Assessment of climate hazards and sectoral impacts for Nauru under current and future conditions

TECHNICAL REPORT

CSIRO
SPREP
Secretariat of the Pacific Regional Environment Programme
GREEN CLIMATE FUND

Assessment of climate hazards and sectoral impacts for Nauru under current and future conditions

Citation: CSIRO, Federation University, Climate Comms (2024). Assessment of climate hazards and sectoral impacts for Nauru under current and future conditions. Technical report prepared for the Secretariat of the Pacific Regional Environment Programme (SPREP) and Government of Nauru as part of the Green Climate Fund supported *Republic of Nauru National Adaptation Planning – Phase One* project, Melbourne, Australia. DOI: https://doi.org/10.25919/wmf3-gg04

The authors and contributors to the report are as follows:

Leanne Webb (lead), Toni Cannard, Anil Deo, Rebecca Gregory, Bryan Hally, Malcolm King, and Marian Sheppard (CSIRO)

Kevin Hennessy (Climate Comms)

Savin Chand, Soubhik Biswas, Krishneel Sharma (Federation University)

Garrik Akken (Nauru Department Climate Change and National Resilience)

Acknowledgements: The authors express their gratitude to the Government and people of Nauru for their valuable contributions and support. The authors also thank Thomas Moore (CSIRO) for technical assistance with the ocean acidification aspects of the report, Kathy McInnes (CSIRO) and Alexei Trundle (University of Melbourne) for their technical review of this report, and David Rissik (Deloitte) for providing additional helpful comments.

Nauru climate hazards technical report

Executive Summary i

Chapter 1 Introduction 1

Section 1: PAST, PRESENT AND FUTURE CLIMATE 9

Chapter 2 Data, confidence, limitations and uncertainties 10

Chapter 3 Average temperature 20

Chapter 4 Extreme temperature 23

Chapter 5 Average annual and seasonal rainfall 26

Chapter 6 Extreme rainfall events 30

Chapter 7 Drought 34

Chapter 8 Average and extreme winds 45

Chapter 9 Sea level rise and coastal inundation 57

Chapter 10 Ocean warming 75

Chapter 11 Ocean acidification 92

Section 2 HAZARD-BASED IMPACTS AND RATINGS FOR SECTORS 98

Chapter 12 Water resources 99

Chapter 13 Health and wellbeing 107

Chapter 14 Agriculture 114

Chapter 15 Fisheries and marine resources 120

Chapter 16 Disaster management 129

Chapter 17 Coastal protection and infrastructure 134

Chapter 18 Biodiversity and environment 156

Chapter 19 Land management and rehabilitation 162

Chapter 20 Community and culture 167

Chapter 21 Climate hazard ratings 176

Chapter 22 Knowledge gaps and research priorities 183

Chapter 23 Glossary 188

Executive Summary

Context

Nauru is an isolated, uplifted limestone island located 60 km south of the equator. The landmass of the island is only 21.1 km^2, with a circumference of 19 km, and is divided into 14 districts. Nauru's marine area (Exclusive Economic Zone) extends to 309,261 km^2.

The population of 11,680 (in 2021) reside mainly on the lower, narrow (100 to 400 metres wide) coastal plain (0 to 10 m above sea level). The highest point is 70 metres above sea level, on the central plateau. Due to phosphate mining, about 80 % of the island is deemed uninhabitable.

The purpose of this report is to assess the climate hazards affecting Nauru over recent and future decades, with a focus on nine priority sectors: water, health, agriculture, fisheries, disaster management, infrastructure and coastal protection (including energy), biodiversity, human and community development, and land rehabilitation and management. This assessment, along with a separate assessment of exposure and vulnerability, provides science-based evidence to inform an integrated Climate Impact, Vulnerability and Risk Assessment (CIVRA) as part of the development of a Republic of Nauru National Adaptation Planning (NAP) – Phase One funded by the Green Climate Fund (GCF). The key audience for this report is the Secretariat of the Pacific Regional Environment Programme (SPREP), as the designated GCF-Delivery Partner for the Republic of Nauru NAP project, and the Government of Nauru through the mechanism of the Republic of Nauru NAP Country Team. The report also has broader utility for other key stakeholders that require a better understanding of Nauru's recent and future climate.

Climate averages

Nauru's climate is tropical, with minimum temperatures around 25 °C and maximum temperatures around 31 °C. The monthly-average sea surface temperature (SST) at the Nauru tide gauge is 28.6 °C. Annually averaged, there are 15 days per year over 32 °C and 16 marine heatwave days.

The wet season is from December to April (over 200 mm/month) and the dry season is from May to November (below 150 mm/month). Annual-average rainfall is about 2100 mm. The annual-average maximum daily rainfall is 105 mm. Being close to the equator means there are no tropical cyclones. An average of three moderate drought events occur every 20 years, i.e. 1.5 per decade.

Climate variability

Climate variability on daily, monthly and yearly timescales affects the frequency, intensity and duration of heatwaves, droughts, floods, winds, waves, storm surges and ocean swells. Variability in the western tropical Pacific is significantly influenced by a large-scale ocean-atmosphere circulation called the El Niño Southern Oscillation (ENSO). SST northeast of Nauru 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. These SST anomalies affect 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 Nauru gets more rainfall. During La Niña events, the SPCZ tends to move south-west, so Nauru gets less rainfall. 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
Sea surface temperature	Cooler	Warmer

Sea level	Lower	Higher

Climate trends

Increases in greenhouse gas concentrations are causing global climate change. In Nauru, this has contributed to changes in temperature, rainfall, sea level and ocean chemistry.

During 1979 to 2021, minimum temperatures increased by 0.17 °C per decade, maximum temperatures increased by 0.19 °C per decade, the number of hot days[1] increased by 22 days per decade, and sea surface temperatures increased by 0.22 °C per decade. While annual maximum 1-day rainfall has been increasing, there has been no significant trend in annual rainfall or drought.

From the 1980s to 2000s, the average duration of marine heat waves (MHWs) in the south-west Pacific was 5–16 days. This increased in the 2010s to 8–20 days. Oceanic pH measurements since 1988 at Station ALOHA near Hawaiʻi show that the ocean became 12 % more acidic, due to higher atmospheric concentrations of carbon dioxide being sequestered by the ocean. Sea level has been rising around Nauru at an average rate of 3.5–4.5 mm/year since 1993.

Climate projections

Projected changes in climate have been estimated over the coming decades for low and high greenhouse gas emissions pathways based on simulations from climate models (see Chapter 2). These changes are summarised in Figure 0-1 with more detail in Table 0-1.

Figure 0-1 Climate change projections for Nauru. Photo credit: CSIRO, 2024.

Annual-average temperature is projected to increase 0.7 °C by 2030 regardless of the emissions pathway, relative to the average for 1995–2014. By 2050, the warming is 1.0 °C for low emissions and 1.5 °C for high emissions. By 2090, the warming is 1.1 °C for low emissions and 3.5 °C for high emissions. This means more extremely hot days.

---

[1] days with maximum temperatures above the 90th percentile for 1981-2010.

Annual-average rainfall is projected to increase 11 % by 2030 relative to the 1995–2014 average. By 2050, the projected increase is 32 % for low emissions and 24 % for high emissions. Drought intensity, frequency and duration are projected to decrease.

Extreme daily rainfall events are projected to become more intense. By 2050, annual maximum daily rainfall may increase by 48 mm/day (43 %) for low emissions and 54 mm/day (52 %) for high emissions. The average return period between extreme rainfall events is projected to become shorter (more frequent). For example, a 200 mm/day event with a return period of 28 years during 1970–2000 may have a return period of 6 years for low emissions and 2 years for high emissions during 2070–2100.

Storm surges and swell waves from remotely occurring cyclones can influence coastal inundation. Cyclones passing through the 500 km zone around Nauru are projected to become less frequent but more intense in future.

Sea level is projected to rise 0.10 m by 2030 compared to 1995–2014. By 2050, the rise is 0.21 m for low emissions and 0.25 m for high emissions. By 2090, the rise is 0.45 m for low emissions and 0.69 m for high emissions.

The average number of MHW days is projected to increase from 16 days per year during 1995–2014 to 105-140 days per year by 2050 for low emissions and 180-270 days per year by 2050 for high emissions. There is a large increase in ‘Strong’ and ‘Severe’ MHW days, with implications for coral bleaching.

Ocean acidification is projected to continue. By 2050, ocean pH is projected to decline 0.05 units for low emissions and 0.12 units for high emissions. Related to pH, aragonite saturation states may fall below 3 by 2060 under high emissions, a level where coral reefs may not only stop growing but start to get smaller because they dissolve faster than they are built. However, under a low emissions scenario, the aragonite saturation state may start to recover after 2060.

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

Confidence, limitations and uncertainties

Confidence ratings are provided for most climate projections. 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.

Limitations are highlighted throughout this report. For example, climate projections over the next decade are strongly influenced by natural variability, which is hard to predict. Projections beyond the next decade are affected by different emissions scenarios, which depend on assumptions about population change, economic development, technological advances and land-use change. The CMIP6 models used in this assessment have coarse resolution (100-200 km between data points) which 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.

Uncertainties are quantified where possible. The median (50th percentile) change is usually given along with an uncertainty estimate, often defined by the 10-90th 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 Northern Hemisphere permafrost, collapse of the overturning circulation in the north Atlantic Ocean, and rapid disintegration of the Greenland and Antarctic ice sheets.

A summary of Nauru's historical and projected climate is described in Table 0-1.

Impacts and hazard ratings

This assessment is focussed on climate hazards impacting nine sectors, closely aligned with priority sectors in the Nauru Framework for Climate Change Adaptation and Disaster Risk Reduction (RONAdapt, 2015):

1. Water resources
2. Health and wellbeing
3. Agriculture
4. Fisheries and marine resources
5. Disaster management and emergency response
6. Infrastructure and coastal protection (including coastal assets and flood defences, buildings and structures, health and fisheries infrastructure, energy, telecommunications, transport and supply chains, and waste management)
7. Biodiversity and environment
8. Land management and rehabilitation
9. Community and culture

These sectors are interconnected, so in practice there can be cascading and compounding impacts across multiple sectors. A review of sectoral impacts is provided in Section 2 and summarised in Table 0-2.

Table 0-1 Historical climate averages (20-years centred on 2005) are given in the first column. Projected climate change for 20-year periods centred on 2030 and 2050, relative to a 20-year period centred on 2005, are given in the last four columns. Changes are based on simulations from CMIP6 global climate models for low (SSP1-2.6) and high (SSP5-8.5) greenhouse gas emissions scenarios. Uncertainty estimates (in brackets) are based on the 10-90th percentile range. For some variables, the Nauru Exclusive Economic Zone (EEZ) region is assessed, rather than the island, as indicated. Confidence ratings are based on the IPCC framework involving an assessment of the amount of evidence and the degree of agreement between lines of evidence. Drought projections are for SPI 3-month between –1.0 and –1.5 (moderate drought).

Nauru		Projected change			
20-years centred on 2005		2030 Low/High Emissions*	2050 Low emissions	2050 High emissions	Confidence
	ATMOSPHERIC VARIABLES				
28.0 °C	Annual average temperature (°C)	+0.7 (0.3-1.3)	+1.0 (0.9-1.2)	+1.5 (1.2-2.0)	high
15 (6 to 34) days	Annual hot days (days > 32 °C) [a]	N/A	+120 (44 to 169)	+193 (69 to 242)	high
2100 mm	Annual average rainfall (%)	+11 (-19 to 39)	+13 (-1 to +52)	+24 (-6 to +63)	medium
105 mm/day	Annual maximum daily rainfall (mm/day)	N/A	+48	+54	medium
3 (0 to 5) events per 20 years	Average drought frequency (%) [d]	-33 (-77 to +100) %	-33 (-77 to +67) %	0 (-73 to +107) %	medium
	OCEAN VARIABLES				
0	Annual average sea level (cm)	+10 (7-14)	+21 (15-28)	+25 (19-33)	high
28.6 °C	Sea surface temperature (°C) over EEZ	+0.2 (-1.5 to +1.6)	+0.5 (-1.2 to +2.0)	+1.0 (-0.9 to +2.3)	high
16 days per year	Marine heatwave frequency (days/year) [b]	N/A	+105 to 140	+180 to 270	high
6.3 days per year	Degree heating weeks (ave days per year) [c]	N/A	+92 to 236	+107 to 344	high
8.04	Annual average ocean pH over EEZ[e]	8.00 (7.96 to 8.05)	7.97 (7.92 to 8.02)	7.92 (7.87 to 7.98)	high
3.8	Annual average aragonite saturation[e]	~3.7 (3.3 to 4.0)	3.5 (3.1 to 3.98)	3.2 (2.8 to 3.7)	high

[a] number of days over the 95th percentile of 1995-2014 daily temperatures

[b] Future values are reported, not changes.

[c] Exceed coral bleaching Alert level 2.

[d] Further information on projections for drought intensity, frequency and duration can be found in Chapter 7

[e] Future values shown, not changes compared to historical.

* Little difference between low and high emissions at 2030

Table 0-2 Climate hazards affecting sectors in Nauru based on RONAdapt priority areas Water, Health, Agriculture, Fisheries & marine resources, Disaster management, Energy, Land management & rehabilitation, Infrastructure and coastal protection (includes telecommunication and transport), Biodiversity, Education & human/community development.

Hazard	Water	Health and wellbeing	Agriculture	Fisheries & marine resources	Disaster Management and Emergency Response	Infrastructure and coastal protection (includes energy, transport, telecommunication and waste management)	Land management and rehabilitation	Biodiversity and environment	Community and culture
Extreme temperature	Increased water demand and evaporation. Reduced efficiency in desalination plant operations.	Increased heat stress and reduced labour productivity for outdoor workers and vulnerable people. Increased enteric infections. Mental health disorders. If blackouts occur, there may be inadequate cooling and impact critical health services, particularly during surgery. Surges caused in blackouts can damage medical equipment. Reduced opportunity and incentive for outdoor exercise with cascading impacts on efforts to reduce NCDs.	Animal and crop suitability/ stress. Reduced labour productivity.	Fish refrigeration and storage.	Blackouts can cause cascading and compounding impacts across multiple sectors	Road and runway integrity affected. Heat stress reduces labour productivity (e.g. airport and road crews). Disruption to telecommunications due to heat-related blackouts. Increased energy demand for air conditioning and fans. Greater risk of blackouts.	Slower progress due to reduced labour productivity.	Heat stress and mortality for some animals and plants. Warmer sand temperature can affect gender ratios for turtle hatchlings.	Heat stress for trainees and students. Success of kitchen gardens compromised by heat. Reduced labour productivity in communities. Increasing temperatures reduce community movements during the middle of the day and increase reliance on car transport to avoid exposure.
Extreme rainfall	Poor water quality due to high sediment and pollution load in streams. Filling of water-tanks means reduced reliance on desalinated water. Damaged storage, treatment and drainage systems	Flood-related damage to main hospital and disruption to health services. Water-borne diseases (rotavirus in children) from overflow of septic tanks. Trauma and mental health disorders. Reduced ground water quality. Improved access to tank water for WASH. Increased hospital admissions due to asthma placing increased pressure on health services.	Reduced access to crops and farms. Flood damage.	Increased pollution and sediment entering coastal waters can harm coastal fisheries and coral reefs	Flood damage and disruption to property and infrastructure. Poor water quality. High demand for emergency response and recovery services. Major impacts on the economy. Reliance on international aid.	Flooding damage to roads, bridges and runway. Road integrity affected by potholes (top side and private land). Disruption to port operations due to low visibility. Sediment and debris in drainage systems Communication systems direct damage or capacity overload during flood disasters Flood-related damage to energy infrastructure. Cloudiness reducing the effectiveness of solar panels.	Flood damage to land rehabilitation sites. Changes in flood risk have implications for land management (e.g. flood zones).	Increased pollution and sediment entering Buada Lake, streams and coastal waters. Indigenous plants regrow following periods of rainfall	Transport disruption for trainees and students. Flood-related damage to energy infrastructure.

Drought	Increased demand for desalinated water increasing pressure on delivery trucks. Greater use of poor-quality groundwater. Reduced availability of fresh food sources and increased reliance on imported processed food.	Increased use of poor-quality ground water.	Limited water for crops and livestock. Reduction in free food sources and mortality of important cultural foods. Increased reliance on imported food sources.		Fewer flood-related demands for disaster management. Increased risk of fires and greater reliance on desalinated water to extinguish fires	Fibre cable and power pole cross arms affected by accumulated salt spray, causing blackouts. Communications support structures can rust. Extra power needed to run desalination plant.	Less rain interruption to land rehabilitation. Increased mortality rate of seedlings. Increased dust from rehabilitation works and secondary mining.	Water stress for plants and animals.	Stress and die back of cultural plants (pandanus). Success of kitchen gardens affected by water availability and cost of desalinated water. Schools close due to lack of water
Sea level rise and coastal inundation	Contamination of freshwater lens. Greater demand for desalinated water. Damage to water infrastructure.	Damage to hospitals and health services located in low-lying coastal areas. Increased distribution and transmission of vector-borne disease, threats to physical safety, and mental stress.	Inundation of crops.	Increased coastal erosion affects ports/boat moorings.	Saltwater damage to property and infrastructure, especially at spring and king tides. High demand for emergency response and recovery services. Major impacts on the economy. Warnings for communities not to swim at beaches during high spring tides.	Inundation affecting roads. Coastal erosion undermining roads. Damage to telecommunication infrastructure. Greater energy demand for desalinated water due to saltwater contamination of freshwater lens.	Disruption and damage to rehabilitation areas due to inundation and erosion.	Habitat damage. Traditional plant (Emit shrub) used to stabilise coast during high tides may become inundated.	Disruption for trainees and people at school or university, especially at spring and king tides.
Ocean temperature and marine heatwave				Good tuna fishing grounds could be displaced further eastward. Decrease in coral fish biomass. Algal blooms can cause fish deaths.	Fish kills			Reduced biodiversity. Coral bleaching and stress for invertebrate species.	
Ocean pH				Coral integrity. Invertebrate species may have poor shell / skeleton formation. Algae growth.				Reduced biodiversity	
Aragonite saturation				Coral, plankton, shellfish, and fish skeletons' integrity reduced.					

Based on an assessment of climate hazards, exposure, vulnerability and related impacts experienced in Nauru, each hazard has been assigned a rating for the current climate and future climate scenarios (Chapter 21 and Table 0-3). For example, drought has a current rating of high and a future rating of medium by 2050. Extreme sea level has a current rating of medium and a future rating of medium for low emissions and high for high emissions by 2050. The impact ratings also increase for marine heatwaves and extreme rainfall. The future ratings do not explicitly consider sectoral/system interdependencies. However, such interdependencies are considered in the CIVRA integrated risk ratings (Deloitte, 2024).

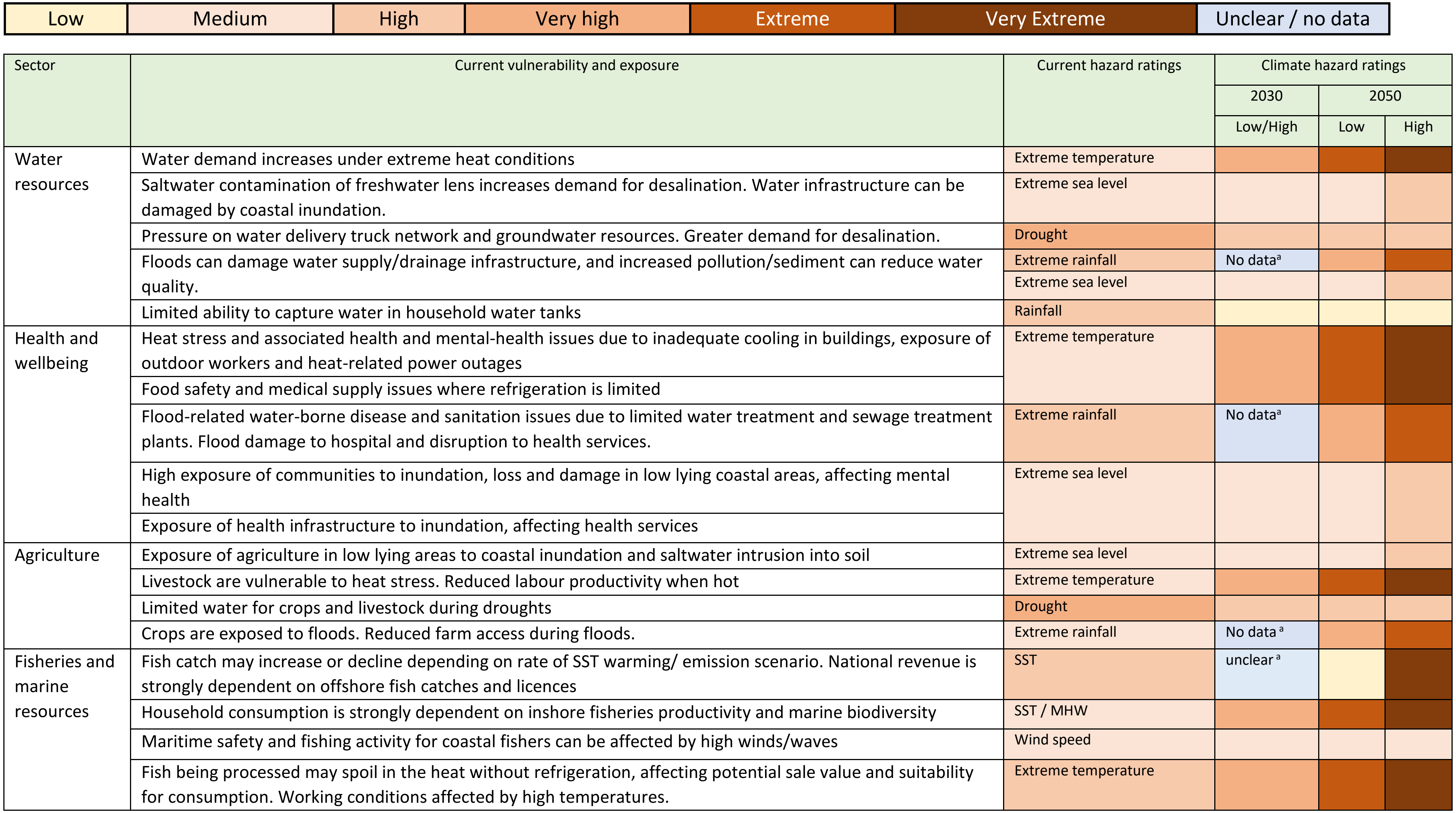
Knowledge gaps and research priorities

This assessment is mostly based on readily accessible data that are scientifically robust, supplemented by anecdotal information that is appropriately validated through stakeholder engagement. Therefore, the assessment provides a compelling evidence base to inform the CIVRA integrated risk assessment and associated NAP for Nauru. However, it has also revealed some knowledge gaps and informed the following list of research priorities for future reference and planning:

- Enhanced monitoring of climate variability and change, including causes of trends and extreme events.
- Better information about historical links between climate hazards, exposure, vulnerability and impacts, e.g. for heat-related impacts on health and electricity demand. This would inform 'damage functions' that can be used in risk assessments and associated ‘loss and damage’ negotiations.
- Consider recording heat stress related hospital admissions.
- Better information about the effect of phosphate dust on population health.
- Better information about insect/pollinator capacity to assist with agricultural production.
- Assess impacts on coastal fishery ecosystems using clearly defined reference points to better understand current health and future sustainability.
- Assess how Buada Lagoon, and other groundwater/lagoon levels around the coastal plain, are linked to sea level variability and respond to sea level rise.
- Assess potential flooding of the airport due to the compounding effects of wave over-washing, coastal defence design, the capacity of the airport drainage system, infiltration rates, coinciding heavy rainfall and high groundwater levels.
- Further analysis of a larger sample of CMIP6 climate models with low biases, especially SST and ENSO biases in the Pacific.
- Dynamical and statistical downscaling of CMIP6 climate models over the western tropical Pacific to improve regional and local climate projections.
- Better data for extreme weather events, e.g. wave and wind monitoring.
- Reduced uncertainty about potential tipping points.
- Improved guidance about emission pathway likelihoods.
- Co-design and co-develop products and services to support the uptake of climate change information in policy development, planning, capacity development and decision-making.

There is an opportunity to address these issues at a regional level 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 0-3 Climate hazard assessment for Nauru, based on current and future climate hazards (Table 0-1) for 2030 (when low and high emissions pathways are similar) and 2050 (when low and high emissions pathways are different), noting current vulnerability and exposure (described in Chapter 2 of this report). The nine sectors reflect the 11 Priority Areas in the RONAdapt. 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 / no data

Sector	Current vulnerability and exposure	Current hazard ratings	Climate hazard ratings		
			2030	2050	
			Low/High	Low	High
Water resources	Water demand increases under extreme heat conditions	Extreme temperature			
	Saltwater contamination of freshwater lens increases demand for desalination. Water infrastructure can be damaged by coastal inundation.	Extreme sea level			
	Pressure on water delivery truck network and groundwater resources. Greater demand for desalination.	Drought			
	Floods can damage water supply/drainage infrastructure, and increased pollution/sediment can reduce water quality.	Extreme rainfall	No data[a]		
		Extreme sea level			
	Limited ability to capture water in household water tanks	Rainfall			
Health and wellbeing	Heat stress and associated health and mental-health issues due to inadequate cooling in buildings, exposure of outdoor workers and heat-related power outages	Extreme temperature			
	Food safety and medical supply issues where refrigeration is limited				
	Flood-related water-borne disease and sanitation issues due to limited water treatment and sewage treatment plants. Flood damage to hospital and disruption to health services.	Extreme rainfall	No data[a]		
	High exposure of communities to inundation, loss and damage in low lying coastal areas, affecting mental health	Extreme sea level			
	Exposure of health infrastructure to inundation, affecting health services				
Agriculture	Exposure of agriculture in low lying areas to coastal inundation and saltwater intrusion into soil	Extreme sea level			
	Livestock are vulnerable to heat stress. Reduced labour productivity when hot	Extreme temperature			
	Limited water for crops and livestock during droughts	Drought			
	Crops are exposed to floods. Reduced farm access during floods.	Extreme rainfall	No data [a]		
Fisheries and marine resources	Fish catch may increase or decline depending on rate of SST warming/ emission scenario. National revenue is strongly dependent on offshore fish catches and licences	SST	unclear [a]		
	Household consumption is strongly dependent on inshore fisheries productivity and marine biodiversity	SST / MHW			
	Maritime safety and fishing activity for coastal fishers can be affected by high winds/waves	Wind speed			
	Fish being processed may spoil in the heat without refrigeration, affecting potential sale value and suitability for consumption. Working conditions affected by high temperatures.	Extreme temperature			

	Pollution and sediments degrade coastal water quality	Extreme rainfall	No data[a]		
Disaster management and emergency response	Lack of property protection from extreme sea level and extreme rainfall elevates disaster risk	Extreme sea level			
		Extreme rainfall	No data[a]		
	Blackouts can cause cascading and compounding impacts across multiple sectors which increase demand for emergency services	Extreme temperature			
	Increased risk of fire, resulting in the requirement for increased firefighting capacity. As there is limited water storage on Nauru, firefighting capacity is also limited.				
	Exposure to coastal inundation in low lying areas affects essential infrastructure	Extreme sea level			
	Flood damage to roads, airport, water, energy and telecommunication facilities can disrupt emergency services	Extreme rainfall	No data[a]		
Infrastructure and coastal protection	Roads and airport runway are exposed to coastal inundation/erosion, flooding and heat-related deterioration. Flooding may cause increased runoff/pollution to the sea	Extreme sea level			
		Extreme rainfall	No data[a]		
		Extreme temperature			
	Telecommunication, building and coastal protection and electricity assets subject to surface flooding, coastal inundation, and groundwater intrusion	Extreme rainfall	No data[a]		
		Extreme sea level			
	Increased energy demand and blackout risk on hot days	Extreme temperature			
	Salt spray may affect transmission wires	Drought			
		Wind speed			
Biodiversity and environment	Heat stress for some animals and plants. Sea turtle gender affected by sand temperature.	Extreme temperature			
	Declining health of coastal marine habitat such as coral reefs and lagoons	MHW and ocean acidification			
Land rehabilitation and land management	Rehabilitation areas are exposed to coastal inundation and erosion	Extreme sea level			
	Workers and community are vulnerable to heat stress	Extreme temperature			
	Rehabilitation sites may be susceptible to flood damage	Extreme rainfall	No data[a]		
	Lack of access to water for building construction	Drought			
Community and culture	Reduced labour productivity in hot conditions	Extreme temperature			
	Rehabilitation sites may be susceptible to flood damage	Extreme rainfall	No data[a]		
	Population and gardens are vulnerable to dry conditions and cost of desalinated water.	Drought			
	Disruption for people at school or university.	Extreme rainfall	No data[a]		
	Community disruption, especially at spring and king tides.	Extreme sea level			

[a] Unclear/no data’ refers to where no analysis was conducted for that climate variable (for the period 2030).

Chapter 1 Introduction

The purpose of this report is to assess the climate hazards affecting Nauru over recent and future decades, in particular as relates to nine priority sectors: water resources, health and wellbeing, agriculture, fisheries and marine resources, disaster management and emergency response, infrastructure and coastal protection, biodiversity and environment, land rehabilitation and management, and community and culture. This hazard assessment informs an integrated Climate Impact, Vulnerability and Risk Assessment (CIVRA) as part of the development of a National Adaptation Plan (NAP) for Nauru commissioned by the Green Climate Fund (GCF).

The report draws contextual information from a separate environmental scan of relevant 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. The report is also based on readily accessible data and information from peer-reviewed literature and/or anecdotal data and information that are deemed to be scientifically robust.

The key audience for this report is the Secretariat of the Pacific Regional Environment Programme (SPREP), as the designated GCF Delivery Partner for the Nauru NAP project, and the Government of Nauru through the mechanism of the Nauru NAP Country Team. It is however expected the report also has broader utility for other key stakeholders that might require better understanding of Nauru’s current and future climate.

Photo credit: CSIRO, 2024.

Background

Nauru is an isolated, uplifted limestone island located 60 km south of the equator [1] (Figure 1-1). The nearest island is Banaba (Ocean Island), 300 km due east, which is part of the Republic of Kiribati, with the main islands of Kiribati located a further 400 km to the east.

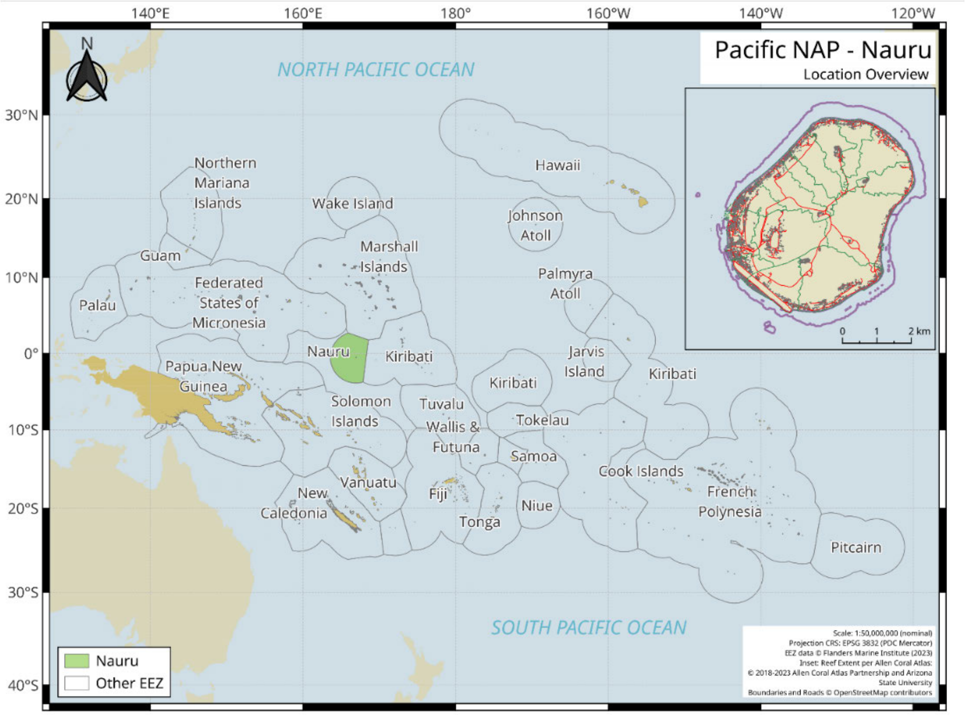


Figure 1-1 Nauru's Exclusive Economic Zone (EEZ) (green) and the surrounding western tropical Pacific EEZs (grey lines). Inset shows Nauru island with district boundaries in green, roads in red, buildings in brown and reef extent in purple. Map prepared by B. Hally, 2024 CSIRO.

Geomorphology and geography

The island of Nauru is divided into 14 administrative districts of varying sizes and populations (Figure 1-2). The total land area is only 21.1 km^2 (2200 ha). Nauru is six km long (from the north-east to the south-west) and four km wide (from the north-west to the south-east); and its circumference measures 19 km [1]. Even though the island is relatively small, Nauru has a large marine area (Exclusive Economic Zone) which extends to 309,261 km^2 [2].

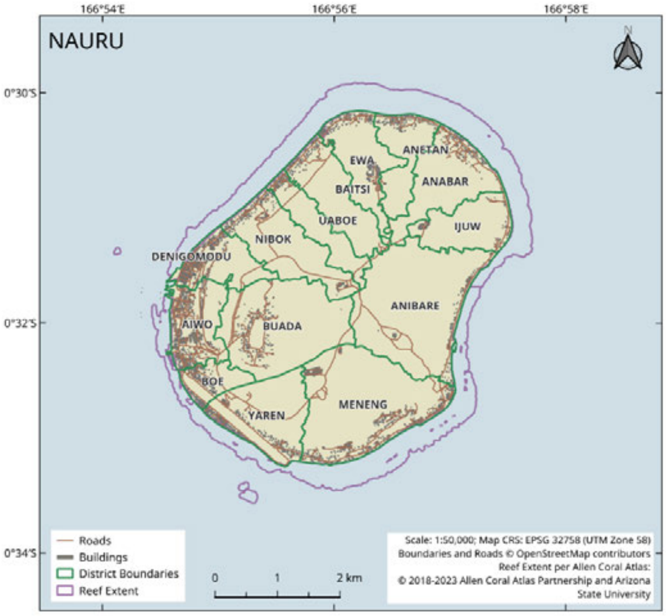


Figure 1-2 Nauru with district boundaries (green lines), roads and buildings (brown), and reef extent (purple) indicated.

The land area consists of a narrow coastal plain or Bottomside (0 to 10 m above sea level), ranging from 100 to 400 metres wide, encircled by a 100-300 m limestone/coral intertidal flat which drops away sharply on the seaward edge, to a depth of about 4,000 metres (Figure 1-3, left). The Bottomside area has a limestone escarpment rising 30 metres to a central plateau, known locally as Topside which ranges 20 to 45 m above sea level [3]. The surface of the raised atoll, which covers approximately 1600 ha (over 70 % of the island) [4], is characterised by limestone pinnacles with the depressions between these pinnacles filled with seabird deposited guano which has been mined for phosphate [5]. The pinnacle-and-pit relief varies between 2 and 10 metres from the top of the pinnacles to the bottom of the pits [4]. The highest point on the island, Command Ridge, is in the west and rises to an elevation of 70 m above sea level [3].

Scattered limestone outcrops or pinnacles can be found on both the coastal plain and on the inter-tidal flats of the fringing reef, with particularly good examples in the Anibare Bay area (Figure 1-3; middle). The escarpment ranges in gradient from vertical cliffs to gradually sloping areas of colluvial soil (deposits that accumulate on and at the base of slopes due to movement by gravity) interspersed with limestone outcrops and pinnacles ([4]; Figure 1-3, right).

Figure 1-3 Fringing reef at low tide (left). Fringing reef and protruding limestone pinnacles in Anibare Bay at mid-tide (middle). Limestone escarpment rising vertically to 'Topside' from grassy section of 'Bottomside' (right). Photo credit: CSIRO, 2024

The coastal plain was built up by wave action breaking down and transporting coral reef material from the fringing reef. This sand and other material is deposited by waves or wind and piled up between the reef and at the base of the escarpment [5]. The coastal plain is composed of a zone of sandy or rocky beach on the seaward edge, and a beach ridge or fore-dune. The height of the plain is a function of the wave exposure, with larger waves from the northwest creating a 7-8 m barrier, and smaller waves from the south, east and north shorelines creating a 4-6 m barrier [5]. Behind the coastal plain is either relatively flat ground or, in some places, low-lying depressions or small lagoons filled by brackish water where the surface level is below the water table (freshwater lens). The most extensive system of these landlocked lagoons is found near the border of Ijuw and Anibare Districts (Figure 1-4). Most of Nauru's population inhabit the coastal strip, with most assets, infrastructure and roads also on the plain [5].

Buada Lagoon is a landlocked, slightly brackish, freshwater lake, and its associated fertile depression (about 12 ha in area) is in the low-lying southwest-central portion of Topside at an elevation of about 5 metres above sea level (Figure 1-4).

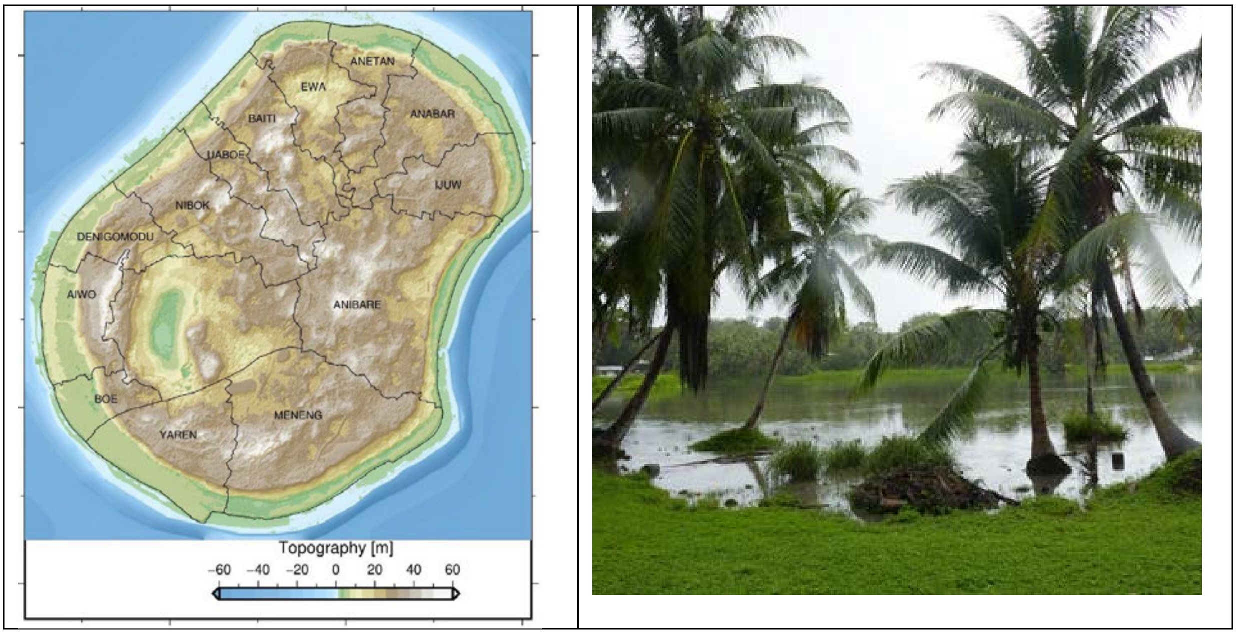


Figure 1-4 Map of the districts and seamless 5 m DEM of Nauru Island, including bathymetry. [Data source [6]](left). Buada lagoon (right). Photo credit (right): CSIRO, 2024.

Climate overview

Nauru is in a high rainfall zone. In the central tropical Pacific Ocean, easterly trade winds help to moderate the heat and humidity associated with the warm ocean close to the equator (Figure 1-5). Extreme weather events such as heatwaves, droughts and floods can cause considerable damage and loss for Nauru. There are no tropical cyclones.

The four climate features relevant to Nauru are the Western Pacific Warm Pool (WPWP), the Western Pacific Monsoon (WPM), the South Pacific Convergence Zone (SPCZ) and Intertropical Convergence Zone (ITCZ). Changes to El Niño Southern Oscillation (ENSO) modulate these features on interannual time scales [7]. Nauru is in the region where the SPCZ and ITCZ merge [8]. The South Pacific Convergence Zone (SPCZ) is the dominant influence on the regional weather and climate [7, 9]. In the wet season (November to April), Nauru rainfall increases as the SPCZ intensifies and the ITCZ moves equatorward. In the dry season (May to October), Nauru rainfall decreases as the SPCZ weakens and the ITCZ moves northward [7].

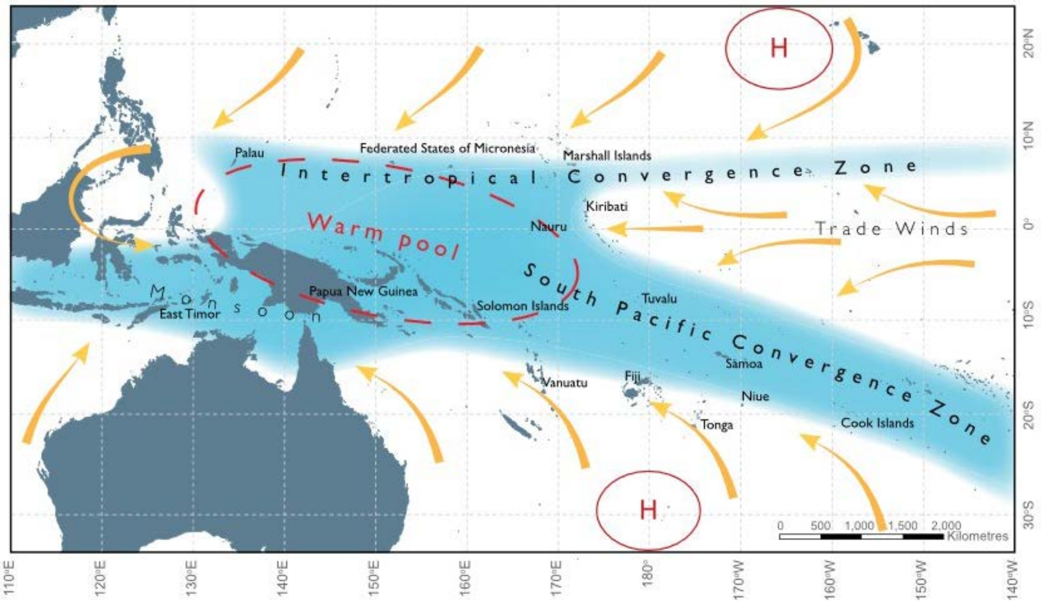


Figure 1-5 Schematic representation of major climatic features and drivers in the western tropical Pacific. The Intertropical Convergence Zone (ITCZ), South Pacific Convergence Zone (SPCZ) and West Pacific Monsoon are characteristic features where convective activities such as tropical cyclones and thunderstorms are frequently spawned. (Source: [8]).

Recent history and culture

From the 19th century onwards, Nauru increasingly encountered Europeans including whalers, German administration and missionaries, and phosphate mining personnel from 1906. The mining brought large numbers of contractors who outnumbered Nauruans [10]. It also introduced access to a wider range of foods and technologies. Mining effectively destroyed pandanus and coconut plantations, further increasing dependency on imported food and clothing purchased from the mining store at inflated prices [10].

Figure 1-6 Topside mine area (left) with secondary mining operations currently being undertaken (right) (Photos taken L. Webb and M. Sheppard CSIRO 2024).

Due to the Japanese occupation of Nauru during World War 2 (1942-1945), the Nauruan population was reduced by approximately 30 % [1], with much traditional cultural knowledge lost [1]. The land is currently owned by 12 different clans/family groups and land use needs to be negotiated among these family groups. Land is inherited through the maternal line, although most decision-making power is held by men [11].

Socio-economic status

The relatively young population (median age 21.6 years) of Nauru was estimated at 11,680 in 2021 (5893 males and 5787 females) [1]. High population density is related to about 80 % of the island being unsuitable for human habitation and people residing mainly in coastal areas; the population is highly concentrated (554 people/km^2). By 2050, Nauru's projected population density is 800 people/km^2 [1]. Nauru currently has an acute housing shortage resulting in multiple families living in single houses [1].

In the early 1980s, Nauru had the highest GDP per capita, with 95 % of the workforce being public servants and strong reliance upon phosphate royalties for income. In 2000, commercial mining of phosphate ceased but, while residual phosphate mining continues, government revenue and average household income and living standards had reduced dramatically. This decreased revenue also put pressure on power generation, drinking water and health services. Nauru has a small domestic fisheries industry, which provides some revenue, but Nauru is heavily dependent on foreign aid [12, 13], revenue from international fishing licences in its Exclusive Economic Zone [14], and fees/visas relating to the Regional Processing Centre (RPC). The national economy (at least in terms of revenue) has improved very significantly since national bankruptcy and sanctions due to tax haven/possible terrorism finance etc. and is now back up to high income status as of 2022 (A. Trundle, Pers Comm).

The Republic of Nauru Framework for Climate Change Adaptation and Disaster Risk Reduction (RONAdapt) [13], identified the following key vulnerabilities:

- **Scarce water resources;** Nauru has limited groundwater sources that are often polluted by leakage from sewage, mine and refuse sources. Delivery of water from the reverse osmosis desalination plant is via truck and is limited. A pipeline for water reticulation is planned. Rainwater tanks are an important water source but poorly maintained roofs and gutters limit catchment potential. Water quality is compromised during transport and storage in poorly maintained water tanks.
- **Limited land and soil resources;** the majority (80 %) of Nauru's land has limited usability owing to a history of phosphate mining, leaving only the coastal fringe suitable for agriculture, housing, critical infrastructure including the power station, hospital and main road. Many of these assets are exposed to future climate change impacts from sea level rise, storm surge and inundation.
- **Environmental degradation;** land degradation from mining reduces resilience of people and the environment to climate change and impacts future earning potential from tourism. Opportunities for Nauru's coastal based communities to relocate to avoid future climate change impacts from sea level rise and storm surge is reliant on rehabilitation of land in Topside, however the rehabilitation costs are considerable and require long-term commitment. The loss of indigenous vegetation reduces the ability to practice traditional medicine, traditional agriculture and create cultural products. Nauru's limited land area also reduces options for waste disposal.
- **High concentration of income activities;** Nauru's distance from other countries and limited land area restricts possibilities for foreign earnings to fund development opportunities, including adaptation to climate change. Foreign earnings have been generated through a limited number of sources: phosphate mining, the Regional Processing Centre (RPC) for refugees, and fisheries licencing. Some of these economic activities are ending, e.g. the secondary phosphate mining, and fisheries are at risk from climate change, e.g., ocean acidification and increasing sea surface temperature [15]. National financial challenges in the

past have affected the delivery of services including electricity generation, drinking water and health services [13]. Costs to address climate change impacts reduce the budget available to deliver other essential services such as health and education [13].

- **Dependence on imports;** due to limited land for subsistence and commercial food production, Nauru is highly reliant on food imports, leaving the country exposed to global markets and price shocks. Nauru is heavily reliant on fossil fuel imports for energy generation and transport.
- **Geographical isolation;** geographic isolation not only limits economic opportunities, but also services including high quality, cost effective health care and further education and training opportunities. High costs for import/export have an associated flow on effect to household and government budgets.
- **Low human capacity;** Nauru's small workforce has vulnerabilities in skilled labour and technical knowledge, and is heavily dependent on expatriate expertise. The sustainability strategy identifies weaknesses in human capacity in every sector (renewable energy technologies; marine science; fisheries techniques; monitoring and analysing the effects of climate change; health care). Education is highlighted as important to meeting the country's future needs for sustainable development and to adapt to climate change. Limited income restricts opportunities for Nauru students to study overseas for higher degrees.
- **Chronic health problems;** reliance on highly processed food imports has reduced the quality of food available, i.e. lack of fresh and healthy foods, with associated impacts on health such as high incidences of obesity and non-communicable disease (NCD) including cardio vascular disease, respiratory disease and, particularly, diabetes.
- **Aid dependency;** only 25 % of the 2009-2025 National Sustainable Development Strategy milestones had been achieved in 2016. Milestone activities were most likely implemented in Education, Environment, Public Administration, Sports, Governance Institutions, and Fisheries sectors, with international aid.
- **Poverty**; in 2013, around 24 % of the population were living below the national poverty line. In 2019, the GDP of Nauru was estimated at $118 million and its GDP per capita at $10,983 [16].

References

1. SPC and Government of the Republic of Nauru, *Nauru 2021 population and housing census - Analytical report*. 2023 SPC: Noumea, New Caledonia; Available from: https://sdd.spc.int/news/2023/08/23/nauru-2021-population-and-housing-census-analytical-report
2. Straza, T., *State of Environment and Conservation in the Pacific Islands: 2020 Regional Report.* 2020 Secretariat of the Pacific Regional Environment Programme: Apia, Samoa; Available from: https://pacific-data.sprep.org/system/files/SOE-conservation-pacific-regional-report.pdf
3. Alberti, L., I. La Licata, and M. Cantone, Saltwater intrusion and freshwater storage in sand sediments along the coastline: hydrogeological investigations and groundwater modeling of Nauru Island. *Water Research,* 2017. 9(10): p. 788. DOI: https://doi.org/10.3390/w9100788
4. Alberti, L., M. Antelmi, G. Oberto, I. La Licata, and P. Mazzon, Evaluation of fresh groundwater Lens Volume and its possible use in Nauru island. *Water Research,* 2022. 14(20): p. 3201. DOI: https://doi.org/10.3390/w14203201
5. Allis, M., S. Williams, and S. Wadwha, *Coastal flooding from sea-level rise in Nauru: Stage 1 - static inundation mapping, Prepared for the Nauru Higher Ground Project*. 2020: Prepared

for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited. Available from: https://nauru-data.sprep.org/system/files/Nauru_Coastal_Inundation%20with%20SLR_final%20-%20Oct%202020%20reduced%20%281%29.pdf

6. Bosserelle, C. and S. Williams, *Coastal flooding from sea-level rise in Nauru: Stage 2 - wave inundation mapping, Prepared for the Nauru Higher Ground Project*. 2023 Prepared for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited: Christchurch, NZ.
7. Brown, J.N., J.R. Brown, C. Langlais, R. Colman, J.S. Risbey, B.F. Murphy, A. Moise, A.S. Gupta, I. Smith, and L. Wilson, Exploring qualitative regional climate projections: a case study for Nauru. *Climate Research,* 2013. 58(2): p. 165-182.
8. 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: https://doi.org/10.1007/s10584-022-03467-z
9. 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: https://doi.org/10.1038/s43017-020-0078-2
10. Pollock, N.J., Nauru Phosphate History and the Resource Curse Narrative. *Journal de la Société des Océanistes,* 2014. 138(139): p. 107-120. Available from: https://nauru-data.sprep.org/system/files/pollock.pdf
11. Hambruch, P., *Nauru* in *Results of the South Sea Expedition- Ethnography: B Micronesia. Vol 1.* , G. Thilenius, Editor. 1914 DOI: https://doi.org/10.1080/00223340701692007
12. UNDRR, *Disaster Risk Reduction in the Republic of Nauru: Status Report 2022*. 2022 United Nations Office for Disaster Risk Reduction, Sub-Regional Office for the Pacific; Available from: https://www.undrr.org/media/85130/download
13. Republic of Nauru. *Nauru Framework for Climate Change Adaptation and Disaster Risk Reduction (RONAdapt).* 2015 Available from: https://policy.asiapacificenergy.org/sites/default/files/Nauru%20Framework%20for%20Climate%20Change%20Adaptation%20and%20Disaster%20Risk%20Reduction%20%28EN%29.pdf
14. 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. DOI: https://doi.org/10.1038/s41893-021-00745-z
15. Republic of Nauru, *National Sustainable Development Strategy 2005-2025: Revised 2019.* 2019; Available from: https://nauru-data.sprep.org/dataset/national-sustainable-development-strategy-2005-2025
16. World Bank, *Climate Risk Country Profile: Nauru (2021): The World Bank Group*. 2021 The World Bank Group: Washington, USA.; Available from: https://climateknowledgeportal.worldbank.org/sites/default/files/country-profiles/15819-WB_Nauru%20Country%20Profile-WEB.pdf

Section 1: PAST, PRESENT AND FUTURE CLIMATE

Photo credit (right): CSIRO, 2024.

Chapter 2 Data, confidence, limitations and uncertainties

Data

Each climate variable is assessed separately. The variables are average temperature, extreme temperature, average rainfall, extreme rainfall, drought, 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-year periods centred on 2030 and 2050. In most cases, unless otherwise stated, the projections are presented as changes relative to a 20-year period centred on 2005, i.e. 1995–2014, consistent with the IPCC 6th Assessment Report.

Historical climate data

Datasets sourced for climate analysis for Nauru are presented in Table 2-1.

Table 2-1 Historical datasets

Climate Variable	**Period**
Temperature	HadCRUT5 (1850–2020; [1]) Berkeley Earth (1850–2019; [2]) NOAA GlobalTemp (1880–2019; [3]) Cowtan and Way (1850–2019;[4]) GISTEMP (1880–2019; [5])
Rainfall	CMAP and GPCP gridded gauge-satellite monthly precipitation datasets available from 1979 [6] ERA5 grided reanalysis rainfall data from 1979–2020 ([7])
Drought	ERA5 rainfall data are bias-corrected using data from nearby climate stations.
Sea surface temperature	OISST v2.1 [8]
Tropical cyclones	IBTrACS; [9] 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 on timescales from days to years.

The main greenhouse gases are water vapour, carbon dioxide (CO_2), 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. Shared Socioeconomic Pathways (SSPs) [12] are illustrated in Figure 2-1.

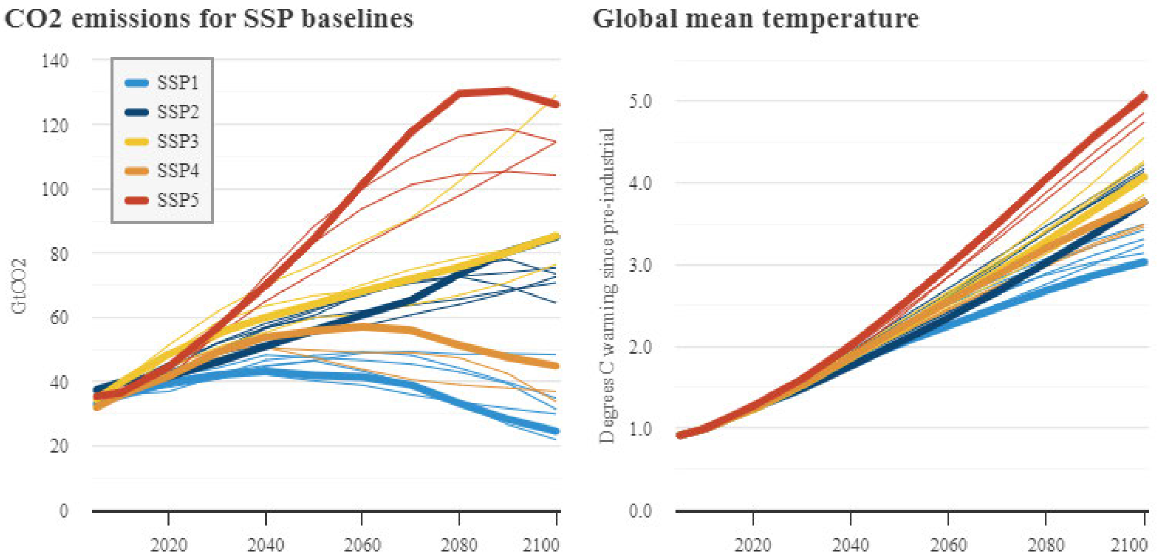


Figure 2-1 CO_2 emissions (left) in gigatonnes ($GtCO_2$) and global mean surface temperature change relative to pre-industrial levels (right) in degrees C across all climate models and SSPs. The "marker" model for each SSP is shown by a thicker line, while all other model simulations for that SSP have thin lines (source: [13]).

The SSPs are like the previously employed RCPs [14], but with some small variations 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 different global warming ranges by 2081–2100, relative to 1995–2014: 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 [15].

Current global emissions reduction policies are projected to lead to a global warming of 2.1°C–3.9°C by 2100 [16]. Another estimate suggests current policies might lead to a global warming of 2.2–3.4 °C by 2100 [17]. CO_2 emissions growth rates most consistent with observations from 2005 to 2020 and data from the International Energy Agency indicate a global warming of 2–3 °C by 2100 [18]. Each of these global warming estimates aligns with the SSP2-4.5 pathway.

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.

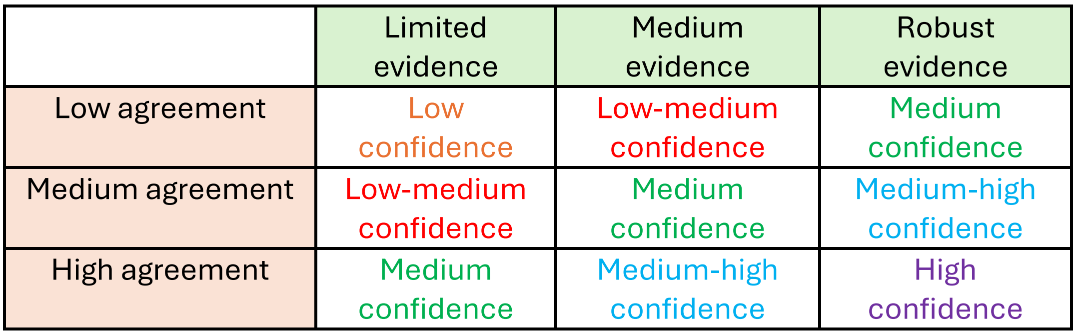
This report uses data from the Coupled Model Intercomparison Project phase 6 (CMIP6) [19] involving up to 28 climate models that have passed evaluation tests [20]. For some climate variables (extreme temperature, extreme rainfall, extreme windspeed), a smaller set of available simulations for SSP1-2.6 and, SSP3-7.0 and SSP5-8.5 were used.

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 timeseries graphs are used to visualise historical and future variability, and statistics are used to quantify variability such as the 10-90th 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 [21]. 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. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence [21].

Limitations of climate models

GCMs have coarse resolution (100–200 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 [15].

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.

For some climate hazards, separate models are needed to provide relevant information. For example, regional sea level projections require the other models to simulate dynamical ice sheet processes and gravitational changes due to melting of ice sheets and glaciers. Projections for storm surges and ocean waves require hydrodynamic and wave models.

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 30 climate models is usually expressed as a range. The IPCC and research organisations typically provide a 10-90th percentile range or a 5-95th 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 moderate uncertainty regarding the direction of change in rainfall. The moderate 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 [22]. Figure 2-3 shows that natural variability over the next decade can enhance or offset the long-term trend in annual temperature over Nauru. Therefore, historical climate trends over recent decades may be the best choice to inform climate trends for the next decade [23]. Climate model simulations can inform trends beyond the next decade.

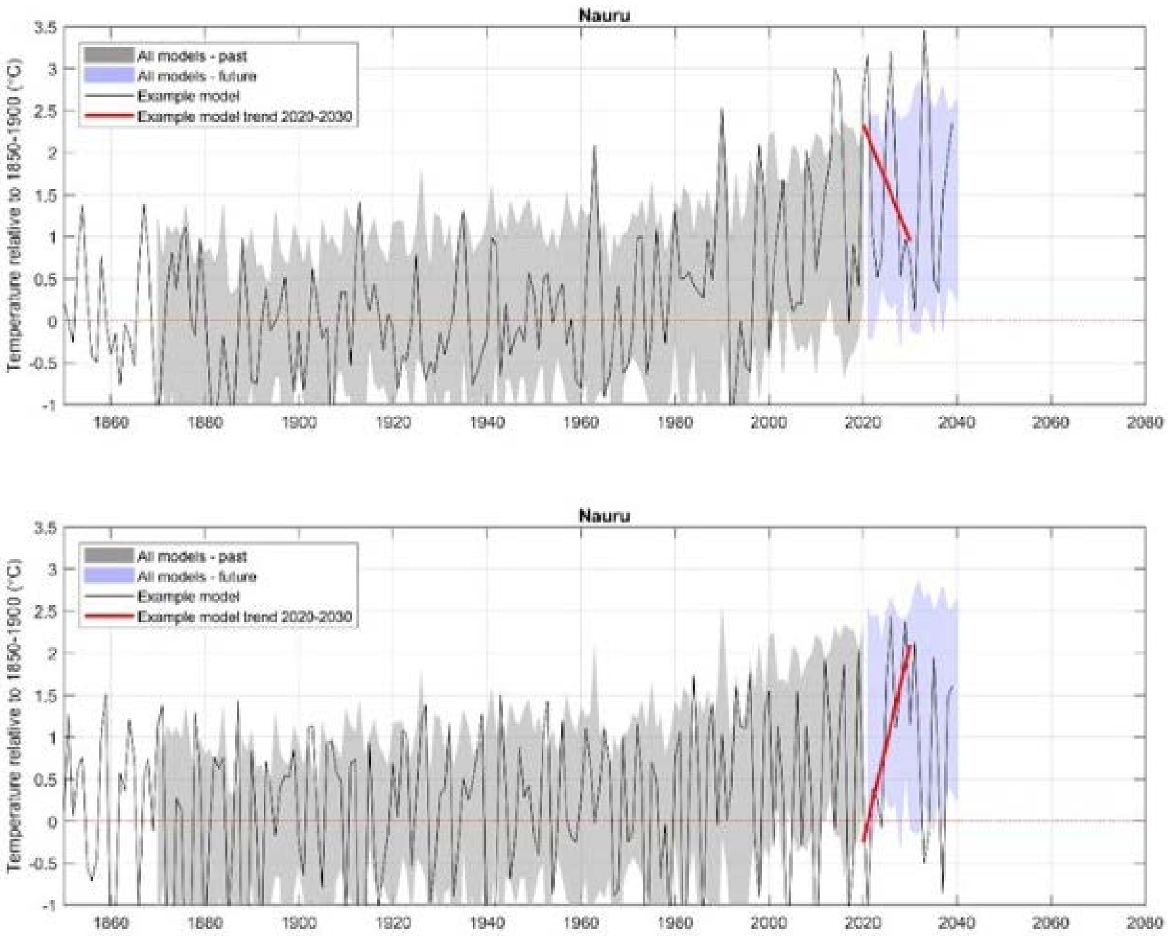


Figure 2-3 Average annual temperature in Nauru relative to 1850-1900 (°C) simulated in CMIP5 models, showing the range of all climate models (historical; grey band, future; blue band) and example model simulations (black line) with the linear trend for 2020-2030 marked (red line); top: an example with suppressed warming in 2020-2030 due to climate variability, bottom: an example with enhanced the warming in 2020-2030 due to climate variability [24].

Caveats[2]

ENSO

Changes in the east-west gradients of sea surface temperature (SST) across the equatorial Pacific have major consequences for global climate [25]. There is inconsistency among climate models on some aspects of future projections, as well as biases (e.g. [26-29]). For example, observational records appear to show a 'La Niña-like' strengthening of the east-west SST gradient since the 1950's [25] whereas most climate model simulations show 'El Niño-like' changes toward a weaker gradient, which becomes more pronounced in the projections [25, 29]. This discrepancy between modelled and observed trends in the CMIP6 model simulations [30, 31] is accompanied by an overestimation of ENSO variability [20]. Therefore, caution must be exercised when interpreting climate change projections. 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 [25].

---

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

Regardless, there is a strong consensus that ENSO variability will continue to dominate regional-scale climate in the future [32, 33], and strongly influence weather-related variables such as drought and rainfall (e.g. [33-35]).

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 [36, 37]. These are called compound events [38-40], but they are difficult to quantify within climate projections [41]. Storyline scenarios involving compound events can be used to ''stress test'' systems [42, 43].

There are several forms of compound hazards, and to read about other types of compounding hazards see https://climateextremes.org.au/why-research-on-compounding-weather-and-climate-hazards-is-important/. Impacts of a hazard can be made worse by pre-existing conditions. An example of a compound event is flooding caused by heavy rainfall on already saturated catchments, or drought and heatwaves causing major damage and disruption.

The scientific literature on compounding hazards events has been growing since 2018 [40, 44]. Recommendations on research priorities [38] include the need for identifying the multiple drivers of risk (i.e. hazard, exposure, vulnerability). The systemic risk caused by compound events is still emerging [45] but multi-hazard assessments in coastal settings are becoming more common [46].

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 [47]. However, there are deep uncertainties about some of the climate processes that could cause tipping points, e.g. thawing of Northern Hemisphere permafrost, collapse of the overturning ocean circulation in the north Atlantic Ocean, and rapid disintegration of the Greenland and Antarctic ice sheets [48]. Further details regarding tipping points and sea level rise are provided in Chapter 9: Sea level rise and coastal inundation.

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). DOI: https://doi.org/10.1029/2011JD017187
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. DOI: https://doi.org/10.5194/essd-12-3469-2020
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. Available from:

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. DOI: https://doi.org/10.1002/qj.2297
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. DOI: https://doi.org/10.1029/2018JD029522
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. DOI: https://doi.org/10.1175/JHM-392.1
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. DOI: https://doi.org/10.1002/qj.3803
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. DOI: https://doi.org/10.1175/2009BAMS2755.1
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. Available from: https://www.aoml.noaa.gov/phod/docs/McPhaden_TheGlobalTropical.pdf
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. DOI: https://doi.org/10.1175/JCLI-D-18-0748.1
12. Riahi, K., D.P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J.C. Cuaresma, S. Kc, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L.A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J.C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, and M. Tavoni, The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change,* 2017. 42: p. 153-168 DOI: https://doi.org/10.1016/j.gloenvcha.2016.05.009
13. Hausfather, Z. *Explainer: How 'Shared Socioeconomic Pathways' explore future climate change*. 2018 Available from: https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change]/
14. Van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, and J.-F. Lamarque, The representative concentration pathways: an overview. *Climatic Change,* 2011. 109(1-2): p. 5-31. DOI: https://link.springer.com/article/10.1007/s10584-011-0148-z
15. 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. Available from: https://www.ipcc.ch/report/ar6/wg1/
16. 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. DOI: https://doi.org/10.1038/s43247-021-00097-8

17. 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/
18. 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. Available from: https://iopscience.iop.org/article/10.1088/1748-9326/ac4ebf/pdf
19. O'Neill, B.C., C. Tebaldi, D.P. van Vuuren, V. Eyring, P. Friedlingstein, G. Hurtt, R. Knutti, E. Kriegler, J.F. Lamarque, J. Lowe, G.A. Meehl, R. Moss, K. Riahi, and B.M. Sanderson, The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.,* 2016. 9(9): p. 3461-3482 DOI: https://doi.org/10.5194/gmd-9-3461-2016
20. Grose, M., 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. DOI: https://doi.org/10.1029/2019EF001469
21. 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
22. 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
23. 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. DOI: https://doi.org/10.1038/s41558-020-00984-6
24. CSIRO and SPREP, *'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for Nauru (updated).* 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/e16a271d-0da5-4013-9fe5-49ee491b4fb7/Nauru%20Country%20Report_Updated.pdf
25. 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. DOI: https://doi.org/10.1038/s41612-022-00301-2
26. 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. DOI: https://doi.org/10.1038/ngeo868
27. 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 DOI: https://doi.org/10.1007/s00382-016-3189-1
28. 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. DOI: 10.1126/science.aay9165

29. 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. DOI: https://doi.org/10.1029/2022JD037563
30. 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. DOI: https://doi.org/10.1175/JCLI-D-21-0648.1
31. 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. DOI: https://doi.org/10.1038/s43017-021-00199-z
32. Power, S., F. Delage, C. Chung, G. Kociuba, and K. Keay, Robust twenty-first-century projections of El Niño and related precipitation variability. *Nature,* 2013. 502(7472): p. 541-545 DOI: https://doi.org/10.1038/nature12580
33. 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. https://doi.org/10.1002/9781119548164.ch1
34. 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. DOI: https://doi.org/10.1175/JCLI-D-11-00252.1
35. 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. DOI: https://doi.org/10.1007/s10584-021-03112-1
36. 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
37. 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
38. 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. DOI: https://doi.org/10.1038/s41558-018-0156-3
39. 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). DOI: https://doi.org/10.1016/j.isci.2023.105926
40. 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). DOI: https://doi.org/10.1016/j.isci.2023.105926
41. 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
42. Shepherd, T.G., Storyline approach to the construction of regional climate change information. *Proceedings of the Royal Society A,* 2019. 475(2225): p. 20190013. DOI: https://doi.org/10.1098/rspa.2019.0013
43. Shepherd, T.G., E. Boyd, R.A. Calel, S.C. Chapman, S. Dessai, I.M. Dima-West, H.J. Fowler, R. James, D. Maraun, and O. Martius, Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Climatic change,* 2018. 151: p. 555-571. DOI: https://doi.org/10.1007/s10584-018-2317-9

44. Pescaroli, G., A. Suppasri, and L. Galbusera, Progressing the research on systemic risk, cascading disasters, and compound events. *Progress in Disaster Science,* 2024. 22: p. 100319 DOI: https://doi.org/10.1016/j.pdisas.2024.100319
45. 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: https://doi.org/10.1038/s41612-021-00224-4
46. Oppenheimer, M., B.C. Glavovic , J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari, *Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities* in *IPCC Special Report: The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*, D.C.R. H.-O. Pörtner, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer, Editor. 2019, Cambridge University Press: Cambridge, UK and New York, NY, USA. p. 321-446. Available at: https://www.ipcc.ch/srocc/chapter/chapter-4-sea-level-rise-and-implications-for-low-lying-islands-coasts-and-communities/
47. 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. DOI: https://doi.org/10.1126/science.abn7950
48. CSIRO Workshop Report, *Understanding the risks to Australia from global climate tipping points.* 2024 CSIRO, Australia. DOI: https://doi.org/10.25919/dts9-5478

Chapter 3 Average temperature

Introduction

Daily air temperature records for Nauru from 1951 were obtained from the Australian Bureau of Meteorology and the Nauru Emergency Services Ministry [1, 2]. These data were used to quantify monthly and annual average temperatures.

Observed temperature

For Nauru, monthly-average air temperatures are similar through the year (Figure 3-1). Monthly-average maximum air temperatures are around 31 °C while minimum temperatures are around 25 °C. ERA5 reanalysis[3] data from 1979-2020 [3] indicated a statistically significant warming trend of 0.17–0.21 °C per decade [2] (Table 3-1).

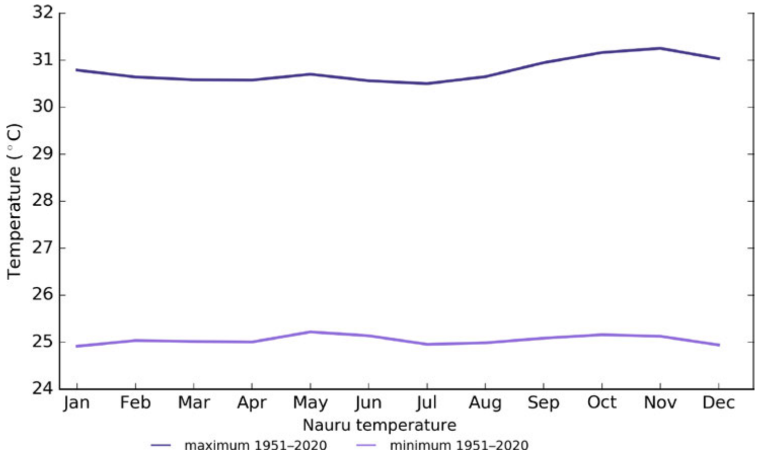
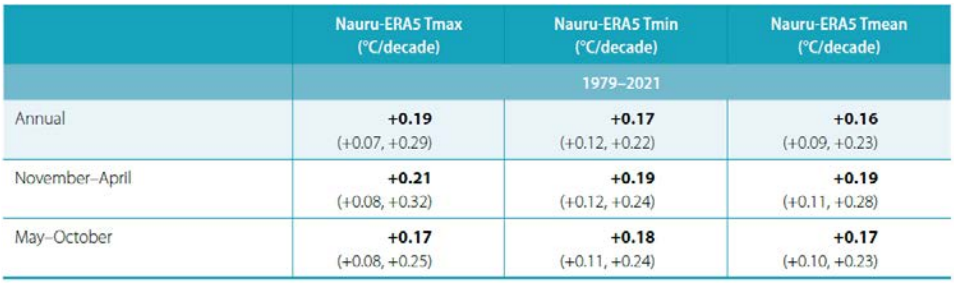


Figure 3-1 Monthly-average maximum and minimum air temperature for Nauru, based on data from 1951-2020. Source: McGree et al. (2022).

Table 3-1 Trends in annual and seasonal air temperatures for Nauru from ERA5 reanalysis data. Tmax is maximum temperature, Tmin is minimum temperature and Tmean is mean temperature. The 95 % confidence intervals are shown in brackets, and trends significant at the 95 % level are shown in bold. Source: McGree et al. (2022).



	Nauru-ERA5 Tmax (°C/decade)	Nauru-ERA5 Tmin (°C/decade)	Nauru-ERA5 Tmean (°C/decade)
		1979–2021	
Annual	**+0.19** (+0.07, +0.29)	**+0.17** (+0.12, +0.22)	**+0.16** (+0.09, +0.23)
November–April	**+0.21** (+0.08, +0.32)	**+0.19** (+0.12, +0.24)	**+0.19** (+0.11, +0.28)
May–October	**+0.17** (+0.08, +0.25)	**+0.18** (+0.11, +0.24)	**+0.17** (+0.10, +0.23)

The El Niño Southern Oscillation is a large-scale ocean-atmosphere interaction in the Pacific Ocean. In El Niño years, ocean temperatures and minimum air temperatures near Nauru are typically higher. During La Niña years, ocean temperatures and minimum temperatures near Nauru are typically lower, and similarly for maximum air temperatures during the wet season (November to April) [2].

---

[3] A reanalysis is a global weather simulation merged with observations and represents the most complete picture of the historical climate but shares the same limitations as climate models.

Projected temperature

Temperature projections for Nauru are presented for low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways. The projected warming for the near-term (2021–2040) relative to 1995–2014 is 0.7 °C (uncertainty range 0.3-1.0 °C) for low emissions and 0.8 °C (0.6-1.3 °C) for high emissions. In the medium term (2041–2060), it's 1.0 °C (0.9-1.2 °C) for low emissions and 1.5 °C (1.2-2.0 °C) for high emissions. In the long-term (2081–2100), it's 1.1 °C (1.0-1.3 °C) for low emissions and 3.5 °C (3.0-3.8 °C) for high emissions (Figure 3-2 and Table 3-2).

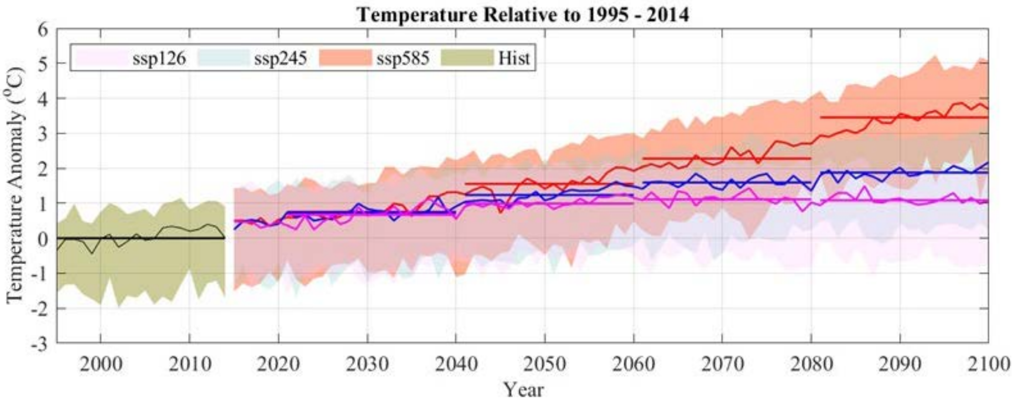


Figure 3-2 Average annual temperature anomalies in the Nauru region relative to 1995–2014 (°C) simulated in 28 CMIP6 climate models, showing the range of all models for the past period (grey band), and the future under a high emissions pathway (orange band), medium emissions pathway (blue band) and a low emissions pathway (pink band). Thick horizontal lines show the mean of all models in the 20-year baseline period 1995–2014 (grey) and future 20-year periods centred on 2030, 2050, 2070 and 2090 (SSP5-8.5; orange horizontal lines, SSP2-4.5; blue horizontal lines, and SSP1-2.6; pink horizontal lines).

Table 3-2 Projected changes in annual-average temperature (°C) for Nauru for three time periods and two emissions pathways, relative to 1995–2014.

Emissions pathway	2021-2040	2041-2060	2081-2100
Low (SSP1-2.6)	0.7 (0.3-1.0)	1.0 (0.9-1.2)	1.1 (1.0-1.3)
High (SSP5-8.5)	0.8 (0.6-1.3)	1.5 (1.2-2.0)	3.5 (3.0-3.8)

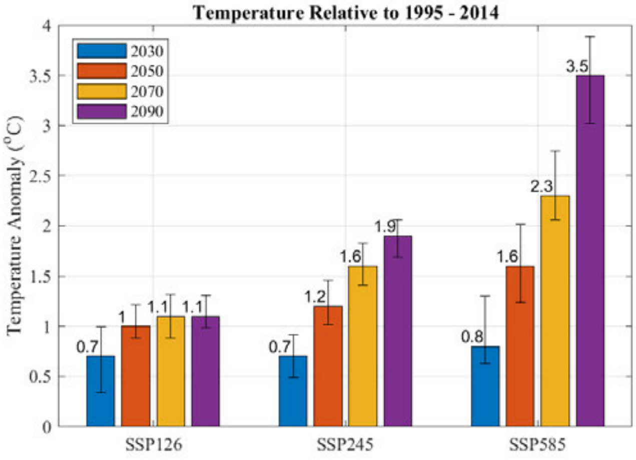


Figure 3-3 Projected change in Nauru annual-average temperature for 20-year periods centred on 2030, 2050, 2070 and 2090, relative to a 20-year period centred on 2005, for low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways. Median changes are shown with the 10-90th percentile range of uncertainty. Based on data from 28 CMIP6 climate models.

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. 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. DOI: https://doi.org/10.1002/qj.3803

Chapter 4 Extreme temperature

Introduction

Extremely high temperatures can cause heat stress for humans, animals and crops, increased water and energy demand, and power outages. This can lead to disruption, loss and damage.

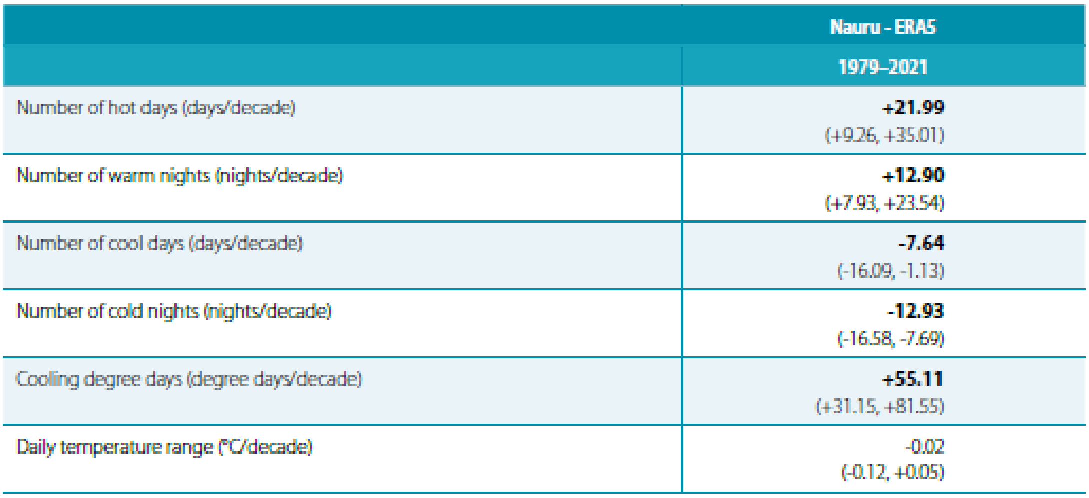
Extreme temperature definitions

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. Alternatively, extreme events can refer to actual temperatures, such as minima below 20 °C or maxima above 32 °C. Events with longer duration often have larger impacts, e.g. a 5-day heatwave with maximum temperatures over 32 °C.

Observed extreme temperature

Since 1979, the number of hot days (maximum temperatures above the 90th percentile for 1981–2010) has increased by 22 days/decade, and the number of warm nights (minimum temperatures above the 90th percentile for 1981–2010) has increased by 13 days/decade. The number of cool days (maximum temperatures below the 10th percentile for 1981–2010) has decreased by almost 8 days/decade and the number of cold nights (minimum temperatures below the 10th percentile for 1981–2010) has decreased by 13 days/decade (Table 4-1).

Table 4-1 Trends in annual temperature extremes in Nauru from ERA5 reanalysis data. The 95 % confidence intervals are shown in parentheses, and trends significant at the 95 % level are shown in bold. Hot and cool days, and warm and cold nights are measured relative to 1981–2010. Source [1].



	Nauru - ERA5
	1979–2021
Number of hot days (days/decade)	**+21.99** (+9.26, +35.01)
Number of warm nights (nights/decade)	**+12.90** (+7.93, +23.54)
Number of cool days (days/decade)	**-7.64** (-16.09, -1.13)
Number of cold nights (nights/decade)	**-12.93** (-16.58, -7.69)
Cooling degree days (degree days/decade)	**+55.11** (+31.15, +81.55)
Daily temperature range (°C/decade)	-0.02 (-0.12, +0.05)

Projected extreme temperature

Extreme temperature projections for Nauru consider low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways, simulations from five CMIP6 climate models, and statistics that include natural variability.

By mid-century (2041–2060), relative to 1995–2014, annual maximum temperatures increase by 0.9 °C (0.2 to 1.4 °C) under low emissions and 1.5 °C (0.6 to 2.0°C) under high emissions (Figure 4-1, left). However, by late-century (2081–2100), annual maximum temperatures increase by 1.1 °C (0.5 to 1.5°C) for low emissions and 3.8 °C (3.2 to 4.5 °C) for high emissions (Figure 4-1; right).

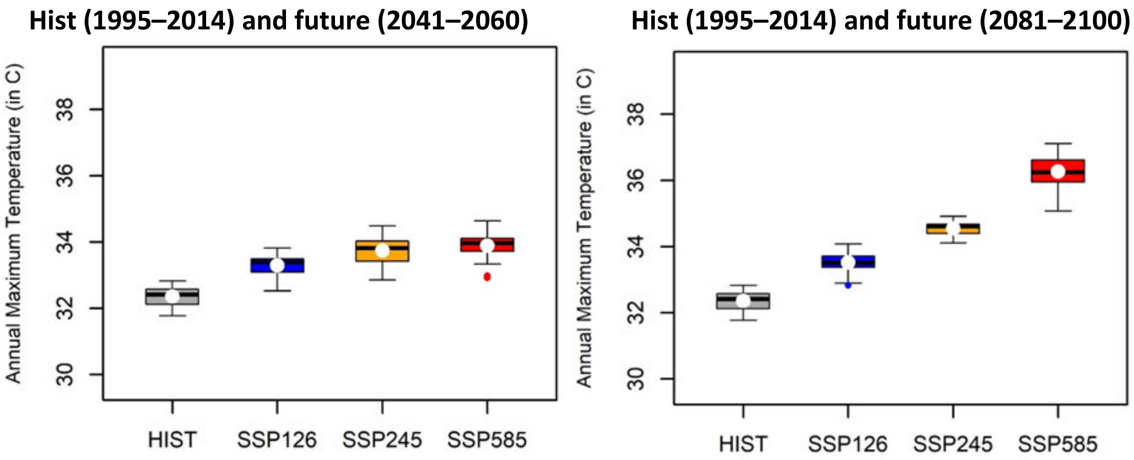


Figure 4-1 Comparison of annual maximum temperature distributions for two periods (1995–2014 and 2041–2060) (left) and (1995–2014 and 2081–2100) (right) for low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways. Results are based on five CMIP6 climate models. In each box/whisker plot, the central dot/line is the median, the box defines the 25–75th percentile range, and the whiskers define the 10–90th percentile range.

During 1995–2014, an average of 15 days (6 to 34 days) exceeded the 95th percentile of 32.0 °C. By mid-century (2041–2060), this increases by about 120 days (44 to 169 days) for low emissions and 193 days (69 to 242 days) for high emissions (Figure 4-2; left panel). By late-century (2081–2100), the increase is 139 days (91 to 213 days) for low emissions and 339 days (308 to 348 days) for high emissions (Figure 4-2; right).

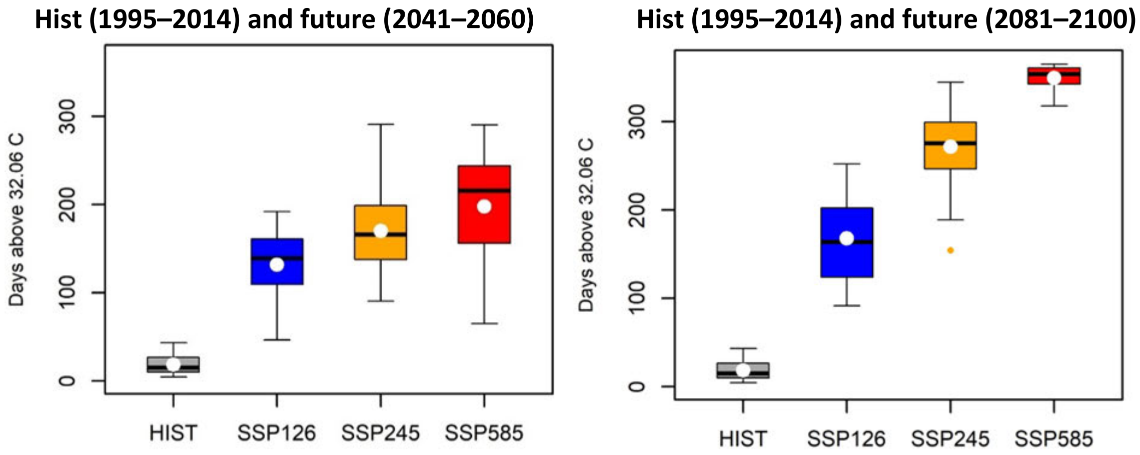
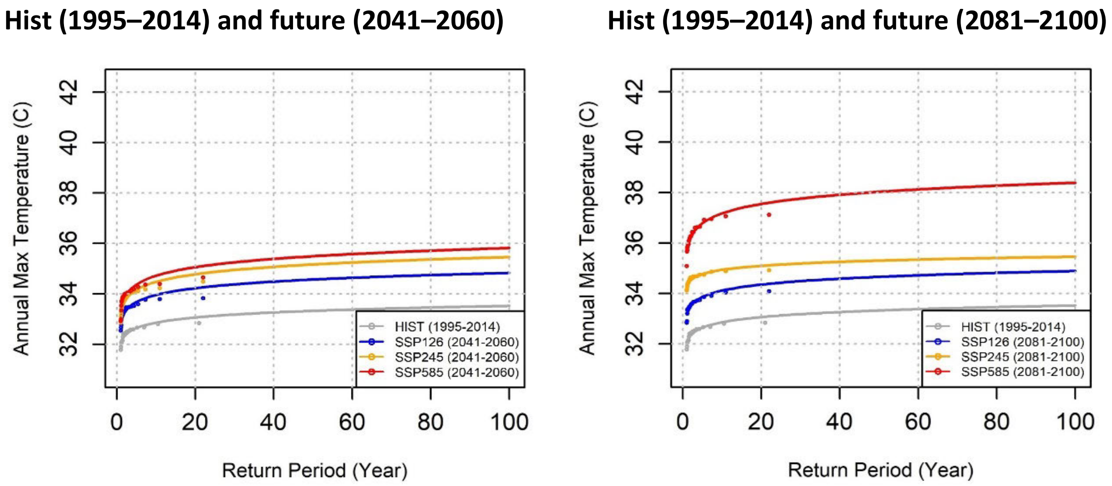


Figure 4-2 Number of Nauru 'hot' days (over 32 °C: the 95th percentile for 1995–2014) for two periods (1995–2014 and 2041–2060) (left) and (1995–2014 and 2081–2100) (right) for low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways. Results are based on five CMIP6 climate models. In 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. The orange dot below the whisker for SSP2-4.5 is an outlier.

Extreme annual maximum temperature was also calculated for average return periods of up to 100 years by fitting an extreme value distribution (Figure 4-3). Overall, extreme temperatures have shorter return periods in future. For example, a 33.7 °C event has a return period of approximately 100 years during 1995–2014, but by mid-century (2041–2060) the return period has decreased to 6.6 years for low emissions, 3.1 years for medium emissions and 1.8 years for high emissions (Figure 4-3, left). By late century (2081–2100), the return period has decreased to 1.3 years for low emissions and 1 year for medium and high emissions (i.e. 33.7 °C will be experienced almost every year, Figure 4-3, right).


Hist (1995–2014) and future (2041–2060)

Hist (1995–2014) and future (2081–2100)

Figure 4-3 Comparison of Nauru annual maximum daily temperature distributions for return periods of 1 to 100 years for historical (HIST: 1995–2014) and future (2041–2060 left and 2081–2100 right) timeframes, for low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways. Results are based on six CMIP6 climate models.

References

1. McGree, S., G. Smith, E. Chandler, N. Herold, Z. Begg, Y. Kuleshov, P. Malsale, and M. Rittman, *Climate Change in the Pacific 2022: historical and recent variability, extremes and change*. 2022 SPC: Suva, Fiji. Available at: https://library.sprep.org/content/climate-change-pacific-2022-historical-and-recent-variability-extremes-and-change

Chapter 5 Average annual and seasonal rainfall

Introduction

Average rainfall plays a key role in water security, food security, health and biodiversity. Rainfall observations in Nauru show large year-to-year and decade-to-decade variability. This variability can pose challenges, especially during drought years.

Historical and projected changes in extreme daily rainfall are provided in Chapter 6, while historical and projected changes in drought are covered in Chapter 7.

Historical rainfall

Nauru's rainfall monitoring site is in the Nibok district (Figure 5-1). Nauru has an average annual rainfall of about 2100 mm. There is a distinct wet season between December and April with average monthly rainfall above 200 mm per month, and 60 % of the annual rainfall occurs during the wet season [1]. The wettest month of the year is December, which averages rainfall of 270 mm. In contrast, the driest month of the year is September, which averages 130 mm.

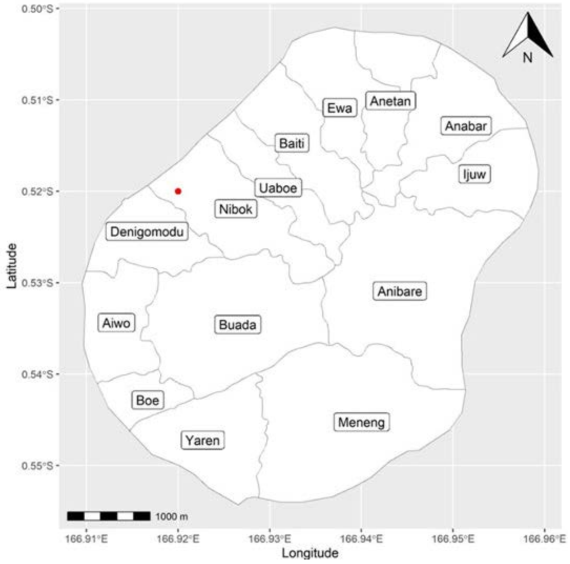


Figure 5-1 Nauru, with districts indicated. The red dot indicates the observational rainfall station. (Source: Biswas 2024, Fed Uni)

The Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ) are regions of high rainfall just north and south of the equator, respectively. Nauru sits in the region where the SPCZ and ITCZ merge. In the wet season, Nauru is in a stormy, convective regime as the SPCZ intensifies and the ITCZ moves equatorward. In the dry season, rainfall decreases as the SPCZ weakens and the ITCZ moves northward [2].

Trends in annual-total rainfall since 1951 are not statistically significant for Nauru [1]. Annual rainfall has varied from about 300 to 4400 mm (Figure 5-2), and on average, over half of the days each year experience rain. El Niño years are usually wetter than La Niña years [1] (Figure 5-2, right). The variability of annual rainfall in Nauru is strongly correlated with the variability in sea surface temperature (Figure 5-3).

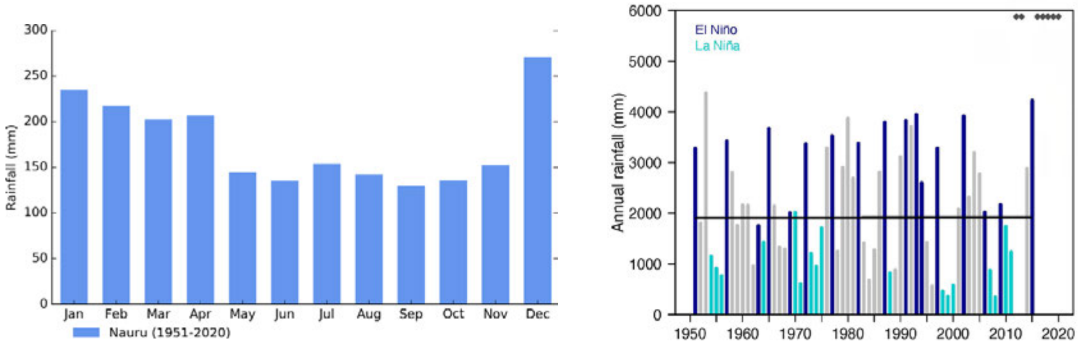


Figure 5-2 Monthly average rainfall for Nauru, based on data from 1951-2020. Source: McGree et al. (2022) (left). Annual rainfall variability (right) includes El Niño years (dark blue), La Niña years (light blue) and neutral years (grey). Diamonds in the top right indicate years with missing data. Source [1].

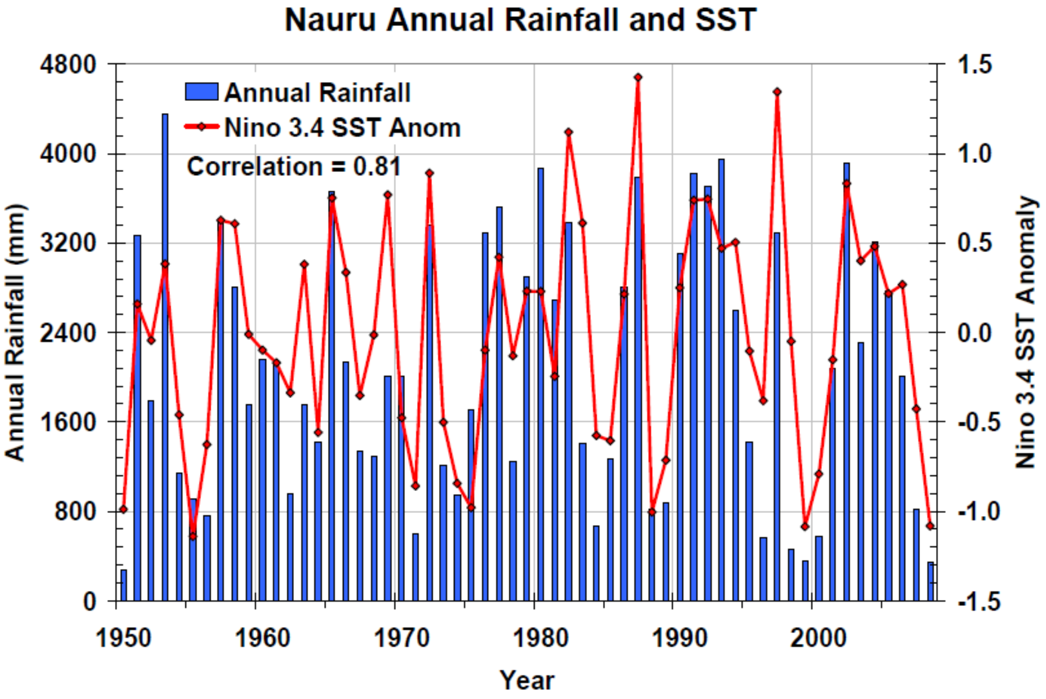


Figure 5-3 The variability of annual rainfall in Nauru is strongly correlated with the variability in sea surface temperature (SST) in the region. El Niño or La Niña events are defined when the Niño 3.4 SST anomaly exceeds +/- 0.4C for a period of six months or more (source [3]).

Projected rainfall

There is a large range of possible change in annual-average rainfall due to future increases in greenhouse gases. Simulations from 25 climate models were analysed. However, climate models have difficulty simulating climate processes in the equatorial region, particularly around Nauru [2], and most models underestimate historical Nauru annual-average rainfall. Therefore, the rainfall projections have medium confidence and should be interpreted with caution. Further research is needed to reduce uncertainty.

Projected changes in annual-average rainfall for a 20-year period centred on 2030 are +3 % (-24 to +46), +11 % (-19 to +39) and +8 % (-22 to +38) relative to a 20-year period centred on 2005, for low, medium and high emissions pathways, respectively. By 2050, the average projected changes are +32 % (-1 to +52), +13 % (-7 to +47) and +24 % (-6 to +63) for low, medium and high emissions, respectively. By 2070, it's +26 (-2 to +70 %), +41 % (+10 to +64 %) and +55 % (+13 to +78 %) for low, medium and high emissions, respectively. By 2090, it’s +32 % (+12 to +74 %), +44 % (+10 to +79 %) and +78 % (+47 to +130 %) for low, medium and high emissions respectively (Table 5-1, Figure 5-4 and Figure 5-5).

Table 5-1 Projected changes in annual-average rainfall (%) for Nauru for four time periods and three emissions pathways, relative to 1995–2014.

Emissions pathway	2021-2040	2041-2060	2061-2080	2081-2100
Low (SSP1-2.6)	+3 (-24 to +46)	+32 (-1 to +52)	+26 (-2 to +70)	+32 (+12 to +74)
Medium (SSP2-4.5)	+11 (-19 to +39)	+13 (-7 to +47)	+41 (+10 to +64)	+44 (+10 to +79)
High (SSP5-8.5)	+8 (-22 to +38)	+24 (-6 to +63)	+55 (+13 to +78)	+78 (+44 to +130)

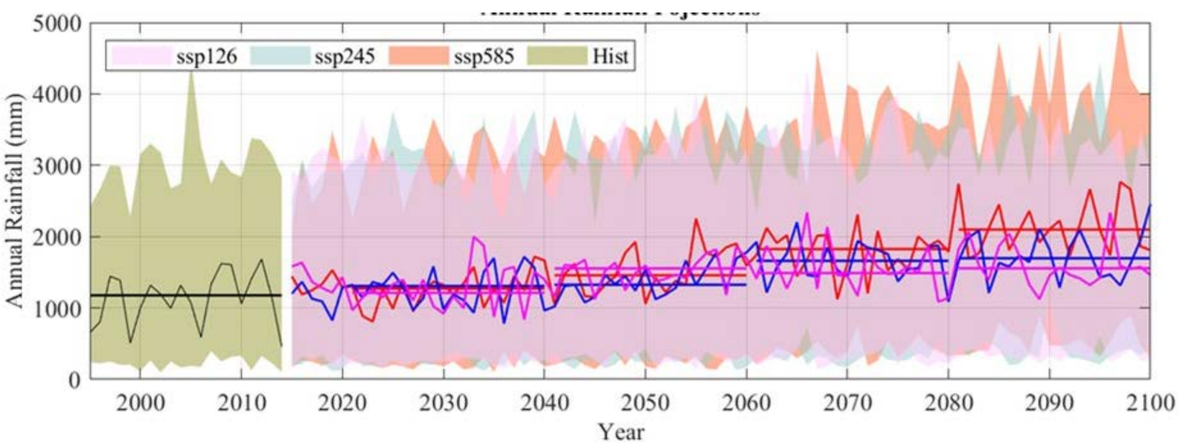


Figure 5-4 Annual rainfall (mm) for Nauru relative to the 1995–2014 baseline in CMIP6 climate model data. Simulations from up to 25 models are shown for the historical period (Hist; green), and the future under low (SSP1-2.6; pink), medium (SSP2-4.5; blue) and high (SSP5-8.5; orange) emissions pathways, with the 10th to 90th percentile of the 25 models indicated (shading). Thick lines show the median of all models for 20-year periods centred on 2005, 2030, 2050, 2070 and 2090 (Hist black line, SSP1-2.6 pink lines, SSP2-4.5 red lines and SSP5-8.5 red lines).

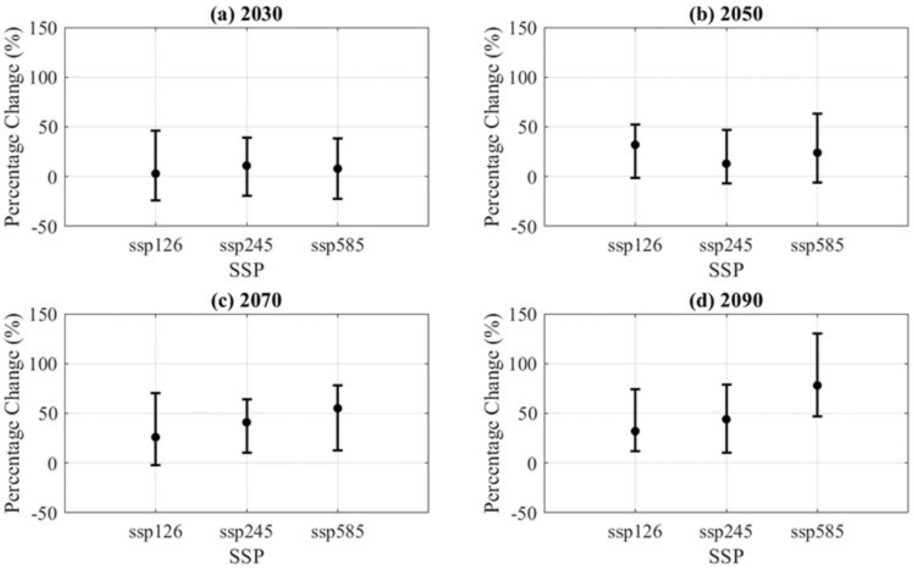


Figure 5-5 Projected change in Nauru annual-average rainfall for 20-year periods centred on 2030, 2050, 2070, and 2090 relative to a 20-year period centred on 2005, for low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways using 25 CMIP6 models. Median changes are shown with the 10-90th percentile range of uncertainty as error bars.

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. Brown, J.N., J.R. Brown, C. Langlais, R. Colman, J.S. Risbey, B.F. Murphy, A. Moise, A.S. Gupta, I. Smith, and L. Wilson, Exploring qualitative regional climate projections: a case study for Nauru. *Climate Research,* 2013. 58(2): p. 165-182.
3. Republic of Nauru, *National Water, Sanitation and Hygiene Implementation Plan*. 2012: Nauru; Available from: https://www.theprif.org/sites/default/files/2020-08/Nauru%20NWSHIP.pdf

Chapter 6 Extreme rainfall events

Introduction

Extreme rainfall is strongly affected by the South Pacific Convergence Zone (SPCZ), which is most intense during the wet season [1]. Extreme rainfall over hours to days can cause flooding and landslips, with associated damage and disruption. This can have implications for disaster risk management, transport, water quality, food security, community health, waste management, income security and tourism [2].

Extreme rainfall definitions

Frequency, intensity and duration are common metrics for defining extreme rainfall. Frequency can be expressed as the number of hours, days or months above a specified intensity threshold. The threshold should be considered rare for the given location, e.g., within the top 1-10 % of recorded events. 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 in Nauru varies from around 24-349 mm/day during the period 1950–2023 (Figure 6-1). Trend analysis shows that the annual maximum daily rainfall has been increasing over this period by approximately 8.4 mm/decade (which is statistically significant at the 95 % confidence level).

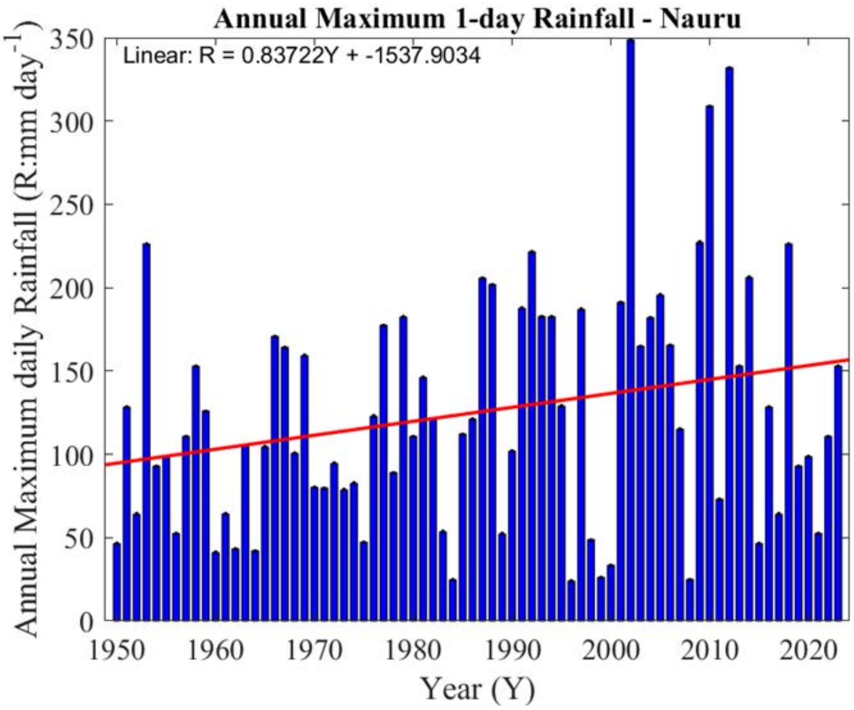


Figure 6-1 Annual maximum daily rainfall in Nauru (bar graph) and linear trend (red regression line) from 1950–2023. The linear trend (equation given at top left corner) is statistically significant at the 95 % confidence level. Due to considerable missing data in the rainfall observations for Nauru, the ERA5 [3] precipitation data have been used, bias corrected with observational data sourced from the Nauru Meteorological Service, using the methodology described by [4].

During El Niño events, the SPCZ tends to move northeast, resulting in warmer sea surface temperatures and heavier rainfall in the central and eastern Pacific including Nauru, with the opposite during La Niña events [5, 6].

Projected extreme rainfall

Simulated annual maximum daily rainfall intensity averaged over 1995–2014 is 105 mm/day, based on data from five CMIP6 climate models. By mid-century (2041–2060), simulated annual maximum rainfall intensity increases to 153 mm/day (+46 %) under low emissions and 159 mm/day (+52%) under high emissions. By the end of the century (2081–2100), annual maximum rainfall intensity increases to 136 mm/day (+29 %) for low emissions and 201 mm/day (+91 %) for high emissions (Figure 6-2).

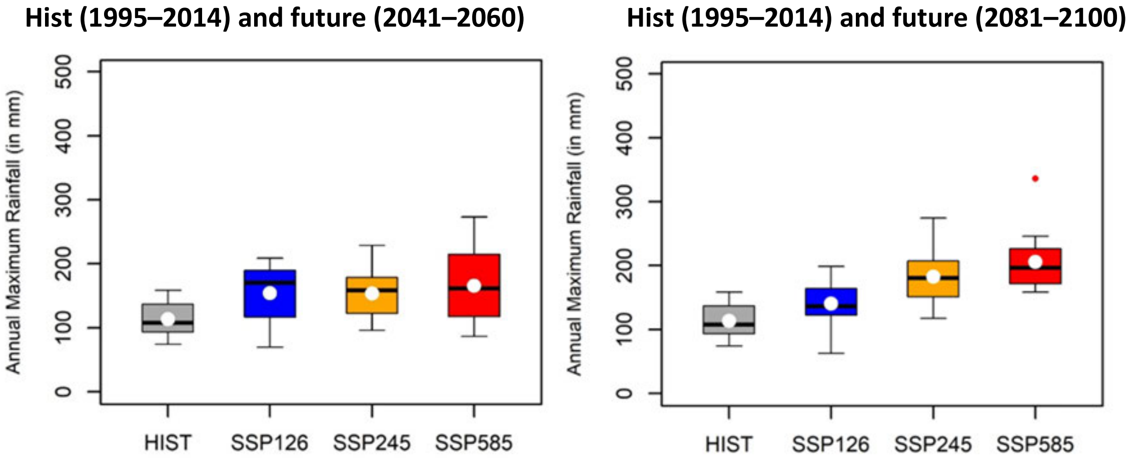


Figure 6-2 Comparison of Nauru annual maximum daily rainfall for two periods (1995–2014 and 2041–2060) (left) and (1995–2014 and 2081–2100) (right) for low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways. Based on the mean of five CMIP6 climate models. In each box/whisker plot, the central dot/line is the median, the box defines the 25-75th percentile range, and the whiskers define the 10-90th percentile range. Red dot outside the whisker for SSP5-8.5 2080–2100 indicates an outlier result.

The annual-average number of days with rainfall above the 95th percentile is also projected to increase. The mean shows that by mid-century (2041–2060) relative to 1995–2014 (which has an average of 15 days per year above the 95th percentile: 31.5 mm), the average increases to 31 days (+107 %) for low emissions, 28 days (+87 %) for medium emissions and 29 days (+93 %) for high emissions (Figure 6-3). By the end of the century (2081–2100), relative to 1995–2014, it increases to 29 days (+93 %) for low emissions, 32 days (+112 %) for medium emissions and 47 days (+212%) for high emissions (Figure 6-3).

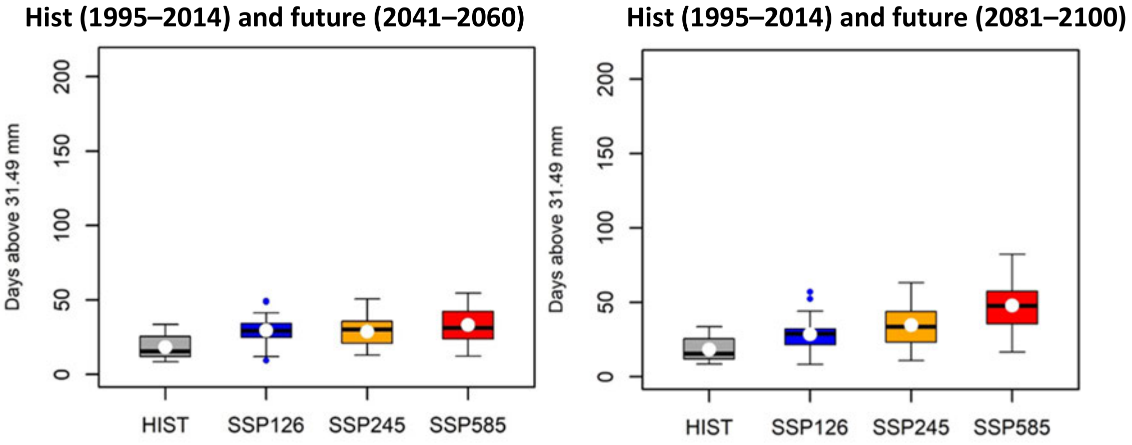
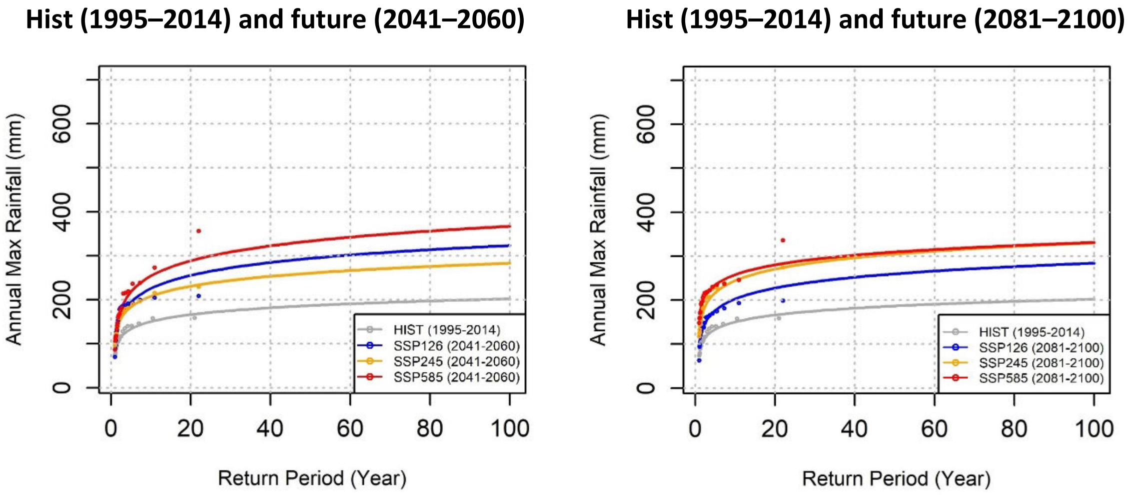


Figure 6-3 Comparison of the annual-average number of days when rainfall is above 31.5 mm (the 95th percentile) for two periods (1995–2014 and 2041–2060) (left) and (1995–2014 and 2081–2100) (right) for low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways. Based on the mean of five CMIP6 climate models. The 95th percentile (shown on the vertical-axis) is obtained from the data for 1995–2014 for each model. 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 daily rainfall intensity was also calculated for average return periods of 1 to 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 have shorter return periods in the future, i.e. higher frequency. For example, the multi-model mean shows a 200 mm/day event with a return period of 80 years during 1995–2014, but by 2081–2100 the return period has decreased to about 6 years for low emissions, 4 years for medium emissions and 2 years for high emissions.



Hist (1995–2014) and future (2041–2060)

Hist (1995–2014) and future (2081–2100)

Figure 6-4 Comparison of annual maximum daily rainfall distributions for return periods of 1 to 100 years for historical (HIST: 1995–2014) and future (2041–2060) timeframes (left) and for historical (HIST: 1995–2014) and future (2081–2100) timeframes (right), for low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways. Results are based on the mean of the five CMIP6 climate models.

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. 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
3. 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. DOI: https://doi.org/10.1002/qj.3803
4. 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. DOI: https://doi.org/10.1175/JAMC-D-21-0034.1
5. 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

6. Brown, J.R., M. Lengaigne, B.R. Lintner, M.J. Widlansky, K. van der Wiel, C. Dutheil, B.K. Linsley, A.J. Matthews, and J. Renwick, South Pacific Convergence Zone dynamics, variability and impacts in a changing climate. *Nature Reviews Earth & Environment,* 2020. 1(10): p. 530-543 DOI: 10.1038/s43017-020-0078-2. DOI: https://doi.org/10.1038/s43017-020-0078-2

Chapter 7 Drought

Introduction

In general, drought refers to a lack of rainfall for an extended period, usually more than a few months, resulting in water shortages for a range of groups, sectors, natural resources (including marine and terrestrial biodiversity), and related activities. The impacts of drought vary significantly depending on (i) the type of drought (e.g. meteorological drought or agricultural drought); (ii) the exposure of people and assets; (iii) socio-economic conditions; and (iv) cultural attitudes towards the causes of drought. Historical droughts and their impacts have been described in a review for other Pacific Island countries (though not for Nauru) [1].

Droughts usually occur during La Niña events when the surrounding sea temperature is cooler than normal for Nauru, resulting in less evaporation, cloud and rainfall [2]. Due to lack of water storage capacity in Nauru, prolonged droughts impact water availability, including the underground fresh-water lens [3, 4], resulting in water supply problems and severe stress on natural ecosystems.

Drought definitions and indicators

Different drought definitions and indicators are used for different purposes [5]:

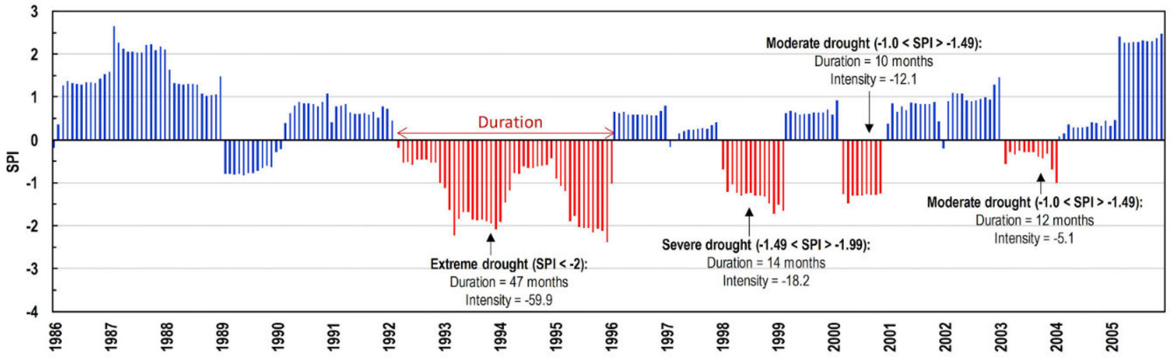
- Meteorological drought (below normal rainfall; used in this hazard assessment).
- Agricultural drought (below normal water storage in the soil; incorporates the influence of rainfall, temperature and evaporation).
- Hydrological drought (below normal water availability in streams, lakes, and groundwater).

Indicators commonly employed for declaring drought include the Standardised Precipitation Index [6] or rainfall percentiles [1, 7], though there are many other methods that also account for factors such as evaporation [8], soil moisture, or crop productivity [9].

Standardised Precipitation Index (SPI)

Rainfall anomalies, preferably normalised by standard deviation (SD), are often used to assess drought [10]. The SPI is a widely used indicator for drought, including by the Nauru Meteorological and Hydrological Service, and it is endorsed by the World Meteorological Organization [5]. The SPI is a statistical indicator comparing the total precipitation during a specific period with the long-term average precipitation. It allows different rainfall regimes to be expressed in relative terms, e.g. drier than usual [11]. Positive SPI values indicate greater than median precipitation and negative values indicate less than median precipitation [12].

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 [6]. The drought intensity is the average of cumulative SPI from all events for the drought period.



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 of a Standardised Precipitation Index (SPI) time series and the associated drought events for the period 1986–2005 [13]. In this 20-year period, the 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 45.4 % and 19.5 % time in drought and in extreme drought, respectively. Drought categories based on SPI are also indicated [6] noting the ranges in the table differ slightly from the example graph.

SPI is calculated using monthly rainfall 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. [12]. The SPI has been used to assess droughts in the Pacific [14]. Since the SPI can be calculated over different rainfall accumulation periods, different potential impacts can be explored. For example, soil moisture conditions and rainwater tank storage respond to precipitation anomalies on a relatively short period such as 3 to 6 months. However, groundwater, streamflow and reservoir storage reflect longer-term (6 months and above) precipitation anomalies [6, 12, 15].

For the case of Nauru, streams, groundwater and reservoirs are usually rare, so short-term water shortages become major issues. For this assessment, therefore, SPI-3 is considered the most suitable index reflecting precipitation anomalies. However, SPI-12 is also computed for comparison.

Observed droughts

A global gridded monthly precipitation dataset, ERA5 [16], was bias corrected [17] using observed rainfall data provided by the Nauru Meteorological and Hydrological Service. SPI was calculated relative to 3- and 12-month rainfall accumulations for the period 1951-2023 (Figure 7-2, a and b).

In total for SPI-3, there have been 19 drought events during 1951-2023, of which three (or 16 %) were moderate, eight (42 %) were severe and eight (42 %) were extreme. For SPI-12, Nauru had 11 droughts, of which two (18 %) were moderate, two (18 %) were severe and seven (64 %) were extreme. Therefore, for SPI-12, there is a higher frequency (82 %) of severe and extreme droughts. So, droughts over Nauru have mostly been severe and extreme.

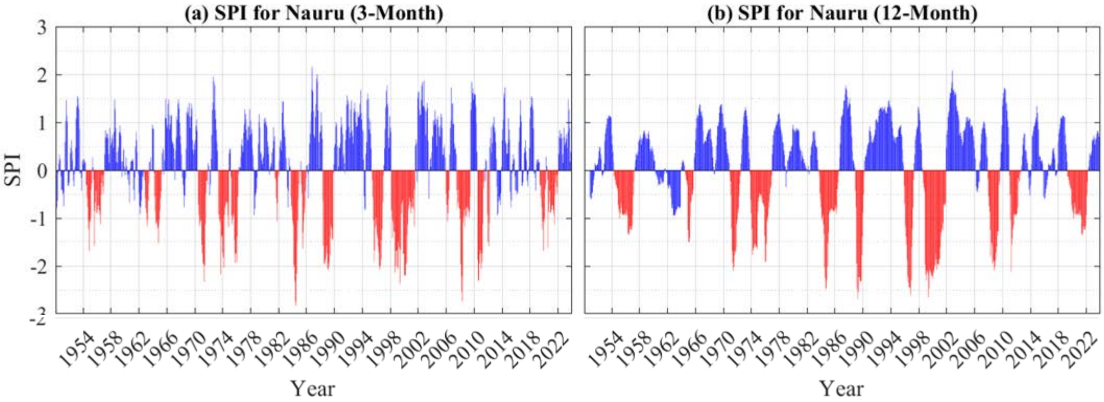


Figure 7-2 Time series plot of (a) SPI-3 and (b) SPI-12 for Nauru for the 1950 to 2023 period

While there has been a slight increase in drought frequency (DF) since 1951, the trend is not statistically significant (Deo et al, in prep) (Figure 7-3). A slight increase in drought intensity (DI) and drought duration (DD) has also been observed (Deo et al, in prep), but these trends are not statistically significant (Figure 7-4).

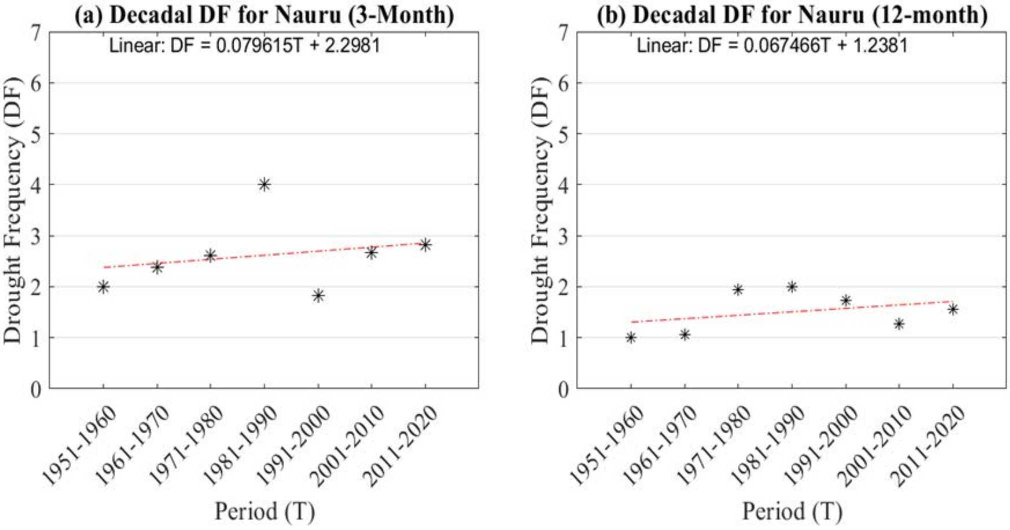


Figure 7-3 Linear regression of decadal drought frequency for SPI-3 and SPI-12 over Nauru for the 1951–2020 period. If a drought event overlaps two decadal periods, then the fraction of that event associated with each period is computed, which explains the fractional values evident in the plot. Note, the trend is not statistically significant at the 95 % confidence level.

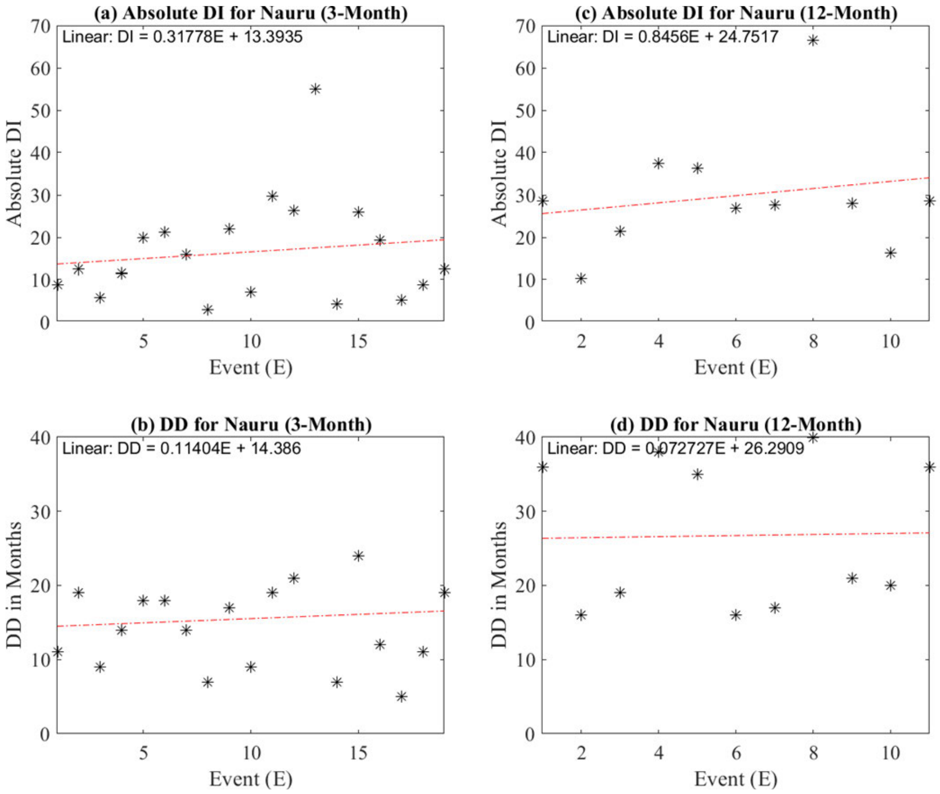


Figure 7-4 Linear regression of drought intensity (DI; a and c) and drought duration (DD; b and d) for SPI-3 and SPI-12 drought events over Nauru for the 1951–2023 period. The trends are not statistically significant at the 95 % confidence level.

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 one of the key factors influencing drought occurrence in the Pacific region, including Nauru [8]. During an El Niño event, wetter conditions are usually experienced in Nauru, while La Niña events tend to bring drier conditions, including droughts [18]. Drought intensity (DI) is highly correlated with the ENSO intensity, represented by the NINO3.4 index (a measure of sea surface temperatures in the central Pacific Ocean) and ENSO Intensity index (Figure 7-5).

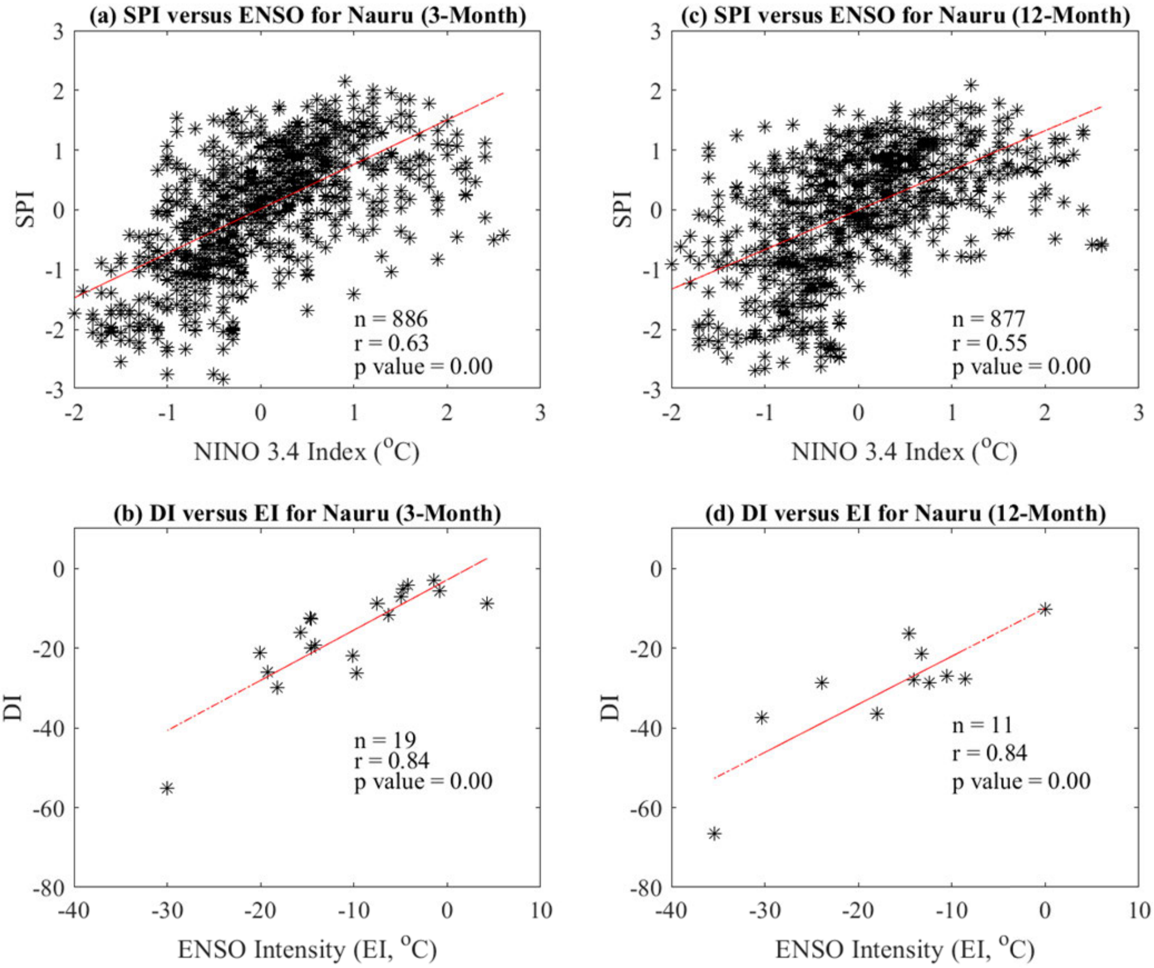


Figure 7-5 a) Linear regression of SPI against the NINO3.4 SST index. This includes all values shown in Figure 7-2-a and b respectively and not just the values corresponding to the 19 drought events. (b) Linear regression of drought intensity (DI) against ENSO intensity (EI) for the 19 drought events. Each EI value is the sum of the corresponding ONI values for each drought event, which is like how DI is computed. n is the sample size, r is the correlation coefficient and p-value is the t-statistic p-value at the 95 % confidence level.

Projected drought

Simulations from 25 CMIP6 climate models [19] have been used to calculate SPI-3, SPI-6, and SPI-12 for a 20-year reference period (centred on 2005) and future 20-year periods (centred on 2030, 2050, 2070 and 2090) under low (SSP1-2.6) and high (SSP5-8.5) greenhouse gas emissions pathways (Figure 7-6 to Figure 7-8). The characteristics of drought are represented by three measures, following [13]:

- Drought duration (DD): the average length (in months) of an event in a selected 20-year period.
- Drought frequency (DF): the number of droughts in a selected 20-year period.
- Drought intensity (DI) 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.

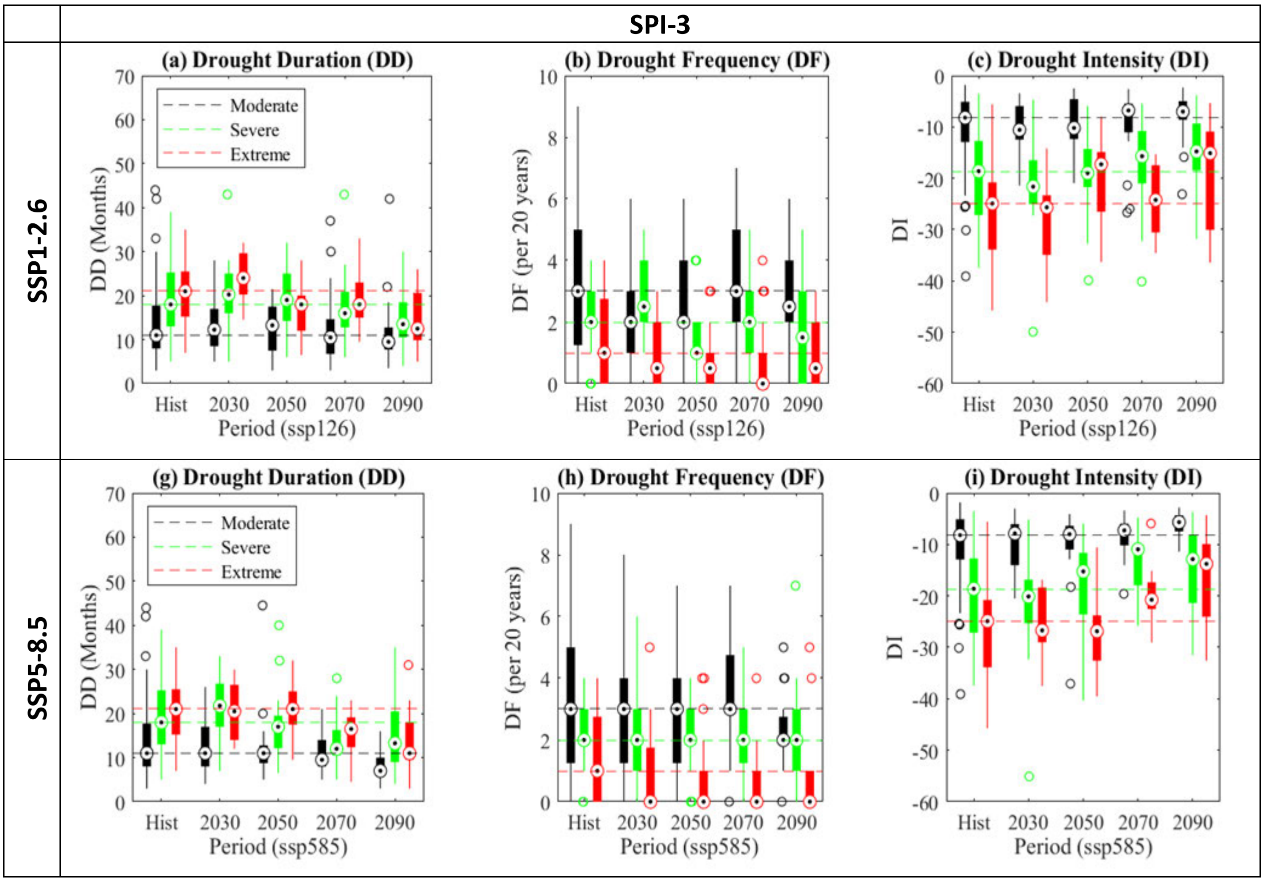


Figure 7-6 Nauru average of SPI-3 drought duration (left), frequency (middle) and intensity (right) in the reference period (20 years centred on 2005) and future periods (20-years centred on 2030, 2050, 2070, 2090) for low (SSP1-2.6; top row) and high (SSP5-8.5; bottom row) greenhouse gas emissions pathways. Different drought categories (moderate, severe, and extreme; Figure 7-1) 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 28 climate model simulations using CMIP6 projections 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. SPI is calculated monthly with the value for each month representing the rainfall anomaly over the past 3 months.

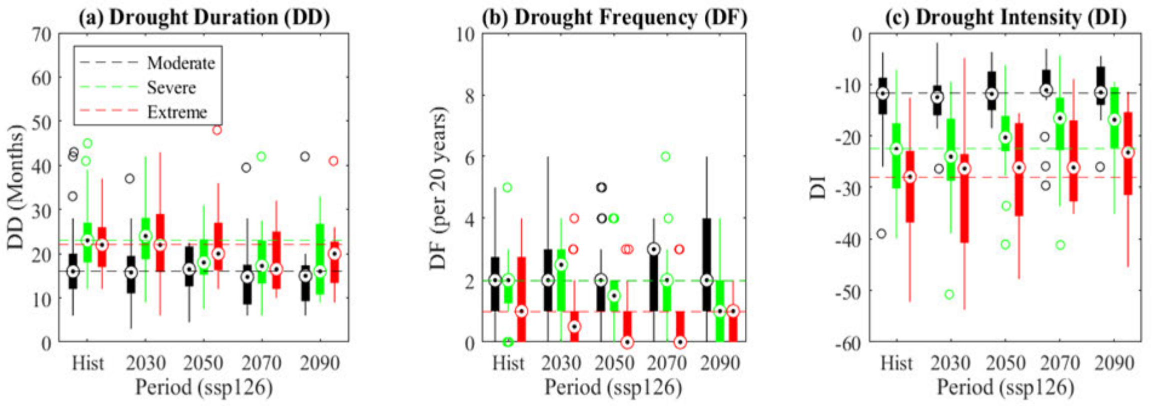
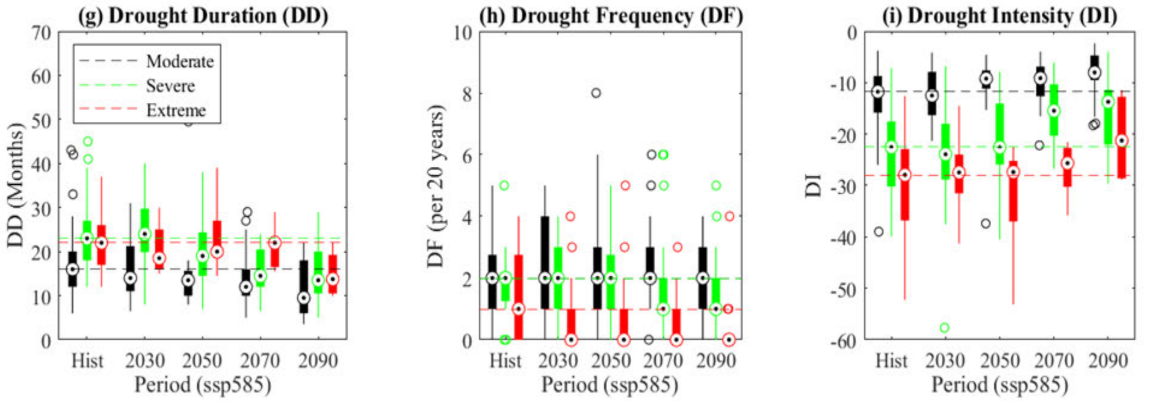
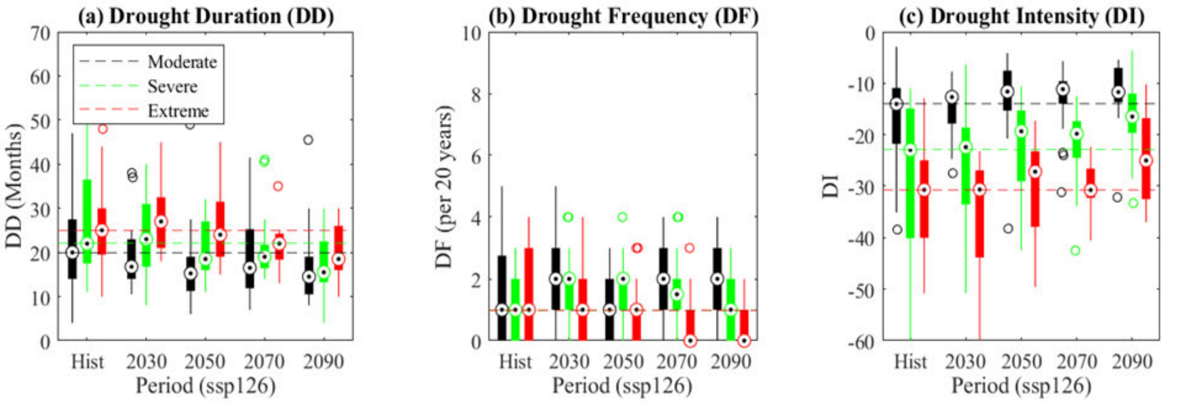
	SPI-6
SSP1-2.6	
SSP5-8.5	

Figure 7-7 Same as

Figure 7-6 except for SPI-6.

	SPI-12
SSP1-2.6	

SSP5-8.5

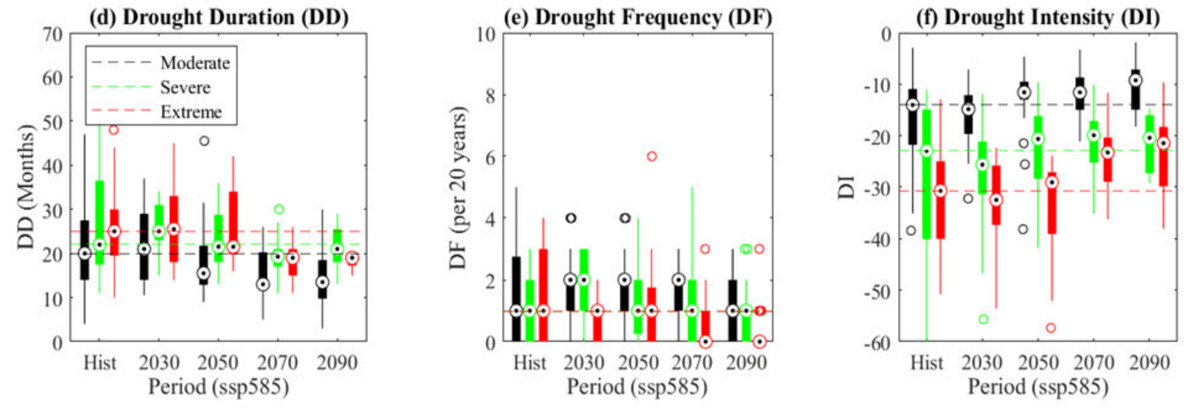


Figure 7-8 Same as

Figure 7-6 except for SPI-12.

A decrease in drought duration is projected for SPI-3, -6 and -12 (Table 7-1). For example, for SPI-3, the change over the future period (20-years centred on 2050), relative to the historical, could range from 20 % to 6 %, to -14 % for moderate, severe and extreme drought respectively (Table 7-1, Figure 7-9 a and d).

A decrease in drought frequency is projected for SPI-3 and -6. For example, for SPI-3, the change drought frequency over the future 20- year period centred on 2050, relative to the historical, could from -33 (moderate), -50 % (severe) and -50 % (extreme) for low emissions (Table 7-1 and Figure 7-9 b and e). For SPI-12, there is no clear trend for moderate and severe drought frequency, but extreme drought frequency is projected to decrease in future.

A decrease in drought intensity is generally projected (Table 7-1 and Figure 7-9 c and f).

Table 7-1 Projected percentage changes in SPI-3 drought duration, frequency and intensity for 20 years centred on 2030, 2050, 2070 and 2090 relative to 20 years centred on 2005, for low (SSP1-2.6) and high (SSP5-8.5) emissions pathways. M, S and E denote moderate, severe and extreme drought conditions, respectively.

Emissions pathway	**Year**	**Drought Metric**								
		Duration			Frequency			Intensity		
		M	S	E	M	S	E	M	S	E
Low	2030	11	13	14	-33	25	-50	29	16	3
	2050	20	6	-14	-33	-50	-50	24	2	-31
	2070	-5	-11	-14	0	0	-100	-17	-16	-3
	2090	-14	-25	-40	-17	-25	-50	-14	-21	-39
High	2030	0	21	-2	0	0	-100	-4	8	7
	2050	0	-6	0	0	0	-100	-2	-18	8
	2070	-14	-33	-21	0	0	-100	-11	-41	-17
	2090	-36	-26	-48	-33	0	-100	-31	-31	-45

	SPI-3

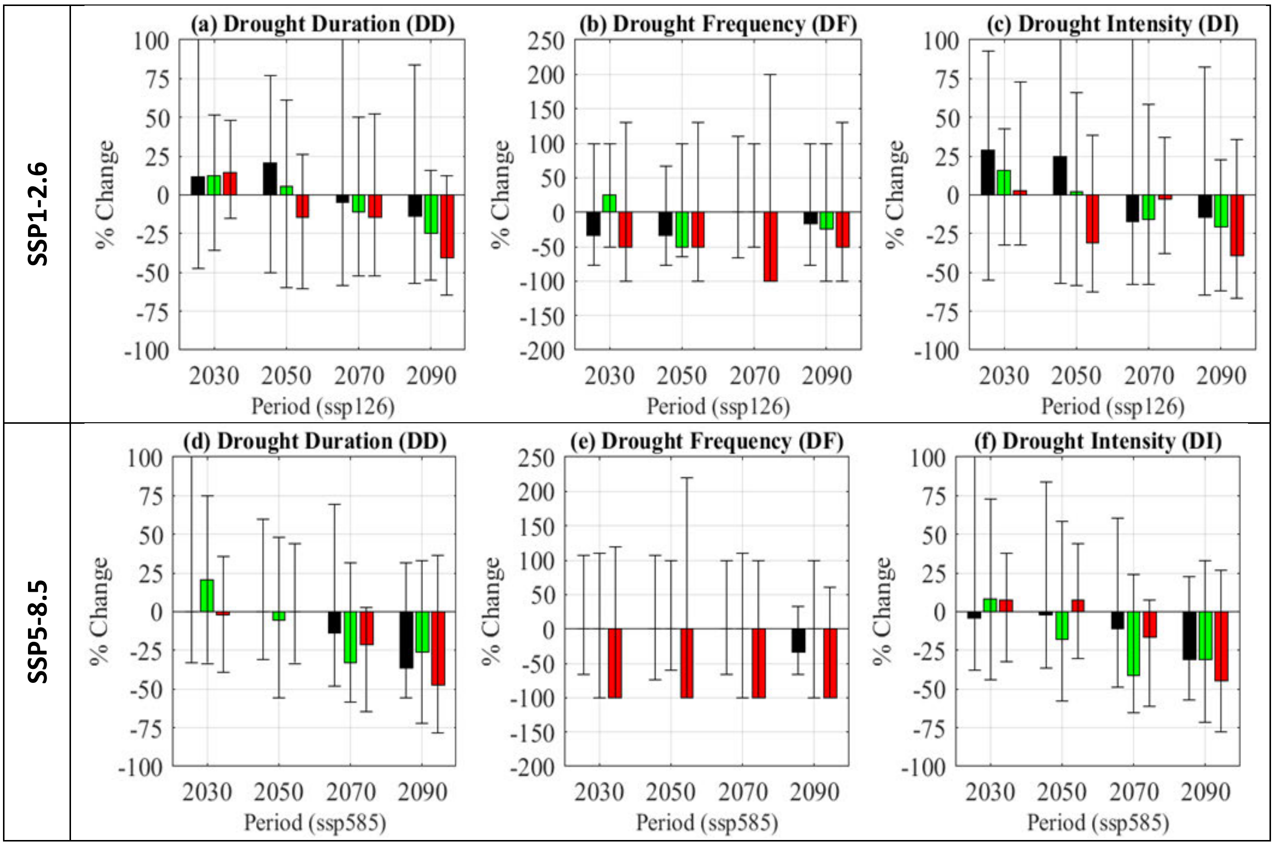


Figure 7-9 Percentage change, with respect to the baseline, for Nauru average SPI-3 drought duration (left), frequency (middle) and intensity (right) in the reference period (20 years centred on 2005) and future periods (20-years centred on 2030, 2050, 2070, 2090) for low (SSP1-2.6; top row) and high (SSP5-8.5; bottom row) emissions pathways. Black, green and red colours denote moderate, severe and extreme drought categories, respectively.

Caveats

The projected decreases in drought intensity, frequency and duration are consistent with projected increases in annual-average rainfall (Chapter 5). However, the drought projections presented in this chapter are based on the SPI, a precipitation index which does not include the effect of projected increases in temperature and evapotranspiration. Droughts are becoming hotter due to global warming associated with increases in greenhouse gas emissions [10]. Over Nauru, maximum air temperatures have increased 0.19 °C per decade since 1951, while minimum air temperatures have increased 0.17 °C per decade, and these trends are projected to continue. Therefore SPI-based drought projections may under-estimate hydrological and agricultural drought.

Furthermore, increased rainfall variability may result in the increasing intensity and frequency of both floods and droughts [20]. This is consistent with projected increases in extreme La Niña and El Niño events due to climate change [21-23]. This could have significant impacts on Nauru's water security.

References

1. 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. DOI: https://doi.org/10.1007/s10584-021-03112-1
2. Australian Bureau of Meteorology and CSIRO, *Current and future climate of Nauru*. 2014 BoM and CSIRO; Available from: https://www.pacificclimatechangescience.org/wp-content/uploads/2013/06/6_PACCSAP-Nauru-9pp_WEB.pdf

3. Alberti, L., M. Antelmi, G. Oberto, I. La Licata, and P. Mazzon, Evaluation of fresh groundwater Lens Volume and its possible use in Nauru island. *Water Research,* 2022. 14(20): p. 3201. DOI: https://doi.org/10.3390/w14203201
4. Alberti, L., I. La Licata, and M. Cantone, Saltwater intrusion and freshwater storage in sand sediments along the coastline: hydrogeological investigations and groundwater modeling of Nauru Island. *Water Research,* 2017. 9(10): p. 788. DOI: https://doi.org/10.3390/w9100788
5. 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. Available from: https://www.droughtmanagement.info/literature/GWP_Handbook_of_Drought_Indicators_and_Indices_2016.pdf
6. 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. Available from: https://www.droughtmanagement.info/literature/AMS_Relationship_Drought_Frequency_Duration_Time_Scales_1993.pdf
7. BoM, *Drought, rainfall deficiencies and water availability. 2023. Australian Bureau of Meteorology.* 2023; Available from: http://www.bom.gov.au/climate/drought/drought.shtm
8. 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. DOI: https://doi.org/10.1175/JCLI-D-16-0332.1
9. Sivakumar, M.V., *Agricultural drought—WMO perspectives*. 2011 World Meteorological Organization: Geneva, Switzerland. Available from: https://www.droughtmanagement.info/literature/WMO_agricultural_drought_indices_proceedings_2010.pdf
10. Dai, A., Drought under global warming: a review. *WIREs Climate Change,* 2011. 2: p. 45-65. DOI: https://doi.org/10.1002/wcc.81
11. 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
12. 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. Available from: https://mountainscholar.org/items/842b69e8-a465-4aeb-b7ec-021703baa6af
13. 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. DOI: https://doi.org/10.1016/j.wace.2020.100280
14. 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
15. WMO, *Standardized Precipitation Index User Guide.* 2012 World Meteorological Organization; Available from: https://www.droughtmanagement.info/literature/WMO_standardized_precipitation_index_user_guide_en_2012.pdf
16. 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. DOI: https://doi.org/10.1002/qj.3803

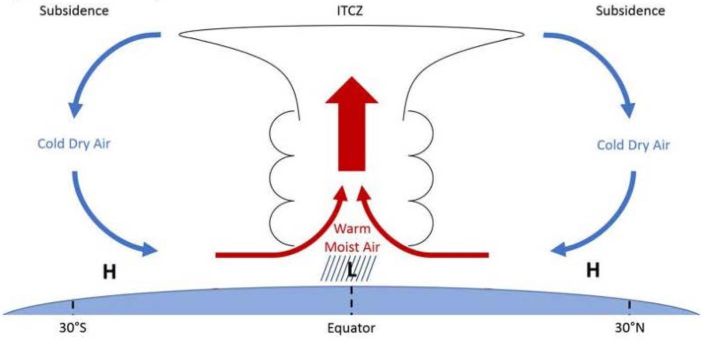
17. Biswas, S., S.S. Chand, A.J. Dowdy, W. Wright, C. Foale, X. Zhao, and A. Deo, Statistical calibration of long-term reanalysis data for Australian fire weather conditions. *Journal of Applied Meteorology and Climatology,* 2022. DOI: https://doi.org/10.1175/JAMC-D-21-0034.1
18. Australian Bureau of 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
19. O'Neill, B.C., C. Tebaldi, D.P. van Vuuren, V. Eyring, P. Friedlingstein, G. Hurtt, R. Knutti, E. Kriegler, J.F. Lamarque, J. Lowe, G.A. Meehl, R. Moss, K. Riahi, and B.M. Sanderson, The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.,* 2016. 9(9): p. 3461-3482 DOI: https://doi.org/10.5194/gmd-9-3461-2016
20. 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: https://doi.org/10.1029/2021EF002524
21. 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. DOI: https://doi.org/10.1038/nclimate2100
22. 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. DOI: https://doi.org/10.1038/s41586-018-0776-9
23. 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. DOI: https://doi.org/10.1038/nclimate2492

Chapter 8 Average and extreme winds

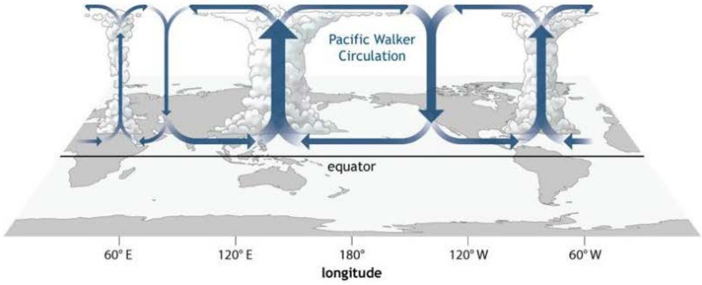
Introduction

The Hadley and Walker circulations are the two large-scale atmospheric processes that influence climate in the tropical Pacific region [1]. The Hadley circulation is aligned north-south with air rising along the intertropical convergence zone (ITCZ), then overturning and descending in the northern- and southern- hemisphere sub-tropics (Figure 8-1 a). Surface winds then flow back, completing the circulation, and converge along the ITCZ. The Hadley circulation provides a mechanism to transport heat in the atmosphere poleward to the sub-tropics (~30° latitude). The surface winds, which blow from the sub-tropics towards the equator, contribute to the equatorward component of the trade winds. Over the past decades, observations and model simulations indicate that the Hadley circulation has widened (i.e. undergone poleward expansion) considerably in both hemispheres ([2, 3].

a) The Hadley Cell



b) The Tropical East-West Overturning Circulation



c) The Walker Circulation

NOAA Climate.gov

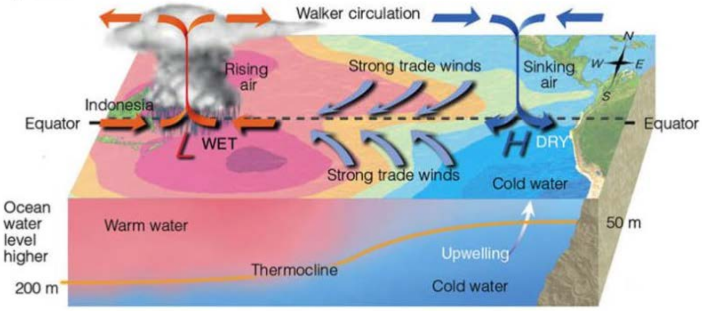


Figure 8-1 Schematic diagrams of (a) the tropical north-south Hadley Cell, (b) the tropical east-west overturning circulation, including the Pacific Walker Circulation, and (c) the combined Hadley and Walker circulations over the tropical Pacific. Source: [4].

The Walker circulation is the east-west component of the tropical circulation, which is mainly related to the sea surface temperature gradient between the western and the eastern Pacific (Figure 8-1 b). The Walker cell has air ascending near Indonesia and descending in the eastern Pacific contributing to the strength of the trade winds (Figure 8-1 c). This circulation is intimately linked to the major source of interannual tropical climate variability, called the El Niño-Southern Oscillation (e.g. [5-7]).

Average winds

In Nauru, easterly trade winds dominate, with a mean wind speed of 4.6 metres per second (m/s) (8.94 knots) (Figure 8-2 and Figure 8-3) [8]. Strongest wind speeds occur from January to March, with weakest winds from May to July.

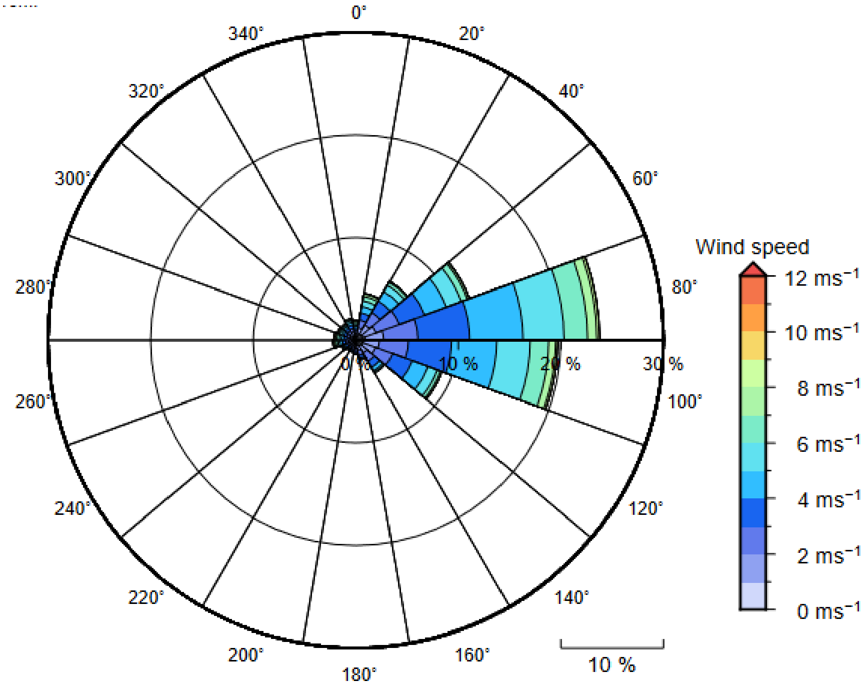


Figure 8-2 Annual wind rose for Nauru. Note that directions are where the wind is coming from (source: [8])

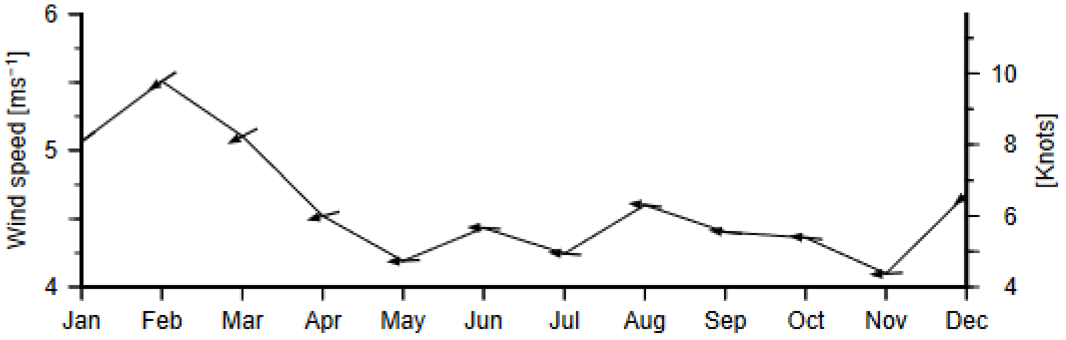


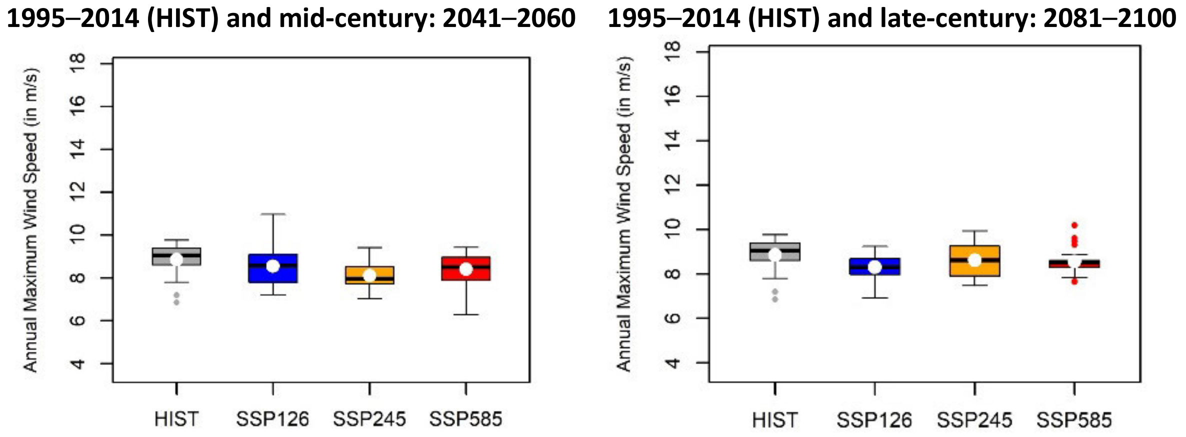
Figure 8-3 Monthly wind speed (Black line) and wind direction (arrows) for Nauru (source: [8]).

Since the 1980s, significant strengthening of trade winds has been noted [9, 10], indicative of increased La Niña-like conditions. The strengthening is more evident in the western equatorial Pacific than in the eastern equatorial Pacific. However, this is at odds with climate models that simulate more El Niño-like conditions in both current and future climate conditions [11]. Therefore, wind projections based on climate models have low confidence.

Strong winds and storminess days

Strong westerly wind bursts that affect Nauru are often associated with Madden Julian Oscillation (MJO) activity (e.g., [12]). The MJO is a dominant mode of intraseasonal (30-90 days) climate variability in the tropics [13]. The MJO undergoes a strong seasonal cycle in both its strength and location. During the warm season (i.e., November–April), the MJO is primarily more active south of the equator.

Maximum windspeeds over Nauru have been analysed for future time periods centred on 2050 and 2090 using five CMIP6 climate models[4] for three emissions pathways (SSP1-2.6, SSP2-4.5 and SSP5-8.5) (Figure 8-4). It is difficult to discern any meaningful trend. Values of annual maximum windspeed are relatively low (< 10 ms^{-1}) compared with typical cyclone-induced winds (> 17 ms^{-1}).


1995–2014 (HIST) and mid-century: 2041–2060

1995–2014 (HIST) and late-century: 2081–2100

Figure 8-4 Annual maximum windspeed (m/s) for 1995–2014 (HIST), mid-century: 2041–2060 (left) and late century: 2081–2100 (right). The multi-model mean is shown from the five CMIP6 models under low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways. In each box/whisker plot, the central dot and line are the mean and median, respectively, whereas the box defines the 25-75th percentile range, and the whiskers define the 10-90th percentile range.

Ocean conditions may be considered ‘unsafe’ for fishing when the daily maximum wind speed exceeds the 20-knot (i.e., 10.29 m/s) threshold. The number of unsafe days in the present climate is around 3 days per decade (Figure 8-5). Projections for 2041–2060 and 2081–2100 based on five climate models are inconclusive (Figure 8-5 and Figure 8-6). Future research is needed to investigate projected changes in ‘unsafe’ fishing days as the livelihoods of many people depend on fishing.

---

[4] Given available resources, only five models were assessed here. Ideally this assessment would be undertaken using all available models to examine winds. The five models were selected from those assessed by 14. Grose, M.R., S. Narsey, R. Trancoso, C. Mackallah, F. Delage, A. Dowdy, G. Di Virgilio, I. Watterson, P. Dobrohotoff, H.A. Rashid, S. Rauniyar, B. Henley, M. Thatcher, J. Syktus, G. Abramowitz, J.P. Evans, C.-H. Su, and A. Takbash, A CMIP6-based multi-model downscaling ensemble to underpin climate change services in Australia. *Climate Services,* 2023. 30: p. 100368 DOI: https://doi.org/10.1016/j.cliser.2023.100368.
It is important to note that CMIP6 models are coarse resolution and can therefore substantially under-estimate island scale extreme winds. While every effort has been undertaken here to statistically bias-correct model wind fields with available observational records (such as station data and TAO/TRITON buoys in the tropical Pacific) 15. 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., care must be exercised when interpreting the following results in the context of future climate change.

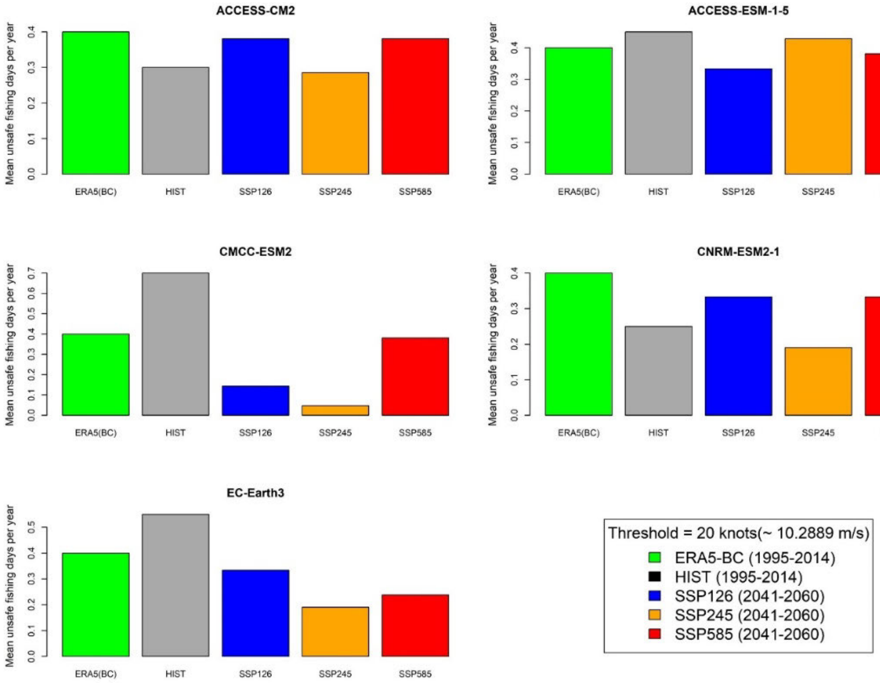


Figure 8-5 Comparison of Nauru 'unsafe' fishing day distributions for the historical period (1995–2014) and for the period 2041–2060 under low (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions pathways.

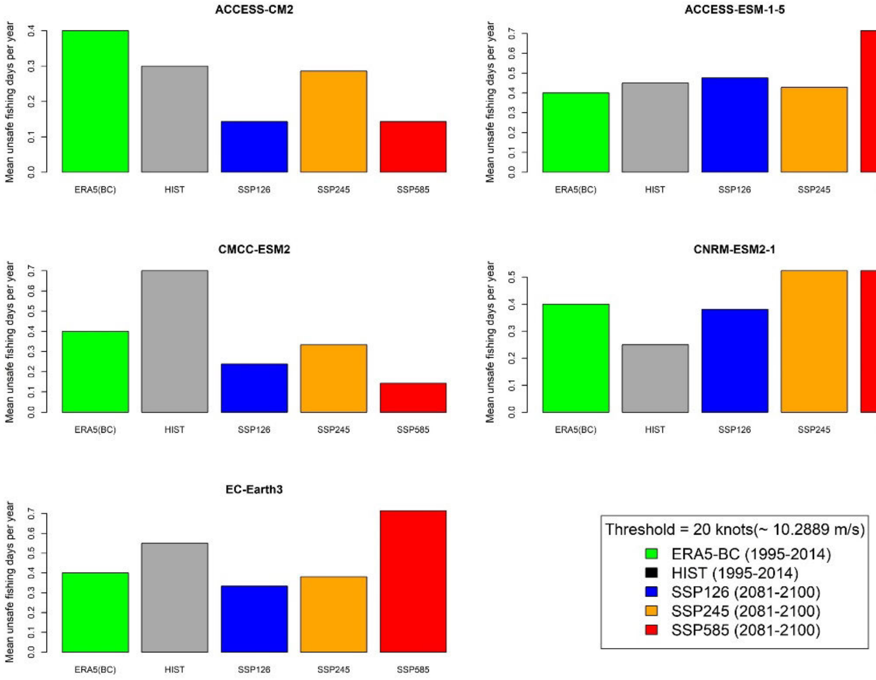


Figure 8-6 Same as Figure 8-5, but for the period 2081–2100.

It is natural to expect that MJO characteristics and associated impacts are likely to change in a warming climate. Some studies using climate model experiments have shown that the frequency of MJO events and eastward propagation speeds are likely to increase with higher greenhouse gas emissions [16]. Under such circumstances, the frequency and intensity of the MJO-associated westerly wind bursts are likely to increase over the equatorial region and affect countries like Nauru (low confidence).

Mid-latitude storms

Extra-tropical cyclones are storm systems that primarily derive energy from the horizontal temperature contrasts that exist in the atmosphere outside the tropics [17]. These storms can generate ocean swells that have disastrous consequences for small islands and atolls in the Pacific [18-20]. They can produce wave heights and hazardous sea states comparable to those caused by cyclones.

For example, a recent significant swell event on 20-21 January 2024 – caused by a distant storm in the Northern Hemisphere – resulted in major impacts to the new seaport construction site in Nauru (Chapter 17, transport section, wave impacts). At the time of this event, no unusual wind activity was recorded at the site, so the swell waves, defined as infragravity waves [21], came as a surprise.

Past studies have suggested that extra-tropical cyclone activity over both hemispheres has changed since the mid-twentieth century. General features include a poleward shift in storm track location, increased storm intensity, but a decrease in frequency [22-24]. In the Northern Hemisphere, McCabe et al [25] found that there has been a significant decrease in mid-latitude cyclone activity and an increase in high-latitude cyclone frequency, suggesting a poleward shift of the storm track, with storm intensity increasing over the North Pacific and North Atlantic. This is consistent with expansion of the Hadley circulation (noted above).

By the end of the century, the frequency of extra-tropical cyclones is projected to decrease (~5 %), whereas mean intensity is projected to increase (~4 %), and tracks are projected to shift poleward [26].

Extreme winds and tropical cyclones

Extreme winds[5] often have major consequences for life and property. In the Pacific, small islands and atolls are often highly exposed to dangerous events such as tropical cyclones, storm surges and large waves [27]. Due to its geographical location close to the equator (0.5°S, 166.9°E), however, Nauru is not impacted by tropical cyclones directly. Nevertheless, remote tropical cyclones and mid-latitude storms in both hemispheres can have considerable indirect effects through destructive waves and storm surges, e.g., [18, 20]. (See Chapters 15 to 17).

Tropical cyclones

Historical variability and trends

Tropical cyclones (TCs) are rapidly rotating storms that originate over tropical oceans with sea surface temperatures (SSTs) that are typically above 25.5 °C, and at least 5° of latitude away from the equator. Southern Hemisphere TCs usually form in the South Pacific Convergence Zone (SPCZ) region and propagate southeast [28, 29]. Consequently, island countries that lie along or poleward of the SPCZ often experience TCs more often, as opposed to those that lie equatorward or farther east [30, 31] (Figure 8-7).

---

[5] Extreme winds can be from multiple sources, which we have not quantified in this work given time limitations and funding. This is something that should be examined in future work.

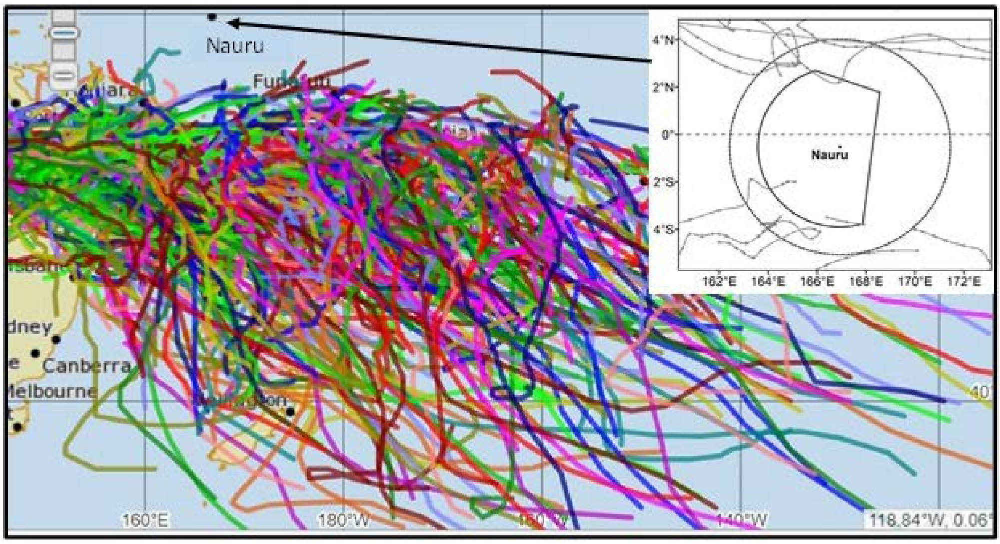


Figure 8-7 Map of TC tracks in the South Pacific for the period 1969/70 to 2021/22 (source: [32]) http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/history/tracks/ . Insert shows a detailed view of initial tracks of TCs within the Nauru EEZ (for 1969/70 to 2021/22 period) and the 500 km (circle) buffer zone, noting the buffer zone includes cyclones from both hemispheres.

Given that Nauru is located very close to the equator (0.5°S, 166.9°E), there has been no evidence of TCs that made any direct impact during 1969/70 to 2021/22 (Figure 8-7). However, there have been instances when initial tracks of a few cyclones were recorded within 500 km of Nauru.

In the South Pacific Ocean basin (east of longitude 145°E), an average of ~11 TCs form each year with the peak activity occurring during January-March. The El Niño Southern Oscillation (ENSO) affects the mean location of TC genesis positions and tracks [33, 34] (Table 8-1). Chand, Walsh [35] showed that the annual number of TCs in the South Pacific Ocean basins have declined since the mid-nineteenth century. There is also some indication that the number of severe TCs (i.e., Categories 4-5 based on Saffir-Simpson scale) may have increased slightly [36]. Deo, Chand [37] showed that TC-induced rainfall has also increased in the South Pacific over recent decades, though it is unclear whether the increase is due to anthropogenic climate change.

In the western North Pacific basin, around 30 TCs form each year but with a large year-to-year variability due to ENSO [34]. Wang and Chan [38] observed an increase in the number of TCs in the western North Pacific during strong El Niño years, though they found no relationship between TC numbers and ENSO indices. The Pacific Decadal Oscillation (PDO) is another important mode of natural climate variability that can affect TCs in the basin. During the PDO warm (or positive) phase, TC activity often gets enhanced in the entire western North Pacific, whereas in the cold (or negative) phase, TC activity is more confined to the eastern part of the basin [39]. The frequency of western North Pacific TCs has decreased significantly since 1950s [35]. The locations of TCs in the western North Pacific have also shifted northward during the last four decades, primarily due to the shift of TC tracks [40].

Table 8-1 Summary of ENSO influences on TC's in the Northern and Southern Hemisphere sections of the Pacific Ocean.

	El Niño years	La Niña years
Western North Pacific Ocean	The mean genesis location is shifted southeast. TC intensity and duration tend to increase. More TCs in the western North Pacific during strong El	The mean genesis location is shifted northwest. TC intensity and duration tend to decrease.

	Niño years. A reduction in the number of TCs in the summer following an El Niño event has also been found [41].	
South Pacific Ocean	TC activity shifts north-eastward across to the Cook Islands and French Polynesia, with the greatest incidence around the dateline, extending east-southeast of the Fiji Islands. Simultaneously, low activity dominates the Coral Sea and Australian regions.	TC activity is displaced south-westward into the New Caledonia, Coral Sea and Australian regions with relatively low activity east of about longitude 170° E.

Projections

Basin-scale projections of TC frequency are uncertain due to climate model limitations, so TC projections have low confidence (Figure 8-8). This includes inconsistencies between models in simulating regional SST patterns, large-scale circulations patterns and the rate of ocean warming. There is general agreement between studies that projected TC frequencies in the Southern Hemisphere will decline and/or shift poleward. TC frequency changes for the Northern Hemisphere basins are more uncertain. Studies that used Global Climate Models (GCMs), such as those from CMIP5/CMIP6 experiments, generally project a decline in TC numbers, whereas those that used dynamically downscaled high-resolution models project an increase [42]. It is difficult to ascertain whether the increase in TC numbers in high-resolution models is a result of changes in environmental conditions that favour TC developments, or a result of increased frequency of incipient vortices, or ‘seeds’, that get converted to cyclones at a much higher rate than those in coarser-resolution GCMs [43].

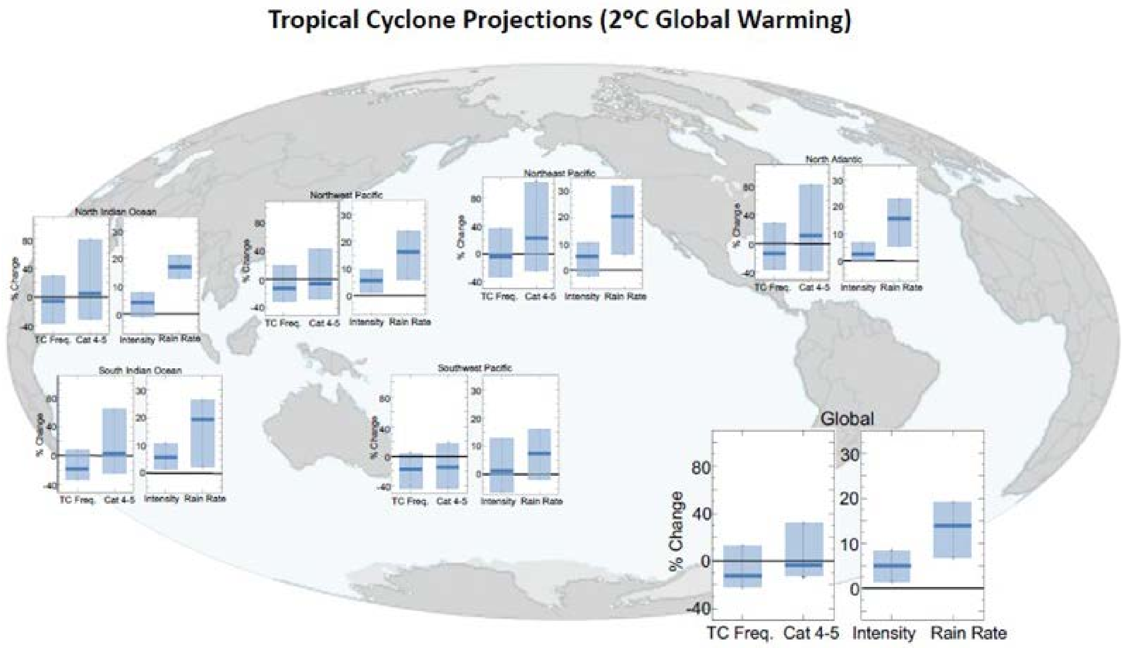


Figure 8-8 Summary of TC projections for a 2 °C global warming reported in Knutson, Camargo [44]. Shown for each basin and the globe are median values and uncertainty ranges for changes in TC frequency, severe (Cat. 4–5) TC frequency, TC intensity (windspeed), and TC rain rate. For TC frequency, the 5th–95th percentile range across published estimates is shown. For the other metrics, the 10th–90th percentile range is shown. Source: Knutson, Camargo [44].

Some studies have also examined effects of global warming on changes in TC frequency under current- and future-climate ENSO conditions [34]. For example, Chand, Tory [45] found that while the general trend is toward fewer TCs in a warming climate globally, including the southwest Pacific, TCs may become more frequent during future-climate El Niño compared with present-climate El Niño events (and less frequent during future-climate La Niña events) around a group of small island nations in the Pacific (for example, Fiji, Vanuatu, Marshall Islands and Hawaii; Figure 8-9). This includes Nauru.

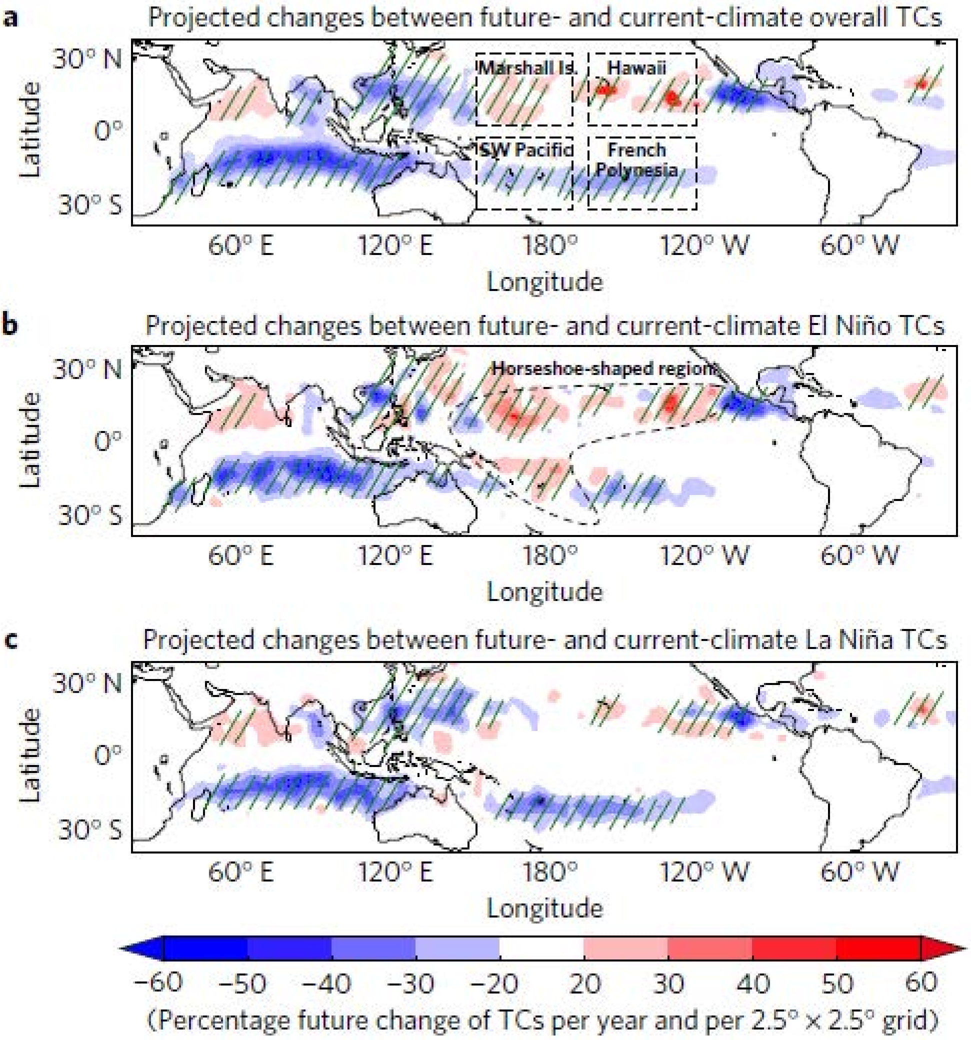


Figure 8-9 Projected future changes in TC frequency: (a) Overall average, (b) El Niño and (c) La Niña. Red shading indicates projected future increases in TC frequency. Stippling denotes changes that are statistically significant at the 95% level. The horseshoe-shaped region where TC frequency gets enhanced during future-climate El Niño is highlighted. Source: Chand, Tory [45].

Caveats, uncertainties, confidence, and limitations

Estimating the future changes in average and extreme wind for Nauru presents significant challenges. This is primarily due to inherent limitations associated with climate models including, but not limited to, the presence of excessive cold tongue biases (SSTs too cold in the tropical western Pacific) [46] and coarse spatial resolution [47]. These limitations are further complicated by the presence of large natural variability that makes it difficult to discern trends. Using a larger sample of

CMIP6 climate models, with low biases, combined with high-resolution downscaling, may reduce some of these limitations.

References

1. Held, I.M., 100 Years of Progress in Understanding the General Circulation of the Atmosphere. *Meteorological Monographs,* 2019. 59: p. 6.1-6.23 DOI: https://doi.org/10.1175/AMSMONOGRAPHS-D-18-0017.1
2. Hu, Y., H. Huang, and C. Zhou, Widening and weakening of the Hadley circulation under global warming. *Science Bulletin,* 2018. 63(10): p. 640-644 DOI: https://doi.org/10.1016/j.scib.2018.04.020
3. Power, S., M. Lengaigne, A. Capotondi, M. Khodri, J. Vialard, B. Jebri, E. Guilyardi, S. McGregor, J.-S. Kug, M. Newman, M.J. McPhaden, G. Meehl, D. Smith, J. Cole, J. Emile-Geay, D. Vimont, A.T. Wittenberg, M. Collins, G.-I. Kim, W. Cai, Y. Okumura, C. Chung, K.M. Cobb, F. Delage, Y.Y. Planton, A. Levine, F. Zhu, J. Sprintall, E.D. Lorenzo, X. Zhang, J.-J. Luo, X. Lin, M. Balmaseda, G. Wang, and B.J. Henley, Decadal climate variability in the tropical Pacific: Characteristics, causes, predictability, and prospects. *Science,* 2021. 374(6563): p. eaay9165 DOI: https://doi.org/10.1126/science.aay9165
4. Höjgård-Olsen, E., *Observations of the tropical atmospheric water cycle and its variations with sea surface temperature using a constellation of satellites*. 2020, Université Paris-Saclay. Available from: https://theses.hal.science/tel-03215903/
5. Trenberth, K.E. and D.J. Shea, On the Evolution of the Southern Oscillation. *Monthly Weather Review,* 1987. 115(12): p. 3078-3096 DOI: https://doi.org/10.1175/1520-0493(1987)115<3078:OTEOTS>2.0.CO;2
6. 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. Available from: https://agupubs.onlinelibrary.wiley.com/doi/book/10.1002/9781119548164
7. Trenberth, K.E., The definition of El Niño. *Bull. Amer. Meteor. Soc.,* 1997. 78: p. 2771–2777.
8. Bosserelle, C., S. Reddy, and D. Lal, *WACOP wave climate reports.* 2015: Suva, Fiji Islands.; Available from: https://wacop.gsd.spc.int/Atlas/Regional/Pdf/NA/Nauru.pdf
9. Li, Y., Q. Chen, X. Liu, J. Li, N. Xing, F. Xie, J. Feng, X. Zhou, H. Cai, and Z. Wang, Long-Term Trend of the Tropical Pacific Trade Winds Under Global Warming and Its Causes. *Journal of Geophysical Research: Oceans,* 2019. 124(4): p. 2626-2640 DOI: https://doi.org/10.1029/2018JC014603
10. 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. DOI: https://doi.org/10.1038/s43247-023-00912-4
11. 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. DOI: https://doi.org/10.1029/2022JD037563
12. Liang, Y., A.V. Fedorov, and P. Haertel, Intensification of Westerly Wind Bursts Caused by the Coupling of the Madden-Julian Oscillation to SST During El Niño Onset and Development. *Geophysical Research Letters,* 2021. 48(9): p. e2020GL089395. DOI: https://doi.org/10.1029/2020GL089395
13. Zhang, C., Madden-Julian Oscillation. *Rev. Geophys,* 2005. 43(2): p. RG2003-n/a DOI: 10.1029/2004RG000158. DOI: https://doi.org/10.1029/2004RG000158
14. Grose, M.R., S. Narsey, R. Trancoso, C. Mackallah, F. Delage, A. Dowdy, G. Di Virgilio, I. Watterson, P. Dobrohotoff, H.A. Rashid, S. Rauniyar, B. Henley, M. Thatcher, J. Syktus, G. Abramowitz, J.P. Evans, C.-H. Su, and A. Takbash, A CMIP6-based multi-model downscaling ensemble to underpin climate change services in Australia. *Climate Services,* 2023. 30: p. 100368 DOI: https://doi.org/10.1016/j.cliser.2023.100368

15. 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. DOI: https://doi.org/10.1175/1520-0477(1991)072<0339:TTAMAF>2.0.CO;2
16. Arnold, N.P., M. Branson, Z. Kuang, D.A. Randall, and E. Tziperman, MJO Intensification with Warming in the Superparameterized CESM. *Journal of climate,* 2015. 28(7): p. 2706-2724 DOI: 10.1175/JCLI-D-14-00494.1. DOI: https://doi.org/10.1175/JCLI-D-14-00494.1
17. Lodise, J., S. Merrifield, C. Collins, P. Rogowski, J. Behrens, and E. Terrill, Global Climatology of Extratropical Cyclones From a New Tracking Approach and Associated Wave Heights From Satellite Radar Altimeter. *Journal of Geophysical Research: Oceans,* 2022. 127(11): p. e2022JC018925 DOI: https://doi.org/10.1029/2022JC018925
18. 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. DOI: https://doi.org/10.1016/j.gloplacha.2013.06.006
19. Pathirana, S., I. Young, and A. Meucci, Modelling swell propagation across the Pacific. *Frontiers in Marine Science,* 2023. 10 DOI: https://doi.org/10.3389/fmars.2023.1187473
20. Semedo, A., K. Sušelj, A. Rutgersson, and A. Sterl, A Global View on the Wind Sea and Swell Climate and Variability from ERA-40. *Journal of Climate,* 2011. 24(5): p. 1461-1479 DOI: https://doi.org/10.1175/2010JCLI3718.1
21. Bertin, X., A. de Bakker, A. Van Dongeren, G. Coco, G. André, F. Ardhuin, P. Bonneton, F. Bouchette, B. Castelle, and W.C. Crawford, Infragravity waves: From driving mechanisms to impacts. *Earth-Science Reviews,* 2018. 177: p. 774-799. DOI: https://doi.org/10.1016/j.earscirev.2018.01.002
22. Gulev, S.K., O. Zolina, and S. Grigoriev, Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. *Climate Dynamics,* 2001. 17(10): p. 795-809 DOI: https://doi.org/10.1007/s003820000145.
23. Simmonds, I. and K. Keay, Variability of Southern Hemisphere Extratropical Cyclone Behavior, 1958–97. *Journal of Climate,* 2000. 13(3): p. 550-561 DOI: https://doi.org/10.1175/1520-0442(2000)013<0550:VOSHEC>2.0.CO;2
24. Wang, X.L., V.R. Swail, and F.W. Zwiers, Climatology and Changes of Extratropical Cyclone Activity: Comparison of ERA-40 with NCEP–NCAR Reanalysis for 1958–2001. *Journal of Climate,* 2006. 19(13): p. 3145-3166 DOI: https://doi.org/10.1175/JCLI3781.1
25. McCabe, G.J., M.P. Clark, and M.C. Serreze, Trends in Northern Hemisphere Surface Cyclone Frequency and Intensity. *Journal of Climate,* 2001. 14(12): p. 2763-2768 DOI: https://doi.org/10.1175/1520-0442(2001)014<2763:TINHSC>2.0.CO;2
26. Priestley, M.D.K. and J.L. Catto, Future changes in the extratropical storm tracks and cyclone intensity, wind speed, and structure. *Weather Clim. Dynam.,* 2022. 3(1): p. 337-360 DOI: https://doi.org/10.5194/wcd-3-337-2022 .
27. Chand, S., S. Power, K. Walsh, N. Holbrook, K. McInnes, K. Tory, H. Ramsay, R. Hoeke, and A.S. Kiem, Climate processes and drivers in the Pacific and global warming: a review for informing Pacific planning agencies. *Climatic Change,* 2023. 176(2): p. 5 DOI: https://doi.org/10.1007/s10584-022-03467-z
28. Vincent, D.G., The South Pacific Convergence Zone (SPCZ): A Review. *Monthly Weather Review,* 1994. 122(9): p. 1949-1970 DOI: https://doi.org/10.1175/1520-0493(1994)122<1949:TSPCZA>2.0.CO;2
29. Vincent, E., M. Lengaigne, C. Menkes, N. Jourdain, P. Marchesiello, and G. Madec, Interannual variability of the South Pacific Convergence Zone and implications for tropical cyclone genesis. *Climate Dynamics,* 2011. 36: p. 1881-1896 DOI: https://doi.org/10.1007/s00382-009-0716-3

30. 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* Ch in *Climate Change and Impacts in the Pacific*, L. Kumar, Editor. 2020, Springer International Publishing: Cham. p. 251-273. Available from: https://www.springerprofessional.de/en/climate-change-and-impacts-in-the-pacific/17615638
31. Bell, S.S., S.S. Chand, and C. Turville, Projected changes in ENSO-driven regional tropical cyclone tracks. *Climate Dynamics,* 2020. 54(3): p. 2533-2559 DOI: https://doi.org/10.1007/s00382-020-05129-1
32. Australian Bureau of Meteorology. *Southern Hemisphere Tropical Cyclone Data Portal*. 2024 Available from: http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/history/tracks/
33. Chand, S.S., *Impact of Climate Variability and Change on Tropical Cyclones in the South Pacific* Ch in *Encyclopedia of the Anthropocene*, D.A. Dellasala and M.I. Goldstein, Editors. 2018, Elsevier: Oxford. p. 217-225.
34. Lin, I.-I., S.J. Camargo, C.M. Patricola, J. Boucharel, S. Chand, P. Klotzbach, J.C.L. Chan, B. Wang, P. Chang, T. Li, and F.-F. Jin, *ENSO and Tropical Cyclones* Ch in *El Niño Southern Oscillation in a Changing Climate*. 2020. p. 377-408. Available from: https://agupubs.onlinelibrary.wiley.com/doi/book/10.1002/9781119548164
35. 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: https://doi.org/10.1038/s41558-022-01388-4
36. Klotzbach, P.J., K.M. Wood, C.J. Schreck III, S.G. Bowen, C.M. Patricola, and M.M. Bell, Trends in global tropical cyclone activity: 1990–2021. *Geophysical Research Letters,* 2022. 49(6): p. e2021GL095774. DOI: https://doi.org/10.1029/2021GL095774
37. Deo, A., S.S. Chand, H. Ramsay, N.J. Holbrook, S. McGree, A. Magee, S. Bell, M. Titimaea, A. Haruhiru, P. Malsale, S. Mulitalo, A. Daphne, B. Prakash, V. Vainikolo, and S. Koshiba, Tropical cyclone contribution to extreme rainfall over southwest Pacific Island nations. *Climate Dynamics,* 2021. 56(11): p. 3967-3993 DOI: https://doi.org/10.1007/s00382-021-05680-5
38. Wang, B. and J.C.L. Chan, How Strong ENSO Events Affect Tropical Storm Activity over the Western North Pacific. *Journal of Climate,* 2002. 15(13): p. 1643-1658 DOI: https://doi.org/10.1175/1520-0442(2002)015<1643:HSEEAT>2.0.CO;2
39. Wang, C., M. Fu, B. Wang, L. Wu, and J.J. Luo, Pacific Decadal Oscillation modulates the relationship between Pacific Meridional Mode and tropical cyclone genesis in the western North Pacific. *Geophysical Research Letters,* 2023. 50(5): p. e2022GL101710. DOI: https://doi.org/10.1029/2022GL101710
40. Chen, T., S. Chen, M. Zhou, C. Tu, A. Zhang, Y. Chen, and W. Li, Northward Shift in Landfall Locations of Tropical Cyclones over the Western North Pacific during the Last Four Decades. *Advances in Atmospheric Sciences,* 2022. 39(2): p. 304-319 DOI: 10.1007/s00376-021-1077-z. DOI: https://doi.org/10.1007/s00376-021-1077-z
41. Chan, J.C.L., Tropical Cyclone Activity in the Northwest Pacific in Relation to the El Niño/Southern Oscillation Phenomenon. *Monthly Weather Review,* 1985. 113(4): p. 599-606 DOI: https://doi.org/10.1175/1520-0493(1985)113<0599:TCAITN>2.0.CO;2
42. 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. DOI: https://doi.org/10.1175/BAMS-D-18-0194.1
43. Vecchi, G.A., T.L. Delworth, H. Murakami, S.D. Underwood, A.T. Wittenberg, F. Zeng, W. Zhang, J.W. Baldwin, K.T. Bhatia, W. Cooke, J. He, S.B. Kapnick, T.R. Knutson, G. Villarini, K. van der Wiel, W. Anderson, V. Balaji, J.H. Chen, K.W. Dixon, R. Gudgel, L.M. Harris, L. Jia, N.C.

Johnson, S.-J. Lin, M. Liu, C.H.J. Ng, A. Rosati, J.A. Smith, and X. Yang, Tropical cyclone sensitivities to CO2 doubling: roles of atmospheric resolution, synoptic variability and background climate changes. *Climate Dynamics,* 2019. 53(9): p. 5999-6033 DOI: 10.1007/s00382-019-04913-y. DOI: https://doi.org/10.1007/s00382-019-04913-y

44. Knutson, T., S.J. Camargo, J.C.L. Chan, K. Emanuel, C.-H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 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 DOI: https://doi.org/10.1175/BAMS-D-18-0194.1
45. Chand, S., K. Tory, H. Ye, and K. Walsh, Projected increase in El Niño-driven tropical cyclone frequency in the Pacific. *Nature Climate Change,* 2017. *7: p. 123-127*. DOI: https://www.nature.com/articles/nclimate3181
46. Zhang, Q., B. Liu, S. Li, and T. Zhou, Understanding models' global sea surface temperature bias in mean state: from CMIP5 to CMIP6. *Geophysical Research Letters,* 2023. 50(4): p. e2022GL100888. DOI: https://doi.org/10.1029/2022GL100888
47. Evans, J.P., A. Belmadani, C. Menkes, T. Stephenson, M. Thatcher, P.B. Gibson, and A. Peltier, Higher-resolution projections needed for small island climates. *Nature Climate Change,* 2024. 14(7): p. 668-670 DOI: 10.1038/s41558-024-02028-9 .

Chapter 9 Sea level rise and coastal inundation

Introduction

Coastal inundation risks arise due to a combination of factors, including tides, storm surges, storm waves, interannual sea level variability, and sea level rise (SLR). The IPCC chapter on *Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities* concludes that the rise in global mean sea level (GMSL) is accelerating [1]. However, extreme waves interacting with SLR are likely to result in severe damage to Nauru's coastal zone over the coming decades.

Sea level rise implications are of particular concern for Nauru given its relatively small land area of 21km^2 [2], and limited surface water resources. The island is divided in three parts: Topside, Bottomside and Fringing Reef [3]. The Bottomside encircles a limestone escarpment that rises some 30 metres to a mainly uninhabitable central plateau, known locally as Topside [4]. Most of Nauru's population (93 %) [5] reside in Bottomside, which ranges from 100 to 300 metres wide and is exposed to sea level rise and coastal inundation [6] (green shading; Figure 9-1).

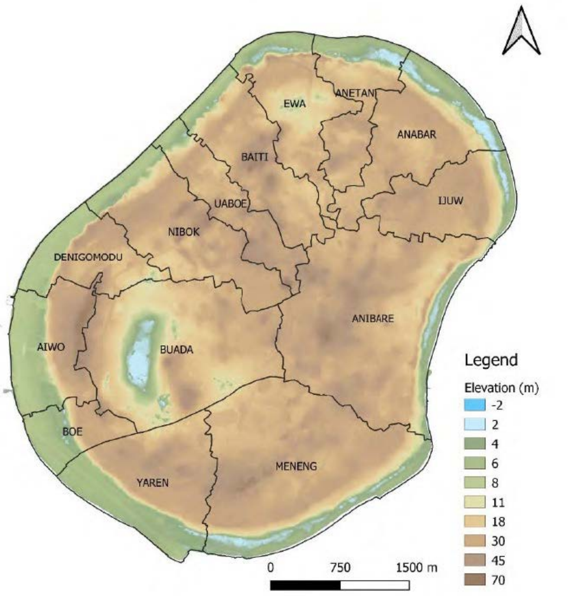


Figure 9-1 Map of Nauru districts and elevations. Colour represents elevation in metres above Nauru Island Datum (NID). Colour scale illustrates high/low topography. [Data source: SPC and [6]].

Coastal inundation is commonly experienced as temporary coastal flooding, along with erosion and the loss or change of coastal ecosystems. However, due to sea level rise, coastal inundation is gradually causing permanent submergence and salinisation of soils, groundwater and surface water, as well as impeded drainage. This is occurring in Nauru with Buada Lagoon which is brackish [3].

Observations and trends

Sea level

Global mean sea level rose 20 cm between 1901–2018 [7, 8]. The long-term rate of sea level rise has more than doubled since the start of the satellite record, increasing from 2.13 mm/year between 1993 and 2002 to 4.77 mm/year between 2014 and 2023 [9].

Over the western tropical Pacific, sea level rose about 10-15 cm between 1993 and 2020 [10], which is faster than in the central and eastern parts of the tropical Pacific [11] (Figure 9-2).

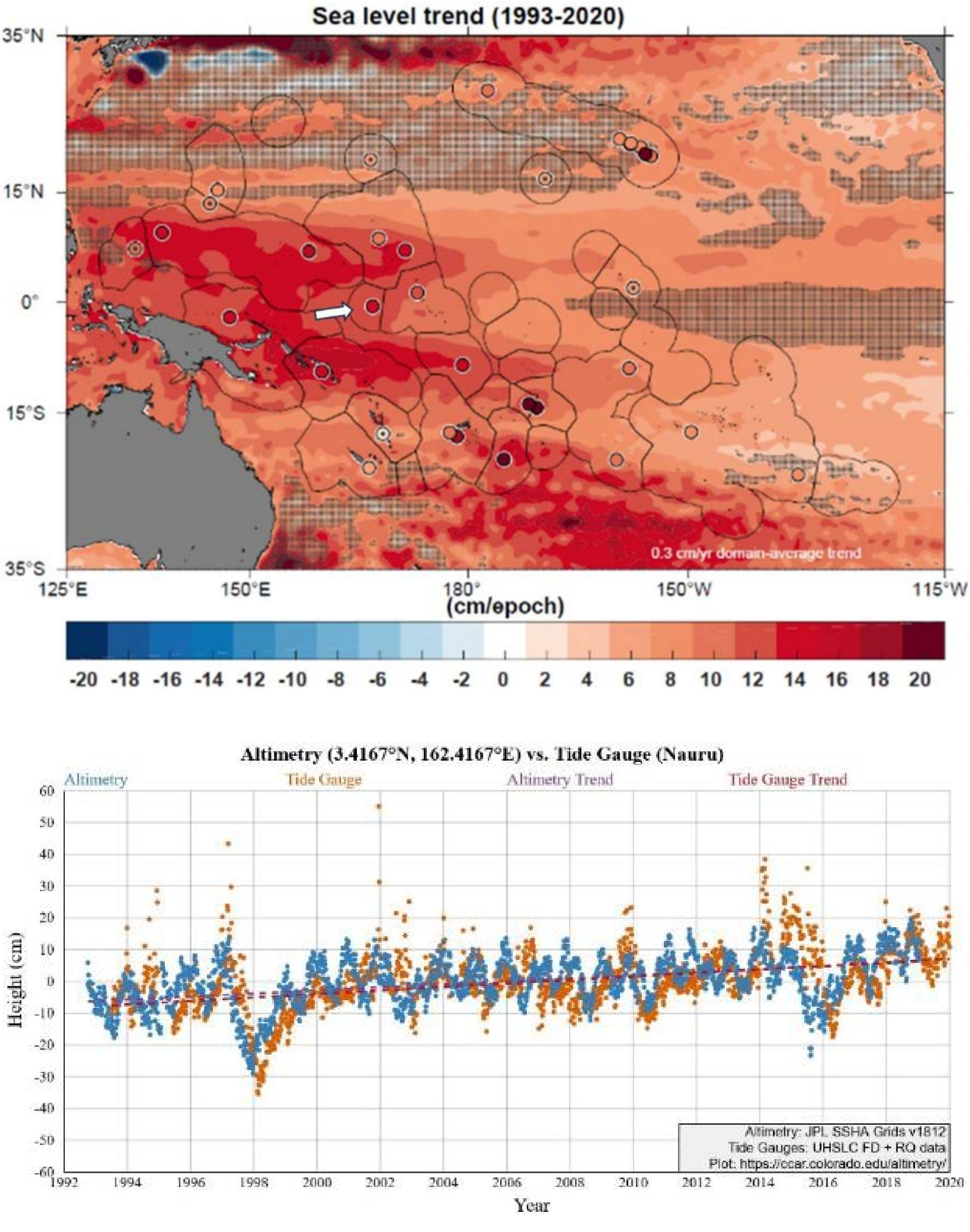


Figure 9-2 Top: Sea surface height (SSH) trends (cm/1993–2020 epoch) from satellite altimetry (shaded contours) and sea level trends from tide gauges (circles), with white arrow indicating Nauru EEZ. Trends that are less than interannual variability, which is determined by the standard deviation of monthly anomalies, are indicated by hatching and circles with dots for the altimetry and tide gauges, respectively. Source: [10] Bottom: Daily SSH data from satellite altimetry and the Nauru tide gauge measured relative sea level (see Sea Level Explorer Tool (https://ccar.colorado.edu/altimetry/)).

In recent decades, the measured rate of relative sea level rise at Nauru has been higher than the global rate [10], with land subsidence also contributing slightly (see altimetry in Figure 9-2 above). The rate of subsidence is below 1 mm/year based on tide gauge analysis (-0.9 ± 0.2 mm/year) or satellite altimetry data (-0.6 ± 0.6 mm/year) based on data from 2003-2014 [6, 12]. Overall, the relative sea level in Nauru in 2020 was about 150 mm higher than it was in 1974 and has been increasing at 2.4 mm/year from 1974–2019 (Figure 9-3) [6]. However, since 1993, sea level rise has been increasing at 3.5-4.5 mm/year [10].

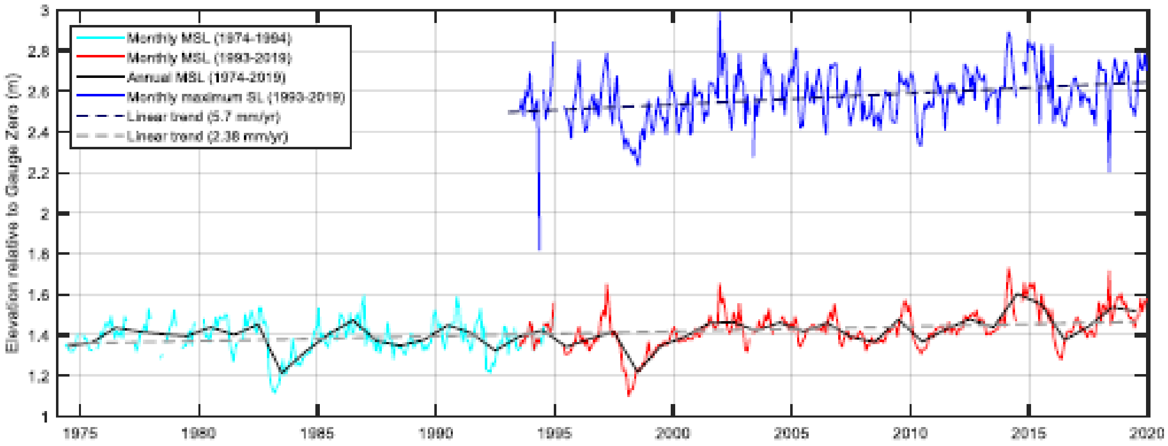


Figure 9-3 Increase in sea level at Nauru tide gauge 1974–2019. Dark blue line is monthly maximum recorded sea level (1993–2019), red/light blue = monthly mean sea level for two measurement periods, black solid line is annual mean sea level (1974–2019). (Data source: Pacific Sea Level and Geodetic Monitoring Project; Station ID: 200858).

Sea level rise increases in the number and elevation of high-water events. In Nauru, the monthly maximum sea level (i.e., the highest tide each month) elevation has increased over 1993–2019 at a rate of 5.7 mm/year (Figure 9-4). This has led to an increase in the intensity and duration of king-tide events [6].

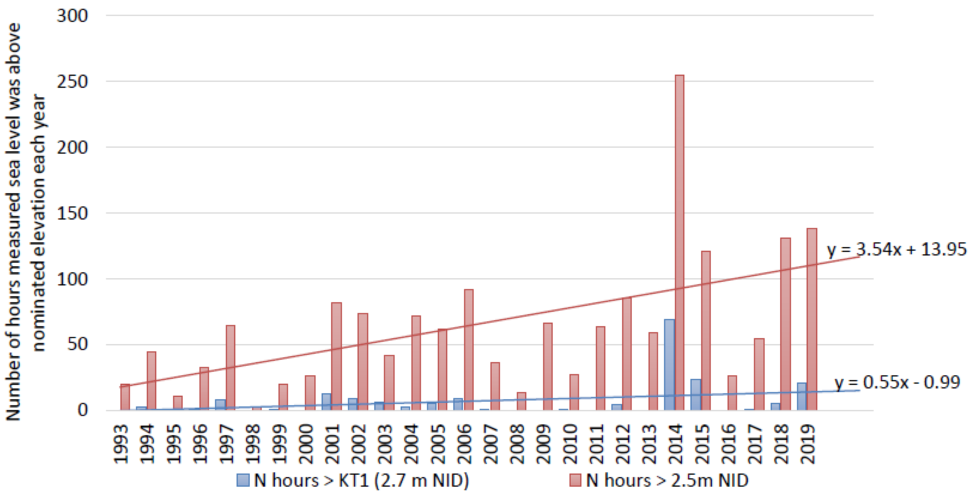


Figure 9-4 Increase in annual duration of high-water events over 1993–2020 tide gauge record. Created from hourly data from Nauru tide gauge [Data source: PSLGM][6].

Extreme sea level and coastal inundation

Introduction

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) [13, 14]. Local geomorphology influences the relative contributions of these factors and how they combine to create extreme sea levels. For example, coastal bathymetry (shape of the seabed), especially the presence of offshore reefs, influence storm surges and wave-driven contributions. Additionally, offshore reefs cause waves to break offshore and thereby reduce the wave energy (and height) that eventually reach the coast (Figure 9-5). The dynamic nature of coastal foreshores can result in highly localised changes in response to currents and waves, resulting in both sand deposition and coastal erosion [15].

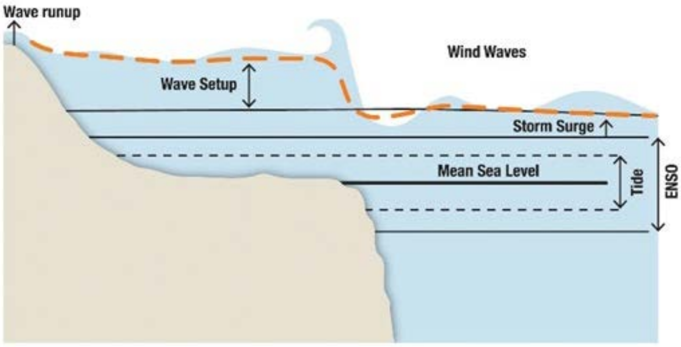


Figure 9-5 Schematic diagram of the contributions to extreme sea levels at the coast for a reef fronted island. The different contributions are tides, storm surge, storm waves and interannual sea level variability. These factors can sometimes coincide but often occur separately; for instance, if a storm surge happens at low tide, the total water level may not be extreme at the adjacent coastline.

Coastal inundation impacts are already being witnessed regularly throughout Nauru on the high spring tides, with most of the large wave events having wave heights exceeding 2 m from a westerly direction [4].

Sea level variability

The interannual variability of mean sea level is around 23 cm after removal of the seasonal cycle [16].

One of the main contributors to sea level variability on seasonal to interannual timescales in the Pacific Ocean is ENSO (Figure 9-6). Four of the five largest wave events occurred during El Niño years [4].

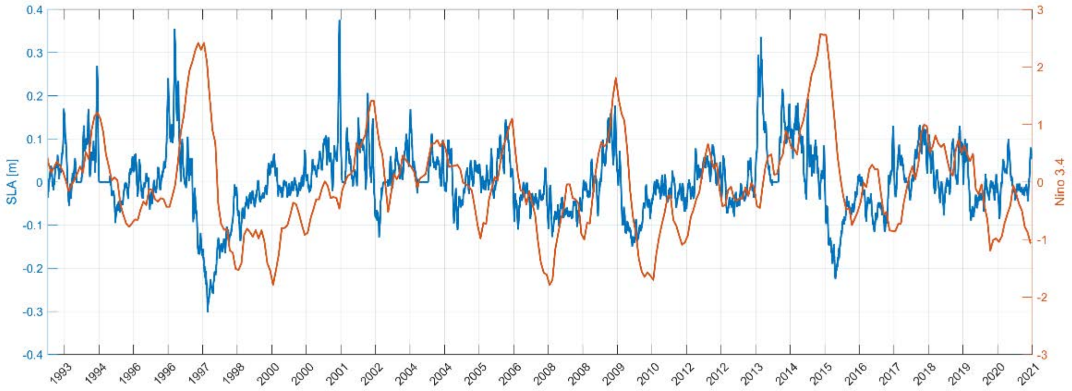


Figure 9-6 Sea-level anomaly (SLA: blue line) for Nauru and ENSO phase (Nino 3.4 index: orange line) (Source: [14]).

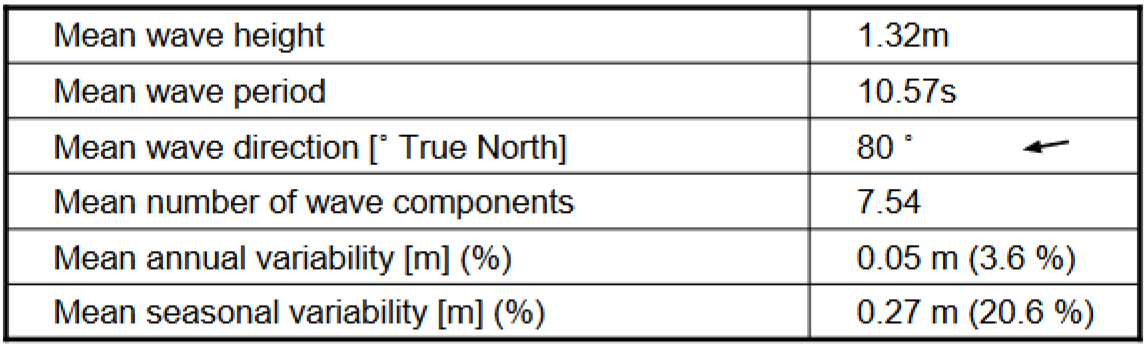
Tides

The term “king tide”[6] is commonly used to describe an especially high spring tide[7]. Allis et al, (2020) [6] produced an analysis of the tide gauge data and determined that the king tide elevation is 2.7 m for Nauru Island Datum (NID) with approximately 1 % exceedance probability at present day sea levels (termed ‘KT1’) (1993–2020). The Mean High Water Spring (MHWS) level calculated at the 90th percentile (10 % exceedance probability) of all high tides is approximately 2.4 m NID [6]. Only 5 tides per year are higher than KT1, generally clustered in the November to March window[6] [6].

Wave climate

The average sea state in Nauru is moderate, dominated by easterly trade winds that generate short period waves from the east (Figure 9-7 Mean and seasonal wave roses for Nauru. The wave hindcast evaluated the wave conditions in the region between 1979 and 2013 [17]. (left). During 1979 to 2012, the annual mean wave height was 1.32 m, the annual mean wave direction was 80˚ (Table 9-1), and the annual mean wave period was 10.57 s (Figure 9-7) [17]. In the Pacific, waves often come from multiple directions and with different wave periods. In Nauru, there are often more than 8 different wave direction/period components. The peak wave activity for Nauru in terms of significant wave height[8] and wave period occurs in the months from November to March [4, 18]. Seasonal wave roses also indicate the seasonal changes in height and direction [17] (Figure 9-7).

Table 9-1 Mean wave conditions calculated between 1979 and 2012 for Nauru



Mean wave height	1.32m
Mean wave period	10.57s
Mean wave direction [˚ True North]	80 ˚ ←
Mean number of wave components	7.54
Mean annual variability [m] (%)	0.05 m (3.6 %)
Mean seasonal variability [m] (%)	0.27 m (20.6 %)

Wave conditions follow a seasonal cycle with the largest waves occurring during December and March. A shift in wave direction occurs during the year, with north-easterly wave directions during the December to February and south-easterly wave directions during June to August (Figure 9-7, right). This shift is likely linked to the seasonal north-southward oscillation of the Intertropical Convergence Zone [18].

---

[6] King tides (or high water spring tides) occur a few times every year, when the gravitational pull of the sun and moon upon the earth is strongest. This happens when the moon is closest to the earth in its monthly orbit, which is between November and March in Nauru. When this coincides with a spring tide, it will produce an especially high tide, or king tide.

[7] Spring tides are very high tides and very low tides that occur during full and new moon phases, when the gravitational forces of the sun and moon combine to exert a stronger pull on the oceans.

[8] In physical oceanography, the significant wave height (SWH, or Hs) is defined traditionally as the mean wave height (trough to crest) of the highest third of the waves. Also see Glossary definition.

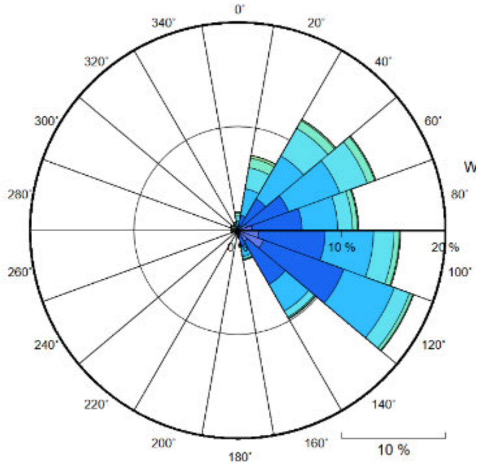
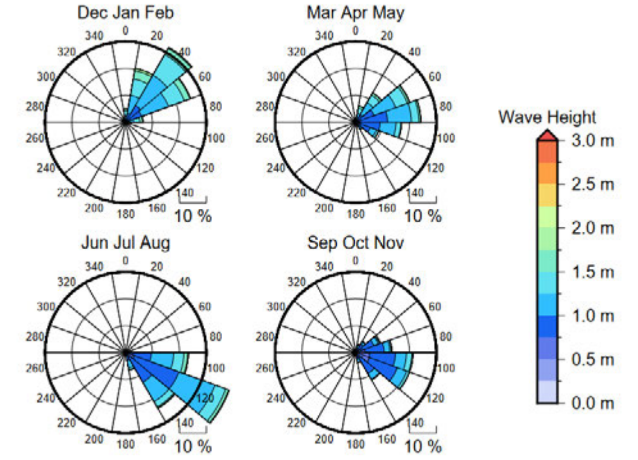
Mean wave rose	Seasonal wave rose
	

Figure 9-7 Mean and seasonal wave roses for Nauru. The wave hindcast evaluated the wave conditions in the region between 1979 and 2013 [17].

While the mean wave climate is dominated by the trade wind waves from the east, the larger waves occur mostly from the west (Figure 9-8) due to the effect of the Kiribati Gilbert Islands blocking wave energy from further east [19]. Large and severe waves (Figure 9-8) can be generated by different weather events such as cyclones, distant extra-tropical storms and strong trade winds [17]. These meteorological events are very dependent on the season and year [17] (Figure 9-9).

Large waves exceed the 90th percentile of the wave height, i.e. they occur 10 % of the time (37 days in a year). Large wave events can cause coastal inundation and erosion when they occur at the same time as a spring tide.

Severe waves are less common than large waves. They occur less than 1 % of the time (4 days in a year) and can be associated with coastal erosion and inundation, especially if they occur during spring tides. Water conditions are hazardous during these events. In Nauru the threshold for severe waves is 2.1 m [17].

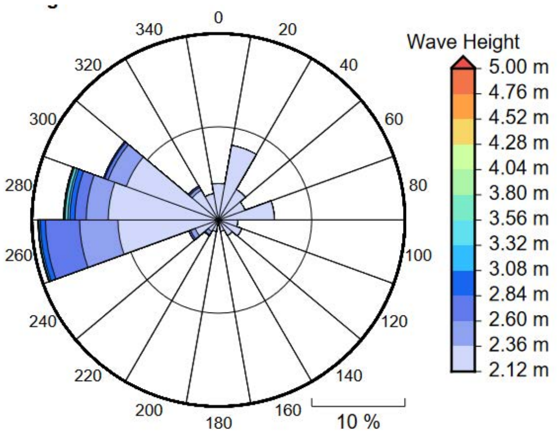
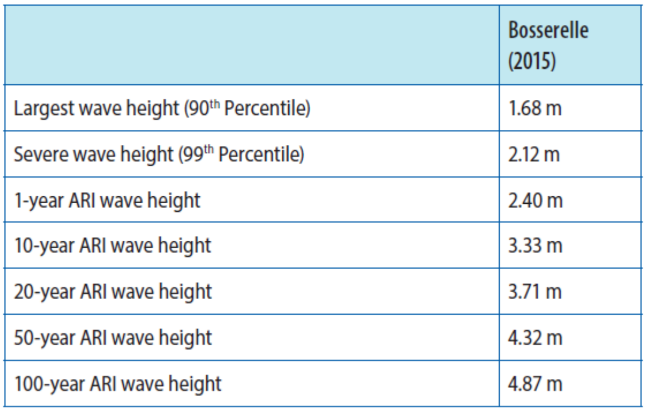


Figure 9-8 Annual large and severe waves (1979–2012) [17]. The circles (polar axis) represent how often a wave direction/height happens (i.e. the percentage of occurrence); each circle shows the 10 % occurrence with the outer circle representing 20 % occurrence. Each wedge represents a range of direction 20 degrees wide with the centre direction of each wedge displayed on the outer circle. Wave heights are split into intervals of 0.25 m. Each interval is associated with a colour on the scale right of the rose. Note that direction is where the waves are coming from. The wave hindcast evaluated the wave conditions in the region between 1979 and 2012.

Extreme waves

Nauru is especially vulnerable to remote swell-driven waves causing coastal inundation due to the narrow fringing reefs. The highest wave experienced by Nauru to date was in 1980 at 4.28 metres [4].

Table 9-2 Nauru extreme wave distributions and summary of extreme wave analysis. The wave hindcast evaluated the wave conditions in the region between 1979 and 2013. Source: [17].



	Bosserelle (2015)
Largest wave height (90th Percentile)	1.68 m
Severe wave height (99th Percentile)	2.12 m
1-year ARI wave height	2.40 m
10-year ARI wave height	3.33 m
20-year ARI wave height	3.71 m
50-year ARI wave height	4.32 m
100-year ARI wave height	4.87 m

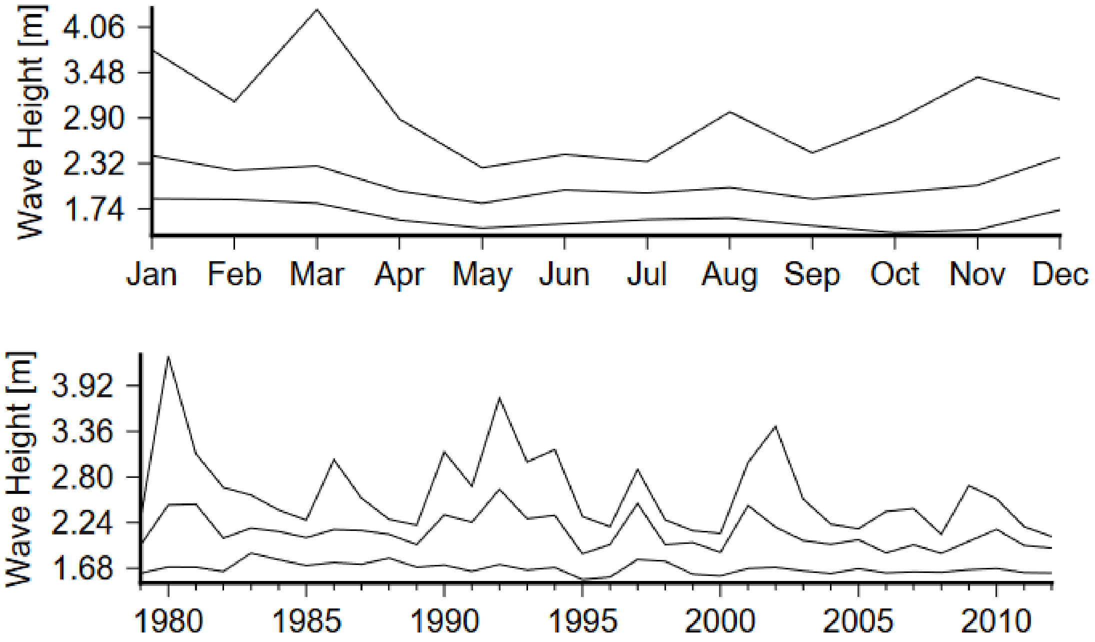


Figure 9-9 Monthly (top) and annual (bottom) variation in large waves (90th percentile; lower curve), severe waves (99th percentile) (middle curve) and the largest wave (upper curve) in Nauru. The wave hindcast evaluated the wave conditions in the region between 1979 and 2013. [17].

Sea level rise and exposure to inundation

Sea level rise projections[9]

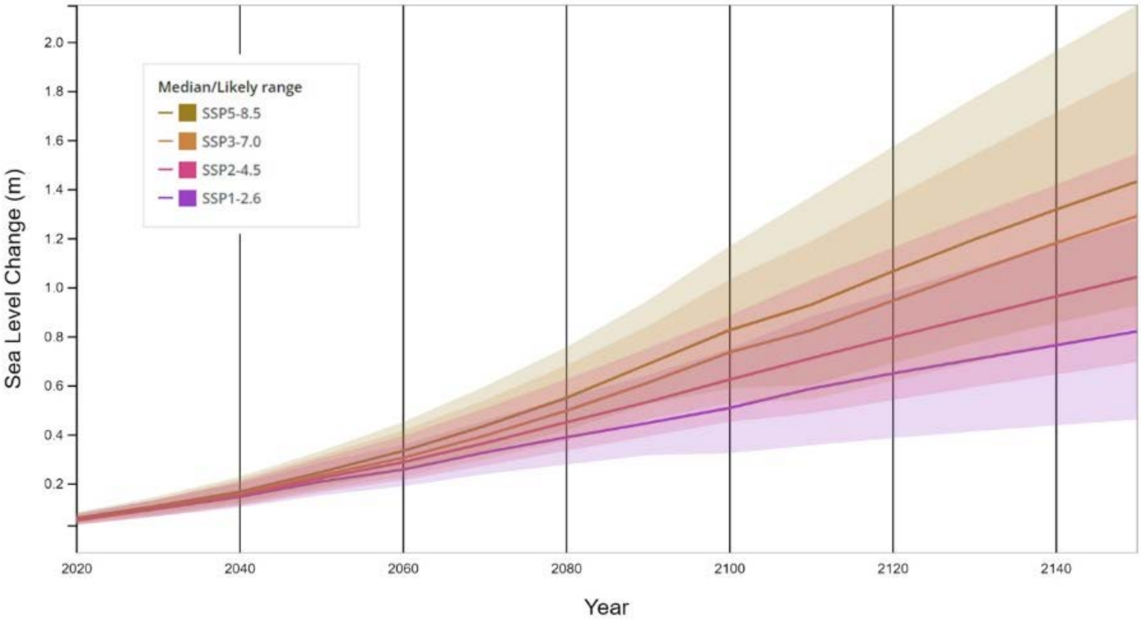
The total sea level rise projections for the Nauru B tide gauge, incorporating contributions from stereodynamic sea level, glaciers, Greenland, Antarctica, land water storage and vertical land motion

---

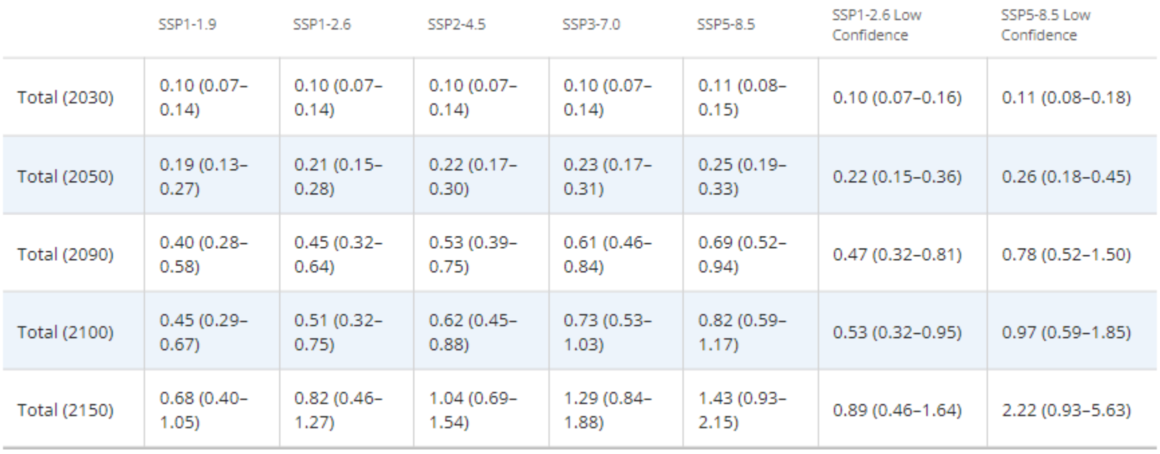
[9] There are significant uncertainties about sea level rise and coastal inundation 20. Toimil, A., P. Camus, I.J. Losada, G. Le Cozannet, R.J. Nicholls, D. Idier, and A. Maspataud, Climate change-driven coastal erosion modelling in temperate sandy beaches: Methods and uncertainty treatment. *Earth-Science Reviews,* 2020. 202: p. 103110 DOI: https://doi.org/10.1016/j.earscirev.2020.103110.. IPCC (2021) 7. 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, . quantifies the 5-95th 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 21. CSIRO Workshop Report, *Understanding the risks to Australia from global climate tipping points.* 2024 CSIRO, Australia.DOI: https://doi.org/10.25919/dts9-5478 template_Tipping Points

[23-25], show a median rise of about 0.10 m by 2030 compared to a 20-year baseline centred on 2005 (1995–2014). By 2050, the rise is 0.21 m for low emissions (SSP1-2.6) and 0.25 m for high emissions (SSP5-8.5). By 2090, the rise is 0.45 m for low emissions and 0.69 m for high emissions (Figure 9-10 with uncertainty ranges also shown).

The sea level rise projections are sourced from the NASA Sea Level Projection Tool which enables the visualisation (and data download) of the sea level rise consensus projections from the IPCC 6th Assessment Report (AR6). The data accessed for Nauru was from the regional sea level projections from 2020 to 2150. Projections based on future global warming levels can also be accessed from the NASA portal (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?psmsl_id=1844&data_layer=scenario).

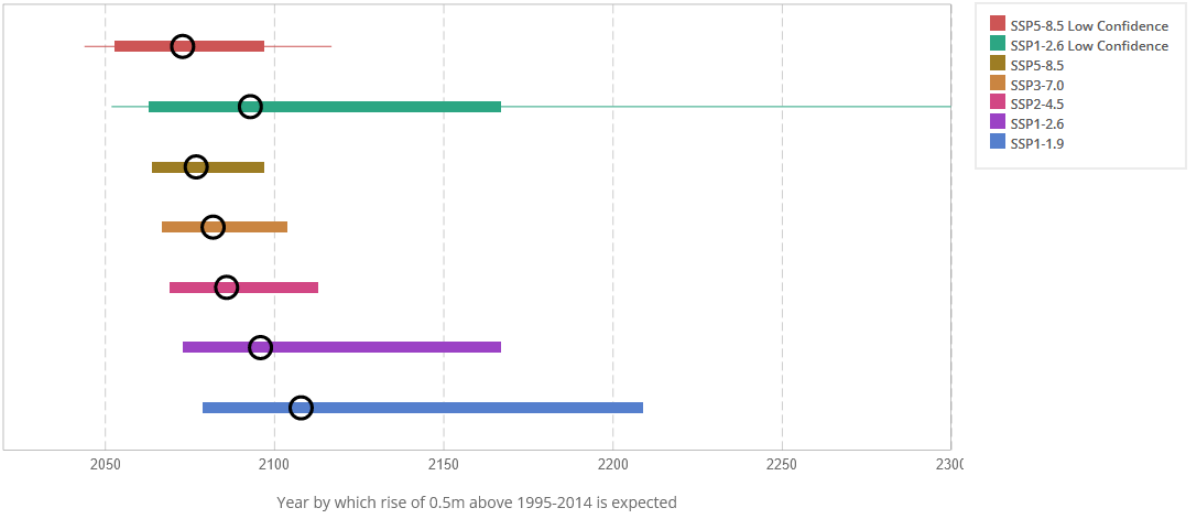


Report_PartnerLogos.pdf . The most relevant sea-level tipping point for Nauru is extremely high sea level rise due to rapid ice sheet disintegration 22. Le Bars, D., S. Drijfhout, and H. De Vries, A high-end sea level rise probabilistic projection including rapid Antarctic ice sheet mass loss. *Environmental Research Letters,* 2017. 12(4): p. 044013., but there is high uncertainty about whether, and on what time scale, such changes will occur. Worst case scenarios are typically used for risk screening and stress testing, as well as for applications where there is low risk tolerance for planning or infrastructure design. Also see caveats section at the end of this chapter for more information.



	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	SSP1-2.6 Low Confidence	SSP5-8.5 Low Confidence
Total (2030)	0.10 (0.07–0.14)	0.10 (0.07–0.14)	0.10 (0.07–0.14)	0.10 (0.07–0.14)	0.11 (0.08–0.15)	0.10 (0.07–0.16)	0.11 (0.08–0.18)
Total (2050)	0.19 (0.13–0.27)	0.21 (0.15–0.28)	0.22 (0.17–0.30)	0.23 (0.17–0.31)	0.25 (0.19–0.33)	0.22 (0.15–0.36)	0.26 (0.18–0.45)
Total (2090)	0.40 (0.28–0.58)	0.45 (0.32–0.64)	0.53 (0.39–0.75)	0.61 (0.46–0.84)	0.69 (0.52–0.94)	0.47 (0.32–0.81)	0.78 (0.52–1.50)
Total (2100)	0.45 (0.29–0.67)	0.51 (0.32–0.75)	0.62 (0.45–0.88)	0.73 (0.53–1.03)	0.82 (0.59–1.17)	0.53 (0.32–0.95)	0.97 (0.59–1.85)
Total (2150)	0.68 (0.40–1.05)	0.82 (0.46–1.27)	1.04 (0.69–1.54)	1.29 (0.84–1.88)	1.43 (0.93–2.15)	0.89 (0.46–1.64)	2.22 (0.93–5.63)

Figure 9-10 (Top graph) Sea level change for different greenhouse gas emissions scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) for Nauru resulting from processes in which there is medium confidence. Shaded ranges show the 17th-83rd percentile ranges. Projections are relative to a 1995–2014 baseline. Projections are for 'Total Sea Level Change' (Sterodynamic Sea Level, Glaciers, Greenland, Antarctica, Land Water Storage and Vertical land motion). (Bottom table) Sea level projections for five medium confidence and 2 low confidence scenarios are also presented, relative to a baseline of 1995-2014, in metres. Median values (and likely ranges) are shown. The SSP5-8.5 low confidence column incorporates a representation of the potential effect of low-likelihood, high-impact ice sheet processes that cannot be ruled out. In particular, this column shows the 17th-83rd percentile range factoring into account information from structured expert judgement and from a model incorporating Marine Ice Cliff Instability [23-25]. The IPCC AR6 Sea-Level Rise Projections are licensed by the authors under a Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/).Sea Level Projection Tool – NASA Sea Level Change Portal The IPCC AR6 Sea-Level Rise Projections are licensed by the authors under a Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/).



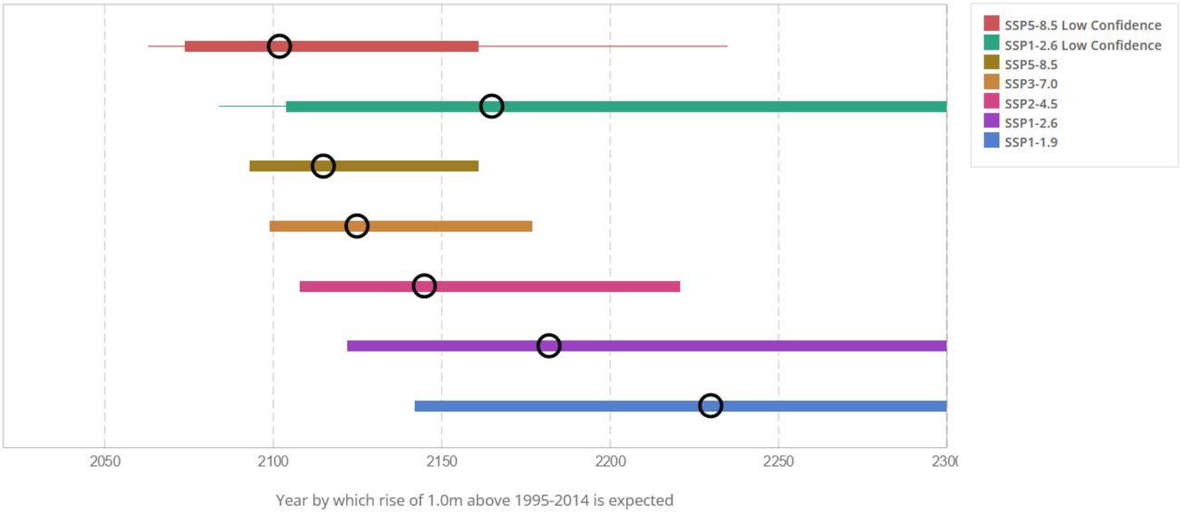


Figure 9-11 Timing of exceedance of 0.5 metre (top) and 1.0m (bottom) under different SSPs for Nauru B. Thick bars show 17th-83rd percentile ranges, and black circles show median value. Thin bars also show 5th–95th percentile ranges for SSP1-2.6 Low Confidence and SSP5-8.5 Low Confidence scenarios. Source: [Sea Level Projection Tool – NASA Sea Level Change Portal](#))

Any rise in mean sea level also generates a rise in the elevation of all tides such that there will be an increase in the number, duration and depth of water levels above the (present-day in 2020) king-tide elevation (2.7 m Nauru Island Datum (NID)) [6]. Tidal exceedance curves for the present day (black) and four increments of sea level rise (Figure 9-12) demonstrates that the king tide elevation will increase from a historical 0.72 % (1 in 138 tides above this elevation) exceedance probability to 30 % (1 in 3 tides are above this elevation) after 0.5 m sea level rise, and 86 % after 1.0 m sea level rise. In their assessment, Allis et al 2020 determined that the increase in exceedances after only 0.5 m sea level rise would mean that instead of 5 tides per year above the present-day king-tide elevation, there will be 212 events (or 109 days) each year [6].

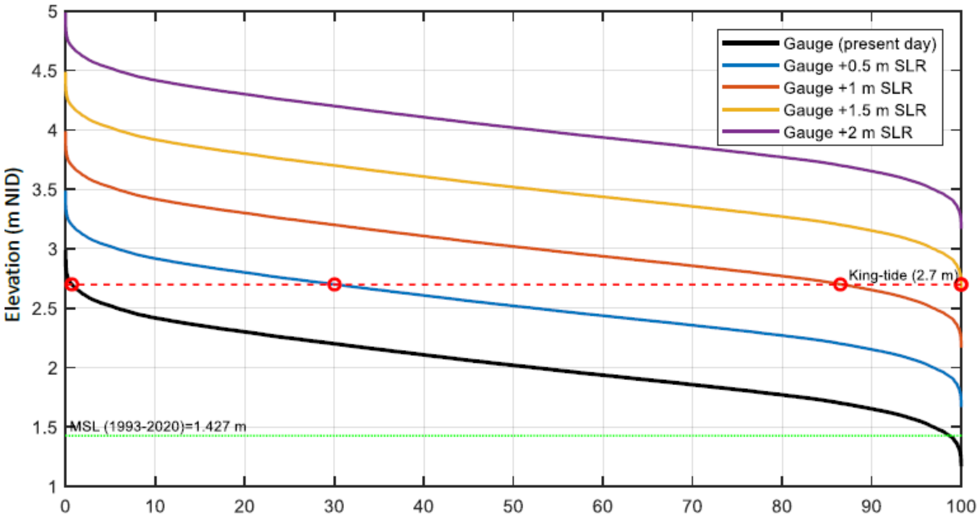


Figure 9-12 Likelihood of tidal elevations during 1993–2019 and after 0.5, 1.0, 1.5 and 2.0 m increments of SLR. The changing frequency of present-day king tide elevation (red dashed line and red circles) shows the increase from 0.72 % exceedance to 30 % after 0.5 m SLR, and only 86 % after a further 0.5 m SLR. All high tides will be above the 1993–2019 king-tide after 1.5 m SLR. See Table 2-4 for details. [Gauge data source: *PSLGM*]. *[6].*

Projected changes to wave characteristics

Annual cycles of the projected changes to waves have been assessed for Nauru [26]. Figure 9-13 shows that waves are projected to be smaller in the wet season than they were historically, with this effect greater at the end of the 21st century (blue and green cycles) than in the middle of the century (yellow and red cycles), and the effect is stronger under higher emissions (RCP8.5; red and blue cycles) than lower emissions (RCP4.5; yellow and green cycles).

The 0.2 m decrease in wave height (December–March) for RCP8.5 by 2090 indicates a weakening of the seasonal cycle, however the historical simulations have been shown to over-predict the seasonal cycle by a similar amount [26]. When combined with consideration of other factors, such as ENSO and modelling method, confidence in this change is assessed as low (Figure 9-13). No significant change is projected in wave heights at Nauru in the dry season. Projections for large, not average, wave heights are needed for impact assessments.

Projected wave period changes are insignificant (Figure 9-13; lower left panel). Wave direction is projected to remain largely unchanged (Figure 9-13, lower right panel), with a suggested clockwise rotation in the dry season (a rotation toward the south), which may be due to enhanced extra-tropical storms in the Southern Hemisphere.

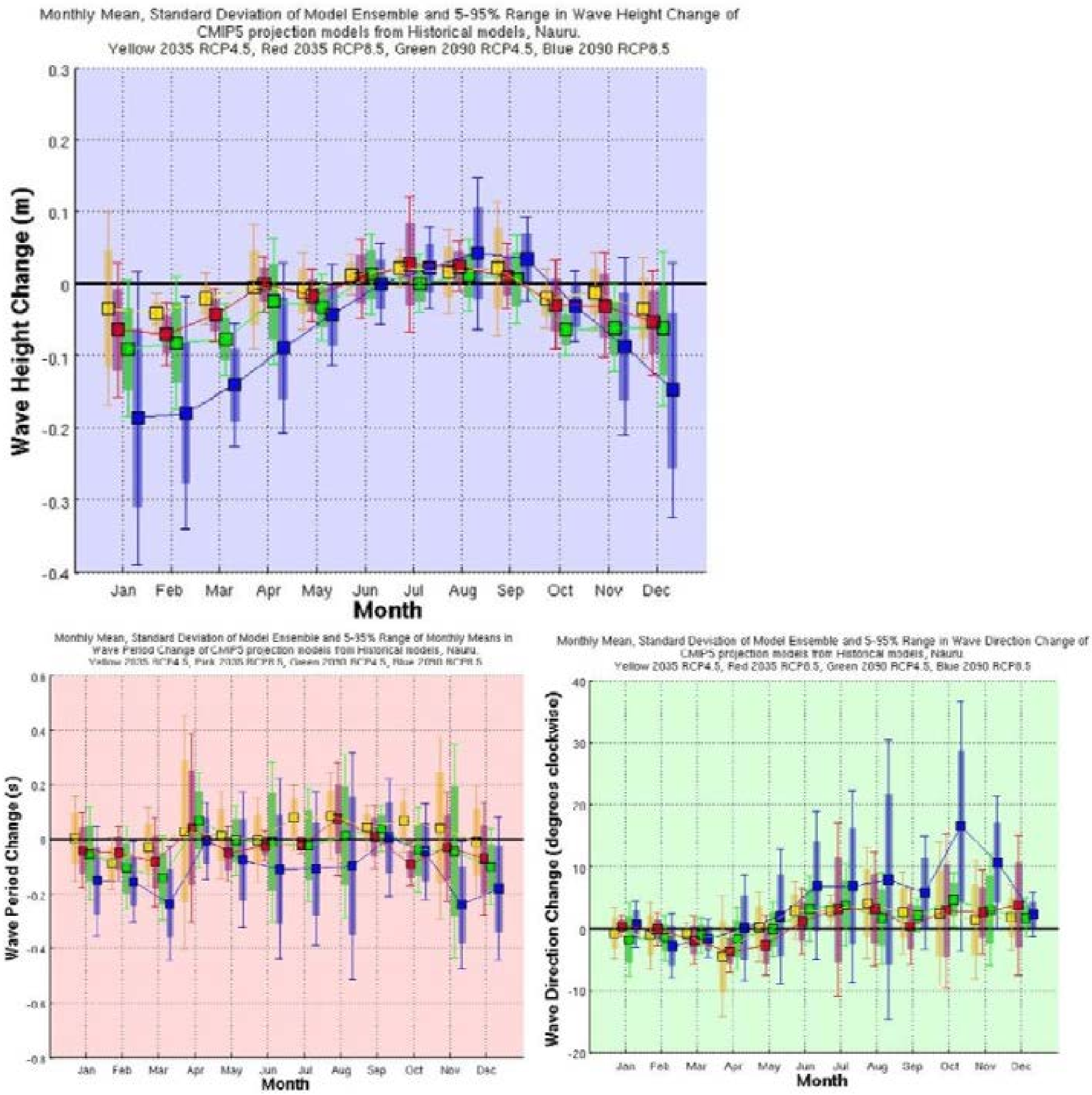


Figure 9-13 Mean annual cycles of projected change in wave height (blue background), period (red background) and direction (green background) for 2030 RCP4.5 (Yellow), 2030 RCP8.5 (Red), 2090 RCP4.5 (Green) and 2090 RCP8.5 (Blue) at Nauru. Shaded boxes show 1 standard deviation of model differences and error bars show estimated 5-95 % range. Source: [26].

Table 9-3 Projected changes in wave parameters at Nauru for December–March (wet season) and June–September (dry season). Blue numbers show RCP4.5 (low) while red numbers show RCP8.5 (high) scenario. The wave model was run for two 20-year periods centred on 2035 (column 3) and 2090 (column 4), subtracting the mean value from a 20-year period centred on 1995 (Table 2). The values in brackets represent the 5th to 95th percentile range of uncertainty. Column 5 gives statistical confidence in these projected values. Source: [26].

VARIABLE	SEASON	2035	2090	CONFIDENCE (RANGE)
Wave height change (m)	December-March	-0.0 (-0.2 – 0.2) -0.1 (-0.3 – 0.1)	-0.1 (-0.2 – 0.1) -0.2 (-0.3 – -0.1)	Low
Wave height change (m)	June-September	+0.0 (-0.1 – 0.1) +0.0 (-0.1 –0.1)	0.0 (-0.1 –0.1) +0.0 (-0.1 – 0.1)	Low
Mean wave period change (s)	December-March	-0.0(-1.1 – 1.0) -0.1 (-1.1 – 1.0)	-0.1 (-1.2 – 1.1) -0.2 (-1.3 –1.0)	Low
Mean wave period change (s)	June-September	+0.0 (-0.6 – 0.7) 0.0 (-0.6 – 0.6)	0.0 (-0.7 –0.7) -0.1 (-0.8 – 0.6)	Low
Mean wave direction change (° clockwise)	December-March	0 (-10 – 10) 0 (-10 – 10)	0 (-10 – 10) 0 (-10 – 10)	Low
Mean wave direction change (° clockwise)	June-September	+0 (-10 – 20) +0 (-10 – 20)	+0 (-10 – 20) +10 (-10 – 30)	Low

Other factors affecting coastal inundation impacts

Tsunami risk

In 2015, the Global Facility for Disaster Reduction and Recovery (GFDRR) assessed Nauru as having a medium tsunami hazard level, which means that there is greater than a 10 % chance of a potentially damaging tsunami occurring in the next 50 years [27]. However, that assessment of Nauru's tsunami hazard risk level was not informed by sites located in Nauru. Geohazards are forecast to increase in both severity and frequency as part of climate change impacts [1]. Tsunamis are exacerbated by sea level rise (which is responsible for causing dynamic morphological changes of the near- and onshore coastal environment). Tsunami hazard intensity tends to increase linearly with sea-level rise and the impacts of climate change on tsunami risk require more research [28, 29]. Figure 9-14 shows that the whole of the Nauru coastline would likely be impacted during a tsunami with both the coastal road and some villages residences in the tsunami inundation zone. Therefore, further detailed assessment of Nauru's tsunami risk may need to be prioritised for future research efforts.

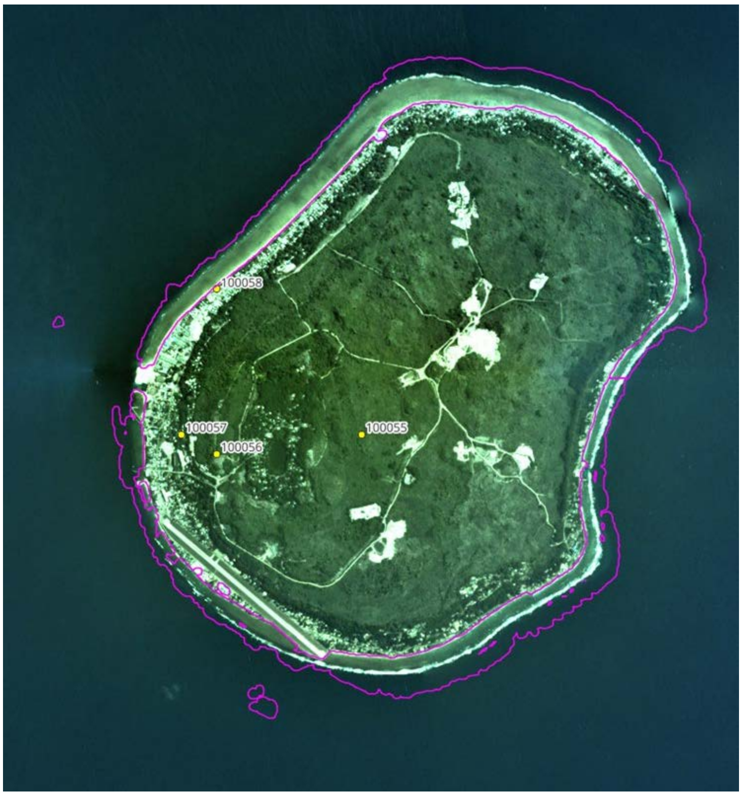


Figure 9-14 Tsunami risk assessment for Nauru, depicting which sample sites were used. Source: https://risk.preventionweb.net/download/Tsunami_hazard_results_g1545.zipavailable

Compound hazard events

Compound hazard events are multiple hazards for which the cumulative effect can result in severe impacts for communities, economies, and ecosystems, especially for flooding, tides, sea level rise and tsunamis [30, 31]. In fringing-reef environments, such as Nauru, coastal inundation is often a compound event in which tides, sea level and wave anomalies interact in a non-linear way to generate extreme total water levels and flooding [4, 32]. (See Chapter 2 for more detailed discussion).

Land reclamation

To date, there have not been any substantial land reclamation projects carried out on the Nauru coastline to reduce the risk of sea level rise impacts. Other countries in the Pacific have undertaken large land reclamation efforts in addition to the installation sea walls, e.g. Tuvalu [33].

Caveats

A predictive sea level rise model (including 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), projects 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 [22]. These findings are significantly higher than IPCC (2021) [7] projections for the high (SSP5-8.5) concentration pathway, where a 'low confidence' 95th percentile value of 2.3 m by 2100, relative to 1995–2014 is indicated (Figure 9-15). 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 [34].

Sweet et al (2022) [35] 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. Sweet et al (2022) note that "Considering 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.” The high-end estimates put a lot of emphasis on a single study (that of DeConto and Pollard 2016 [36]) which was not used by the IPCC [8] [37] 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 in the IPCC 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 [7]. Furthermore, the high concentration pathway is considered to have low likelihood given recent emission reduction policies [38].

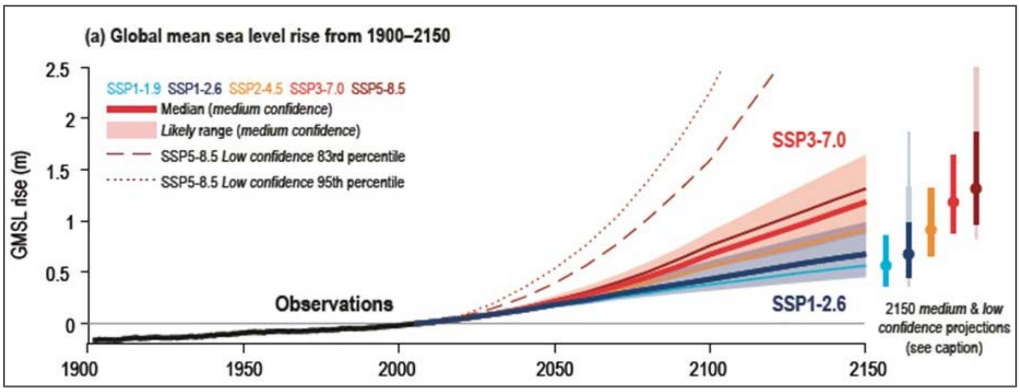


Figure 9-15 Global mean sea level (GMSL) rise on different time scales and under different scenarios. The observed change from 1900 to 2018 (black line) is shown along with projected changes from 2000–2150 relative to a 1995–2014 baseline. Solid lines show median projections. Shaded regions show likely 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: [7] Box TS.4.

There is a significant question about the utility and robustness of low confidence projections that have high impacts. The IPCC and both the USA and EU climate agencies are now including statements around these projections in their reporting [10][11]. Therefore, the implications for risk assessment should not be ignored.

---

[10] European Environment Agency “The global mean sea level (GMSL) in 2022 was the highest ever measured. GMSL reconstructions based on tide gauge observations show a rise of 21 cm from 1900 to 2020 at an average rate of 1.7 mm/year. The rate of GMSL rise accelerated to 3.3 mm/year over the period 1993–2018 and 3.7 mm/year over the period 2006–2018, more than twice as fast as during the 20th century. Global climate models project that the rise in GMSL during the 21st century (i.e. in 2100, relative to the period 1995–2014) will likely (66 % confidence) be in the range of 0.28-0.55 m for a very low emissions scenario (SSP1-1.9), 0.44-0.76 m for an intermediate emissions scenario (SSP2-4.5) and 0.63-1.02 m for a very high emissions scenario (SSP5-8.5).” Source: https://www.eea.europa.eu/en/analysis/indicators/global-and-european-sea-level-rise?activeAccordion=546a7c35-9188-4d23-94ee-005d97c26f2b accessed 6/3/2024

[11] NOAA Climate.gov “In 2022, global average sea level set a new record high—101.2 mm (4 inches) above 1993 levels. The rate of global sea level rise is accelerating: it has more than doubled from 0.06 inches (1.4 millimeters) per year throughout most of the twentieth century to 0.14 inches (3.6 millimeters) per year from 2006–2015. If we are able to significantly reduce greenhouse gas emissions, U.S. sea level in 2100 is projected to be around 0.6 meters (2 feet) higher on average than it was in 2000. On a pathway with high greenhouse gas emissions and rapid ice sheet collapse, models project that average sea level rise for the contiguous United

We conclude that these low confidence SLR scenarios are potentially relevant to coastal decision-makers, for instance when planning and construction of critical infrastructure[12] that has long lifetimes (e.g. hospitals, airports, desalination plants, cemeteries, etc.) alternative locations other than in areas likely to be affected by SLR might also be considered in response to this information.

The inundation modelling discussed in this report is not able to account for small-scale island (or reef) morpho-dynamics (changes in topography/bathymetry) due to natural processes like island erosion/accretion and reef degradation due to ocean acidification, ocean warming or coral bleaching impacts [39]. This is important, since significant changes in all of these factors will occur.

References

1. Oppenheimer, M., B.C. Glavovic , J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari,, *Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities* Ch in *IPCC Special Report: The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*, D.C.R. H.-O. Pörtner, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer, Editor. 2019, Cambridge University Press: Cambridge, UK and New York, NY, USA. p. 321-446.
2. SPC and Government of the Republic of Nauru, *Nauru 2021 population and housing census - Analytical report*. 2023 SPC: Noumea, New Caledonia; Available from: https://sdd.spc.int/news/2023/08/23/nauru-2021-population-and-housing-census-analytical-report
3. Alberti, L., I. La Licata, and M. Cantone, Saltwater intrusion and freshwater storage in sand sediments along the coastline: hydrogeological investigations and groundwater modeling of Nauru Island. *Water Research,* 2017. 9(10): p. 788. DOI: https://doi.org/10.3390/w9100788
4. Wandres, M., J. Giblin, A. Espejo, T. Sovea, R. Simpson, N. Jackson, A.C. Pickering, and H. Damlamian, *Nauru coastal risk assessment*. 2023 Pacific Community (SPC): Suva, Fiji. Available from: https://pacificdata.org/data/dataset/oai-www-spc-int-bd6b8334-7d52-4055-911e-7dccb6c61747
5. 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. DOI: https://doi.org/10.1371/journal.pone.0223249
6. Allis, M., S. Williams, and S. Wadwha, *Coastal flooding from sea-level rise in Nauru: Stage 1 - static inundation mapping, Prepared for the Nauru Higher Ground Project*. 2020: Prepared for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited.
7. 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. Available from: https://www.ipcc.ch/report/ar6/wg1/
8. IPCC, *The ocean and cryosphere in a changing climate*. 2019; Available from: https://www.ipcc.ch/srocc/chapter/summary-for-policymakers/
9. World Meteorological Organization, *State of the Global Climate 2023*. 2024: Geneva; Available from: https://library.wmo.int/records/item/68835-state-of-the-global-climate-2023

States could be 2.2 meters (7.2 feet) by 2100." Source: https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level accessed 6/3/2024

[12] Critical infrastructure provides services that are essential for everyday life such as food, water, power, communications transport, etc.

10. 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
11. 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. DOI: https://doi.org/10.1073/pnas.1813233115
12. Martínez-Asensio, A., G. Wöppelmann, V. Ballu, M. Becker, L. Testut, A.K. Magnan, and V. Duvat, Relative sea-level rise and the influence of vertical land motion at Tropical Pacific Islands. *Global Planetary Change,* 2019. 176: p. 132-143. DOI: https://doi.org/10.1016/j.gloplacha.2019.03.008
13. 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. DOI: https://doi.org/10.1007/s10584-016-1647-8
14. 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
15. 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. Available from: https://nespclimate.com.au/wp-content/uploads/2019/11/Understanding-Coastal-Erosion-on-Beaches_updatedNov19.pdf
16. 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
17. Bosserelle, C., S. Reddy, and D. Lal, *WACOP wave climate reports.* 2015: Suva, Fiji Islands.; Available from: https://wacop.gsd.spc.int/Atlas/Regional/Pdf/NA/Nauru.pdf
18. 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
19. Bosserelle, C. and S. Williams, *Coastal flooding from sea-level rise in Nauru: Stage 2 - wave inundation mapping, Prepared for the Nauru Higher Ground Project*. 2023 Prepared for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited: Christchurch, NZ.
20. 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
21. CSIRO Workshop Report, *Understanding the risks to Australia from global climate tipping points.* 2024 CSIRO, Australia. DOI: https://doi.org/10.25919/dts9-5478
22. 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. Available from: https://iopscience.iop.org/article/10.1088/1748-9326/aa6512/meta
23. Garner, G., R. Kopp, T. Hermans, A. Slangen, G. Koubbe, M. Turilli, S. Jha, T. Edwards, A. Levermann, and S. Nowikci, Framework for assessing changes to sea-level (FACTS). *Geosci. Model Dev.,* 2021. DOI: https://doi.org/10.5194/gmd-16-7461-2023

24. 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.* 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.
25. Garner, G., T.H. Hermans, R. Kopp, A. Slangen, T. Edwards, A. Levermann, S. Nowicki, M.D. Palmer, C. Smith, and B. Fox-Kemper, *IPCC AR6 WGI sea level projections*. 2022 Version 20210809. PO.DAAC, CA, USA. ; Available from: https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool
26. Trenham, C.E., M.A. Hemer, T.H. Durrant, and D.J. Greenslade, PACCSAP wind-wave climate: High resolution wind-wave climate and projections. *Quarterly Journal of the Royal Meteorological Society,* 2013. 137: p. 656. Available from: https://www.cawcr.gov.au/technical-reports/CTR_068.pdf
27. Think Hazard. 2023; Available from: https://thinkhazard.org/en/report/252-tuvalu/TS
28. 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
29. Weiss, R., T. Dura, and J.L. Irish, Modeling Coastal Environmental Change and the Tsunami Hazard. *Frontiers in Marine Science,* 2022. 9 DOI: https://doi.org/10.3389/fmars.2022.871794
30. 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
31. 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
32. 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. DOI: https://www.sciencedirect.com/science/article/pii/S0921818113001483
33. Hall, *Tuvalu welcomes waterfront recreation area.* 2023; Available from: https://www.hallcontracting.com.au/about/news/tuvalu-welcomes-waterfront-recreation-area
34. 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. DOI: https://doi.org/10.1029/2022EF002751
35. 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.
36. DeConto, R.M. and D. Pollard, Contribution of Antarctica to past and future sea-level rise. *Nature,* 2016. 531(7596): p. 591-597. DOI: https://doi.org/10.1038/nature17145
37. IPCC, *Summary for Policymakers. Synthesis of IPCC Sixth Assessment Report.* 2023 IPCC: Geneva, Switzerland; Available from: https://www.ipcc.ch/report/ar6/syr/

38. 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. Available from: https://iopscience.iop.org/article/10.1088/1748-9326/ac4ebf/pdf

Chapter 10 39. 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. DOI: https://doi.org/10.1098/rsos.192153 Ocean warming

Introduction

Global sea surface temperatures (SSTs) were 0.88 °C higher in 2011–2020 than 1850–1900 [1]. Since 1970, the global ocean has taken up more than 90 % of the excess heat in the climate system [2]. Marine heatwaves (MHWs) are episodes of prolonged and anomalously high ocean temperatures [3, 4]. Over the last four decades across the globe, marine heatwave (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 [1]. This has impacts on coastal communities, marine resources and biodiversity (e.g. species redistribution, coral bleaching, die-back of seagrass and mangroves, algal blooms and fish kills) [6]. These emissions have also resulted in ocean acidification (see Chapter 11).

Photo credit: CSIRO, 2024

Observed sea surface temperature

Across the Nauru EEZ, annual average SSTs range from about 28.9 °C to 29.6 °C from north-east to south-west (Figure 10-1, left). During 1993–2021, monthly-average SSTs at the Nauru tide gauge averaged around 28.6 °C in July (the warmest month) and the interannual range is 26.5 to 31 °C (Figure 10-1, top right) [7]. Hourly temperatures can be up to 3 °C higher or 4 °C lower than these averages, although 50 % of observations fall within 2 °C of the average [7]. Equatorial SSTs can drastically change in a given year depending on ENSO. SSTs northeast of Nauru are warmer than normal during an El Niño event, and cooler during a La Niña event [8]. The variability in temperatures between October to March is reflective of peak months of ENSO activity [7].

Satellite-derived SST measurements taken from the NOAA (National Atmospheric and Oceanic Administration) daily Optimum Interpolation Sea Surface Temperature v2-1 dataset[13] (hereafter called OISST v2-1; [9]) have been averaged over the Nauru EEZ, revealing a warming trend of 0.22 °C per decade during 1981–2021 (Figure 10-1, bottom right) [7]. SSTs are reaching record elevated levels globally [10].

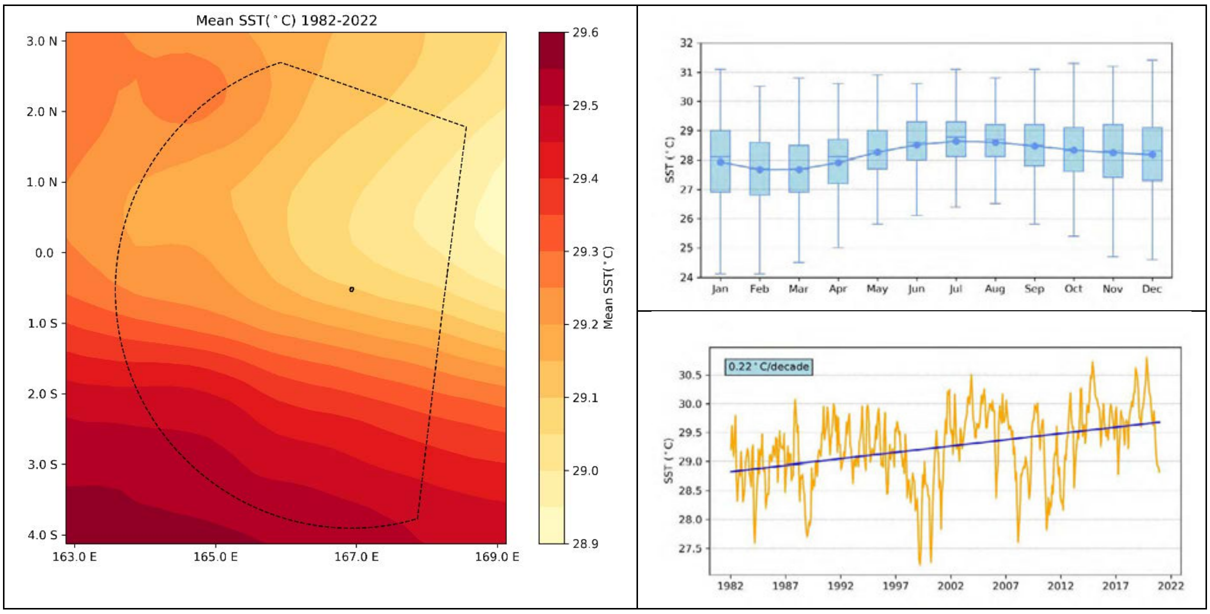


Figure 10-1 Nauru annual-average SST (°C) (1982–2022) (left). SST (° C) averaged across the Nauru tide gauge, with blue dots showing the monthly average, shaded boxes show the median (middle 50 % of observations) and lines showing the top and bottom 25 % of observations (Top right). SST from satellite measurements averaged across the Nauru EEZ (1981–2021), with annual averages shown as the orange line. The blue line shows the linear regression trend of 0.22 °C/decade [7] (Bottom right). Data source for left and bottom right plots: [9].

Projections for SST

Projected increases in SST for the Nauru EEZ region by 2050 relative to a 1995–2014 baseline range from 0.5 °C for low emissions (SSP1-2.6) to 0.7 °C for medium emissions (SSP2-4.5), and 0.9 °C for high emissions (SSP5-8.5), and by 2090 range from 0.6 °C for SSP1-2.6 to 1.3 °C for SSP2-4.5, and 2.7 °C for SSP5-8.5 (Figure 10-2 and Table 10-1). This translates to average ocean temperatures of around 31.9 °C by the 2090 period under SSP5-8.5, compared to the baseline average of just over 29.2 °C (during 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.

---

[13] 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.

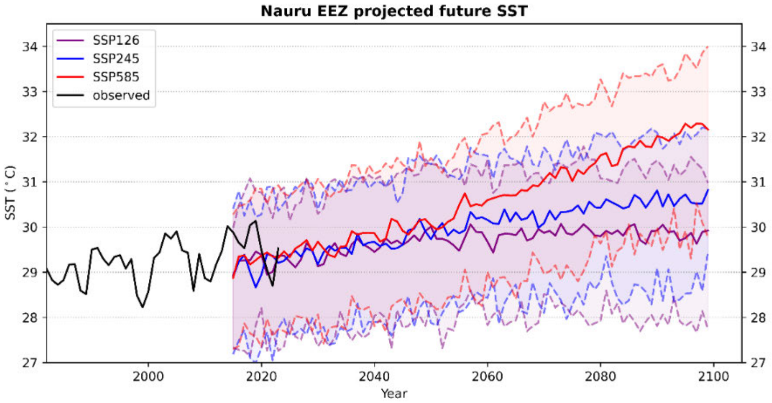


Figure 10-2 Timeseries of observed (1980–2024: black line) and projected annual average SST (2010–2100) for the Nauru EEZ from 23 CMIP6 climate models over three emission scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5. Shown are the median values (bold lines) and the 10th and 90th percentile for each scenario (dashed lines).

Table 10-1 Summary table of the SST changes (°C) for SSP1-2.6, SSP2-4.5 and SSP5-8.5 in Figure 10-2 for four future time periods, relative to the 1995–2014 baseline period. The mean change is shown along with the 10-90th percentile range of uncertainty.

Time period	Emission Scenario	Mean change	10th to 90th percentile
2030 (2021-2040)	SSP126	0.2	-1.6 to 1.5
	SSP585	0.3	-1.4 to 1.7
2050 (2041-2060)	SSP126	0.5	-1.2 to 2.0
	SSP585	0.9	-0.9 to 2.3
2070 (2061-2080)	SSP126	0.6	-1.2 to 2.1
	SSP245	1.0	-0.8 to 2.4
	SSP585	1.8	-0.2 to 3.2
2090 (2081-2100)	SSP126	0.6	-1.2 to 2.0
	SSP245	1.3	-0.5 to 2.8
	SSP585	2.7	0.5 to 4.2

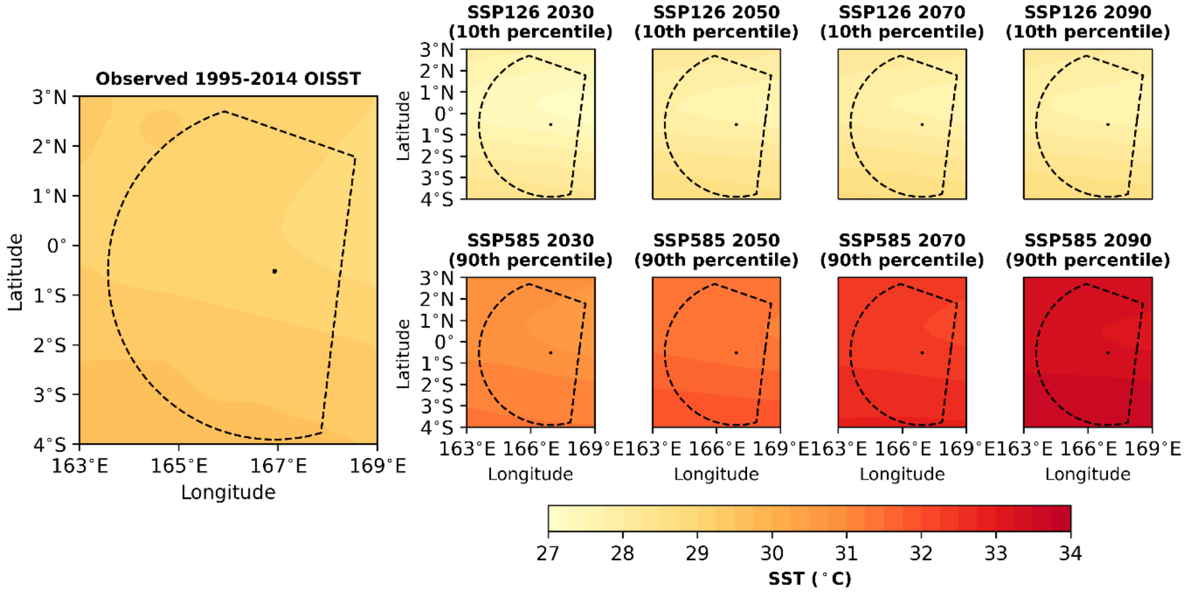


Figure 10-3 (left) Observed 20-year average Nauru SST (°C) (1995–2014; OISSTv2-1), and (right) range of projected SST from 23 CMIP6 models for 2030, 2050, 2070 and 2090 under SSP1-2.6 (top) and SSP5-8.5 (bottom). To show the range of projections, the 10th percentile of the SSP1-2.6 and the 90th percentile of the SSP5-8.5 projections are shown. The Nauru Exclusive Economic Zone is shown by the dashed polygon.

Ocean temperature extremes

Introduction

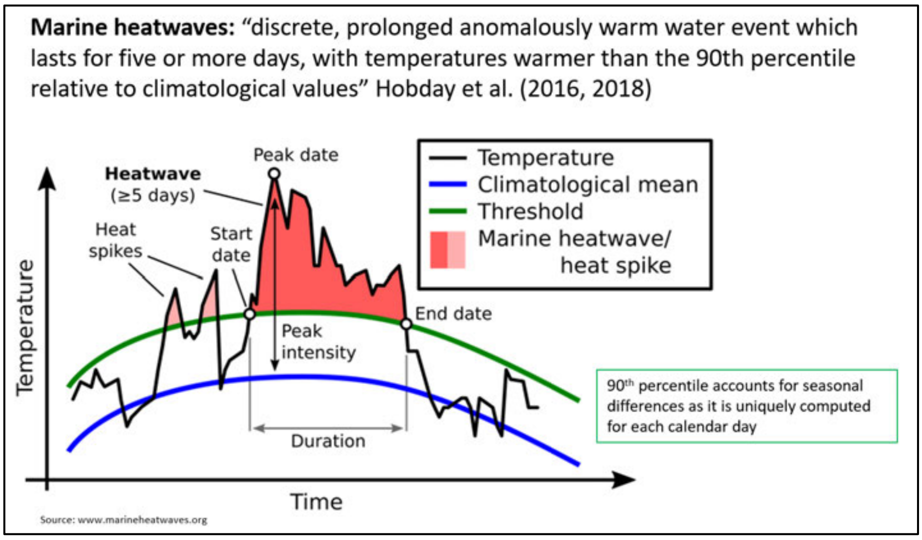
Marine heatwaves (MHWs) are typically caused by either atmosphere-ocean heating or the convergence of heat from changes in ocean currents, which can be modulated by modes of climate variability [11, 12]. MHWs have resulted in substantial impacts to marine ecosystems and the services they provide [13], including biological and socio-economic consequences [14, 15]. Furthermore, projections of MHWs are likely to carry severe consequences for marine species and ecosystems [16].

MHWs can have a very different temperature profile (i.e. °C) depending on the seasonal/regional background temperatures. For example, a heatwave occurring in February is unlikely to reach temperatures as high as those occurring in July in Nauru. However, there may be other biological processes (e.g., spawning, recruitment, food web relationships) that would still be sensitive to MHWs in February, e.g., [17] MHWs on top of long-term warming in February enables establishment of invasive species where a previously cool February would have killed them off [18].

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” [3, 4] where:

- “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
- 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 the 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 10-5. 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].

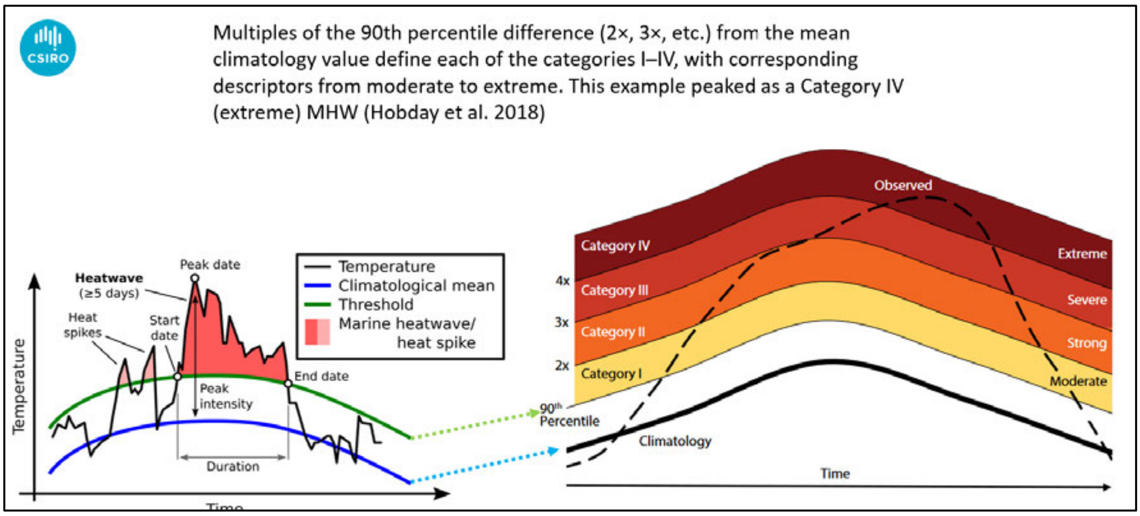

Multiples of the 90th percentile difference (2×, 3×, etc.) from the mean climatology value define each of the categories I–IV, with corresponding descriptors from moderate to extreme. This example peaked as a Category IV (extreme) MHW (Hobday et al. 2018)

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 heatwave events

Globally, MHWs have become more frequent over the 20th century and the early 21st century [5], approximately doubling in frequency and becoming more intense and longer since the 1980s [5, 19]. 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 [20].

Observations in the Pacific Islands region indicate that from the 1980s to 2000s, the average duration of MHWs was 5 to 16 days. However, in the 2010s, this increased to 8 to 20+ days [21].

Timeseries of MHW observations have been assessed for Nauru's northern and southern coasts showing an increasing frequency of MHW's during 1981–2023, mostly in the moderate category (Figure 10-6).

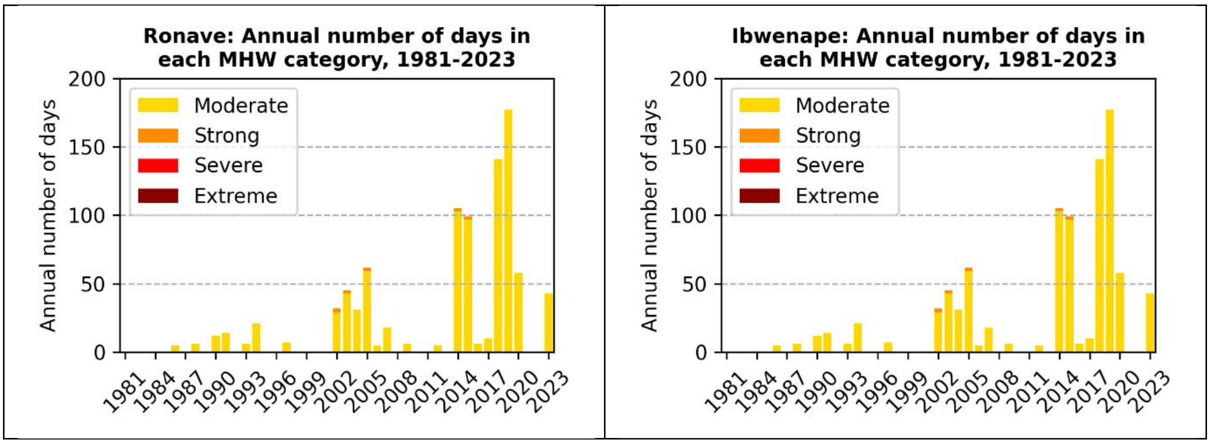


Figure 10-6 Annual number of MHW days (1981-2023) in each category [3, 4] for Ronave (northern Nauru) and Ibwenape (southern Nauru). Data source: NOAA OISST v2-1 [9].

Spatial analyses of trends in observed MHWs

Spatial analyses of MHWs occurring in the Nauru 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 between events [3, 4]. The key findings are:

- Increases in annual MHW frequency have occurred across Nauru's EEZ, with the greatest increases to the west and north-west of Nauru (Figure 10-7, top left).
- Increases in annual MHW duration have occurred across the EEZ, with larger increases to the north of Nauru (Figure 10-7, top right).
- Decreases in annual maximum MHW intensity have occurred over most of Nauru's EEZ, but there are slight increases near Nauru island (Figure 10-7, bottom left). Area-averages show that there is a weak negative trend in MHW intensity as the equatorial region of the Pacific Ocean is dominated by the Interdecadal Pacific Oscillation [6][14].
- The total number of MHW events is around 80 (an average rate of almost 2 per year) for most of Nauru's EEZ, with fewer MHWs to the south (Figure 10-7, bottom right).

---

[14] 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. 22. 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.).

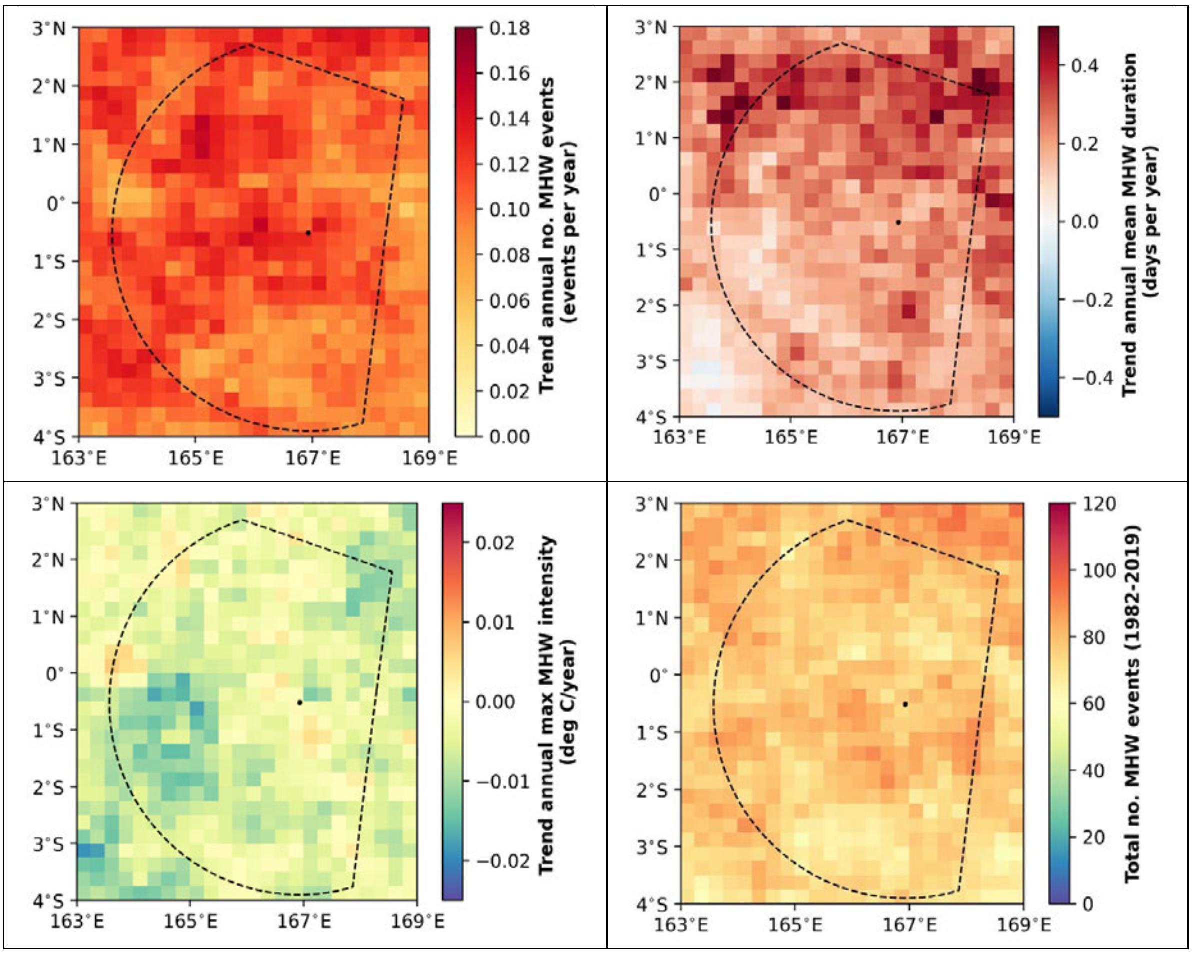


Figure 10-7 Trend (1982–2019) in annual number of MHW events (top left), annual mean MHW duration (top right), annual maximum MHW intensity (bottom left), and total number of MHW events (bottom right). Source data: NOAA OISST v2-1 SST [9].

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 [23]. During El Niño events, higher SST, rainfall, and sea level are clearly apparent in the central tropical Pacific [23], including Nauru. 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 low emissions (SSP1-2.6), and 3–15 times under high emissions (SSP5-8.5), with the largest increases in tropical and Arctic Oceans (Fox-Kemper et al. 2021). Under 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 (Holbrook et al., 2022). Under SSP5-8.5, 200 dpy of 'Moderate' MHW intensity is projected across the region by 2050, with >300 dpy nearer the equator. By 2080, coral bleaching is likely to start on most reefs in spring, rather than late summer, with year-round bleaching risk anticipated to be high for some low-latitude reefs regardless of global efforts to reduce greenhouse gasses [24].

Projected MHWs have been calculated for a low warming climate model and a high warming climate model, under low and high emissions scenarios, to capture the projected range of change (Figure 10-8) (NB: 18 CMIP6 models and two SSPs are employed in this assessment). Historical OISST v2-1 observations (1995–2014) are indicated by the left bar in each plot, denoted with an 'x'. For Nauru, the average number of MHW days is around 16 dpy (1995–2014) (Figure 10-8).

By 2050, under SSP1-2.6, this increases to about 105 dpy for the low warming model and 140 dpy for the high warming model (Figure 10-8, left). By 2050, under SSP5-8.5, this increases to about 180 dpy for the low warming model and 270 dpy for the high warming model, with more days in the 'Strong' and 'Severe' MHW categories than in the historical baseline (Figure 10-8, right).

By 2090, larger increases in MHWs are projected. For SSP1-2.6, the number of MHW days is 130 dpy for the low warming model and 200 dpy for the high warming model, with an increase in 'Strong' events. For SSP5-8.5, it's 250 dpy for the low warming model and 350 dpy for the high warming model, with a large increase in 'Strong' events and some 'Severe' and 'Extreme' events (Figure 10-8).

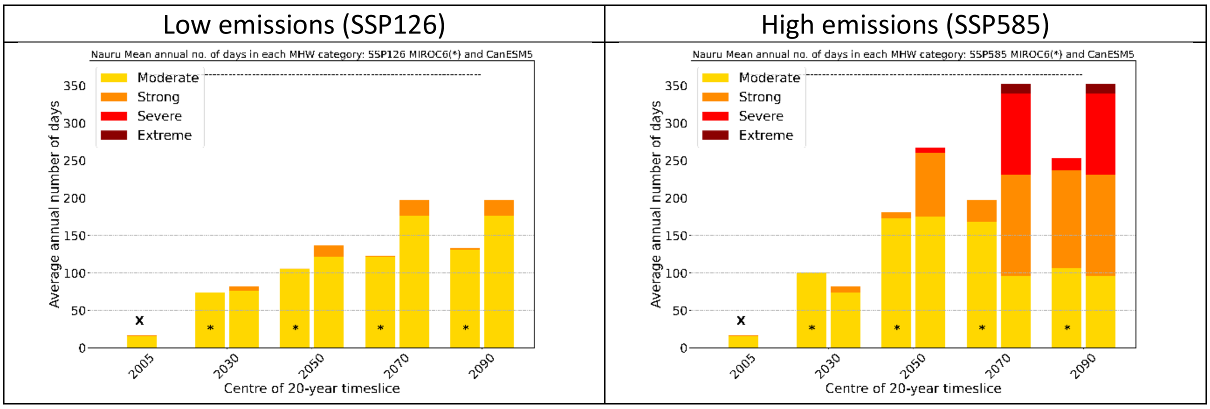


Figure 10-8 Projected average annual number of MHW days for an area-averaged domain encompassing Nauru. The 'x' above the left bar on each plot indicates that a different dataset (OISST v2-1) was used to determine the historical observed MHW frequency for a 20-year period centred on 2005 (1995–2014), quantified by the bar height. Projected MHWs for 20-year periods centred on 2030, 2050, 2070, and 2090 are plotted for a low emission scenario (SSP1-2.6; left panels) and high emission scenario (SSP5-8.5; right panels) under a low warming model (MIROC6) (*) and a high warming model (CanESM5). For all periods, MHWs are categorised: moderate, strong, severe, and extreme [4]). (Data source: OISST v2-1 SST [9]).

Degree heating weeks

Degree heating weeks (DHW) provide a measure of coral stress [25-27]. 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.

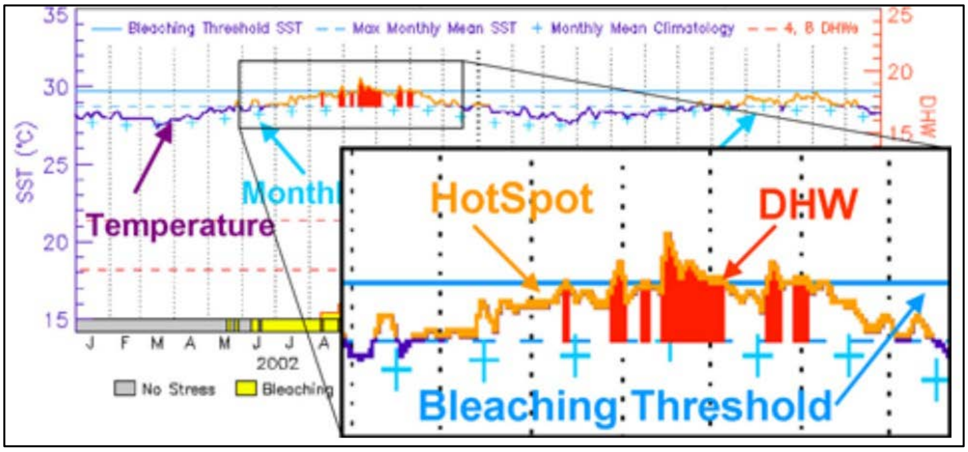


Figure 10-9 Simulated SST (°C) timeseries for a sample site in the Pacific. A HotSpot is included in the DHW calculation when SST reaches or exceeds the bleaching threshold temperature. DHW (red region) is accumulated from HotSpot occurrence as the magnitude of exceedance above the MMM for a period of 12 weeks. (Source; https://coralreefwatch.noaa.gov/product/5km/tutorial/crw09a_hotspot_product.php)

The term 'HotSpot' indicates the extent (in °C) that SST is above the MMM each day. DHW indicates how much heat stress has accumulated[15] 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 based on DHW (e.g. Figure 10-10) warnings for bleaching based on DHW (e.g. Table 10-2).

---

[15] 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.

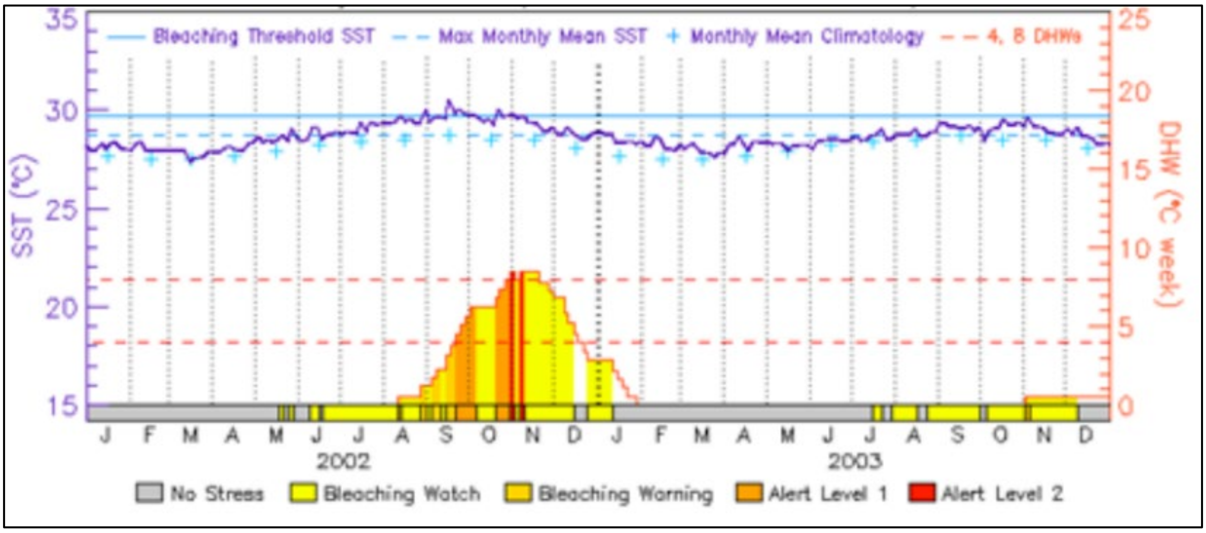
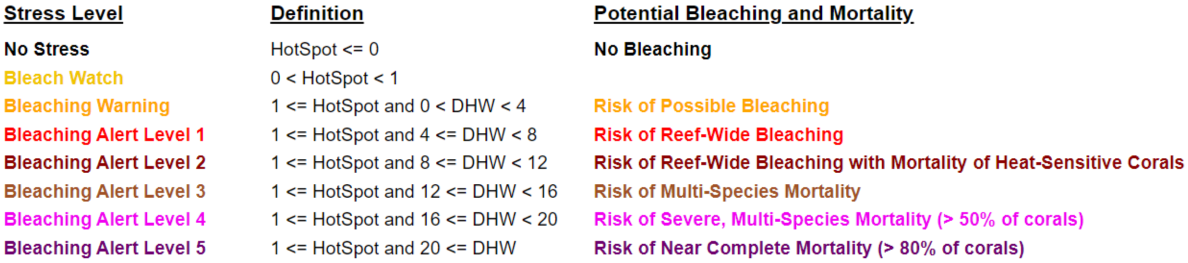


Figure 10-10 DHWs are plotted for a sample site in the Pacific along the bottom of the graph, corresponding to the accumulated threshold exceedance of SST above MMM. The 4-DHW and 8-DHW thresholds are shown as dashed, horizontal red lines. The colours that fill below the DHW line correspond to established satellite bleaching alert level. (Source https://coralreefwatch.noaa.gov/product/5km/tutorial/crw14b_timeseries.php)

'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, if 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 mortality are likely. This scale has been successfully validated across historical observations at eight sites in north-western Pacific Ocean [28].

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))[16]



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 [29].

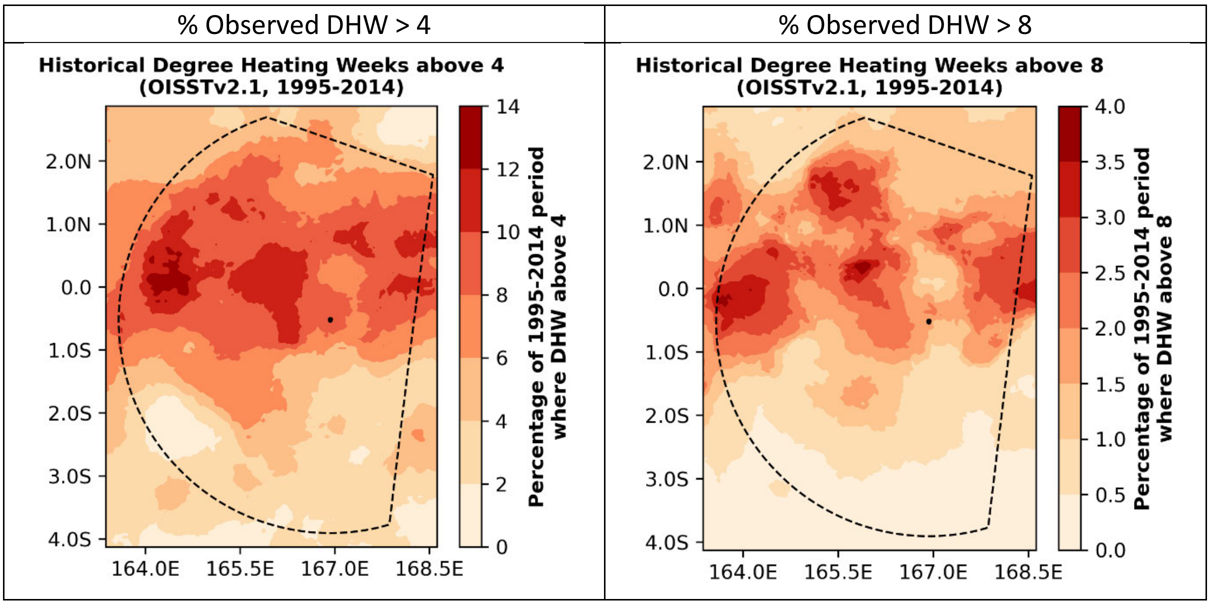
Degree Heating Week observations

For the 20-year historical period centred on 2005, the frequency of DHW greater than 4 is mapped, showing some regional variation (Figure 10-11, left). The areas exposed to more than 4 DHW events,

---

[16] 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.

indicating 'Risk of Reef-wide Bleaching' are located over the equatorial region of the Nauruan EEZ, including the island of Nauru itself. Less exposed areas to DHWs above 4 are located to the south of latitude 2.5 °S. The equatorial region, including the island of Nauru, has also experienced some events with DHW greater than 8 during the period 1995–2014, indicating 'Risk of Reef-wide Bleaching with Mortality of Heat-sensitive corals' (Figure 10-11, right).

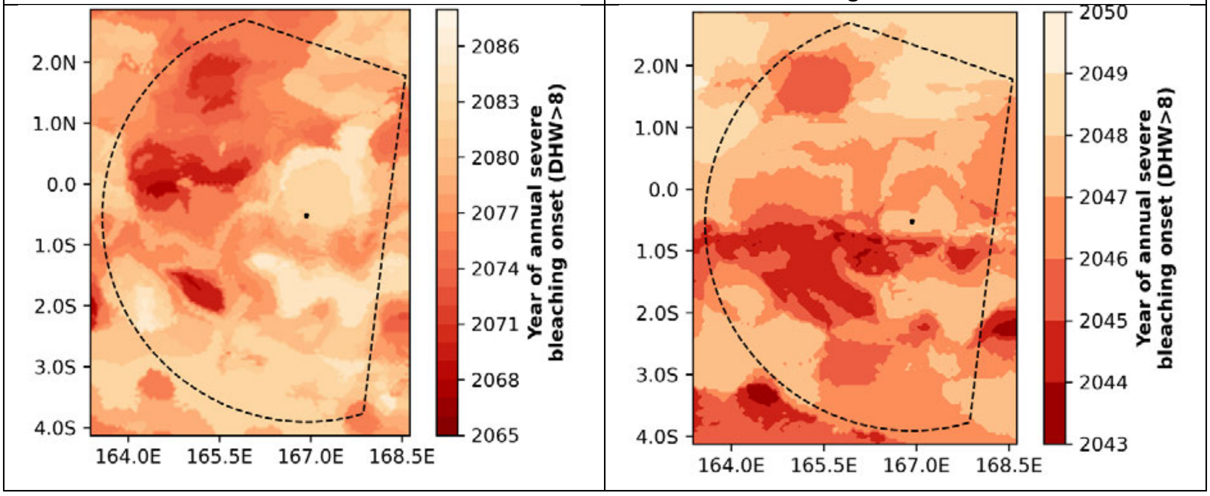


% Observed DHW > 4 | % Observed DHW > 8

Figure 10-11 Occurrence of Degree Heating Weeks above 4 (left) and above 8 (right) in the OISST v2.1 data for the Nauru region for the period 1995–2014. The Nauru EEZ is shown by a dashed polygon. NB Different scale on the separate plots.

Degree Heating Week projections

Annual severe bleaching (DHW > 8) is projected to occur on average for Nauru by the mid-2040s for high emissions; (Figure 10-12, right) and by the mid-2070s for low emissions (Figure 10-12, left). The area to the north-east of Nauru may experience annual severe bleaching seven or more years later than other parts.



Projected mean annual severe bleaching onset
Low emissions | Projected mean annual severe bleaching onset
High emissions

Figure 10-12 Mean onset year for annual severe bleaching (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. The method follows Maynard et al. 2018 [30]. NB: DIFFERENT COLOUR SCALE due to the large difference in the years for SSP5-8.5 and SSP1-2.6.

DHWs were examined for Nauru's coastal reef with projections for 2050 for a range of models (low and high warming) under a low emissions scenario (Table 10-3). Alert level 1 (Significant coral bleaching likely is exceeded 7 times over the 1995–2014 period, with periods in between where coral can recover. Alert level 2 (Risk of reef-wide bleaching with mortality of heat-sensitive corals) was reached twice.

Under low emissions and low warming, Alert level 2 is reached 18 times in the 20-year period centred on 2050, covering around 25 % of the period. Under high emissions and high warming, Alert Level 2 is almost constantly exceeded over this 20-year period (Figure 10-13). Even under low emissions, Alert level 3 is reached in the low warming model 9 times over the period, and Alert Level 5 (representing risk of near complete coral mortality) is reached for around the same amount of time that the reefs around Nauru have experienced Alert level 2 over the historical period.

Table 10-3 Number of events and days per 20-years above the DHW thresholds for Bleaching Alert Level 1 (DHW>4 °C-week) and Bleaching Alert Level 2 (DHW>8 °C-week) in historical OISST v2-1 SST data, and 20-year projections centred on 2050 for Nauru in both high-warming (CanESM5) and low-warming (MIROC6) models, as well as low (SSP1-2.6) and high (SSP5-8.5) emissions scenarios.

Degree heating week thresholds	Historical data (1995-2014)	Low Emissions (SSP126) 2050		High Emissions (SSP585) 2050	
		Low warming (MIROC6)	High warming (CanESM5)	Low warming (MIROC6)	High warming (CanESM5)
# of events exceeding Alert level 1	7	16	14	20	3
Days above Alert level 1	619	3290	5421	3777	7196
# of events exceeding Alert level 2	2	18	12	22	11
Days above Alert level 2	126	1838	4728	2141	6873

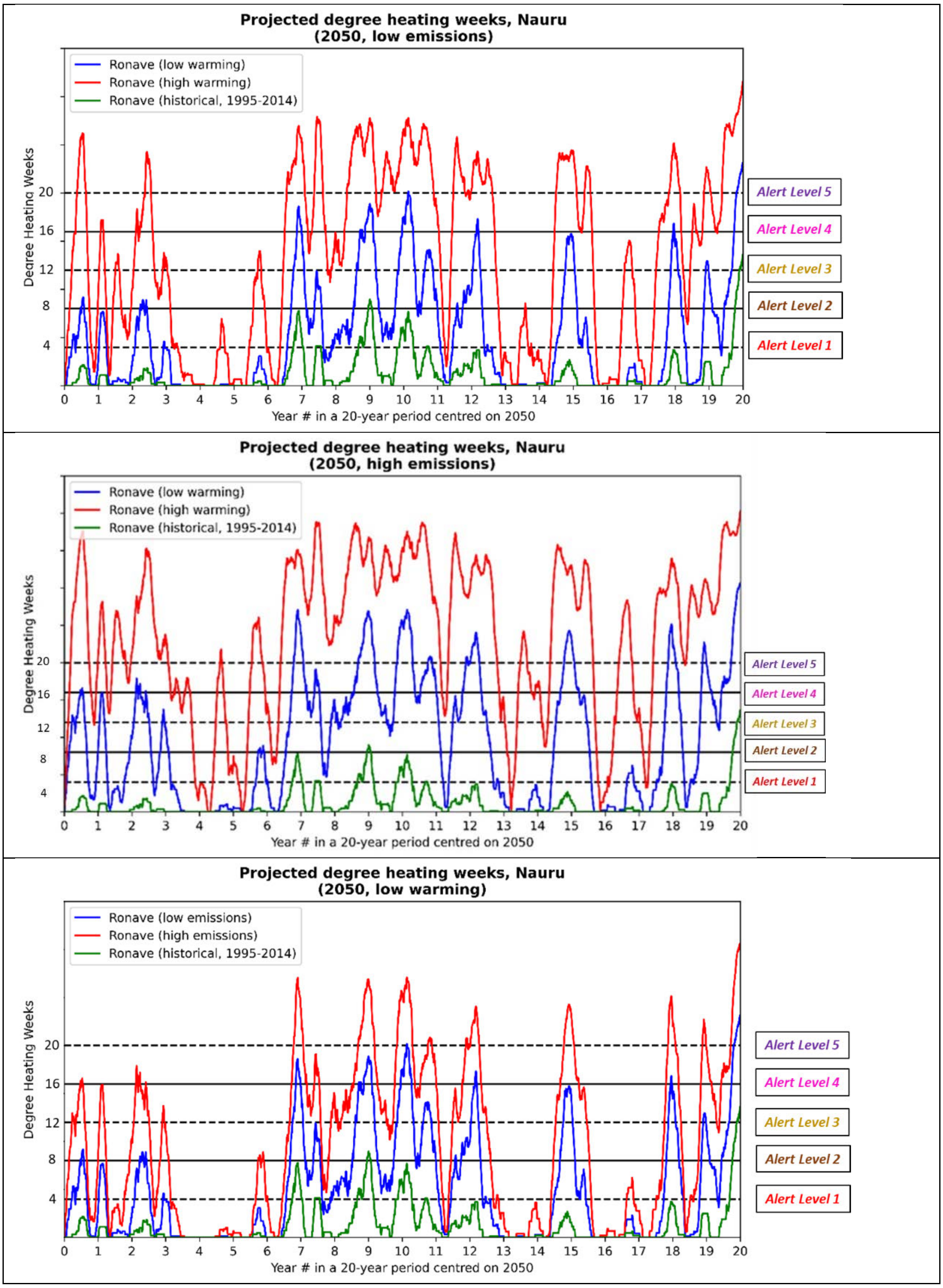


Figure 10-13 Temporal variability of degree heating weeks (DHW) based on time series of DHW (°C-week) for a 20-year period centred on 2050 for 'low warming' (MIROC6) and 'high warming' (CanESM5) model under low emissions (SSP1-2.6) (top) and high emissions SSP5-8.5 (middle) for Ronave. Bottom plot compares high and low emissions for a low warming model (MIROC6). 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. The method follows Langlais et al. 2017 [31], and high-frequency spatial and temporal variability based on that in OISST v2-1 SST [9]. Results for a high warming model are not shown.

Caveats

The resolution of the datasets is relatively coarse and does not capture the detailed spatial and temporal temperature fluctuations and ocean chemistry of Nauru's fringing atoll. To fully understand how large-scale changes of the ocean surrounding the Nauru translate to these localised waters, access to high-quality long-term monitoring data is important. Nauru and its fringing reef (Figure 10-14) sit within one grid cell of the SST data. For local risk assessments, ocean monitoring buoys can be used to inform or calibrate the data [32].

Changes in the east-west gradients of SST across the equatorial Pacific have major consequences for regional climate [33]. There is a large degree of variability among climate models on some aspects of future projections [33], as well as biases (e.g. [34]). Some of the largest biases found in GCMs are in the western Pacific, meaning that confidence in some climate projections is moderate or 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 [35-37].

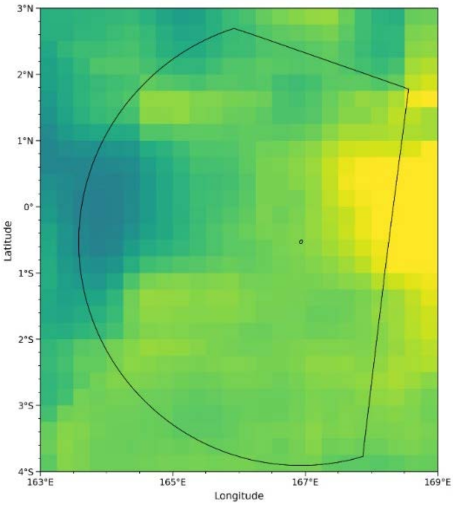


Figure 10-14 NOAA OISST v2-1 grid (0.25 degree or ~ 28 km) [9], showing Nauru island (black dot) and the EEZ boundary, noting the relative size of the grid cell from which each SST timeseries and MHW analysis is taken. Different colours are showing the contrast across the different grids.

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. Available from: 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*
2. IPCC, *The ocean and cryosphere in a changing climate*. 2019; Available from: https://www.ipcc.ch/srocc/chapter/summary-for-policymakers/
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. DOI: https://doi.org/10.1016/j.pocean.2015.12.014
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. Available from: https://tos.org/oceanography/assets/docs/31-2_hobday.pdf

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: https://doi.org/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. DOI: https://doi.org/10.1016/j.gloplacha.2021.103680
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. 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
9. 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
10. Birkel, S.D. *Daily Sea Surface Temperature*. 2023 Available from: Climate Reanalyzer (https://ClimateReanalyzer.org).
11. 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: https://doi.org/10.1038/s41467-019-10206-z
12. 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. DOI: https://doi.org/10.1038/s43017-020-0068-4
13. 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. DOI: https://doi.org/10.1038/s41558-019-0412-1
14. 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. DOI: https://doi.org/10.1126/science.abj3593
15. 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. DOI: https://doi.org/10.1146/annurev-marine-032122-121437
16. 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. DOI: https://doi.org/10.3389/fmars.2019.00734

17. 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. DOI: https://doi.org/10.1002/lno.11331

18. 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. DOI: https://doi.org/10.1111/jpy.13051

19. 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* 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. Available from: https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-9/

20. 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. DOI: https://doi.org/10.1126/science.aba0690

21. 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

22. 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. DOI: https://doi.org/10.1038/nclimate2106

23. 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: https://doi.org/10.1029/2021EF00252

24. Mellin, C., S. Brown, N. Cantin, E. Klein-Salas, D. Mouillot, S.F. Heron, and D.A. Fordham, Cumulative risk of future bleaching for the world’s coral reefs. *Science Advances,* 2024. 10(26): p. eadn9660 DOI: https://doi.org/10.1126/sciadv.adn9660

25. 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

26. 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. Available from: https://coralreefwatch.noaa.gov/product/5km/

27. NOAA. *Coral Reef Watch Satellite Monitoring and Modeled Outlooks*. 2023 Available from: https://coralreefwatch.noaa.gov/satellite/index.php

28. Kayanne, H., Validation of degree heating weeks as a coral bleaching index in the northwestern Pacific. *Coral Reefs,* 2017. 36(1): p. 63-70. DOI: https://doi.org/10.1007/s00338-016-1524-y

29. 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. DOI: https://doi.org/10.1038/srep39666

30. 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
31. 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. DOI: https://doi.org/10.1038/nclimate3399
32. 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
33. 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. DOI: https://doi.org/10.1038/s41612-022-00301-2
34. 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. DOI: https://doi.org/10.1029/2022JD037563
35. Grose, M., 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. DOI: https://doi.org/10.1029/2019EF001469
36. 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. DOI: https://doi.org/10.1007/s00382-016-3189-1
37. 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: DOI: https://doi.org/10.1007/s00382-013-1931-5

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 [1]. Ocean acidification poses a threat to marine ecosystems [2] and affects organisms and ecosystem services, including food security, by reducing biodiversity, degrading habitats and endangering fisheries and aquaculture [3]. 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 [4]. The key implications of acidification are being addressed through regional and national plans and policies for economic development, food security, and livelihoods [4].

Chemical process and impacts

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 [5]. This process, termed 'ocean acidification' (OA) [6], 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 [7]. 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 [8].

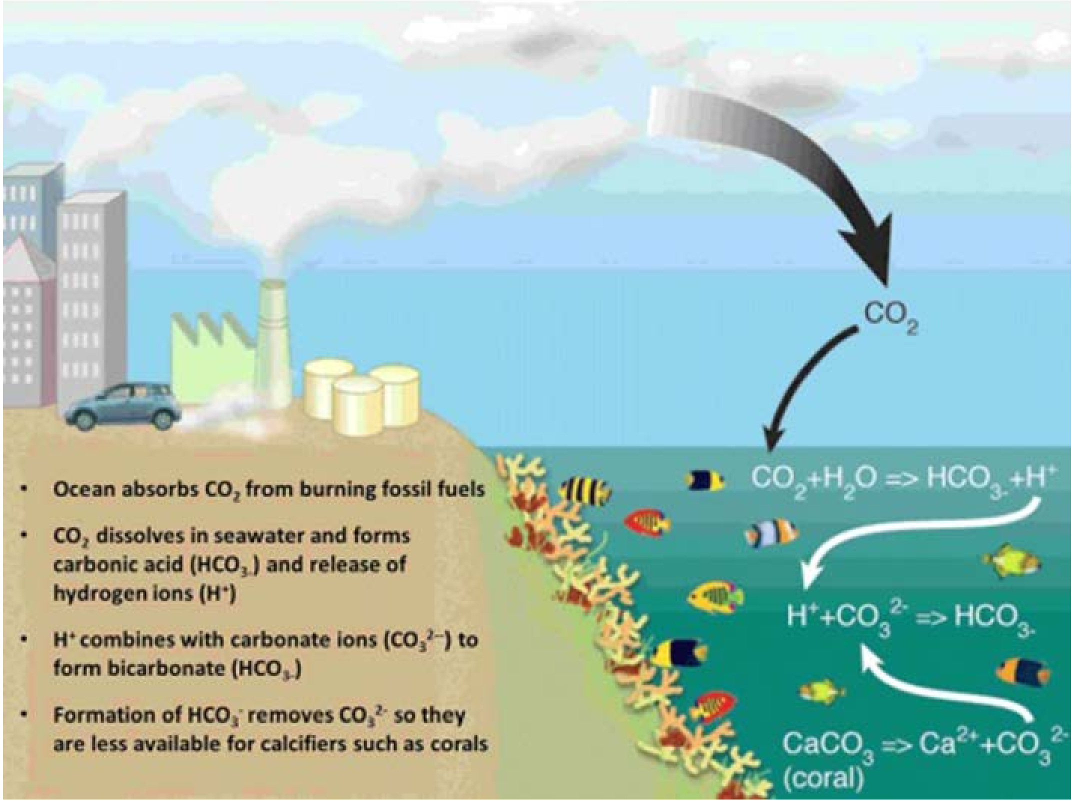


Figure 11-1 The process of ocean acidification. Source: modified from Hoegh-Guldberg et al. 2007 [9].

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 to coastal communities that rely on them for their livelihood and wellbeing. This is a particular hazard impacting the western tropical Pacific, including Nauru, especially for the fisheries sector [10].

Observed changes in aragonite saturation and pH

Atmospheric CO_2 concentrations have increased 47 % since the pre-industrial era (1750) [11] and 30 % of the CO_2 is being absorbed by oceans [12]. The global average pH was 8.05 in 2022, down from 8.11 in 1985 [3]. In 2022, in the equatorial section of the Pacific Ocean (latitudes 7 °S to 7 °S), pH is slightly lower, at around 8.01, where a decrease of 0.070 in pH is observed across the 1982–2022 period, representing an 18 % increase in acidity (Figure 11-2, left). For latitudes 7 °S to 7 °N, aragonite saturation levels have decreased from above 3.8 in 1982 to below 3.3 in 2022 [13] (Figure 11-2). 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 [14].

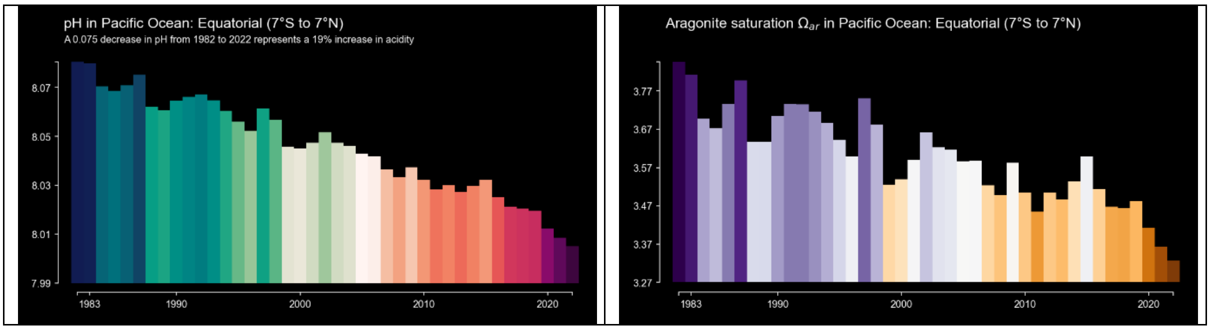


Figure 11-2 pH (left) and aragonite saturation levels (right) in the Equatorial region of the Pacific Ocean Basin (latitudes 7 °S to 7 °S) measured from 1982-2022 [13] Data Source: OceanSODA-ETHZ [15]

Importance of the Pacific OA monitoring network

Local OA observations through better monitoring 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 [16]. There is an opportunity for integration of ocean chemistry monitoring instruments into the existing Sofar Spotter buoy coastal network. Something similar could be done for Nauru. This would improve our understanding of 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 [17]. Under all global CO_2 emission scenarios, a net decrease in pH and aragonite saturation state occurs in the future, with the largest changes associated with the highest CO_2 emissions. Mean 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 low (SSP1-2.6), medium (SSP2-4.5), medium-high (SSP3-7.0) and high (SSP5-8.5) emissions, respectively [2].

Ocean pH for the Nauru EEZ region is projected to decrease to 7.97 units (or a 17 % decrease since a 20-year period centred on 2005) by 2050 under a low emissions scenario (SSP1-2.6) with minimal further changes out to 2090. Under a high emissions scenario (SSP5-8.5), pH levels lower significantly to 7.73 units (or a 104 % decrease since the historical period centred on 2005) up to 2090 (Figure 11-3 and Table 11-1).

While the projected changes in pH seem small, it is important to remember that the pH scale is logarithmic, so for comparison, the reduction in pH of about 0.12 in surface ocean waters around Australia over the past 140 years actually represents a 30 % increase in acidity [18].

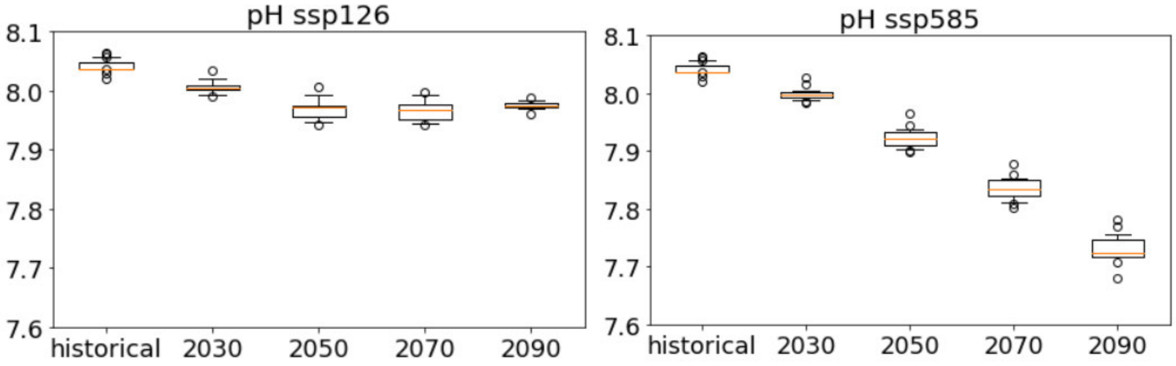


Figure 11-3 pH for the Nauru EEZ for the historical period (2000-2010), 2030, 2050, 2070 and 2090 from 11 CMIP6 models under low emissions (SSP1-2.6 left), and 14 CMIP6 models under high emissions (SSP5-8.5 right). In each box/whisker plot, the central line is the median value whereas the box defines the 25-75th percentile range, and the whiskers define the 10-90th percentiles. Source: Jiang et.al 2023

Table 11-1 Summary table of the median pH for SSP1-2.6 and SSP5-8.5 -for 2030 and 2050 (10th to 90th percentile of model range in brackets; 11 CMIP6 models represented for SSP1-2.6 and 14 CMIP6 models represented for SSP5-8.5).

Year	SSP1-2.6	SSP5-8.5
2030	8.01 (8.00 – 8.02)	8.00 (7.99 – 8.01)
2050	7.97 (7.95 – 7.99)	7.92 (7.90 – 7.94)

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 [19].

For Nauru, under a high emission scenario (SSP5-8.5), aragonite saturation states may fall below 3 by 2070, a level where coral reefs 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 (SSP1-2.6), consistent with the Paris Agreement target of keeping global warming well below 2 °C, then the aragonite saturation state may start to recover after 2050 (Figure 11-4 and Table 11-2).

Aragonite saturation state also shows a steady decline to 3.48 units under all emissions scenarios by 2050 (a 10 % change since the historical period centred on 2005). For a high emissions scenario (SSP5-8.5) by 2090, aragonite saturation state levels decrease to 2.37 units (or a 39 % change). However, if emissions follow a low scenario (SSP1-2.6) consistent with the Paris Agreement target of keeping global warming well below 2 °C, then the aragonite saturation state may start to recover after 2070.

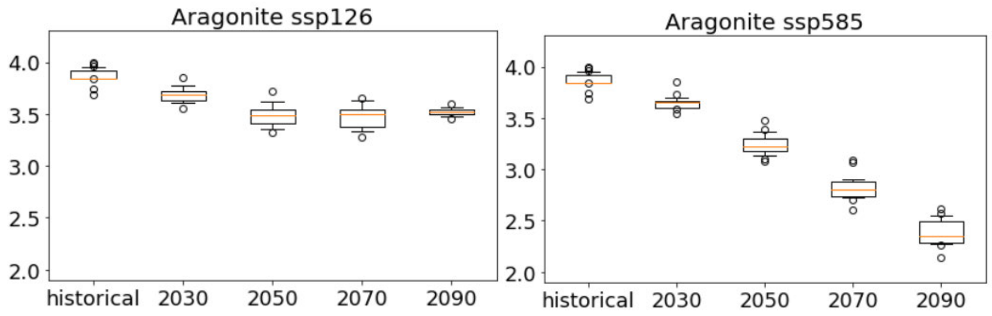


Figure 11-4 Aragonite saturation state for the Nauru EEZ for the historical period (2000-2010[17]), 2030, 2050, 2070 and 2090 from 11 CMIP6 models under low (SSP1-2.6 left), and 14 CMIP6 models under high (SSP5-8.5 right) emissions pathways. In each box/whisker plot, the central line is the median value whereas the box defines the 25-75th percentile range and the whiskers define the 10-90th percentiles. Source: Jiang et. al 2023

Table 11-2 Summary table of the median aragonite saturation state for SSP1-2.6 (11 CMIP6 models) and SSP5-8.5 (14 CMIP6 models) for 2030 and 2050 (10th to 90th percentile of model range in brackets).

Year	SSP1-2.6	SSP5-8.5
2030	3.68 (3.61 – 3.78)	3.69 (3.57 – 3.72)
2050	3.49 (3.35 – 3.61)	3.24 (3.10 – 3.38)

Spatial patterns of projected changes in aragonite saturation state near Nauru are shown in Figure 11-5. Larger changes, spread across the entire EEZ, are obvious for the high emissions scenario compared to the low emissions scenario.

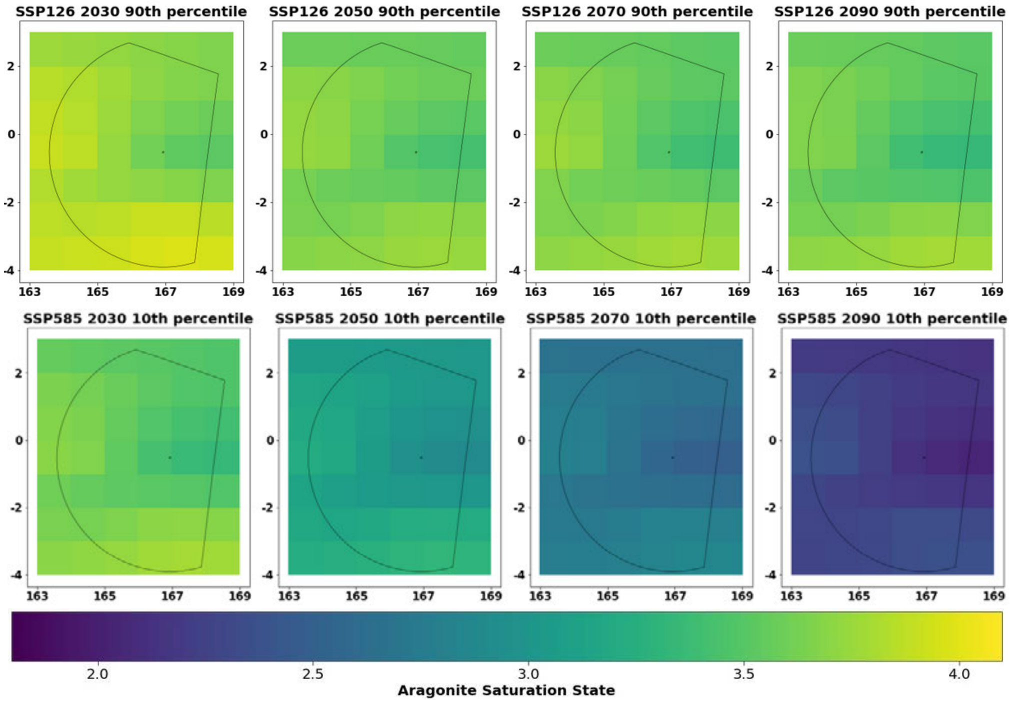


Figure 11-5 Upper and lower projections of aragonite saturation state for the Nauru Exclusive Economic Zone (marked by the black line) 90th percentile under SSP1-2.6 (11 CMIP6 climate models) (top row), and 10th percentile under SSP5-8.5 (14 CMIP6 climate models) (bottom row) for the years 2030, 2050, 2070 and 2090.

---

[17] The historical data provided by Jiang et. al 2023 is presented as decadal averages from 1750-2010. For baseline period consistency with other chapters in this report, 2005 (1995-2014), the historical baseline for ocean acidification variables was also centred on 2005, though as data was unavailable for the same averaging period 2000-2010 was used.

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 [20].
- 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 [2].

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. IPCC WG2, *Climate Change 2022: Impacts, Adaptation and Vulnerability.* 2022 Cambridge University Press, : Cambridge, UK and New York, NY, USA, .
3. World Meteorological Organization, *State of the Global Climate 2023*. 2024: Geneva; Available from: https://library.wmo.int/records/item/68835-state-of-the-global-climate-2023
4. 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
5. DeVries, T., The Ocean Carbon Cycle. *Annual Review of Environment Resources,* 2022. 47: p. 317-341. DOI: https://doi.org/10.1146/annurev-environ-120920-111307
6. Feely, R.A., S.C. Doney, and S.R. Cooley, Ocean acidification: present conditions and future changes in a high-CO_2 world. 2009. *Oceanography* 22(4):36–47. https://doi.org/10.5670/oceanog.2009.95
7. 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). Available from: https://coastfish.spc.int/component/content/article/412-vulnerability-of-tropical-pacifc-fisheries-and-aquaculture-to-climate-change.html
8. 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. DOI: https://doi.org/10.1146/annurev-marine-041911-111611
9. 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. DOI: https://doi.org/10.1126/science.1152509
10. 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
11. IPCC, *Summary for Policymakers. Synthesis of IPCC Sixth Assessment Report.* 2023 IPCC: Geneva, Switzerland; Available from: https://www.ipcc.ch/report/ar6/syr/
12. Rohr, T., A.J. Richardson, A. Lenton, M.A. Chamberlain, and E.H. Shadwick, Zooplankton grazing is the largest source of uncertainty for marine carbon cycling in CMIP6 models.

Communications Earth & Environment, 2023. 4(1): p. 212 DOI: https://doi.org/10.1038/s43247-023-00871-w

13. 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
14. 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. DOI: https://doi.org/10.1029/2019GB006368
15. 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. DOI: https://doi.org/10.5194/essd-13-777-2021
16. CSIRO, VMGD, and SPREP, *Ocean monitoring: Sofar Spotter buoys*. 2023; Available from: https://www.vanclimatefutures.gov.vu/assets/docs/Ocean%20Monitoring%20Factsheet.pdf
17. 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. DOI: https://doi.org/10.1029/2022MS003563
18. CSIRO, *The state of ocean acidification*. 2020; Available from: https://www.csiro.au/en/news/all/articles/2020/november/the-state-of-ocean-acidification
19. 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. Available from: https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-9/
20. 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. Available from: http://www.igbp.net/publications/summariesforpolicymakers/summariesforpolicymakers/oceanacidificationsummaryforpolicymakers2013.5.30566fc6142425d6c9111f4.html

Section 2 HAZARD-BASED IMPACTS AND RATINGS FOR SECTORS

This section has nine chapters, each of which is aligned with a priority sector in Nauru's Framework for Climate Adaptation and Disaster Risk Reduction [1]. Climate hazards causing impacts are described for each chapter, then summarised at the end in Table 20-1.

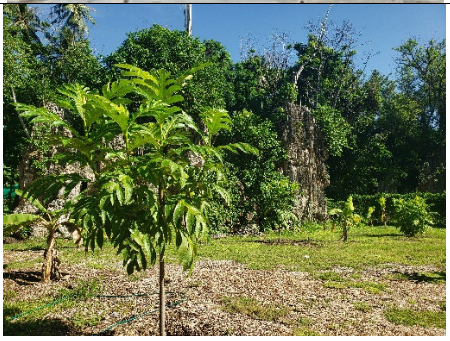
	
	
	

Photo credit: CSIRO, 2024.

Chapter 12 Water resources

Increasing security of water supply and quality remain critical actions for Nauru. This requires improved storage capacity, more efficient delivery, as well as reducing water demand through appropriate conservation measures, and rehabilitation and protection of groundwater resources [1]. The National Sustainable Development Strategy (NSDS) [2] has four priority areas, including infrastructure which notes the importance of enhancing water utilities. The Updated NDC Priority Areas (2019) [3] and the Nauru Climate Change Policy (2023) [4] include water security.

There are three natural sources of water available on Nauru – rainwater, seawater and groundwater.

Rainwater

Nauru has limited surface water resources, with Buada Lagoon, a brackish lake, being the most significant. Therefore, rainfall harvested in water-tanks provides a critical water resource for communities, agriculture, businesses, livelihoods, food security, sanitation and drinking water; 36.5 % of the community use rain catchment for drinking water supply [5] (Figure 12-1).

The overwhelming majority (96.3 %) of households in Nauru had some form of water storage [5]. Most (75.9 %) rainwater tanks can hold between 3,000 and 10,000 litres of water. Very few (2.9 %) had a capacity of less than 3,000 litres. Some households (21.2 %) had large storage tanks, with a capacity of more than 10,000 litres [5]. While over 70 % of households had downpipes only 61.5 % of households had downpipes connected to a water storage tank, and only 56.4 % of households had downpipes that were working. In 11.4 % of households, downpipes needed repair and in 4.1 % they needed to be replaced, particularly in Uaboe and Yaren [5].

Figure 12-1 Rainwater capture from roofs/gutters (Source L Webb CSIRO, 2024)

Seawater - Desalinised water

In the past, Nauru imported water from the neighbouring islands (Marshall Islands and Solomon Islands), but this is very expensive and no longer an option. At present, Nauru supplements rainfall with desalinized sea water, locally termed 'RO' (an abbreviation of reverse osmosis) [6] (Figure 12-2). RO has been identified as Nauru's primary water source for the future. There is one main diesel-powered RO facility located near the port and a smaller facility at the Meneng Hotel which is used to service the hotel [7]. The pump-station for the main RO is located in a solid concrete building with 4 pumps inside (Figure 12-2, middle). The inlet pipe runs under the reef to a deep drop off at the reef edge and is not exposed to wave action. The outlet concentrate is discharged to the ocean [7].

The RO system produces potable water. After desalinating, the RO water is remineralised, then stored, having been disinfected with chlorine. Desalination needs expensive diesel power [8] and expert maintenance [6]. The cost of maintenance, spare parts and airfreight is significant if spare parts are required for urgent repairs. Spare parts are manufactured in Asia, but shipped from

Australia, and require lead times for manufacture and shipping (Inception meeting 2024, Personal Communication).

Figure 12-2 RO intake pipe near port (left), water truck refilling at RO plant (middle) and delivering RO water to household tanks by truck (right). Photo credit: CSIRO, 2024.

The community is heavily reliant on RO to meet a range of water demands including washing, firefighting and, during drought periods, agriculture. Water is transported by truck from the desalination plant to the individual storage tanks where required [9] (Figure 12-2, right). Almost 50 % of households' main source of drinking water was from a tanker truck that delivered water from the desalination plant to their water tanks [5]. Currently (2024) there are six 'official' delivery trucks, supported by six private-contractor owned delivery trucks servicing the entire island's household water supply [7]. While the RO facility can produce enough water, the delivery of water is understood to be problematic (Inception meeting 2024, Per Comms). Only 70 % of water deliveries can be made in the month that they are ordered by customers. Furthermore, truck delivery requires road access, which is not available to all properties in Nauru, particularly newer houses on informal roads [7].

Schools are often closed due to the poor water delivery system [7]. In the past, water scarcity has occurred if the desalination plant has low capacity due to technical issues or high oil prices [10].

Groundwater

Rainfall on Nauru that is not collected and stored in rainwater tanks, or doesn't runoff as stormwater into the ocean, soaks into the ground and contributes to groundwater. In Nauru's case, water infiltrates into the ground and becomes recharged to groundwater that moves from the inner parts of the island towards the coast and discharges along the coastline, where the outflow varies according to changes in permeability and aquifer thickness [6]. The shallower groundwater that is recharged from direct rainfall on the island may nominally be considered freshwater at the water table but, due to some mixing with the underlying saltwater, much of the shallow groundwater is at least slightly brackish, with salinity increasing with depth [7, 11, 12] (Figure 12-3).

The main concentration of groundwater wells is located along the coastline and around Buada Lagoon, where pumping or bailing are the methods used for water extraction. A 2017 survey located the presence of only a few drought-resilient freshwater lenses, in low conductivity sandy deposits, unexpectedly next to the seashore [10]. A recent study has indicated that the 'Bottomside' of the northern part of the island has a fresh groundwater lens that could potentially represent a sustainable solution for meeting water demand for Anetan and Ewa districts only, not the entirety of Nauru [6].

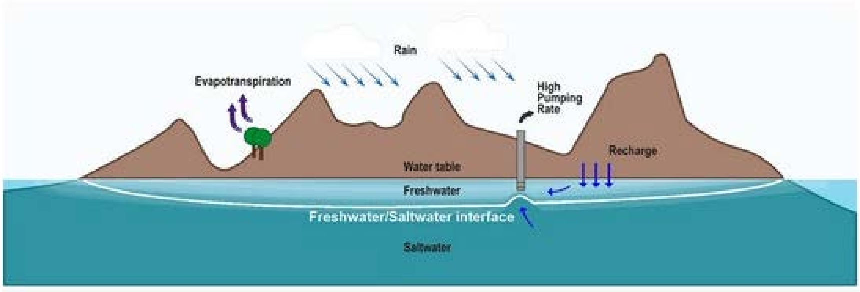


Figure 12-3 Small islands' typical freshwater lens-shape over the brackish/salt water. The effect of a pumping well is indicated (source [10]).

According to the 2023 Census, most households (1,131 or 56 %) did not use underground water. Those that did use it mostly did so for washing (27.5 %) and personal bathing (25.7 %), followed by gardening and other outside uses (17.4 %). Very few households (1.6 %) used it for cooking and drinking [5].

Acceptability of groundwater quality may vary not only according to the season but also depending on local circumstances: water tanks and rainwater harvesting systems maintenance, delays in delivery of RO water, and community awareness about water quality/risks [10]. However, during drought periods, groundwater is used for cooking/boiling and livestock even in those areas where the total dissolved solids (TDS) content is very high [10].

Water storage

Nauru's national water storage capacity is 8 days [13]. Drinking water is stored in household water tanks that either harvest rainwater from roofs/gutters or serve as reservoirs for desalinated water. Households reported their water source dried up frequently (8.4 %) or sometimes (64.2 %), with variation across districts [5].

The quality of rainwater can be adversely affected by the exposed surface onto which it falls. Therefore, the mixing of rainwater with desalinated water results in difficulties in maintaining water quality in the tank [7].

Currently only 8 % of the population have access to piped water, either inside or outside the home [5]. Following extensive consultation [14], a reticulated system, fed from the "Aiwo Water Supply System (WSS)" and "Meneng Water Supply System", is planned to encircle the island along the existing main road [7] (Figure 12-4). The pipeline will deliver water from the Aiwo desalination plant to around 1215 households and businesses between Baitsi and Yaren. Additionally, three storage reservoirs at Command Ridge and Anetan, and an elevated reservoir at Old State House, are included. Piped water supply is expected to be available from 2030 [7].

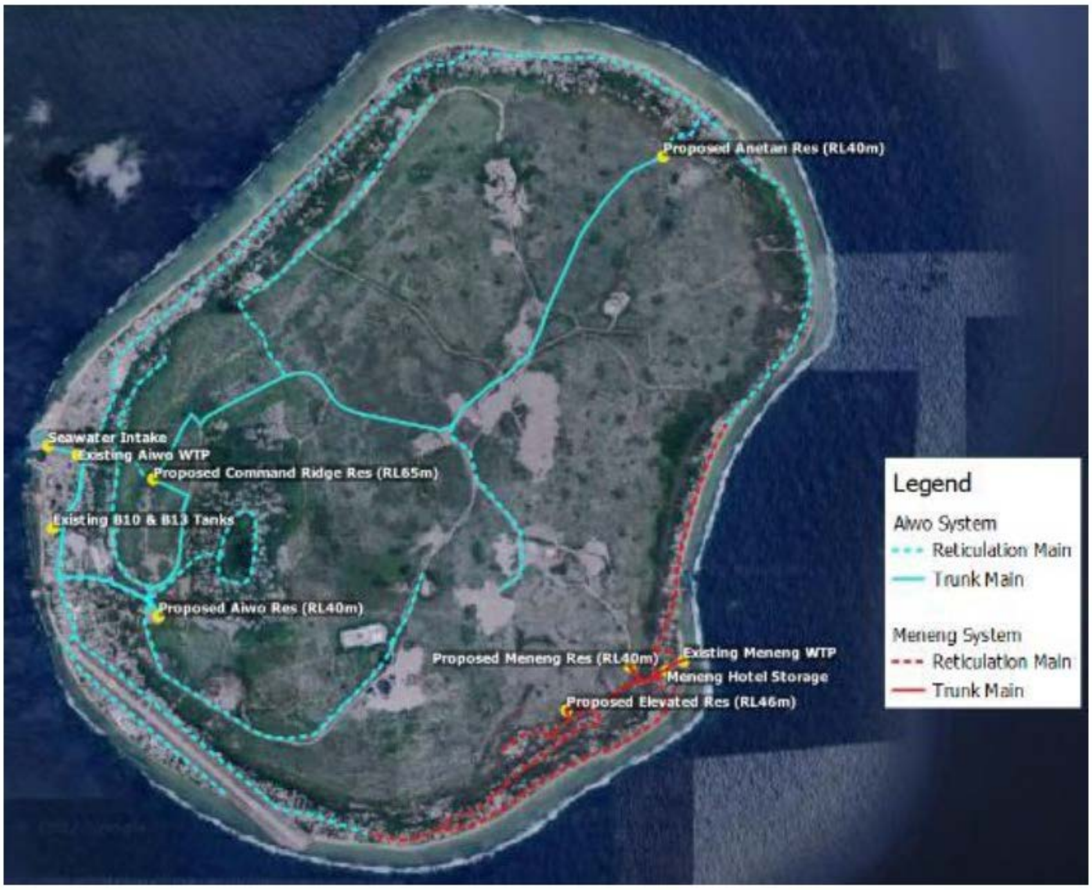


Figure 12-4 Nauru's centralised water reticulation preferred option (Source: [7]).

Water quality and waste management

Households are exposed to potential water quality issues at collection points due to the quality of the exposed surface, contamination of the surface (e.g. phosphate dust), maintenance of water tanks and water tankers [7]. This may have impacts on people's health, gardens and crops.

Water from most groundwater wells in Nauru does not meet WHO drinking-water standards for Total Dissolved Solids (TDS) [10]. Ground water is contaminated primarily from sewage systems, mining, and dumping of industrial and domestic waste [2, 6, 7, 15].

A new sanitation masterplan including the island's sewerage system is being planned for Nauru [16, 17].

Impacts to water security associated with drought, extreme rainfall, and sea level rise

Drought

Water scarcity due to drought is a significant issue. While the present supply of potable water can meet the population demand in most years, it is not enough in dry years [10]. After a dry period, many water tanks may be emptied and the pressure on the water delivery truck network increases, i.e. demand exceeds delivery capability and water cannot be delivered to schedule [7].

The Meteorological and Hydrological Service provides seasonal climate forecasts and drought frequency data to the Water Department. The resilience of households to water scarcity varies and depends on the number of household members and the rainwater storage available (Inception meeting, Pers comm, 2024). In addition, drought periods are often hotter than usual, and higher temperatures can increase water demand and evaporation, while reducing desalination plant efficiency.

In the most recent 2023 census, 62.7 % of households reported being affected by drought in the previous 10 years [18], with the affect varying across districts, potentially reflecting the disaster-preparedness for households in different districts [5]. Nauru has experienced prolonged droughts, of up to 36 months [19], which have had significant impacts on health, food security and the economy.

During droughts, 33.1 % of households relied on ground water, 22.7 % depended on neighbours and relatives, and 12.6 % used desalinated sea water [5]. Only a few drought-resilient freshwater lenses are close to the coast, though not suitable for drinking/potable [10].

During water stress, Pacific Island peoples accessed freshwater from caves, coastal freshwater seeps, and from areas of coastal upwelling offshore; most such knowledge and practices appear to have been lost today [20].

Extreme rainfall

Increased extreme rainfall events may damage water storage, treatment and drainage systems. Extreme rainfall can be harvested in rainwater tanks if capacity exists. This could reduce reliance on desalinated water. However, extreme rainfall can cause poor water quality due to high sediment and pollution load.

Sea level rise

Increases in the frequency of extreme sea level events can cause saltwater intrusion into the soil, saltwater intrusion/thinning of freshwater lenses and reduction in water quality. Rising sea levels will impact water and wastewater infrastructure. Underground water resources are particularly vulnerable to saline contamination. Saltwater intrusion of the freshwater lens can occur through storm-surge over-wash and coastal flooding [6].

The Meneng RO is potentially exposed to sea level rise and extreme wave action, particularly during high spring tides and king tides (Figure 12-5). The intake pipe infrastructure for the Meneng RO plant is not as well fortified against wave action as is the Aiwo plant.

Figure 12-5 Exposed water intake pipes for Meneng RO facility (Photo credit M Sheppard CSIRO, 2024).

While there has been disagreement in the literature about the level and fluctuation of Buada Lagoon in response to coastal tide elevations [21], a recent study [10] monitored a more extensive network of groundwater boreholes around Nauru and suggested Buada Lagoon responds to tidal variations with a tidal lag of 1.5 hrs and tidal efficiency of 0.54 at a borehole close to Buada Lagoon [10].

Assuming that Buada Lagoon is fully connected (tidal efficiency = 1.0) with sea level, the current flood level indicated in Figure 12-6 is overestimated near Buada Lagoon by approximately 0.6 m [21]. These modelled results exemplify the exposure to future flooding hazards (coastal or rainfall) as land around the lagoon is still relatively low-lying and supports important resources (cropping activities such as bananas, pineapples, vegetables, pandanus trees and indigenous hardwoods), houses and assets [21].

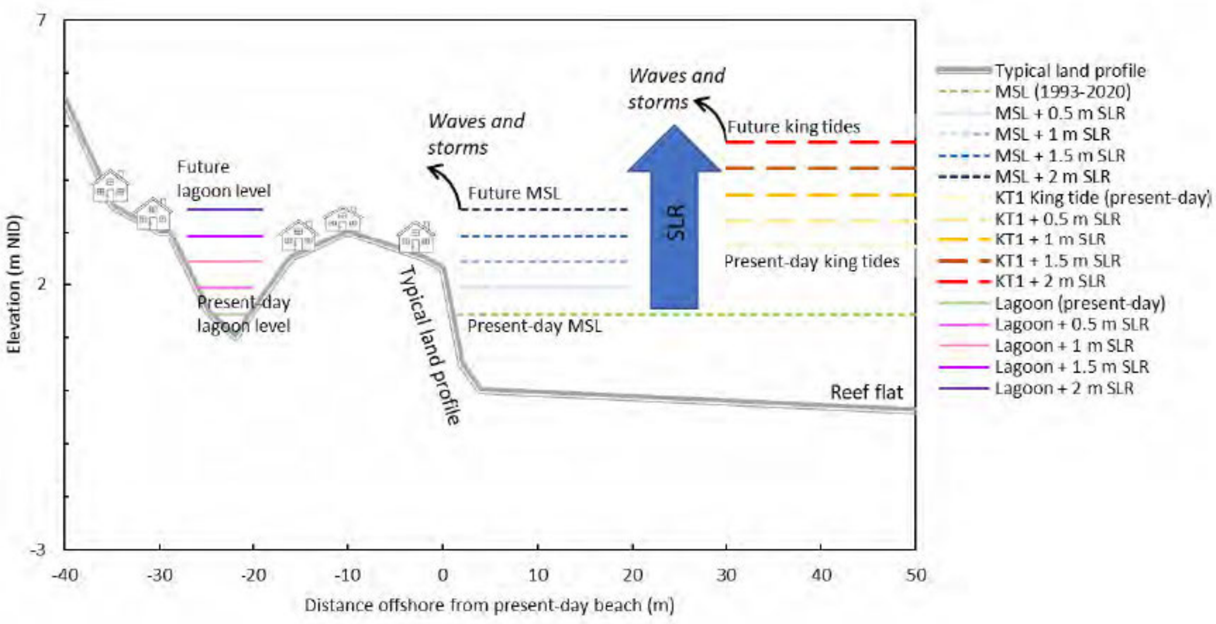


Figure 12-6 Diagram of future elevations of mean sea level (MSL), lagoon level and king-tide (KT1) elevation after sea level rise (SLR) increments. Lagoon level = MSL, King tide = 2.7 m NID. SLR increments of 0.5 m. Ground profile indicative only. Source: Allis et al (2020)

A hydrogeological study will be required to assess how Buada Lagoon, and other groundwater/lagoon levels around the coastal plain, are linked to sea level variability and respond to sea level rise [21].

References

1. Republic of Nauru. *Nauru Framework for Climate Change Adaptation and Disaster Risk Reduction (RONAdapt).* 2015 Available from: https://policy.asiapacificenergy.org/sites/default/files/Nauru%20Framework%20for%20Climate%20Change%20Adaptation%20and%20Disaster%20Risk%20Reduction%20%28EN%29.pdf
2. Nauru Government, *National Sustainable Development Strategy 2019-2030: Revised 2019*. 2019; Available from: https://policy.asiapacificenergy.org/sites/default/files/National%20Sustainable%20Development%20Strategy%20%28NSDS%29%202019-2030%20%28Revised%202019%29_0.pdf
3. Republic of Nauru, *First Nationally Determined Contribution Under the United Nations Convention on Climate Change.* 2019; Available from: https://unfccc.int/reports?f%5B0%5D=corporate_author%3A138

4. Republic of Nauru, *Climate Change Policy – Second Draft*. 2023; Available from: https://nauru-data.sprep.org/system/files/Nauru%20Climate%20Change%20Policy%20%28Final%29.pdf
5. SPC and Government of the Republic of Nauru, *Nauru 2021 population and housing census - Analytical report*. 2023 SPC: Noumea, New Caledonia; Available from: https://sdd.spc.int/news/2023/08/23/nauru-2021-population-and-housing-census-analytical-report
6. Alberti, L., M. Antelmi, G. Oberto, I. La Licata, and P. Mazzon, Evaluation of fresh groundwater Lens Volume and its possible use in Nauru island. *Water Research,* 2022. 14(20): p. 3201. DOI: https://doi.org/10.3390/w14203201
7. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Water Supply System Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor
8. IRENA, *Energy Profile Nauru*. 2017; Available from: https://nauru-data.sprep.org/system/files/Nauru_Oceania_RE_SP.pdf
9. SPC. *Global Climate Change Alliance Plus - Scaling Up Pacific Adaptation (GCCA+ SUPA)* 2019 Available from: https://gem.spc.int/updates/blog/interactive-story/2023/05/securing-naurus-water-lifeline-for-the-most-vulnerable
10. Alberti, L., I. La Licata, and M. Cantone, Saltwater intrusion and freshwater storage in sand sediments along the coastline: hydrogeological investigations and groundwater modeling of Nauru Island. *Water Research,* 2017. 9(10): p. 788. DOI: https://doi.org/10.3390/w9100788
11. Thaman, R.R., F.R. Fosberg, H. Manner, and D. Hassall, The flora of Nauru. *Atoll Research Bulletin,* 1994. Available from: https://repository.si.edu/items/53af5451-4f82-4b7c-bab4-59354aa32dcf
12. Viviani, N., *Nauru: Phosphate and political progress*. 1970: Australian National University Press. Available from: https://openresearch-repository.anu.edu.au/items/a05ac2e7-5a5a-4edb-924c-659434f42c7b
13. UNDRR, *Disaster Risk Reduction in the Republic of Nauru: Status Report 2022*. 2022 United Nations Office for Disaster Risk Reduction, Sub-Regional Office for the Pacific; Available from: https://www.undrr.org/media/85130/download
14. De Jong, E., A. Eskes, J. Hoogstraten, and J. Zadoks, Temperature requirements for germination, germ tube growth and appressorium formation of urediospores of Hemileia vastatrix. *Netherlands Journal of Plant Pathology,* 1987. 93(2): p. 61-71. DOI: https://doi.org/10.1007/BF01998091
15. Republic of Nauru, *National Water, Sanitation and Hygiene Implementation Plan*. 2012: Nauru; Available from: https://www.theprif.org/sites/default/files/2020-08/Nauru%20NWSHIP.pdf
16. NSRUDP, *Nauru : Sustainable and Resilient Urban Development Project (plan)*. 2024 ADB; Available from: https://www.adb.org/projects/54377-002/main
17. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Sanitation System Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor,.
18. World Bank, *Climate Risk Country Profile: Nauru (2021): The World Bank Group*. 2021 The World Bank Group: Washington, USA.; Available from: https://climateknowledgeportal.worldbank.org/sites/default/files/country-profiles/15819-WB_Nauru%20Country%20Profile-WEB.pdf
19. Australian Bureau of Meteorology and CSIRO, *Current and future climate of Nauru*. 2014 BoM and CSIRO; Available from: https://www.pacificclimatechangescience.org/wp-content/uploads/2013/06/6_PACCSAP-Nauru-9pp_WEB.pdf
20. 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. DOI: https://doi.org/10.1002/wcc.882

21. Allis, M., S. Williams, and S. Wadwha, *Coastal flooding from sea-level rise in Nauru: Stage 1 - static inundation mapping, Prepared for the Nauru Higher Ground Project*. 2020: Prepared for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited. Available from: https://nauru-data.sprep.org/system/files/Nauru_Coastal_Inundation%20with%20SLR_final%20-%20Oct%202020%20reduced%20%281%29.pdf

Chapter 13 Health and wellbeing

Nauru has some of the poorest health indicators for non-communicable diseases (NCDs) in the Pacific Islands, with significant impacts on life expectancy (in 2021 only 4 % of Nauru's population were older than 60 years) [1].

The diet of Nauru's people has deteriorated in recent years. Nutrition is a central element of the country's 2014–2020 NCD action plan, which includes initiatives to address obesity, diabetes, and a junk-food epidemic [2]. The high cost of imported food products, limited capacity for food production and constrained economic situation results in lack of fresh and healthy food consumption; over 50 % of households report not having access to healthy and nutritious fresh food because of a lack of money or other resources, 47 % of the population report being worried about insufficient food, and 11.7 % have experienced a whole day without food in the last 12 months [1]. While Pacific communities have long depended on island ecosystems to provide healthy diets, this is something that is declining in many island contexts across the Pacific with the inclusion of more imported (often nutrient-poor) foods in daily diets [3, 4].

Traditional medicines include coconut to alleviate headaches and treat wounds, and pandanus to treat burns. The oil from the fruit of the *calophyllum inophyllum* tree is used to treat ringworm and rheumatism, and an extract from the bark to treat wounds [5].

Figure 13-1: Health message on a building. Photo credit: CSIRO, 2024.

No mental health policy or Act existed in Nauru at the time of writing (2024), although a draft mental health policy has been developed. Nauru is a member of the WHO Pacific Islands Mental Health Network and has recently launched a Mental Health Toll-Free Help Line. Facilities on the island consist of 9.8 mental health outpatient facilities, and 19.5 psychiatric beds in general hospitals, per 100,000 people [6].

Phosphate mining dust is an issue where it is blown onto surfaces such as roofs, and subsequently can enter the water supply. While it is unclear if the phosphate can be ingested by humans (a gap in knowledge that needs exploring for Nauru), but if it does, it is normally excreted unless there is a problem with the kidneys [7]. Phosphate excess has been well recognised as a critical factor in the pathogenesis of mineral and bone disorders associated with chronic kidney disease [7]. Recent investigations have also uncovered toxic effects of phosphate on the cardiovascular system [8], among many other complications [7]. The phosphate deposits also contain high levels of heavy metals such as cadmium, lead and arsenic. These heavy metals can leach into the soil and water and pose a risk to human health and the environment.

Low international travel and tourism numbers have reduced Nauru's exposure to communicable and vector-borne diseases. However, tourism is being increasingly considered as a potential income source for Nauru, including occasional cruise ships with half day or full day packages. Increased visitor numbers could present increased exposure to communicable diseases. Currently, Nauru does not have arrivals surveillance for disease upon entry into the country (deduced from inception interviews 2024).

Climate change is having detrimental effects on the health of communities. In the absence of strong and effective mitigation and adaptation measures, these impacts are projected to worsen [9]. Global studies indicate 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, respiratory illness, eye, ear and skin disorders and diffuse impacts through mental/psycho-social disorders [10].

In Nauru and in other parts of the Pacific, anecdotal reports of the afternoon sea breeze not occurring means that residents will need to run air-conditioners or other cooling devices more often and for longer. This will result in increased energy demand, which may require load-shedding (to balance supply and demand), leading to local electricity service disruption.

Health and wellbeing impacts associated with temperature, rainfall, drought, wind and sea level rise

Temperature

Heat strain, characterised by thermal, cardiovascular, and renal strain, can lead to adverse health outcomes such as heat exhaustion, heat stroke, or cardiovascular collapse [11]. The concerns for human health, productivity, and well-being are greater in humid climates [12]. Risk is higher in people with pre-existing illnesses (e.g., cardiovascular disease, or are immunocompromised). Aging, certain medications, and differences in body composition may exacerbate heat strain due to impairments to sweating and/or blood flow or the internal management of body heat storage. Conversely, fitness, heat acclimatisation, and behavioural adaptations protect against excessive heat strain [11]. New heat survivability modelling frameworks and approaches have recently been developed for use in climate change research and introduce an approach to assess liveability [11].

Heat-related stress and deaths could increase under a warmer climate and unfavourable socio-demographic conditions [10, 13]. Extreme heat directly impacts local communities, causing increased morbidity [14]. It can also exacerbate existing health conditions, especially for those with respiratory/cardiovascular diseases and diabetes where indoor temperatures are above 26 °C [15], particularly in the absence of cooling (e.g. no air conditioning). Extreme heat is also associated with deaths [13]. For each 1 °C increase in temperature, there is a statistically significant increase in the risk of mental health-related morbidity [16] and increased hospital admissions [17]. For the Oceania region (excluding Australia and New Zealand), heat stress 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 [18].

Under extreme heat, the reduction in workforce productivity affects business continuity, water security, food security, infrastructure development, and health [10, 19, 20]. Evidence of heat stress has been reported for airport workers in Nauru (Inception meeting 2024, Pers Comm). Increasing temperature has reduced the amount of outdoor activities Nauruan's are undertaking (Pers Comm: Inception meeting, 2024) with a preference to remain indoors to avoid the heat. This could have flow on impacts for opportunities to exercise and efforts to reduce the incidence of NCD.

The cooling degree days index is 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 Nauru since 1951 [21]. If energy demand exceeds energy capacity, blackouts may occur, so there may be inadequate cooling for businesses and communities, increasing the risk of heat-stress.

The land is warmer than the ocean. For coastal areas, this differential heating can induce the formation of sea breezes. With ocean warming, the benefits from a sea breeze can be lost or reduced [22]. This can have implications for land temperatures and therefore human comfort. The Higher Ground Initiative (https://www.climatechangenauru.nr/higher-ground-initiative) aims to relocate housing and critical infrastructure inland, to higher ground, and better harness prevailing winds to passively cool homes and buildings [23].

Vector borne diseases are influenced by temperature [24]. Mosquito vectors for dengue fever and chikungunya, *Aedes aegypti* and *Aedes albopictus,* are present in Nauru. There have been sporadic outbreaks of dengue (most recently in 2017: 902 cases and 2019: 42 cases) and chikungunya (in 2015: 21 cases) [25]. There are currently (as of May 2024) no disease vectors present for malaria [26], however it can occur infrequently when carried into the country by overseas visitors.

High temperature is linked with some diarrheal diseases [27] and other enteric (stomach) infections [28], and is associated with a substantial burden of ill-health in low-income and middle-income countries [28, 29] potentially straining or exceeding health service capacity. Food handling in households is increasingly a food safety issue due to increasing air temperatures and limited cold storage. These issues are likely to remain a public health risk under climate change due to higher temperatures [27]. Overall, 72.6 % of households in Nauru had a refrigerator, although this percentage was less than half of all households in Ijuw, and only just over half in Location. About two thirds (65.1%) of households owned a deep freezer. The proportion of households with a deep freezer was particularly high in Uaboe (82.5 %), Baitsi (76.9 %), Aiwo (76.0 %) and Anabar (75.3 %) and lower than average in Location (47.4 %) and Nibok (58.2 %) [1].

Hot and dry conditions are associated with fires in the waste dump facility (Pers Comm: Inception meeting 2024). Smoke spreading from these fires contributes to poor air quality, particularly due to the burnt materials containing plastic waste (Pers Comm: Inception meeting 2024). The open burning of plastic waste is toxic to human and environmental health, and a critical—but often overlooked—aspect of plastic pollution [30]. Burning municipal solid waste and plastic materials produces various toxic substances in the air and is associated with an increased risk of heart disease, respiratory issues, neurological disorders, nausea, skin rashes, numbness or tingling in the fingers, headaches, memory loss, and confusion [31, 32]. In one study [32], ash from burning plastic was used as fertiliser and found related to an alarming level of toxins, such as dioxins and polychlorinated biphenyls, in the soil and in the eggs of free-range chickens in the area.

Rainfall

While Nauru differs from many other Pacific Islands in having low rates of diarrheal disease despite high temperatures, this is potentially due to the reliance on desalinated water. In saying that, it is noted that the rates per population are still 10x higher than Australia and 59x higher than Singapore [33]. Heavy rainfall can be correlated to increase in reported diarrheal diseases [27, 34]. Lack of maintenance of rainwater tanks, poor drainage and overflow of septic systems has been associated with poor water quality in Nauru [35], and this can exacerbate these health issues particularly in densely populated areas (Inception mission, Pers Comm, July 2024).

Infants have high sensitivity to diarrheal disease due to their developing immune system and can be highly exposed if bottle feed [34]. There have been recent anecdotal reports of increasing cases of rotavirus in infants suspected to be related to children playing in puddles or mud along the roadside following heavy rainfall. Roadside drainage is via soak pits, and it takes about half a day for water to subside, or longer during a period of heavy rain (Pers comm: Inception meeting, 2024).

Extreme weather events, such as extreme heat, thunderstorms, floods and storm surges, are associated with increased incidence of hospital admissions for asthma [36]. Anecdotal information from stakeholders working in the Nauru health sector suggest an increase in asthma related admissions when heavy rain follows a long dry spell (Inception meeting, Pers Comm, July 2024). Where more than five people are admitted at once, it becomes difficult for the hospital to triage cases (Inception meeting, Pers Comm, July 2024).

Drought

During drought periods, some of the population access groundwater. The water derived from the freshwater lenses has lower quality than the RO water or the rainwater because of saltwater contamination and leakage from domestic sewage pits. Alternative strategies for sustainable use of groundwater must be accompanied by sewage infrastructure design, monitoring activities and well-head protection area definition [35, 37]. A new sewerage system is being currently planned for Nauru [38, 39]. Lack of access to a reliable water supply through drought periods can cause anxiety and related mental health impacts.

Wind

Extreme wind events can cause injuries and deaths, with associated trauma and mental health impacts. Storms can cause damage and disruption to health infrastructure and services.

Changing wind patterns and rising temperatures due to climate change may exacerbate health risks caused by phosphate dust pollution [1]. Water quality may also be affected by dust from the phosphate mine blowing onto roofs and ending up in the water tanks. It is unclear what the health impacts may be from this type of exposure with no knowledge of any assessments around this issue being undertaken (Inception meeting 2024, Pers Comm.). Projected changes in extreme wind are uncertain (Chapter 8).

Sea level rise

Sea level rise will increase threats to physical safety, property and livelihoods, contributing to increases in mental health-related illness [40, 41], and strain on health service capacity. These impacts could be reduced through strong and effective mitigation and adaptation measures [9].

References

1. SPC and Government of the Republic of Nauru, *Nauru 2021 population and housing census - Analytical report*. 2023 SPC: Noumea, New Caledonia; Available from:

https://sdd.spc.int/news/2023/08/23/nauru-2021-population-and-housing-census-analytical-report

2. Maclellan, N., Nauru. *The contemporary Pacific JSTOR,* 2020. 32(1): p. 213-225. Available from: https://www.jstor.org/stable/e27126685
3. 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. Available from: https://apjcn.nhri.org.tw/server/apjcn/14/4/298.pdf
4. 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. DOI: https://doi.org/10.3390/nu11061328
5. Hambruch, P., *Nauru* in *Results of the South Sea Expedition- Ethnography: B Micronesia. Vol 1.* , G. Thilenius, Editor. 1914. Available from: https://www.tandfonline.com/doi/full/10.1080/00223340701692007
6. Government of Nauru, *RoN Hospital*. 2024 Government of Nauru: Nauru; Available from: http://naurugov.nr/government/departments/department-of-health-and-medicinal-service.aspx
7. Komaba, H. and M. Fukagawa, Phosphate—a poison for humans? *Kidney International,* 2016. 90(4): p. 753-763 DOI: https://doi.org/10.1016/j.kint.2016.03.039
8. Foley, R.N., A.J. Collins, C.A. Herzog, A. Ishani, and P.A. Kalra, Serum phosphorus levels associate with coronary atherosclerosis in young adults. *Journal of the American Society of Nephrology,* 2009. 20(2): p. 397-404. Available from: https://doi.org/10.1681/asn.2008020141
9. IPCC WG2, *Climate Change 2022: Impacts, Adaptation and Vulnerability.* 2022 Cambridge University Press, : Cambridge, UK and New York, NY, USA. Available from: https://www.ipcc.ch/report/ar6/wg2/
10. 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. DOI: https://doi.org/10.1289/ehp.15097
11. Vanos, J., G. Guzman-Echavarria, J.W. Baldwin, C. Bongers, K.L. Ebi, and O. Jay, A physiological approach for assessing human survivability and liveability to heat in a changing climate. *Nature Communications,* 2023. 14(1): p. 7653 DOI: https://doi.org/10.1038/s41467-023-43121-5
12. Ravanelli, N.M., S.G. Hodder, G. Havenith, and O. Jay, Heart rate and body temperature responses to extreme heat and humidity with and without electric fans. *Jama,* 2015. 313(7): p. 724-725. Available from: https://jamanetwork.com/journals/jama/fullarticle/2110959
13. 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. Available from: https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(21)00081-4/fulltext
14. Franchini, M. and P.M. Mannucci, Impact on human health of climate changes. *European journal of internal medicine,* 2015. 26(1): p. 1-5. DOI: https://doi.org/10.1016/j.ejim.2014.12.008
15. 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
16. 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. DOI: https://doi.org/10.1016/j.envint.2021.106533

17. 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
18. 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
19. 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. DOI: https://doi.org/10.1038/nclimate2623
20. 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. DOI: https://doi.org/10.1108/BEPAM-03-2022-0040
21. 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
22. Xiao, Y., J. Yang, L. Cui, J. Deng, P. Fu, and J. Zhu, Weakened Sea-Land Breeze in a Coastal Megacity Driven by Urbanization and Ocean Warming. *Earth's Future,* 2023. 11(8): p. e2022EF003341. DOI: https://doi.org/10.1029/2022EF003341
23. Republic of Nauru. *Nauru Framework for Climate Change Adaptation and Disaster Risk Reduction (RONAdapt).* 2015 Available from: https://policy.asiapacificenergy.org/sites/default/files/Nauru%20Framework%20for%20Climate%20Change%20Adaptation%20and%20Disaster%20Risk%20Reduction%20%28EN%29.pdf
24. 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. DOI: https://doi.org/10.1371/journal.pntd.0010514
25. Matthews, R.J., I. Kaluthotage, T.L. Russell, T.B. Knox, P.F. Horwood, and A.T. Craig, Arboviral Disease Outbreaks in the Pacific Islands Countries and Areas, 2014 to 2020: A Systematic Literature and Document Review. *Pathogens,* 2022. 11(1): p. 74. DOI: https://doi.org/10.3390/pathogens11010074
26. PacMOSSI. *Pacific Mosquito Surveillance Strengthening for Impact. Mosquito-borne disease situation report: Tuvalu.* 2024 Available from: https://pacmossi.org
27. Levy, K., A.P. Woster, R.S. Goldstein, E.J. Carlton, 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 Technology,* 2016. 50(10): p. 4905-4922. DOI: https://doi.org/10.1021/acs.est.5b06186
28. 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. DOI: https://doi.org/10.1016/S2542-5196(21)00152-2
29. 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. DOI: https://doi.org/10.1186/1471-2458-12-220
30. Pathak, G., M. Nichter, A. Hardon, E. Moyer, A. Latkar, J. Simbaya, D. Pakasi, E. Taqueban, and J. Love, Plastic pollution and the open burning of plastic wastes. *Global Environmental Change,* 2023. 80: p. 102648 DOI: https://doi.org/10.1016/j.gloenvcha.2023.102648
31. Velis, C.A. and E. Cook, Mismanagement of plastic waste through open burning with emphasis on the global south: a systematic review of risks to occupational and public health.

Environmental Science Technology, 2021. 55(11): p. 7186-7207. DOI: https://doi.org/10.1021/acs.est.0c08536

32. Adetona, O., O.B. Ozoh, T. Oluseyi, Q. Uzoegwu, J. Odei, and M. Lucas, An exploratory evaluation of the potential pulmonary, neurological and other health effects of chronic exposure to emissions from municipal solid waste fires at a large dumpsite in Olusosun, Lagos, Nigeria. *Environmental science pollution research,* 2020. 27: p. 30885-30892.
33. Our world in Data, *Diarrheal disease episodes*. 2021; Available from: https://ourworldindata.org/grapher/incidence-of-diarrheal-diseases?tab=chart&country=NRU~OWID_OCE~FJI~VUT~PNG~SLB~TUV~KIR~FSM~GUM~WSM~TON~AUS~SGP
34. Singh, R.B., Hales, S., de Wet, N., Raj, R., Hearnden, M., & Weinstein, P., The influence of climate variation and change on diarrheal disease in the Pacific Islands. . *Environmental Health Perspect,* 2021. 109(2) DOI: 10.1289/ehp.01109155. Available at: https://ehp.niehs.nih.gov/doi/10.1289/ehp.01109155
35. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Water Supply System Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor.
36. Makrufardi, F., A. Manullang, D. Rusmawatiningtyas, K.F. Chung, S.-C. Lin, and H.-C. Chuang, Extreme weather and asthma: a systematic review and meta-analysis. *European Respiratory Review,* 2023. 32(168). DOI: https://doi.org/10.1183/16000617.0019-2023
37. Alberti, L., M. Antelmi, G. Oberto, I. La Licata, and P. Mazzon, Evaluation of fresh groundwater Lens Volume and its possible use in Nauru island. *Water Research,* 2022. 14(20): p. 3201. DOI: https://doi.org/10.3390/w14203201
38. NSRUDP, *Nauru : Sustainable and Resilient Urban Development Project (plan)*. 2024 ADB; Available from: https://www.adb.org/projects/54377-002/main
39. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Sanitation System Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor,.
40. 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. Available from: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Citation.pdf
41. 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. DOI: https://doi.org/10.1016/j.envint.2021.106533

Chapter 14 Agriculture

In Nauru, a limited variety of fruit trees and vegetables are cultivated. In 2021, only 5.2 % of households reported growing food crops, 4.9 % growing fruits, and 7.9 % raising livestock [1]. The overwhelming majority (93.9 %) of households involved in agricultural activities did so for their own consumption. In Boe, Buada, Denigmodu and Meneng, there were only six households who sold part of their production, and none that produced exclusively for selling their crops [1]. Nauruans therefore remain heavily dependent on expensive imports for up to 90 % of food, and are consequently exposed to food insecurity, price fluctuations in the global market, and interruptions in global supply chains such as during the COVID-19 pandemic [2, 3].

Past high levels of mining income and ready access to imported goods has resulted in limited technical skills and local knowledge of food production in Nauru [4]. Before European arrival, coconut and pandanus palms were cultivated providing a staple source of food, also being used in cultural ceremonies [5]. In the mid-19th century breadfruit (de me), bananas, and paw paw (baba͡ias) were also introduced by Europeans [5]. To make way for mining, under the *Lands Act 1976* (Government of Nauru), the landowners were (and still are) compensated for the removal of coconut palm, pandanus, breadfruit, banana, pawpaw, mango, lime, tomano (*Calophyllum inophyllum*) and almond (Pers Comm: Inception visit 2024).

A total of 105 households were involved in agricultural activities other than producing fruits. The crops cultivated by most of them were chilli (61 households), cabbage (49), eggplant (35) and cherry tomatoes (33), this is fewer than reported in the 2011 census [1]. The number of households raising livestock was similarly small and almost exclusively limited to pigs (136 households) and chickens (46). The total number of pigs held was 491 (compared to 1,306 in 2011) and the total number of chickens was 541 (compared to 4,683 in 2011)[18]. This indicates a dramatic decrease in household livestock raising [1].

Factors limiting reintroduction of agricultural production include water availability and quality, combined with soil fertility and land constraints [6, 7]. Nauru has limited water storage and the soils have limited moisture retention capacity (1,500 kPa tension 10-25%, 30 kPa tension ranged from 8-26%). Soil carbon has been depleted by disturbances including mining, road building and housing construction [8]. In addition, there is only about 4 km^2 of arable land on Nauru, the average plot size available for agriculture is less than 100 square metres, and much of the arable land is occupied by residential dwellings [1]. The difficulties surrounding land ownership often restricts the yield a single farmer can produce due to the limited size of allotments available for agriculture [8].

Currently, the growth of 'wild food species', such as mango, is confined to the Buada district which has rich black soils [4]. These sources of wild food are available for anyone to harvest. Initiatives to encourage additional food gardens exist with a range of small-scale trial agriculture projects,

---

[18] Nauru's largest supplier of whole frozen chickens is Australia, 21,260kg in 2021 (World Trade Integrated Solutions, 2024 https://wits.worldbank.org/trade/comtrade/en/country/All/year/2022/tradeflow/Exports/partner/NRU/product/020721). The recent confirmation of avian flu strains H7N3, H7N9 and H7N8 in Australia (CSIRO, 2024 https://www.csiro.au/en/news/All/News/2024/July/Expert-Commentary-bird-flu-in-Australia) has affected a suspension of imports from Australia to Nauru. This highlights the vulnerabilities in Nauru's reliance on imports. The Government of Nauru has issued a media release (31 May 2024) confirming current supplies of frozen chickens and eggs are safe. http://www.nauru.gov.nr/government-information-office/media-release/nauru-not-affected-by-recent-avian-influenza-outbreak-in-victoria,-australia.aspx

including vegetable and breadfruit farms (Meneñ farm) (Figure 14-1), piggeries, seedling distribution, kitchen gardens and public education [2].

Agricultural pests found in Nauru include the Coconut Hispine Beetle (*Brontispa longissima*) which is controlled by a biological agent [8]. Yellow crazy ants *Anoplolepis gracilipes* are also a pest in Nauru (Pers Comms, July 2024).

The Higher Ground Initiative has plans to incorporate scaled-up food production at household, community, and national levels as well as deployment of land- and water-efficient food production methods, such as hydroponics, aquaponics, and aeroponics [9].

Breadfruit

Breadfruit cropping is being developed at Meneñ farm (Figure 14-1). The Pacific Islands are the centre of origin for Breadfruit trees (*Artocarpus altilis*) [10], an important staple crop grown in the Pacific [11]. They produce an abundance of nutritious fruit, are easy to grow, require little attention, thrive under a wide range of ecological conditions, begin bearing fruit in 3–5 years, and produce nutritious fruit for many decades [10].

Breadfruit is well adapted to the wet tropics, with optimum conditions being temperatures ranging from 21 °– 32 °C, an annual rainfall of 1500–2500 mm and adequate drainage [10, 11].

While deep, fertile, well-drained soils are preferred for breadfruit, some varieties are adapted to the shallow sandy soils of coral atolls [11]. There are two varieties of breadfruit in Nauru. The particular varieties are unknown (Inception meeting, Pers Comm.) Breadfruit has less tolerance to salt soil than Pandanus or coconut, and this plays an important role in planting on islands and atolls [12].

There are no honey bees in Nauru, so pollination is highly dependent on wind, which is a key limitation for high productivity of fruit trees [4, 8]. This may be an issue for breadfruit production as honeybees visit the male inflorescences of the fertile seeded varieties of breadfruit, as well as *A. camansi* and *A. mariannensis*, to gather pollen [11].

The fungi *Phytophthora palmivora* and *Phellinus noxius* cause rot in breadfruit, with *P. palmivora* affecting the fruit and *P. noxius* affecting the trunk and root, and eventually killing the tree. *Bactrocera frauenfeldi*, known as the mango fly, can also attack breadfruit [11], though it's not reported as present in Nauru [11].

Figure 14-1 Small scale food security initiatives: Breadfruit tree growing in Meneñ farm (Left and Centre), Breadfruit Inflorescence in Vanuatu (right). Photo credit: L.Webb, CSIRO, 2024.

Impacts related to temperature, rainfall and sea level rise

Temperature

Temperature ranges can affect suitability for agricultural production. Whereas increased average temperatures may result in less optimal growing conditions for some crops, opportunities for new crop varieties may 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 [11]. For breadfruit, optimum temperatures range from 21 °– 32 °C [11].

Increasing air temperature will have negative impacts on crops and home gardens, and may increase invasive species, pests, and diseases [11]. Extreme heat causes stress for crops and livestock [11], with associated increase in water demand. Throughout the Pacific region, free-range chickens and pigs are an integral part of self-sufficiency. The thermal comfort zone for adult pigs is 16–25 °C, young pigs 25–32 °C, and chickens 10–20 °C [11]. Extreme heat also causes heat stress for humans and reduces farm labour productivity in tropical and mid-latitudes [13].

Rainfall and drought

Increased rainfall is likely to exacerbate damage caused by the fungus *Phytophthora palmivora*, adversely affecting breadfruit fruit quality.

Extreme rainfall can reduce access to gardens due to flooding. Damage, increased disease pressure, and/or waterlogging can affect some crops [11].

Droughts are a significant climate hazard for Nauru. Only a few drought-resilient freshwater lenses are close to the coast [14]. The low water retention capacity of soils and ground water availability limits the potential for intensive cropping during drought periods [8], while poor fruiting of wild food mangos in the Buada district has also been reported during drought [4].

The most recent drought caused mortality in breadfruit, pandanus and coconut plants, and many plants have not recovered. The Department of Agriculture imported coconut and breadfruit plants from Solomon and Marshall Islands to restore Nauru’s stocks of these important food sources (Inception meeting, Pers Comm, July 2024).

Drought 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 [15].

Historical observations of drought

Hambruch (1914) [5] describe the impact of drought on the natural environment in the early 1900s:

“In good years, when there is regular rainfall, Nauru has dense greenery. Then the island wears a lush green robe, which the eye is used to seeing in tropical forests. It is different in years when there is poor rainfall or no rain at all. The picture changes then. Dry spells do considerable damage to the plant growth. Only tall trees with deep roots survive such times on the mountainous terrain, while bushes, shrubs and groundcovers die. The green island then becomes grey, as fine dust covers the branches and leaves with a thin, even, dirty white layer. Not even trees and plants that are exposed to more favourable conditions on the seashore and can still eke out a miserable existence and escape this dust. The greenery of the palm trees disappears; the leaves turn yellow, then brown and then die. The palms produce no fruit. Nature shows signs of serious illness. This is how the island looked when I visited it in May 1909 and October 1910. Only one place on Nauru was thriving then, the edge of the Buada lagoon. It is thickly covered with palms that are doing brilliantly. That has much to do with the supply of ground water.”

Observations from Hambruch (1914) [5] indicate that coconut palms were susceptible to drought, producing a limited amount of fruit or ceasing to fruit, however pandanus and calophyllum and ficus were more resilient to drought.

Sea level rise

Much of the island’s arable land is located in the coastal zone, and therefore vulnerable to erosion and sea level rise. These processes can further reduce arable area and affect soil quality through salinisation (due to intrusion of saline water into the groundwater) [16].

Most varieties of breadfruit, a crop being trialled at Meneñ farm, do not tolerate salinity, whether in groundwater, soil or in salt spray [10]. However, in many of the Pacific low-lying coastal areas, breadfruit grows in a relatively saline environment in terms of both groundwater and salt spray [11].

The inundation exposure of areas with potential for coconut cropping was used as a proxy for potentially productive land area, being 1.09 km^2 or around 5 % of the total island area [16]. About 0.09 km^2 (8.4 % of total) of this area is already below the king tide elevation (Table 14-1); the northern districts of Anetan and Anibar have the highest absolute and proportional exposure, with around 25 % below king tide elevation. With a 2-metre sea level rise, this increases to 65 %. Most other districts show a linear increase from 5 % to 25 % over the scenarios tested (0.2 to 2.0 metres sea level rise) [16]. Results for the whole island are tabulated and plotted in Figure 14-2.

Table 14-1 Coconut crops exposed (m^2) within each district and percentage of total area under king tide (KT1) and KT1+sea level rise (SLR) increments. Analysis of the tide gauge data determined that the king tide elevation (KT1) is 2.7 m Nauru Island Datum (NID). The king-tide elevation selected for the base elevation of this sea-level rise analysis is defined here as the 1 % exceedance elevation of the Nauru tide gauge record from 1993–2020 (Source: [16]).[19]

	KT1 (2.7m NID)	KT1 +0.2m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +2m SLR
All of Nauru	91825	117,825	160,225	227,775	345,450
% of total	8.4	10.8	14.7	20.8	31.6

---

[19] The exposure of coconut crops is reported, however note that the accuracy of the data is unknown, as the database is from the year 2000 and has not been updated. Within the data it is unclear if the original “coconut crop polygons” dataset refers to single coconut palm, an aggregate of palms within a set area, or open ground which could suit coconut palms. For this study, we converted the polygons to represent an area of potential coconut crop features as evaluated over the 5 m DEM grid. In this study the output represents the area (m^2) of potential coconut cropping 16. Allis, M., S. Williams, and S. Wadwha, *Coastal flooding from sea-level rise in Nauru: Stage 1 - static inundation mapping, Prepared for the Nauru Higher Ground Project*. 2020: Prepared for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited.

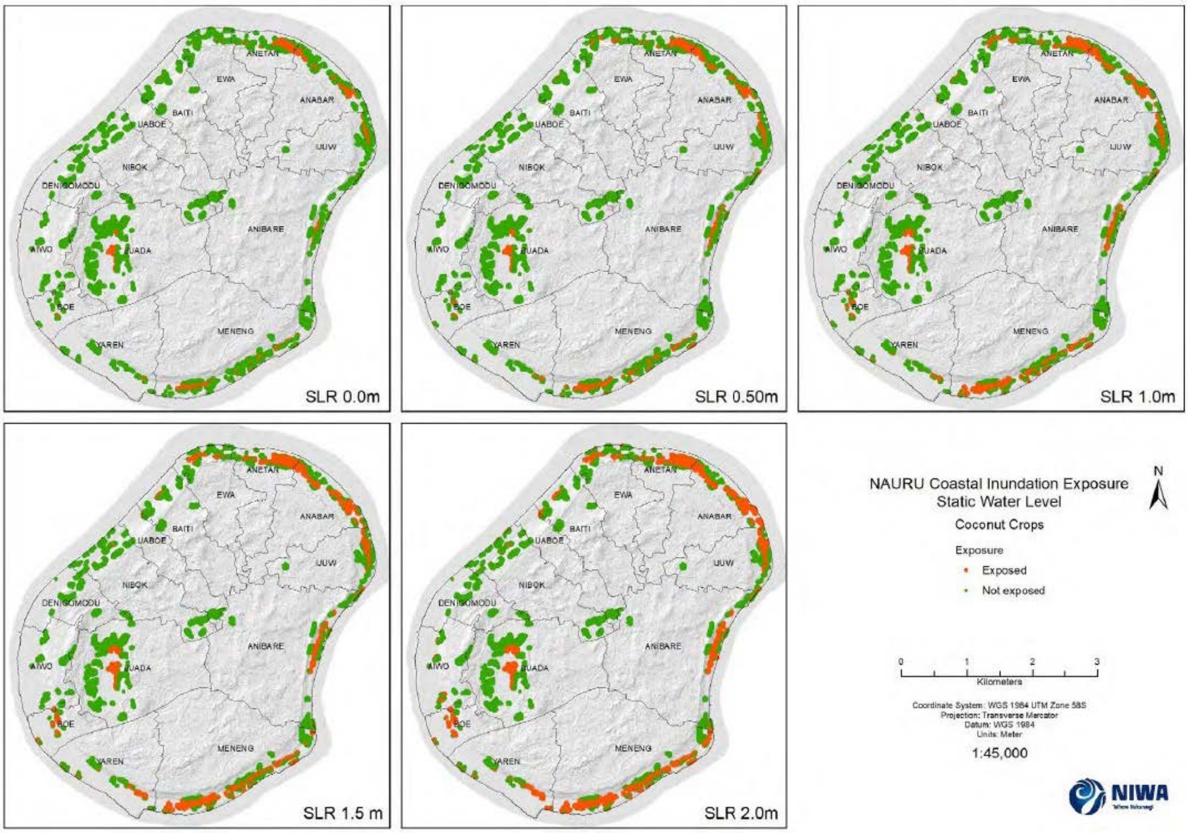


Figure 14-2 Map of coconut crops (proxy for productive land) exposed to king-tide inundation and 0.5 m increments of sea-level rise. Colours show whether land elevation beneath coconut crop feature is below static water level elevation (see legend).

Rising sea level will increase saltwater intrusion. Land surrounding Buada Lagoon is noted for cropping activities including bananas, pineapples, vegetables, pandanus and indigenous hardwoods. The Lagoon, however, is affected by tidal fluctuations, and is expected to become more saline due to sea level rise, negatively impacting important food resources [16].

References

1. SPC and Government of the Republic of Nauru, *Nauru 2021 population and housing census - Analytical report*. 2023 SPC: Noumea, New Caledonia; Available from: https://sdd.spc.int/news/2023/08/23/nauru-2021-population-and-housing-census-analytical-report
2. Republic of Nauru. *Nauru Framework for Climate Change Adaptation and Disaster Risk Reduction (RONAdapt).* 2015 Available from: https://policy.asiapacificenergy.org/sites/default/files/Nauru%20Framework%20for%20Climate%20Change%20Adaptation%20and%20Disaster%20Risk%20Reduction%20%28EN%29.pdf
3. UNDRR, *Disaster Risk Reduction in the Republic of Nauru: Status Report 2022*. 2022 United Nations Office for Disaster Risk Reduction, Sub-Regional Office for the Pacific; Available from: https://www.undrr.org/media/85130/download
4. FAO, *Country Reports: The State of Nauru's Biodiversity for Food and Agriculture.* . 2019; Available from: https://openknowledge.fao.org/server/api/core/bitstreams/6692d0ca-5baf-4cf5-bc11-c161bede17c5/content
5. Hambruch, P., *Nauru* Ch in *Results of the South Sea Expedition- Ethnography: B Micronesia. Vol 1.* , G. Thilenius, Editor. 1914, https://www.tandfonline.com/doi/full/10.1080/00223340701692007

6. Nauru Government, *National Sustainable Development Strategy 2019-2030: Revised 2019*. 2019; Available from: https://policy.asiapacificenergy.org/sites/default/files/National%20Sustainable%20Development%20Strategy%20%28NSDS%29%202019-2030%20%28Revised%202019%29_0.pdf
7. Thaman, R.R., F.R. Fosberg, H. Manner, and D. Hassall, The flora of Nauru. *Atoll Research Bulletin,* 1994.
8. FAO, TCP/NAU/3301: An assessment for Increased Agricultural Production Project Development for the Republic of Nauru. 2012.
9. Department of Climate Change and National Resilience. *Higher Ground initiative*. 2024 Available from: https://www.climatechangenauru.nr/higher-ground-initiative
10. Ragone, D., *Breadfruit—Artocarpus altilis (Parkinson) Fosberg* Ch in *Exotic Fruits*, S. Rodrigues, E. de Oliveira Silva, and E.S. de Brito, Editors. 2018, Academic Press. p. 53-60.
11. Taylor, M., A. McGregor, and B. Dawson. Vulnerability of Pacific Island agriculture and forestry to climate change. 2016: SPC.
12. Lincoln, N.K., D. Ragone, N.J. Zerega, L.B. Roberts-Nkrumah, M. Merlin, and A.M.P. Jones, Grow us our daily bread: A review of breadfruit cultivation in traditional and contemporary systems. *Horticultural Reviews,* 2018. 46: p. 299-384.
13. Dunne, J.P., R.J. Stouffer, and J.G. John, Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change,* 2013. 3(6): p. 563-566.
14. Alberti, L., I. La Licata, and M. Cantone, Saltwater intrusion and freshwater storage in sand sediments along the coastline: hydrogeological investigations and groundwater modeling of Nauru Island. *Water Research,* 2017. 9(10): p. 788. DOI: https://doi.org/10.3390/w9100788
15. Sinclair, P., F. Atumurirava, and J. Samuela, *Rapid drought assessment Tuvalu 13 October-8 November 2011: SOPAC technical report (PR38)*. 2012: Funafuti, Tuvalu.
16. Allis, M., S. Williams, and S. Wadwha, *Coastal flooding from sea-level rise in Nauru: Stage 1 - static inundation mapping, Prepared for the Nauru Higher Ground Project*. 2020: Prepared for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited. Available from: https://nauru-data.sprep.org/system/files/Nauru_Coastal_Inundation%20with%20SLR_final%20-%20Oct%202020%20reduced%20%281%29.pdf

Chapter 15 Fisheries and marine resources

Increasing sea surface temperatures and ocean acidification can affect commercial and subsistence catches due to shifting fisheries, reduction in fish size, and degradation of coral reefs [1]. Impacts associated with each of these climate hazards are described below.

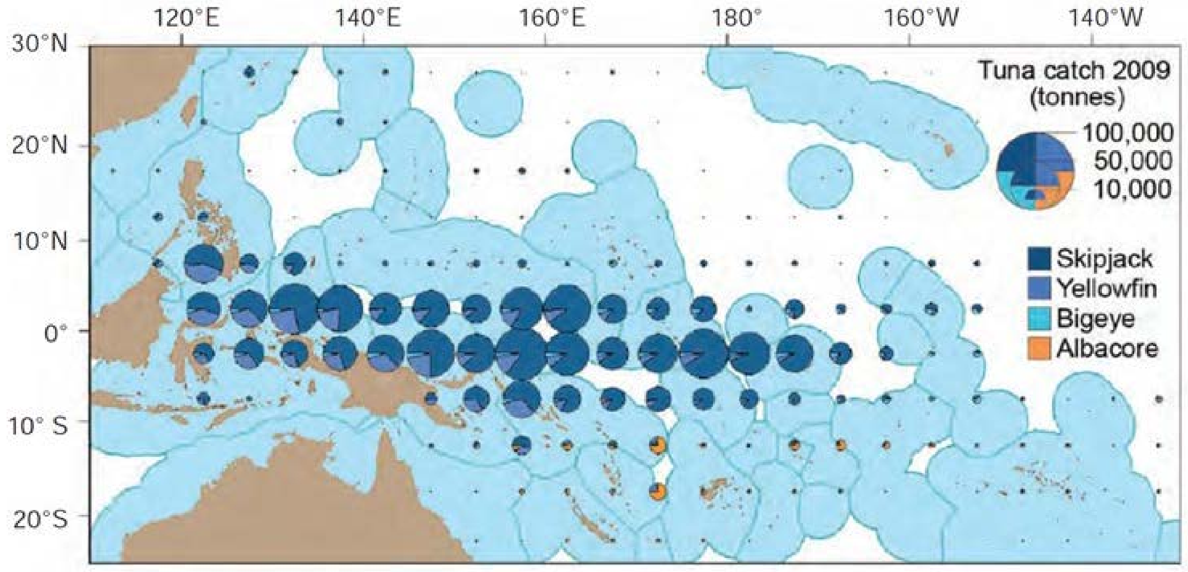
Nauru's fisheries sector can be divided in two distinct categories of activities; (1) the commercial oceanic fisheries sector, where a high proportion of government revenue is derived from selling fishing license access; and (2) the coastal fisheries sector, characterised by subsistence, small-scale artisanal fishing. Marine resources and coastal biodiversity are also discussed below.

Oceanic fishing

Nauru does not directly operate commercial fishing vessels or process any fish. Oceanic fisheries activities do not generate any direct benefits or co-benefits for communities, in the form of livelihoods or food security, as the catch is mainly exported. This is because most tuna fishing vessels belong to foreign nations, which do not pass by Nauru to process their catch. Currently, the commercial operators cannot dock at Nauru's port. While Phase one of the port upgrade is currently underway, it is Phase two of the development (the timing of phase two is not confirmed, however, fishing vessels will be able to use the current design, once completed hopefully early next year; Inception mission, Pers comm.) that will potentially enable the commercial fishing boats to unload, clean the fish, and re-deliver the fish fillets to a cannery for processing in another country. Currently Nauru does not have the infrastructure, e.g. electricity generation capacity, water etc. to handle the processing step (Inception meeting with fisheries department, Pers comm).

To take advantage of the tuna fish stocks available from Nauru's EEZ, 'fishing days' are sold to external commercial operators (around 200). Therefore, oceanic fish and fisheries contribute significantly to the economy [2]. Nauru's economy has been termed 'tuna-dependent' with tuna access fees being US$29.5 million, equivalent to ~31 % of government revenue [2] (~20 % for the last three financial years; A. Trundle Pers Comm). Longline and pole-and-line fishing also occurs, making relatively minor contributions to the economy compared with purse-seine fishing [2].

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 15-1; top) [3]. Combined harvests across the Pacific yield more than 1 million tonnes each year, and support fishing operations ranging from industrial fleets to subsistence catches [3]. Each species of tuna has a limited range of ocean temperature within which it occurs [3]. Skipjack tuna, for example, are most abundant in water temperatures around 20 to 29 °C, though they are found in temperatures slightly outside this range (Figure 15-1; bottom). With global warming, locations of suitable foraging and spawning habitat may change, and the availability of tuna species within Nauru's EEZ may alter [3].



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 15-1 Distribution of catches of the four species of tuna that dominate oceanic fisheries in the Western and Central Pacific Ocean in 2009 [3] (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) [4] (bottom).

Impacts related to sea surface temperature and ocean acidification

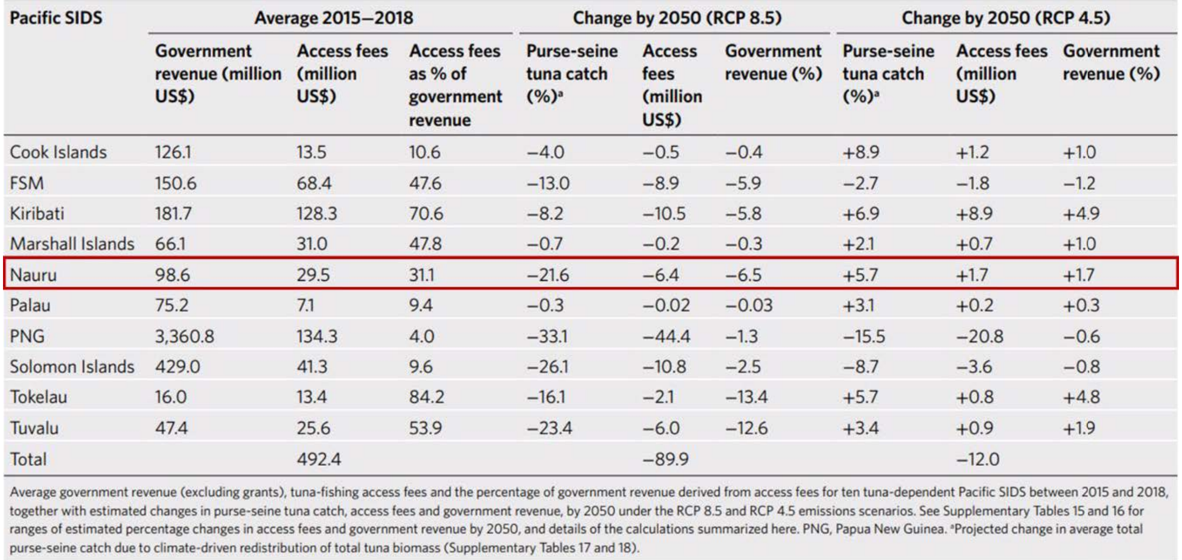
Sea surface temperature

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 [3]. Potential impacts on fisheries would have flow-on impacts on Nauru's ability to generate revenue, contributing to increased economic vulnerability [5].

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 CMIP5 climate models [2]. The general consensus is that tropical tuna distributions in the Pacific are projected to shift eastwards [2, 6-9] 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 a high emissions scenario (RCP8.5).

For Nauru, there is considerable uncertainty in the timing and magnitude of tuna redistributions, with varied consequences for fisheries catch depending on the emissions scenario. By 2050 under a medium emissions scenario (RCP4.5), the average purse-seine catch of skipjack, yellowfin, and bigeye tuna is projected to increase by 5.7 %, however under RCP8.5 the average catch is projected to decline by 21.6 % [2]. By 2050, revenue is projected to increase by 1.7 % under RCP4.5 or decline by 6.5 % under RCP8.5 [2] (Table 15-1).

Table 15-1 Projected changes in tuna-fishing access fees and government revenue for the ten tuna-dependent Pacific SIDS



Pacific SIDS	Average 2015–2018			Change by 2050 (RCP 8.5)			Change by 2050 (RCP 4.5)		
	Government revenue (million US$)	Access fees (million US$)	Access fees as % of government revenue	Purse-seine tuna catch (%)[a]	Access fees (million US$)	Government revenue (%)	Purse-seine tuna catch (%)[a]	Access fees (million US$)	Government revenue (%)
Cook Islands	126.1	13.5	10.6	−4.0	−0.5	−0.4	+8.9	+1.2	+1.0
FSM	150.6	68.4	47.6	−13.0	−8.9	−5.9	−2.7	−1.8	−1.2
Kiribati	181.7	128.3	70.6	−8.2	−10.5	−5.8	+6.9	+8.9	+4.9
Marshall Islands	66.1	31.0	47.8	−0.7	−0.2	−0.3	+2.1	+0.7	+1.0
Nauru	98.6	29.5	31.1	−21.6	−6.4	−6.5	+5.7	+1.7	+1.7
Palau	75.2	7.1	9.4	−0.3	−0.02	−0.03	+3.1	+0.2	+0.3
PNG	3,360.8	134.3	4.0	−33.1	−44.4	−1.3	−15.5	−20.8	−0.6
Solomon Islands	429.0	41.3	9.6	−26.1	−10.8	−2.5	−8.7	−3.6	−0.8
Tokelau	16.0	13.4	84.2	−16.1	−2.1	−13.4	+5.7	+0.8	+4.8
Tuvalu	47.4	25.6	53.9	−23.4	−6.0	−12.6	+3.4	+0.9	+1.9
Total		492.4			−89.9			−12.0	

Average government revenue (excluding grants), tuna-fishing access fees and the percentage of government revenue derived from access fees for ten tuna-dependent Pacific SIDS between 2015 and 2018, together with estimated changes in purse-seine tuna catch, access fees and government revenue, by 2050 under the RCP 8.5 and RCP 4.5 emissions scenarios. See Supplementary Tables 15 and 16 for ranges of estimated percentage changes in access fees and government revenue by 2050, and details of the calculations summarized here. PNG, Papua New Guinea. [a] Projected change in average total purse-seine catch due to climate-driven redistribution of total tuna biomass (Supplementary Tables 17 and 18).

When considering the changes reported in Table 15-1, there is low 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).

In addition to the overall warming of the ocean, east-west displacements of skipjack tuna are correlated with ENSO [7], leading to large yearly fluctuations in catches from different Pacific countries (Figure 15-2). SSTs northeast of Nauru are usually warmer than normal during an El Niño event, and cooler during a La Niña event [13]. In La Niña events, the fish can occur in a more westward area following the warm water [2, 14]. During El Niño events, the fish move eastward following the warm water [2], so higher purse-seine catches occur in the central Pacific, such as Nauru. Projected changes in ENSO have significant uncertainty (Chapter 2).

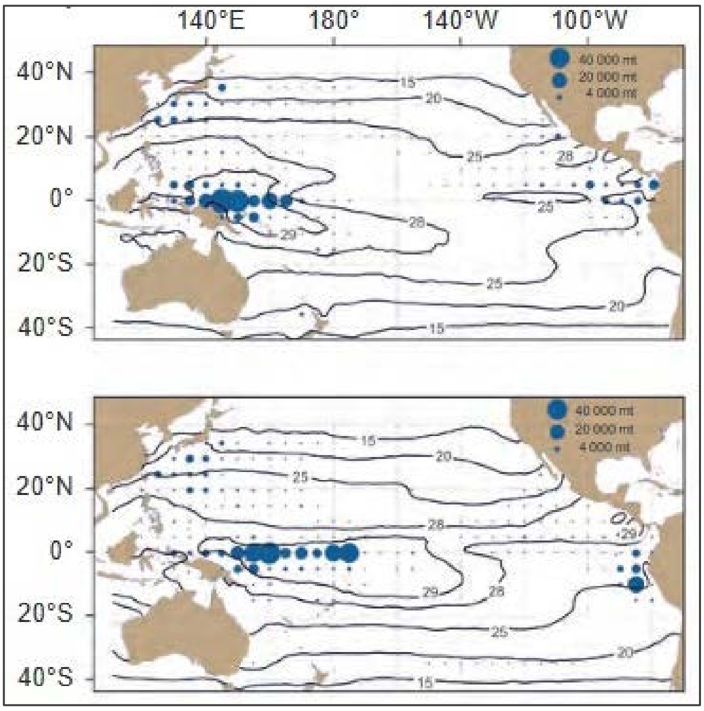


Figure 15-2 Impact of the El Niño-Southern Oscillation (ENSO) on skipjack catch distribution and movement in the Western and Central Pacific Ocean. (a) Skipjack tuna catch (tonnes) and mean sea surface temperature (°C) in the tropical Pacific Ocean during the first half of 1989 (La Niña period) (top 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: [14].

Ocean acidification

As atmospheric carbon dioxide levels increase, ocean acidification occurs (decreased pH). The main species of tuna in the tropical Pacific are expected to be sensitive to the projected decrease in pH in at least four ways.

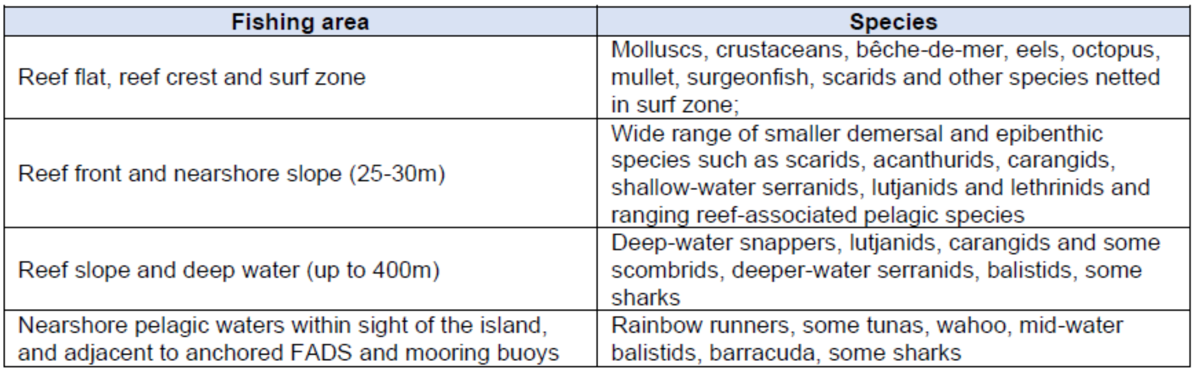
1. an increase in carbonic acid in the body fluids (acidosis) is likely to cause lower blood pH levels, potentially affecting fish's metabolic demands [15].
2. the growth and formation of the ear bones (otoliths) of tuna may be susceptible to lower pH because they are composed of aragonite, affecting orientation and hearing, especially during the larval stage [16].
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 [17].
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 [18].

Coastal fishing and aquaculture

Nauru is surrounded by reef flats which are just above the level of the lowest tides and about 100–300 m wide. The reef flat was "cut into the original limestone of the island and typified by the presence of numerous emergent coral pinnacles" [19]. The Nauru reef flat extends from the shoreline to the reef crest where waves break, and the reef slope begins. It is almost completely devoid of corals. The dominant organisms on the reef flat are algae and some introduced species, e.g. sea cucumbers, but in many parts of the reef flat, zones clear of visible algae can be seen.

The narrow reef surrounding the island supports a wide range of finfish (snappers, surgeonfish, parrot fish, groupers, mullet, trevally, scads etc.) and invertebrates (cephalopods, gastropods, bivalves, crustaceans, echinoderms etc.) (Table 15-2). Coastal resources are harvested using a variety of methods. Finfish are typically captured by handlines (including the local 'Christmas tree' rigs), cast nets, seine nets or by spearfishing (either by freediving or using scuba) [20]. Invertebrate resources are typically gathered from the shallows or using snorkel or scuba. Lobsters are usually speared using scuba [21].

Table 15-2 Fish species found in different fishing areas in Nauru.



Fishing area	Species
Reef flat, reef crest and surf zone	Molluscs, crustaceans, bêche-de-mer, eels, octopus, mullet, surgeonfish, scarids and other species netted in surf zone;
Reef front and nearshore slope (25-30m)	Wide range of smaller demersal and epibenthic species such as scarids, acanthurids, carangids, shallow-water serranids, lutjanids and lethrinids and ranging reef-associated pelagic species
Reef slope and deep water (up to 400m)	Deep-water snappers, lutjanids, carangids and some scombrids, deeper-water serranids, balistids, some sharks
Nearshore pelagic waters within sight of the island, and adjacent to anchored FADS and mooring buoys	Rainbow runners, some tunas, wahoo, mid-water balistids, barracuda, some sharks

Of the 29.6 % of households that were involved in some form of fishing in 2021, the majority (72.3 %) fish for home consumption. Over 30 % of households collect fish from reefs (18.4 % collect by hand, 11.3 % using rods, line or spear) [22]. Reef invertebrate food resources include crabs, eels, octopus, lobsters, sea snails and sea urchins [20]. A 2015 survey of Nauru's reef invertebrate resources found many had been over-harvested due to Nauru's high reliance on coastal resources for food security [20]. Nauru has also explored the possibility of some reef species, such as sea cucumbers, contributing to commercial export, but over-exploitation leading to low densities and small sizes led to recommendations to prohibit export of all invertebrate species [20]. There are prohibitions on the commercial fishing and export of all species of sea cucumbers: http://ronlaw.gov.nr/nauru_lpms/files/gazettes/e63f40afe82546d12f8cb52e7248bc05.pdf .

Coastal subsistence and commercial fisheries contribute to Nauru's food security, livelihood and culture. Gillett (2016) [23] recorded coastal commercial fisheries production at 163 tonnes, and coastal subsistence fisheries production at 210 tonnes, for a total of 373 tonnes in 2016, worth US$ 2,036,713 (US$ 1,071,275 and US$ 965,438 respectively) [24]. Nauru's artisanal fleet comprises small (less than 6 m) powered skiffs or canoes operated by local fishers. The catch obtained from fishing in shallow inshore waters is landed all around Nauru wherever fishers can swim, wade, or walk ashore. Most of the catch from fishing further offshore from canoes and skiffs is landed at a few artificial channels through the fringing reef. The powered boats are mostly used for trolling and often target pelagic species [23].

Some commercial fishing activities are practiced but mostly on a part-time basis, meaning that fish catches are sold only when there is surplus after meeting subsistence needs. The reliance on marine products for basic food needs, and the lack of transportation and outlets for marketing contribute to this aspect. Currently the fish market is not open (Figure 15-3). Most fish are purchased at the small boat ramp straight from the boats by the 'Chinese demographic of the population'. Other fresh-fish purchases are through a 'Facebook marketplace' system (Fisheries representative at 2024 inception meeting, Pers comm).

Figure 15-3 Fishing boats (left and middle) and Nauru fish market (currently non-operational) (right). Photo credit: CSIRO, 2024.

New research is strongly recommending ecosystem-based fisheries monitoring, rather than using a target-indicator species to signal system health. This approach can re-use existing fisheries management approaches and infrastructure, however giving more reliable reporting outcomes [25, 26]. These indicator species can still be recorded separately, helping define targeted management actions. But the combination, produces a more informative qualitative score of ecosystem traits and health [25].

Aquaculture plays a small role in providing food and income for Nauruans. The primary aquaculture species is milkfish or *ibiya* (*Chanos chanos*) farmed in Buada Lake. Milkfish farming is a tradition and already established at the time of European arrival on Nauru. Small fry were caught in the sea and raised in small family owned ponds, passed down through the female line [27]. Milkfish have cultural significance and feature in traditional costumes [28]. Fry is no longer available to catch on the reefs surrounding Nauru (Pers Comm, July 2024), so fry was imported from Kiribati, but imports stopped during the COVID pandemic when the borders closed. Pollution from phosphate mining and the introduction of Tilapia has also impacted milkfish farming (Pers Comm, July 2024). Nauru's lakes are estimated to have 22 tonne carrying capacity for aquaculture, imports are estimated to be about 80 tonnes annually (Pers Comm, July 2024).

Impacts related to air temperature, sea surface temperature, marine heatwaves, rainfall and wind

Temperature

Fish is a perishable commodity. Spoilage begins immediately after harvest by autolytic bacteria especially in the tropics [29]. Higher temperature favours the growth of micro-organisms. With lower temperatures the chemical reactions in the organism are slowed down leading to suspended growth [29]. Nauru's fisheries have an ice plant that supplies ice for iceboxes to take on board coastal fishing vessels (Fisheries representative at 2024 inception meeting, Pers Comm). Increased incidence of extreme heat events (including heatwaves) may impact the coastal fishery processing sector through pressure on storage facilities, and a reduction in workforce productivity; it may be too hot for work outdoors at certain times of the day and year.

SST

Changes to ocean temperatures in conjunction with other climate impacts are expected to directly and indirectly affect the distribution and production of coastal fish and invertebrates [30, 31]. By 2050, coral reef fish biomass is projected to decrease by 20 % under a high emissions scenario [30]. A decrease in coastal fish production threatens food security for Nauruans who are dependent on subsistence 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 Fish Aggregation Devices (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.

Increases in ocean temperatures will impact aquaculture species productivity, growth, survival, and disease risk for cultured species [32, 33].

Marine heatwaves

Marine heatwaves are already causing coral bleaching. Projected increases in marine heatwave intensity, frequency and duration will further damage coral reefs and dependant coastal fisheries.

Rainfall

Extreme rainfall can lead to increased nutrient and sediment runoff into coastal regions [34]. Mining has significantly altered the vegetation on the central plateau, increasing surface water runoff and associated soil erosion, nutrient loading and pollutants entering ground and coastal waters [35]. These pollutants can harm coastal reef fisheries.

Extreme sea level events

Extreme sea level events are caused by high tides, storm surges, ocean swell, wind-driven waves and sea level rise. These coastal inundation events may be exacerbated if coral reefs are damaged by marine heatwaves and ocean acidification. Coral reefs play a critical role in providing natural protection to reef lagoons and resources, shoreline stability, turtle nesting sites, coastal communities and infrastructure.

Wind

Salt spray is increasingly a problem for maintenance of fisheries equipment, and this would be exacerbated through dry periods where rainfall does not wash the salt away.

The Nauru Meteorological and Hydrological Service issues wind alerts for ‘no fishing’ days based on a threshold of 25kt using Facebook and text blasts (Met office representative at 2024 inception meeting, Pers Comm). 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 in Tuvalu [36]. There is a pressing need for this type of equipment to be introduced in Nauru.

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., 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. DOI: https://doi.org/10.1038/s41893-021-00745-z
3. 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). Available from: https://www.spc.int/DigitalLibrary/Doc/FAME/Reports/Bell_11_Vulnerability_Pacific_Fisheries_to_Climate_Change.html
4. 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. DOI: https://doi.org/10.1007/s11160-017-9500-3
5. 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
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. DOI: https://doi.org/10.1007/s10584-012-0606-2
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 Climate Change* Ch in *Secretariat of the Pacific Community. Noumea New Caledonia.* 2011. Available from: https://fish.gov.au/Archived-Reports/2012/reports/Documents/Lehody_et_al_2011a.pdf
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., 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. DOI: https://doi.org/10.1029/2019EF001469

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. DOI: https://doi.org/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. DOI: https://doi.org/10.1007/s00382-013-1931-5
13. 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
14. 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. Available from: https://library.sprep.org/sites/default/files/2023-01/Bell_11_Vulnerability_Pacific_Fisheries_to_Climate_Change.pdf
15. 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. DOI: https://doi.org/10.1007/s10872-004-5763-0
16. 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. DOI: https://doi.org/10.1073/pnas.080999610
17. 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
18. 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. DOI: https://doi.org/10.1038/ngeo719
19. Fenner, D., *Nauru* Ch in *World Seas: An Environmental Evaluation*. 2019, Elsevier. p. 793-805.
20. Harris, D., G. Gioura, N. Helagi, and B. Moore. Survey of reef invertebrate resources in the Republic of Nauru: May 2015. 2016: SPC. Available at: https://nauru-data.sprep.org/index.php/system/files/Harris%20et%20al_16_Nauru_invertebrate.pdf
21. Dalzell, P. and A. Debao, *Coastal fisheries production on Nauru. Inshore Fisheries Research Project country assignment report.* 1994 SPC: Noumea, New Caledonia.
22. SPC and Government of the Republic of Nauru, *Nauru 2021 population and housing census - Analytical report*. 2023 SPC: Noumea, New Caledonia; Available from: https://sdd.spc.int/news/2023/08/23/nauru-2021-population-and-housing-census-analytical-report
23. 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
24. FAO, *Fishery and Aquaculture Country Profiles, Nauru 2017*. 2024 Fisheries and Aquaculture Division: Rome; Available from: https://www.fao.org/fishery/en/facp/nru?lang=en

25. Fulton, B. and K. Sainsbury, *Moving from A to B: Guidelines for Practical Ecosystem-Based Fishery Management*. 2024 Lenfest Ocean Program; Available from: https://www.lenfestocean.org/en/news-and-publications/fact-sheet/moving-from-a-to-b-guidelines-for-practical-ecosystem-based-fishery-management
26. Link, J.S. and R.A. Watson, Global ecosystem overfishing: Clear delineation within real limits to production. *Science Advances,* 2019. 5(6): p. eaav0474. DOI: https://doi.org/10.1126/sciadv.aav0474
27. Spennemann, D.H., Traditional milkfish aquaculture in Nauru. *Aquaculture International,* 2002. 10: p. 551-562. DOI: https://doi.org/10.1023/A:1023900601000
28. Hambruch, P., *Nauru* in *Results of the South Sea Expedition- Ethnography: B Micronesia. Vol 1.* , G. Thilenius, Editor. 1914, https://www.tandfonline.com/doi/full/10.1080/00223340701692007
29. Ikape, S., Fish spoilage in the tropics: A review. *Octa Journal of Biosciences,* 2017. 5(2).
30. 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. DOI: https://doi.org/10.1038/nclimate1838
31. 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. Available from: https://library.sprep.org/sites/default/files/2023-01/Bell_11_Vulnerability_Pacific_Fisheries_to_Climate_Change.pdf
32. 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. Available from: https://library.sprep.org/sites/default/files/2023-01/Bell_11_Vulnerability_Pacific_Fisheries_to_Climate_Change.pdf
33. 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. DOI: https://doi.org/10.1007/s10811-014-0435-y
34. 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. DOI: https://doi.org/10.1016/j.marpolbul.2020.111651
35. Jungblut, V. and B. Dowiyogo, *Directory of Wetlands of Nauru - 2016.* 2016 Report to the Secretariat of the Pacific Regional Environment Programme (SPREP). Available from: https://nauru-data.sprep.org/libraries/pdf.js/web/viewer.html?file=https%3A%2F%2Fnauru-data.sprep.org%2Fsystem%2Ffiles%2FDirectory%2520of%2520Wetlands%2520of%2520Nauru%25202016_FINAL.pdf
36. 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

Chapter 16 Disaster management

There are numerous examples of disasters causing significant loss of property and disruption to services in Nauru, often requiring impact assessments and financial compensation for loss and damage to individual landowners, businesses and public entities. In addition to extreme rainfall and drought, remote cyclones and sub-tropical storms can cause storm surges and coastal inundation in Nauru [1]. Tsunamis originating in the Solomons, New Hebrides and Kurils trenches [2] are also identified in the Strategic Roadmap for Emergency Management [1].

The Division of National Disaster Management (DNDM) has 4 fire trucks – 2 for aviation, 1 domestic, and 1 tanker as a backup. The fire trucks access RO water to fill the tankers, as groundwater is too saline and affects the integrity of the machinery (Inception meeting, 2024). The Meteorological and Hydrological Service and Fire Service conduct awareness campaigns in schools, including annual fire and tsunami evacuations conduct for all nine schools, including the Able Disable Centre (Figure 16-1). School children are taught to follow designated evacuation pathways to higher ground, but information is outdated, and houses have been built on two pathways (Inception meeting, Pers Comm, July 2024).

Figure 16-1 Fire trucks in Nauru. Photo credit: CSIRO, 2024.

The biggest problem for most households is drought or irregular rainfall, which in some form affected 62.7 % of households during the past ten years. Drought impacts have shown regional differences, with 94.3 % of households in Nibok being affected, against only 26.7 % in Boe and 32.9 % in Ewa. These variations may be related to adaptive capacity in different areas, including variations in disaster-preparedness [3].

Alerts for drought, for example to reduce water use, are also issued on Facebook and in text messages (Inception meeting 2024, Pers Comm). There are two thresholds for drought which trigger access to financial support to access water. The first threshold triggers a subsidy for vulnerable people for water delivery, usually A$ 96 for 10,000 litres (Inception meeting, Pers Comm). If drought continues, the second threshold will fund the full amount, including subsiding road maintenance to enable water supply and boost generation of RO.

There is only one road around the island, splitting around the airport runway, with the shorter route being blocked if an airplane is about to land. Presently, there are approximately 323 m (out of the 72.5 km of roads in Nauru) exposed to wave inundation, primarily in the districts of Anabar, Anetan and Meneng [4]. The total population exposed to wave inundation at present is 108, with Anabar, Anibare, and Meneng being the districts with the largest proportion of population exposed [4].

For Nauru, components of the early warning system in 2024 were assessed as being at a moderate to low level of development, as depicted in Figure 16-2. The most developed component was for impact based early warning, under the ‘dissemination and communication’ theme. Progress in other components ranged from minimal to moderate levels. Within the ‘risk knowledge’ theme (component 1), most development was directed to the risk-informed multi-hazard early warning system theme. However, Hazards Knowledge, and knowledge of ‘Exposure, Vulnerabilities, Capacities and Risks’ were identified as gaps [5].

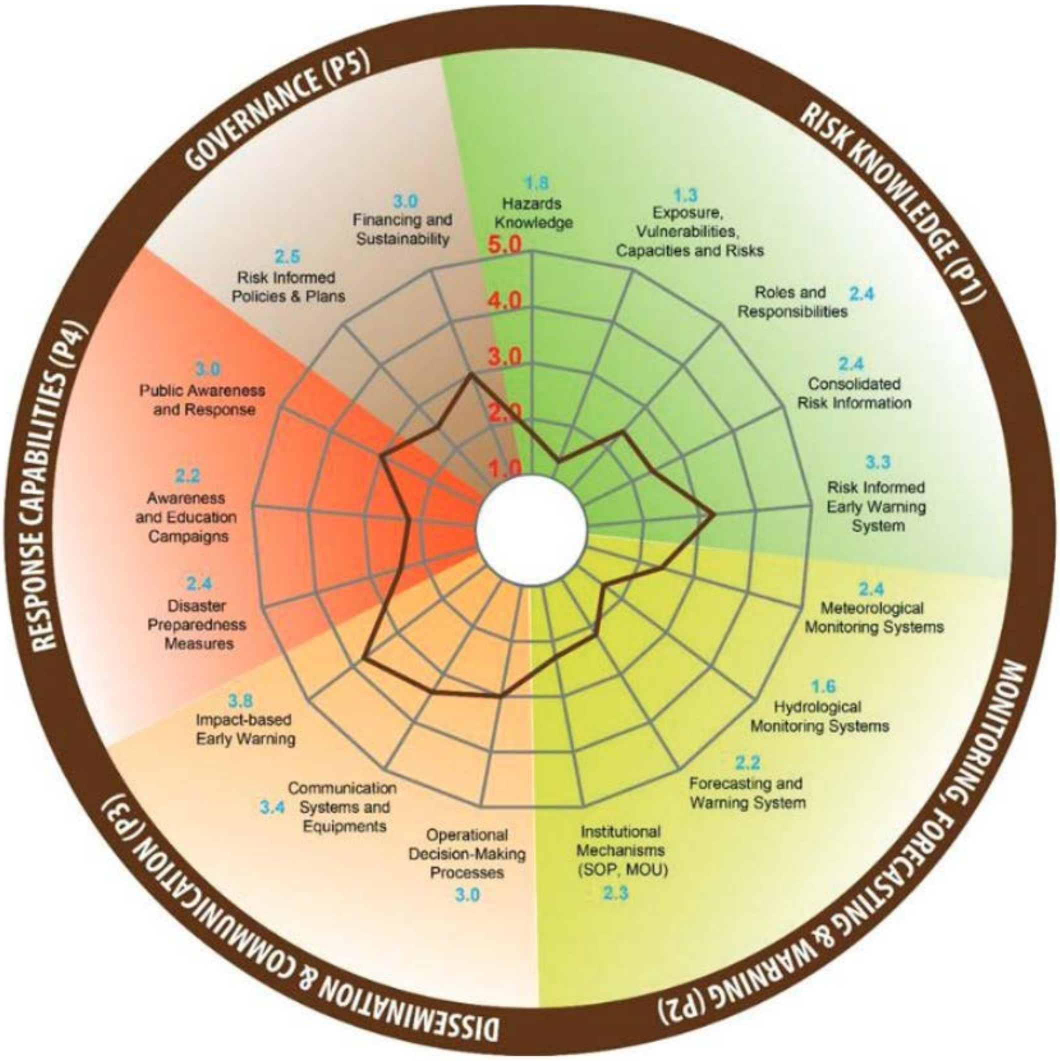


Figure 16-2 Assessment of the multi-hazard early warning systems in Nauru. (Source: [5]).

Given the unpredictability and rising occurrence of extreme weather events, significant improvements in weather forecasting and early warning capabilities have been recommended [6]. Regional organisations, such as SPREP and SPC, are key to enhancing regional cooperation for hazard detection and analytical services. The Pacific Islands Meteorological Strategy 2017-26 (PIMS Strategy) [7] facilitates better cooperation for investment in multi-hazard early warning systems [5]. Priority 2 of the five different key priority areas is focused on disaster risk reduction, including strengthening the National Meteorological and Hydrological Service capacity to implement a Multi-

Hazard Early Warning System [7]. New initiatives developed under Weather Ready (2024+) will enhance these services.

Currently, alert messages are also broadcast by telecoms for extreme sea levels. The Meteorological and Hydrological Service provides stakeholders with updates via email and issues emergency information via SMS or text message (e.g. Figure 16-3) [5].

NES Alert

Today 16:11

Large waves and sea swell above 2.5m the general public is advised to refrain from any beach activities

Today 16:41

Sea swell will commence Sunday 10th March. Precaution will remain in force until further notice

Figure 16-3 Text message received due to large waves occurring around the time of a spring tide (early March 2024).

Disaster management/early warning for ocean impacts

To strengthen their ocean monitoring and coastal inundation warning services, we recommend Nauru seek to adopt the Climate Risk Early Warning Systems (CREWS) initiative which involves sensor-loaded wave buoys. Early warning systems are a cost-effective disaster risk management measure to strengthen community resilience.

The water level experienced at the shore is compounded by tides, sea level rise, storm surges and waves, particularly wind-driven waves. Wave setup and runup are the primary components causing coastal inundation. Having an early warning system that aims to provide accurate, timely and actionable wave forecast information is an important way to ensure safety at sea and increase resilience of communities to coastal inundation. This system can be programmed to issue alerts when waves exceed certain parameters, including wave height and wave period.

Impacts related to extreme temperature, fire, extreme rainfall, drought and sea level rise

Extreme temperature

Extreme temperatures can reduce labour productivity and increase the risk of blackouts, with cascading impacts for disaster management, including disruption to telecommunication and transport, and lack of cooling and lighting.

Extreme rainfall

Floods can cause damage and disruption to property and infrastructure, including roads and electricity. Water quality is affected by flood-related sediment and pollution [8]. Floods drive high demand for emergency response and recovery services, with major impacts on the economy and increased reliance on international aid.

Drought

Nauru has experienced prolonged droughts of up to 36 months which have had significant impacts on health, water security, food security and the economy (see Water Resources section, above).

Droughts are slowly evolving disasters because water deficits accumulate over months, with impacts exacerbated by high exposure and vulnerability. Response and recovery options are limited. Through drought periods there is increased demand for desalinated water, and an increase in requests for water tanker deliveries. The existing tankers are not able to deliver all orders within the schedule [9]. Furthermore, some houses in Nauru cannot be accessed by tankers, particularly newer houses on informal roads [9].

Droughts are likely to be hotter in future, increasing fire risk. This would increase pressure on disaster management. Since fire engines use RO water, this creates additional pressure on limited water resources [9].

Sea level rise

Storm surges, spring tides and large waves can create local impacts. For example, while 80.5 % of households in Anetan reported problems with storm surge and 79.7 % reported having been affected by spring (commonly referred to as king) tides, fewer than 5 % of households in Ijuw, Anibare, Uaboe, Buada and Ewa reported the former and fewer than 5 % in Uaboe, Aiwo and Buada reported the latter [3].

Sea level rise superimposed on spring tides will cause greater coastal erosion, wave inundation, freshwater contamination, and risks to human safety [10]. This will increase the demand for disaster management and emergency services. Warnings should be broadcast for communities not to swim at beaches during high spring tides, noting the local nature of these events as described above [3].

Emergency response infrastructure and assets may be exposed to damage from coastal inundation. Mapping of future coastal inundation risk is available for sea level rise scenarios of 0.35, 0.5, 1.0, 1.5 and 2.0 metres [4].

Common wave monitoring solutions can be expensive to acquire and deploy, and typically require specialist training and equipment to process and receive measurements from equipment. With wider availability of high-quality imaging devices, the ability to use fixed camera images to isolate and measure individual waves is becoming increasingly feasible for real-time monitoring purposes. Some studies [11] have demonstrated that if the geometry of a camera location is well-measured, individual waves can be identified from images, and an estimate of wave height can be attached to each wave. Such systems, in which capital outlays on equipment are very low, require a significant amount of training data to seed the estimation models (typically in the form of user derived training sets cross-validated with wave height information), but once established, such monitoring can continue in an automated form. Solutions like these would be site-dependent, with monitoring equipment likely to be deployed to measure the impact of waves on critical infrastructure, assets and property.

Monitoring of sea level rise and prediction of high spring tides, storm surges and large waves will be vital for early warning systems. The Pacific Coastlines product provided by Digital Earth Pacific is likely to be helpful in detecting trends and is available at https://maps.digitalearthpacific.org/#share=s-pzzMOVCCoPWNeWFs33Sg. Additional monitoring of large waves is being achieved by Tuvalu and Kiribati with the CREWS wave buoys (details available at https://gem.spc.int/projects/climate-risk-early-warning-systems-crews-inundation-forecast-system-for-tuvalu-kiribati).

Unexploded ordinates from World War II are increasingly exposed by coastal erosion. When these are discovered, the area surrounding is cordoned off and the Australian Defence Force is engaged to discharge the explosives. For example: https://www.loopnauru.com/nauru-news/australian-defence-force-conducts-reconnaissance-work-nauru-121510

References

1. PIEMA & SPC, *Nauru Strategic Roadmap For Emergency Management 2021-2023*. 2023: Nauru; Available from: https://spc.int/resource-centre/publications/nauru-strategic-roadmap-for-emergency-management-2021-2023
2. SOPAC, *SOPAC Member Countries National Capacity Assessments: Tsunami Warning and Mitigation Systems: Nauru Tsunami Capacity Assessment Report.* 2013; Available from: http://www.bom.gov.au/tsunami/assessments/pdf/Nauru_Results_Outline.pdf
3. SPC and Government of the Republic of Nauru, *Nauru 2021 population and housing census - Analytical report*. 2023 SPC: Noumea, New Caledonia; Available from: https://sdd.spc.int/news/2023/08/23/nauru-2021-population-and-housing-census-analytical-report
4. Bosserelle, C. and S. Williams, *Coastal flooding from sea-level rise in Nauru: Stage 2 - wave inundation mapping, Prepared for the Nauru Higher Ground Project*. 2023 Prepared for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited: Christchurch, NZ.
5. Dashora, L.K., S. Basnayake, G.C. Ganepola, and S. Jayasinghe, Readiness stocktaking of multi-hazard early warning systems in Pacific small Island developing states. *Asia-Pacific Sustainable Development Journal,* 2024. 31(1): p. 47-75. DOI: https://doi.org/10.18356/26178419-31-1-4
6. WMO, *Multi-Hazard Early Warning Systems: A Checklist: Outcome of the First Multi-Hazard Early Warning Conference*. 2018; Available from: https://www.preventionweb.net/publication/multi-hazard-early-warning-systems-checklist
7. SPREP, *Pacific Islands Meteorology Strategy (PIMS) 2017–2026*. 2016; Available from: https://library.sprep.org/sites/default/files/pims.pdf
8. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Sanitation System Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor.
9. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Water Supply System Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor.
10. 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
11. Hwang, I.-K., M. Lee, J. Han, and J. Choi, Wave height measurement scheme using wave detector based on convolutional neural network and PPM calculator with ocean wave images. *International Journal of Naval Architecture and Ocean Engineering,* 2023. 15: p. 100542 DOI: https://doi.org/10.1016/j.ijnaoe.2023.100542

Chapter 17 Coastal protection and infrastructure

Introduction

Most of Nauru's population and critical infrastructure, including the airport and hospital, are concentrated along the coastal plain (50-300 metres wide), known as "Bottomside" [1] [2, 3] (Figure 17-1). Within this coastal plain, the ground elevation is highest (7-8 m Nauru Island Datum; [20]) around the west/northwest fringe (including the districts of Aiwo, Denigomodu, Nibok, Uaboe and Baiti, and the north-western end of the airport runway) and is hence the least exposed to sea level rise [4]. Conversely, the low-lying land around lagoons and backshore depressions have the lowest elevation (2-4 m NID) and are the most exposed, particularly around lagoons on the southern, eastern and northern shorelines (i.e., Meneng, Anibare, Ijuw and Yaren) [4].

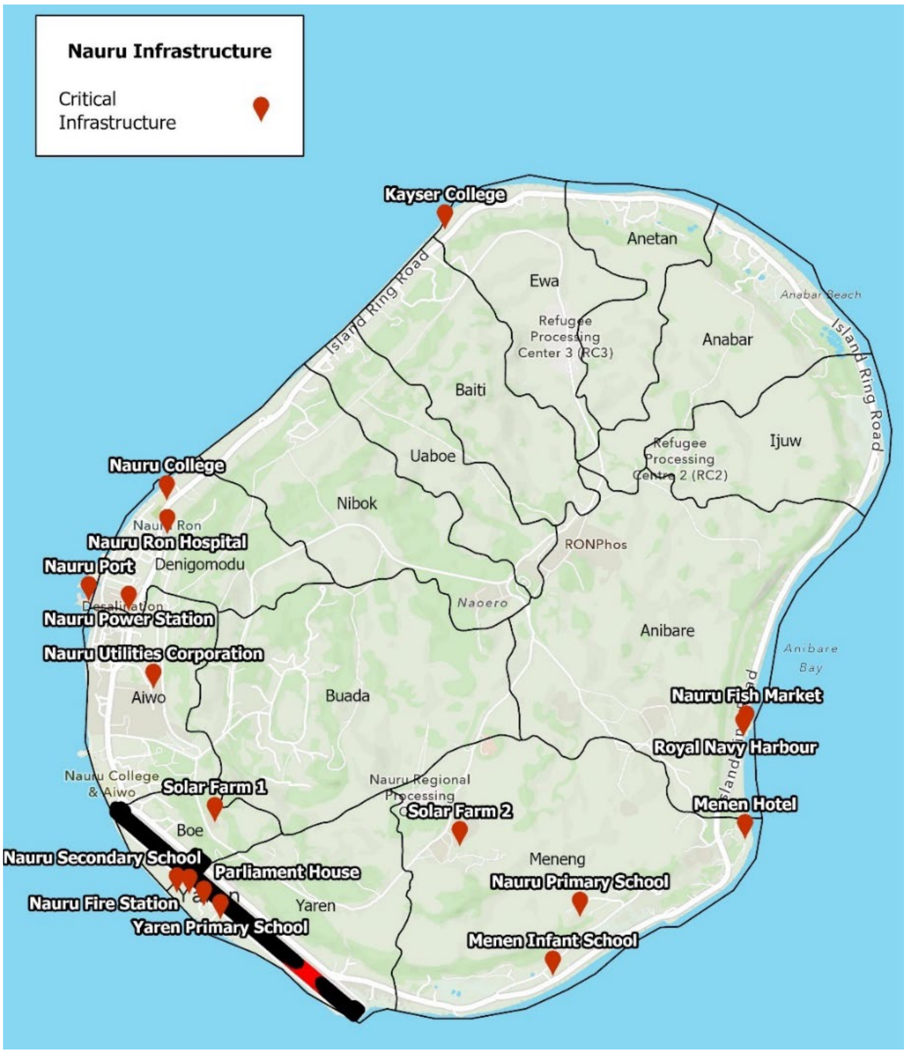


Figure 17-1 Map of Nauru showing locations of some of the important infrastructure. District boundaries marked with black lines (Credit: N Eaton (NGIS)).

---

[20] Analysis of the tide gauge data determined that the king tide elevation is 2.7 m NID with *approximately* 1 % exceedance probability at present-day sea levels (KT1). The true exceedance probability of a 2.7 m NID tide gauge reading is 0.72 %, and KT1 is 1.2723 m above MSL (1993-2020).

The relatively low elevation of the coastal plain is the primary driver of exposure to king-tide inundation and sea level rise. The impacts from coastal inundation depend on the exposure and vulnerability of local communities and related infrastructure and commerce/trade.

Both static sea level rise (no waves considered) and wave overtopping can cause coastal inundation. In the following section, sea level rise impacts (SLR + king tide) e.g. [4] are reported separately to those including wave overtopping (SLR + king tide + storm surge + waves), e.g., [3, 5].

1 - Coastal assets and flood defences

Shoreline dynamics have been assessed during the period 1992 to 2020 [3]. Some areas have been gaining mass, or accreting (59 %), while others have been eroding (41 %). Major shoreline erosion was noted around the southern tip of the island at the edge of the airport, with an erosion rate of 0.73 m/year. A closer look at the data indicates that there was a high erosion event between 1992 and 2005, after which the shoreline stabilised (Figure 17-2). Shoreline changes between 1992 and 2005 are likely a result of the airport extension (completed in the early 1990s) [3]. Shoreline accretion (Transect 291) is linked to the reclamation of land for the construction of a new port (Figure 17-2).

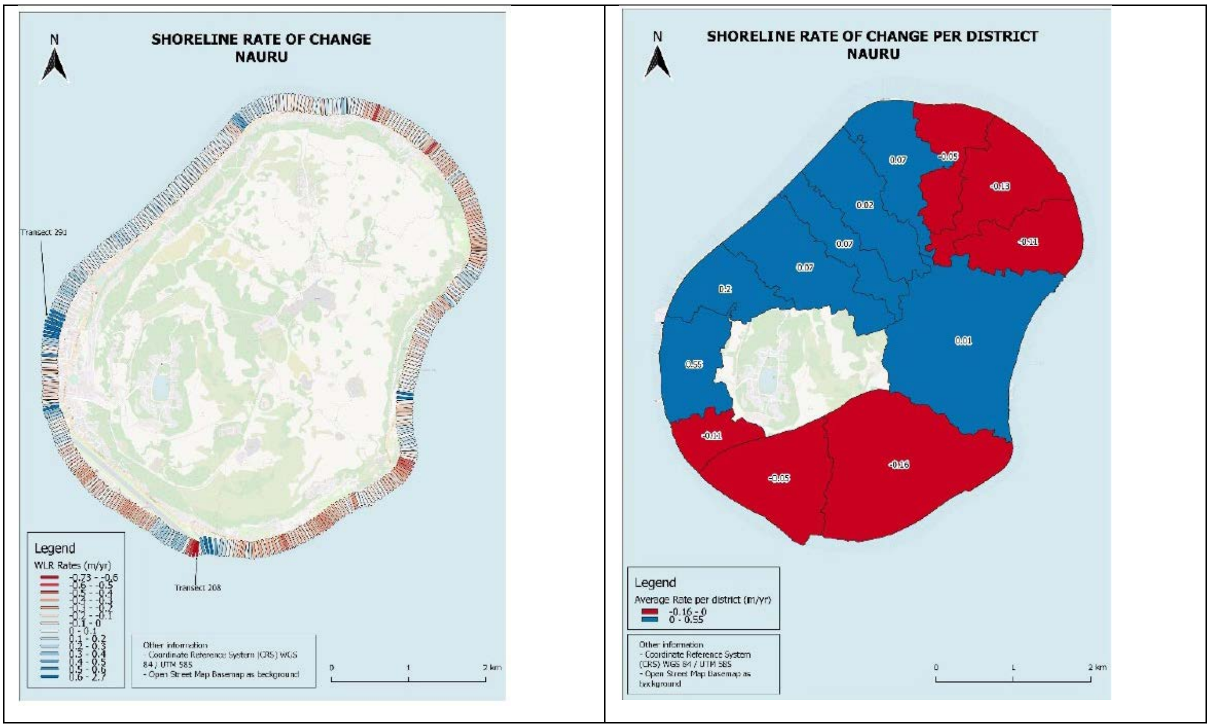


Figure 17-2 Transects showing weighted linear regression rates for Nauru. Blue indicates areas of accretion, while red indicates areas of erosion. Transects 291 and 208, which are labelled, show the largest accretion and erosion, respectively (left) and the average rate of change for each coastal district in Nauru (right) [3].

Infrastructure currently located within 100 m of the coast accounts for 34 % of the total asset number and 40 % of the total infrastructure replacement value [6]. To mitigate the risks, seawalls have been introduced in some areas. These are concrete structures and large boulders sourced from broken-down pinnacles. Materials were selected for their durability and availability (G Akken Pers Comm, 2024). The overall length of seawalls increased from 2014 to 2020, with most recent seawall sections built in Uaboe, Ewa and Ijuwa (Figure 17-3) [3]. However, most of Nauru's coastline is still without seawalls. For example, in the district of Uaboe, there are only two small sections of coastline protected by seawalls (Figure 17-3), with the bigger of the two sections, built after 2014, resulting in the large increase in seawall length displayed in Figure 17-4 [3]. A more in-depth study is advised to investigate the effects of seawalls on nearby shorelines since seawalls often lead to coastal erosion along adjacent beaches [3].

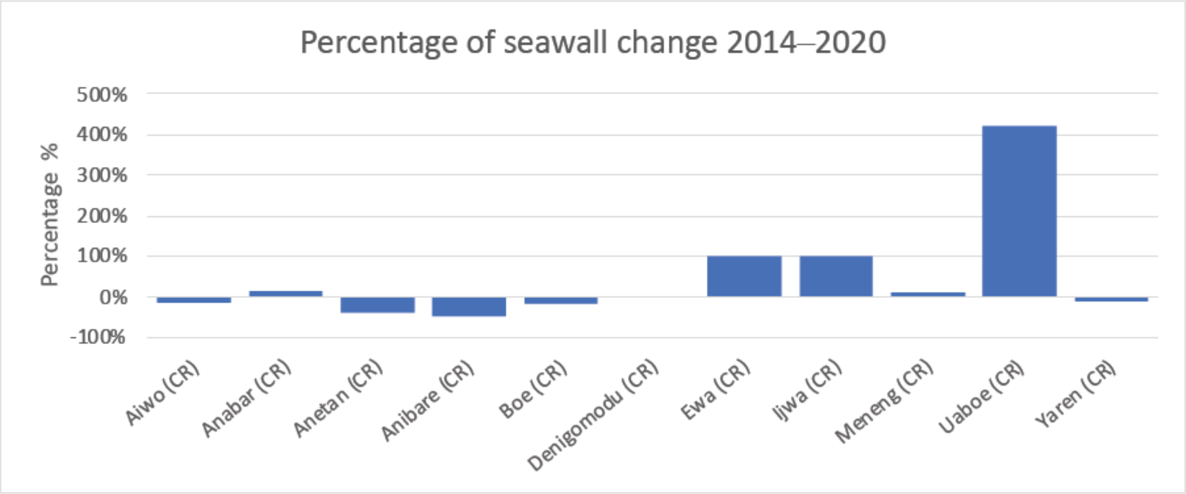


Figure 17-3 Percentage of seawall change per district between 2014–2020. CR = coastal region (source: [3])

Figure 17-4 Newly built seawall at Uaboe district (Source: [3])

Climate hazard related impacts

Extreme rainfall

Extreme rainfall causes flooding, particularly if the drains are not well maintained (Figure 17-5) (Inception meeting, Pers comm 2024). Impacts near the coast can be exacerbated if flooding occurs at high tide and/or during a storm surge.

Figure 17-5 Flooded carpark after heavy rain (left) and blocked drain (right). Photo credit L. Webb CSIRO, 2024.

Coastal inundation

Whilst only 1.4 % of the total land area of Nauru is exposed to wave inundation with annual recurrence intervals (ARIs) of 5-10 years, this represents just over 7 % of land within the coastal plain (Figure 17-6). Under current conditions, a 5-year ARI inundation event directly impacts 46 % of Nauru's population, flooding 6.2 % of buildings and 2.7 km of roads, while a 100-year ARI inundation event impacts 54 % of Nauru's population, flooding 9.2 % of buildings and 3.6 km of roads [3].

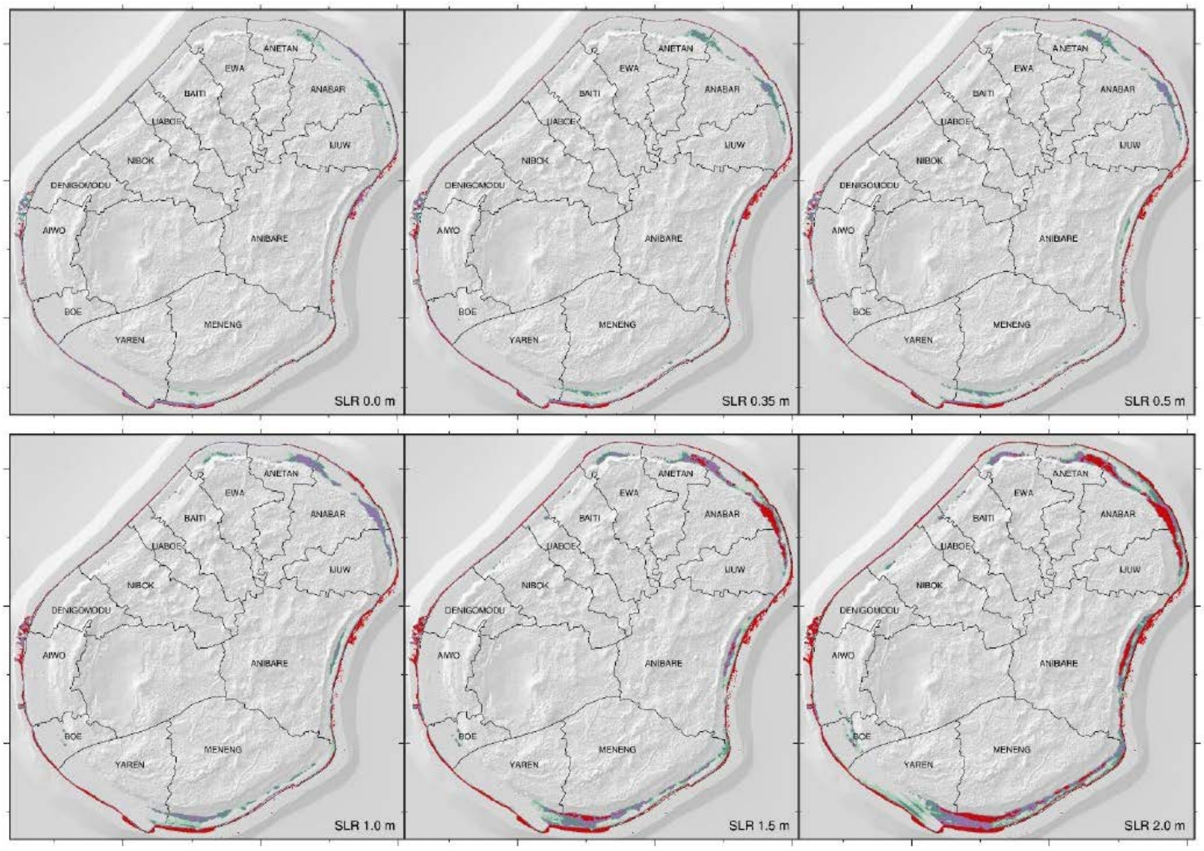


Figure 17-6 Land exposure for wave inundation for a 5 to 10-year ARI event under a range of sea level rise (SLR) scenarios (0 m to 2.0 m) (source [5]).

2 - Fisheries infrastructure

Two boat ramps provide access to the open water. The Anibare community boat harbour has a protective sea wall, and the locals also use the compound for swimming, while the other harbour is just a ramp to the open water (Figure 17-7). The protected Anibare community boat harbour is located next to the disused fish market. Very few people were engaged in fishing exclusively for commercial purposes, though around a third of fishers sold part of their catch [2] at the enclosed boat ramp, directly off the boat, or through Facebook marketplace (Inception meeting, Pers Comm, 2024).

Figure 17-7 Boating access points: Anibare community boat harbour (left and centre) and alternative boat ramp (right). Photos L Webb, CSIRO 2024.

Climate hazard related impacts

Wind

Ocean conditions may be considered ‘unsafe’ for fishing when the daily maximum wind speed exceeds the 20-knot threshold. These conditions are rarely reached in Nauru, and likely to stay the same under future climate conditions, noting low levels of confidence in wind projections (see caveats in Chapter 8).

Waves

Wave height and wave period (time between waves) may reduce for Nauru, while wave direction may rotate clockwise by up to 5 to 10 ° by the end of the century [7]. See Chapter 9 for more details on this.

3 - Internet and telecommunications

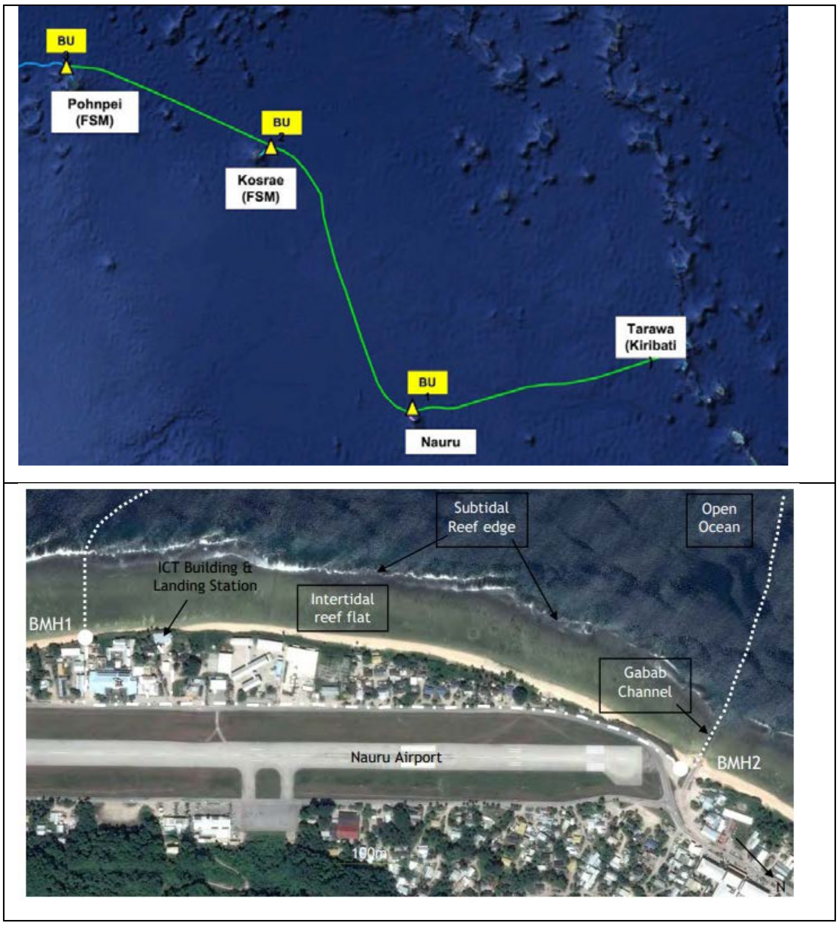
Telecommunications and internet facilities are focussed around the Bottomside and are therefore potentially vulnerable to coastal changes. In 2021, 64 desktop computers were counted, 980 laptops, 905 tablets, 274 Wi-Fi connections, 6,650 telephones/mobile phones and 172 SkyTV/Free TV connections [2]. Over 80 % of households were connected to the internet (Figure 17-8). A small number of households (12.2 %) had modem Wi-Fi connections. The numbers were particularly low in Location (5.3 %) and Nibok (6.6 %) [2].

Figure 17-8 A rooftop satellite dish, common around Nauru. Photo credit: CSIRO, 2024.

Cenpac[21] Corporation and Digicel (owned by Telstra) are the telecommunication providers in Nauru. Digicel is the primary internet and mobile provider and uses Ka-band satellite to connect to Papua New Guinea.

Digicel owns and operates nine telecommunication towers around the island, and the highest is on Command Reach, Nauru's highest point. More towers are planned to improve service, but this is dependent on permission from landowners. Cenpac uses the Digicel network to deliver internet service to government and state-owned enterprises. Starlink is also offering a competitive product and the signal is currently being accessed by some of the community (Inception meeting, Pers Comm, 2024). Nauru's Department of ICT (Information and Computing Technology) implemented the fibre network around the island. This network can be susceptible to corrosion from salt spray; replacing cables with a higher grade, more durable, option can reduce susceptibility (Inception meeting, Pers Comm, 2024).

In addition to the current communications infrastructure, the East Micronesia Cable (EMC) project is rolling out a submarine fibre-cable that will benefit up to 100,000 people, running from Poh Peh in Guam across the Federated States of Micronesia, Kiribati and Nauru, and is expected to be online by December 2025 (Figure 17-9) [8].



---

[21] Cenpac is a state owned corporation established under Cenpac Corporation Act 2018 to 'establish, operate, manage and invest in communication services; (b) establish, operate and manage a network for accessing the world wide web and international gateway for communication to and from the Republic; (c) establish and operate as an internet service provider for wholesale and retail purposes;" http://ronlaw.gov.nr/nauru_lpms/files/acts/e24451850631b9136b0c77c1f2afe142.pdf

Figure 17-9 Planned route of the East Micronesia Cable (EMC) project (top). Potential submarine and terrestrial cable alignments for BMH1 & 2 (white dashed lines) in Nauru. (Note terrestrial fibre cable is already in place) [8].

In Nauru, the EMC cable will run across the top of the fringing reef and will be armour plated where it comes ashore next to the ICT Centre (BMH1 in Figure 17-10). The landing site is 4-5 metres above sea level. Significant/extreme wave events waves (e.g. November 2023 event) have never overtopped the seawall. The EMC is designed to provide quality, secure and reliable telecommunications connectivity via a submarine cable between these countries (see East Micronesia Cable System | Home).

Figure 17-10 East Micronesia Cable landing site looking south (left), looking north (middle), and looking across the reef (right). (Photo credit: M Sheppard and G Akken).

Once the EMC is connected, it will be relatively expensive to maintain the existing satellite network as a back up to EMC fibre optic communications. It is not known if redundancy in communications access is being considered within the frameworks to manage disaster risk reduction communications (Inception Meeting, Pers Comm, 2024).

Climate hazard related impacts

Extreme heat

Extreme heat can cause blackouts affecting telecoms. Since 1979, the number of hot days (maximum temperatures above the 90th percentile for 1981–2010) has increased by 22 days/decade (Chapter 4) and further increases are projected in future.

Wind

Digicel and ICT rely on consistent supply of electricity and are susceptible to power outages and wind damage. ICT has installed their own back-up power generator in February 2024 to improve reliability.

Rainfall

Ka-band satellite is more susceptible to rain fade and Papua New Guinea notifies Digicel Nauru if there is a ‘weather issue’ whereby the connection gets patchy at times (Inception mission, Pers Comm, 2024).

Lightning is also a risk for telecom towers.

Tropical cyclones

While tropical cyclones do not directly affect Nauru, remote cyclones can affect EMC cables. For example, there were communication problems when a tropical cyclone damaged the cable in Guam (Inception meeting, Pers comm, 2024).

4 - Transport and supply chains

A new port facility is currently under construction and will service shipping and fishery industries, and provide local business opportunities through value-add services (Inception meeting 2024 Pers Comm).

Roads

In the 2021 census, 41.5 % of households owned one or more motor vehicle. Motor bikes were much more common than cars, and 69.3 % of households had at least one motor bike [2].

Currently there are 72.5 km of roads in Nauru [4], and the longest section circumnavigates the island, while a few gravel roads access the Topside area from different points around the island. There is no road that goes across the island. The coastal road was constructed in 1973 and is mostly made of asphaltic-concrete. Roadside soak drainage pits are used to prevent road run off and contamination flowing into the sea and onto the reef. Through time, increases in compacted and sealed surfaces, as well as inadequate maintenance, has resulted in sediment and litter blocking the soak pits and causing ponding on the road surface in some places (Inception meeting 2024, Pers Comm).

A project funded through the Australian Infrastructure Financing Facility for the Pacific to resurface sections of the ring road (in conjunction with the airport runway upgrade) is planned for 2024/2025 [9].

Sea Port

The sea port, located on the western shore of Nauru, is under development with major works (US$100 million supported by the Green Climate Fund) initially being undertaken to enable Nauru's main shipping vessel, the 'Micronesian Pride', to dock and unload onshore (Figure 17-11). 'Micronesian Pride' is Nauru's only container vessel and brings in most of Nauru's food. The new port also includes pipelines for four types of fuel used on Nauru (diesel for portable power generator, standard diesel, petrol, aviation), the RO intake pipe, two container yards (south and north), a harbour basin (~10 metres deep on completion) and wharf. The port is considered unsafe if swell waves over 0.5 metre wash into the narrow dock. The Higher Ground Initiative has plans for a second boat harbour on the eastern shore of the island which would provide an alternative site during adverse swell conditions (see Figure 19-1) [10].

Phosphate carrier ships (27000 t; 130-170 m long) are not able to use the old or new wharf. Currently, processed phosphate is loaded via cantilever conveyers onto large vessels that are tied up to the reef and held in place with two tugboats (Inception meeting, Pers Comm, 2024). A study would be useful to determine additional engineering requirements to enable the large vessels to moor in the wharf.

Figure 17-11 Construction works at the port (left) Cantilever conveyor used for loading phosphate onto carrier ships (right). Photo credit: CSIRO, 2024.

Nauru is vulnerable to remote swell-driven coastal inundation due to its narrow fringing reefs. Mid-latitude storms in the North Pacific and Tasman Sea/Southern Ocean are by far the most common source of large, damaging swell events through most of the central Pacific ([11]). However, wave period and wave direction also must be accounted for to understand local impacts.

Airport

Nauru's airport is located on the southwest corner of the island, with some land reclaimed at the southern edge to accommodate the runway (Figure 17-12). The perimeter road runs either side of the runway, with the inland road being closed when planes are taking off and landing.

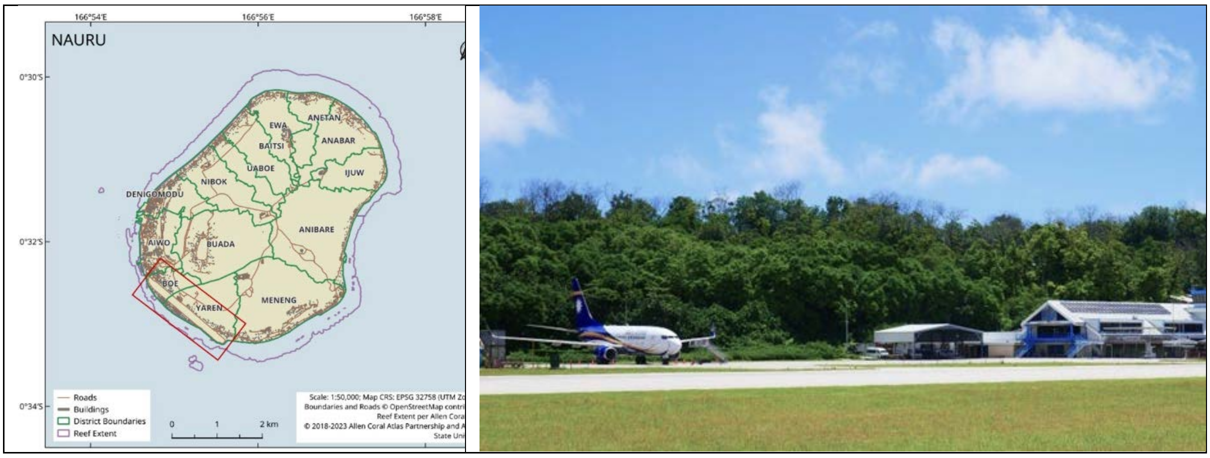


Figure 17-12 The airport crosses through Yaren and Boe districts on the south-west coastal strip of Nauru (red box in left panel). Photo credit: CSIRO, 2024.

Climate hazard related impacts

Temperature

Asphalt road pavements are important in transport, and bitumen is an important component of these. At high temperatures, bitumen is more fluid; at intermediate temperatures, a viscoelastic liquid; and at low temperatures, it is solid [12]. Extreme temperatures can melt bitumen and affect asphalt road surface performance [13].

For the airport, runway surface cracks over 3 mm need to be resurfaced to prevent water seeping into the ground and damaging the substrate (Inception meeting, Pers comm, 2024). The runway should be resurfaced every 15 years in extreme heat (the exact heat threshold defining 'extreme heat' was not provided), but Nauru airport hasn't been resurfaced in more than 30 years, since the early 1990s (Inception meeting, Pers comm, 2024).

Increased heat stress affects labour productivity [14], e.g. road, port and airport service crews.

Extreme rainfall

Heavy rainfall has caused flexible pavement surfaces to be significantly affected [15, 16]. The existence of a good drainage system is crucial [17] as roads frequently flood during heavy rainfall, impacting both safety and access. Design and maintenance affect drainage performance.

Extreme rainfall affects the port worker safety as the surfaces become slippery and it is difficult to view overhead containers during loading/unloading from ships (Inception meeting, Pers Comm, 2024).

Wind

Fallen trees can disrupt road transport, with significant economic cost to clear debris and repair damaged transport infrastructure. Large and extreme wind-driven waves, sometimes generated by distant storms, can disrupt shipping and port services, and damage port infrastructure. High winds can disrupt flights and airport services.

Waves

While development of the port has taken sea level rise into consideration, as well as wave direction and storm surge, a storm event in January 2024 adversely affected port development (Figure 17-13). Port management remain concerned about damage due to swell waves and the future vulnerability of the port to large swell waves.

Figure 17-13 Large swell affected the new port building works (Jan 14 2024). The swell was related to a distant typhoon (in the Northern Hemisphere). There was no wind in Nauru at the time of the event. Steel structures were damaged, the new fuel line was re-exposed and 4000 m^3 of back fill (yet to be secured by holding bags) was washed away (Source: Graham Moody, Nauru Port).

The peak in significant wave height (Hs ~3 m), just after 21 January 2024 (UTC), was accompanied by extremely long wave period (Tp ~18 s), and wave direction was from the north/NNW (Figure 17-14).

It is likely this event was generated by a significant North Pacific storm event, probably centred ~40 N latitude. The long wave period is significant, since this translates into much greater wave energy flux – i.e. much bigger breaking waves and resulting infragravity waves for a given significant wave height. Videos from the event clearly show most direct destruction was caused by infragravity waves[22] generated by breaking waves over the reef flats [18].

The same storm also catastrophically inundated Roi-Namur (a US base on Kwajalein Atoll, Marshall Islands, creating many news items, e.g. https://abcnews.go.com/International/extreme-waves-marshall-islands-highlights-dangers-climate-change/story?id=106598347). It also caused flooding impacts to other parts of the Marshall Islands and Kosrae (FSM).

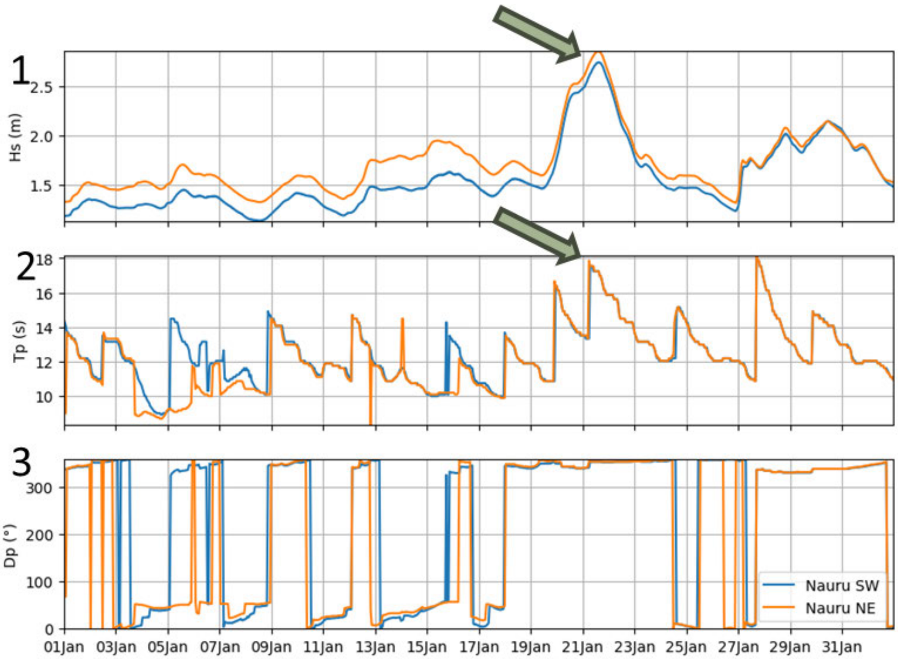


Figure 17-14 Timeseries of significant wave height (Hs; m), wave period (Tp; s) and Wave direction (Dp) for two points near Nauru for January 2024. Arrows indicate the timing of the event.

Given that the port area is adversely affected by swell above 0.5 m, any change in wave direction can have an impact (see Chapter 9).

Sea level rise

Nauru has approximately 72 km of roads [4]. With 1.0 m of sea level rise, 3.7 % of the roads would be exposed to coastal inundation during spring (commonly referred to as king) tides (refer to Figure 17-15) [4]. This includes sections of the coastal ring road which are crucial for mobility.

---

[22] **Infragravity waves** are surface ocean waves with frequencies below those of wind-generated “short waves” (typically below 0.04 Hz). Bertin et al 2018 note that “Infragravity wave impacts, especially during storms, need to be taken into account when providing operational forecasts, and when assessing longer-term coastline stability. Infragravity waves should also be considered during harbour design, as they can effect harbour operations substantially through resonance.”

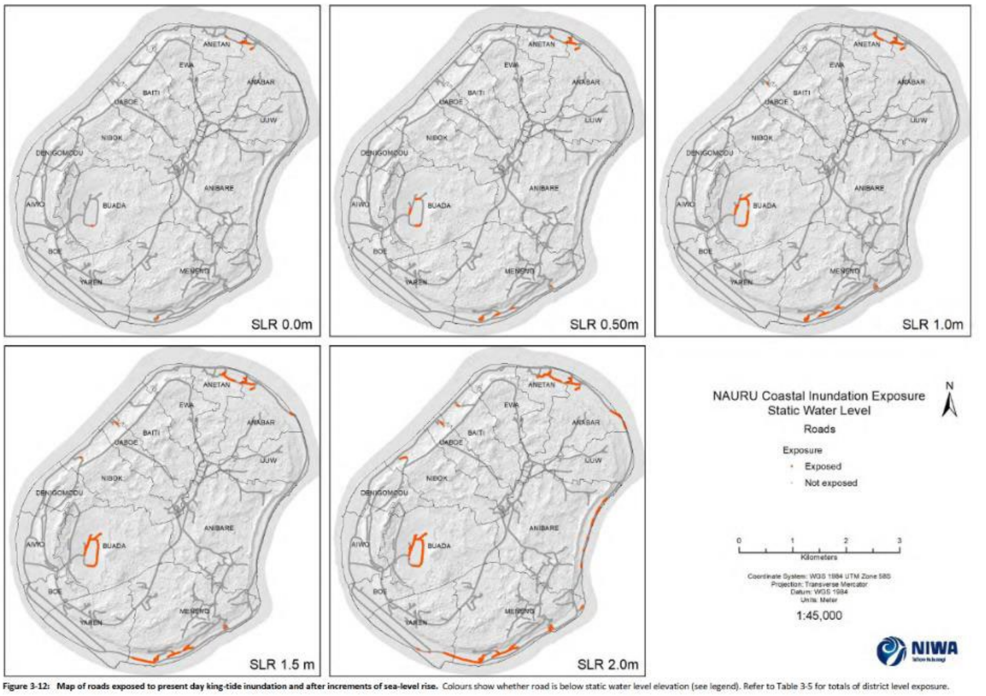


Figure 3-12: Map of roads exposed to present day king-tide inundation and after increments of sea-level rise. Colours show whether road is below static water level elevation (see legend). Refer to Table 3-5 for totals of district level exposure.

Figure 17-15 Roads exposed due to present day king tide inundation with sea level rise (SLR) increments [4]

The airport runway may be impacted by sea level rise. The map produced by NIWA, shown in Figure 17-16, reveals the specific areas of the airport that may be affected. While the paved runway elevation ranges from 5 m up to 7.5 m in the northwest, it has grassed areas on either side of the runway with elevation as low as 4.5 m [4]. The lowest point of the paved runway is 0.3 m above the king tide elevation, so parts of the runway become inundated for sea level rise scenarios of 0.5-2.0 m (Figure 17-16) [4].

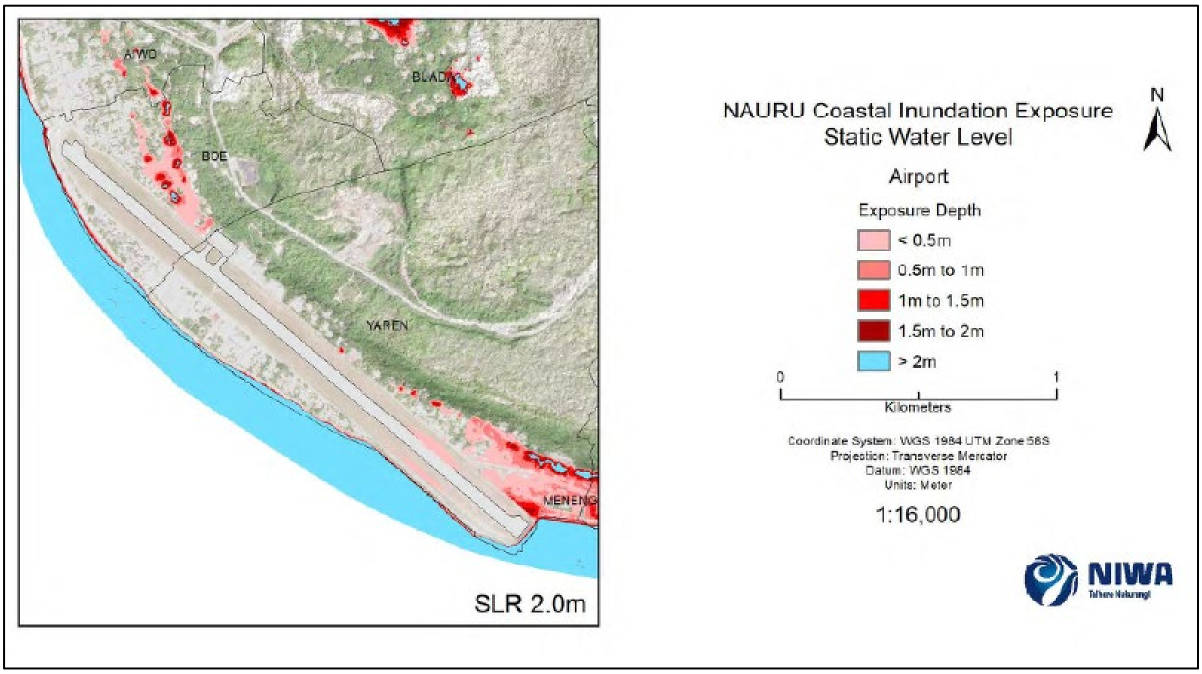


Figure 17-16 Airport runway and surrounds forecast inundation at SLR levels from 0.5 m to 2.0 m [4].

The NIWA report [4] noted there may be additional inundation impacts from over-wash (over-topping) of the southern boundary coastal revetment. This may result in water flowing across the grassed areas and into the drainage stormwater channels, so that in severe inundation plus over-topping events, the southern sections of the paved runway may also be inundated. The NIWA report recommends further research to assess the compounding effects of over-washing, coastal defence design, the capacity of the airport drainage system, infiltration rates, coinciding heavy rainfall and high groundwater levels [4].

Coastal inundation (sea level rise plus wave overtopping)

Coastal inundation significantly impacts transport infrastructure such as roads. Modelling indicates that, during a 100-year flooding event, 914 m of roads would be affected in the district of Anabar, followed by Anibare (905 m), Meneng (594 m), and Anetan (506 m) [3]. Coastal inundation of roads involves the movement of sand and debris, which can impede safe travel and require extensive efforts to clear, and an example from 2012 is shown in Figure 17-17.

Figure 17-17 Sand and debris on a road caused by a coastal inundation event. (Credit Godwin Cecil pers. Comm. 13 November 2022)

The southern corner of the airport in the Yaren District does not appear to experience significant inundation from wave overtopping at present, but land adjacent to the airport does experience wave inundation. Under the storm conditions shown in the figures below, wave overtopping begins to cause significant areas of potential inundation of the apron and runway for sea level rise of 1 m and above (Figure 17-18; [5]).

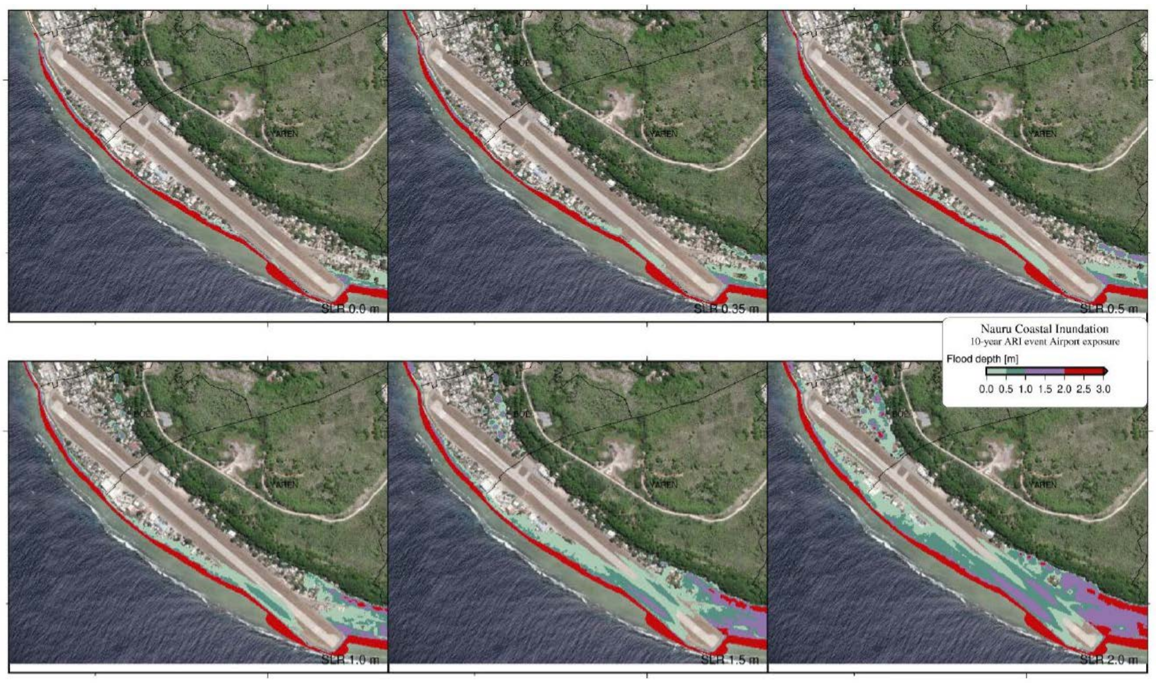


Figure 17-18 Airport land exposure for wave inundation for a 100-year ARI event for different increments of sea level rise (SLR) (source: [5]).

5 – Energy

Nauru Utilities Corporation provides both power and water to the community (Figure 17-19). They are located next to each other and adjacent to the port. From June 2022 to July 2023, Nauru Utilities indicated that the maximum of power demand was 5-6 MW each month [19].

In 2021, 10.1 % of households used electricity for cooking. By far the most common source of energy is butane gas (74.0 %), which is mostly used in Anibare (93.2 %) and Ijuw (91.8 %) [2].

Figure 17-19 Nauru Utilities company logo (left) and overhead power lines (right). Photo credit: CSIRO, 2024.

Currently, 1.6 MW of solar power is already operating, and another 6 MW is anticipated to be online by the end of 2024. (NUC 2021 annual report had this figure at 2.4 MW - 1.6 MW ‘ground mounted’, but also a figure 0.831 MW of ‘rooftop’ PV). Solar power is integrated into the grid and uses Battery Energy Storage Systems to compensate for loss or outages without affecting the supply to the grid. Solar panel operation is impacted by cloudiness and currently requires a manual transfer across to diesel generation if solar input is interrupted. This takes about 30 minutes. A morning forecast from the Meteorology and Hydrology Service allows the Electricity Department to plan management of electricity during the day. Solar installations are on private land and require owner's permission and compensation (Inception meeting, Pers Comm 2024).

A 2010 feasibility study for wind power generation potential was conducted after monitoring wind speeds at two sites in Anibare and Ijuw. Wind resources (annual average wind resource of 4.22 m/s at 30 metres) were found to be at the low end of practical wind energy generation and, although wind turbines could be optimised for a low wind resource environment, it was determined not economically feasible to pursue [20]. This 14-year-old study could be revisited to account for improvements in technology and return-on-investment.

The world's first pilot Ocean Thermal Energy Conversion (OTEC) plant was established in Nauru in 1981 by the Japanese Tokyo Electric Power company to take advantage of the enormous potential of ocean energy. The concept proved technically feasible and was the first and last plant to feed power to an operating commercial grid. However, the pilot plant was destroyed by extreme weather events (unknown date) [21].

Figure 17-20 Electricity company located adjacent to the port (left). Air conditioning units are common in Nauru (right). Photo credit: CSIRO, 2024.

Climate hazard related impacts

Any electricity outage can have cascading effects across multiple sectors, businesses and communities. For example, loss of power can affect critical infrastructure such as transport, telecommunications and wastewater, with disruption to services such as lighting, cooling, internet and hospitals. Generators and batteries can provide back-up power for a few hours, but multi-day outages can cause major problems.

Extreme temperature

On hot days, air conditioners and fans are used for cooling, which increases electricity demand. A non-linear but directly proportional relationship between temperature and electricity demand was found in a recent study undertaken in Vanuatu [22] (Figure 17-21). A similar relationship may exist for Nauru. If demand exceeds supply on hot days, outages can occur, with implications for heat stress, critical infrastructure and services.

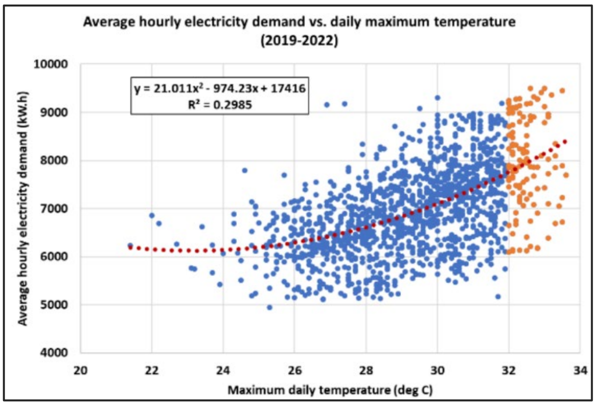


Figure 17-21 Average hourly energy demand (kW/hr) for Efate (Vanuatu) compared to daily maximum temperature. Demand rises rapidly above 32 °C (orange dots). Source [23].

Future increases in air temperatures will lead to increasing energy demand for fans, air-conditioning and refrigeration [24, 25]. International studies indicate demand increases of up to 6.6 % in Vanuatu by 2050 [23] and 4 % in Brisbane (Australia) for 2–3 °C warming [26].

Extreme heat can reduce labour productivity [14], including the ability to undertake routine maintenance and repairs.

Drought

Extended dry periods lead to salt build-up on crossarms of transmission lines, increasing the risk of outages. The electricity supply needs to be shut down and the salt washed off with desalinated water (Inception meeting, Pers comm, 2024). Wooden crossarms are being replaced with fibreglass to improve the resilience of the transmission lines to conductivity from salt accretion.

Extreme rainfall

Flooding of electricity infrastructure may cause blackouts [27] which affect multiple services including health, telecommunications, transport and water treatment.

Wind

The prototype Ocean Energy Conversion station was destroyed by waves (timing unknown) [21], which may be associated with remote cyclones/typhoons. Wind borne debris and dust can affect electrical transmission lines and solar panels. Salt spray can build up on transmission towers.

Sea level rise

Electricity poles around the low-lying coastal fringe are exposed to sea level rise. The southern districts of Meneng and Yaren have 63 % (42 of 67) of all poles exposed at ‘king tide plus 2 m of sea level rise’, mostly along a 700 m stretch east of the southern runway. All other districts have 11 or less poles exposed [4].

Salinisation of the soil from sea level rise and spring tide inundation can impact the existing underground copper wire network infrastructure for telecommunication (which needs to be replaced with fibre-optic cable) (Inception meeting, Pers Comm, 2024).

6 - Buildings and structures

Infrastructure within 100 m of the coast accounts for 34 % of the total asset number and 40 % of the total infrastructure replacement value [6]. Critical infrastructure, including the power station, roads, schools, and hospitals are in low-lying coastal areas that are susceptible to coastal inundation [3].

The Higher Ground Initiative [10] uses the NIWA assessment [4] to inform the risk of exposure to inundation under a range of sea level rise scenarios. The assessment indicated that 154 of 2471 buildings would be exposed under a 1.0 m sea level rise scenario, with the bulk of these being residential buildings.

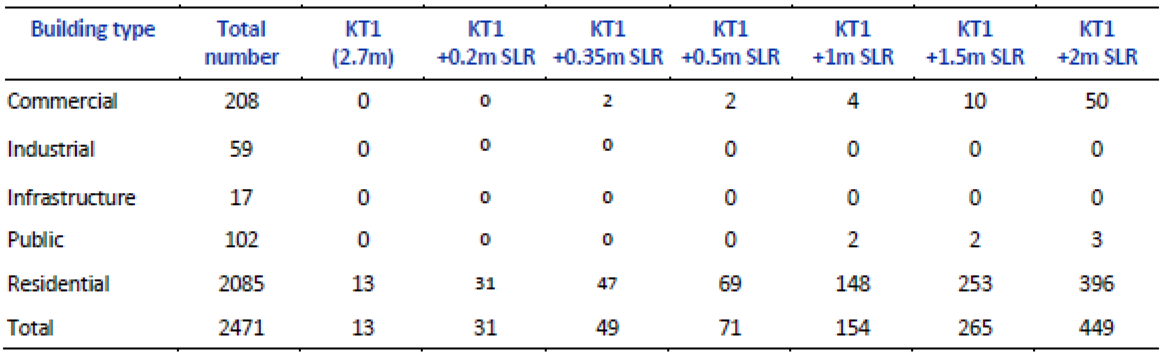
Some low-lying districts (Buada, Ijuw, Anabar and Meneng) are already experiencing inundation during king-tide events. The west and north of the island (Nibok, Denigomodu, Uaboe, Baiti and Aiwo) have a lower exposure due to higher elevation. Major infrastructure including the main Reverse Osmosis plant, hospital, government offices, and fire services are in Aiwo (and the future telecommunication cable in Denigomodu) [4].

Climate hazard related impacts

Sea level rise

Building exposure in Nauru is presented in (Table 17-1). Exposure of a building does not necessarily mean inundation inside the building, rather it means the ground level around the building is below the static water level [4].

Table 17-1 Total building type exposure for all of Nauru for KT1 (king tide) and KT1+SLR increments (Source: [4]).



Building type	Total number	KT1 (2.7m)	KT1 +0.2m SLR	KT1 +0.35m SLR	KT1 +0.5m SLR	KT1 +1m SLR	KT1 +1.5m SLR	KT1 +2m SLR
Commercial	208	0	0	2	2	4	10	50
Industrial	59	0	0	0	0	0	0	0
Infrastructure	17	0	0	0	0	0	0	0
Public	102	0	0	0	0	2	2	3
Residential	2085	13	31	47	69	148	253	396
Total	2471	13	31	49	71	154	265	449

Under current conditions, a 2.7 m king tide (KT1) would expose 13 residential buildings to inundation. At 0.2 m of sea level rise, 31 residential buildings would be exposed. At 0.5 m of sea level rise, 69 residential buildings and 2 commercial buildings would be exposed. At 1.0 m of sea level rise, 148 residential buildings, 4 commercial buildings and 2 public buildings would be exposed. At 2.0 m of sea level rise, Meneng has the highest total exposure with 139 of its 300 buildings exposed (33 %). These are predominantly residential (122 of 139) with 22 commercial and 2 public buildings. Anibare and Yaren are the next most exposed with 17 % and 16 % of their buildings exposed, respectively, at the highest KT1+2m SLR increment. Denigomodu, Aiwo, Nibok, Baiti and Uaboe have less than 10 buildings (all types) exposed at KT1+2m SLR, and this exposure reflects the generally higher ground elevations on the west/north-western sides of Nauru [4].

Using the RiskScape model, the exposure of Nauru's buildings, roads and population to coastal inundation was assessed. Economic losses were based on the estimated damage to buildings and the expected replacement costs. The annual expected loss due to wave-driven flooding in Nauru indicates most damage occurs along the north and south-eastern coasts. In particular, the buildings in Ewa, Anetan and Anabar in northern Nauru, and Meneng and Yaren in south-eastern Nauru are expected to experience the most serious damage. Damage is exacerbated due to projected sea level rise (Figure 17-22) [3].

With present sea level conditions, a 5-year annual recurrence interval (ARI) inundation event would flood 6.2 % of Nauru's buildings, and by 2100 (under the SSP5-8.5 scenario) a 5-year ARI event would flood 16.7 % of buildings [3]. The annual economic losses associated with coastal flooding is US$1.3 million/year for the current climate and 3.3 to 5.7 times this estimate by 2100 [3].

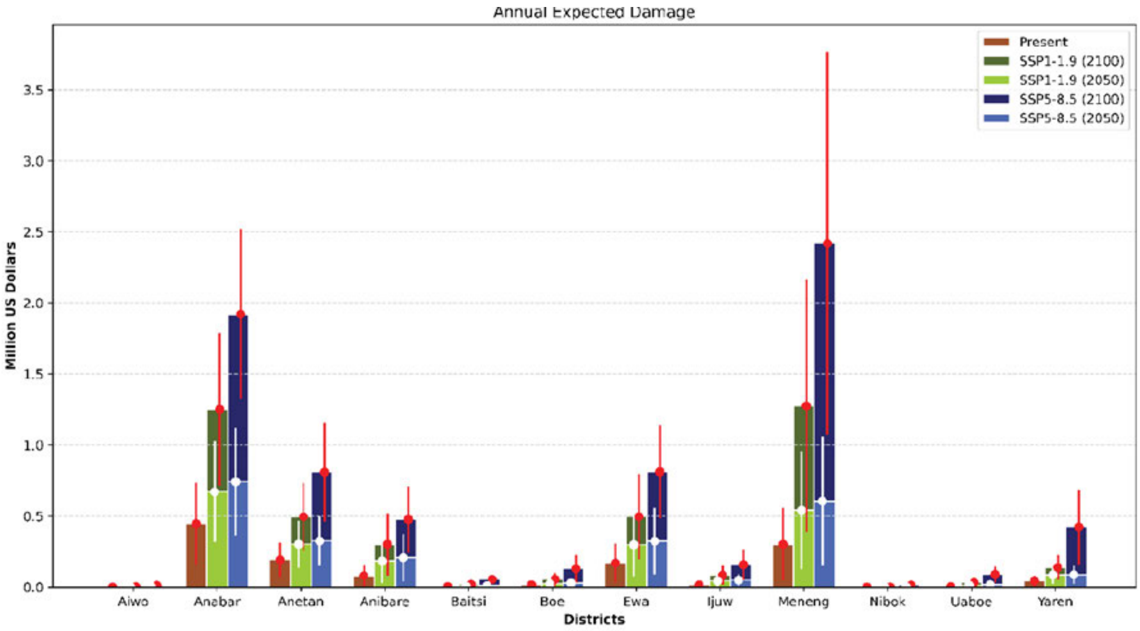


Figure 17-22 Annual expected economic loss incurred for each Nauru district due to coastal inundation for the present climate, 2050 and 2100, for a very low emissions scenario (SSP1-1.9) and a high emissions scenario (SSP5-8.5). The plot shows the annual loss each district may incur for 2020 using the 2012 US dollar valuation. Upper limits reveal the inferred loss from a tsunami fragility function with lower limits for the storm surge fragility function. The Buada and Denigomodu districts are not plotted as little to no buildings are exposed to the hazard. Source: [3].

Ocean temperature and acidification

Coral bleaching due to higher ocean temperatures and weaker reef structures due to ocean acidification can reduce island protection [28]. Marine infrastructure (e.g. fixings such as nails, rivets, and bolts) may also be affected by ocean acidification.

7 - Health Infrastructure

Republic of Nauru Hospital (RoNH) is located in Yaren and provides basic medical care; special treatment is limited to diabetes and other obesity-related diseases at the Naoero Public Health Centre, run by the Department of Public Health. Anyone with serious illnesses and injuries that cannot be treated on the island must be sent by air to Australia or Fiji. RoNH provides free health care and dental treatment to Nauru citizens [29]. All pharmaceuticals are imported from Australia or the Netherlands and are vulnerable to supply disruptions [29].

Using the EMC cable, RoNH is implementing Picture Archiving and Communication System (PACS), a medical imaging system that will enable the remote analysis of digital medical images, for example mammograms, by experts. While there are significant advantages in having this capacity, this new technology will increase the hospital's reliance on internet access and electricity connectivity [23].

---

[23] NUC is good about communicating planned outages, however unplanned outages are a concern, particularly when these occur during surgery. The hospital has a battery to maintain power for short time and a backup generator managed by NUC. In addition to the impacts to hospital services dependent on power, surges associated with outages can affect expensive specialised equipment critical for the delivery of health care.

Climate hazard related impacts

Temperature

On extremely hot days and during heatwaves, heat stress can occur. Increased hospital admissions are possible, especially if power outages occur and communities are unable to run fans and air conditioners. The hospital and Naoero Public Health Centre may require back-up power to cover a multi-day outage.

Extreme rainfall

Nauru's main hospital regularly experiences flooding following extreme rain, in part due to poor maintenance of the drainage system. The hospital has purchased a submergible pump to manage flooding (Figure 17-23), but there's still a risk of water inundating the hospital wards. This risk is likely to grow in future because extreme rainfall intensity is projected to increase.

Figure 17-23 Republic of Nauru (RoN) Hospital entrance (left) and in flood after heavy rain (right). Source M Sheppard CSIRO, 2024.

8 - Waste management

Waste is collected from households, Government facilities, and businesses then transported to the Nauru Dump Site for disposal. Each waste layer is compacted, and organics are separated. There have been small scale trials separating recyclables from general waste, but these have been of limited success because there are no enabling activities to reuse or recycle these materials (Inception meeting, Pers Comms, July 2024). The Dump Site has periodic fires requiring excavation of waste and the use of significant quantities of water to extinguish. Some waste (including hazardous waste) is stored due to lack of a disposal route [30].

The 2021 census found that most households (86.6 %) used personal bins that were publicly collected. Another 9.3 % used personal bins that they delivered to the garbage dump. This was more common in Ewa (43.9 %) and Aiwo (19.1 %). Among the other methods used, the most common (2.3 %) was burning, particularly in Ijuw (16.3 %) and Denigomodu (8.3 %). Composting of household waste was limited to 17 households in Location [2].

Based on the MCA assessment [30], the proposed option for enhancing solid waste management is improvements to the existing Nauru Dump Site, construction of a new disposal site at the Dump Site, improvements to hazardous waste management (including e-waste, used oil, healthcare waste), provision for stockpiling/disposal of bulky waste, and implementation of the Nauru National Recycling Plan (Figure 17-24).

Figure 17-24 Poster highlighting the plastic waste issue (left) and car wrecks at the waste dump (right) (Photo credit: M Sheppard, CSIRO 2024).

Climate hazard related impacts

Air temperature

Increased fires at the waste dump are associated with hot days (Inception meeting, Pers Comm, 2024).

Extreme rainfall

Flooding can impact drainage systems and cause overflows of septic tanks. This can have associated water quality and health impacts [31, 32].

The dump site is unlined [30], so increases in heavy rainfall may lead to increased land-based pollution in groundwater and surface water, also adversely affecting water quality.

Drought

As with hot days, waste dump fires are more frequent during drought (Inception meeting, Pers Comm, 2024).

Sea level rise

Sea level rise will lead to increased flooding and erosion of coastal dumpsites causing greater pollution of coastal waters. There are no formal dumpsites on the coast but there are ad hoc disposal areas [30-32].

References

1. 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. DOI: https://doi.org/10.1371/journal.pone.0223249
2. SPC and Government of the Republic of Nauru, *Nauru 2021 population and housing census - Analytical report*. 2023 SPC: Noumea, New Caledonia; Available from: https://sdd.spc.int/news/2023/08/23/nauru-2021-population-and-housing-census-analytical-report
3. Wandres, M., J. Giblin, A. Espejo, T. Sovea, R. Simpson, N. Jackson, A.C. Pickering, and H. Damlamian, *Nauru coastal risk assessment*. 2023 Pacific Community (SPC): Suva, Fiji. Available from: https://pacificdata.org/data/dataset/oai-www-spc-int-bd6b8334-7d52-4055-911e-7dccb6c61747
4. Allis, M., S. Williams, and S. Wadwha, *Coastal flooding from sea-level rise in Nauru: Stage 1 - static inundation mapping, Prepared for the Nauru Higher Ground Project*. 2020: Prepared

for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited. Available from: https://nauru-data.sprep.org/system/files/Nauru_Coastal_Inundation%20with%20SLR_final%20-%20Oct%202020%20reduced%20%281%29.pdf

5. Bosserelle, C. and S. Williams, *Coastal flooding from sea-level rise in Nauru: Stage 2 - wave inundation mapping, Prepared for the Nauru Higher Ground Project*. 2023 Prepared for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited: Christchurch, NZ.
6. 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. DOI: Exposure of coastal built assets in the South Pacific to climate risks. *Nature Climate Change,*
7. Trenham, C.E., M.A. Hemer, T.H. Durrant, and D.J. Greenslade, PACCSAP wind-wave climate: High resolution wind-wave climate and projections. *Quarterly Journal of the Royal Meteorological Society,* 2013. 137: p. 656. Available from: https://www.cawcr.gov.au/technical-reports/CTR_068.pdf
8. Argo Environmental Ltd, *East Micronesia Cable Project*. 2016 Argo Environmental Consultants,; Available from: https://www.eastmicronesiacable.com/
9. AIFFP, *Nauru Airport Upgrade and Road Rehabilitation Project*. 2022 Australian Infrastructure Financing Facility for the Pacific: Australia; Available from: https://www.aiffp.gov.au/sites/default/files/2023-12/Business%20Case%20-%20Nauru%20Airport%20Refurbishment.pdf
10. Department of Climate Change and National Resilience. *Higher Ground initiative*. 2024 Available from: https://www.climatechangenauru.nr/higher-ground-initiative
11. Lodise, J., S. Merrifield, C. Collins, P. Rogowski, J. Behrens, and E. Terrill, Global Climatology of Extratropical Cyclones From a New Tracking Approach and Associated Wave Heights From Satellite Radar Altimeter. *Journal of Geophysical Research: Oceans,* 2022. 127(11): p. e2022JC018925 DOI: https://doi.org/10.1029/2022JC018925
12. Krishnan, J.M. and K. Rajagopal, On the mechanical behavior of asphalt. *Mechanics of materials,* 2005. 37(11): p. 1085-1100. DOI: https://doi.org/10.1016/j.mechmat.2004.09.005
13. Almeida, A. and L. Picado-Santos, Asphalt Road Pavements to Address Climate Change Challenges—An Overview. *Applied Sciences,* 2022. 12(24): p. 12515. DOI: https://doi.org/10.3390/app122412515
14. 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
15. 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. DOI: https://doi.org/10.1260/1369-4332.18.4.4
16. 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. DOI: https://doi.org/10.1080/10298436.2018.1508844
17. 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. DOI: https://doi.org/10.1080/23249935.2020.1720035
18. Bertin, X., A. de Bakker, A. Van Dongeren, G. Coco, G. André, F. Ardhuin, P. Bonneton, F. Bouchette, B. Castelle, and W.C. Crawford, Infragravity waves: From driving mechanisms to impacts. *Earth-Science Reviews,* 2018. 177: p. 774-799. DOI: https://doi.org/10.1016/j.earscirev.2018.01.002
19. Nauru Utilities Corporation. 2024; Available from: https://www.nuc.com.nr/.

20. Thorp, W., W. Dowiyogo, and A. Soakai, *Third party assessment of the PIGGAREP-funded wind monitoring activity in Nauru* 2010; Available from: https://pacific-data.sprep.org/dataset/nauru-wind-resource-mapping
21. UN environment program. *OTEC: Ocean Energy Technical Pre-Feasibility Study* 2024 Available from: https://www.ctc-n.org/technical-assistance/projects/otec-ocean-energy-technical-pre-feasibility-study
22. 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
23. CSIRO and SPREP, *Extreme heat impacts on electricity demand in Efate. Infobyte prepared for the Vanuatu Meteorology and Geo-hazards Department as part of the Van-KIRAP project.* 2023 CSIRO: Melbourne, Australia; Available from: https://www.vanclimatefutures.gov.vu/assets/docs/Electricity%20Infobyte.pdf
24. 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. DOI: https://doi.org/10.1073/pnas.1613193114
25. 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. DOI: https://doi.org/10.1038/s41467-019-10399-3
26. Howden, S.M. and S. Crimp. Effect of climate change on electricity demand in Australia. . in *Proceedings of Integrating Models for Natural Resource Management across Disciplines, Issues and Scales (2), in "MODSIM 2001 International Congress on Modelling and Simulation"*. 2004: Modelling and Simulation Society of Australia and New Zealand. Canberra.
27. 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. DOI: A research and innovation agenda for energy resilience in Pacific Island Countries and Territories. *Nature Energy,* 2021
28. 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. DOI: https://doi.org/10.1098/rsos.192153
29. Government of Nauru, *RoN Hospital*. 2024 Government of Nauru: Nauru; Available from: http://naurugov.nr/government/departments/department-of-health-and-medicinal-service.aspx
30. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Solid Waste Management Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor.
31. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Water Supply System Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor.
32. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Sanitation System Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor.

Chapter 18 Biodiversity and environment

Terrestrial biodiversity

The global populations of noddy birds and frigate birds are in decline [1]. On Nauru, seabird populations are also declining. Black noddy (*Anous minutus*) and brown noddy (*A. stolidus*) are a food source for Nauruans, with 9.5 % of households catching noddy birds for consumption [2]. A loss of transmission of cultural knowledge from older generations around skill for hunting and collecting traditional food has resulted in less awareness of cultural hunting times in younger generations, i.e. closed seasons for noddy birds from October to December (Inception meeting, Pers Comm, July 2024).

Frigate birds have cultural significance and are symbolised on the Nauru coat of arms (see Figure 18-1). Frigate birds have traditionally been captured and tamed for sport, and one estimate is 310 birds per year, with many birds dying during the capture [3]. Frigate bird sport is now very rare due to lack of feed for the birds, also some migratory birds seen in the past like the white heron, blue heron, long tailed cuckoo and sandpipers are no longer seen (Inception meeting, Pers Comm, August 2024)

Figure 18-1 Noddy birds (left). Nursery for Indigenous plants (right). (Photo credit M Sheppard, CSIRO, 2024)

Nauru does not have any native terrestrial mammals; all mammals are introduced species including Polynesian rats, dogs, cats, pigs and chickens [3]. Owning to its young geological age, Nauru has small numbers of lower order terrestrial species, including endemic insects (moths, dragonflies) and snails [3]. Reptiles include four species of gecko, three skinks and a blind snake [1].

On the plateau, there are many native plants, which are dominated by littoral species [3]. While Indigenous forests on Topside were cleared for phosphate mining, baseline information of Nauru's biodiversity has been well established in recent decades. Indigenous plants are limited, representing only 63 species out of 573 species recorded on Nauru, and there are no endemic plants [4]. Remnants of native forest can be found along the cliffs dividing Topside from the coastal plain (FAO, 2019). Most of the island vegetation is secondary scrub and forest and restricted mostly to the edges of the central plateau, Topside and around Buada Lagoon [3]. Naturalised exotic species that compete with indigenous species include *Adenanthera pavonina*, *Casuarina equisetifolia*, *Lantana camara*, *Leucaena leucocephala*, *Mangifera indica*, *Muntingia calabura* and *Psidium guajava* [3].

Habitat modification, restricted land area, and disturbance caused by introduced and invasive species are threatening processes to indigenous plants [3], resulting in significant loss of diversity in both ecosystems and species [4]. Nauru does not have a building code, and this has led to unregulated clearing which has reduced nesting trees for noddy birds (Inception meeting, Pers

Comm, July 2024)[24]. A few rare plants have cultural uses, for example tree species *Hernandia nymphaeifolia* (etui in Nauruan) previously favoured for traditional fishing boats is no longer available for harvest (Inception meeting, Pers Comm, March 2024). Other rare culturally significant plants include *Thespesia populnea* (itira) used for construction and carving, and *Tournefortia argentea* (deren) which is an important medicine plant (McKenna, 2015). Other rare plants offer ecosystem services including coastal protection (*Tournefortia argentea* and *Thespesia populnea*), rookery trees for noddy birds (*Pisonia grandis* or yangis), filtering water (*Bruguiera gymnorrhiza,* etõm or etam), and shade (*Ochrosia elliptica* or eoerara) [1].

Nauru has less than 2 hectares of mangrove forest consisting of *Bruguiera gymnorrhiza*[25] and *Rhizophora stylosa*. Due to limited suitable shallow habitats with muddy bottoms protected from strong wave action [5], mangroves are not found along the coast, but they are found in landlocked ponds in Menen, Anibare and Anetan districts [1], and around Buada Lagoon [6].

Climate hazard related impacts

Extreme temperature

Extreme temperature causes plant and animal stress and is associated with fires.

Drought

Indigenous Pacific plants such as pandanus are adapted to harsh conditions and have historically survived long periods of drought [7]. However, in the most recent drought, even pandanus were dying (Inception meeting, Pers comm, 2024). Indigenous plants not seen for a long time have been regrowing following short bursts of rain and heat (Pers Comms, July 2024). Droughts with reduced intensity, frequency and duration in future could result in better conditions for indigenous plants.

Many of the people interviewed in the inception visit (March 2024) noted that trees such as pandanus and coconut were affected by the recent drought with dieback evident even on species usually hardy to Nauru's climate (Inception mission, Pers comm, 2024).

Sea level rise

Relocation of communities due to sea level rise will limit some areas available to rehabilitate vegetation on topside. This should be considered in the Higher Ground Initiative [8].

Aquatic and coastal biodiversity

Figure 18-2 Reef flat with some limestone pinnacles on Nauru coast (left). Sea cucumbers are prolific on the reef flat (right). Photo L. Webb CSIRO 2024.

---

[24] In late 2023 Nauru's draft building code was endorsed by the government appointed Technical Working Group

[25] July inception mission noted only one species (Bruguiera gymnorrhiza) in very small numbers in the Ijuw-Anibare wetlands.

On the reef slope, a 2004 study reported coral communities were either sparse or contained mostly dead corals, especially near the populated and developed areas of Nauru [9]. At this time, small encrusting colonies grew on the reef slope and live coral cover was 0–20 % in areas from Uaboe district to Gahab channel and Boe district. In the most recent (2013) survey of 20 sites around the island, live hard coral cover averaged 48 % in deeper water (>12 m depth) and 65.5 % in shallow water (<11 m depth). This is a significant increase in coral cover since 2005 when live coral cover was only 21 % [6]. The state of Nauru's coral reefs was reported in 2019 as healthy, but the coral assemblage had low diversity and low potential for recruitment due to the distance from other islands, posing a future risk of local extinction [6]. Low diversity may also be attributed to poor water quality, phosphate mining, and coral bleaching [6]. The healthiest coral is found on the northeast of the island, off Anetan and Anabar (Pers Comm, 2024).

In Nauru, there are limited mangroves or seagrass beds along the coast [6]. A small amount of aquaculture is being encouraged, with a milkfish project being carried out in Buada (Fisheries representative at 2024 inception meeting, Pers Comm).

Green turtles are reported to nest in Nauru, with legislation prohibiting the collection of sea turtle eggs, disturbance when nesting, and the taking and killing both Green Turtles and Hawksbill turtles [10]. Nauru's coral reefs might be turtle foraging habitats, though further investigation is needed [11], noting recent studies indicate that in the Indian Ocean, adult hawksbill turtles (Eretmochelys imbricata) almost exclusively foraged at 30-150 m depths on remote submerged banks [12].

The 'Status of Coral Reefs of the World 2020' report [13] 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 bleaching events [14, 15]. Degree Heating Weeks (DHW) is a metric that quantifies bleaching events, taking account of both the length and magnitude of MHWs [16].

Climate hazard related impacts

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 females [17]. Sand temperature is related to air temperature and SST [18]. In the northern Great Barrier Reef, Australia, for example, green turtle rookeries have been skewed toward females for more than two decades and complete feminization of this population is possible soon [19]. This gender imbalance could lead to populations becoming compromised or extinct.

Sea surface temperature

In 2005, Nauru experienced a 'mysterious' fish kill speculated to be caused by an algal bloom and/or heat shock triggered by prolonged elevated water temperature, or an upwelling of de-oxygenated water from depth [6]. Further research is needed to understand the causes.

Marine heatwaves

Impacts from MHWs have been detrimental across the region [15], with devastating impacts on aquaculture and marine ecosystems, including many that provide critical habitat and ecosystem services (e.g., coral reefs). Coral bleaching is caused by MHWs. This will also adversely impact some tourism and recreation activities [20].

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 [21]. Severe coral bleaching in Nauru may occur on an annual basis by 2035 under RCP8.5 (van Hooidonk et al., 2016). The health of Nauru's coral reefs is patchy. Reefs near pollution sources (e.g. Aiwo district) are less healthy (Fisheries representative at 2024 inception meeting, Pers Comm).

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 [22, 23]. 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 [24, 25]. For example, ocean acidification has been shown to lower the temperatures at which corals bleach [26], potentially reducing the resilience of these environments to natural climate variability and long-term climate change. It also has the potential to impact fisheries, aquaculture, and overall marine productivity. Coastal protection may be reduced because inshore reefs are likely to deteriorate [27].

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 [28]. 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 [28, 29].

References

1. McKenna, S., D. Butler, and A. Wheatley, *Rapid biodiversity assessment of Republic of Nauru. SPREP. Apia, Samoa.* 2015. Available from: https://www.sprep.org/publications/rapid-biodiversity-assessment-biorap-of-republic-of-nauru-full-report
2. SPC and Government of the Republic of Nauru, *Nauru 2021 population and housing census - Analytical report*. 2023 SPC: Noumea, New Caledonia; Available from: https://sdd.spc.int/news/2023/08/23/nauru-2021-population-and-housing-census-analytical-report
3. FAO, *Country Reports: The State of Nauru's Biodiversity for Food and Agriculture.* 2019; Available from: https://openknowledge.fao.org/server/api/core/bitstreams/6692d0ca-5baf-4cf5-bc11-c161bede17c5/content
4. Government of Nauru, *Convention on Biological Diversity Sixth National Report of Nauru.* 2019 Department of Commerce, Industries & Environment; Available from: https://www.cbd.int/doc/nr/nr-06/nr-nr-06-en.pdf
5. Thammin, R., F. Fosberg, H. Manner, and D. Hassall, The Flora of Nauru. *Atholl Research Bulletin,* 1994(No. 32).
6. Fenner, D., *Nauru* in *World Seas: An Environmental Evaluation*. 2019, Elsevier. p. 793-805.
7. Hambruch, P., *Nauru* Ch in *Results of the South Sea Expedition- Ethnography: B Micronesia. Vol 1.* , G. Thilenius, Editor. 1914, https://www.tandfonline.com/doi/full/10.1080/00223340701692007
8. Department of Climate Change and National Resilience. *Higher Ground initiative*. 2024 Available from: https://www.climatechangenauru.nr/higher-ground-initiative.
9. 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. Available from: https://nauru-data.sprep.org/system/files/Lovell%20etal_2004_Status%20of%20coral%20rees%20in%20the%20SWPacific.pdf

10. Republic of Nauru, *Government gazette. Fisheries Act* 2018; Available from: http://ronlaw.gov.nr/nauru_lpms/files/gazettes/2c13c54f855ce8a21b9de1629c9e96e6.pdf
11. Madden Hof CA, Riskas KA, Jensen MP, Hamilton RJ, Pilcher N, Gaos AR, and Hamann M, *Assessment of the conservation status of the hawksbill turtle in the western Pacific Ocean region.* 2022 CMS Technical Series No. 45; Available from: https://wwfint.awsassets.panda.org/downloads/hawksbill_assessment_western_pacific_report_complete__1_.pdf
12. Hays, G.C., J.-O. Laloë, J.A. Mortimer, A. Rattray, J.J. Tromp, and N.J.S.A. Esteban, Remote submerged banks and mesophotic ecosystems can provide key habitat for endangered marine megafauna. 2024. 10(8): p. eadl2838. DOI: https://doi.org/10.1126/sciadv.adl2838
13. 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
14. 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.
15. 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. DOI: https://doi.org/10.1016/j.gloplacha.2021.103680
16. 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. DOI: https://doi.org/10.1890/10-0107.1
17. Standora, E.A. and J.R. Spotila, Temperature dependent sex determination in sea turtles. *Copeia,* 1985: p. 711-722. DOI: https://doi.org/10.2307/1444765
18. 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. Available from: https://www.int-res.com/articles/esr2009/9/n009p033.pdf
19. 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: https://doi.org/10.1016/j.cub.2017.11.057
20. 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.
21. 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. DOI: https://doi.org/10.1038/nclimate3399
22. 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
23. 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
24. 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. DOI: https://doi.org/10.1038/nclimate1122
25. 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). DOI: https://doi.org/10.1029/2008GL036282
26. 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. DOI: https://doi.org/10.1073/pnas.0804478105
27. Cooley, S.R., H.L. Kite-Powell, and S.C. Doney, Ocean acidification's potential to alter global marine ecosystem services. *Oceanography,* 2009. 22(4): p. 172–181. DOI: https://doi.org/10.5670/oceanog.2009.106
28. 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. DOI: https://doi.org/10.1007/s00338-003-0331-4
29. 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 19 Land management and rehabilitation

Land management

Nauru does not have a building code. This has resulted in land clearing for housing, with associated biodiversity impacts, for example noddy birds are now nesting along the coast instead of inland in the escarpment trees (Inception meeting, Pers Comm, July 2024).

Land is owned by 12 different clans/groups and land-use needs to be negotiated and compensated. Most of the land (> 90 %) is owned on a customary basis. The Land Portion 230, and a few other parcels, is owned by the government [1].

Currently stored in a pile (quantity ~100,000 tonnes) is the ~10 inches of topsoil that was removed from Topside prior to mining (inception meeting, Pers Comm, July 2024). This is planned to be reclaimed for agricultural purposes during the Higher Ground Initiative, noting it may not be adequate to rehabilitate the entire area.

There is a market for limestone as armour rock for low lying islands, and Nauru has exported limestone to the Marshall Islands and Tuvalu. The rock from the Topside does not contain salt, so it has a broader range of uses. For example, rocks are treated with epoxy to prevent salt leaching when used in building to prevent rusting of nails. The price of the limestone rock (US$30/ tonne) for export is around half the price of phosphate (USD$50/tonne). The price paid for local use is AUD$60/ tonne (USD$40/tonne). More than 50 million tonnes of limestone rock from the Topside pinnacles have been used for the airstrip, port and other infrastructure (Inception meeting, Pers Comm, July 2024).

Land Rehabilitation: Nauru's Higher Ground Initiative

The Higher Ground Initiative (HGI) (https://www.climatechangenauru.nr/higher-ground-initiative) is an important project. It has been proposed as a priority by the Nauru Government to increase Nauru's resilience to climate change by relocating housing and critical infrastructure inland, to the 'Topside' area [2]. The HGI incorporates sustainable development with the aim to provide multiple mitigation and adaptation co-benefits including land rehabilitation, food security, water security, health and wellbeing.

The HGI was launched in 2021 and is undergoing consultation and documentation. Extensive feasibility studies were conducted to ensure a solid basis for the project, e.g. [3, 4]. Currently, the project is in its engineering phase with the completion date dependent on funding [26]. The timeline for the project's completion is estimated to be between 2030 and 2035 [3]. The implementation process for development of a pilot project on a government owned 10-hectare tract of land, known as Land Portion 230 (LP230), was commenced in September 2023 and is ongoing (Figure 19-1). Future plans are to expand beyond the government owned land to a potential new township adjacent to the port as part of a comprehensive island-wide master plan. The site would link the eastern part of Nauru to the western part of Nauru.

---

[26] The HGI was endorsed by Cabinet in 2021 and was given a timeline of five years until completion. However, due to resource and funding constraints, there has been a delay in completing the project, but the Government is eager to put together a coalition of partners who will work together to fund it.
One of the funding mechanisms that the Government is hoping to access climate financing from is the Green Climate Fund (GCF). Currently, Nauru does not have a Direct Access Entity to the GCF, which is something the current Nauru Readiness II Project is working to change. https://www.sprep.org/news/rebuilding-nauru-the-island-nations-ambitious-climate-change-adaptation-plan

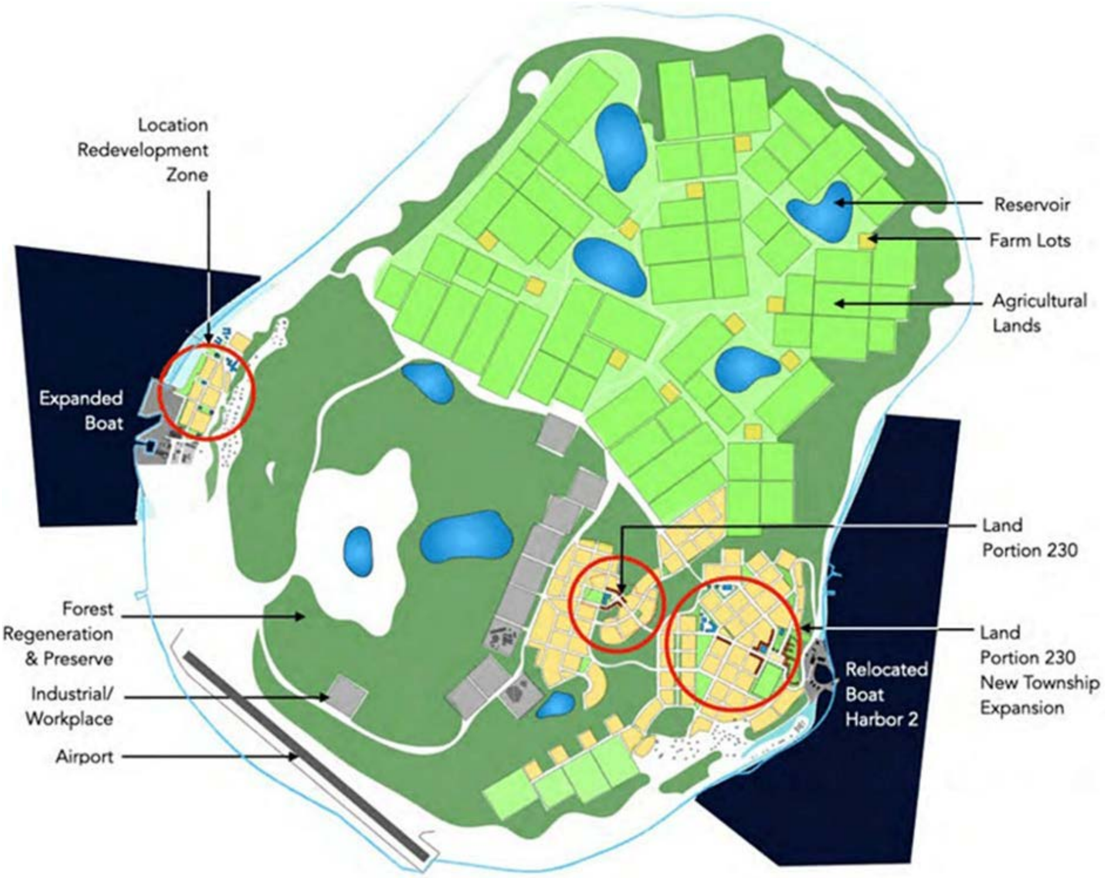


Figure 19-1 Nauru's planned new HGI development project (Source: [2])

The 11 Pillars of the Higher Ground Initiative are listed in Figure 19-2.

Economic Diversification

- Access to finance for new businesses or housing
- Government/private investment in public services and infrastructure (roads, schools, hospitals, water, sanitation) through $ and siting.

Energy Security

- Basis for land use and spatial planning
- Clear basis for planning and projecting demand
- Siting and access negotiation for key infrastructure

Public Health

- Tenure security promotes healthy environments, mental health and social cohesion, particularly in urban areas*.
- Land information supports emergency services, infrastructure development, siting and demand planning.

Affordable Green Housing

- Housing access, affordability and resilience to disaster.
- Facilitate land dispute resolution
- Facilitate land use planning, optimal siting, service provision and sustainability.

Food Security

- Protection of land and marine environments, improving soil and water quality.
- Mixed land uses to promote land productivity
- Spatial data supports mitigation of climate impacts

Environmental Restoration

- Mechanisms that protect and conserve land and marine areas
- Pollution controls, coastal and tidal protections
- Clear responsibilities for rehabilitation and management, recognising trad. knowledge.

Education and Training

- Tenure security can lead to better educational outcomes for children.
- Enhanced GIS and spatial information capacity can lead to new business areas and support ag., marine and other industries

Water Security

- Planning and provision of key infrastructure and services
- Controls to protect water sources and prevent pollution
- Spatial data can support monitoring of water supplies and usage

Cultural Restoration

- Identify and manage data and appropriate tenures for cultural site protection
- Support traditional connections and relationships to land.

Good Governance

- Fewer land disputes, greater process transparency and fewer infrastructure project delays
- Geater ability to identify un/under-utilized land, financing of municipal service provision

Low/Zero Emissions Transport

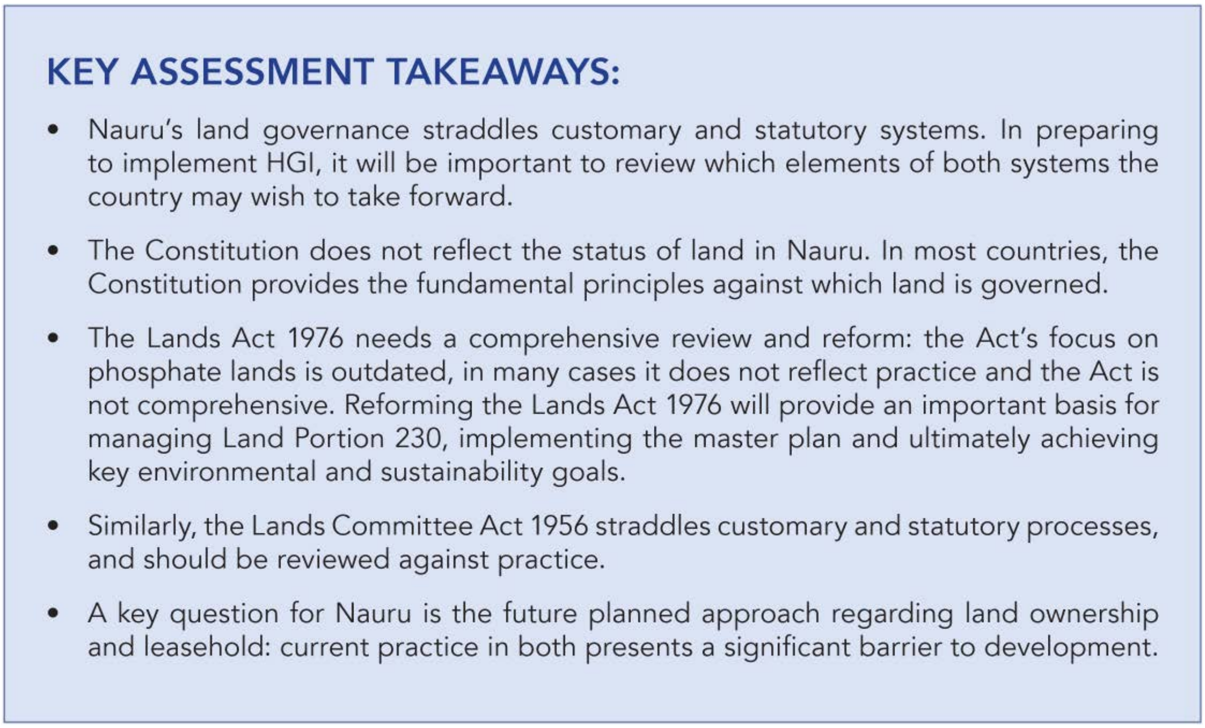
- Planning support for infrastructure planning, route planning, investment in public transport options

Figure 19-2 Eleven pillars of the Higher Ground Initiative [1].

However, the HGI is reliant on:

- Restoration of the interior, including removing the coral pinnacles resulting from phosphate mining [5].
- A thorough evaluation of land governance structure in order to effectively execute the HGI. The Constitution and Lands Act of 1976, along with the Lands Committee Act of 1956, require evaluation (see Figure 19-3).
- A housing strategy and an evaluation of land succession customs. Comprehensive direction and legal regulations are necessary for the transfer of land, leasing agreements, land appraisal, and urban planning.
- Investment in government staff and infrastructure. Development of a policy framework for land conveyancing is needed to facilitate a functioning land market that will allow the HGI vision to be fully implemented; as with the master plan, this framework should include broad consultation, with clear recognition of custom as well as the legal environment.

- Rehabilitation, which has been slow and costly, estimated to be approximately AUD$1million per hectare per year in 2020 [3].
- The facility functioning as a base for water and energy production, housing a sewage treatment plant and modern reticulated water system (see [6, 7]).



KEY ASSESSMENT TAKEAWAYS:

- Nauru's land governance straddles customary and statutory systems. In preparing to implement HGI, it will be important to review which elements of both systems the country may wish to take forward.
- The Constitution does not reflect the status of land in Nauru. In most countries, the Constitution provides the fundamental principles against which land is governed.
- The Lands Act 1976 needs a comprehensive review and reform: the Act's focus on phosphate lands is outdated, in many cases it does not reflect practice and the Act is not comprehensive. Reforming the Lands Act 1976 will provide an important basis for managing Land Portion 230, implementing the master plan and ultimately achieving key environmental and sustainability goals.
- Similarly, the Lands Committee Act 1956 straddles customary and statutory processes, and should be reviewed against practice.
- A key question for Nauru is the future planned approach regarding land ownership and leasehold: current practice in both presents a significant barrier to development.

Figure 19-3 Key points summarised from the Land Tenure and Social Safeguarding report developed for the HGI (Source: [1]).

Climate hazard related impacts

Extreme Temperature

Heat stress reduces worker productivity, which may hamper land rehabilitation. Projected increases in extreme temperature will exacerbate this risk.

Extreme Rainfall

Extreme rainfall and flooding affect site access and worker safety. Projected increases in extreme rainfall will exacerbate this risk.

Drought

Drought affects access to water for building construction, e.g. cement preparation. Projected decreases in drought frequency, intensity and duration may reduce this risk.

References

1. Department of Climate Change and Natural Resilience, *Higher Ground Initiative - Land Portion #230*. 2022 The Government of the Republic of Nauru; Available from: https://issuu.com/civicurban/docs/land_tenure_social_safeguarding
2. Department of Climate Change and National Resilience. *Higher Ground initiative*. 2024 Available from: https://www.climatechangenauru.nr/higher-ground-initiative
3. Allis, M., S. Williams, and S. Wadwha, *Coastal flooding from sea-level rise in Nauru: Stage 1 - static inundation mapping, Prepared for the Nauru Higher Ground Project*. 2020: Prepared for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited. Available from: https://nauru-

data.sprep.org/system/files/Nauru_Coastal_Inundation%20with%20SLR_final%20-%20Oct%202020%20reduced%20%281%29.pdf

4. Bosserelle, C. and S. Williams, *Coastal flooding from sea-level rise in Nauru: Stage 2 - wave inundation mapping, Prepared for the Nauru Higher Ground Project*. 2023 Prepared for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited: Christchurch, NZ.
5. SPC and Government of the Republic of Nauru, *Nauru 2021 population and housing census - Analytical report*. 2023 SPC: Noumea, New Caledonia; Available from: https://sdd.spc.int/news/2023/08/23/nauru-2021-population-and-housing-census-analytical-report
6. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Water Supply System Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor.
7. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Sanitation System Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor.

Chapter 20 Community and culture

A review of Nauru prior to European discovery is given in the climate vulnerability assessment (relating to this CIVRA Hazards report), noting tradition teaches that its early history was one of inter-tribal warfare [1]. There were traditionally 12 clans or tribes on Nauru; these are represented in the 12-pointed star in the nation’s flag (Figure 20-1).

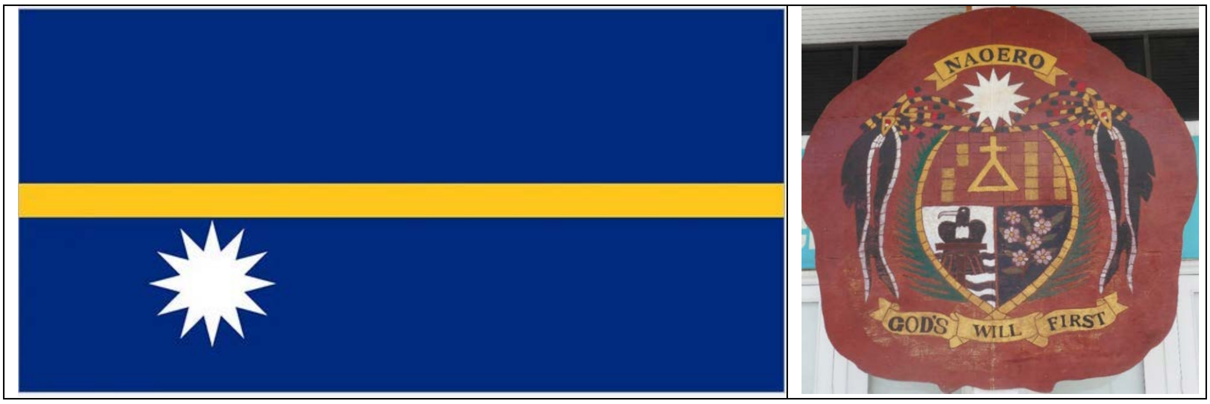


Figure 20-1 Nauru’s flag: The background is blue for the Pacific Ocean, and the yellow horizontal stripe stands for the Equator, which lies less than one degree north of Nauru. The location of the island is reflected by the white star located below the stripe (left). Coat of arms (right). Photo credit: CSIRO, 2024.

From the 19th century onwards, Nauru increasingly encountered Europeans including whalers, German administration and missionaries, phosphate mining, and two world wars [2]. This brought large numbers of contractors who outnumbered Nauruans [3]. During the Japanese occupation, 1,201 Nauruans were sent to Truuk (now Chuuk in the Federated States of Micronesia) where they suffered hardship, with over 40 % dying and only 745 (mostly young) Nauruans repatriated at the end of the war. At the beginning of the war, the Nauruan population was 1,848 but, by the end, it was 1,278, a reduction of approximately 30 % [2]. Through mining, by 1992 there were 70 % foreigners, and only 30 % Indigenous Nauruans. As reported in the 2021 census, 92.1 % of the population were born in Nauru, with ex-patriates leaving as phosphate mining declined [2]. Much war paraphernalia and other relics are displayed in the Nauru museum and cultural centre (Figure 20-2), with the developing tourism sector offering tours of World War 2 relics including guns, cannons and bunkers.

Figure 20-2 Nauru museum (left) and traditional canoe carving (right). Photo credit: CSIRO, 2024.

Through these historic events, much traditional knowledge was lost (Inception meeting, Pers Comm, 2024). During the 20th century, harsh regulations were applied by administrators on the practice of Nauru culture, for example the Native Dancing Regulations of 1936 which had the effect of restricting the practice of traditional dancing (Pers Comm, August 2024). Physical removal and damage of cultural sites also occurred; two major hillocks that represented the landing place of Nauruan founding ancestors, attributed with spiritual meaning and managed with reverence, were removed during the mining [3]. Milkfish (Ibiya) has an important place in Nauruan culture and is linked to pregnancy and puberty festivals, as well as the Ibia dance (Pers Comms, August 2024; [1]).

The revival and strengthening of community and culture provides an opportunity to build resilience and adaptation to climate risks (Pers Comms, July 2024). Traditional knowledge and practices for the cultivation and use of a relatively limited range of plants and animals on land and inshore marine resources have proven to be valuable social assets for survival in the harsh conditions of Nauru's environment in the past. These have been revived more recently to support food and livelihood security during the downturn of the country's economy in modern times. Traditions such as noddy bird collection, bird catching, aqua-farming and traditional medicines and taboo lands still exist though much of the traditional knowledge has been lost. Reviving these practices will require significant efforts in research and education [4]. For example, loss of cultural plants like pandanus has resulted in difficulty accessing resources to practice weaving, and the number of Nauruan weavers has declined (Pers Comms, August 2024).

The educational infrastructure in Nauru consists of four early childhood centres, three primary schools and two public secondary schools. From ages 5 to 11 attendance was roughly constant (~80 %). At age 11, attendance was 83 % of all people at school, but it was only 72 % at age 14, and declined further to less than half of the population aged 17 [2] (Figure 20-3). Almost 5 % of people – 135 males and 168 females – had a tertiary qualification, such as a matriculation certificate, other certificate, diploma, or undergraduate or post-graduate degree [2].

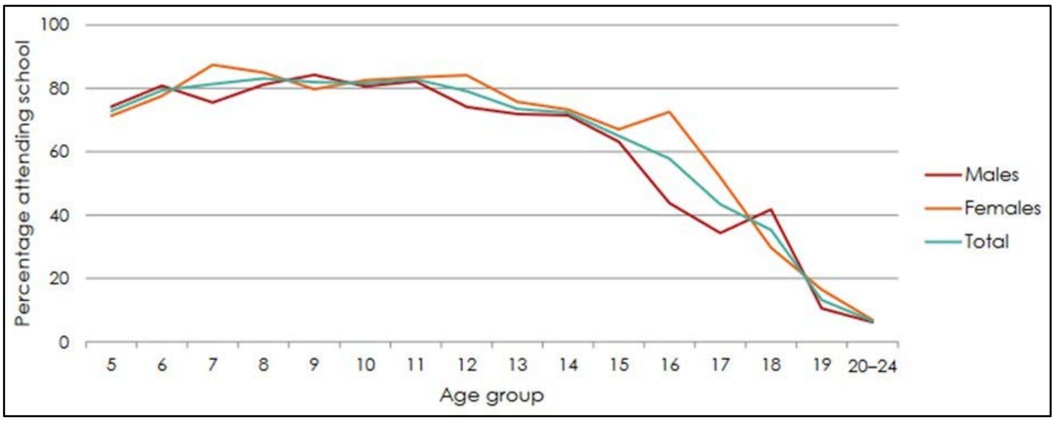


Figure 20-3 Percentage of the population aged 5–24 by age and sex attending school, Nauru: 2021 [2].

The adult literacy rate (reading and writing in any language) for the population 15+ years was very high; 89.6 %. The labour force participation rate was calculated at 67.0 % in 2021. The most common occupation in Nauru is in administrative and support, with the proportion in all activities indicated in **Error! Reference source not found.** [2].

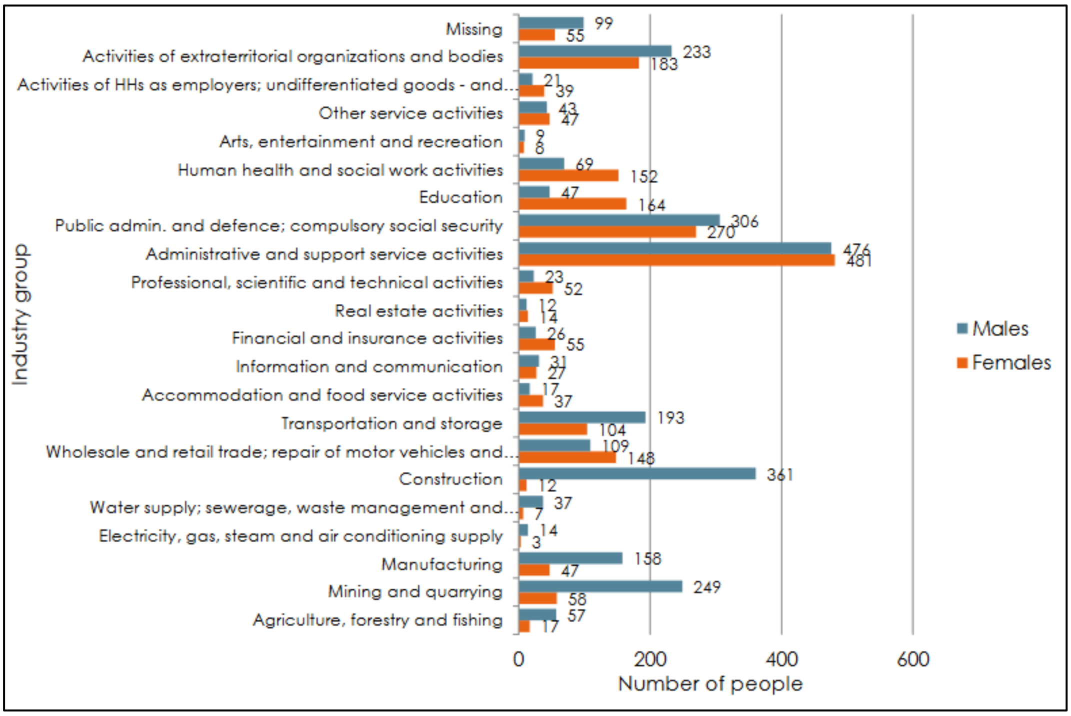


Figure 20-4 Employed population by gender and industry, Nauru: 2021

The average household size is 5.8 people. The highest average household size was recorded in Anetan, with 6.7 people per household on average, followed by Boe and Ewa, with 6.5. The lowest household sizes were found in Location (4.8) [2], with almost 60 % of heads of household in Nauru were men. During the three months before the 2021 census, 89.2 % of households received wages or salaries, 36.2 % had income from land lease, 12.2 % received pensions or retirement benefits, 12.1 % had income from their own business, and 8.3 % received income from rents of houses or flats. Note that households can have more than one source of income [2].

In 2021, the Nauruan Congregational Church was the dominant religious denomination in Nauru, with 34.3 % (4,001), next was Roman Catholic Church with 3,959 members (33.9 % of all denominations), then Assemblies of God with 1,365 members (11.7 %) affiliated with this church [2].

Figure 20-5 Nauruan Congregational Church. (Photo credit: L Webb, CSIRO, 2024)

Fishing was the most common activity (29.6 % of all households), particularly in Anetan (52.5 %), Ewa (48.8 %) and Denigomodu (46.7 %). The second most common activity was noddy bird catching

(9.5 %), which was particularly common in Anetan (28.0 %) and Denigomodu (26.7 %). The other activities were raising livestock (7.9 %), particularly in Anetan (24.6 %), growing food crops (5.2 %), growing fruits (4.9 %) and handicraft production (2.9 %), especially in Ewa (12.2 %) [2].

Climate hazard related impacts

Extreme temperature (as for Health and well-being section)

Heat-related stress and deaths could increase under a warmer climate and unfavourable socio-demographic conditions [5, 6]. Extreme heat directly impacts local communities, causing increased morbidity [7] and can exacerbate existing human health conditions especially for those with respiratory and cardiovascular diseases and diabetes where indoor temperatures are elevated above 26 °C [8], particularly in the absence of a cool refuge (e.g. no air conditioning). Extreme heat is also associated with deaths [6]. For each 1 °C increase in temperature, there exists a statistically significant increase in the risk of mental health-related morbidity [9], associated with increased hospital admissions [10]. 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 [11].

Under extreme heat, the reduction in productivity affects business continuity, water security, food security, infrastructure development, and health [5, 12, 13]. Evidence of heat stress has been reported for airport workers in Nauru (Inception meeting 2024, Pers Comm). Additionally, increasing temperature has reduced the amount of outdoor activities Nauruan's are undertaking (Pers Comm: Inception meeting, 2024) with a preference to remain indoors to avoid the heat. This could have flow on impacts for opportunities to exercise and efforts to reduce the incidences of NCDs.

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 since 1951 [14]. If energy demand exceeds energy capacity, blackouts may occur, so there may be inadequate cooling for businesses and communities, increasing the risk of heat-stress.

Drought

During drought periods, some of the population access the groundwater. This water has lower quality than RO water or harvested rainwater because of saltwater contamination and leakage from domestic sewage pits. Alternative strategies for sustainable use of groundwater must be accompanied by sewage infrastructure design, monitoring activities and well-head protection areas [15, 16]. A new sewerage system is being planned for Nauru [17, 18].

Community gardens are negatively impacted by drought because water is prioritised for human consumption (Inception meeting, Pers comm, 2024). More than 70 % of households reported that their water supply dried up sometimes or frequently [2], particularly during drought [15, 16]. Poor guttering and downpipes [2] exacerbate lack of reliability of water in rainwater tanks. Water shortages during drought periods can cause anxiety and related mental health impacts.

Figure 20-6 Collecting rainwater. (Photo credit: L Webb, CSIRO)

Extreme rainfall

Flooding can cause damage and loss to property and infrastructure. Critical services can be disrupted, such as health, transport, electricity, telecommunication, and waste management.

Figure 20-7 Floods affecting roads. (Photo credit L Webb, CSIRO 2024)

Flooding can also have impacts on water quality due to overflow of septic systems [18]. Extreme rainfall may impact houses with some of the roofs potentially leaking through poor roofing materials or roof maintenance. In Ijuw 8.2 % and Uaboe 5.3 % have houses with a wooden roof [2].

Sea level rise

Some residences are already experiencing inundation from sea level rise (SLR). In Nauru, the population currently exposed to spring tide flooding is 46 people, but this increases to 335 for 0.5 m SLR, 757 for 1.0 m SLR, and 1,988 for 2m SLR [19].

There is significant variability between districts at all SLR increments, from no exposure (Denigmodu) to 45 % exposed after 0.5 m SLR (Anibare) [19]. After the 0.5 m SLR the exposure can be grouped as:

- 0-10 people exposed: Aiwo, Anetan, Baiti, Boe, Denigmodu, Nibok, Uaboe.
- 10-100 people exposed: Anabar, Anibare, Buada, Ewa, Ijuw, Yaren.
- 100-1000 people exposed: Meneng.

The total population exposed to wave inundation on high spring tides at present is 108. This rises to 1,171 and 4,137 for wave inundation with 1 m and 2 m SLR respectively. Anabar, Anibare, and Meneng are the districts with the largest proportion of population exposed for all SLR scenarios [20].

Bomb shelters located along the coast have been impacted by coastal erosion, with spring tides potentially further destroying these relics (Pers Comm, August 2024), subsequently affecting developing tourism opportunities and potential income sources for Nauruans.

References

1. Hambruch, P., *Nauru* Ch in *Results of the South Sea Expedition- Ethnography: B Micronesia. Vol 1.* , G. Thilenius, Editor. 1914, https://www.tandfonline.com/doi/full/10.1080/00223340701692007
2. SPC and Government of the Republic of Nauru, *Nauru 2021 population and housing census - Analytical report*. 2023 SPC: Noumea, New Caledonia; Available from: https://sdd.spc.int/news/2023/08/23/nauru-2021-population-and-housing-census-analytical-report
3. Pollock, N.J., Nauru Phosphate History and the Resource Curse Narrative. *Journal de la Société des Océanistes,* 2014. 138(139): p. 107-120. Available from: https://nauru-data.sprep.org/system/files/pollock.pdf4. FAO, *Country Reports: The State of Nauru's Biodiversity for Food and Agriculture.* 2019; Available from: https://openknowledge.fao.org/server/api/core/bitstreams/6692d0ca-5baf-4cf5-bc11-c161bede17c5/content
5. 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. DOI: https://doi.org/10.1289/ehp.15097
6. 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. Available from: https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(21)00081-4/fulltext
7. Franchini, M. and P.M. Mannucci, Impact on human health of climate changes. *European journal of internal medicine,* 2015. 26(1): p. 1-5. DOI: https://doi.org/10.1016/j.ejim.2014.12.008
8. 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
9. 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. . DOI: https://doi.org/10.1016/j.envint.2021.106533
10. 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
11. 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
12. 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. DOI: https://doi.org/10.1038/nclimate2623
13. 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. DOI: https://doi.org/10.1108/BEPAM-03-2022-0040

14. 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
15. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Water Supply System Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor.
16. Alberti, L., M. Antelmi, G. Oberto, I. La Licata, and P. Mazzon, Evaluation of fresh groundwater Lens Volume and its possible use in Nauru island. *Water Research,* 2022. 14(20): p. 3201. DOI: https://doi.org/10.3390/w14203201
17. NSRUDP, *Nauru : Sustainable and Resilient Urban Development Project (plan)*. 2024 ADB; Available from: https://www.adb.org/projects/54377-002/main
18. Beca Tonkin and Taylor, *Nauru Sustainable Urban Development Phase 1: Sanitation System Subproject Master Plan, Prepared for Government of Nauru*. 2023 Beca, Tonkin and Taylor,.
19. Allis, M., S. Williams, and S. Wadwha, *Coastal flooding from sea-level rise in Nauru: Stage 1 - static inundation mapping, Prepared for the Nauru Higher Ground Project*. 2020: Prepared for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited. Available from: https://nauru-data.sprep.org/system/files/Nauru_Coastal_Inundation%20with%20SLR_final%20-%20Oct%202020%20reduced%20%281%29.pdf
20. Bosserelle, C. and S. Williams, *Coastal flooding from sea-level rise in Nauru: Stage 2 - wave inundation mapping, Prepared for the Nauru Higher Ground Project*. 2023 Prepared for: New Zealand Ministry of Foreign Affairs and Trade The Government of the Republic of Nauru, and Calibre Group Limited: Christchurch, NZ.

Summary

Table 20-1 Climate hazards affecting sectors in Nauru based on RONAdapt priority areas Water, Health, Agriculture, Fisheries & marine resources, Disaster management, Energy, Land management & rehabilitation, Infrastructure and coastal protection (includes telecommunication and transport), Biodiversity, Education & human/community development.

Hazard	Water	Health and wellbeing	Agriculture	Fisheries & marine resources	Disaster Management and Emergency Response	Infrastructure and coastal protection (includes energy, transport, telecommunication and waste management)	Land management and rehabilitation	Biodiversity and environment	Community and culture
Extreme temperature	Increased water demand and evaporation Reduced efficiency in desalination plant operations.	Increased heat stress and reduced labour productivity for outdoor workers and vulnerable people. Increased enteric infections. Mental health disorders. If blackouts occur, there may be inadequate cooling and impact critical health services, particularly during surgery. Surges caused in blackouts can damage medical equipment. Reduced opportunity and incentive for outdoor exercise with cascading impacts on efforts to reduce NCDs.	Animal and crop suitability/ stress. Reduced labour productivity.	Fish refrigeration and storage.	Blackouts can cause cascading and compounding impacts across multiple sectors	Road and runway integrity potentially affected. Heat stress reduces labour productivity (e.g. airport and road crews). Disruption to telecommunications due to heat-related blackouts). Increased energy demand for air conditioning and fans. Greater risk of blackouts.	Slower progress due to reduced labour productivity.	Heat stress and mortality for some animals and plants. Warmer sand temperature can affect gender ratios for turtle hatchlings.	Heat stress for trainees and students. Success of kitchen gardens compromised by heat. Reduced labour productivity in communities. Increasing temperatures reduce community movements during the middle of the day and increase reliance on car transport to avoid exposure.
Extreme rainfall	Poor water quality due to high sediment and pollution load in streams. Filling of water-tanks means reduced reliance on desalinated water. Damaged storage, treatment and drainage systems	Flood-related damage to main hospital and disruption to health services. Water-borne diseases (rotavirus in children) from overflow of septic tanks. Trauma and mental health disorders. Reduced ground water quality. Improved access to tank water for WASH. Increased hospital admissions due to asthma placing increased pressure on health services.	Reduced access to crops and farms. Flood damage.	Increased pollution and sediment entering coastal waters can harm coastal fisheries and coral reefs	Flood damage and disruption to property and infrastructure. Poor water quality. High demand for emergency response and recovery services. Major impacts on the economy. Reliance on international aid.	Flooding damage to roads, bridges and runway. Road integrity affected by potholes (top side and private land). Disruption to port operations due to low visibility. Sediment and debris in drainage systems Communication systems direct damage or capacity overload during flood disasters Flood-related damage to energy infrastructure. Cloudiness reducing the effectiveness of solar panels.	Flood damage to land rehabilitation sites. Changes in flood risk have implications for land management (e.g. flood zones).	Increased pollution and sediment entering Buada Lake, streams and coastal waters. Indigenous plants regrow following periods of rainfall	Transport disruption for trainees and students. Flood-related damage to energy infrastructure.

Drought	Increased demand for desalinated water increasing pressure on delivery trucks. Greater use of poor-quality groundwater. Reduced availability of fresh food sources and increased reliance on imported processed food.	Increase use of poor-quality ground water for sanitation and hygiene.	Limited water for crops and livestock. Reduction in free food sources and mortality of important cultural foods. Increased reliance on imported food sources.		Fewer flood-related demands for disaster management. Increased risk of fires and greater reliance on desalinated water to extinguish fires	Less flood damage. Less rain interruption to repairing and maintaining transport infrastructure. Fibre cable and power pole cross arms affected by salt spray and causing blackouts. Communications support structures can rust. Extra power needed to run desalination plant.	Less rain interruption to land rehabilitation. Increased mortality rate of seedlings. Increased dust from rehabilitation works and secondary mining.	Water stress for plants and animals.	Stress and die back of cultural plants (pandanus). Success of kitchen gardens affected by water availability and cost of desalinated water. Schools close due to lack of water
Sea level rise and coastal inundation	Contamination of freshwater lens. Greater demand for desalinated water. Damage to water infrastructure.	Damage to hospitals and health services located in low-lying coastal areas. Increased distribution and transmission of vector-borne disease, threats to physical safety, and mental stress.	Inundation of crops.	Increased coastal erosion affects ports/ boat moorings.	Saltwater damage to property and infrastructure, especially at spring and king tides (which are highest spring tides). High demand for emergency response and recovery services. Major impacts on the economy. Warnings for communities not to swim at beaches during king tides.	Inundation affecting roads. Coastal erosion undermining roads. Damage to telecommunication infrastructure. Greater energy demand for desalinated water due to saltwater contamination of freshwater lens.	Disruption and damage to rehabilitation areas due to inundation and erosion.	Habitat damage. Traditional plant (Emit shrub) used to stabilise coast during high tides i.e. in Aneatan.	Disruption for trainees and students, especially at spring and king tides.
Ocean temperature and marine heatwave				Good tuna fishing grounds could be displaced further eastward. Decrease in coral fish biomass. Algal blooms can cause fish deaths.	Fish kills			Reduced biodiversity. Coral bleaching and stress for invertebrate species.	
Ocean pH				Coral integrity. Invertebrate species skeletal structure compromised. Algae growth.				Reduced biodiversity	
Aragonite saturation				Coral, plankton, shellfish, and fish skeletons' integrity reduced.					

Chapter 21 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 21-1).

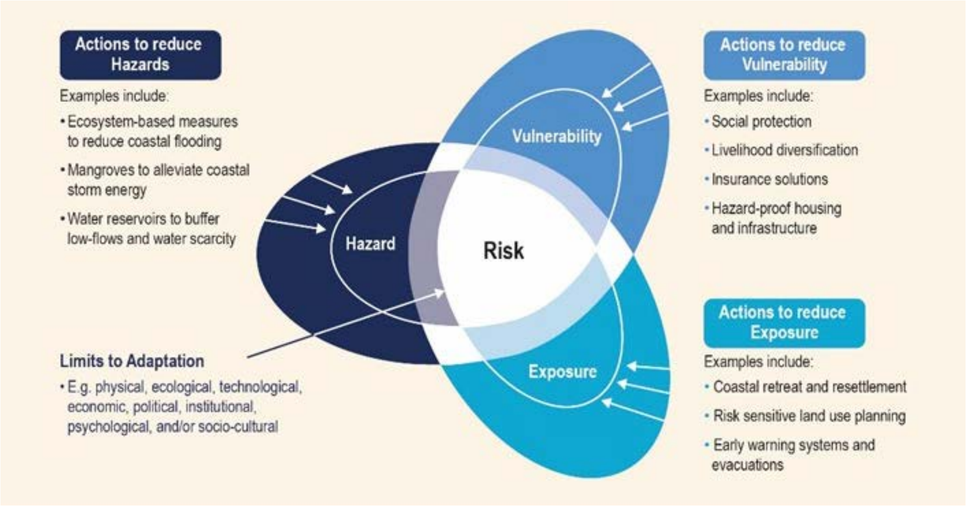


Figure 21-1 Risk is derived from the combination of hazard, exposure and vulnerability. Source: [1]

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].

Vulnerability and exposure for Nauru are described in a separate report (Melbourne University, 2024). Key points include:

- Fishery licencing contributes about 20 % of Nauru’s revenue.
- Of the 30 % of households involved in fishing, 72 % did so for subsistence.
- Nauru has one of the Pacific’s lowest subsistence food production levels.
- 90 % of food is imported, with significant health-related impacts.
- 49 % of households are unable to eat healthy or nutritious food over a 12-month period.
- 40 % of residents have type 2 diabetes.
- E-coli outbreaks are common due to poor quality of groundwater and septic systems.
- There is only about 4 km^2 of arable land on Nauru.
- Less than 10 % of households have some form of home garden.
- There is no major livestock farming (7 % of households have pigs, 2 % have chicken, 9.5 % hunt Noddy Birds).
- Most of Nauru’s forest and woodland has been removed or intermingled with about 160 invasive species.
- There are endemic native birds (Reed Warbler, Black/Brown Noddy) and reptiles (skinks).
- Conservation hotspots include Buada Lagoon (a national conservation site), Ewa Wetlands and Ijuw-Anabar Wetlands.

- Key assets include the National Hospital, Port Facility, Airport Runway and Ring Road.
- Desalinated water is used in 12.6 % of households when water is scarce.
- 88.5 % of households use gas for cooking and 10 % use electricity.
- 62 % of households reported that their main water supply was disrupted sometimes, and 8 % reported frequent disruption.
- Nauru's national water storage capacity is 8 days. 96 % of households had some form of water storage. 76 % of rainwater tanks hold 3,000-10,000 litres. 21 % of households have more than 10,000 litres water storage, and 3 % had less than 3,000 litres.
- Almost 1/3 of households have no guttering. Of those with guttering, 35 % need repair.
- 44 % of households use ground water for washing, bathing and gardening. Water from most groundwater wells does not meet WHO drinking-water standards.
- 53 % of households have septic-piped flush toilets. 30 % share toilet facilities with another household.
- 20 % of households had a least 1 bicycle, 69 % had at least 1 motorbike, and 42 % had a car.
- At age 11, school attendance was 83 % of all people at school, 72 % at age 14, and less than 50 % at age 17. Almost 5 % of people had a tertiary qualification.
- The average household size is 5.8 people.
- Rainwater tanks are used by 37 % of households for drinking water
- 49 % of households depend on tanker trucks to deliver desalinated water. Only 70 % of water deliveries can be made in the month that they are ordered by customers.
- The coastal plain is exposed to king-tide inundation and sea level rise. Most of Nauru's coastline is without seawalls.
- Infrastructure located within 100 m of the coast accounts for 34 % of the total asset number and 40 % of the total infrastructure replacement value. Critical infrastructure, including the power station, roads, schools, and hospitals are located in low-lying coastal areas.
- Extreme rainfall causes flooding, particularly if the drains are not well maintained.
- The port is considered unsafe if swell waves over 0.5 metre wash into the narrow dock.
- Components of the hazard early warning system are at a moderate to low level of development.
- The most common source of energy is butane gas. Solar power is integrated into the grid and uses Battery Energy Storage Systems to compensate for loss or outages.
- Northern freshwater lens is 7 m thick and resilient to saltwater intrusion and drought. Southern freshwater lens is 3.5 m thick and resilient to saltwater intrusion. Central Topside water is mostly brackish.
- 22 % of households do not have air conditioning (A/C), and 13.5 % of households do not have A/C or a ceiling fan.
- Topside's degraded state is a limitation for adaptation. The Higher Ground Initiative is a key rehabilitation process.
- 92 % of the population identifies with one of 12 Tribes.
- 98 % of households have mobile phone access, but 20 % do not have internet access.

Climate hazards

A summary of climate hazards (Table 21-1) is provided for the historical climate (20-year period centred on 1995) and the future climate (20-year periods centred on 2030 and 2050) for low emissions (SSP1-2.6) and high emissions (SSP5-8.5) pathways. Uncertainty ranges and confidence levels are included (Chapter 2 provides more detail). There is high confidence that temperature, sea level, marine heatwaves and ocean acidification will increase. There is medium confidence in an increase in annual average rainfall, a decrease in droughts, and an increase in extreme rainfall intensity. There is low confidence in wind and wave changes.

Information about current vulnerability and exposure has been summarised for priority sectors in Table 21-2. Information about current climate hazards is also summarised, along with hazard ratings based on expert judgement. Projected changes in hazards from Table 21-1 alter the hazard ratings in future (Table 21-2). These hazard ratings are intended to provide science-based evidence to inform the integrated risk assessment for the Nauru CIVRA project (Deloitte Risk Report, 2024). The risk ratings are also based on the hazard ratings below and exposure/vulnerability ratings from Melbourne University Vulnerability report (2024).

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.

Table 21-1 Historical climate (20-years centred on 2005) and projected climate change for 20-year periods centred on 2030 and 2050, relative to a 20-year period centred on 2005. Changes are based on simulations from CMIP6 global climate models (GCMs) for low (SSP1-2.6) and high (SSP5-8.5) greenhouse gas emissions scenarios. For some variables, the Nauru Exclusive Economic Zone (EEZ) region is assessed, rather than the island, as indicated. Confidence ratings are based on the IPCC framework [1] involving an assessment of the amount of evidence and the degree of agreement between lines of evidence. The uncertainty range is defined as the 10-90th percentile range, shown in brackets. Drought projections are for SPI 3-month between –1.0 and –1.5 (moderate drought).

Nauru		Projected change			
20-years centred on 2005		2030 Low/High Emissions	2050	2050	
			Low emissions	High emissions	Confidence
	ATMOSPHERIC VARIABLES				
28.0 °C	Annual average temperature (°C)	+0.7 (0.3-1.3)	+1.0 (0.9-1.2)	+1.5 (1.2-2.0)	high
15 (6 to 34) days	Annual hot days (days > 32 °C) [a]	N/A	+120 (44 to 169)	+193 (69 to 242)	high
2100 mm	Annual average rainfall (%)	+11 (-19 to +39)	+13 (-1 to +52)	+24 (-6 to +63)	medium
105 mm/day	Annual maximum daily rainfall (mm/day)	N/A	+48	+54	medium
3 (0 to 5) events per 20 years	Average drought frequency (%)[d]	-33 (-77 to +100) %	-33 (-77 to +67) %	0 (-73 to +107) %	medium
	OCEAN VARIABLES				
0	Annual average sea level (cm)	+10 (7-14)	+21 (15-28)	+25 (19-33)	high
28.6 °C	Sea surface temperature (°C) over EEZ	0.2 (-1.5 to +1.6)	0.5 (-1.2 to +2.0)	1.0 (-0.9 to +2.3)	high
16 days per year	Marine heatwave frequency (days/year) [b]	N/A	105 to 140	180 to 270	high
6.3 days per year	Degree heating weeks (ave days/year) [c]	N/A	92 to 236	107 to 344	high
8.04	Annual average ocean pH over EEZ [b]	8.00 (7.96 to 8.05)	7.97 (7.92 to 8.02)	7.92 (7.87 to 7.98)	high
3.8	Annual average aragonite saturation [b]	~3.7 (3.3 to 4.0)	3.5 (3.1 to 3.98)	3.2 (2.8 to 3.7)	high

[a] number of days over the 95th percentile of 1995-2014 daily temperatures

[b] Future values are reported, not changes.

[c] Exceed coral bleaching Alert level 2.

[d] Further information on projections for drought intensity, frequency and duration can be found in Chapter 7

[e] Future values shown, not changes compared to historical.

* Little difference between low and high emissions at 2030

References

1. 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

Table 21-2 Climate hazard assessment for Nauru, based on current and future climate hazards (Table 21-1) for 2030 (when low and high emissions are similar) and 2050 for low and high emissions scenarios, noting current vulnerability and exposure. The nine sectors reflect the 11 Priority Areas in the RONAdapt framework. 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 / no data

Sector	Current vulnerability and exposure	Current hazard ratings	Climate hazard ratings		
			2030	2050	
			Low/High	Low	High
Water resources	Water demand increases under extreme heat conditions	░ Extreme temperature	▓	🟧	🟫
	Saltwater contamination of freshwater lens increases demand for desalination. Water infrastructure can be damaged by coastal inundation.	░ Extreme sea level	░	░	▒
	Pressure on water delivery truck network and groundwater resources. Greater demand for desalination.	▓ Drought	▒	▒	▒
	Floods can damage water supply/drainage infrastructure, and increased pollution/sediment can reduce water quality.	▒ Extreme rainfall	🟦 No data	▓	🟧
		░ Extreme sea level	░	░	▒
	Limited ability to capture water in household water tanks	▒ Rainfall	🟨	🟨	🟨
Health and wellbeing	Heat stress and associated health and mental-health issues due to inadequate cooling in buildings, exposure of outdoor workers and heat-related power outages	░ Extreme temperature	▓	🟧	🟫
	Food safety and medical supply issues where refrigeration is limited				
	Flood-related water-borne disease and sanitation issues due to limited water treatment and sewage treatment plants. Flood damage to hospital and disruption to health services.	▒ Extreme rainfall	🟦 No data	▓	🟧
	High exposure of communities to inundation, loss and damage in low lying coastal areas, affecting mental health	░ Extreme sea level	░	░	▒
	Exposure of health infrastructure to inundation, affecting health services				
Agriculture	Exposure of agriculture in low lying areas to coastal inundation and saltwater intrusion into soil	░ Extreme sea level	░	░	▒
	Livestock are vulnerable to heat stress. Reduced labour productivity when hot	░ Extreme temperature	▓	🟧	🟫
	Limited water for crops and livestock during droughts	▓ Drought	▒	▒	▒
	Crops are exposed to floods. Reduced farm access during floods.	░ Extreme rainfall	🟦 No data	▓	🟧
Fisheries and marine resources	Fish catch may increase or decline depending on rate of SST warming/ emission scenario. National revenue is strongly dependent on offshore fish catches and licences	▒ SST	🟦 unclear	🟨	🟫
	Household consumption is strongly dependent on inshore fisheries productivity and marine biodiversity	░ SST / MHW	▓	🟧	🟫
	Maritime safety and fishing activity for coastal fishers can be affected by high winds/waves	░ Wind speed	░	░	░

	Fish being processed may spoil in the heat without refrigeration, affecting potential sale value and suitability for consumption. Working conditions affected by high temperatures.	Extreme temperature			
	Pollution and sediments degrade coastal water quality	Extreme rainfall	No data		
Disaster management and emergency response	Lack of property protection from extreme sea level and extreme rainfall elevates disaster risk	Extreme sea level			
		Extreme rainfall	No data		
	Blackouts can cause cascading and compounding impacts across multiple sectors which increase demand for emergency services	Extreme temperature			
	Increased risk of fire, resulting in the requirement for increased firefighting capacity. As there is limited water storage on Nauru, firefighting capacity is also limited.				
	Exposure to coastal inundation in low lying areas affects essential infrastructure	Extreme sea level			
	Flood damage to roads, airport, water, energy and telecommunication facilities can disrupt emergency services	Extreme rainfall	No data		
Infrastructure and coastal protection	Roads and airport runway are exposed to coastal inundation/erosion, flooding and heat-related deterioration. Flooding may cause increased runoff/pollution to the sea	Extreme sea level			
		Extreme rainfall	No data		
		Extreme temperature			
	Telecommunication, building and coastal protection and electricity assets subject to surface flooding, coastal inundation, and groundwater intrusion	Extreme rainfall	No data		
		Extreme sea level			
	Increased energy demand and blackout risk on hot days	Extreme temperature			
	Salt spray may affect transmission wires	Drought			
		Wind speed			
Biodiversity and environment	Heat stress for some animals and plants. Sea turtle gender affected by sand temperature.	Extreme temperature			
	Declining health of coastal marine habitat such as coral reefs and lagoons	MHW and ocean acidification			
Land rehabilitation and land management	Rehabilitation areas are exposed to coastal inundation and erosion	Extreme sea level			
	Workers and community are vulnerable to heat stress	Extreme temperature			
	Rehabilitation sites may be susceptible to flood damage	Extreme rainfall	No data		
	Lack of access to water for building construction	Drought			
Community and culture	Reduced labour productivity in hot conditions	Extreme temperature			
	Rehabilitation sites may be susceptible to flood damage	Extreme rainfall	No data		
	Population and gardens are vulnerable to dry conditions and cost of desalinated water.	Drought			
	Disruption for people at school or university.	Extreme rainfall	No data		
	Community disruption, especially at spring and king tides.	Extreme sea level			

Chapter 22 Knowledge gaps and research priorities

This report has described historical and projected climate hazards that pose risks to Nauru. Confidence ratings, uncertainties, limitations and caveats have also been provided (Chapter 2), along with hazard ratings for priority sectors, incorporating aspects of exposure and vulnerability (Chapter 21). This information is being used in an integrated risk assessment (Nauru risk report Deloitte, 2024).

A few knowledge gaps have emerged. Addressing these gaps will inform research priorities to enhance the knowledge base for future risk assessments. These research priorities should be included in the Pacific Climate Change Research Roadmap coordinated by SPREP in partnership with Pacific Island countries including Nauru.

Based on knowledge gaps in the previous chapters, the following research priorities were identified:

- Enhanced monitoring of climate variability and change, including causes of trends and extreme events.
- Better information about historical links between climate hazards, exposure, vulnerability and impacts, e.g. for heat-related impacts on health and electricity demand. This would inform 'damage functions' that can be used in risk assessments and associated ‘loss and damage’ negotiations.
- Consider recording heat stress related hospital admissions.
- Better information about the effect of phosphate dust on population health.
- Better information about insect/pollinator capacity to assist with agricultural production.
- Assess impacts on coastal fishery ecosystems using clearly defined reference points to better understand current health and future sustainability.
- Assess how Buada Lagoon, and other groundwater/lagoon levels around the coastal plain, are linked to sea level variability and respond to sea level rise.
- Assess potential flooding of the airport due to the compounding effects of wave over-washing, coastal defence design, the capacity of the airport drainage system, infiltration rates, coinciding heavy rainfall and high groundwater levels.
- Selection of CMIP6 models with low biases, especially SST and ENSO biases in the Pacific.
- Dynamical and statistical downscaling of CMIP6 climate models over the western tropical Pacific.
- Gather evidence of heat stress in the community, heat related damage to infrastructure, and design standards for managing heat stress. Heat strain, characterised by thermal, cardiovascular, and renal strain, can lead to adverse health outcomes such as heat exhaustion, heat stroke, or cardiovascular collapse. New heat survivability modelling frameworks and approaches have recently been developed for use in climate change research and introduce an approach to assess liveability, and would be useful for assessing heat stress risk in Nauru.
- Incidences of increased hospital admissions for asthma following heavy rainfall after extended periods of dry were identified by Nauru stakeholders. The exacerbation of respiratory allergy and asthma associated with moulds has been linked to thunderstorms. More data is needed to understand potential association between asthma related hospital admissions following heavy rain and indoor air quality to understand potential linkages.
- Better data for extreme weather events.
- Reduced uncertainty about potential tipping points.

- Improved guidance about emission pathway likelihoods.
- Co-design and co-develop products and services to support the uptake of climate change information in policy development, planning, capacity development and decision-making.

Further detail is provided below.

Historical climate

This report has quantified historical climate averages, variability and trends. For some climate variables, this information was patchy or missing. A revised or extended monitoring network is needed for atmospheric and oceanic variables in Nauru. For example, wind and high-resolution wave observations are not readily available. Without reliable, high (spatial and temporal) resolution and quality controlled/homogenised atmospheric and ocean measurements, it is difficult to (a) analyse variability and trends, and (b) evaluate the performance of climate models, which influences the level of confidence in climate projections. High-quality historical data is also needed to produce application-ready future-climate data tailored to the needs of target sectors.

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]. This analysis would provide more reliable insights to the causes of historical climate trends, particularly in terms of elucidating the impacts of climate change from natural variability.

Future climate

The climate projections in this report were based on simulations from CMIP6 climate models driven by low (SSP1-2.6) and high (SSP5-8.5) greenhouse gas concentration pathways. These models show incremental improvements in the simulation of the climate of the western tropical Pacific compared to CMIP5 models [2-4]. However, the western tropical Pacific remains a challenging area to simulate climate variability and change. For example, climate models tend to simulate the wrong shape for the West Pacific warm pool and equatorial 'cold tongue'; the so-called "cold-tongue bias" is 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]. CMIP6 models with relatively small biases should be selected for risk assessments in the Pacific [5]. This issue needs to be addressed in the updated CMIP7 climate simulations.

Projected changes in ENSO strongly affect SST, rainfall, sea level and cyclones, but ENSO projections remain uncertain. The east-west gradients of SST across the equatorial Pacific have major consequences for both Pacific and global climate [6]. Reducing biases and uncertainty in ENSO projections (e.g. [3, 7-9]) are high priorities.

These challenges could be explored using dynamical and statistical downscaling of 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 currently include the Pacific. However, 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 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:

- Extreme sea level: intensity, frequency, duration and location.
- Wave intensity, frequency, duration and direction.
- Extreme rainfall: intensity, frequency, duration and location.
- Flood: intensity, frequency, duration and location.
- Extreme heat: intensity, frequency, duration and location.
- Thermal comfort: temperature and relative humidity analysis.
- Drought: intensity, frequency, duration and location.
- Marine heatwaves: intensity, frequency, duration and location.
- Tropical cyclones (remote): frequency, intensity (peak wind speeds, storm surge and rainfall), duration, and location (latitude of maximum intensity, area of gale-force winds).

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 Nauru case study.

Improved guidance about emission pathway 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. Likelihoods would allow Nauru (and the western tropical Pacific) to improve the communication of uncertainty in risk assessments, adaptation planning and decision-making.

Co-design and co-development of products and services is essential for raising awareness and boosting the uptake of science in planning and decision-making. Products could include brochures, reports, journal papers, videos, posters, slides and presentations. A web portal with decision-support tools could provide access to standardised, authoritative and quality-assured information, including data visualisation (e.g. graphs, maps, tables) to download. Services could include knowledge-brokering, capacity-building, training, workshops, communities of practice, and tailored information for sector-specific or location-specific risk assessments.

Some recommendations

The Pacific Coastlines product provided by Digital Earth Pacific is likely to be helpful in detecting trends and is available at https://maps.digitalearthpacific.org/#share=s-pzzMOVCCoPWNeWFs33Sg. Additional monitoring of large waves is being achieved by Tuvalu and Kiribati with the CREWS wave buoys (details available at https://gem.spc.int/projects/climate-risk-early-warning-systems-crews-inundation-forecast-system-for-tuvalu-kiribati).

To strengthen their ocean monitoring and coastal inundation warning services, we recommend Nauru seek to adopt the Climate Risk Early Warning Systems (CREWS) initiative which involves sensor-loaded wave buoys.

Wind resources (annual average wind resource of 4.22 m/s at 30 metres) were found to be at the low end of practical wind energy generation and, although wind turbines could be optimised for a low wind resource environment, it was determined not economically feasible to pursue [10]. This 14-year-old study could be revisited to account for improvements in technology and return-on-investment.

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 or health impacts. 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.

Historical information about climate-related impacts helps to (a) establish the key drivers (i.e. hazard, exposure, vulnerability), and (b) develop statistical or process-based models for assessing climate impact/risk (sometimes called damage functions). This CIVRA project has focused on (a) rather than (b). Further effort is required to develop damage functions that can be used with climate projections data to estimate future impacts. For example, historical energy demand data could be combined with historical temperature data to create a damage function relating energy demand and temperature, and this could be used with future temperature data to estimate future energy demand.

Damage functions can also be used with future climate data to estimate future economic impacts of climate change under different scenarios, potentially including the cost-benefit of selected adaptation interventions. Currently, 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 for loss and damage.

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. Capacity-building can enhance resilience to climate change.

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. Available from: Available from: https://www.ipcc.ch/report/ar6/wg1/
2. Grose, M., 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. DOI: https://doi.org/10.1029/2019EF001469
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. DOI: https://doi.org/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: DOI: https://doi.org/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. DOI: https://doi.org/10.1038/s41612-022-00301-2

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. DOI: https://doi.org/10.1038/ngeo868
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. DOI: https://doi.org/10.1126/science.aay9165
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. DOI: https://doi.org/10.1029/2022JD037563
10. Thorp, W., W. Dowiyogo, and A. Soakai, *Third party assessment of the PIGGAREP-funded wind monitoring activity in Nauru* 2010; Available from: https://pacific-data.sprep.org/dataset/nauru-wind-resource-mapping

Chapter 23 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 Organization[27]. 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 use[27].

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 variable[27]. Extreme events include hot/cold days, heavy rainfall, droughts and windstorms. 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 biology[22], and

---

[27] IPCC (2022) Annex 1 Glossary

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 analysis[27]. 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 actions[22]. 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) [27].

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.

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 [27].

D

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 [27].

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[27].

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 [27].

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 [27], 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 [27].

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 [27].

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 realised 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 wellbeing, ecosystems and species, socio-economic and cultural assets, services and infrastructure. Impacts may be adverse or beneficial [27].

Infragravity Waves are surface ocean waves with frequencies below those of wind-generated "short waves" (typically below 0.04 Hz). Infragravity wave impacts, especially during storms, need to be taken into account when providing operational forecasts, and when assessing longer-term coastline stability. Infragravity waves should also be considered during harbour design, as they can effect harbour operations substantially through resonance.

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 [27].

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

Mean High Water (MHW): The average of all high waters observed over a sufficiently long period.

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 [27].

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[22]. 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 [27].

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 [27]. 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: 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 development[27]. 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.

Significant Wave Height: In physical oceanography, the significant wave height (SWH, or Hs) is defined traditionally as the mean wave height (trough to crest) of the highest third of the waves. This statistical concept can be used to estimate several parameters of the waves in a specific forecast. The highest ten per cent of the waves are roughly equal to 1.3 times the significant wave height, and the likely maximum wave height will be roughly double the significant height. While the most common waves are lower than the significant wave height, it is statistically possible to encounter a wave that is much higher—especially if you are out in the water for a long time. It is estimated that approximately one in every 3000 waves will reach twice the height of the significant wave height—roughly equivalent to three times every 24 hours. (Source: https://media.bom.gov.au/social/blog/870/ruling-the-waves-how-a-simple-wave-height-concept-can-help-you-judge-the-size-of-the-sea/)

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 [27].

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.

Timeseries: The values of a variable generated successively in time. Graphically, a timeseries 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 [27]. 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 knowable[27]. 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 [27].

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.

CSIRO

SPREP
Secretariat of the Pacific Regional Environment Programme

GREEN
CLIMATE
FUND