, including underground wiring and terminals/junction boxes and inspection pits, may cause blackouts [20].

Funafuti experiences multiple floods annually due to spring tides, even in the absence of large waves or mean sea level rise. The porosity of the ground results in a strong hydraulic connectivity between the ocean and Funafuti's interior (e.g., [21, 22]. This results in spring high tides penetrating the island from the ground up, without the need of wave overtopping. Furthermore, much of Funafuti's islets are extremely narrow (less than 100 m wide). Consequently over 50 % of the atoll area floods once every 10 years due to a combination of perigean spring high tides (king tides) and waves [19]. Recent inundation modelling indicates that nearly 40 % of Tuvalu’s population is exposed due to inundation events that occur every 5-years, while inundation events that occur every 100 years affects about 68 % of the population [5]. Saltwater intrusion of the freshwater lens can occur through storm-surge over-wash and coastal flooding.

Other islands such as Niutao and Niulakita are less frequently and less extensively flooded. Only 17 % of the Niulakita's land area and only 11 % of Niutao's land area floods once in 10 years. The reason for the reduced flood susceptibility lies in the islands' geomorphology as they are significantly higher than the rest of Tuvalu (>2.4 m above mean sea level) [19].

Greater impacts will occur when storm surge is combined with a high tide and sea level rise [23] (Figure 14-3). Before the storm event associated with TC Pam, Tuvalu’s electricity was switched off, plunging the island into darkness and cutting off communication lines that wouldn’t be re-established for three days [24]. Damage to ancestral graves on the island of Nui are also associated with these type of events (K. Morioka, Pers Comm).

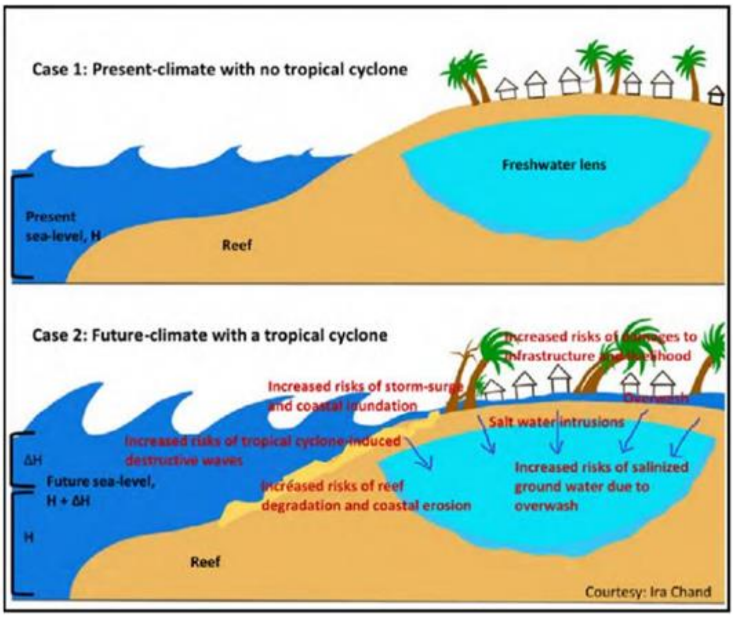


Figure 14-3 Conceptual diagram of current and future tropical cyclone-induced risks in a warming climate for two cases: Case 1 represents a condition in present-climate without any tropical cyclone, and Case 2 represents a future climate scenario in the presence of a severe tropical cyclone event and future sea level rise (source: [23]).

Coastal reclamation undertaken in Funafuti lagoon as part of the Tuvalu Coastal Adaptation Project (TCAP) has created additional land at elevation designed to protect communities and infrastructure from projected SLR and storm surge (e.g. Figure 14-4). Additional coastal reclamation is planned for Tuvalu in other locations as part of TCAP, although final usage of the reclaimed land is yet to be determined. Reclaimed land is fortified by geotextile bags (Ref). Regular monitoring of the geotextile bag integrity on the very low tides is advised as early *in-situ* repairs make economic sense given integrity loss in one bag can affect the whole stack [25].

Figure 14-4 Land reclamation undertaken in Tuvalu Source G. Gooley CSIRO. The picture on the left is from TCAP/SPC or GoT. We need to check copyright on this.

Wind

Slightly positive trends in high-frequency (~10 s) wave energy from the east and low-frequency (~15 s) wave energy from the southwest were linked to an intensification of trade winds and an intensification and poleward displacement of the Southern Ocean storm belt over recent decades potentially resulting in overtopping. The interannual variability of Tuvalu's wave climate is strongly linked to large-scale climate modes such as El Niño Southern Oscillation, Pacific Decadal Oscillation, and Arctic and Antarctic Oscillation [9].

Disruption of air and sea transport is related to higher winds. Wind borne debris can affect electrical transmission lines and affect telecommunications. Salt can build up on transmission towers located on the ocean side of Funafuti. There is a requirement for an SMS/text msg early warning system for natural disasters, extreme heat impacting i) labour to undertake critical maintenance, and ii) loss of mains power for critical infrastructure impacting phone and internet services, salinisation of the soil from SLR and Spring tide inundation impacting existing underground copper wire infrastructure (needs to be replaced with fibre-optic cable).

Ocean temperature and acidification

Integrity through coral bleaching, die-back, and reef erosion can result in reduced protection from reefs surrounding the islands, reducing island protection [26]. Marine infrastructure e.g. fixings such as nails, rivets, bolts etc. may be affected by ocean acidification.

References

1. Kumar, L. and S. Taylor, Exposure of coastal built assets in the South Pacific to climate risks. *Nature Climate Change,* 2015. 5(11): p. 992-996.
2. Andrew, N.L., P. Bright, L. de la Rua, S.J. Teoh, and M. Vickers, Coastal proximity of populations in 22 Pacific Island Countries and Territories. *PLoS One,* 2019. 14(9): p. e0223249.
3. SPC. *Mapping (Coastal)*. 2021 Available from: https://sdd.spc.int/mapping-coastal.
4. Wandres, M., A. Espejo, T. Sovea, S. Tetoa, F. Malologa, A. Webb, J. Lewis, G. Lee, and H. Damlamian, A national ‐ scale coastal flood hazard assessment for the atoll nation of Tuvalu. *Earth's Future,* 2024. 12(4): p. e2023EF003924.

5. SPC, *Tuvalu Coastal Adaptation Project*. 2023; Available from: https://opm.gem.spc.int/tcap/risk.
6. World Bank, *Tuvalu School Infrastructure Risk Assessment*. 2021 World Bank: Sydney, Australia.
7. World Bank, *Consulting Services for the Review of the Tuvalu Draft National Building Code and Regulations Completion Report*. 2022 World Bank: Brisbane, Australia.
8. Government of Tuvalu, *Tuvalu: Follow-up of the Implementation of the Instanbul Programme of Action for the Least Developed Countries* 2019; Available from: https://www.un.org/ldc5/sites/www.un.org.ldc5/files/tuvalu_instanbul_report_post_dcc_191219revise.pdf.
9. Wandres, M., A. Espejo, and H. Damlamian, Wave climate variability and trends in Tuvalu based on a 44‐year high‐resolution wave hindcast. *Journal of Geophysical Research: Oceans,* 2023. 128(4): p. e2022JC019523.
10. Krishnan, J.M. and K. Rajagopal, On the mechanical behavior of asphalt. *Mechanics of materials,* 2005. 37(11): p. 1085-1100.
11. Almeida, A. and L. Picado-Santos, Asphalt Road Pavements to Address Climate Change Challenges—An Overview. *Applied Sciences,* 2022. 12(24): p. 12515.
12. Webb, L.B., K. Nguyen, K. Hennessy, and M. Matou, *Extreme Heat Impacts on Electricitity demand in Efate, Vanuatu.* 2023: Infobyte prepared for the Vanuatu Meteorology and Geo-hazards Department as part of the Van-KIRAP project. CSIRO, VMGD, SPREP, Melbourne, Australia; Available from: https://staging-dot-van-kirap.ts.r.appspot.com/assets/docs/Electricity%20Infobyte.pdf.
13. Auffhammer, M., P. Baylis, and C.H. Hausman, Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. *Proceedings of the National Academy of Sciences,* 2017. 114(8): p. 1886-1891.
14. Van Ruijven, B.J., E. De Cian, and I. Sue Wing, Amplification of future energy demand growth due to climate change. *Nature communications,* 2019. 10(1): p. 2762.
15. Marra, J.J., G. Gooley, M.-V.V. Johnson, V.W. Keener, M.K. Kruk, S. McGree, J.T. Potemra, and O. Warrick, *Pacific Islands Climate Change Monitor: 2021*. 2022 The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC); Available from: https://www.pacificmet.net/pacific-climate-change-monitor-report.
16. Wang, Y., Y. Huang, W. Rattanachot, K. Lau, and S. Suwansawas, Improvement of pavement design and management for more frequent flooding caused by climate change. *Advances in Structural Engineering,* 2015. 18(4): p. 487-496.
17. Lu, D., S.L. Tighe, and W.-C. Xie, Impact of flood hazards on pavement performance. *International Journal of Pavement Engineering,* 2020. 21(6): p. 746-752.
18. Chan, K.-m. and Y. Wang, Resilient pavement design with consideration of flooding effect caused by climate change. *Transportmetrica A: Transport Science,* 2020. 16(3): p. 1136-1155.
19. Wandres, M., A. Espejo, and H. Damlamian, Wave Climate Variability and Trends in Tuvalu Based on a 44-Year High-Resolution Wave Hindcast. *Journal of Geophysical Research: Oceans,* 2023. 128(4): p. e2022JC019523 DOI: https://doi.org/10.1029/2022JC019523.
20. To, L.S., A. Bruce, P. Munro, E. Santagata, I. MacGill, M. Rawali, and A. Raturi, A research and innovation agenda for energy resilience in Pacific Island Countries and Territories. *Nature Energy,* 2021. 6(12): p. 1098-1103.
21. Webb, A., *Assessment of salinity of groundwater in swamp taro (Cyrtosperma chamissonis)“Pulaka” pits in Tuvalu*. 2007 EU EDF8-SOPAC Project report Suva, Fiji, SOPAC.
22. Yamano, H., H. Kayanne, T. Yamaguchi, Y. Kuwahara, H. Yokoki, H. Shimazaki, and M. Chikamori, Atoll island vulnerability to flooding and inundation revealed by historical reconstruction: Fongafale Islet, Funafuti Atoll, Tuvalu. *Global and Planetary Change,* 2007. 57(3): p. 407-416 DOI: https://doi.org/10.1016/j.gloplacha.2007.02.007.

23. CSIRO and SPREP, *Tropical Cyclones and Climate Change: implications for the Western Tropical Pacific.* 2022 Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP): Melbourne, Australia.
24. Reliefweb, *Nowhere to run. Tuvaluans consider their future after Tropical Cyclone Pam*. 2015 International Federation of Red Cross And Red Crescent Societies; Available from: https://reliefweb.int/report/tuvalu/nowhere-run-tuvaluans-consider-their-future-after-tropical-cyclone-pam.
25. Restall, S.J., L.A. Jackson, G. Heerten, and W.P. Hornsey, Case studies showing the growth and development of geotextile sand containers: an Australian perspective. *Geotextiles and Geomembranes,* 2002. 20(5): p. 321-342 DOI: https://doi.org/10.1016/S0266-1144(02)00030-4.
26. Perry, C.T., K.M. Morgan, I.D. Lange, and R.T. Yarlett, Bleaching-driven reef community shifts drive pulses of increased reef sediment generation. *Royal Society Open Science,* 2020. 7(4): p. 192153.

Chapter 15 Disaster management and emergency response

In addition to extreme rainfall and drought, remote TC-driven storm-surge and coastal inundation are risk factors triggering natural disasters. There are numerous examples of disasters causing significant loss of property and disruption to services in Tuvalu, often requiring impact assessments and financial compensation for loss and damage to individual land-owners, businesses and public entities. It is also the case that this sector is cross-cutting in terms of climate change impacts, many of which have already been described in previous chapters.

Extreme rainfall

More extreme rainfall is projected, with an associated increase in flooding, freshwater contamination, and risks to human safety [1]. International airport closures have occurred due to extreme rainfall, damaging the runway https://www.abc.net.au/news/2023-12-16/australians-stuck-in-tuvalu-flights-cancelled-fiji-airways/103237676 Australians left stuck in Tuvalu after airport's runway damaged - ABC News

Flood early warning systems, evacuation centres, post flood impact assessments, and climate-resilient recovery are essential, particularly during El Niño events.

Drought

Drought is one of the biggest risk factors triggering natural disasters in Tuvalu. There are numerous examples of drought causing significant loss of agricultural productivity and stress on community health, wellbeing, and livelihoods due to water restrictions, requiring assessments and remedial action by the DRM sector and government more generally. For example, the Government of Tuvalu declared a state of emergency on 28th September 2011 as the drought directly or indirectly affected the entire population of Tuvalu [2].

Tropical cyclones

Tropical Cyclone Pam formed in the central south Pacific in early March 2015 [3]. The resulting swell propagated throughout the central Pacific, causing flooding and damage to communities in Tuvalu, Kiribati, and Wallis and Futuna, all over 1,000 km from TC Pam’s track [4]. The cyclone affected almost half of Tuvalu’s population, causing an estimated US$10 million in damage and at least US$17 million in reconstruction costs [5]. While cyclones are projected to occur less often in future, an increase in intensity would have significant implications for DRM.

TCs are associated with storm surges mainly through strong wind and low atmospheric pressure. Destructive waves generated by strong wind, even from far-located TCs [4], have been associated with coastal flooding, coastal erosion, and damage to jetties and harbours in Tuvalu. These cascading and compounding impacts pose challenges for DRM.

Extreme sea level

Ninety percent of coastal flooding events in Funafuti have occurred between January and March (Tui and Fakhruddin, 2022). Flooding from king tides and waves could be 3–5 m and a 3.2 m king tide could inundate half of Fongafale land [6].

As part of the Climate Risk Early Warning Systems (CREWS) initiative, SPC is partnering with the meteorological services in Tuvalu to strengthen their ocean monitoring and coastal inundation warning services. Early Warning Systems are a proven cost-effective disaster risk measure to strengthen community resilience. In virtually enclosed atolls, the water level experienced at the shore is compounded by tides, sea level anomaly, storm surge and the contribution of waves. While wave setup and runup, are the primary components driving inundation along the ocean-facing shorelines, sea level rise, wind setup and wave pumping through the atoll rim contributes more inside lagoons [7]. Having an Early Warning System aims to provide accurate, timely and actionable forecast information for safety at sea and increase resilience of communities. See: https://gem.spc.int/projects/climate-risk-early-warning-systems-crews-inundation-forecast-system-for-tuvalu-kiribati

References

1. Marra, J.J., G. Gooley, M.-V.V. Johnson, V.W. Keener, M.K. Kruk, S. McGree, J.T. Potemra, and O. Warrick, *Pacific Islands Climate Change Monitor: 2021*. 2022 The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC); Available from: https://www.pacificmet.net/pacific-climate-change-monitor-report.
2. Iese, V., A.S. Kiem, A. Mariner, P. Malsale, T. Tofaeono, D.G. Kirono, V. Round, C. Heady, R. Tigona, and F. Veisa, Historical and future drought impacts in the Pacific islands and atolls. *Climatic Change,* 2021. 166(1): p. 1-24.
3. UNDP. *Cyclone Pam recovery in Tuvalu and Vanuatu*. 2024 Available from: https://www.undp.org/crisis-response/past-crises/tuvalu.
4. Hoeke, R.K., H. Damlamian, J. Aucan, and M. Wandres, Severe flooding in the atoll nations of Tuvalu and Kiribati triggered by a distant Tropical Cyclone Pam. *Frontiers in Marine Science,* 2021. 7: p. 539646.
5. World Bank, *Tuvalu Gets Continued Support for Cyclone Pam Recovery*. 2015.
6. Tui, S. and B. Fakhruddin, Food for thought: Climate change risk and food (in)security in Tuvalu. *Progress in Disaster Science,* 2022. 16: p. 100255 DOI: https://doi.org/10.1016/j.pdisas.2022.100255.
7. Espejo, A., M. Wandres, H. Damlamian, A. Divesh, J. Giblin, J. Aucan, M. Eria, and U. Toorua, Efficient coastal inundation early-warning system for low-lying atolls, dealing with lagoon and ocean side inundation in Tarawa, Kiribati. *Weather and Climate Extremes,* 2023. 42: p. 100615 DOI: https://doi.org/10.1016/j.wace.2023.100615.

Chapter 16 Health

Climate change is having detrimental effects on the health of local communities in the Pacific, including Tuvalu. In the absence of strong and effective mitigation and adaptation measures, these impacts are projected to worsen under future climate conditions [1]. Health related climate impacts include direct impacts (e.g. heat stress and injuries from extreme weather events), and indirect impacts on water security and safety (e.g. water borne diseases), food security and safety (e.g. malnutrition and food borne diseases), vector borne diseases, and non-communicable diseases (NCDs) including hypertension, coronary and diabetes ailments, respiratory illness, eye, ear and skin disorders and diffuse impacts through mental/psycho-social disorders [2].

The health and climate change country profile for Tuvalu, developed with WHO as part of a shared commitment to the UNFCCC, provides a summary of available evidence on climate hazards, health vulnerabilities, health impacts and progress to date in the health sector's efforts to realize a climate-resilient health system [3]. For example, Tuvalu has a surveilance service for vector-borne diseases (Malaria, Dengue, Zika, Chikungunya, and Lymphatic filariasis) noting their current occurrence [4].

Existing NCD vulnerabilities include an epidemic of obesity and consequent chronic diseases [5]. Revisiting a more traditional diet based on increased consumption of local fisheries and agricultural produce, for example by using traditional techniques of drying, salting and smoking fish [6], or sourcing local agricultural produce (e.g. pulaka; a core crop for socio-cultural and food security reasons [7]), can have nutritional benefits.

Temperature

Heat-related stress and deaths could increase under a warmer climate and unfavourable socio-demographic conditions [2, 8]. High temperature is linked with some diarrheal diseases [9] and other enteric infections [10], and is associated with a substantial burden of ill-health in low-income and middle-income countries [10, 11] potentially straining or exceeding health service capacity. For each 1 °C increase in temperature, there exists a statistically significant increase in the risk of mental health-related mortality and morbidity [12].

The transmission of the two most common mosquito vector species for dengue, *Aedes aegypti* and *Ae. Albopictus*, is related to temperature [13] as indicated by the non-linear relationship in Figure 16-1, noting this temperature relationship would also correlate to vector distribution and abundance.

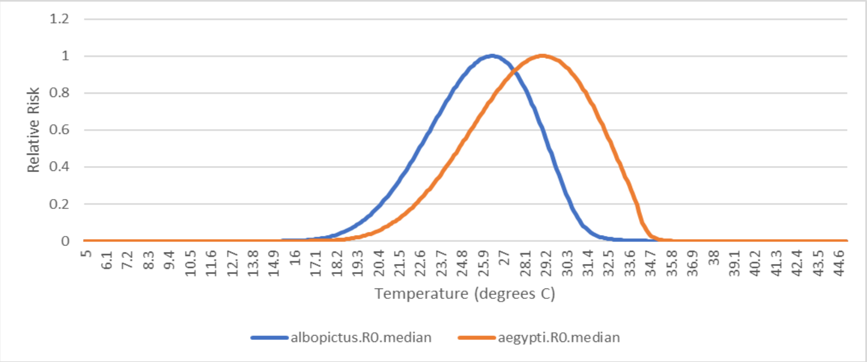


Figure 16-1 Relative Risk across constant temperatures for Ae. albopictus (light blue) and Ae. aegypti (orange) (Source: [13])

In the Western Pacific, the land area where temperatures are suitable for transmission of dengue by the main vector, *Ae. aegypti*, is projected to increase under a high emissions scenario. The picture for *Ae. albopictus* is more complex, with hot season temperatures in many regions becoming too hot for the mosquito under a high emissions scenario [14].

Heat also affects human comfort and labour productivity. For the Oceania region (excluding Australia and New Zealand), heat associated with a 2 °C global warming is projected to cause a 12.9 % reduction in labour productivity for agriculture, a 4.24 % reduction for manufacturing, and a 0.12 % reduction for services [15].

Under extreme heat, the reduction in workforce productivity affects business continuity, water security, food security, infrastructure development, and health [2, 16, 17]. Extreme heat also directly impacts livelihoods and community wellbeing through increased incidence of heat-related illness and morbidity from heat stroke.

Extreme heat directly impacts local communities, causing increased morbidity [18] and diabetes where indoor temperatures are elevated above 26 °C [19], particularly in the absence of a cool refuge (e.g. no air conditioning). Hot days and heat waves are also associated with increased hospital admissions and worsening of mental health symptoms [20].

Medical supplies, including vaccines, need to be stored at certain temperatures. Transportation can take 6-12 hours to travel between islands, so higher temperatures may affect the safe transport of these supplies (K. Morioka, Pers Comm).

Food handling and storage in households is increasingly a food safety issue due to increasing air temperatures and limited cold storage.

Rainfall

Flooding can result in water quality issues, water-borne and vector-borne diseases. An increase in diarrheal disease has been reported following heavy rainfall and flooding [9].

Lack of maintenance of rainwater tanks, drainage and septic systems can cause poor water quality and disease transmission; a previous Typhoid outbreak in Tuvalu has affected both physical and mental health of affected communities.

Less is known about the effect of drought on diarrhea transmission. However in 2011, Tuvalu experienced a drought and large diarrhea outbreak [21]. Well water was tested and found not fit for human consumption, and there was decreased handwashing frequency [21]. Four children and three adults were hospitalised for diarrhea and vomiting in Nukulaelae during the drought [22].

Water scarcity, particularly through droughts, can lead to increased rates of infection and disease (e.g. water-borne diseases, skin disease, eye infections), threatening health and well-being [2].

Extreme sea level

Tuvalu, a country comprised entirely of low-lying coral islands and atolls, has experienced the notion of climate refugees as a discursive force with significant emotional effects [23]. For Tuvalu, psychological distress has been attributed to literally experiencing impacts caused or exacerbated by climate change, and through hearing about global climate change, e.g. ‘Tuvalu is sinking’, and contemplating its future implications [24].

Coastal inundation can cause threats to physical safety, contributing to increases in mental health-related illness [25, 26]. Health infrastructure is exposed to sea level rise; in Tuvalu two medical facilities are located within 50 m of the coast, including the Princess Margaret Hospital which is the national reference hospital and major medical facility [27].

During Cyclone Pam in 2015, the winds were moderate, but the waves were so strong they damaged concrete houses. The storm demoralised the community [28]. While cyclones are projected to occur less often in future, an increase in intensity would have significant mental implications for health and wellbeing of local communities.

References

1. IPCC WG2, *Climate Change 2022: Impacts, Adaptation and Vulnerability.* . 2022 Cambridge University Press, : Cambridge, UK and New York, NY, USA, .
2. McIver, L., R. Kim, A. Woodward, S. Hales, J. Spickett, D. Katscherian, M. Hashizume, Y. Honda, H. Kim, and S. Iddings, Health impacts of climate change in Pacific Island countries: a regional assessment of vulnerabilities and adaptation priorities. *Environmental health perspectives,* 2016. 124(11): p. 1707-1714.
3. World Health Organisation, *Health & Climate Change: Country Profile: Tuvalu. COUNTRY PROFILE 2020*. 2020 Small Island Developing States Initiative; Available from: https://www.who.int/publications/i/item/WHO-CED-PHE-EPE-19.3.3.
4. PacMOSSI. *Pacific Mosquito Surveillance Strengthening for Impact. Mosquito-borne disease situation report: Tuvalu.* . 2024 Available from: https://pacmossi.org.
5. Hughes, R.G. and M. Lawrence, Globalisation, food and health in Pacific Island countries. *Asia Pacific journal of clinical nutrition,* 2005. 14(4): p. 298-305.
6. Kent, G., Fish and nutrition in the Pacific Islands. *Asia Pacific Journal of Public Health,* 1987. 1(2): p. 64-73.
7. Tekinene, M., *An assessment of the impacts of climate change on cultivated pulaka (Cyrtosperma chamissonis) in Tuvalu*. 2014, University of the South Pacific, Fiji.
8. Zhao, Q., Y. Guo, T. Ye, A. Gasparrini, S. Tong, A. Overcenco, A. Urban, A. Schneider, A. Entezari, and A.M. Vicedo-Cabrera, Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. *The Lancet Planetary Health,* 2021. 5(7): p. e415-e425.
9. Levy, K., A.P. Woster, R.S. Goldstein, E.J. Carlton, and technology, Untangling the impacts of climate change on waterborne diseases: a systematic review of relationships between diarrheal diseases and temperature, rainfall, flooding, and drought. *Environmental science,* 2016. 50(10): p. 4905-4922.
10. Chua, P.L., V. Huber, C.F.S. Ng, X.T. Seposo, L. Madaniyazi, S. Hales, A. Woodward, and M. Hashizume, Global projections of temperature-attributable mortality due to enteric infections: a modelling study. *The Lancet Planetary Health,* 2021. 5(7): p. e436-e445.
11. Fischer Walker, C.L., J. Perin, M.J. Aryee, C. Boschi-Pinto, and R.E. Black, Diarrhea incidence in low-and middle-income countries in 1990 and 2010: a systematic review. *BMC public health,* 2012. 12: p. 1-7.
12. Liu, J., B.M. Varghese, A. Hansen, J. Xiang, Y. Zhang, K. Dear, M. Gourley, T. Driscoll, G. Morgan, and A.J.E.i. Capon, Is there an association between hot weather and poor mental health outcomes? A systematic review and meta-analysis. 2021. 153: p. 106533.
13. Mordecai, E.A., J.M. Cohen, M.V. Evans, P. Gudapati, L.R. Johnson, C.A. Lippi, K. Miazgowicz, C.C. Murdock, J.R. Rohr, and S.J. Ryan, Detecting the impact of temperature on transmission of Zika, dengue, and chikungunya using mechanistic models. *PLoS neglected tropical diseases,* 2017. 11(4): p. e0005568.
14. Hales, S., K. Bowen, L. Webb, P.N. Schwerdtle, K. Nguyen, G. Gooley, H. Bambrick, K. Ebi, M. Mangeas, and C. Menkes, *Health Risks of Climate Change in the Western Pacific*. 2022 Australian Pacific Climate Partnership,: Melbourne, Australia; Available from: https://climatewise.apclimatepartnership.com.au/apex/f?p=208:52:12430683599322:APPLICATION_PROCESS%3DGET_PDF:::FILE_ID:1142
15. Roson, R. and M. Sartori, *Estimation of climate change damage functions for 140 regions in the GTAP9 database*. 2016 Policy Research Working Paper 7728. World Bank Development

Prospects Group,; Available from: https://openknowledge.worldbank.org/handle/10986/24643

16. Zander, K.K., W.J. Botzen, E. Oppermann, T. Kjellstrom, and S.T. Garnett, Heat stress causes substantial labour productivity loss in Australia. *Nature climate change,* 2015. 5(7): p. 647-651.
17. Al-Refaie, A., A. Alashwal, Z. Abdul-Samad, H. Salleh, and A. Elshafie, Evaluation of weather-productivity models of construction labour for tropics. *Built Environment Project Asset Management,* 2023. 13(2): p. 238-252.
18. Franchini, M. and P.M. Mannucci, Impact on human health of climate changes. *European journal of internal medicine,* 2015. 26(1): p. 1-5.
19. Tham, S., R. Thompson, O. Landeg, K.A. Murray, and T. Waite, Indoor temperature and health: a global systematic review. *Public Health,* 2020. 179: p. 9-17 DOI: https://doi.org/10.1016/j.puhe.2019.09.005.
20. Thompson, R., R. Hornigold, L. Page, and T. Waite, Associations between high ambient temperatures and heat waves with mental health outcomes: a systematic review. *Public Health,* 2018. 161: p. 171-191 DOI: https://doi.org/10.1016/j.puhe.2018.06.008.
21. Emont, J.P., A.I. Ko, A. Homasi-Paelate, N. Ituaso-Conway, and E.J.J. Nilles, Epidemiological investigation of a diarrhea outbreak in the South Pacific island nation of Tuvalu during a severe La Niña–associated drought emergency in 2011. *The American journal of tropical medicine hygiene,* 2017. 96(3): p. 576.
22. Sinclair, P., F. Atumurirava, and J. Samuela, *Rapid drought assessment Tuvalu 13 October-8 November 2011: SOPAC technical report (PR38)*. 2012: Funafuti, Tuvalu.
23. Farbotko, C. and H. Lazrus, The first climate refugees? Contesting global narratives of climate change in Tuvalu. *Global Environmental Change,* 2012. 22(2): p. 382-390 DOI: https://doi.org/10.1016/j.gloenvcha.2011.11.014.
24. Gibson, K.E., J. Barnett, N. Haslam, and I. Kaplan, The mental health impacts of climate change: Findings from a Pacific Island atoll nation. *Journal of Anxiety Disorders,* 2020. 73: p. 102237 DOI: https://doi.org/10.1016/j.janxdis.2020.102237.
25. Pörtner, H.O., D.C. Roberts, H. Adams, C. Adler, P. Aldunce, E. Ali, R.A. Begum, R. Betts, R.B. Kerr, and R. Biesbroek, *Climate change 2022: impacts, adaptation and vulnerability*. 2022 IPCC.
26. Liu, J., B.M. Varghese, A. Hansen, J. Xiang, Y. Zhang, K. Dear, M. Gourley, T. Driscoll, G. Morgan, and A. Capon, Is there an association between hot weather and poor mental health outcomes? A systematic review and meta-analysis. *Environment international,* 2021. 153: p. 106533.
27. Taylor, S., The Vulnerability of Health Infrastructure to the Impacts of Climate Change and Sea Level Rise in Small Island Countries in the South Pacific. *Health services insights,* 2021. 14: p. 11786329211020857 DOI: 10.1177/11786329211020857.
28. Reliefweb, *Nowhere to run. Tuvaluans consider their future after Tropical Cyclone Pam*. 2015 International Federation of Red Cross And Red Crescent Societies; Available from: https://reliefweb.int/report/tuvalu/nowhere-run-tuvaluans-consider-their-future-after-tropical-cyclone-pam.

Chapter 17 Water resources

Rainfall provides a critical water resource for ecosystems, communities, agriculture, businesses and livelihoods more generally. Ready availability of potable quality water for drinking and general sanitation use is critical to ensuring health and wellbeing of the population. Rapid urbanisation and water-table salinisation caused by sea-level rise makes the population of Tuvalu reliant on rooftop rainwater catchment and tank storage for private homes and via rooftop catchment and tank and underground reservoir storage collectively across public buildings for potable water supply [1, 2]. As Tuvalu's limestone islands and atolls have no fresh surface water, the community also relies on groundwater extraction (for washing clothes etc.) [2] and where available, sea-water desalination (reverse osmosis/RO) for supplementary and/or emergency purposes.

The available land for water storage tanks is a problem, particularly in Funafuti where population density is high, so there is competition for space between houses, recreation areas, infrastructure, livestock and crops.

A recent review of Tuvalu's 'de-sal' plants is listed in Table 17-1. Based on this assessment and as the key body responsible for overseeing, implementing and managing Tuvalu's infrastructure (including water), the Public Works Department (PWD) recommended a new 20m^3/day desalination plant [3].

Table 17-1 Existing RO units in Tuvalu (source: [3])

Desalination Plant	**Year Installed**	**Donor**	**Supplier / Manufacturer**	**Quantity**	**Status**	**Location**	**Remarks**
10m3/day	2011	PEC Fund	Hitachi	3	1 still operational 2 broken-down /mechanical failure	Nanumea/Nanumaga/Vaitupu	Portable desalination plant only use on outer islands, when emergency water supplies is required.
100m3/day	2010	PEC Fund	Hitachi	1	Operational	Funafuti	Operate 24/7 and will shut down only when: • Heavy rain • 90% of the total volume of the Government water reservoir is filled.
65m3/day	2009	Japan Government	Water boy	1	Broken-down/mechanical failure	Funafuti	The RO broke-down since 2010, and it has been replaced with the 100m3/day RO.
50m3/day	1999	Hitachi Company, Japan	Water boy	1	Broken-down /mechanical failure	Funafuti	The RO broke-down since 2018, and it is irreparable.

There are only two water trucks in Tuvalu that transport desalinated water from RO plants to consumers. This is inadequate and the PWD requires at least two more 10,000 litre water trucks to meet delivery demands. Any extra desalination capacity would not significantly increase the efficiency of supplying water to the community without increased transport capacity [3]. Maintenance of the 'de-sal' plant remains an ongoing problem.

Drought

The 2010-2013 drought [4] led to severe water shortages and loss of crops critical for food security, e.g. [5]. At Funafuti, rainfall was the lowest on record with only 515 mm (36% of the long-term average of 1430 mm) received between May to October 2011.

Due to the severe freshwater shortage, the Tuvaluan Government declared a national state of emergency on 28 September 2011 [1] because the drought had directly or indirectly affected Tuvalu's entire population. Communal water supplies were rationed to as little as 2.1 L/person/day.

On some islands, 61 % of households relied solely on brackish well water for bathing, washing clothes and flushing toilets.

During the 1999 drought, two 30m³/day mobile RO units were deployed to Vaitupu and Nanumanga islands to counter the water shortage experienced during the drought [3]. There is currently only one 10m³/day mobile RO unit.

The cost of water from the desalination plant is an issue during drought when households need to purchase water from PWD, noting also that the community has a preference for rainwater as opposed to de-sal water due to quality, where and when there is a choice.

Extreme rainfall

Extreme rainfall can potentially improve water security if capacity exists to harvest and store rainwater in tanks [6].

Projected increases in heavy rainfall can also lead to increased runoff into the lagoon, and increased pollution in groundwater, adversely affecting water quality. Sediment and debris from floods can damage drainage systems, increasing the frequency and cost of repair and maintenance.

Tropical cyclones

Despite a projected decrease in cyclone frequency, coastal inundation associated with increasing cyclone severity and rising sea levels would impact water and wastewater infrastructure.

Accessing adequate and clean water in the aftermath of a cyclone is often a major challenge [7]. While cyclones are projected to occur less often in future, an increase in intensity would have significant implications for health and wellbeing of local communities through limited availability of potable water for household use.

Sea level rise

Due to sea level rise, groundwater is brackish and generally not considered safe for consumption. Increasing sea level will lead to increasing saltwater intrusion/thinning freshwater lenses and reduction in water quality, especially during spring tides. The Fongafale Islet is less affected by this issue due to no significant freshwater lens [8]. Bores have been brackish for more than a decade already. On Vaitupu, water from bores is now only being used in drought periods, and mainly for non-potable usage, e.g. watering pigs [9]. Rising sea levels threaten water security in coastal settings, and some communities in the Pacific Islands have responded by revisiting their traditional practices for obtaining water, e.g. pools in rock caves [10].

References

1. Baarsch, F. and L.M.N. Berg, The Significance of contextual vulnerability in effective adaptation to Climate Change on Tuvalu. *Climate Change in the Asia-Pacific Region,* 2015: p. 301-317.
2. Mimura, N., L. Nurse, R.F. McLean, J. Agard, L. Briguglio, P. Lefale, R. Payet, and G. Sem, Small islands. *Climate change,* 2007. 16: p. 687-716.
3. Government of Tuvalu and Pacific Community (SPC), *ASSESSMENT REPORT: EXISTING DESALINATION UNITS IN TUVALU*. 2020 Pacific Community (SPC); Available from: http://ccprojects.gsd.spc.int/wp-content/uploads/2021/03/Assessment-on-all-existing-RO-Plants-in-Tuvalu-Final.pdf
4. Iese, V., A.S. Kiem, A. Mariner, P. Malsale, T. Tofaeono, D.G. Kirono, V. Round, C. Heady, R. Tigona, and F. Veisa, Historical and future drought impacts in the Pacific islands and atolls. *Climatic Change,* 2021. 166(1): p. 1-24.
5. Paeniu, L., *Understanding and predicting drought in Tuvalu*, in *Sustainable Development,* . 2018, The University of the South Pacific, Fiji.
6. Nyman, N., *Mid-term Evaluation of the Tuvalu NAPA-1 and NAPA-1+ Project. Annex VIII – Evaluation Report of the Baseline Project*. 2013 GREEN CLIMATE FUND FUNDING PROPOSAL; Available from: https://www.adaptation-undp.org/sites/default/files/resources/evalutation_report_of_the_baseline_project_0.pdf
7. Johnston, I., Disaster management and climate change adaptation: a remote island perspective. *Disaster Prevention Management,* 2014. 23(2): p. 123-137.
8. Kumar, L. and S. Taylor, Exposure of coastal built assets in the South Pacific to climate risks. *Nature Climate Change,* 2015. 5(11): p. 992-996.
9. Sinclair, P., F. Atumurirava, and J. Samuela, *Rapid drought assessment Tuvalu 13 October-8 November 2011: SOPAC technical report (PR38)*. 2012: Funafuti, Tuvalu.
10. Nunn, P.D., R. Kumar, H.M. Barrowman, L. Chambers, L. Fifita, D. Gegeo, C. Gomese, S. McGree, A. Rarai, and K. Cheer, Traditional knowledge for climate resilience in the Pacific Islands. *Wiley Interdisciplinary Reviews: Climate Change,* 2024: p. e882.

Chapter 18 Climate hazard ratings

Introduction

According to the IPCC (2022) [1], climate risk is the combination of climate hazard, exposure and vulnerability. Risk can be reduced by actions that reduce hazard and/or exposure and/or vulnerability Figure 18-1.

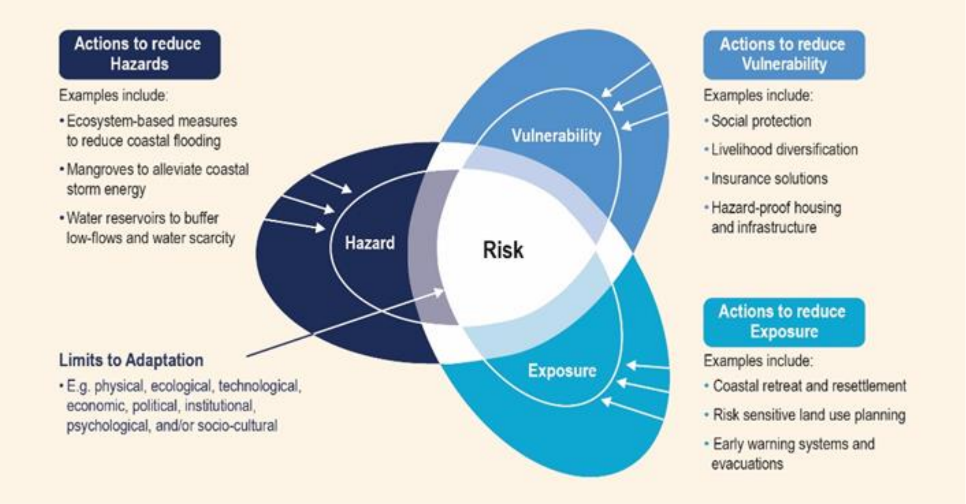


Figure 18-1 Risk is derived from the combination of hazard, exposure and vulnerability. Source: [1]

In this section, integration of the Tuvalu Vulnerability Assessment Report (TVAR) vulnerability and exposure priorities [2], combined with current and projected climate hazards assessed for Tuvalu (described in the Appendices of this report), are assessed to inform the analysis of risks and associated actions. This in turn will be used to inform the Tuvalu National Adaptation Plan (NAP).

Vulnerability and exposure

Vulnerability is defined as 'The propensity or predisposition to be adversely affected. This encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt' [1]. Exposure is defined as 'The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected' [1].

In 2018-2021, Tuvalu completed an integrated vulnerability analysis (IVA) for all nine islands. The initial phase of the IVA was supported by the Global NAP Network via the International Institute for Sustainable Development [2]. The TVAR vulnerability assessment implicitly includes exposure because it refers to assets such as houses, infrastructure, crops, evacuation centres, and marine protected areas.

While the TIVA provides rich and diverse snapshots of vulnerability at the sub-national levels, the key findings were aggregated to generate a high-level national summary for the purpose of informing the NAP development (Morioka, et al. 2024). The following summary will be used as a broad overview of vulnerabilities, however for a more granular and contextualised understanding of vulnerability, one should refer to the individual TIVA reports [2].

Climate hazards

A summary of climate hazards including climatology (Table 18-1) and sectoral impacts (Table 19-2) is provided for the current climate (20-year period centred on 1995) and the projected climate (20-

year periods centred on 2030 and 2050). The 2050 climate is presented for low emissions (RCP2.6) and high emissions (RCP8.5) pathways. Confidence levels around the projections are also given (See Chapter 2 for a discussion of emission pathways and confidence levels).

There is high confidence that temperature, sea level, marine heatwaves and ocean acidification will increase. There is medium confidence in a slight increase in annual average rainfall, a slight decrease in droughts, and an increase in extreme rainfall intensity. There is low confidence in a decrease in cyclone frequency and an increase in cyclone intensity.

A combination of these hazard and hazard-based impact data and information, together with information about current vulnerability and exposure from the TVAR [2], has been summarised for priority sectors in Table 18-3. Information about relevant climate hazards is also summarised, along with hazard ratings based on expert judgement, e.g. if impacts are medium then the hazard rating is medium, and if the impacts are high then the hazard rating is high. Projected changes in hazards from Table 18-1 change the hazard ratings in future (Table 18-3). These hazard ratings are intended to provide consolidated lines of science-based and reliable/validated anecdotal evidence to inform the integrated risk assessments for the Tuvalu CIVRA project; noting that the risk ratings specifically are reported separately for the project.

Table 18-1 Historical climate (20-years centred on 1995) and projected climate change for 20-year periods centred on 2030 and 2050, relative to a 20-year period centred on 1995. Changes are based on simulations from CMIP5 global climate models (GCMs) for low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenarios. However, changes in extreme wind speed and marine heat waves are based on CMIP6 GCMs for low (SSP1-2.6) and high (SSP5-8.5) emissions scenarios. For some variables, the Tuvalu EEZ region is assessed, rather than Funafuti, as indicated. Confidence ratings are based on the IPCC framework (Mastrandrea et al, 2010) involving an assessment of the amount of evidence and the degree of agreement between lines of evidence.

Funafuti		Projected change			
20-years centred on 1995		2030	2050	2050	
			Low emissions RCP2.6	Very high emissions RCP8.5	Confidence
	ATMOSPHERIC VARIABLES				
Min 26 °C Max 31 °C	Annual average temperature (°C)	+0.7 (0.4 to 1.0)	+0.8 (0.5 to 1.2)	+1.4 (1.0 to 1.9)	high
12 (0 to 31) °C	Hot days (days > 33 °C) [a]		+181 (140 to 222)	+264 (140 to 331)	high
3460 mm	Annual average rainfall (%)	+4 (-4 to +12)	+3 (-6 to +11)	+3 (-11 to +17)	medium
134 (119 to 160) mm/day	Annual maximum daily rainfall (mm/day)		+12 (-17 to 39)	+15 (-15 to 65)	medium
	Average drought intensity (more negative = more intense)	Slight increase	No data	Slight increase	medium
1.2 per 20 years	Average drought frequency (per 20 years)	Slight decrease	No data	Slight decrease	medium
~17 months	Average drought duration (months)	Slight decrease	No data	Slight decrease	medium
~30 (20-39) m/s	Tropical cyclone windspeed (m/s)			Increase	low
	Tropical cyclone frequency (%)			Decrease	low
	OCEAN VARIABLES				
0m	Annual average sea level (m)	+0.13 (0.09 to 0.17)	+0.22 (0.17 to 0.29)	+0.27 (0.19 to 0.37)	high
11 km^2	Extreme sea level proxy: 50-yr ARI Tuvalu flooded area (km^2)[b]	No data	~16 (2060; SSP2-4.5)	~16.5 (2060)	high
28.6-29.5 °C	Sea surface temperature (°C) over EEZ [c, f]	+0.7 (-0.6 to 1.7)	+0.9 (-0.5 to 2.1)	+1.3 (0.0 to 2.5)	high
~ 10 days/ yr	Marine heatwave frequency (days/year) [c,f]	110-290	130-340	220-360	high
0 days/ 20 yr	Coral bleaching days (per 20 years) [d,f]	No data	169-2934	1652-6460	high
~8.08 (8.1-8.07)	Annual average ocean pH over EEZ ([c,e])	8.02 (7.99-8.04)	8.0 (7.99-8.02)	7.95 (7.93-7.96)	high
~4.1 (4.0-4.2)	Annual average aragonite saturation ([c,e])	3.77 (3.51-4.06)	3.69 (3.53-4.01)	3.4 (3.18-3.70)	high

[a] number of days over the 95th percentile of 1985-2014 daily temperatures [b] data source [3].[c] Future values are reported, not changes. [d] Exceed coral bleaching Alert level 2 at Niutao. [e] Baseline figures are estimated from Figure 11-2. [f] CMIP6/SSPs and baseline period 1994-2014 used.

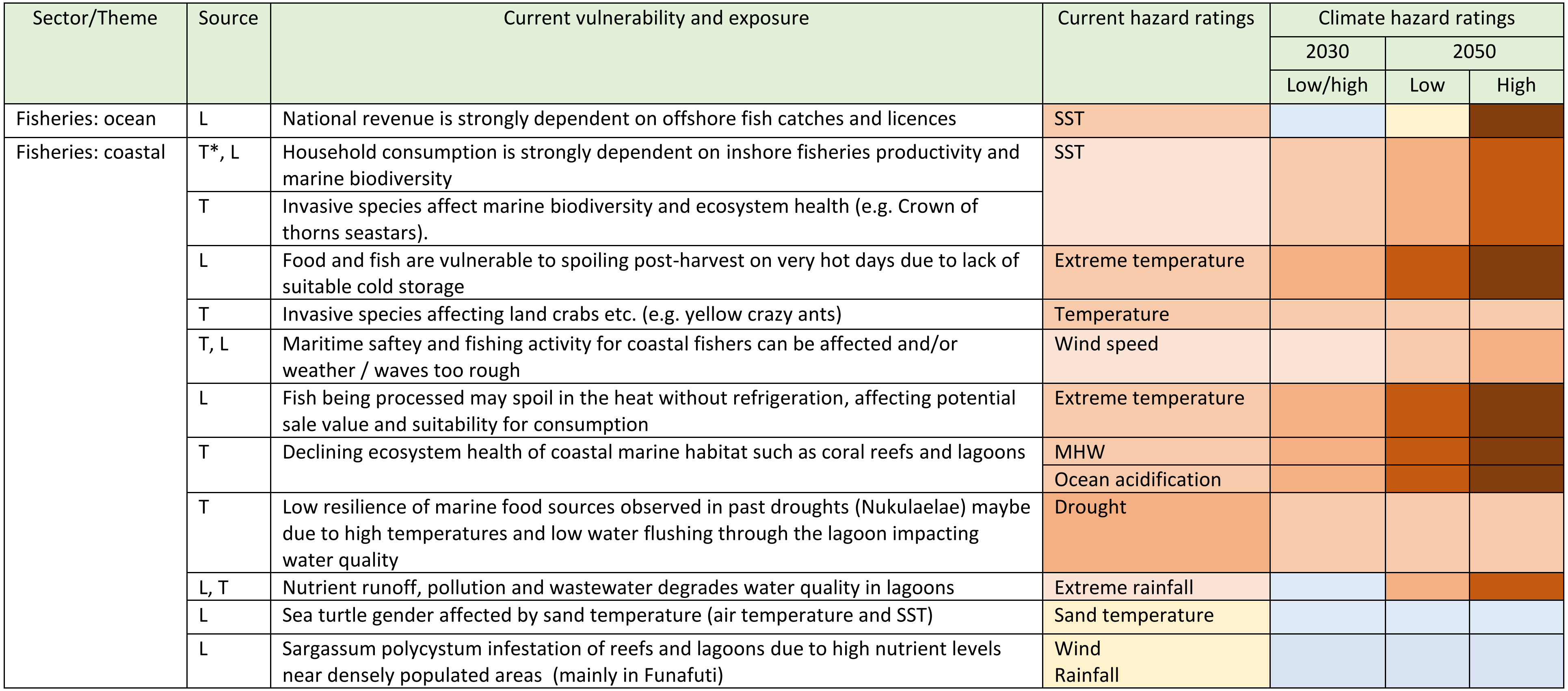
Table 18-2 Climate related hazards affecting sectors in Tuvalu.

Climate Hazard	Fisheries and marine resources	Agriculture	Coastal development and infrastructure	Disaster Management and emergency response	Health	Water resources
Annual average temperature	Fish storage in boats and while processing	Crop suitability. Crop disease			Vector borne disease	
Extreme temperature	Fish storage at port and on vessel. Fishers' and fish processors heat stress and workforce productivity.	Crop stress Farm-worker heat-stress Pig and chicken heat-stress	Health of outside workers for general maintenance and installations. Melting of Road tar. High energy demand for air conditioning may cause black outs. May require more solar/battery back-up. Increased demand for replacement parts and equipment. Black outs may cut telecoms.	Increased demand for communal air-conditioned refuges to escape heat.	Heat stress increases hospital and health centre admissions from heat stroke. Power outages may affect sewage pumping facilities. Food-borne disease due to inadequate cooling. Labour productivity Mental/ psychosocial disorders	High water demand for domestic and agricultural use for stock watering and irrigation.
Annual average rainfall		Crop suitability. Water for livestock.			Vector borne disease.	Availability/ storage
Extreme rainfall	Nutrient and sediment Runoff into coastal areas.	Limited farm access due to flooding. Damage to some crops. Increased disease pressure.	Flood risk depends on road design and flood mitigation e.g. drainage. Extreme rain can result in flooding of Funafuti airport runway. Flooding of electricity infrastructure may cause blackouts. Flood related black outs may cut telecoms. Require functioning gutters and rooves to collect water to water tanks.	Require flood early warning systems, evacuation centres, and post-flood impact assessments.	Water quality affects health, sanitation and hygiene. Post-flood trauma may affect mental health.	Flooding can overwhelm drains, with overflow of septic tanks, affecting ground water quality.
Drought	Invasive seaweed e.g. *Sargassum polycystum* has been observed during drought events.	Crop stress e.g. reduced yield from Pulaka (Giant swamp Taro). Loss of cultural livelihood.	Towers caking with salt, with no rainfall to wash salt away, can also affect telecoms. Water supply from household water tanks becomes inadequate.	RO capacity. Reliance on trucks to deliver RO water. Supply of RO water to outer islands.		Water Shortage. Reliance on RO water.

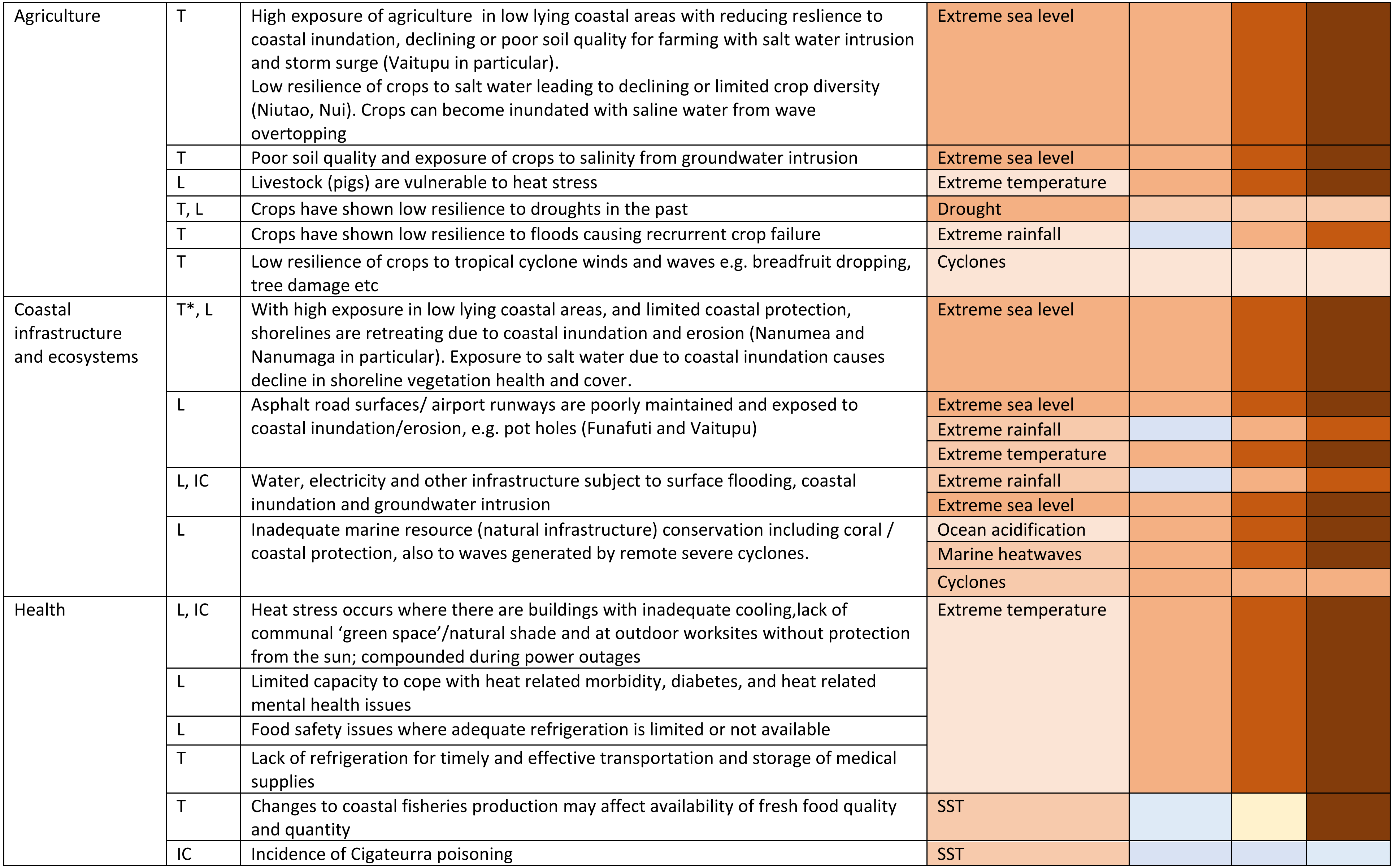
Extreme windspeed	More days too windy for fishing (<20 knots) Relevant to both lagoon and off-reef/FAD pelagic fishery. When very windy more fishing in the lagoon.	Crop damage.	Large waves and storm surges causing overtopping of barriers Disruption of air and sea transport Wind-damage to infrastructure can cause blackouts. Blackouts, wind-borne debris and fallen trees may cut telecoms. Towers caking with salt from sea spray can affect telecoms.	Deaths, injuries, damage and disruption in general. Post cyclone impact assessments can inform climate-resilient recovery.	Injuries due to airborne debris and building collapse during cyclones.	Ocean overtopping of barriers can cause salt-water contamination of groundwater.
Sea level rise, extreme sea level (inc waves and TC impacts)	Coral reefs provide less defence against storm surge and tsunami. Sea-Turtle nests may be inundated. Mangroves	Saltwater inundation affects Pulaka pits.	Infrastructure, houses, roads and bridges affected. Underground copper wiring becoming corroded with inundation, with upgrading to fibre-optic cable expensive.	Need barriers and land reclamation to reduce inundation risk.	Mental health issues due to inundation of property, and loss of livelihood & income, internal and external relocation.	Contamination of freshwater lens.
Ocean temperature and marine heatwave	Changing distribution of Tuna fisheries ($). Coral bleaching. Sea-Turtle gender. Fish kills.		Coral bleaching/die-back/reef erosion.		Ciguatera- links to SST unclear. More study needed.	
Ocean pH	Fisheries, reef and aquatic ecosystem viability, productivity, and diversity.		Marine infrastructure e.g. fixings such as nails, rivets, bolts etc. Coral bleaching/die-back/reef erosion reducing island protection.			
Aragonite saturation	Coral formation and reef integrity, shells, and fish skeletons.		Coral integrity, lagoon protection			

Table 18-3 Climate hazard assessment for Tuvalu, based on current and future climate hazards (Table 18-1) for 2030 and 2050 for low and high emissions scenarios, noting current vulnerabilities and exposure based on the TVAR [2], Chapter 2 of this report (L), or in-country (IC) missions. Colours are aligned to the consequence rating scale below. SST is sea surface temperature and MHW is marine heatwave.

Low	Medium	High	Very high	Extreme	Very Extreme	Unclear



Sector/Theme	Source	Current vulnerability and exposure	Current hazard ratings	Climate hazard ratings		
				2030	2050	
				Low/high	Low	High
Fisheries: ocean	L	National revenue is strongly dependent on offshore fish catches and licences	SST			
Fisheries: coastal	T*, L	Household consumption is strongly dependent on inshore fisheries productivity and marine biodiversity	SST			
	T	Invasive species affect marine biodiversity and ecosystem health (e.g. Crown of thorns seastars).				
	L	Food and fish are vulnerable to spoiling post-harvest on very hot days due to lack of suitable cold storage	Extreme temperature			
	T	Invasive species affecting land crabs etc. (e.g. yellow crazy ants)	Temperature			
	T, L	Maritime saftey and fishing activity for coastal fishers can be affected and/or weather / waves too rough	Wind speed			
	L	Fish being processed may spoil in the heat without refrigeration, affecting potential sale value and suitability for consumption	Extreme temperature			
	T	Declining ecosystem health of coastal marine habitat such as coral reefs and lagoons	MHW			
			Ocean acidification			
	T	Low resilience of marine food sources observed in past droughts (Nukulaelae) maybe due to high temperatures and low water flushing through the lagoon impacting water quality	Drought			
	L, T	Nutrient runoff, pollution and wastewater degrades water quality in lagoons	Extreme rainfall			
	L	Sea turtle gender affected by sand temperature (air temperature and SST)	Sand temperature			
	L	Sargassum polycystum infestation of reefs and lagoons due to high nutrient levels near densely populated areas (mainly in Funafuti)	Wind Rainfall			



Agriculture	T	High exposure of agriculture in low lying coastal areas with reducing reslience to coastal inundation, declining or poor soil quality for farming with salt water intrusion and storm surge (Vaitupu in particular). Low resilience of crops to salt water leading to declining or limited crop diversity (Niutao, Nui). Crops can become inundated with saline water from wave overtopping	Extreme sea level	🟧	🟧	🟫
	T	Poor soil quality and exposure of crops to salinity from groundwater intrusion	Extreme sea level	🟧	🟧	🟫
	L	Livestock (pigs) are vulnerable to heat stress	Extreme temperature	🟧	🟧	🟫
	T, L	Crops have shown low resilience to droughts in the past	Drought	🟧	🟧	🟧
	T	Crops have shown low resilience to floods causing recrurrent crop failure	Extreme rainfall	🟦	🟧	🟧
	T	Low resilience of crops to tropical cyclone winds and waves e.g. breadfruit dropping, tree damage etc	Cyclones	🟧	🟧	🟧
Coastal infrastructure and ecosystems	T*, L	With high exposure in low lying coastal areas, and limited coastal protection, shorelines are retreating due to coastal inundation and erosion (Nanumea and Nanumaga in particular). Exposure to salt water due to coastal inundation causes decline in shoreline vegetation health and cover.	Extreme sea level	🟧	🟧	🟫
	L	Asphalt road surfaces/ airport runways are poorly maintained and exposed to coastal inundation/erosion, e.g. pot holes (Funafuti and Vaitupu)	Extreme sea level	🟧	🟧	🟫
			Extreme rainfall	🟦	🟧	🟧
			Extreme temperature	🟧	🟧	🟫
	L, IC	Water, electricity and other infrastructure subject to surface flooding, coastal inundation and groundwater intrusion	Extreme rainfall	🟦	🟧	🟧
			Extreme sea level	🟧	🟧	🟫
	L	Inadequate marine resource (natural infrastructure) conservation including coral / coastal protection, also to waves generated by remote severe cyclones.	Ocean acidification	🟧	🟧	🟫
			Marine heatwaves	🟧	🟧	🟫
			Cyclones	🟧	🟧	🟧
Health	L, IC	Heat stress occurs where there are buildings with inadequate cooling,lack of communal 'green space'/natural shade and at outdoor worksites without protection from the sun; compounded during power outages	Extreme temperature	🟧	🟧	🟫
	L	Limited capacity to cope with heat related morbidity, diabetes, and heat related mental health issues				
	L	Food safety issues where adequate refrigeration is limited or not available				
	T	Lack of refrigeration for timely and effective transportation and storage of medical supplies				
	T	Changes to coastal fisheries production may affect availability of fresh food quality and quantity	SST	🟦	🟨	🟫
	IC	Incidence of Cigateurra poisoning	SST	🟦	🟦	🟦

	T	Exposure to vector borne disease (Chikungunya, dengue and lymphatic filariasis)	Temperature			
			Rainfall			
	T	Exposure to water borne diseases due to poor water quality, availability and environmental health and sanitation, especially during floods	Extreme rainfall			
	L	Flood related water borne disease and sanitation issues due to limited water treatment and sewage treatment plants				
	L	High exposure to inundation, loss and damage in low lying coastal areas, affecting mental health	Extreme sea level			
	T	Low resilience of health infrastructure to inundation				
	L	Communities affected by lack of access to potable quality water and reduced water for agriculture, contributing to water/food stress and physical (sanitation-related) and mental health issues	Drought			
Water	L, IC	Water demand increases under extreme heat conditions	Extreme temperature			
	T	Salt water intrusion affects ground water quality, affecting potable water supply	Extreme sea level			
	L, T	Increasing pressure on water resources occurs during drought due to limited access to water treatment equipment, inadequate household and communal water tank capacity, leaking or faulty household water tanks, and inadequate public water supply system and services	Drought			
	L	Drainage affected during flooding events leading to reduced water quality, excessive run-off, damage to infrastructure and loss of public amenity	Extreme rainfall			
	T*	Limited ability to capture water in household water tanks due to land availability and cost of purchasing and maintaining water tanks	Rainfall			
Disaster risk management	T	Lack of cyclone-proof and extreme climate-resilient housing, e.g cyclone straps, poorly fixed roofing materials	Cyclones			
			Extreme rainfall			
	T	Limited access to post-disaster building reconstruction services, including shipping and transporation being affected by waves generated by remote severe cyclones.	Cyclones			
	T*	Limited or no access to adequately sized and located climate-resilient evacuation centres (Vaitupu, Nui and Nukufetau) (Top TIVA priority)	Cyclones			
			Extreme sea level			
	T, IC	High exposure to coastal inundation in low lying areas affects power supply, ctelecommunications and evacuation centres	Extreme sea level			
	L, IC	Inundation and damage to roads and airports and other public infrastructre affecting transport and other critical support services	Extreme rainfall			

*denotes vulnerability issue with the highest frequency of total responses across all islands, according to TVAR

References

1. IPCC, *Summary for Policymakers. IPCC Sixth Assessment Report from Working Group 2 on Impacts, Adaptation and Vulnerability.* . 2022; Available from: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf.
2. Government of Tuvalu, *Tuvalu Integrated Vulnerability Assessment Report – Funafuti community, Funafuti. Government of Tuvalu and NAP Global Network/International Institute for Sustainable Development (IISD).* 2020; Available from: https://napglobalnetwork.org/wp-content/uploads/2021/01/napgn-en-2020-Tuvalu-IVA-report-Amatuku-Islet.pdf.
3. Wandres, M., A. Espejo, T. Sovea, S. Tetoa, F. Malologa, A. Webb, J. Lewis, G. Lee, and H. Damlamian, A national‐scale coastal flood hazard assessment for the atoll nation of Tuvalu. *Earth's Future,* 2024. 12(4): p. e2023EF003924.

Chapter 19 Knowledge gaps and research priorities

This report has described historical and projected climate hazards that potentially pose risks to Tuvalu. Confidence ratings, uncertainties, limitations and caveats have also been provided along with consolidated hazard ratings for priority sectors incorporating aspects of climate-related hazards, impacts, exposure and vulnerability under current and future climate conditions for Tuvalu. These hazard ratings are in turn used to inform integrated climate change risk assessments (reported separately) as science-based evidence to inform the new NAP for Tuvalu.

Through this assessment process a few key knowledge gaps have emerged. Addressing these gaps will inform research priorities to enhance the knowledge base for future assessments; in particular as might inform the future implementation and evaluation of the new NAP. Likewise, implementation of the Pacific Climate Change Research Roadmap coordinated by SPREP in partnership with Pacific Island countries including Tuvalu, will facilitate these gaps to be addressed.

Historical climate

This report has quantified historical climate averages, variability and trends. In addition to the primary purpose of informing the risk assessment as part of the new Tuvalu NAP, this report also serves effectively as a 'state of the climate' report for Tuvalu relevant across current and future, multi-decadal (climate change) timescales. This analysis should be updated every two-three years, including potentially by refreshing the 2022 report on Climate Change in the Pacific: Historical and Recent Variability, Extremes and Change [1] at a national level for Tuvalu. Better supporting the historical analyses of observed station data could be via a revised or extended monitoring network for digitising and quality controlling observed atmospheric and oceanic variables in Tuvalu. Without reliable, high (spatial and temporal) resolution and quality controlled/homogenised atmospheric and ocean measurements, it is difficult to evaluate the performance of climate models, which influences the level of confidence in climate projections. Likewise the ability to produce application-ready projections data tailored to the needs of target sectors is also limited.

While global trends in temperature and sea level have been attributed to climate change, there is uncertainty about whether local trends and extreme weather events can be attributed to climate change. This could be explored using detection and attribution methods described in IPCC AR6 Working Group 1 Chapter 10 [1]. Such analysis will provide more reliable insights to better understand the historical and current climate trends, particularly in terms of elucidating the impacts of climate change from natural variability.

Future climate

Most of the climate projections in this report were based on simulations from CMIP5 climate models driven by low (RCP2.6) and high (RCP8.5) greenhouse gas concentration pathways. These datasets are becoming outdated due to the growing availability of more contemporary simulations from CMIP6 climate models driven by low (SSP1-2.6), medium (SSP2-4.5), medium-high (SSP3-7.0) and high (SSP5-8.5) concentration pathways. Projections for Tuvalu (and the broader western tropical Pacific region) should be updated with data from CMIP6 climate models driven by SSPs. In this report, projected changes in extreme windspeed, marine heatwaves and ocean acidification (pH and aragonite saturation) are based on existing/ available CMIP6 GCMs for low (SSP1-2.6) and high (SSP5-8.5) emissions scenarios.

While the newer CMIP6 models show incremental improvements in the simulation of the climate of the western tropical Pacific compared to CMIP5 GCMs, and there will be new insights and new opportunities to understand the future climate using these models, the western tropical Pacific remains a challenging area to simulate climate variability and change. For the Pacific region, for example, there is lower confidence in SST projections where the climate models tend to simulate the wrong shape for the Warm Pool and equatorial 'cold tongue'; the well-known "cold-tongue bias" where the West Pacific warm pool is pinched in at the equator by a tongue of cold water and the 'cold tongue' is generally too strong in models [2-4]. This issue is reduced, but still persists in the CMIP6 models [5].

Projected changes in ENSO also have significant uncertainty. Understanding the zonal gradients of sea surface temperature (SST) across the equatorial Pacific have major consequences for both Pacific and global climate [6]. Improvements on the large degree of inconsistency among climate models on some aspects of future ENSO projections, as well as biases (e.g. [3, 7-9]) will be very important going forward.

These challenges could be explored using dynamical and statistical downscaling of the CMIP6 climate models over the western tropical Pacific. An internationally coordinated downscaling experiment called CORDEX-CMIP6 is running simulations at 12.5 and 25 km resolution over 14 domains, but this does not include the Pacific. A CORDEX Pacific Flagship Pilot Study has been proposed. Downscaling is computer-intensive in terms of data processing and storage. Artificial intelligence and machine learning capabilities could enhance data processing.

Regarding extreme weather events, more information from scientifically robust extremes analysis is needed at spatial and temporal scales relevant to assessing climate risks, i.e. less than 50 km and less than 24 hours between data points. Key parameters include:

- Tropical cyclones: frequency, intensity (peak wind speeds, storm surge and rainfall), duration, and location (latitude of maximum intensity, area of gale-force winds).
- Extreme sea level: intensity, frequency, duration and location.
- Extreme rainfall: intensity, frequency, duration and location.
- Flood: intensity, frequency, duration and location.
- Extreme heat: intensity, frequency, duration and location.
- Drought: intensity, frequency, duration and location.
- Marine heatwaves: intensity, frequency, duration and location.

Further research is needed to reduce uncertainty about potential (low risk/high consequence) tipping points. While much of this research is already occurring internationally, having a 'Pacific' voice in these activities could improve the local relevance of information, e.g. a Tuvalu case study.

An analysis of SSP likelihoods would be highly policy-relevant, bearing in mind the COP28 Global Stocktake of emission reduction policies, recent emission growth rates, and revision of SSPs for the CMIP7 project aligned to the next IPCC AR7 reporting cycle. This would allow Tuvalu (and the western tropical Pacific) to use the latest climate models and emissions scenarios in risk assessments, adaptation planning and decision-making.

Co-design and co-development of communication products is essential for raising awareness and boosting the uptake of science in planning and decision-making. Communication products could include brochures, reports, journal papers, videos, posters, slides and presentations. Adding or updating climate information on an existing web portal can also add value, in particular where tailored climate change data and information can be readily accessed, analysed, visualised and spatially-referenced. Ongoing climate change services such as these can provide information tailored for specific purposes, such as sector-based national and sub-national impact and risk assessments.

Linking climate hazards to impacts, exposure and risks

Another gap is understanding the historical links between climate hazards and impacts. Knowledge is patchy in the Pacific e.g. a good understanding of the link between marine heatwaves and coral bleaching, but a poor understanding of the link between extreme temperature and electricity consumption. New work on tuna biomass modelling has been proposed, as there are key gaps in our understanding of the likely responses of tuna to climate change. The existing modelling assumes that each tuna species forms a single stock across the tropical/subtropical Pacific Ocean basin. Evidence is accumulating that this is not the case. Location specific assessments may be required to understand the effects on ciguatera fish poisoning from ocean warming.

Further research is needed to develop reliable, scientifically robust 'damage functions' which provide statistical links between hazards and economic impacts for different sectors and activities. Once established, these statistical links can be used with future climate data to estimate future economic impacts of climate change under different scenarios, including potentially the cost-benefit of selected adaptation interventions and the application of climate information services to enhance adaptation planning and decision-making. It follows there is limited information about economic loss and damage related to climate change. Economic models need to be configured to account for annual-average losses due to extreme events. The economic costs and benefits of adaptation and mitigation can guide international policy negotiations and local action.

Finally, the technical capacity of policy-makers, adaptation planners and associated sectoral decision-makers needs to be enhanced to ensure the available scientific data and information is well understood, routinely accessed and effectively applied as a mainstream outcome for civil society in Tuvalu; thereby resulting in building resilience to climate change for local communities going forward.

References

1. IPCC, ed. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. ed. V. Masson-Delmotte, et al. 2021, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, .
2. Grose, M.R., S. Narsey, F. Delage, A.J. Dowdy, M. Bador, G. Boschat, C. Chung, J. Kajtar, S. Rauniyar, and M. Freund, Insights from CMIP6 for Australia's future climate. *Earth's Future,* 2020. 8(5): p. e2019EF001469.
3. Graham, F.S., A.T. Wittenberg, J.N. Brown, S.J. Marsland, and N.J. Holbrook, Understanding the double peaked El Niño in coupled GCMs. *Climate Dynamics,* 2017. 48(5): p. 2045-2063 DOI: 10.1007/s00382-016-3189-1.
4. Brown, J.N., C. Langlais, and C. Maes, Zonal structure and variability of the Western Pacific dynamic warm pool edge in CMIP5. *Climate Dynamics,* 2014. 42(11): p. 3061-3076 DOI: 10.1007/s00382-013-1931-5.
5. CSIRO and SPREP, *'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for Tuvalu.* . 2021: Final report to the Australia-Pacific Climate Partnership for the Next Generation Climate Projections for the Western Tropical Pacific project. Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP). Melbourne, Australia; Available from: https://www.rccap.org/uploads/files/909d29f7-7cb7-4618-b58b-3ca889669965/Tuvalu%20Country%20Report%20Final.pdf
6. Lee, S., M. L'Heureux, A.T. Wittenberg, R. Seager, P.A. O'Gorman, and N.C. Johnson, On the future zonal contrasts of equatorial Pacific climate: Perspectives from Observations, Simulations, and Theories. *Climate Atmospheric Science,* 2022. 5(1): p. 82.

7. Collins, M., S.-I. An, W. Cai, A. Ganachaud, E. Guilyardi, F.-F. Jin, M. Jochum, M. Lengaigne, S. Power, and A. Timmermann, The impact of global warming on the tropical Pacific Ocean and El Niño. *Nature Geoscience,* 2010. 3(6): p. 391-397.
8. Power, S., M. Lengaigne, A. Capotondi, M. Khodri, J. Vialard, B. Jebri, E. Guilyardi, S. McGregor, J.-S. Kug, and M. Newman, Decadal climate variability in the tropical Pacific: Characteristics, causes, predictability, and prospects. *Science Advances,* 2021. 374(6563): p. eaay9165.
9. Erickson, N.E. and C.M. Patricola, Future projections of the El Niño—Southern Oscillation and tropical Pacific mean state in CMIP6. *Journal of Geophysical Research: Atmospheres,* 2023. 128(21): p. e2022JD037563.

Chapter 20 Glossary

A

Adaptation: In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

Anomaly: In climate science, a deviation from the normal value of a variable. It is usually the deviation of a variable from the average value at a specific place and time.

Aragonite saturation state – see also Ocean acidification, pH: Aragonite is a form of calcium carbonate that makes up the shells and skeletons of key organisms in reef ecosystems, including reef-building corals. The saturation state of aragonite in seawater (known as Ω) is a measure of the potential for the mineral to form or to dissolve. When the $\Omega = 1$, the seawater is in equilibrium with respect to aragonite, so aragonite does not dissolve or precipitate. When $\Omega > 1$ seawater is supersaturated with respect to aragonite and aragonite will precipitate, and when $\Omega < 1$ aragonite will dissolve. Aragonite saturations states above about 4 are considered optimal conditions for healthy coral reef ecosystems, with values below 3.5 becoming increasingly marginal for supporting healthy coral reef growth.

C

Carbon dioxide (CO_2): A naturally occurring gas, CO_2 is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land use changes and of industrial processes (e.g., cement production).

Climate: Climate is usually defined as the average weather. The relevant quantities are most often surface variables such as temperature, precipitation and wind. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization1. In various parts of this portal different averaging periods, such as a period of 20 years, are also used.

Climate change: A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for decades or longer. Climate change may be due to natural internal processes or external forcings such as changes in solar irradiance, volcanic eruptions and human-induced changes in the composition of the atmosphere or in land use1.

Climate extreme: A weather/climate event above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the weather/climate variable1. Extreme events include hot/cold days, heavy rainfall, droughts and wind-storms. The extreme threshold can be defined in different ways for different purposes, e.g. daily maximum temperature above the long-term 95th percentile, a 3-hourly rainfall-total with an annual exceedance probability of 1% (1-in-100-year return period), 10-second windspeed exceeding 200 kph.

Climate model – also see Global climate model: A mathematical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes. These mathematical models are run on powerful computers. There is an evolution towards more complex models with interactive chemistry and biology1, and finer spatial and temporal detail. Climate models are used to simulate the past and future climate variability and change.

Climate projection: The response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models and statistical analysis1. Climate projections are distinguished from climate predictions in order to emphasise that climate projections depend upon the emission/concentration/ radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised and are therefore subject to substantial uncertainty.

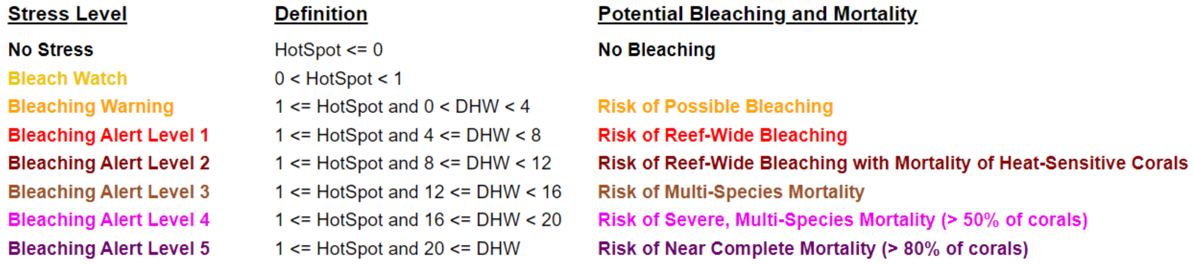
Climate scenario: A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., demographic change, technological change, energy use, land use). Scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions1. Climate scenarios quantify three main sources of uncertainty: greenhouse gas emission pathways, regional climate responses to each emission pathway, and natural climate variability.

Climate variability: Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Climate variability on a range of timescales can be due to internal and external factors. Internal variability stems from natural processes (e.g. the El Niño Southern Oscillation), while external variability is due natural processes (e.g. volcanic eruptions, sunspot cycles) or human-induced processes (e.g. increases in greenhouse gases and aerosols) 1.

Confidence: The robustness of a finding based on the type, amount, quality and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement across multiple lines of evidence.

Coral Bleaching Alert Level:

Coral bleaching thermal stress levels based on the NOAA Coral Reef Watch warnings (NOAA Coral Reef Watch Daily 5km Satellite Coral Bleaching Heat Stress Bleaching Alert Area Product (Version 3.1).



Stress Level	Definition	Potential Bleaching and Mortality
No Stress	HotSpot <= 0	**No Bleaching**
Bleach Watch	0 < HotSpot < 1	
Bleaching Warning	1 <= HotSpot and 0 < DHW < 4	**Risk of Possible Bleaching**
Bleaching Alert Level 1	1 <= HotSpot and 4 <= DHW < 8	**Risk of Reef-Wide Bleaching**
Bleaching Alert Level 2	1 <= HotSpot and 8 <= DHW < 12	**Risk of Reef-Wide Bleaching with Mortality of Heat-Sensitive Corals**
Bleaching Alert Level 3	1 <= HotSpot and 12 <= DHW < 16	**Risk of Multi-Species Mortality**
Bleaching Alert Level 4	1 <= HotSpot and 16 <= DHW < 20	**Risk of Severe, Multi-Species Mortality (> 50% of corals)**
Bleaching Alert Level 5	1 <= HotSpot and 20 <= DHW	**Risk of Near Complete Mortality (> 80% of corals)**

Coupled Model Intercomparison Project (CMIP): A climate modelling activity from the World Climate Research Programme (WCRP) which coordinates and archives climate model simulations from around the world. The CMIP5 climate simulations are driven by Representative Concentration Pathways (RCPs) and used in the IPCC Fifth Assessment Report. The CMIP6 climate simulations are driven by Shared Socio-economic Pathways (SSPs) and used in the IPCC Sixth Assessment Report 1.

D

Degree heating weeks (DHW): A measure of coral stress relating to when SSTs are warmer than a defined bleaching threshold for the location. Heat stress builds up the longer SST stays above the bleaching threshold. Both the magnitude of threshold exceedance and length of the exceedance are important factors in measuring stress, and thereby DHW.

Downscaling: A method that derives local- to regional-scale climate information from larger-scale models or data analyses. Two main methods exist: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution, or high-resolution global models. The empirical/statistical methods are based on observations and develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the driving model remains an important limitation on quality of the downscaled information. The two methods can be combined.

E

El Niño – see also El Niño-Southern Oscillation, La Niña: This is the warm phase of the El Niño-Southern Oscillation. El Niño events occur on average once every two to seven years. They are associated with basin-wide warming of the tropical Pacific Ocean east of the dateline and a weakening of the Walker Circulation.

El Niño-Southern Oscillation (ENSO) – see also El Niño, La Niña: The term El Niño was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Perú, disrupting the local fishery. It has since become identified with a basin-wide warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This naturally occurring coupled atmosphere-ocean phenomenon, with time scales of approximately two to seven years, is known as the El Niño-Southern Oscillation (ENSO). The state of ENSO is often measured by the Southern Oscillation Index (SOI) and sea-surface temperatures in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea-surface temperatures warm, further weakening the trade winds. This event has a great impact on the wind, sea-surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world. The cold phase of ENSO is called La Niña.

Emissions – see also Greenhouse gases: Emissions of greenhouse gases and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use and land use changes, livestock production, fertilisation, waste management, and industrial processes. The main greenhouse gases are water vapour, carbon dioxide (CO2), methane (CH4), ozone (O3) precursors, aerosols such as black carbon and sulphur dioxide, nitrous oxide (N2O) or other fluorinated gases. 1.

Exposure: The presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected. See also Hazard, Risk and Vulnerability 1.

G

Global Climate Model (GCM): A mathematical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes. These mathematical models are run on powerful computers. There is an evolution towards more complex models with interactive chemistry and biology 1, and finer spatial and temporal detail. Climate models are used to simulate the past and future climate variability and change.

Greenhouse gases – see also Emissions: Atmospheric gases that absorb and emit radiation at specific wavelengths. This property causes the greenhouse effect which keeps the Earth warm enough for life. Water vapour, carbon dioxide, nitrous oxide, methane and ozone are the main greenhouse gases. Some human-made greenhouse gases, such as the halocarbons and other chlorine- and bromine-containing substances, are dealt with under the Montreal Protocol 1.

Gridded data – see also Reanalysis: A set of climate data that are given for the same time or average period on a regular grid in space. Data at each grid point represent the average value over a grid box whose size is determined by the spacing between the grid points (also called the grid resolution). Global climate model and reanalysis data are produced as gridded data.

H

Hazard: The potential occurrence of a physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. See also Exposure, Risk and Vulnerability 1.

Homogenisation: Observed climate variables sometimes show sudden shifts in the average values or variability. Not all of these shifts are caused by real changes in climate. Non-climate related shifts can be due to changes in instrumentation, observation site, surrounding environment and observation practices, or other factors. Climate data homogenisation aims to adjust data if necessary, so that all variations in the data series are caused by real changes in the climate, and not due to changes in the way the data have been recorded.

I

Impact: The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards, exposure and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, socio-economic and cultural assets, services and infrastructure. Impacts may be adverse or beneficial 1.

Interdecadal Pacific Oscillation (IPO) – see also Pacific Decadal Oscillation (PDO): The Interdecadal Pacific Oscillation (IPO) is a natural recurring pattern of variability in tropical Pacific Ocean sea-surface temperatures occurring on periods of about 15 years and longer. While defined differently the IPO and PDO (Pacific Decadal Oscillation) describe essentially the same variability. The Interdecadal Pacific Oscillation (IPO) Index is a measure of the strength and phase of the Interdecadal Pacific Oscillation pattern.

Intertropical Convergence Zone: The Intertropical Convergence Zone (ITCZ) is a persistent east-west band of converging low-level winds, cloudiness and rainfall stretching across the Pacific just north of the equator. It affects most countries across the tropical North Pacific, being strongest in the Northern Hemisphere summer/wet season (April to October). The ITCZ tends to move towards the equator in El Niño years and to the north in La Niña years, affecting rainfall in northern tropical Pacific countries 2.

L

La Niña – see also El Niño, El Niño–Southern Oscillation: The most common of several names given to cold phase of the El Niño–Southern Oscillation. La Niña is the counterpart to the El Niño warm event, although La Niña events tend to be somewhat less regular in their behaviour and duration. La Niña is associated with large-scale cooling of the surface waters of the eastern tropical Pacific Ocean and a strengthening of the Walker Circulation.

Likelihood: The chance of a specific outcome occurring, often expressed as a percentage probability.

M

Marine Heat Wave (MHW): Marine heatwaves are defined as discrete, anomalously warm water events which last for five or more days, with SSTs warmer than the 90th percentile relative to climatological values.

Mean sea level – see also Sea level change/rise: Mean sea level is normally defined as the average relative sea level over a period, such as a month or a year, long enough to average out transients such as waves and tides.

Marine heatwave: Marine heatwaves (MHWs) are a "discrete, prolonged anomalously warm water event" which lasts for five or more days, with temperatures warmer than the 90th percentile. MHW events were defined by their duration (number of days above the 90th percentile threshold), maximum intensity (maximum temperature above the climatological mean attained during the event), mean intensity, and cumulative intensity (sum of the daily intensities through the duration of the MHW event occurrence; Hobday et al. 2016). MHWs are categorised into four intensity categories, defined by multiples of difference between the mean climatology and the 90th percentile threshold, and includes "Moderate" (Category I, 1-2x), "Strong" (Category II, 2-3x), "Severe" (Category III, 3–4×), and "Extreme" (Category IV, >4x) (Hobday et al. 2018).

Methane: CH_4, One of the six greenhouse gases to be mitigated under the Kyoto Protocol. It is the major component of natural gas and associated with all hydrocarbon fuels. Significant emissions stem from animal husbandry and agriculture.

N

Nitrous oxide: N_2O, One of the six greenhouse gases to be mitigated under the Kyoto Protocol. The main source is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, fossil fuel combustion, and chemical industrial processes. It is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests.

Ocean acidification – see also Aragonite saturation state, pH: A reduction in the pH of the ocean, accompanied by other chemical changes (primarily in the levels of carbonate and bicarbonate ions), over decades or longer, which is caused primarily by uptake of carbon dioxide (CO2) from the atmosphere.

Optimum Interpolation Sea Surface Temperature v2-1 dataset (OISST): The NOAA 1/4° Daily Optimum Interpolation Sea Surface Temperature (OISST) is a long-term Climate Data Record that incorporates observations from different platforms (satellites, ships, buoys, and Argo floats) into a regular global grid. The dataset is interpolated to fill gaps on the grid and create a spatially complete map of sea surface temperature. Satellite and ship observations are referenced to buoys to compensate for platform differences and sensor biases. (https://www.ncei.noaa.gov/products/optimum-interpolation-sst)

P

Pacific Decadal Oscillation (PDO): A naturally recurring pattern of variability in the tropical and northern Pacific characterised by warming and cooling sea-surface temperature, similar to that of ENSO, although broader in a north-south direction. Oscillations in the PDO take multiple decades usually 20–30 years.

Paris Agreement: The Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 2015 by 196 countries. One of the goals of the Paris Agreement is

‘Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels’, recognising that this would significantly reduce the risks and impacts of climate change. Additionally, the Agreement aims to strengthen the ability of countries to deal with the impacts of climate change.

Percentiles: When data values are sorted in ascending order, percentiles can be calculated. For example, half the values will be larger than the 50th percentile, 10 % will be larger than the 90th percentile and 90 % will be larger than the 10th percentile. Percentiles are often used to estimate the extremes of a data distribution 1.

pH– see also Aragonite saturation state, Ocean Acidification: A measure of the acidity or alkalinity of a solution, numerically equal to 7 for neutral solutions, increasing with increasing alkalinity and decreasing with increasing acidity. The pH scale ranges from 0 to 14.

R

Reanalysis – see also Gridded data: An analysis combining many irregular meteorological or oceanographic observations from close to the same time into a physically consistent, complete gridded data set for a given time and usually for the whole globe.

Relative sea level: Sea level measured by a tide gauge with respect to the land upon which it is situated.

Relative sea-level rise – see also Mean sea level, Sea level change/rise: Relative sea level rise occurs where there is a local increase in the level of the ocean relative to the land, which might be due to ocean rise and/or land level subsidence.

Representative Concentration Pathways (RCPs): Time series of emissions and concentrations of the full suite of greenhouse gases and aerosols and chemically active gases, as well as land use/land cover. Each RCP provides only one of many possible pathways that would lead to the specific radiative forcing characteristics 1. RCPs were used in CMIP5 climate models to develop climate projections (also see Shared Socio-economic Pathways).

- RCP2.6: a low emissions pathway where radiative forcing reaches 2.6 W/m2 in 2100 with 0.9-2.4°C global warming by 2081-2100, relative to 1850-1900.
- RCP4.5: a medium emissions pathway where radiative forcing reaches 4.5 W/m2 in 2100, with 1.7-3.3°C global warming by 2081-2100, relative to 1850-1900.
- RCP8.5: a high emissions pathway where radiative forcing reaches 8.5 W/m2 in 2100, with 3.2-5.4°C global warming by 2081-2100, relative to 1850-1900 3.

Risk – see also Exposure and Vulnerability: The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. Relevant adverse consequences include those on lives, livelihoods, health and wellbeing, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems, and species. Risks result from interactions between climate-related hazards with the exposure and vulnerability of the affected system 1. See also Hazard, Exposure and Vulnerability.

S

Sea level change/rise – see also Mean sea level, Relative sea-level rise, Thermal expansion: Sea level can change, both globally and locally, due to; (1) changes in the shape of the ocean basins; (2) changes in the total mass of water and, (3) changes in water density. Factors leading to sea level rise under global warming include both increases in the total mass of water from the melting of land-based snow and ice, and changes in water density from an increase in ocean water temperatures and salinity changes.

Sea-surface temperature: The temperature of the ocean surface. The term sea-surface temperature is generally representative of the upper few metres of the ocean as opposed to the skin temperature, which is the temperature of the upper few centimetres.

Shared socio-economic pathways (SSPs): Shared socio-economic pathways (SSPs) have been developed to complement the Representative Concentration Pathways (RCPs). The SSP-RCP framework is now widely used in the climate impact and policy analysis literature. Climate projections obtained under the RCP scenarios are analysed against the backdrop of five socio-economic pathways denoted SSP1 to SSP5, including sustainable development, regional rivalry, inequality, fossil-fueled development, and middle-of-the-road development1. The abbreviations SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 denote the main SSP-RCP combinations used in the IPCC Sixth Assessment Report.

South Pacific Convergence Zone: The South Pacific Convergence Zone (SPCZ) is a diagonal band of intense rainfall and deep atmospheric convection extending from the equator to the subtropical South Pacific. Movement of the SPCZ causes variability in rainfall, tropical-cyclone activity and sea level that affects South Pacific island populations and surrounding ecosystems 4.

Standardised Precipitation Index: Indicators commonly employed for declaring drought include the Standardised Precipitation Index (SPI). The concept which underpins the SPI is that it allows quite different rainfall regimes to be expressed in relative terms, i.e. drier than usual relative to what is expected at the time of year for the particular location, by expressing the rainfall anomaly as a standard deviation.

Storm surge: The temporary increased height of the sea above the level expected from tidal variation alone at that time and place due to extreme meteorological conditions.

T

Thermal Expansion – see also Sea level change/rise, Mean sea level: The increase in volume (and decrease in density) that results from warming water.

Time-series: The values of a variable generated successively in time. Graphically, a time series is usually plotted with time on the horizontal axis (x-axis), and the values of the variable on the vertical axis (y-axis).

Trade winds: The wind system, occupying most of the tropics that blow from the subtropical high pressure areas toward the equator.

Traditional Knowledge: The understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings. For many indigenous peoples, this knowledge informs decision-making about fundamental aspects of life, from day-to-day activities to longer-term actions. This Traditional Knowledge (TK) is integral to cultural complexes, which also encompass language, systems of classification, resource use practices, social interactions, values, ritual and spirituality 1. The TK informs weather and climate predictions based on the behaviour of plants and animals, temperature and rainfall, and astronomical indicators such as stars and the sun.

Tropical cyclone: A tropical cyclone is a tropical depression of sufficient intensity to produce sustained gale force winds (at least 63 km per hour). A severe tropical cyclone produces sustained hurricane force winds (at least 118 km per hour). Severe tropical cyclones correspond to the hurricanes or typhoons of other parts of the world.

U

Uncertainty: A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable1. For a given climate variable, the uncertainty range is typically expressed as the 10-90th percentile range of values simulated by an ensemble of climate models. For example, in an ensemble of 40 climate models, the 10th percentile is the 4th lowest value and the 90th percentile is the 4th highest value.

V

Vulnerability – see also Exposure and Risk: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm, and lack of capacity to cope and adapt 1.

W

Walker Circulation: The Walker Circulation is the east-west circulation of air, oriented along the Equator, across the Pacific region.

West Pacific Monsoon: A monsoon is a tropical and subtropical seasonal reversal of both surface winds and associated rainfall, caused by differential heating between a continental scale land mass and the adjacent ocean. The Western Pacific Monsoon is the eastern edge of the Indonesian or Maritime Continent Monsoon, and the southern extension of the larger Asian-Australian Monsoon system.

Weather: The state of the atmosphere at a specific time. It is usually expressed in terms of sunshine, cloudiness, humidity, rainfall, temperature, wind, and visibility.