‘NextGen’ Projections for the Western Tropical Pacific:

Climate change projections to inform **black pearl production vulnerability in the Cook Islands**

Case Study

January 2022

CSIRO and SPREP (2022). ‘NextGen’ Projections for the Western Tropical Pacific: Climate change projections to inform black pearl production vulnerability in the Cook Islands. Technical 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), CSIRO Technical Report, Melbourne, Australia. https://doi.org/10.25919/sr2h-8282

This report is dedicated to the memory and legacy of Mehau Johnson (1976-2021), a passionate contributor to the Cook Island pearl industry and member of the local farming community in Manihiki.

Acknowledgements

This report has been prepared for the Australia-Pacific Climate Partnership (APCP) as part of the APCP-funded project entitled Next Generation Climate Projections for the Western Tropical Pacific. The report is based on a sectoral use case led by CSIRO and SPREP, and the authors and contributors to the report are as follows:

Leanne Webb (CSIRO) (Author)
Vanessa Hernaman (CSIRO) (Author)
Savin Chand (Federation University) (Contributor)
Anil Deo (Federation University) (Contributor)

The project team would like to acknowledge Andrew Lenton (CSIRO), Jules Kajtar (University of Tasmania, Australia) and Lara Ainley (Ministry of Marine Resources, Cook Islands) for provision of datasets, Teina Rongo (K rero O Te `rau, Cook Islands) and Ian Bertram (Secretariat of the Pacific Community) for their helpful advice, and Johanna Johnson (APCP) and Arona Ngari (Cook Islands Meteorological Service) for their ongoing support through the project.

Dewi Kirono, Kevin Hennessy and Geoff Gooley (CSIRO) kindly reviewed drafts of this report.

Design and layout of the report was coordinated by Kate Morioka and Amanda Opanubi.

Contents

Summary

This study is one of five case studies selected to represent various sectors across several different Pacific Island countries. These case studies serve to assist stakeholders in terms of understanding and visualising climate change projections and putting them in context for sectoral applications as part of the *Next Generation Climate Projections for the Western Tropical Pacific*, referred to here as 'NextGen'. The methodological framework used in this assessment can be found in the report by CSIRO and SPREP (2017), with updated guidance by CSIRO and SPREP (2022).

This NextGen case study investigates the potential impacts of current and future climate change on the black-lip pearl oyster, *Pinctada margaritifera* (Linnaeus), and black pearl production in the Cook Islands. This is an important mariculture industry in the region, also supporting local tourism.

This report is for governments, meteorological services and sector stakeholders in the Cook Islands to use for general communications and policy related questions. The principles and datasets used in this case study can also inform sector impact assessments. **Rather than providing a comprehensive analysis of sectoral impacts, we aim to demonstrate the application of climate projections in a relevant context, i.e. a case study. The results are to be used as a guide to inform more detailed assessments as required.**

Pearl Oyster. Photo courtesy John Daly, Ministry of Marine Resources, Cook Islands

Key Results

Through recent and ongoing consultation with Cook Island pearl farmers and researchers, using their knowledge and experience of what has been occurring under current climate settings (both natural variability and recent changes), several climate-related impacts were identified. Historical and projected changes in key stressors were assessed in this study:

Climate-related conditions to be assessed	Projected ocean conditions affecting pearl oyster production
Pearl oyster viability is affected by lagoon water temperatures above 34°C, with recent sea surface temperature (SST) warming trends of potential concern.	The projected increase in ocean temperatures would likely result in more episodes of lagoon water close to or above the 34°C threshold by 2030, potentially affecting productivity of Manihiki Lagoon pearl farming in future.
Marine heatwaves (MHWs) are becoming more frequent in the region over the past decade. Pearl production has already been affected by marine heatwaves.	The typical number of MHW days is under 50 days per year (1982-2019), but under a low emission scenario (RCP2.6), this increases to about 150 days per year by 2030 and about 200 days per year by 2050. Under a high emission scenario (RCP8.5), this increases to about 200 days per year by 2030 and more than 300 days per year by 2050, with a high proportion of days in the “Severe” and “Extreme” categories.
Farmers are noticing problems with oysters; shells are thinner and deformities in the pearls have become common in recent years. Climate-related changes in ocean chemistry, known as ocean acidification, can deleteriously affect shell growth and pearl oyster quality. Coral reefs currently protecting the atoll can be affected with associated severe impacts on fisheries and other livelihoods based on marine ecosystems.	Ocean acidification is projected to increase. Under low emissions (RCP2.6), the median aragonite saturation state never falls below 3.5 (marginal conditions) and increases slightly toward the end of the century. Under high (RCP8.5) emissions, the median aragonite saturation state may transition to marginal conditions for coral growth from 2040 and continues to strongly decline thereafter to values where coral reefs have not historically been found (< 3.0).
Manihiki Lagoon is exposed to tropical cyclone activity, with Cyclone Martin (1997) for example, causing devastating destruction.	Cyclone projections indicate less frequent occurrence overall, however, the decrease is counteracted by a possible increase in the projected average intensity of TCs. Sea level rise will exacerbate the impact of storm surges on atolls.

The production of pearls is already vulnerable to marine heatwaves, ocean acidification and tropical cyclones. This vulnerability is likely to rise due to projected increases in marine heatwaves and ocean acidification by 2050, especially under a high emission scenario. While the projected decrease in cyclone frequency would reduce vulnerability, TC impacts on island countries are likely to be exacerbated when combined with sea level rise and a possible increase in average cyclone intensity. The projected rise in sea level is expected to increase the vulnerability of people living on the atolls, especially under a high emission scenario.

1 Introduction

1.1 Reason for conducting this case study

Black pearls are an important product supporting the Cook Island economy through direct export sales and tourism. The Cook Islands Ministry of Marine Resources, Pearl Farming Association, pearl farmers/producers, Cook Islands Meteorological Service, Secretariat of the Pacific Community (SPC), as well as pearl oyster farmers, identified an interest in improving their understanding of impacts of climate variability and projected climate change to black pearl production.

Many changes and concerns for the future of the industry have also been identified in the *Draft National Aquaculture Development Plan 2020 – 2025 (Ministry of Marine Resources and SPC Pacific Community 2020)*, with measures to address these issues outlined in the Draft Cook Islands Pearl Industry Strategic Plan. Findings reported here can be integrated into these initiatives.

Given this interest, as part of an Australian Government's Australian Pacific Climate Partnership (APCP) funded project, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), working with the Secretariat of the Pacific Regional Environment Programme (SPREP) have undertaken this case study with the support of the Cook Island Meteorological Service. Collaboration between local farmers and producers, scientists and associated sectoral decision-makers was critical in development of this report.

The case study has three goals:

- **Awareness raising** – the results can be used to start discussions and raise awareness of the climate change impacts on pearl production in the Cook Islands in terms of past, present and future.
- **Climate change impacts** – provide decision makers with a preliminary illustration of the potential impact of climate change on the Cook Islands, particularly to conditions in the ocean; to be used as input to a more detailed climate hazard-based impact assessment and adaptation plan, as well as identifying key knowledge/research gaps.
- **Provide incentive for the global community to mitigate greenhouse gas emissions** – in order to demonstrate the benefit of global emissions reductions, this report illustrates impacts for 'worst case' and 'best case' scenarios which consider high and low global emission pathways. These scope the potential range of projected climate outcomes for the Pacific Island Countries, while also incorporating any beneficial outcomes gained through the global community achieving the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement targets.

2 Black pearl oysters in the Cook Islands

2.1 Socio-economic context

In the Cook Islands, black pearls were originally gathered through free-diving for the black-lip pearl oyster, *Pinctada margaritifera* (Linnaeus). Over the past 20 to 30 years, a pearl farming industry has been established, becoming the main aquaculture commodity in the Cook Islands, and the second largest world supplier of South Sea black pearls (Ponia 2010).

The main pearl farming area in the Cook Islands is in Manihiki Lagoon, a coral atoll situated 1200 kilometres northwest from Rarotonga (Figure 1). Pearl farming is a critically important employer for the atoll (Brown 2019), supporting local livelihoods in fisheries and tourism.

Figure 1 Map of Cook Islands (Wikimedia commons).

Total pearl exports in the Cook Islands reached an all-time high in 2000 at just over NZ $18 million, however the industry has since seen a decline in the value of exports (Brown 2017). At its peak, there were 81 farms with 2 million shells in the water, accounting for more than 90% of national exports and 20% of gross domestic product (MMR & SPC 2012). Since its peak, the industry reached a low of $191,000 in 2013. The industry has rebounded somewhat in recent years, however its value remains very low (Brown 2017). Two factors caused the decline in Cook Islands pearl revenue: a rapid fall in international pearl prices in the 1990s due to increasing pearl supply from French Polynesia, and a bacterial disease *(Vibrio harveyi)* outbreak in Manihiki in 2000 (Ponia 2005, Hambrey Consulting 2011). Warmer than average SSTs related to El Niño in 2001 are reported to have contributed to oyster vulnerability resulting in bacterial disease outbreak and 10-20 % oyster death (Diggles and Hine 2001, Cambers et al. 2017). Farmers changed practices during this outbreak by lowering the lines from 5 m deep to 10-12 m deep. The industry has rebounded somewhat in recent years but has never fully recovered (Southgate 2011) with an export value of around NZ $300,000 reported in 2016 (Brown 2017).

The bacterial disease outbreak was due to a combination of sub-optimal conditions relating to oyster health, rendering them vulnerable to infection (Diggles and Hine 2001, McKenzie 2004, Cambers et al. 2017) including:

- Localised overstocking of oysters led to restricted food and oxygen availability.
- Poor handling of oysters (holding the animals in shallow areas for extended periods during seeding) further weakened the oysters.
- Windless and dry weather conditions in September and October 2000 reduced the amount of lagoon flushing[1] and caused a rise in water temperature.
- A massive spawning event caused high concentrations of *Vibrio harveyi* bacteria in the water.

Pearl farmers have observed changes in black pearl production and quality since the outbreak, particularly poor spat formation, lower quality (dull) pearls, smaller pearls and a reduction in the production of rare and more valuable varieties (e.g. white pearls) (McKenzie 2004).

Oyster farming activity © John Daly, Ministry of Marine Resources, Cook Islands

---

[1] Lagoon flushing involves the exchange of water between the lagoon and the open ocean, and typically is driven by wind, tides, and waves, with the latter being of prime importance in Manihiki Lagoon

2.2 Biophysical context of Manihiki Lagoon

Manihiki is a roughly triangular-shaped coral atoll, consisting of approximately 43 islets *(motu)* surrounding a deep, nine km wide lagoon, which is almost completely enclosed by the surrounding reef. Complete lagoon bathymetry is now available for Manihiki among a collection of seven pearl farming atolls (Andréfouët et al. 2020). This collection allows for the first time a precise estimate of a number of morphometric features (e.g., volume) and provides detailed views of each lagoon geomorphology and new potential for pearl farming related investigations.

Cook Islands (denoted by black square; Figure 2) lie within the Indo-Pacific Warm Pool (IPWP), with long-term (1982-2019) average sea surface temperatures (SST) being above 25°C, and Manihiki being located in the warmest part of the Cook Islands region (Figure 3). The IPWP has been coined the 'heat engine of the globe' with significance for world oceanography and climate (de Dekker, 2016).

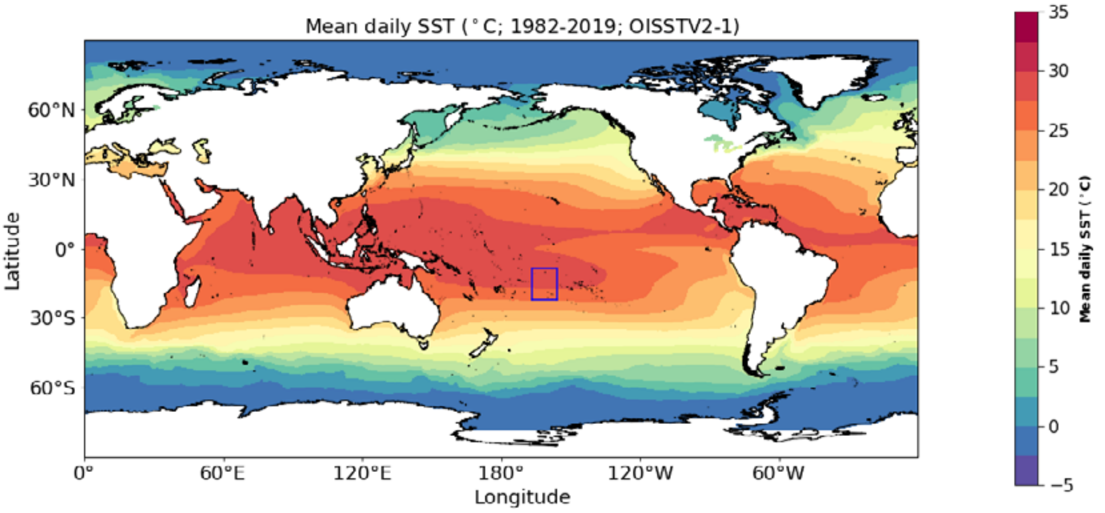


Figure 2 Mean daily SST (°C) over the period 1982-2019 using the NOAA OISST v2-1 ¼° gridded product (Huang et al. 2020). Black box indicates Cook Islands region.

The northern Cook Islands, including the Manihiki Lagoon region, experiences sea surface temperatures (SSTs) that are on average ~3-4°C warmer, as well as relatively little seasonal variation, compared to islands in the southern Cook Islands (Figure 3). Analysis of 38-year mean SST for each month (Figure 4) indicates warmest months occur from December to May, with a peak in April.

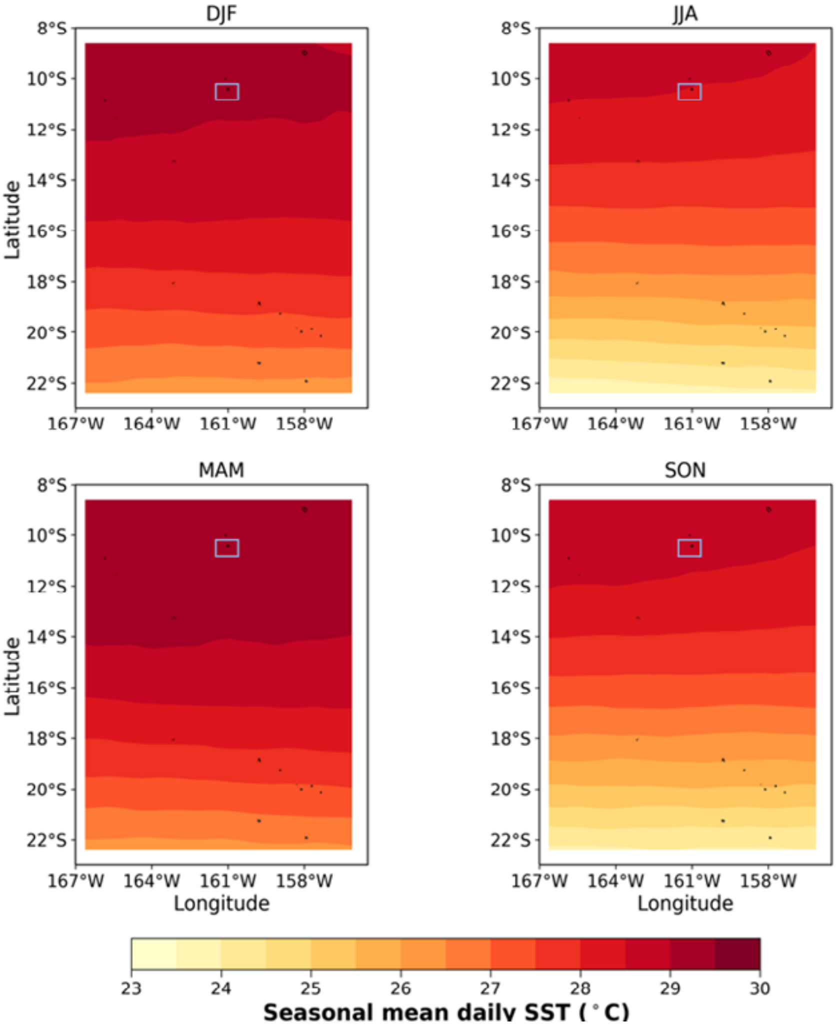


Figure 3 Seasonal mean SST (°C) from 1982-2019 for the Cook Islands region (black box Figure 2) for Dec-Feb (DJF), Mar-May (MAM), Jun-Aug (JJA), and Sep-Oct (SON). Manihiki Lagoon denoted by blue box. Data: OISSTv2-1 Huang et al. (2020).

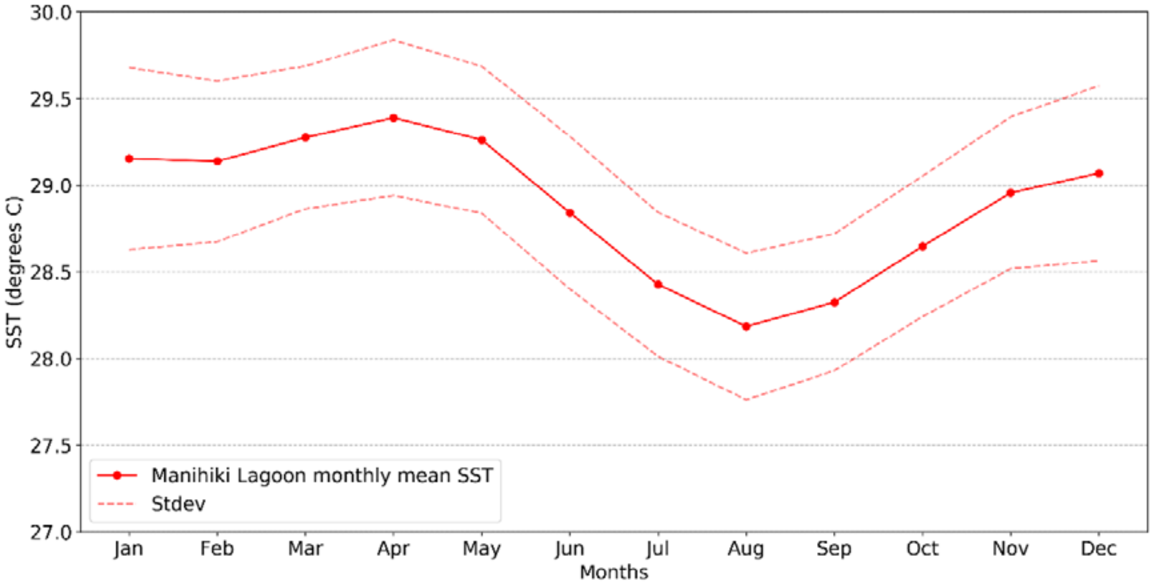


Figure 4 Monthly mean SST (°C) for region encompassing Manihiki Lagoon (1982-2019 OISSTv2-1; Huang et al. (2020). The standard deviation (Stdev) is indicated by the dashed line.

Selection of pearls © John Daly, Ministry of Marine Resources, Cook Islands.

2.3 Black Pearl production environment

2.3.1 Interaction of environmental influences on pearl oyster farming

Pearl oyster viability involves inputs and complex interactions from multiple climate and ocean chemistry related factors (Figure 5). For example, SSTs directly affect oyster health, but indirect impacts also occur through effects of SST on oyster bacteria prevalence (e.g. *Vibrio harveyi*), and temperature-related changes to oxygen solubility which affects water quality. Air temperature affects worker comfort and related farming practices. Seawater chemistry, including aragonite saturation levels and pH (related to atmospheric carbon dioxide concentrations), can affect the oyster shell and pearl quality, and the coral reefs protecting the atoll. The characteristics and water quality of the lagoon seawater experienced by the pearl oysters is heavily influenced by lagoon circulation, which can be modified by sea level rise and changes to wind-driven waves, as well as extreme rainfall events, through cyclone activity or other extreme weather events (Bell, 2011).

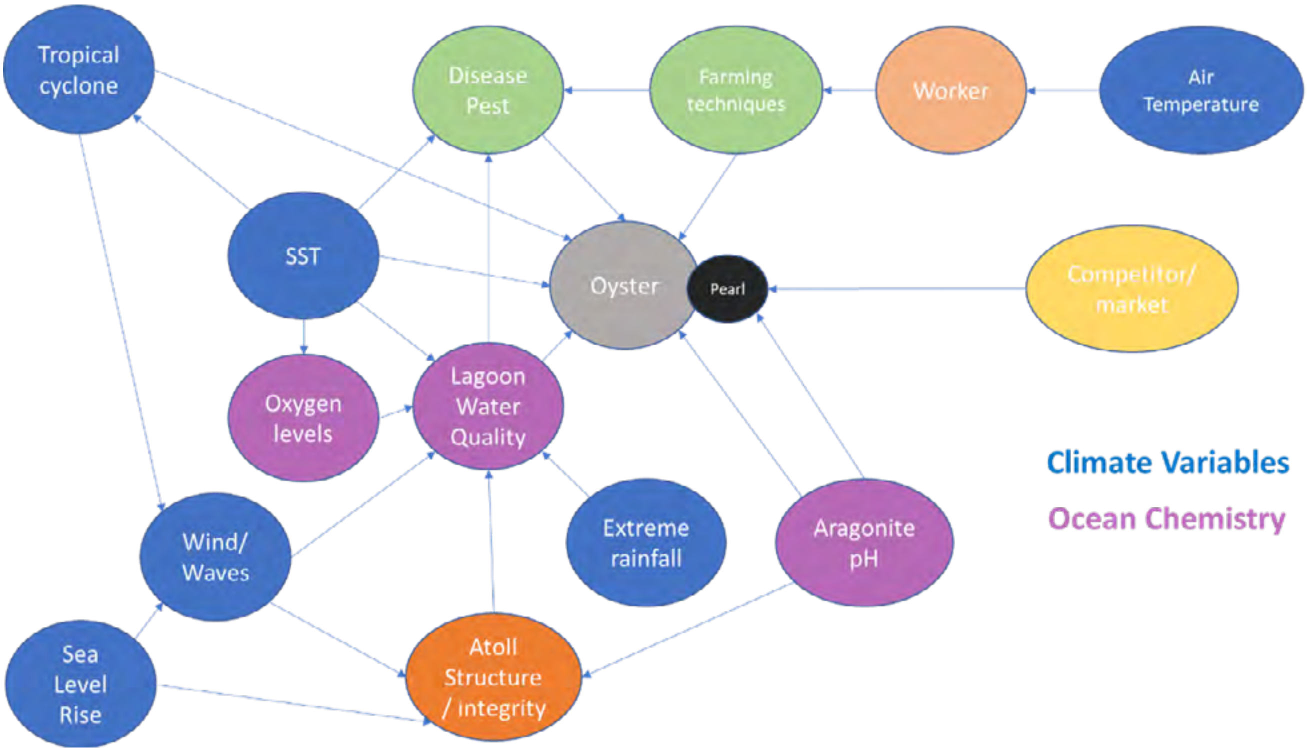


Figure 5 Interaction of climate, ocean chemistry, human, market and geographical factors on pearl production.

In the PACCSAP analysis (Australian Bureau of Meteorology and CSIRO, 2014) the projected changes in different climate drivers were treated as largely independent, e.g. warming and ocean acidification. However, the interaction of all of the changes, e.g. winds, waves, warming, sea water chemistry, nutrients, human factors etc. is best considered together, in order to develop an integrated view on how this projected variability and change will impact black pearl production. The case study focusses on some of the ocean and climate variables illustrated in the blue and purple circles (Figure 5).

2.3.2 Pearl oyster sea surface temperature optimum range

In one study, Gueguen et al. (2016) found that the optimal temperature for *P. margaritifera* somatic growth and reproduction was 28.7°C under experimental conditions. Until information specific to Manihiki Lagoon oysters is available, this value can be considered as a reference value for *P. margaritifera*. Temperatures above this level cause heat stress, inducing an energy deficit (Le Moullac et al. 2016a), noting oysters in Manihiki Lagoon may respond differently, and have many other factors affecting their viability. The reported threshold agrees with previous work highlighting an optimal temperature range for growth between 23 to 28°C for adult Australian populations of *P. margaritifera* (Yukihira et al. 1998), and that farmers tend to stop seeding operation when water temperature is above 29°C (Ian Bertram pers comm.)

In another study, using a theoretical approach via the use of a Dynamic Energy Budget (DEB) model, Sangare et al. (2020) investigated the effect of temperature on pearl oyster *P. margaritifera* growth and reproduction, using a temperature range from 23-34°C. The DEB model predicted low physiological performance at low temperature and food availability, and improved performance with rising conditions until the temperature reached 34.5°C, after which degrading performances prevented oysters' long-term survival (Sangare et al. 2020).

The internal lining of shells and the external surface of pearls is composed of nacre, a smooth crystalline substance composed of calcium carbonate and an organic protein called conchiolin. Elevated SST affects nacre deposition and pearl quality and increases the susceptibility of pearl oysters *P. margaritifera* to disease (Bell et al. 2013).

Given the Manihiki Lagoon is a coral atoll, it is also relevant to understand the impacts of ocean warming on the viability of coral. As the ocean warms, the risk of coral bleaching increases. Coral bleaching often leads to mass coral mortality, with coral recovery dependent on many factors including the frequency with which corals are exposed to stressors. Globally, projected increases in the frequency (recurrence) and duration of temperature-related severe bleaching episodes will shorten the period between successive events and may result in insufficient time for complete recovery of corals (Grottoli et al. 2014; Schoepf et al. 2015; Innis et al. 2021), potentially leading to selective loss of coral diversity as well as the overall decline of coral reefs (van Hooidonk et al, 2016). If severe bleaching events occur more often than once every five years, the long-term viability of coral reef ecosystems, and therefore coral atoll integrity, becomes threatened (Australian Bureau of Meteorology and CSIRO 2014). Severe coral bleaching in the Cook Islands may occur on an annual basis by 2044 for RCP8.5 (van Hooidonk et al, 2016).

2.3.3 Seawater chemistry influences on pearl oyster farming

Pinctada spp contain calcium carbonate substrates (calcite and aragonite) in their shell structure and are therefore sensitive to increasing ocean acidification (which is associated with reductions in calcite and aragonite saturation state). Ocean acidification is occurring ten times faster than in the past 300 million years (Hurd et al, 2018). This can potentially impact pearl quality, wild spat, shell formation, growth, and survival (Welladsen et al. 2010, Bell et al. 2013, Le Moullac et al. 2016b). On Manihiki, farmers are noticing problems with oysters; shells are thinner and deformities in the pearls have become common in recent years (Rongo and Dyer 2015). Atoll integrity may also be affected by ocean acidification because coral skeletons are made from aragonite, and reductions in aragonite concentration can result in slower growth and/or weaker skeletons in some coral species. Damaged coral reefs would leave coastlines defenceless with severe impacts on terrestrial ecosystems, coastal tourism, fisheries and other livelihoods based on marine ecosystems (IPCC, 2019).

2.3.4 Assessments undertaken in this case study

Projections for ocean related variables:

1. What are the projections for sea surface temperature and how might these changes affect oyster viability in the Manihiki lagoon region?
2. How may frequency, intensity and duration of marine heatwaves change in future?
3. What are the projections for ocean chemistry and how might these changes affect the Manihiki lagoon region?

Projections for atmospheric related variables:

4. What are the projections for tropical cyclones in the region under future climate conditions?

This study investigates historical and projected climate change surrounding the lagoon. To fully understand how those changes affect the waters within Manihiki Lagoon requires access to good-quality long-term monitoring data within the lagoon, and/or a three-dimensional hydrodynamic-wave model that can simulate the interplay of the various physical factors. If coupled to a biogeochemical model, these models could also simulate many biological changes too.

Lagoon monitoring data were not made available in time for integration into this study (other than for a comparison between the monitoring data and large-scale historic datasets; see Appendix), and hydrodynamic modelling was out of scope, however the information given here:

1) identifies key variables that can potentially impact pearl oyster farming in Manihiki Lagoon,
2) quantifies the observed and projected changes in these variables enabling the assessment the potential impacts
3) and provides the critical inputs for future hydrodynamic modelling efforts that can simulate the interplay of the projected changes within Manihiki Lagoon and further elucidate likely impacts.

3 Datasets and methods used in this assessment

3.1 Marine heatwave analyses

This case study follows the marine heatwave definition of Hobday et al. (2016, 2018), where a marine heatwave is defined as 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 the difference between the average 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).

3.2 Datasets

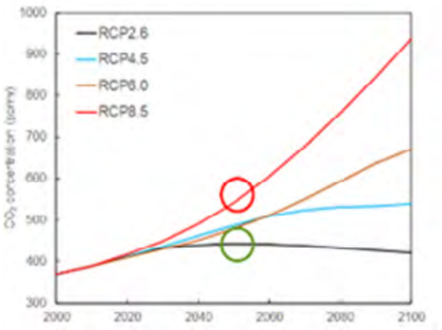
Results presented in this case study include ocean climate variable observations, and the likely range of change under different greenhouse gas emissions pathways for 20-year time periods centred on 2030, 2050, 2070, and 2090.

SST observations were taken from the NOAA daily Optimum Interpolation Sea Surface Temperature v2-1 dataset (hereafter called the daily OISST; Huang et al. 2020). Daily OISST is an analysis constructed by combining observations from different platforms (satellites, ships, buoys, and Argo floats) on a regular ¼° global grid (around 27 km at the equator) with interpolation to fill the gaps. Full-year data are available from 1982-2019.

Ocean chemistry observations came from OceanSODA-ETHZ, a global gridded dataset of the surface ocean carbonate system at a monthly resolution over the period 1985 through 2018 at a spatial resolution of 1° x 1° (about 100 km) (Gregor and Gruber 2021). OceanSODA-ETHZ was created by extrapolating in time and space the surface ocean observations of CO_2 concentration (pCO_2 from the Surface Ocean CO_2 Atlas, SOCAT) and total alkalinity (TA; from the Global Ocean Data Analysis Project, GLODAP). Surface ocean dissolved inorganic carbon, pH and aragonite saturation state were computed from the globally mapped pCO_2 and TA using the thermodynamic equations of the carbonate system (Gregor and Gruber 2021).

Climate projections from a subset of global climate models from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012) were used to investigate the range of projected change in ocean variables under different emissions scenarios, known as Representative Concentration Pathways (RCPs) (Figure 6).

- RCP2.6 is a low emissions pathway and represents ambitious mitigation, where net global emissions peak in the 2020s and then decline quite rapidly to zero around 2070. This leads to a global warming of 1.3-2.4°C by the period 2081-2100 relative to 1850-1900 (IPCC, 2021).
- RCP8.5 is a high emissions pathway, where net global emissions continue to rise throughout the 21st century. This leads to a global warming of 3.3-5.7°C by the period 2081-2100 relative to 1850-1900 (IPCC, 2021).



- ***High case*** - the world is following a high emissions pathway (RCP8.5) on track for 3.3-5.7°C global warming by 2100 (or even more), under a 'fossil-fuelled development' socio-economic pathway.

- ***Low case*** - the world is following a pathway to decarbonise the economy (net zero emissions) by 2070 (RCP2.6), giving a two-thirds chance of staying below 2°C global warming by 2100.

Figure 6 CO_2 concentration pathways (ppm) through the century under different RCPs (Van Vuuren et al. 2011).

This assessment utilised existing projections of SST, pH, and aragonite saturation state that were reported in PACCSAP (Australian Bureau of Meteorology and CSIRO 2014), which used a subset of six CMIP5 models for ocean chemistry projections. These models were judged to perform well in the southwest Pacific region. MHWs were not included in Australian Bureau of Meteorology and CSIRO (2014) and therefore new MHW analyses were conducted for the current assessment using a subset of 17 CMIP5 models[2].

For this assessment, the area denoted by the blue square (Figure 7, left) was used for historical SST analyses and evaluating MHW characteristics to ensure trends in the vicinity of Manihiki Lagoon were captured. For historical and projected ocean chemistry and MHW analyses, a slightly larger domain was used (green dashed line Figure 7, right) because CMIP5 models operate on much larger grids, typically 100-200 km (IPCC, 2021), and the use of only one grid cell in any analysis is not advised.

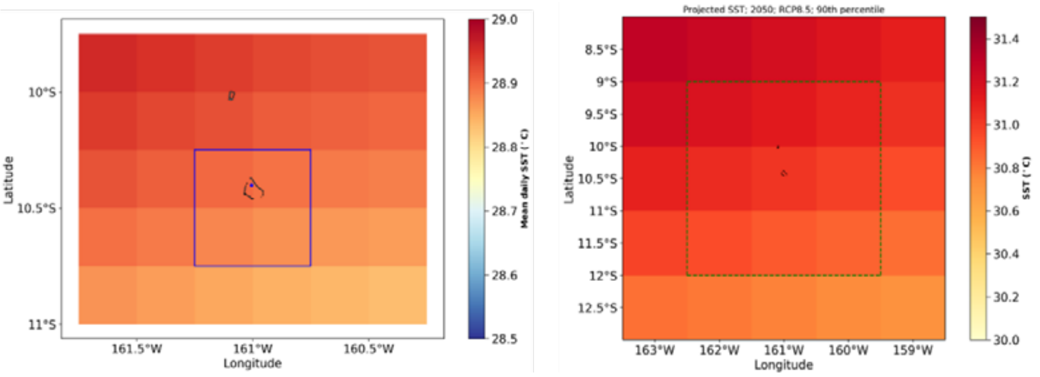


Figure 7 Left: Mean daily SST (°C; 1982-2019) for Manihiki Lagoon and surrounding region (OISSTv2-1). Blue square denotes the domain used in historical area-averaged SST analyses and characterising marine heatwave events. Right: CMIP5 projected SST (90th percentile) centred on the year 2050 under RCP8.5, showing domain (dashed green box) used for projections and historical comparisons.

---

[2] As highlighted by Australian Bureau of Meteorology and CSIRO (2014), projections of future change should be used as a guide to what is plausible for a particular emissions scenario, not as a firm single 'prediction' of the future. Some projections provided below (e.g., sea level rise, wind, and wave projections) are associated with a confidence statement, which is a characterisation of uncertainty and an estimation of the level of confidence in the projections based on expert judgment. Greater confidence is placed in a result if the driving mechanism is understood, when models have low biases in their simulation of the processes involved, and there is high model agreement on the projected change (see Australian Bureau of Meteorology and CSIRO 2014 for further information on confidence statements).

The resolution of the datasets described above does not capture the detailed spatial and temporal temperature fluctuations and ocean chemistry of the Manihiki lagoon itself. To fully understand how large-scale changes surrounding the lagoon translate to the waters within Manihiki Lagoon, access to good-quality long-term monitoring data within the lagoon is important.

The oceanographic monitoring buoy in Manihiki lagoon (Smith et al. 2004) (Figure 7) has been used to verify the global datasets (e.g. OISST; Huang et al. 2020; see Appendix) used in this study. However, the data were not made available in our reporting timeframe to enable further analysis. However, lagoon monitoring data are now available for subsequent reporting.

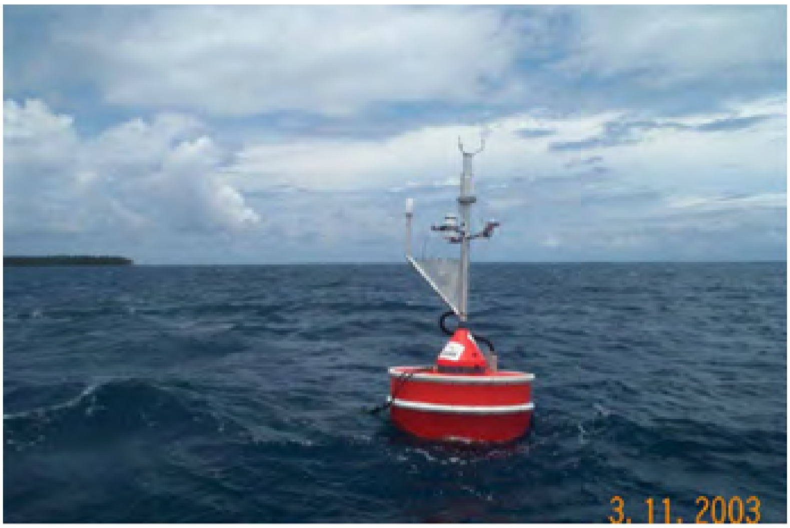


Photo taken from: Smith (2004)

Manihiki buoy (S 10 24” 5.2”, W 161 00” 18.1”, Water depth 30 M).

Three lines of evidence support the use of the daily OISST as a proxy:

1. Monitoring buoy temperature data were extracted from a report (Smith et al. 2004) for a seven-month period (November 2003-May 2004) and compared to monthly mean OISST temperatures (Figure 8). The mean difference between the two datasets was 0.32°C, with the largest difference evident in April and November; an encouraging similarity, especially for the warm months when elevated SSTs and MHWs are likely to have most impact on pearl oyster production, noting this period is too short for a robust assessment of differences between the 2 datasets. Further analyses are provided in the Appendix.

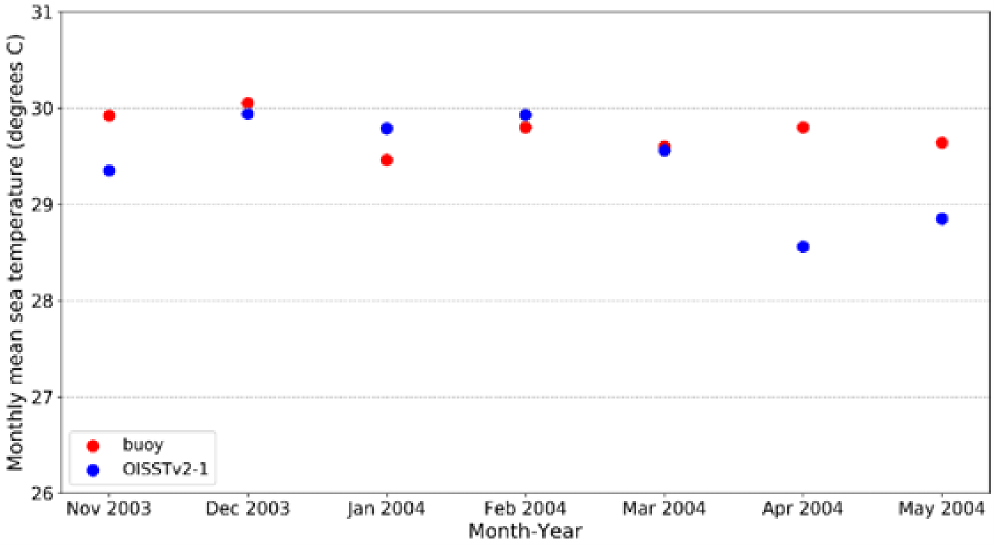


Figure 8 Monthly mean seawater temperature (°C) for SST from OISSTv2-1 (blue dots) and subsurface temperature from the Manihiki Lagoon monitoring buoy (161.005°W, 10.4014°S; (red dots) for 7 months (November 2003 to May 2004). Monitoring buoy sample obtained from Smith et al. (2004).

2. Evidence from a different study that showed daily OISST (up to 7 years observations) was a reliable indicator of daily average temperatures when compared to temperature loggers installed on reefs in three Pacific countries (Fiji, Samoa, and Palau) (Holbrook et al. 2021).
3. Other studies showing that similarly-derived daily SST products (Multi-scale-Ultra-high-Resolution; MUR) compared favourably with data loggers deployed during 10-months in the wide Raroia atoll (Tuamotu Archipelago, French Polynesia) where differences between observations and MUR SST ranged between –0.75°C and + 1.12°C and were influenced by seasons and locations, depth, and hours of measurements. Because these differences resulted in little differences in pearl oyster life traits when used in a Dynamic Energy Budget model, MUR SST was deemed suitable to monitor lagoon temperature in wide atolls, model oyster population dynamics and assist pearl oyster research and management (Van Wynsberge et al. 2020). Van Wynsberge et al. (2017) also found for Manihiki that MUR SST from lagoons did not provide better correlation coefficients with in-situ measurements than the oceanic MUR SST.

4 Observed climate for the Manihiki Lagoon region

4.1 Ocean observations

4.1.1 Sea surface temperature observations

Analysis of daily mean SST from 1982-2019 (OISSTv2-1) for the Manihiki Lagoon region (Figure 9) illustrates:

- Seasonal range is within ~27-31°C, with particularly high SSTs observed in 2006 and 2009, and minimum temperatures rarely under 27°C post-2003. A stronger warming of cool-season temperatures is evident with little trend in warm-season temperatures.
- This warming trend is also evident in the annual mean SST anomaly for Manihiki Lagoon region (Figure 10), with a predominance of warmer than average SST after 2001.

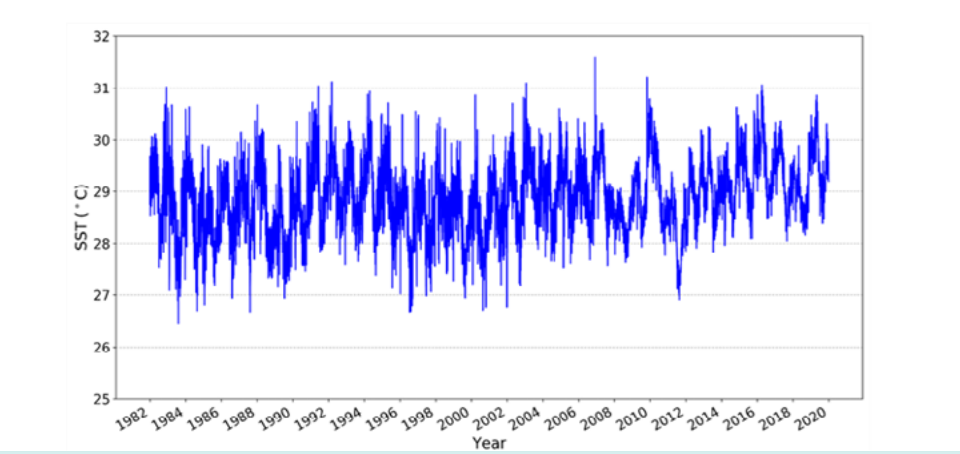


Figure 9 Daily mean SST (°C) for Manihiki Lagoon region (blue box in Figure 6) from 1982-2019. Data: OISSTv2-1.

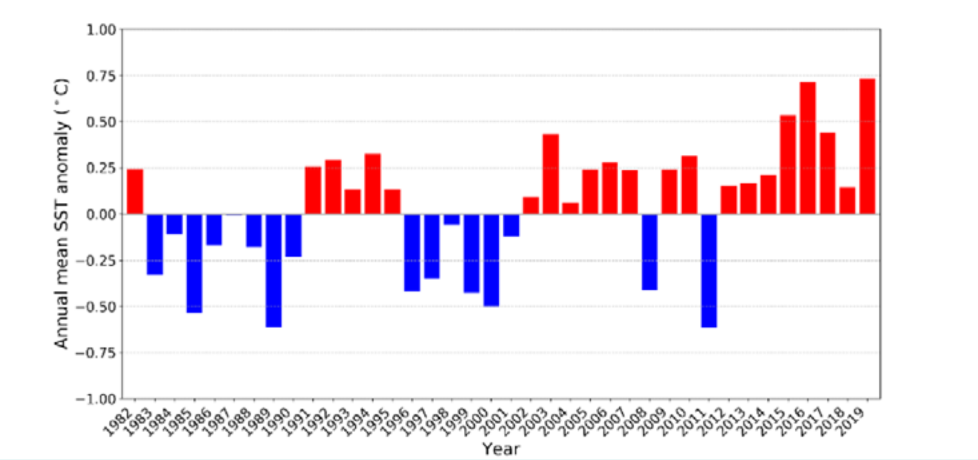


Figure 10 Annual mean SST anomaly (°C) for Manihiki Lagoon region (blue box in Figure 6). Anomaly is relative to the 30-year baseline of 1986-2015. Red bars indicate a positive anomaly (i.e., warmer than average years), blue bars a negative anomaly (i.e., cooler than average years). Data: OISSTv2-1.

4.1.2 Marine heatwave observations

A total of 85 MHW events were recorded in a region encompassing Manihiki Lagoon over the period 1982-2019. The most intense MHW event occurred from 3-7 December 2006, reaching an area-averaged maximum intensity of 2.7°C and a cumulative intensity of 8.3°C days. The longest MHW event occurred in 2019, with a duration of 101 days (12th March to 20th June 2019) and a cumulative intensity of 102.0°C days. This event had a maximum intensity at its peak of 1.6°C and ranked 18th in terms of maximum intensity (See BOX 1).

Historically, the ocean waters encompassing Manihiki Lagoon region experienced MHW events that were predominantly in the "Moderate" severity category (Figure 11) with a higher incidence of "Strong" events during the last 10 years. Typically, the total number of MHW days per year were well below 50 days over the period 1982 to 2019.

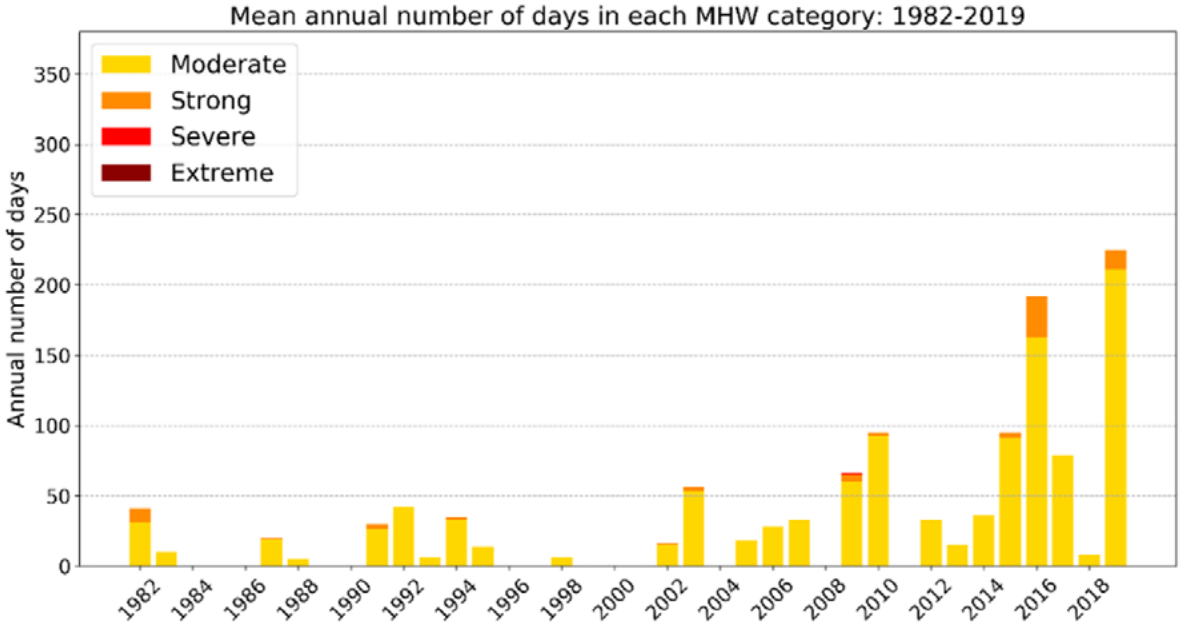


Figure 11 Historical annual number of marine heatwave days in each of four categories (moderate, strong, severe, and extreme) using area-averaged OISSTv2-1 for a domain encompassing Manihiki Lagoon region (Figure 7, right).

BOX 1. Analysis of two heatwave events

The December 2006 MHW event was a "Severe" (Category III) event at its peak (Figure 12), while the 2019 event was a "Moderate" MHW event for much of its duration but reached "Strong" (Category II) at several peaks over its duration. These events were selected as they represent the events with the highest maximum intensity (2006 event) and the longest duration (2019 event). See (Hobday et al. 2018) for category definitions.

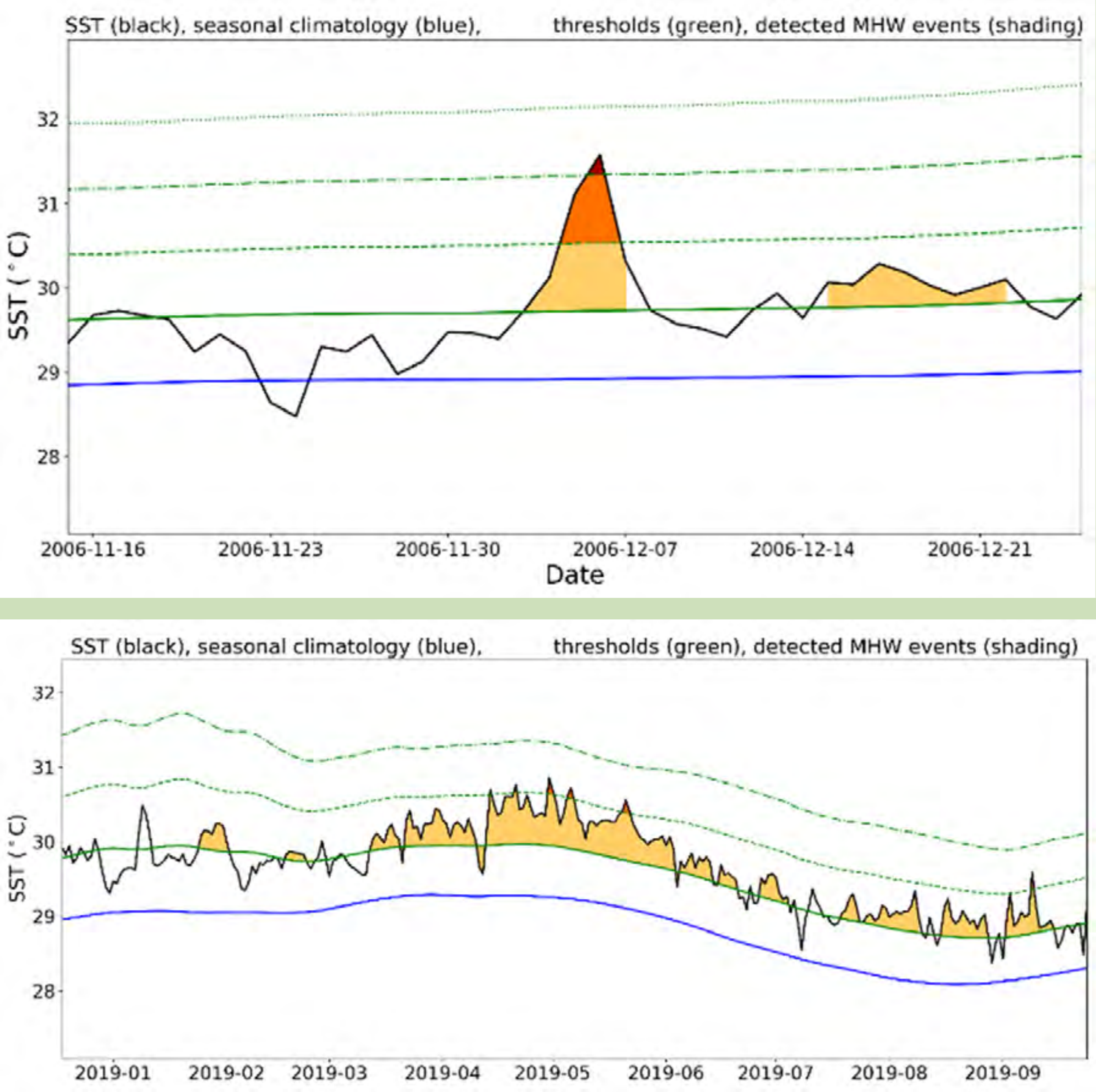


Figure 12 Area-averaged SST (°C) timeseries of the December 2006 event (top) and the 2019 event (bottom) for the Manihiki Lagoon domain (blue box in Figure 7), showing observed SST (black line), seasonal climatology (blue line), 90th percentile threshold (green solid line), 2x threshold (dashed line), 3x threshold (dash-dot line), and 4x threshold (dotted line). Filled colours represent the proportion of time spent in each MHW category: yellow - Category I "Moderate" MHW; orange - Category II "Strong" MHW; red – Category III "Severe" MHW (following Hobday et al. (2018)).

4.1.3 Aragonite observations

In the Northern and Southern Cook Islands, the aragonite saturation state has declined from about 4.5 in the late 18th century to an observed value of about 4.1±0.2 in 2000 (Kuchinke et al. 2014). Aragonite saturation state (Ωarag) shows little seasonal variability in the Cook Islands region (Figure 13, bottom), and a relatively high annual mean relative to the rest of the Pacific (Figure 13, top).

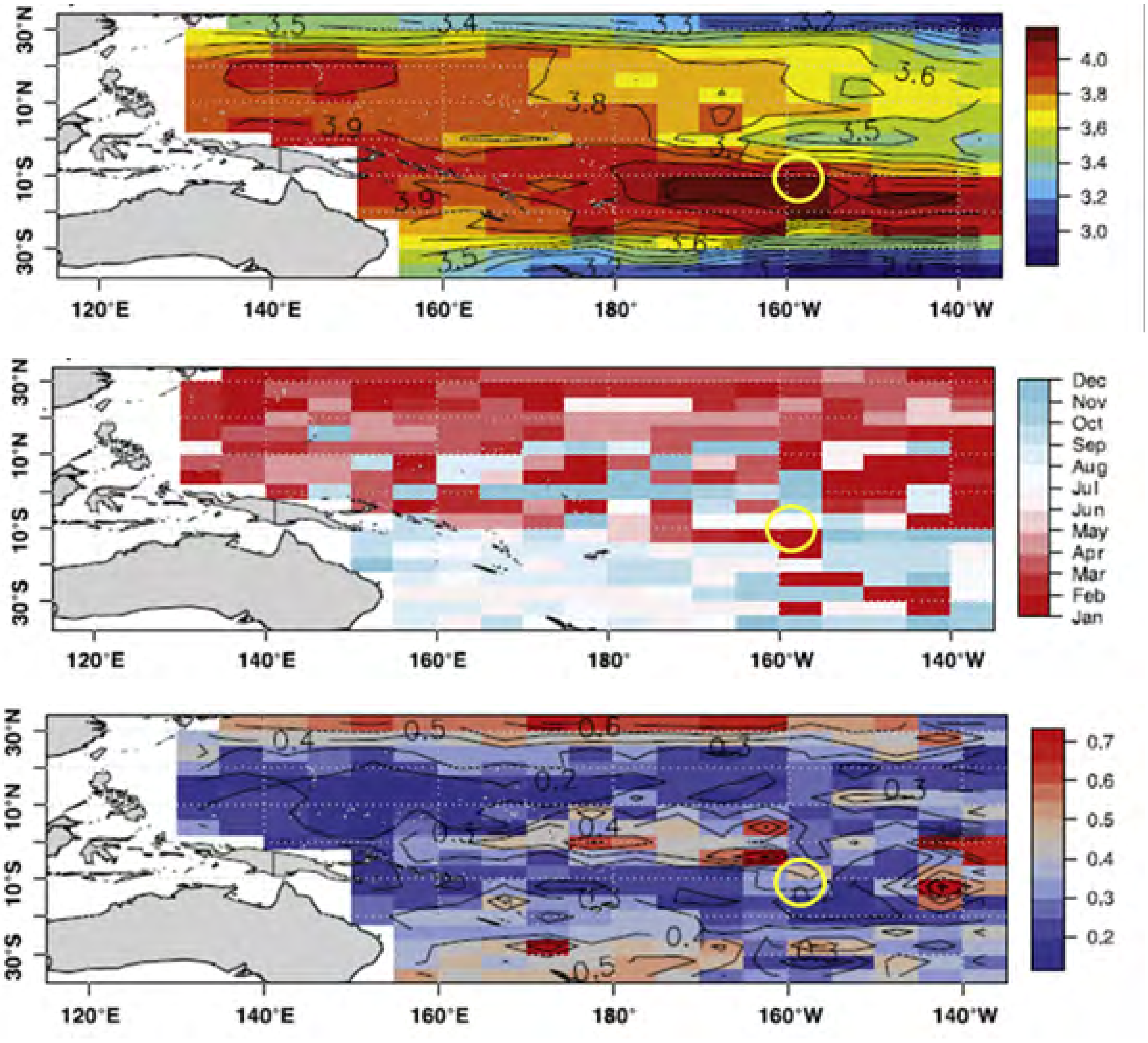


Figure 13 Aragonite saturation state (Ωarag): annual mean (top), month of minimum (middle) and season amplitude defined as the max-min value (bottom). Plots reproduced with permission from Kuchinke et al. (2014). NB: Yellow circle is indicative of the location of the Cook Islands.

4.2 Atmospheric observations

4.2.1 Tropical cyclones

On November 1st, 1997, a devastating cyclone struck Manihiki. The worst storm in living history, Cyclone Martin was said to have generated waves of such height that they swept over this small island, killing 19 and devastating most of the surface infrastructure, with many people never returning to the island (GHD 2015).

The Southern Cook Islands have been more than twice as frequently affected by cyclones as the Northern Cook Islands (Figure 14). Since 1982, 96% of TCs have occurred during the official November–April cyclone season, with February alone accounting for 29%. Nevertheless, Cyclone Martin in October–November 1997 demonstrated the dangers of a cyclone occurring outside the official season. While the frequency of TCs is less in the Northern region, risk to human life is greater there due to the potential for inundation of the atolls by storm surges (De Scally 2008).

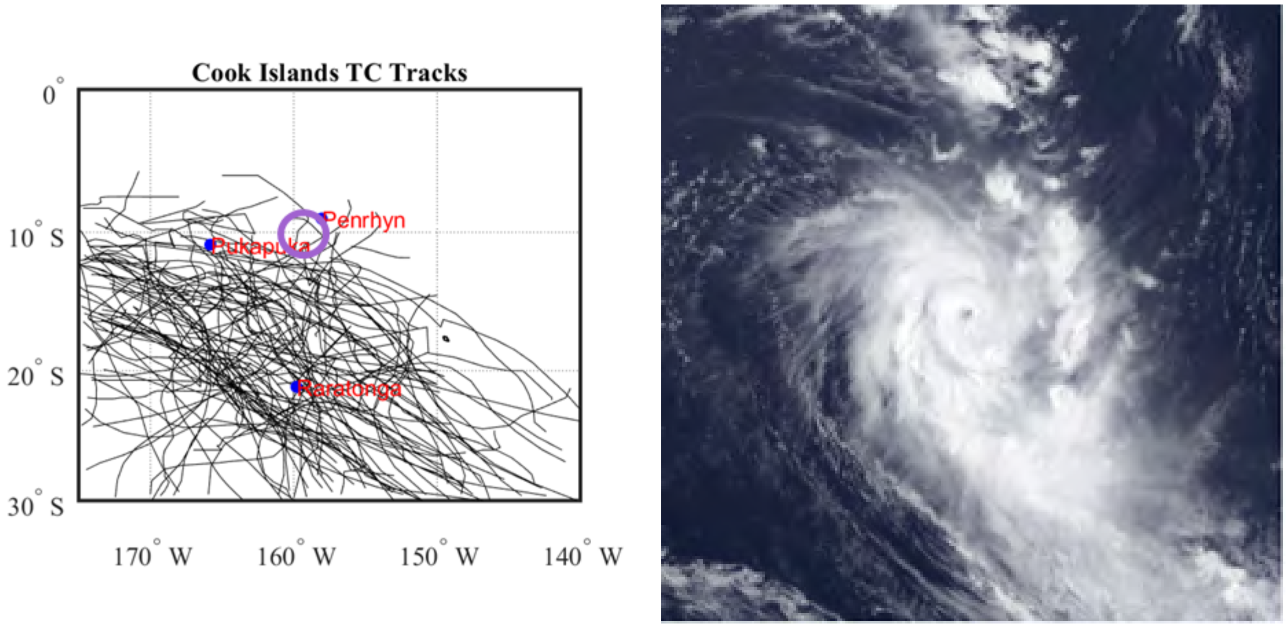


Figure 14 Generalized tracks of 100 cyclones in the Cook Islands, for the period 1970-2019 (Left) and TC Martin (right). TC tracks have been obtained from the Southwest Pacific Enhanced Archive of Tropical Cyclones (SPEArTC) database (Diamond et al. 2012). NB: Purple circle is indicative of the location of Manihiki.

Additional information on historical tropical cyclones in the Cook Islands region can be found at www.bom.gov.au/cyclone/history/tracks/index.shtml (Figure 15).

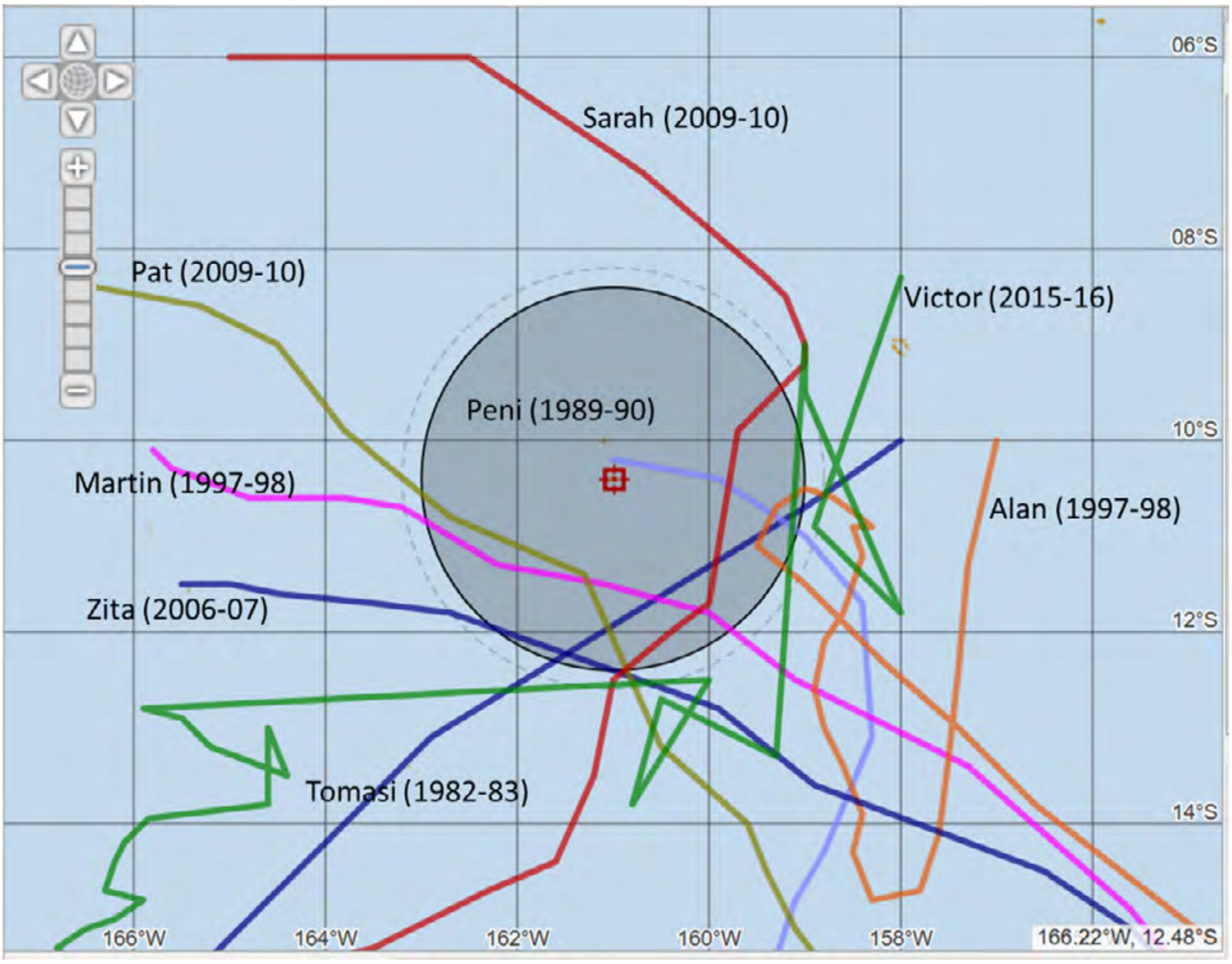


Figure 15 TC tracks from 1970 – 2018 within 200 km (grey circle) of Manihiki Lagoon site (red square)
(Source: http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/history/tracks/)

5 Projected climate hazard-based impacts for black pearl production in Manihiki Lagoon

As atmospheric carbon dioxide concentrations continue to rise, oceans will warm and acidify. These changes will affect the health and viability of mariculture systems, and other marine ecosystems including coral reefs that provide many key ecosystem services, such as food, resources for livelihoods (e.g. tourism) and coastal protection (Australian Bureau of Meteorology and CSIRO 2011, Australian Bureau of Meteorology and CSIRO 2014).

Pearl oyster viability involves inputs and complex interactions from multiple climate and ocean chemistry related factors. Increasing sea surface temperature and ocean acidification, and severe cyclones, are expected to reduce the survival and growth of pearl oyster spat in the Cook Islands (Bell et al. 2013). Ocean acidification is also expected to affect the formation of nacre by pearl oysters, and therefore pearl quality (Pickering et al. 2011). Perhaps the greatest potential impact on pearl farming in the region, however, will be the combined effects of higher water temperatures, changes to lagoon water quality affected by flushing regimes, and ocean acidification on pearl quality (Bell et al. 2013).

Stakeholder workshop interaction and scientific literature reviews informed our approach when assessing the potential impacts of future projected climate changes, leading to the identification of questions focused on SST and ocean chemistry in relation to future pearl oyster viability in the Manihiki Lagoon.

Pearl farming infrastructure © Ministry of Marine Resources, Cook Islands.

5.1 Ocean related projections

5.1.1 Sea surface temperature (SST)

Potential implications of higher SST for pearl oysters

While hydrodynamic modelling is needed to fully understand what large-scale SST increases mean for Manihiki Lagoon, it would likely result in episodes of lagoon water close to or above the 34°C threshold found in theoretical studies to be limiting to pearl oyster physiological performance and long-term survival (Sangare et al. 2020) and far beyond critical temperature thresholds of ~29°C ascertained through experimental trials (e.g., Yukihara et al. 1998; Gueguen et al. 2016; Le Moullac et al. 2016a).

Further study using coupled wave-flow hydrodynamic models would enable better understanding of the potential impacts from ocean warming (and projected changes to other variables such as winds e.g., Dutheil et al. 2020 and sea level rise) on conditions experienced within Manihiki Lagoon. This more detailed analysis could be facilitated by the recent acquisition of improved bathymetry for Manihiki (Andréfouët et al. 2020), which is a key element required for robust hydrodynamic modelling.

How may changes to SST affect oyster viability in the Manihiki lagoon?

Projected increases in SST for the Manihiki Lagoon region by 2050 ranges from 0.2°C for RCP2.6 to 1.8°C for RCP8.5, or up to ~3°C by the end of the century (Figure 16). This translates to average ocean temperatures in the Manihiki Lagoon region of over 32°C by the end of the century under RCP8.5, compared to the baseline average of 29°C (1986-2005). The spatial patterns of SST in 2030, 2050, 2070 and 2090 for RCP2.6 and RCP8.5 are shown in Figure 17).

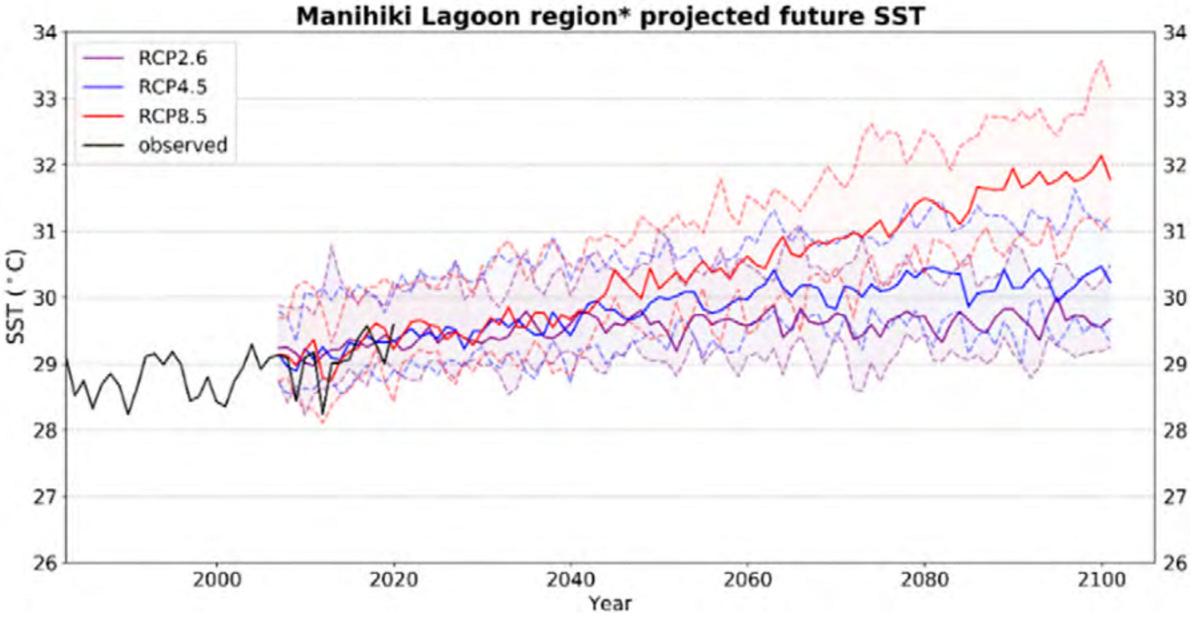


Figure 16 Timeseries of projected increase in annual average SST (°C) (2010-2100) for the Manihiki Lagoon area from six CMIP5 models under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. Shown are the median values (bold coloured lines), and the 10th and 90th percentiles (dashed lines and shading). Also shown are observed annual average SST (black line) from the OISSTv2-1 data from 1982-2019.

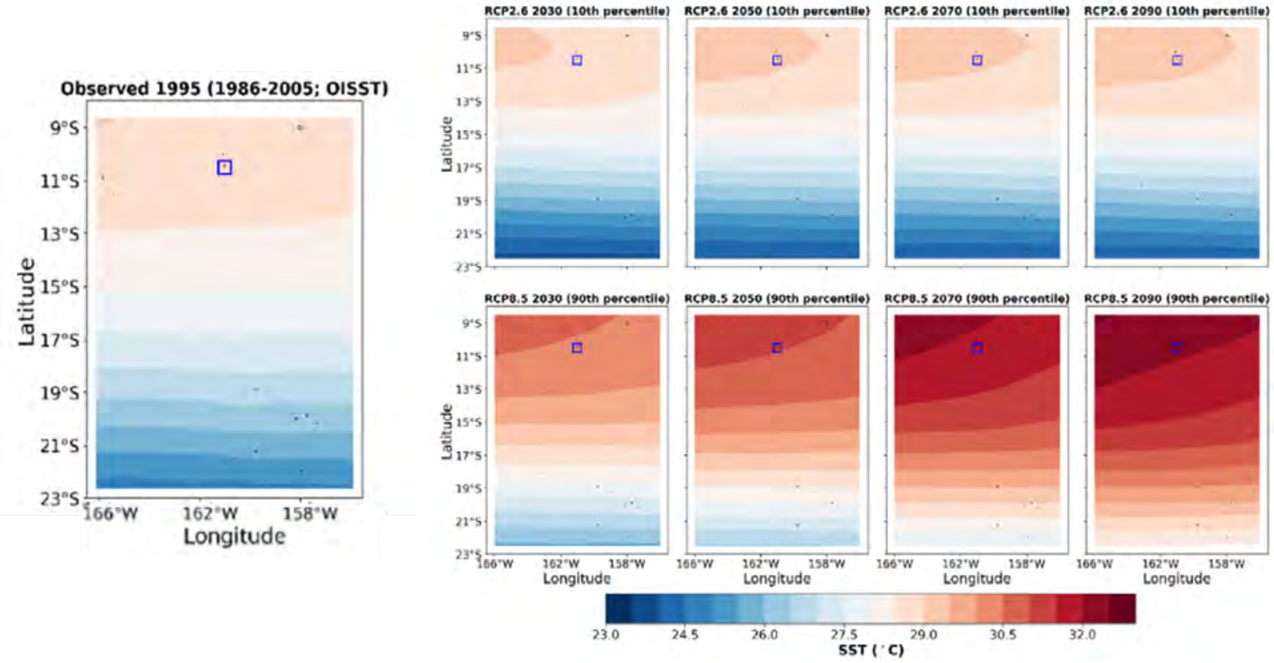


Figure 17 Historic 20-yr average SST (°C) (left; OISSTv2-1) and range of projected future values for the Cook Islands region (right) from six CMIP5 models for 2030, 2050, 2070, and 2090 (columns) under RCP2.6 (top) and RCP8.5 (bottom). To illustrate the potential range of change, 10th percentile of RCP2.6 CMIP5 models and 90th percentile of RCP8.5 CMIP5 models are shown. The location of Manihiki Lagoon is denoted by the blue box.

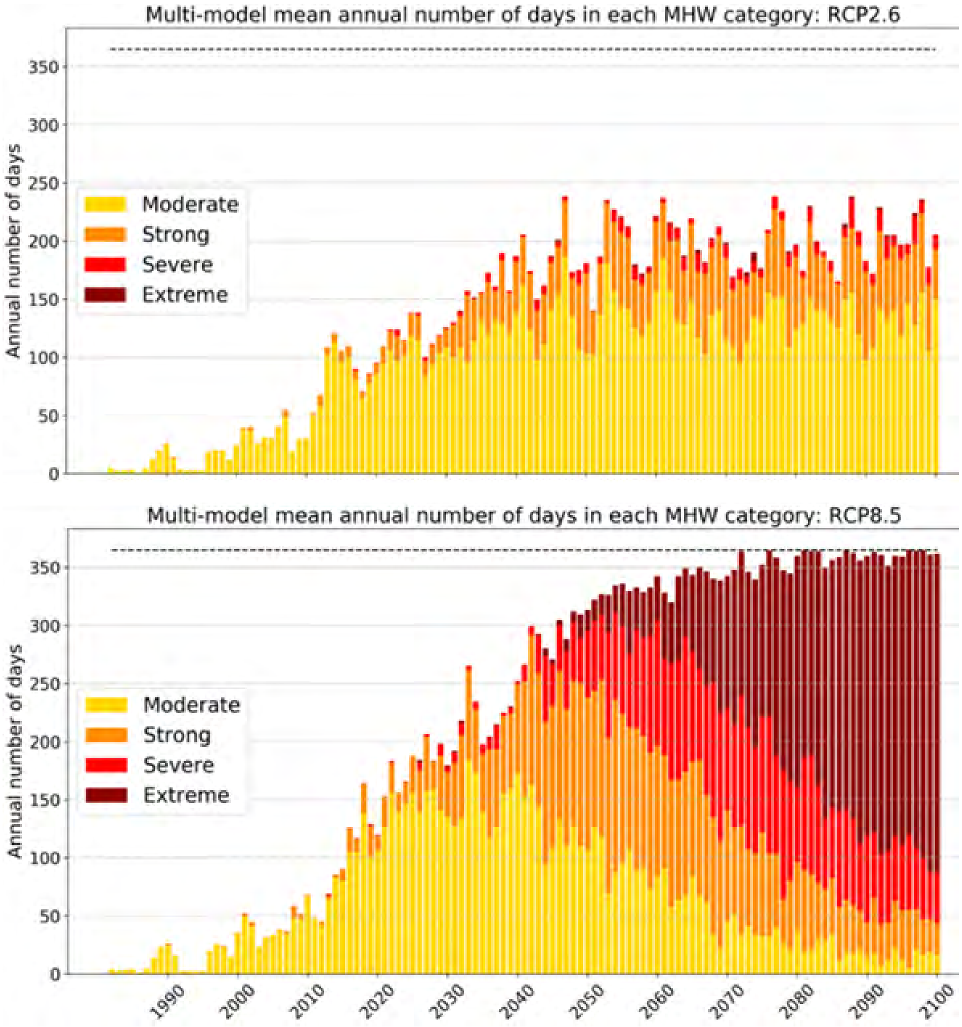
5.1.2 Marine heatwaves

Potential implications of marine heatwaves for pearl oysters

The increased severity and duration of projected MHWs by 2030 has potentially serious consequences for pearl oyster production through the effects of prolonged and repeated elevated temperatures on oyster growth and physiology. It also has implications through indirect impacts such as on water quality, disease prevalence, and food availability, given the relationships between elevated temperatures and oxygen concentrations, algal blooms, and nutrients. More frequent and severe coral bleaching, with reduced periods between for recovery, is also likely to have a detrimental effect on corals and associated ecosystems within the lagoon.

Marine heat wave (MHW) observations and projections

Historically, the typical number of MHW days is under 50 days per year (1982-2019) (Figure 10). However, under the low emission scenario (RCP2.6), this increases to about 150 days per year by 2030 and about 200 days per year by 2050. Under the high emission scenario (RCP8.5), this increases to about 200 days per year by 2030 and more than 300 days per year by 2050, with a high proportion of days in the “Severe” and “Extreme” categories (Figure 18). Under the high emissions scenario, by the end of the century, the region could experience almost year-round MHW conditions, with more than two-thirds of the year in the “Extreme” category. In contrast, the impact of following the low emissions RCP2.6 trajectory is clearly evident, with MHW days projected to be mostly less than 200 days per year on average even by 2100, and with the majority of those remaining in the “Moderate” category with “Extreme” MHW conditions remaining a rare event.


Multi-model mean annual number of days in each MHW category: RCP2.6

Multi-model mean annual number of days in each MHW category: RCP8.5

Figure 18 Projected annual number of marine heatwave days in each of four categories (moderate, strong, severe, and extreme) under RCP2.6 (top) and RCP8.5 (bottom). Data are area-averaged for a domain encompassing Manihiki Lagoon region (green dashed line in Figure 6), based on the mean from 17 CMIP5 models. The black dashed line indicates a full year (i.e., 365 days).

5.1.3 Ocean chemistry

Ocean chemistry and implications for pearl oysters

Global oceanic surface waters have absorbed ~30 % of the additional carbon dioxide (CO_2) introduced to the atmosphere by anthropogenic greenhouse gas emissions (Gruber et al. 2019). This changes the chemistry of the oceans, with a reduction in pH and carbonate ions, which affects a wide variety of marine species and ecosystems. It is particularly relevant to animals that produce calcium carbonate shells and skeletons, such as shellfish and corals.

While there is no existing study on the impact of ocean acidification (pH reduction) on pearl oysters in Manihiki lagoon specifically, we can learn from experimental trials in other regions. The normal pH of sea water is around 8.1. For example, experimental trials where *P. margaritifera* were held in high pCO_2 (corresponding to pH 7.4 and 7.8) for 100 days revealed little impact on reproduction or bioenergetics descriptors (e.g., rates of respiration and ingestion, and assimilation efficiency), but did significantly impact shell growth.

Oysters held in pH 7.4 showed significantly reduced shell deposition rates at the ventral side and signs of chemical dissolution on the inside of the shell (Le Moullac et al. 2016b). These trials were conducted on adults, and the authors point out that larval stages could be even more susceptible to low pH. However, even for larval stages, impacts are most apparent at very low pH (i.e., ~7.4). For example, experimental trials on larval Pacific Oyster, *Crassostrea gigas*, indicated that larval shell development was only impacted at pH 7.4, with larval development under pH 7.8 being no different from controls (pH 8.1) (Zhang et al. 2019).

Similarly, in a South China Sea study, adult pearl oyster, *P. fucata*, was able to compensate for the acid-base homeostasis disturbance caused by reduced pH at the level predicted for the year 2100 (~pH 7.8), but this regulation was not possible at ~pH 7.5 (projected for the year 2300 in that region), suggesting that such stress will exceed the resistance thresholds of crucial physiological processes (Li et al. 2016). However, it is possible that natural adaptation over those timeframes or selective breeding could increase this compensation ability and oysters' resilience to acidification. Both larval and adult stages of the Sydney Rock Oyster, *Saccostrea glomerata*, selectively bred for fast growth or disease resistance, exhibited enhanced resilience to acidification: larvae exhibited better shell growth and development compared to wild-type oysters under experimental acidification (Parker et al. 2012), and adults from elevated coastal acidification environments altered their mechanisms of calcite crystal biomineralization, promoting resilience to acidification (Fitzer et al. 2019).

How will ocean chemistry change in the Manihiki lagoon region?

Even relatively small changes in pH can be of concern because pH levels influence many chemical processes associated with metabolism, reproduction, and growth. Seawater concentrations of the calcium carbonate ions (aragonite and calcite) are important because they are needed for pearl oyster shell formation, and aragonite is used in coral skeleton formation. As noted in earlier sections, projected changes in seawater chemistry provided here are for ocean surface waters for the region encompassing Manihiki Lagoon, and do not necessarily reflect conditions within the lagoon, which will experience considerable variation on multiple spatial and temporal scales, including daily and seasonal timeframes. However, the projections can be used to better understand the range of likely future change in variables important to seawater chemistry and pearl oyster growth and survival.

Projections of pH and aragonite saturation state

Under a high emissions scenario, RCP8.5, oceanic surface pH in the region of Manihiki Lagoon is projected to decrease to less than 7.8 by the end of the century (Figures 19 and 20). In contrast, under a low emissions scenario, RCP2.6, the projected decrease is small and does not fall below 8.0, and then increases slightly toward the end of the century, though remains below historical levels.

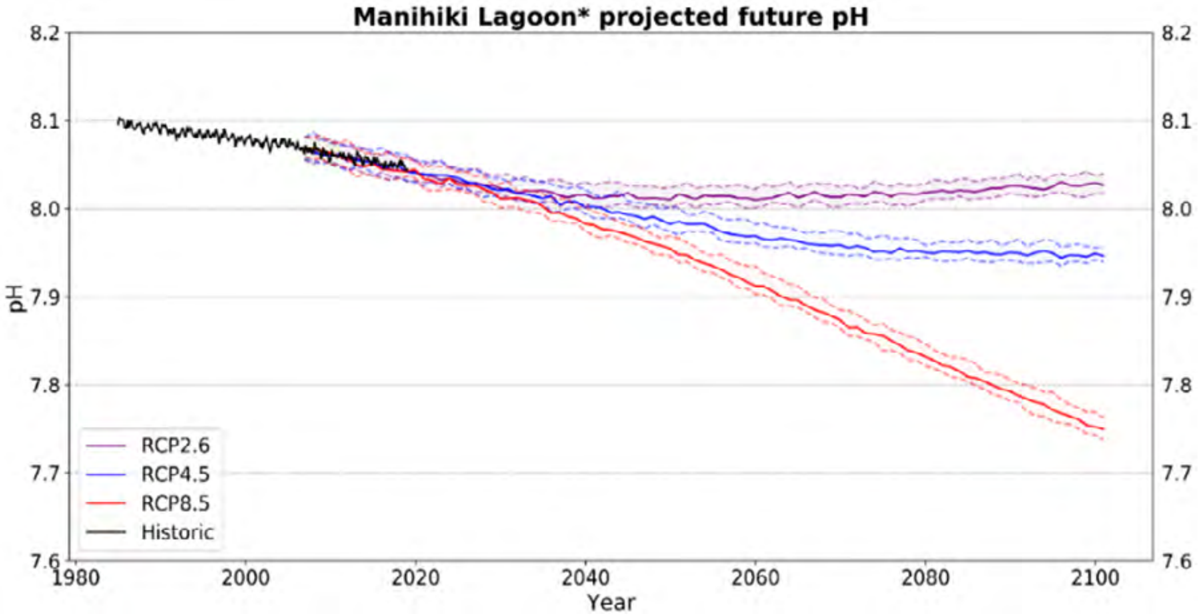


Figure 19 Projected decreases in pH for the *region encompassing Manihiki Lagoon from six CMIP5 models under RCP2.6, RCP4.5, and RCP8.5. Shown are the median values (bold lines), and the 10th and 90th percentiles (dashed lines and shading). Also shown are historical data for the region encompassing Manihiki Lagoon from the OceanSODA-ETHZ dataset from 1985-2018.

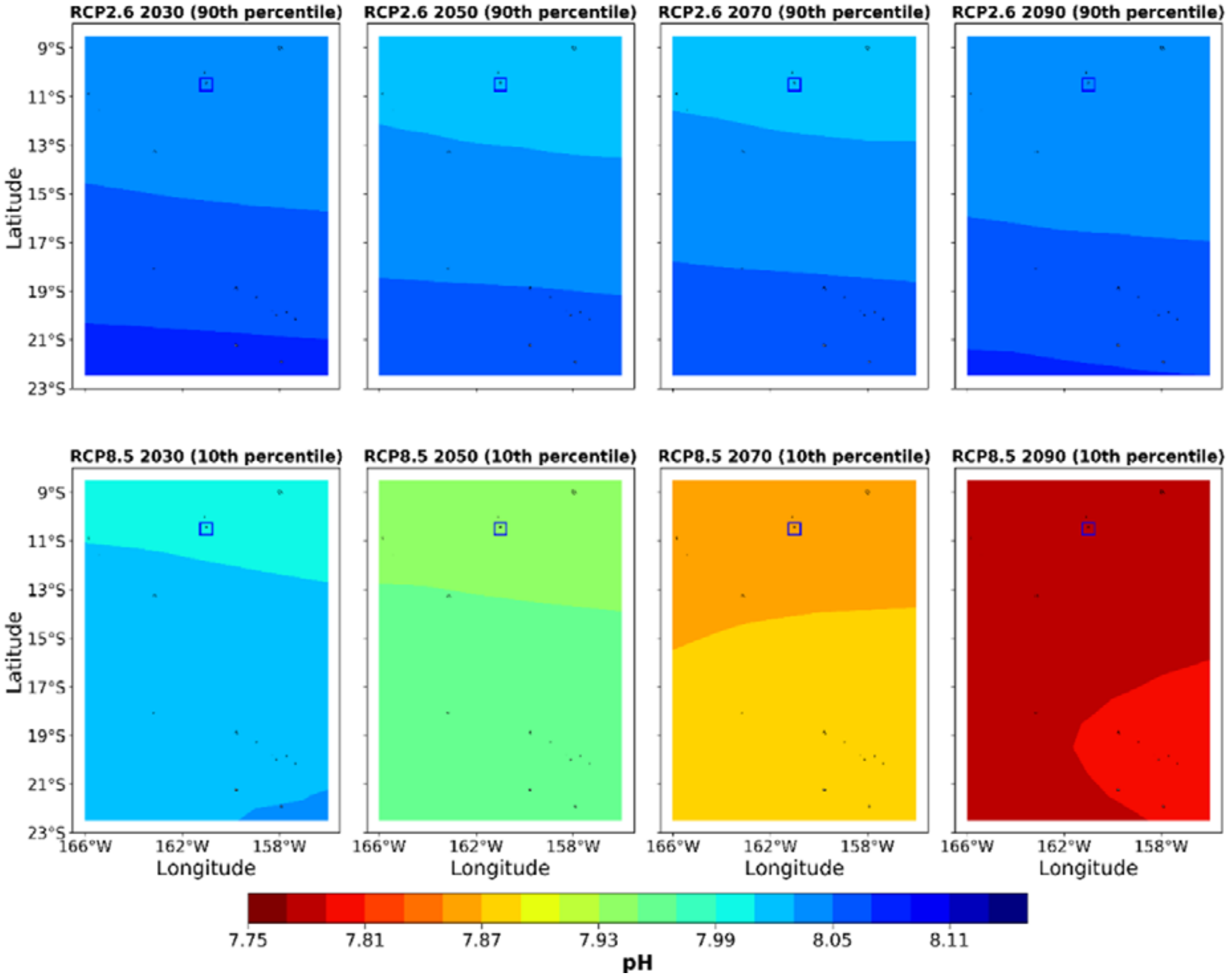


Figure 20 Range of projected future values in pH for the Cook Islands region from six CMIP5 models for 2030, 2050, 2070, and 2090 (columns) under RCP2.6 (top row) and RCP8.5 (bottom row). Blue boxes indicate location of Manihiki Lagoon.

All models show that the aragonite saturation state will continue to decrease as atmospheric CO_2 concentrations increase (very high confidence). Projections from CMIP5 models indicate that the median aragonite saturation state may transition to marginal conditions (3.5) for coral growth by 2070 under RCP4.5, but much earlier (by 2040) under RCP8.5 (Figure 21). Under RCP8.5 (high emissions), the aragonite saturation state continues to strongly decline thereafter to values where coral reefs have not historically been found (< 3.0). Under RCP4.5 (medium emissions), the aragonite saturation plateaus towards the end of the century at around 3.2. Under RCP2.6 (broadly in line with the UNFCCC Paris Agreement), the median aragonite saturation state never falls below 3.5, and increases slightly toward the end of the century (Figures 21 and 22), suggesting that the conditions remain adequate for healthy corals reefs.

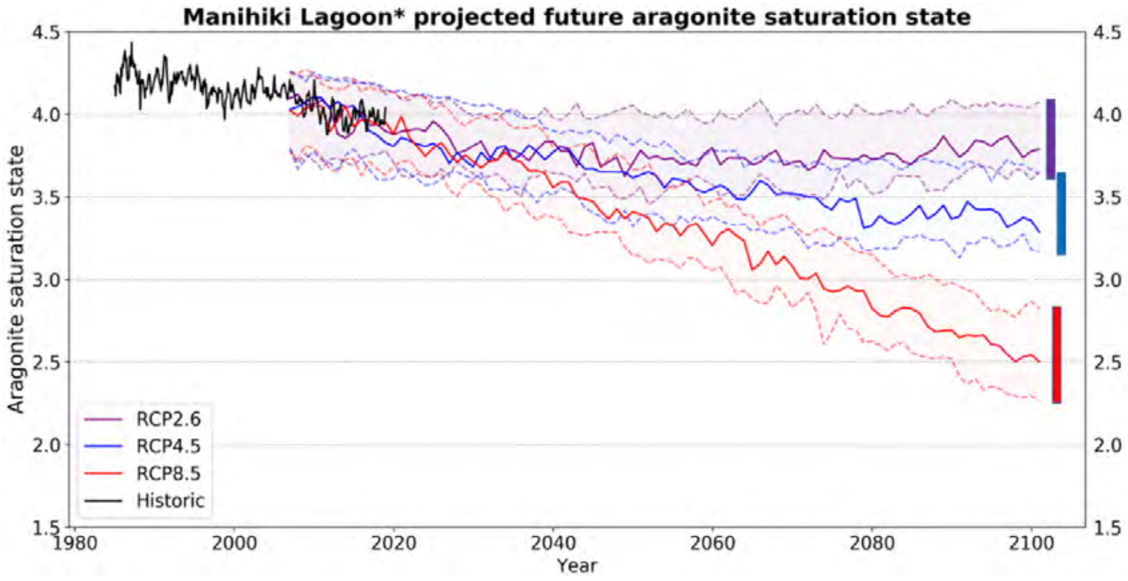


Figure 21 Projected decreases in aragonite saturation state for the Manihiki Lagoon region from six CMIP5 models under RCP2.6, RCP4.5, and RCP8.5. Shown are the median values (bold lines), and the 10th and 90th percentiles (dashed lines and shading). Also shown are historic data (black line) for the Manihiki Lagoon region from the OceanSODA-ETHZ dataset from 1985-2018. *data encompasses Manihiki Lagoon region

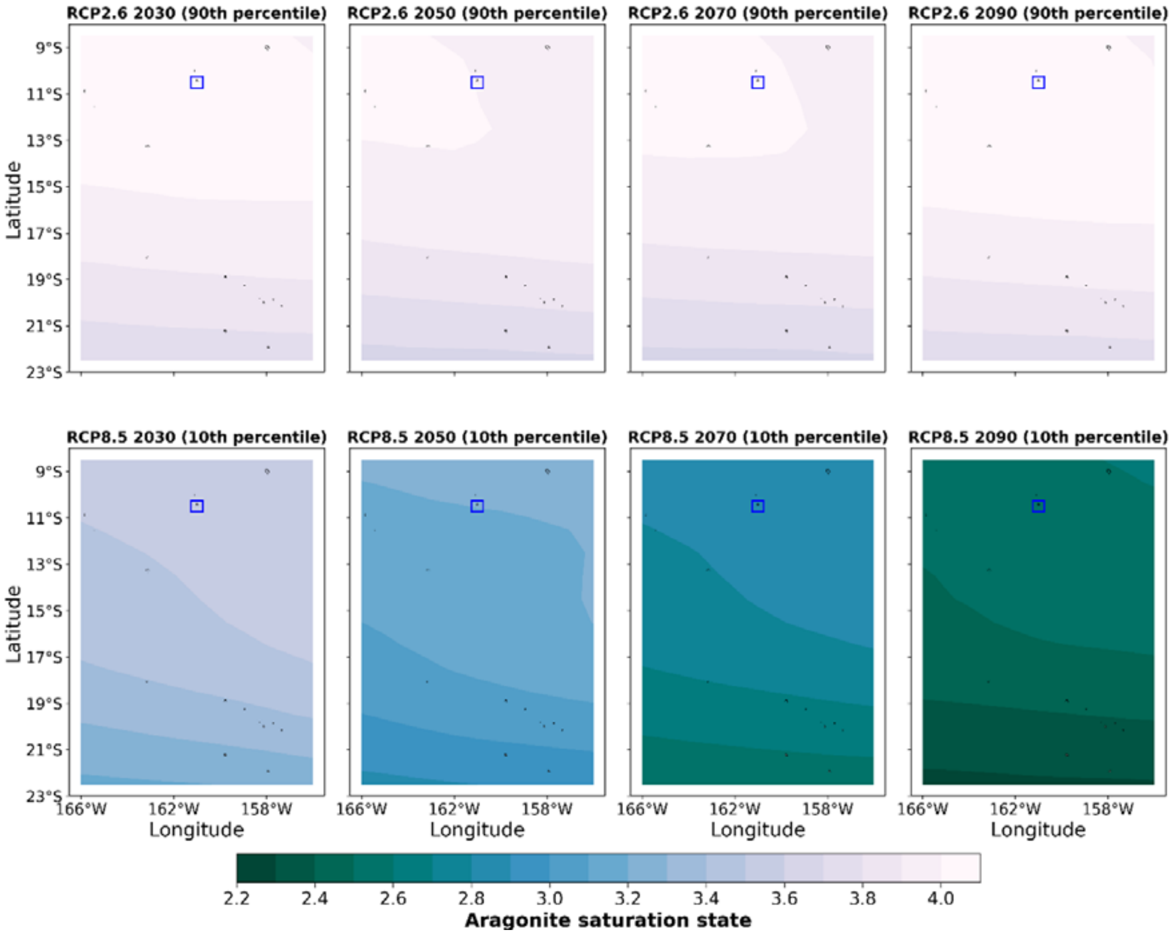


Figure 22 Range of projected values of aragonite saturation state for the Cook Islands region from six CMIP5 models for 2030, 2050, 2070, and 2090 (columns) under RCP2.6 (top row) and RCP8.5 (bottom row).

Projected pH at least to the end of the century under RCP2.6 and RCP4.5 are likely to be less of a concern to pearl oyster production than other stressors such as projected changes in temperature. However, under the higher emissions scenario RCP8.5, projected values of pH for the year 2100 (pH <7.8) and beyond are likely to produce observable impacts.[3] These assumptions would need to be verified by understanding how broader scale oceanic surface pH translate into changes within the lagoon.

5.1.4 Lagoon circulation

Why is lagoon circulation important for pearl production in Manihiki Lagoon?

Sea level rise can affect pearl oyster farming in Manihiki Lagoon through impacts on housing and infrastructure from erosion and storm surge inundation, and also affect pearl oysters and production by modifying circulation and water exchange between the open ocean and the lagoon (known as lagoon flushing). The latter is extremely important because circulation patterns within reef environments play a primary role in many processes (Green et al. 2018) including regulating the spatial distribution of temperature (Zhang et al., 2013), nutrients (Falter et al., 2004), oxygen (Gruber et al., 2017), larvae (Pineda, 1991), and other planktonic organisms (Wyatt et al., 2010)

What are the likely changes to key drivers of lagoon circulation?

As indicated in Figure 5, lagoon water quality is important to pearl oyster health. Lagoon flushing (exchange of seawater between the open ocean and the lagoon) is affected by sea levels, winds, tides, and waves, as well as the morphology of the lagoon (Andréfouët et al. 2012; Dutheil et al. 2020; Green et al. 2018). Flushing of Manihiki Lagoon is thought to be primarily wave-driven, with waves on the exposed side pushing water into the lagoon during most of the tidal cycle while water leaves the lagoon on the protected side (Callaghan et al. 2006). Therefore, key projections related to lagoon flushing are indicated below for sea level rise, wind, and waves. Overall, with little change in wave properties projected (see below), it is likely that the greatest influence on lagoon circulation in the future will be sea level rise, wind-waves, reef integrity, and sedimentation. Further work is needed to clarify how these future changes are likely to influence wind-waves and circulation within Manihiki Lagoon. This could be achieved using scenario-based wave-hydrodynamic modelling which tests the sensitivity of lagoon-ocean seawater exchange to various scenarios of future changes in sea level rise, reef integrity, and sedimentation.

Sea level rise projections

According to Oppenheimer et al. (2019), mean sea level is projected to continue to rise over the course of the 21st century and beyond *(very high confidence)*. By 2100, global mean sea level is projected to rise by 0.43 m (range: 0.29–0.59 m) under the RCP2.6 emissions scenario, and by 0.84 m (range: 0.61–1.10 m) under the high emissions scenario (RCP8.5) relative to a baseline of 1986–2005 (IPCC, 2019). Beyond 2100, sea level will continue to rise for centuries due to continuing deep ocean heat uptake and mass loss of the Greenland and Antarctic ice sheets.

---

[3] While pH and aragonite saturation state are both components of ocean acidification, they do not have to be necessarily equal in terms of degree of impact as they can affect different processes: aragonite is important for growth of shells and skeletons, whereas pH can also affect many other physiological responses and chemical reactions within an organism.

Wind projections

Dutheil et al. (2020) classified and analysed wind regimes in the South Pacific from regional climate simulations for present-day and for the end of the 21st century under RCP8.5. All regimes were characterized by a ~15% wind speed increase by 2100, while directions and occurrence frequencies underwent marginal changes.

Wave projections

There is little change in annual mean wave height historically or projected for the future in the northern Cook Islands. In Penrhyn, the mean annual wave height has remained relatively unchanged since 1979 (SPC Wave climate: Penrhyn; accessed July 2020; Bosserelle et al. 2015). In the Northern Cook Islands, projected changes in wave properties under RCP8.5 by 2090 (purple bar in Figure 23) show a small and non-significant decrease in wave height in November to May with no change in wave period or direction during December–March (Australian Bureau of Meteorology and CSIRO 2014). Wave height is projected to increase in September, otherwise no significant changes are projected *(low confidence)*, with less variable wave directions. An increase in the height of storm waves is indicated in December–March *(low confidence)*.

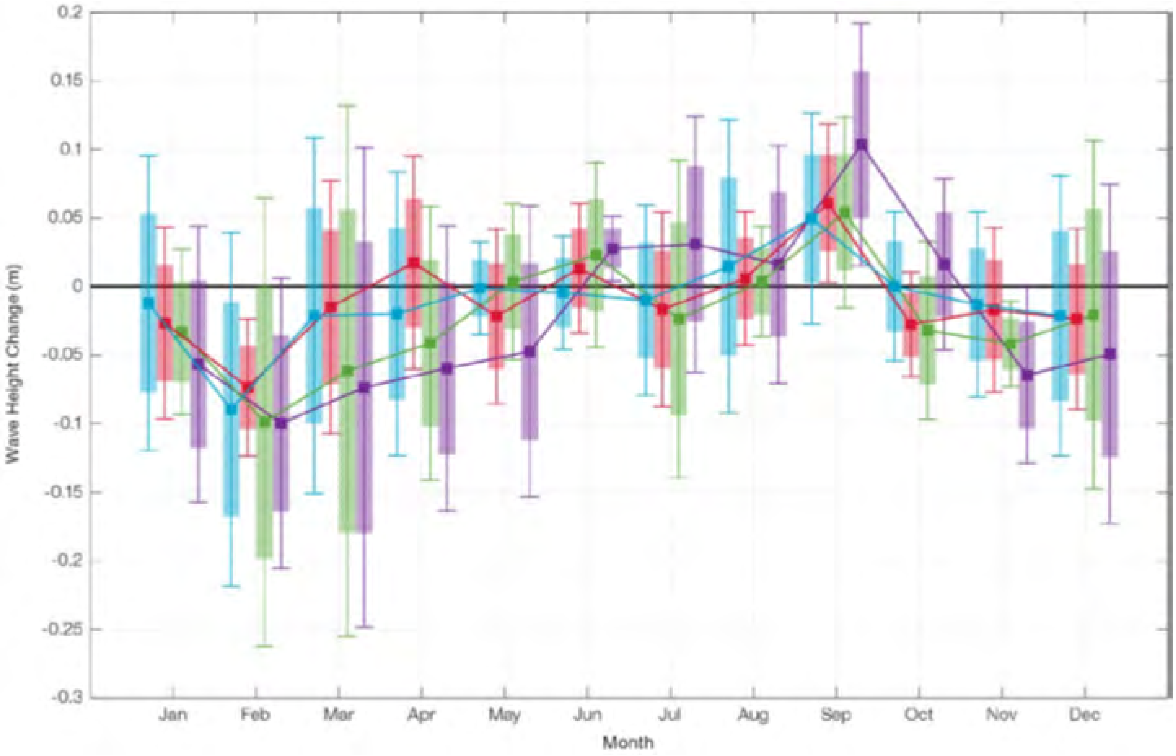


Figure 23 Mean annual cycle of change in wave height (m) in the Northern Cook Islands. Shaded boxes show 1 standard deviation around the ensemble means, and error bars show the 5–95% range inferred from the standard deviation. Colours represent RCP scenarios and time periods: blue 2035 RCP4.5 (medium emissions), red 2035 RCP8.5 (high emissions), green 2090 RCP4.5 (medium emissions), purple 2090 RCP8.5 (high emissions). Source: Australian Bureau of Meteorology and CSIRO (2014)

Inspecting shells on the chaplets © Cook Islands Ministry of Marine Resources

5.2 Atmosphere related projections

5.2.1 What are the projections for tropical cyclones under future climate conditions?

A recent study by Knutson et al. (2020) assesses the impact of a 2°C global warming on TC activity around the world. This includes the southwest Pacific (Figure 24). Below are some key messages from that study relevant to the southwest Pacific region; care must be exercised when interpreting these results for any local region in the Pacific, such as the Cook Islands.

- High confidence that TC frequency will decrease over the coming century (-40% to 0%).
- Low confidence in the changes in frequency of category 4-5 TCs (-40% to +20%).
- Medium to high confidence in an increase in TC rainfall rates (-2 to +16%)
- Medium to high confidence in the increase in average TC intensity (-6 to +12%).

The projected change in average TC intensity, combined with sea level rise and increased rainfall rates would increase TC impacts (CSIRO and SPREP, 2021). The reader is referred to Chand et al. (2020) for a review of tropical cyclones in the Pacific and implications of climate change.

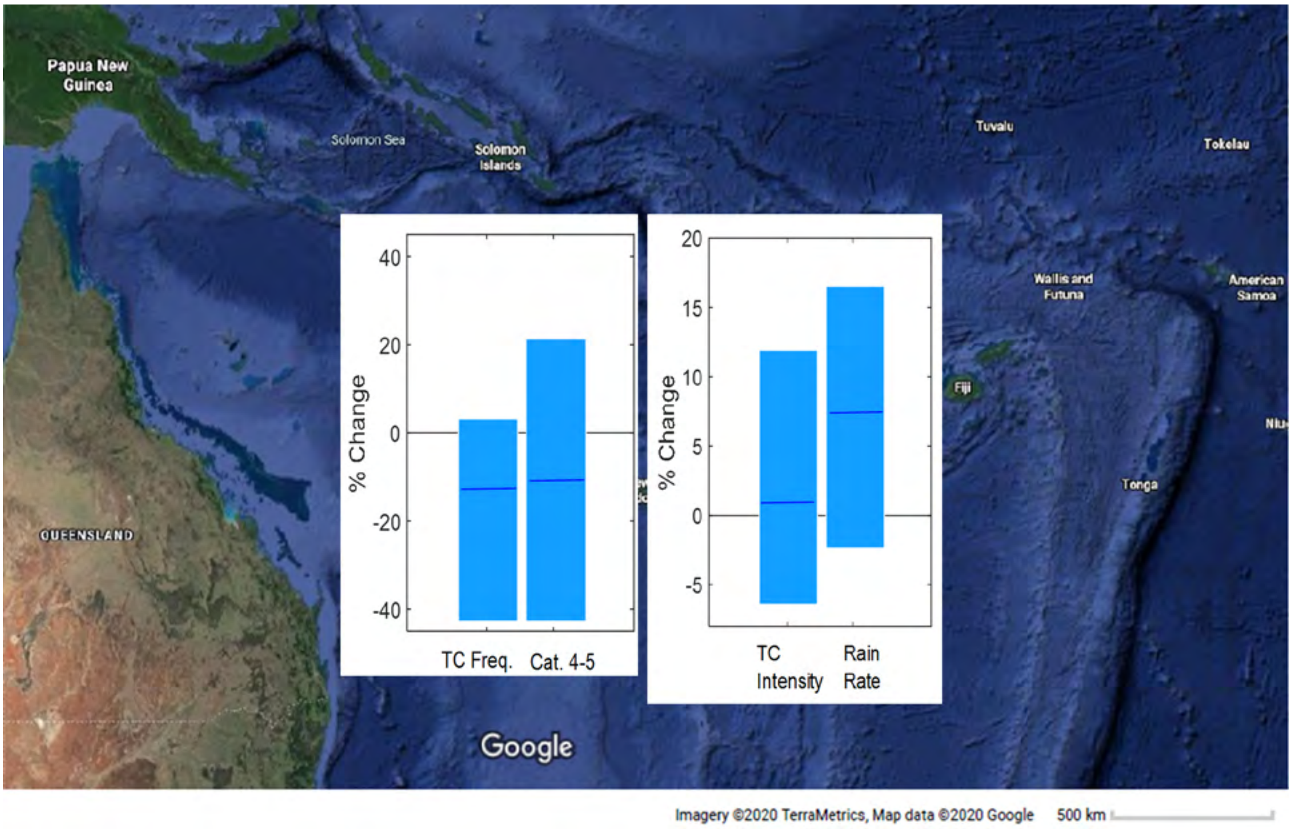


Figure 24 Southwest Pacific TC activity projection for a 2°C global warming. The bars on the left indicate a likely decrease in the total number of TCs, and a likely decrease but possible increase in severe (category 4-5) TCs. Bars on the right plot indicate a likely increase (but possible decrease) in the average intensity of TCs, and the very likely increase in the rainfall they bring. Shown are the median (blue line) and the 10th–90th-percentile ranges (blue bars). Information used to construct this figure is derived from Knutson et al. (2020).

Chand et al. (2017) found that around a group of small island nations (for example, Fiji, Vanuatu, Marshall Islands and Hawaii, including Tuvalu) by the late 21st century, TCs could become more frequent (20–40 %) during El Niño events and less frequent during La Niña events (Figure 25). Therefore, year to year variability will remain high.

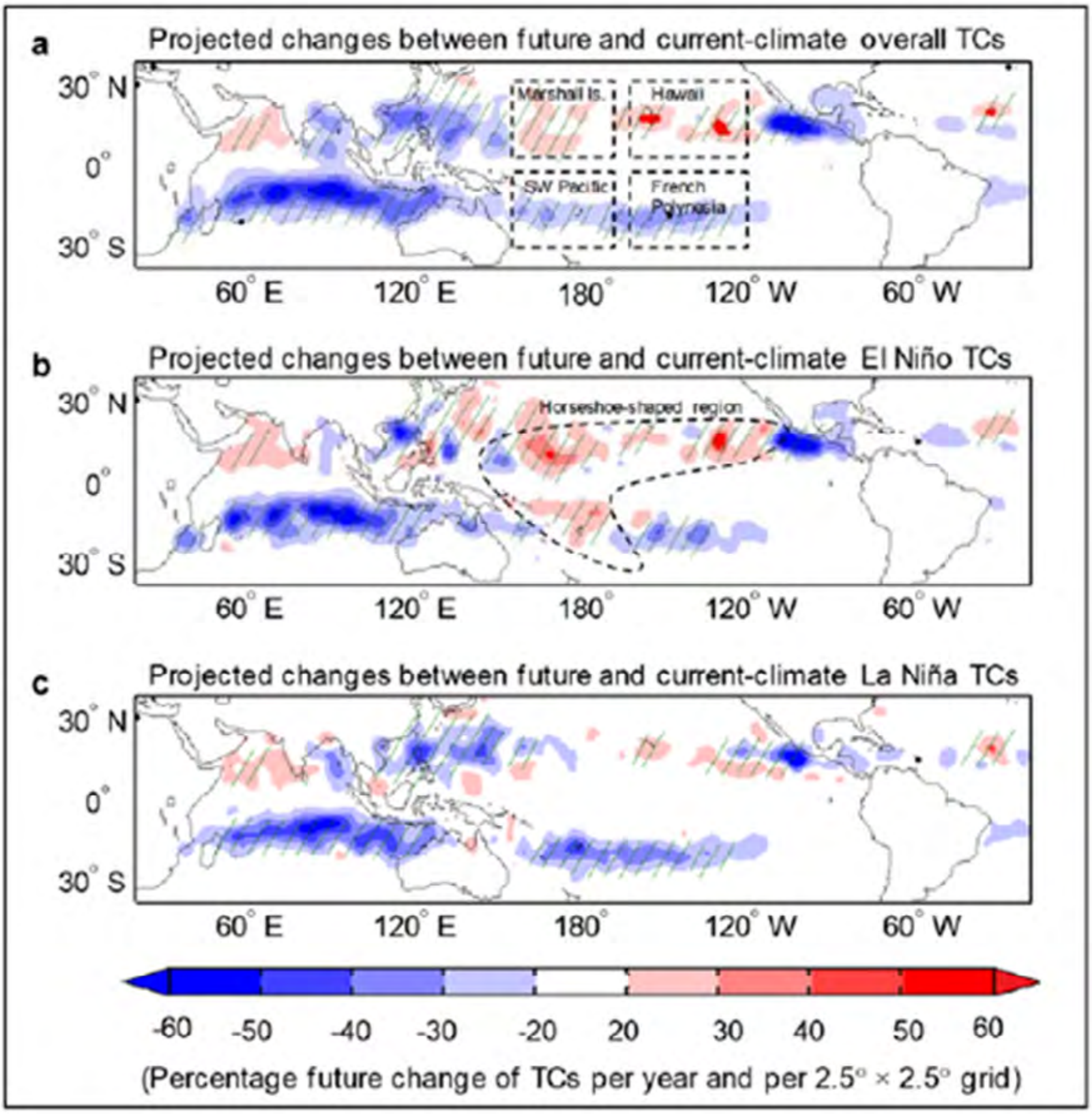


Figure 25 CMIP5 based projected changes in tropical cyclone density between the late-20th and late 21st centuries for (a) all years, (b) El Niño years, and (c), La Niña years. Red shading indicates projected increases in tropical frequency. Stippling denotes changes that are statistically significant at the 95% level. See Chand et al. (2017).

Higher sea-level projections in future are likely to increase the impacts from storm surge, destructive waves and coastal inundation over Manihiki lagoon in the event of a cyclone, and these in turn are also likely to accelerate coastal erosion and salt water intrusion over freshwater aquifers and cultivable land (Figure 26).

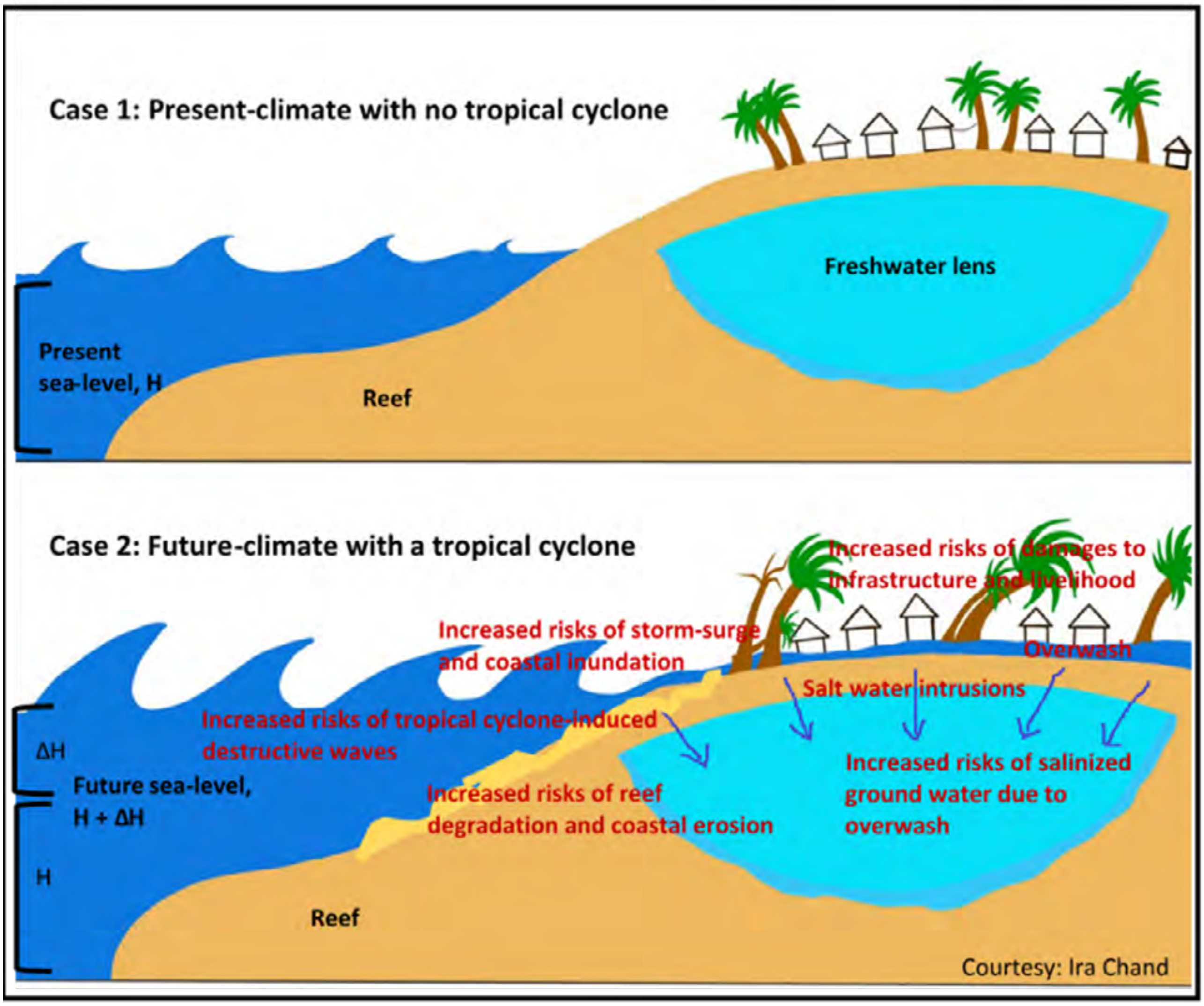


Figure 26 Conceptual diagram of likely changes in tropical cyclone-induced impacts a warming climate for two cases: Case 1 represents a condition in the present climate without any tropical cyclone, and Case 2 represents a likely condition in a future climate with a severe tropical cyclone event.

6 Conclusions and recommendations for future work

Many changes and concerns for the future of the industry have been identified in the *Draft National Aquaculture Development Plan 2020 – 2025 (Ministry of Marine Resources and SPC Pacific Community 2020)*, with measures to address these issues outlined in the *Draft Cook Islands Pearl Industry Strategic Plan*. Work undertaken in the NextGen case study can inform some of the proposed initiatives outlined in the strategic plan, e.g. pearl farming technologies: spat collection methods; conditioning time; shell cleaning etc., identifying potential future farming locations, predation issues, and oyster nutrition driven by nutrient availability (MMR and SPC 2012).

This Next Gen assessment is indicating the production of pearls is already vulnerable to marine heatwaves and tropical cyclones. This vulnerability is likely to rise due to projected increases in marine heatwaves and ocean acidification by 2050 especially under a high emission scenario. While the projected decrease in cyclone frequency would reduce vulnerability, the projected change in average cyclone intensity, combined with sea level rise and increased rainfall rates would increase cyclone impacts. The projected rise in sea level is expected to increase the vulnerability of people living on the atolls, especially under a high emission scenario.

The severity of that impact will be influenced considerably by the magnitude and direction of change of factors that influence lagoon flushing and circulation, such as increased sea level, and changes to wind, waves, and reef integrity. Given the complexity of interacting factors, addressing the question of vulnerability requires scenario-based wave-flow hydrodynamic modelling. The projections provided in this study provide a credible envelope of change to be used within hydrodynamic modelling.

Combating the likely effects of ocean acidification on pearl quality will be difficult because pearl oysters cannot be maintained economically under controlled conditions for the time it takes to produce pearls – the oysters need to be held in sheltered marine areas. However, there may be scope for identifying areas that remain buffered against lower aragonite saturation states. Such places can be found near well-flushed, carbonate-rich coral reefs, and close to areas with a good cover of seagrass and macrophytes (Bell et al. 2013). Selective breeding is also likely to provide an important mitigation strategy to provide increased resistance to long-term changes in ocean chemistry (Fitzer et al. 2019).

The design of the entire infrastructure of pearl farms needs to be assessed to increase durability during severe cyclones. Placing pearl oysters in deeper water to reduce the adverse effects of higher SST on nacre quality should also reduce damage by storms.

The pearl industry is in a reasonable position to adapt to some of the projected effects of climate change. Any effects of higher SSTs and ocean acidification on the collection of spat can probably be overcome by increasing the proportion of spat produced in hatcheries under controlled temperature and pH conditions, albeit at increased cost. It may also be possible to harvest the pearls during the cooler months of the year (Pickering et al. 2011). Relocation of pearl farming operations to atolls located further south in the Cook Islands region can also provide an adaptation option in the longer term.

7 References

Andréfouët, S., et al. (2020). "The lagoon geomorphology of pearl farming atolls in the Central Pacific Ocean revisited using detailed bathymetry data." *Marine Pollution Bulletin* 160: 111580.

Australian Bureau of Meteorology and CSIRO (2011). Climate Change in the Pacific: Scientific Assessment and New Research. Volume 1: Regional Overview.

Australian Bureau of Meteorology and CSIRO (2014). Climate Variability, Extremes and Change in the Western Tropical Pacific: New Science and Updated Country Reports., Pacific-Australia Climate Change Science and Adaptation Planning Program, Australian Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation, Melbourne, Australia.

Bell, J. D., et al. (2013). "Mixed responses of tropical Pacific fisheries and aquaculture to climate change." *Nature Climate Change* 3(6): 591-599.

Bell, J.D., Johnson, J.E. and Hobday, A.J. (2011). Vulnerability of tropical Pacific fisheries and aquaculture to climate change. SPC FAME Digital Library.

Brown, M. (2017). Bill Appropriation, BUDGET ESTIMATES 2017/2018. Book 1 Appropriation bill Appropriations and commentary. http://procurement.gov.ck/wp-content/plugins/ck_procurement/uploads/100943_18-07-2018_2018_Cook-Islands_Budget-Book-1_Appropriation-Bill_Appropriations-and-Commentary.pdf

Bosserelle, C., Reddy, S. and Krüger, J. (2016). Waves and Coasts in the Pacific: cost analysis of wave energy in the Pacific, SPC.

Callaghan, D.P., Nielsen, P., Cartwright, N., Gourlay, M.R. and Baldock, T.E. (2006). Atoll lagoon flushing forced by waves. *Coastal Engineering*, 53(8): 691-704.

Cambers, G., et al. (2017). Implementing climate change adaptation interventions in remote outer islands of the Pacific Island Region. *Climate Change Adaptation in Pacific Countries*, Springer: 3-18.

Chand, S. S., et al. (2017). "Projected increase in El Niño-driven tropical cyclone frequency in the Pacific." *Nature Climate Change* 7(2): 123-127.

Chand, S. S., et al. (2020). A Review of South Pacific Tropical Cyclones: Impacts of Natural Climate Variability and Climate Change. *Climate Change and Impacts in the Pacific*, Springer: 251-273.

CSIRO and SPREP (2017). Developing Climate Change Information for the Pacific: Guidance Material to Raise Awareness and Facilitate Sectoral Decision-Making Using Science-Based Climate Change information and Services. Melbourne, Australia, Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat for the Pacific Regional Environment Program (SPREP).

CSIRO and SPREP (2021). Enhanced 'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for Cook Islands. Final report to the Australia-Pacific Climate Partnership for the NextGen Climate Projections for the Western Tropical Pacific Project. Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP), CSIRO Technical Report, Melbourne, Australia.

CSIRO and SPREP (2022). Step-by-step: How to undertake a hazard-based climate change impact assessment. A report to the Australia-Pacific Climate Partnership-funded Climate Projections for the western tropical Pacific (NextGen) project. Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP), CSIRO Technical Report, Melbourne, Australia.

De Deckker, P. (2016). "The Indo-Pacific Warm Pool: critical to world oceanography and world climate." *Geoscience Letters* 3(1): 1-12.

De Scally, F. A. (2008). "Historical Tropical Cyclone Activity and Impacts in the Cook Islands" *Pacific Science* 62(4): 443-459.

Diamond, H., Lorrey, A., Knapp, K. and Levinson, D. (2012). Development of an enhanced tropical cyclone tracks database for the southwest Pacific from 1840 to 2010. *International Journal of Climatology*, 32(14): 2240-2250.

Diggles, B. and Hine, P. (2001). "Mortality of black-lip pearl oysters (Pinctada margaratifera) in Manihiki Lagoon." *NIWA client report prepared for the Ministry of Marine Resources, Government of the Cook Islands. Wellington. New Zealand.*

Dutheil, C., et al. (2020). "Characterization of south central Pacific Ocean wind regimes in present and future climate for pearl farming application." *Marine Pollution Bulletin* 160: 111584.

Falter, J.L., Atkinson, M.J. and Merrifield, M.A. (2004) Mass-transfer limita tion of nutrient uptake by a wave-dominated reef flat community. *Limnology and Oceanography* 49: 1820-1831.

Fitzer, S.C., et al. (2019). Selectively bred oysters can alter their biomineralization pathways, promoting resilience to environmental acidification. *Global Change Biology*, 25(12): 4105-4115.

GHD (2015). Manihiki Lagoon - Strategic Environmental Assessment for Removal of Derelict Black Pearl Farming Infrastructure, Ministry of Marine Resources.

Green, R.H., Lowe, R.J. and Buckley, M. (2018) Hydrodynamics of a tidally forced coral reef atoll. *Journal of Geophysical Research: Oceans* 123: 7084-7101. DOI: https://doi.org/10.1029/2018JC013946.

Gregor, L. and Gruber, N. (2021). 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* 13, 777–808. DOI: https://doi.org/10.5194/essd-13-777-2021.

Grottoli, A.G., Warner, M.E., Levas, S.J., Aschaffenburg, M.D., Schoepf, V., McGinley, M., Baumann, J.H. and Matsui Y. (2014). The cumulative impact of annual coral bleaching can turn some coral species winners into losers. *Global Change Biology* 20, 3823–3833. DOI: doi: 10.1111/gcb.12658.

Gruber, N., et al. (2019). The oceanic sink for anthropogenic CO_2 from 1994 to 2007. *Science*, 363(6432): 1193-1199.

Gueguen, Y., et al. (2016). "Integrated management of pearl culture in French Polynesia in the context of global change: Synopsis of existing results." *Estuarine, Coastal and Shelf Science* 182: 229-234.

Gruber, N., Clement, D., Carter, B.R., Feely, R.A., van Heuven, S., Hoppema, M., Ishii, M., Key, R.M., Kozyr, A., Lauvset, S.K., Lo Monaco, C., Mathis, J.T., Murata, A., Olsen, A., Perez, F.F., Sabine, C.L., Tanhua, T. and Wanninkhof, R. (2019). The oceanic sink for anthropogenic CO_2 from 1994 to 2007. *Science* 363: 1193-1199. DOI: 10.1126/science.aau5153.

Hambrey Consulting (2011). Opportunities for the development of the Pacific islands' mariculture sector. Noumea, New Caledonia., Secretariat of the Pacific Community. .

Hobday, A.J., Alexander, L.V., Perkins, S., Smale, D.A., Straub, S.C., Oliver, E.C.J., Benthuysen, J.A., Burrows, M.T., Donat, M.G., Feng, M., Holbrook, N.J., Moore, P.J., Scannell, H.A., Sen Gupta, A. and Wernberg, T. (2016) A hierarchical approach to defining marine heatwaves. *Progress in Oceanography* 141: 227-238.

Hobday, A.J., Oliver, E.C.J., Sen Gupta, A., Benthuysen, J.A., Burrows, M.T., Donat, M.G., Holbrook, N.J., Moore, P.J., Thomsen, M.S., Wernberg, T. and Smale, D.A. (2018) Categorizing and naming marine heatwaves. *Oceanography* 31. DOI: https://doi.org/10.5670/oceanog.2018.205.

Holbrook, N.J., et al. (2021). Impacts of marine heatwaves on tropical western and central Pacific Island nations and their communities. *Global Planet Change:* 103680.

Hurd, et al. (2018). Current understanding and challenges for oceans in a higher-CO_2 world. *Nature Climate Change*, 8, 686–694

Huang, B., Liu, C., Banzon, V., Freeman, E., Graham, G., Hankins, W., Smith, T. and Zhang, H-M. (2020). Improvements of the Daily Optimum Sea Surface Temperature (DOISST) - Version 2.1. DOI: https://doi.org/10.1175/JTECH-D-19-0177.1.

Innis, T., Allen-Waller, L., Brown, K.T., Sparagon, W., Carlson, C., Kruse, E., Huffmyer, A.S., Nelson, C.E., Putnam, H.M. and Barott, K.L. (2021). Marine heatwaves depress metabolic activity and impair cellular acid–base homeostasis in reef-building corals regardless of bleaching susceptibility. *Global Change Biology* 27, 2728-2743. DOI: 10.1111/gcb.15622.

IPCC (2019). Summary for Policymakers. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.).

IPCC (2021). Summary for Policymakers. 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* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

Knutson, T., Camargo, S.J., Chan, J.C., Emanuel, K., Ho, C.H., Kossin, J., Mohapatra, M.,Satoh, M., Sugi, M., Walsh, K. and Wu, L. (2020). Tropical cyclones and climate change assessment: Part II. Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society,* 101 (3): E303E322.

Kuchinke, M., et al. (2014). "Seasonal variability of aragonite saturation state in the Western Pacific." *Marine Chemistry* 161: 1-13.

Le Moullac, G., et al. (2016a). "*Pinctada margaritifera* responses to temperature and pH: Acclimation capabilities and physiological limits." *Estuarine, Coastal and Shelf Science* 182: 261-269.

Le Moullac, G., et al. (2016b). "Impact of pCO_2 on the energy, reproduction and growth of the shell of the pearl oyster Pinctada margaritifera." *Estuarine, Coastal and Shelf Science* 182: 274-282.

Li, S., Liu, C., Huang, J., Liu, Y., Zhang, S., Zheng, G., Xie, L. and Zhang, R. (2016). Transcriptome and biomineralization responses of the pearl oyster Pinctada fucata to elevated CO_2 and temperature. *Scientific Reports* 6: 18943. DOI: https://doi.org/10.1038/srep18943.

McKenzie, E. (2004). *A cost-benefit analysis of projects implemented to assist the black pearl industry in Manihiki Lagoon, Cook Islands*, South Pacific Applied Geoscience Commission.

Ministry of Marine Resources and SPC Pacific Community (2020). DRAFT Cook Islands Aquaculture Development Plan 2012–2016. Noumea., Ministry of Marine Resources, Rarotonga and Secretariat of the Pacific Community.

MMR and SPC (2012). Cook Islands Aquaculture Development Plan 2012–2016. Rarotonga., Ministry of Marine Resources.

Oppenheimer, M., et al. (2019). Chapter 4: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.* H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte et al. https://www.ipcc.ch/srocc/

Parker, L., Ross, P., O'Connor, W., Borysko, L., Raftos, D. and Pörtner, H. (2012) Adult exposure influences offspring response to ocean acidification in oysters. *Global Change Biology* 18: 82-92. DOI: https://doi.org/10.1111/j.1365-2486.2011.02520.x.

Pickering, T.D., et al. (2011). Vulnerability of aquaculture in the tropical Pacific to climate change. *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Bell JD, Johnson JE and Hobday AJ (eds). Noumea, New Caledonia., Secretariat of the Pacific Community.

Pineda, J. (1991). Predictable upwelling and the shoreward transport of planktonic larvae by internal tidal bores. *Science* 253: 548-551.

Ponia, B. (2005). "A quiet achiever: aquaculture in the Pacific." *Fisheries Newsletter-South Pacific Commission* 115: 41.

Ponia, B., (2010). A review of aquaculture in the Pacific Islands 1998-2007: tracking a decade of progress through official and provisional statistics, SPC Noumea (New Caledonia)

Rongo, T. and C. Dyer. (2015). *Using local knowledge to understand climate variability in the Cook Islands,* Office of the Prime Minister.

Sangare, N., Lo-Yat, A., Le Moullac, G., Pecquerie, L., Thomas, Y., Lefebvre, S., Le Gendre, R., Beliaeff, B. and Andréfouët, S. (2020). Impact of environmental variability on *Pinctada margaritifera* life-history traits: A full life cycle deb modeling approach. *Ecological Modelling* 423, 109006.

Schoepf, V., Grottoli, A.G., Levas, S.J., Aschaffenburg, M.D., Baumann, J.H., Matsui, Y. and Warner, M.E. (2015). Annual coral bleaching and the long-term recovery capacity of coral. *Proceedings of the Royal Society B: Biological Sciences* 282, 20151887. DOI: https://doi.org/10.1098/rspb.2015.1887.

Smith, R., et al. (2003). Manihiki and Penrhyn Atoll oceanographic monitoring buoys: an application of coastal GOOS. Suva., South Pacific Applied Geoscience Commission.

Southgate, P. (2011). PEARL OYSTER information bulletin #19, SPC.

Taylor, K.E., Stouffer, R.J. and Meehl, G.A. (2012). An Overview of CMIP5 and the Experiment Design. Bulletin of the American Meteorological Society 93, 485-498. DOI: 10.1175/BAMS/-D-11-00094.1.

Welladsen, H.M., et al. (2010). "The effects of exposure to near-future levels of ocean acidification on shell characteristics of Pinctada fucata (Bivalvia: Pteriidae)." *Molluscan Research* 30(3): 125.

Van Hooidonk, R., et al. (2016). Local-scale projections of coral reef futures and implications of the Paris Agreement. *Scientific reports,* 6(1): 1-8.

Van Vuuren, D.P., et al. (2011). "The representative concentration pathways: an overview." *Climatic Change* 109(1-2): 5-31.

Van Wynsberge, S., Menkes, C., Le Gendre, R., Passfield, T. and Andréfouët, S. (2017). Are sea surface temperature satellite measurements reliable proxies of lagoon temperature in the South Pacific? *Estuarine, Coastal and Shelf Science* 199: 117-124.

Van Wynsberge, S., Le Gendre, R., Sangare, R., Aucan, J., Menkes, C., Liao, V. and Andréfouët, S. (2020). Monitoring pearl farming lagoon temperature with global high resolution satellite-derived products: An evaluation using Raroia Atoll, French Polynesia. *Marine Pollution Bulletin* 160: 111576.

Wyatt, A.S.J., Lowe, R.J., Humphries, S. and Waite, A.M. (2010). Particulate nutrient fluxes over a fringing coral reef: relevant scales of phytoplankton production and mechanisms of supply. Marine Ecology Progress Series 405: 113-130.

Yukihira, H., et al. (1998). "Effects of body size on suspension feeding and energy budgets of the pearl oysters Pinctada margaritifera and P. maxima." *Marine Ecology Progress Series* 170: 119-130.

Zhang, Z.L., Falter, J., Lowe, R., Ivey, G. and McCulloch, M. (2013). Atmospheric forcing intensifies the effects of regional ocean warming on reef-scale temperature anomalies during a coral bleaching event. *Journal of Geophysical Research: Oceans* 118: 4600–4616.

Zhang, Y., Liu, Z., Song, X., Huang, S., Wang, L. and Song, L. (2019). The inhibition of ocean acidification on the formation of oyster calcified shell by regulating the expression of Cgchs1 and Cgchit4. *Frontiers in Physiology* 10. DOI: 10.3389/fphys.2019.01034.

8 Appendix

Comparison of the Manihiki Lagoon monitoring buoy seawater temperature and pH measurements (3 m depth) with the larger scale gridded observation datasets is provided in Figure A1 (top). Analyses confirmed that the OISST data are representative of values obtained at the monitoring buoy location, particularly from 2012 onwards. Prior to 2012, the monitoring buoy recorded relatively low temperatures on occasions that were not reflected in the daily mean values of the OISST data. The monitoring buoy data owners are investigating the prevalence of lower temperatures in the record prior to 2012, which are absent after 2012, to assess whether it is associated with changes in the instrument, location, or sampling program.

The OceanSODA-ETHZ data provide monthly mean surface pH values (Figure A1, bottom) and understandably does not reflect the natural day-to-day variation in pH measured within the lagoon. However, OceanSODA-ETHZ values are well within the range of values measured at the monitoring buoy.

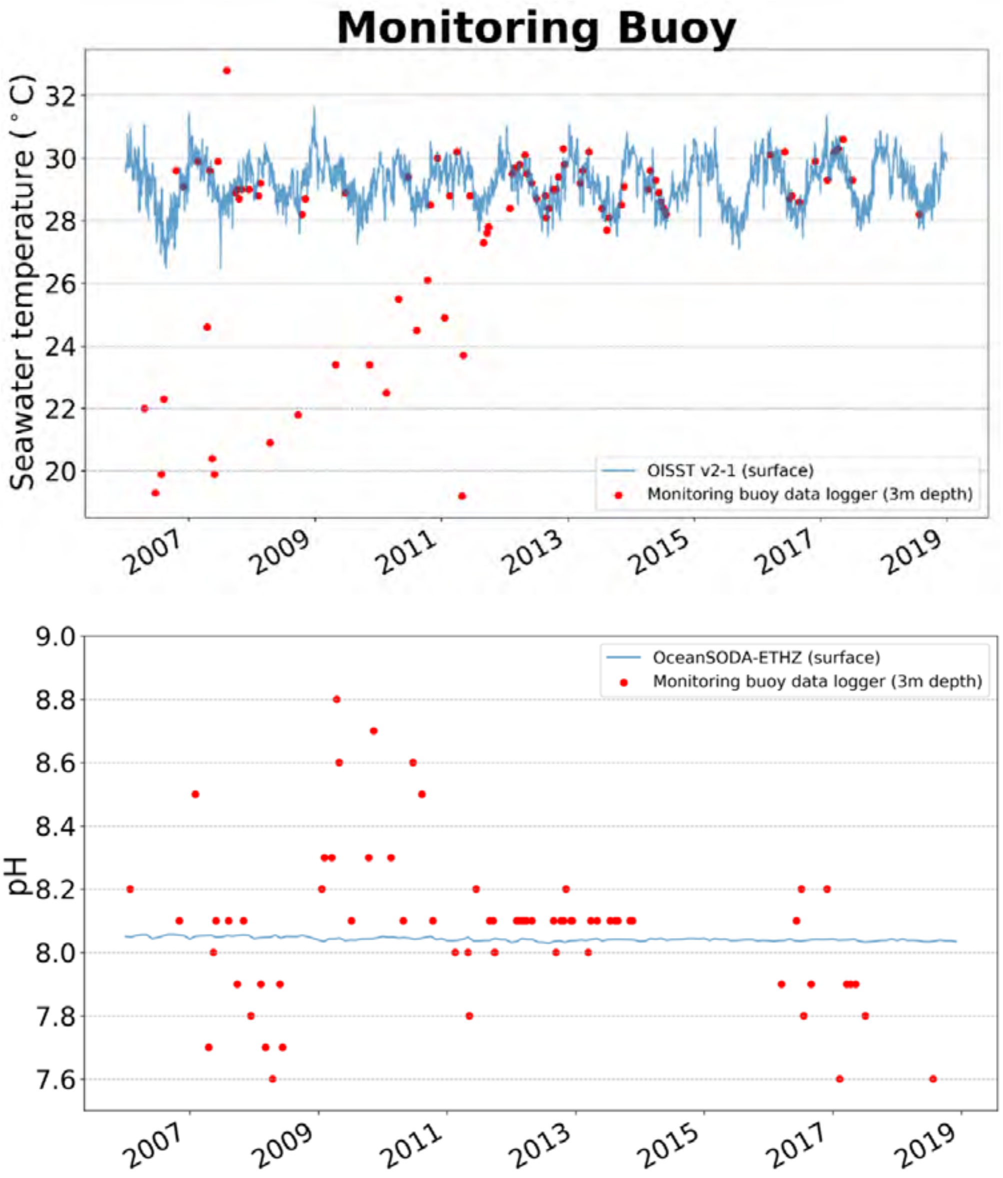
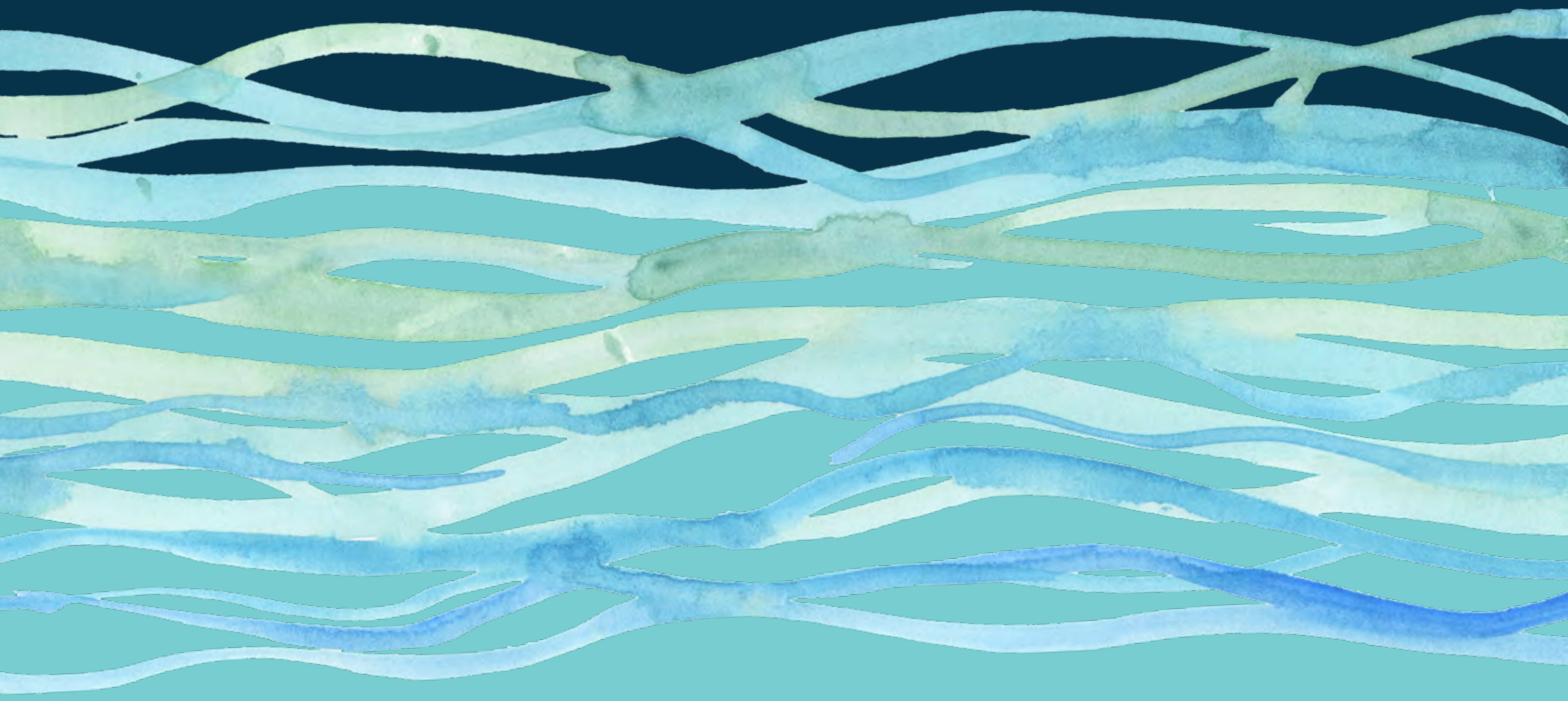


Figure A1. Comparison of seawater temperature (°C) (top) and pH (bottom) from the Manihiki Lagoon monitoring buoy (measured at 3m depth; red circles). Daily OISST v2.1 SST data and monthly mean OceanSODA-ETHZ data (blue line) extracted at the location of the monitoring buoy (latitude: -10.398194; longitude: 160.9994).

This type of comparison is very useful in evaluating whether the gridded datasets are representative of values typically found at the monitoring buoy location within the lagoon. This is despite the values for the monitoring buoy and the gridded datasets being on different time and space scales. While measurements from the monitoring buoy are snapshots in time, i.e. different times of the day and various intervals throughout a year, the OISST data are gridded (1/4 °) daily mean surface temperature measurements, and the OceanSODA-ETHZ data are gridded (1 °) monthly mean surface measurements.

Unfortunately, data from the Manihiki Lagoon monitoring buoy only became available at the end of the project timeframe, and this, together with the low sampling at the buoy and hence low sample size (88 measurements over 13 years, 2006-2018), precluded applying a detailed delta-scaling (i.e. applying projected changes to local observations) approach in this case study.



www.rccap.org www.pacificmet.net www.pacificclimatechange.net

Australian Aid
CSIRO
SPREP
Secretariat of the Pacific Regional Environment Programme