ICRI
International Coral Reef Initiative

GCRMN
Global Coral Reef Monitoring Network

Status and Trends of Coral Reefs of the PACIFIC 1980 - 2023

Edited by:
Jérémy Wicquart, Erica K. Towle, Thomas Dallison, Francis Staub, and Serge Planes

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GCRMN Global Coral Reef Monitoring Network
www.gcrmn.net

ICRI International Coral Reef Initiative
www.icriforum.org

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Citation

Wicquart J., Towle E. K., Dallison T., Staub F., and Planes S. (eds.), 2025. *Status and Trends of Coral Reefs of the Pacific: 1980-2023.* Global Coral Reef Monitoring Network (GCRMN) and International Coral Reef Initiative (ICRI). http://doi.org/10.59387/WIUJ2936.

ACKNOWLEDGEMENTS

Funding

The publication of this report would not have been possible without the encouragement and financial support provided by the French Ministry for Ecological Transition, the Gouvernement Princier - Principauté de Monaco, the Government Offices of Sweden, and the Bloomberg Ocean Initiative. We sincerely thank them for their invaluable contribution.

Coordination

We would like to give our acknowledgements to the Australian Institute of Marine Science (AIMS) as the host of the Global Coral Reef Monitoring Network (GCRMN). We also acknowledge the guidance and support from the International Coral Reef Initiative (ICRI) Secretariat, and the US Department of State, and the National Oceanic and Atmospheric Administration (NOAA) as the 2021-2024 ICRI co-chairs.

We further thank the Secretariat of the Pacific Regional Environment Programme (SPREP) for their continued support to the GCRMN Pacific regional node, the production of this report and continued advocacy for the conservation of coral reefs in the Pacific.

The coordination of this report would not have been possible without the support from MAREPOLIS and Blue Pangolin Consulting Ltd. And we extend our gratitude to the supporting agencies, organisations and programmes who have enabled the production of this report.

The production of this report benefited greatly from the organisation of a workshop held in Auckland, New Zealand (November 2023) and we sincerely thank James Nikitine and Gabriella Wina from the Blue Cradle foundation, and Anne Tessier, for their invaluable contributions to the organization of this event.

Data contribution

This report would not have been possible without the dedicated efforts of all those who collected data on benthic cover in coral reefs of the Pacific over the last decades. We extend our deepest gratitude to them for generously sharing their data, which was instrumental in the production of this report. Their contributions are recognized in the following paragraphs or in the “Authors’ Contributions” section.

We thank the Reef Check Foundation, and its volunteers who have spent countless hours collecting these data.

We thank the Service National d’Observation CORAIL from CRIOBE who kindly provided data.

We thank the National Park Service, Pacific Island Network Inventory and Monitoring Program, for sharing their benthic marine database. Funding for the collection of these data was provided by the National Park Service Inventory and Monitoring Program.

We gratefully acknowledge the Ministries of Fisheries and Environment of the Government of Tonga, the Waitt Institute, the 100 Island Challenge, Scripps Institution of Oceanography, and the Vava’u Environmental Protection Association for generously providing coral reef monitoring data from Tonga.

We thank C2O (Coasts, Climate, Oceans) Pacific for providing coral reef monitoring data, made possible through the support of the TasiVanua and Nguna-Pele Resource Networks, the Vanuatu Fisheries Department, and the Vanuatu Department of Environment, and funding from the PEBACC project (SPREP) and RESCCUE project (SPC).

This publication makes use of data products provided by the Micronesia Coral Reef Monitoring Program, the Marshall Islands Marine Resources Authority, the Marshall Islands Conservation Society, and the College of the Marshall Islands. The data analysis and interpretations presented in this report are solely that of the current authors.

We thank the Wildlife Conservation Society (WCS) and particularly Emily Darling, Kim Fisher, Sharla Gelfand and Amkieltiela for the development of the MERMAID platform and their help with the use of the associated mermaidr R package.

We thank the ReefCloud team for their help on contacting project administrators within this platform, notably Samuel Chan and Manuel Gonzalez Rivero.

Data analyses

We are grateful to Murray Logan for his valuable guidance on machine learning models and for generously sharing an R script for visualizing grey ribbons on modeled temporal trends. We also extend our thanks to Jacqueline De La Cour, Gang Liu, Erick Geiger, and Liam Lachs for their insightful advice on the CoralTemp dataset.

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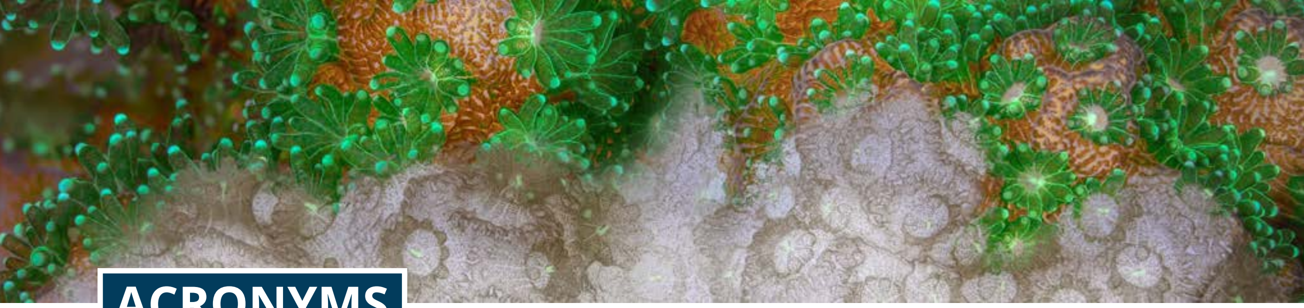


ACRONYMS

ACA	Allen Coral Atlas
CI	Confidence Interval
COTS	Crown-of-Thorns Starfish
EEZ	Economic Exclusive Zone
ENSO	El Niño Southern Oscillation
GBM	Gradient Boosting Machine
GCRMN	Global Coral Reef Monitoring Network
GEE	Google Earth Engine
ICRI	International Coral Reef Initiative
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
ML	Machine Learning
MPA	Marine Protected Area
NOAA	National Ocean and Atmospheric Administration
PRIA	Pacific Remote Island Areas
RMSE	Root Mean Squared Error
SPREP	Secretariat of the Pacific Regional Environment Programme
SST	Sea Surface Temperature
WoRMS	World Register of Marine Species
WRI	World Resources Institute

FOREWORD

The Pacific is home to a quarter of the world's coral reef ecosystems, vital to the wellbeing of our communities and beyond. Yet the unprecedented global mass coral bleaching event, still observed in many parts of the world, stresses the urgent and transformative actions needed to alter the increasing pressure from the impacts of climate change, land-based pollution, coastal development, and unsustainable fishing practices.

Our Pacific Leaders have agreed that the Ocean and Environment is one of the 7 thematic priorities under the "2050 Blue Pacific Strategy", recognising the need for the region to continue the work to meet SDG targets beyond 2030. Our SPREP Strategic Plan addresses the ocean as a cross-cutting theme across our four programmatic areas of biodiversity conservation, climate change, environmental governance, and waste and pollution. SPREP is the secretariat for the Noumea Convention, the Pacific's regional seas convention, our regional legal instrument to safeguard the health, conservation and protection of our marine environment.

Central to the stewardship and care of our ocean is the health of our coral reef and coastal ecosystems. The Pacific Coral Reef Action Plan 2021-2030 provides a framework to foster collaborative actions and initiatives and ensure that they are developed and implemented in a coordinated and synergistic way. Using research and monitoring is one of the key priority areas of the Plan to investigate the health of coral reefs, inform decisions and measure the impacts of initiatives to manage reefs.

In this journey, the GCRMN provides the necessary support to process, standardise and synthesize all the data collected by many scientific and technical organisations, government departments, NGOs, academic institutes and individuals throughout the region. I would like to commend the collaborative efforts and work in producing this Pacific GCRMN report, coordinated by CRIOBE research laboratory, and its timely release and launch during the third United Nations Ocean Conference in Nice, France.

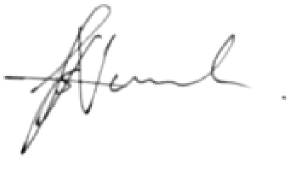
The report provides evidence and signals in both ways: the overall trend shows that Pacific coral reefs are still coping with ongoing ecological changes, while also highlighting the variety of national situations and changes in coral species composition, along with other indicators such as macroalgae. This means that ecosystem services provided by coral reefs are also evolving and could affect the way they contribute to provide food, protection from the sea, and critical tourism revenue for Pacific Island countries and territories.

The report comes at the right time as it provides evidence and validates some of the key messages that our Pacific delegations are taking to the 3rd UN Ocean Conference. It also further validates and supports the advocacy of Pacific Small Island Developing States for urgent and ambitious emissions reduction that enable us to stay within "1.5°C to Stay Alive." While the report is slightly optimistic that our coral reefs continue to fight strongly to survive, we need to continue to fight for global cooperation to minimize and manage the multiple pressures we continue to subject our ocean and its ecosystems, many to the extent of tipping beyond the point of no return.

SPREP will ensure that the report is accessible, shared and utilised as much as possible. We hope that this new report will serve as a catalyst for increased collaboration towards coral reef conservation and management strategies in our region.

To complement this work, SPREP is currently undertaking a Pacific coral monitoring assessment aimed at better understanding coral monitoring programmes and initiatives. The results and findings will add to our body of knowledge, identifying where coral reef monitoring could be strengthened as we work to support Pacific Island countries to build the additional capacities and resources needed to strengthen evidence-based policy making.

We can only survive as the Pacific Islands Region if our coral reef ecosystems are in a state to continue to protect and provide for our Pacific Island communities, as they have done since we first settled our islands.



Sefanaia Nawadra
Director General
Secretariat of the Pacific Regional Environment Programme (SPREP)

EXECUTIVE SUMMARY

Key Points

- Coral reefs of the GCRMN Pacific region cover **65,255 km^2** which represent **26.13%** of the world's coral reef extent.
- Overall, hard coral cover remained relatively stable at around **25.5%** from 1990 to 2022.
- However, hard coral cover declined in 1998 (**-2.4%**) and again in 2014-2017 (**-3.7%**) due to global coral bleaching events induced by marine heatwaves.
- Macroalgae cover and coralline algae cover increased by **2.7%** and **1.9%**, respectively, from 1990 to 2022.
- The number of people living within 5 km from coral reefs increased by **28.7%** from 2000 to 2020 at the regional scale.
- Mean sea surface temperature over coral reef areas across the Pacific increased by **+0.82°C** between 1985 and 2023, driven by climate change, representing a warming rate of **0.22°C** per decade.
- Coral reef monitoring efforts varied between countries and territories within the region, ranging from **0** monitoring sites in Nauru to over **2,000** in Hawai'i, underscoring the need to strengthen and expand monitoring initiatives throughout the Pacific.

Introduction

Coral reefs are increasingly threatened by a range of human-induced stressors from anthropogenic local drivers of loss including overfishing, pollution, and coastal development, to regional stressors such as climate change and ocean acidification. These stressors lead to multiple changes in coral reef structure, function, and composition, threatening the well-being, livelihoods, and cultural identity of the millions of people who rely on them worldwide. One of the most evident consequences of these stressors is the continued decline in global hard coral cover, intensified by mass coral bleaching events as a result of human-driven climate change. In recognition of these losses, and the global loss of biodiversity, international and regional targets have been adopted, requiring robust, large-scale, and long-term monitoring to inform policies and conservation strategies.

Established in 1995 as an operational network of the International Coral Reef Initiative (ICRI), the Global Coral Reef Monitoring Network (GCRMN) supports this effort through a network of 10 regional nodes. The GCRMN produces reports on the status and trends of coral reefs at both regional and global scales, and aims to provide the best-available data on the world's coral reefs to inform policy, strengthen management capacity, and build technical expertise. Since its inception, the GCRMN has released six global reports and several regional assessments, offering critical scientific insights to support countries in implementing and achieving their national and international commitments.

Regional Context

The Pacific, one of the 10 GCRMN regions, accounts for 26.13% (65,255 km²) of the world's coral reef extent. The coral reefs in this region fall under the jurisdiction of 30 different countries and territories, with coral reef extent ranging significantly from 6 km² in Jarvis Island to 14,592 km² in Papua New Guinea.

Pacific coral reefs are characterized by extraordinary biodiversity shaped by a wide range of geological and environmental conditions. The region is home to approximately 600 hard coral species accounting for nearly 70% of all known hard coral species worldwide. Species richness is particularly high in the Western Pacific, which hosts the greatest diversity of hard corals in the region, whereas more isolated territories such as Hawai'i and Pitcairn exhibit lower comparative species richness.

The Pacific region, though vast, has a relatively small human population of 14.2 million as of 2020, with Papua New Guinea's population accounting for 65% of the total Pacific region. Due to the geography of the region, a significant portion of people live near coral reefs. It is estimated that 30% of the population live within 5 km of a coral reef, which rises to 70% when Papua New Guinea, the region's largest island, is excluded. Of the 30 countries and territories in the region, the entire population of 12 countries or territories lives within 5 km of a coral reef. From 2000 to 2020, the number of people living within 5 km of a coral reef grew by 28.7%.

Coral reefs in the Pacific provide critical ecosystem services that support food security, coastal protection, cultural identity, and local economies. Fisheries are a key provisioning service, supplying essential protein as well as income to millions of inhabitants. Reefs also regulate coastal environments by dissipating wave energy - reducing flood risk for nearly half of the region's hazard-exposed coastal populations. Culturally, reefs are deeply woven into traditions, spirituality, and social life, while also critical to economies by driving tourism in destinations like Palau, Fiji, and Hawai'i. In some areas, reef-related tourism contributes significantly to Gross Domestic Product (GDP) and employment. However, human impacts on coral reefs threaten these services, endangering both the ecosystems and the livelihoods that depend on them.

Hence, quantifying how coral reefs of the Pacific have changed over the previous decades is key to understanding the drivers of these changes and to guide appropriate measures to protect these ecosystems.

Methods used

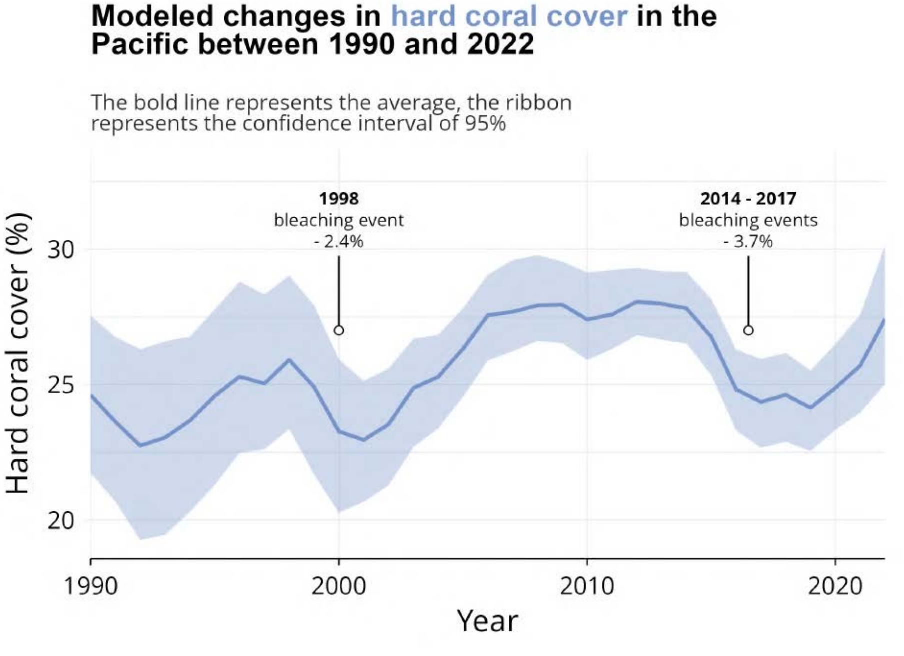
We estimated the temporal trends in hard coral cover, three groups of algae (coralline algae, macroalgae, turf algae), and three hard coral families (*Acroporidae, Pocilloporidae, Poritidae*), through the integration of 50 datasets. Together, these datasets aggregate a total of 8,193 monitoring sites where 15,482 surveys were conducted between 1987 and 2023. The temporal trends were estimated using machine learning statistical models to take into account the bias of the non-homogeneous distribution of monitoring over time and space.

Results

Stability of hard coral cover

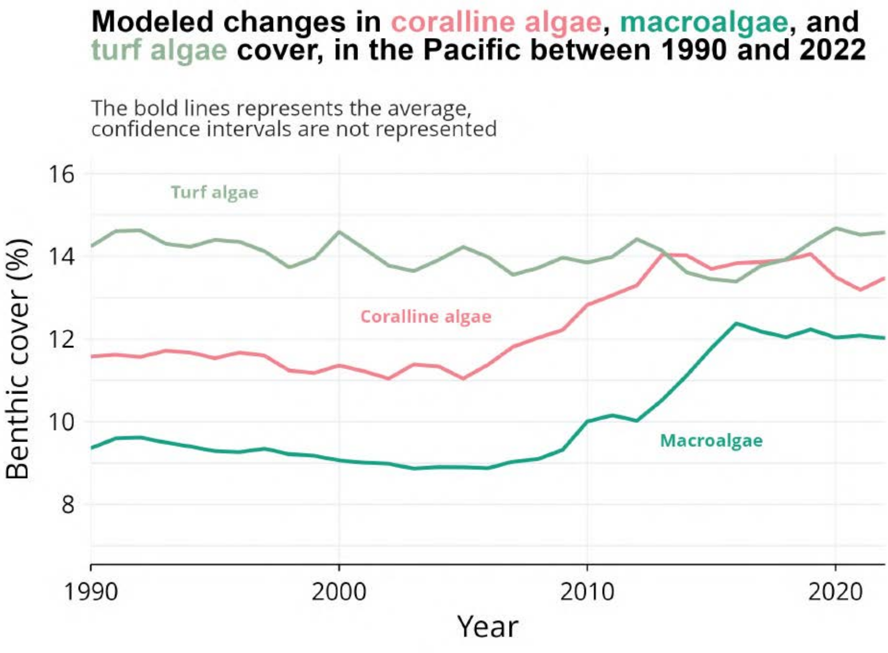
Hard coral cover remained relatively stable at around 25.5% from 1990 to 2022 across the coral reefs of the Pacific, contrasting with declining trends reported in some other regions worldwide. However, the trend in hard coral cover over the 32-year period was not continuous, showing alternating phases of decline, recovery, and stability. Periods of abrupt declines occurred following El Niño events, which triggered widespread coral bleaching events. In particular, hard coral cover declined by 2.4% and 3.7% following the global coral bleaching events in 1998 and 2014-2017, respectively. The recent impact of the 2023-2024 Fourth Global Coral Bleaching Event was outside of the study's time period and its impacts have therefore not been quantified. Because of the likely impacts of this recent event, if the study considered monitoring data from 1990-2025 and not 1990-2022, it is likely that a decline, rather than an overall stability in hard coral cover, would have been observed. Interestingly, the mean hard coral cover recovered over a 6-year period following the aforementioned bleaching events to the regional average value of 25.5%. The recovery capacity of hard coral cover in the region can be attributed to the vast geographical distribution and high ecological diversity of reefs which result in asynchronous dynamics - declines in some areas are balanced by recoveries in others - creating a patchwork of trends throughout the Pacific. Additionally, this resilience might also be explained by the fact that most reefs are located in areas with low human population density, and their remoteness helps minimize chronic anthropogenic local pressures such as overfishing, pollution, and sediment runoff following deforestation.

In addition to regional hard coral cover, we explored the composition of hard coral assemblage, looking at the evolution of three major families over time. Our results show that the cover of hard corals from the *Acroporidae* and *Pocilloporidae* families have slightly declined from 1990 to 2020, whereas the cover of *Poritidae* remained stable. This indicates that although hard coral cover remained relatively stable over the period studied, the composition of the coral assemblage has changed. Since coral species belonging to the *Poritidae* family are mostly massive corals, and a part of those belonging to *Acroporidae* and *Pocilloporidae* are branching, the structural complexity of reefs is likely to have decreased between 1990 and 2022.



Increase in algae cover

In addition to hard coral cover, we estimated the temporal trends in the benthic cover of three algae categories. The long-term average cover of coralline algae across Pacific coral reefs from 1990 to 2022 was 12.3%. Coralline algae cover showed a significant increasing trend over the period, with a rise from 11.6% in 1990 to 13.5% in 2022. Since these algae are known for their role in facilitating coral recruitment, their increase may have contributed to the increase in hard coral cover. Macroalgae cover followed a similar pattern to coralline algae with a positive trend over the period from 9.3% in 1990 to 12% in 2022. Although we have not been able to explain the reason for the increase in macroalgae, it is possible that it is due to a decrease in the biomass of herbivorous fishes or an increase in nutrient inputs. Macroalgae compete with hard corals for space and light, and their increase may have negatively impacted reef accretion. The increase of macroalgae can be viewed as a precursor signal of change in coral reef ecosystems and attention should be taken in controlling macroalgal overgrowth wherever possible. Finally, turf algae, although the most abundant algae category with an average cover of 14.1%, remained stable from 1990 to 2022.

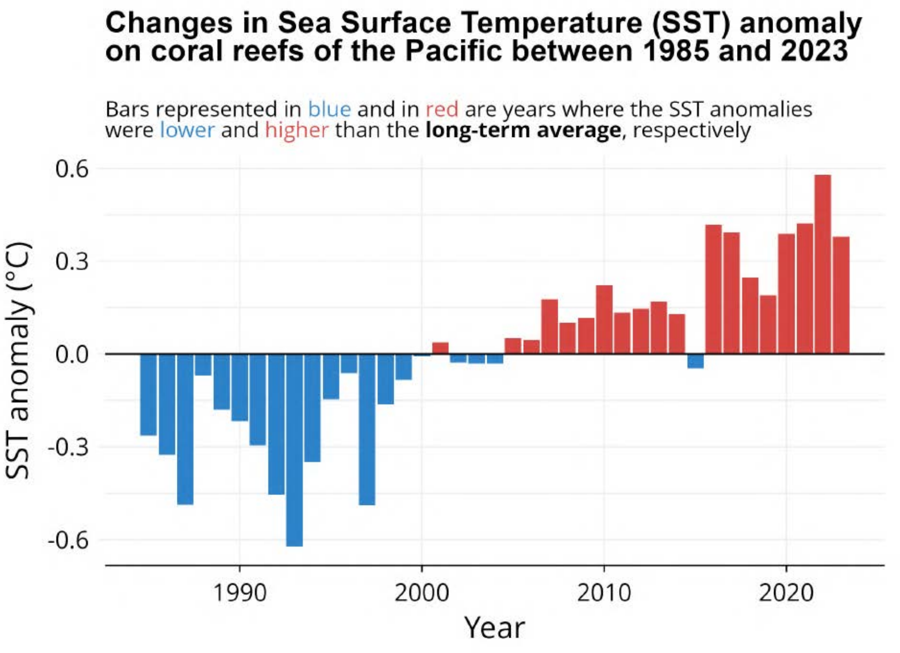


Increase of threats

The effects of climate change are an escalating threat to coral reefs of the Pacific. Driven by the rise in atmospheric greenhouse gas concentrations over the past century due to human activities, the environmental conditions in which coral reefs evolve have changed. Between 1985 and 2023, the average Sea Surface Temperature (SST) over Pacific coral reefs rose by 0.82°C, equivalent to a warming rate of 0.22°C per decade. This trend is observed across nearly all Pacific countries and territories, with Hawai'i, Fiji, and Tonga experiencing the highest increases. In parallel, marine heatwaves - periods of unusually high and prolonged sea temperatures - have become more frequent, intense, and longer-lasting. These events, especially those in 1998, 2014–2017, and 2023-2024, have led to widespread coral bleaching.

Coral reefs of the Pacific are also impacted by cyclones, another disturbance affected by climate change. Between 1980 and 2023, 945 cyclones passed within 100 km of reefs in the region, with the Northwestern and Southwestern Pacific experiencing the highest exposure. The impacts vary widely based on cyclone characteristics and geographical context. Climate projections suggest that while cyclone frequency may decrease or remain stable by the end of the century, cyclone intensity is expected to rise, particularly in the South Pacific.

In addition to the increasing threats associated with climate change, coral reefs of the Pacific are affected by a wide range of threats that are often more spatially localized. Although we have not been able to quantify the evolution of these threats due to the lack of available data sources at the regional scale, their impacts are relatively well known. For example, Crown-of-Thorns Starfish which can decrease hard coral cover during population outbreaks are potentially exacerbated by human-induced changes such as nutrient runoff and predator depletion due to overfishing. Other examples include nutrient enrichment and sedimentation, unsustainable fishing practices, pollution, and the introduction of non-native species.



Recommendations

Monitoring coral reefs is essential for the effective implementation of conservation and management plans, and reporting on and implementing national policies, regional targets, and international commitments. Regular and long-term monitoring allows scientists and managers to detect early signs of stress, such as coral bleaching, coral mortality, incidents of disease or declining fish populations. Data collected through monitoring provides a scientific basis for making informed decisions and quantifies the effectiveness of management actions. Without accurate and up-to-date information, conservation efforts risk being ineffective or too late to prevent damage. From the present report, it is clear that a homogeneous and standardised coral reef monitoring in the Pacific is lacking. Four main recommendations are proposed to remedy this situation.

First, spatial representativeness should be improved as monitoring is currently biased toward a small number of countries and territories like Hawai'i and French Polynesia, leaving significant reef areas like Papua New Guinea under-monitored. Solutions include redirecting funding, developing and enhancing capacity both locally and nationally, utilising citizen science programs, and organizing scientific expeditions.

Second, long-term monitoring programs need to be developed and maintained as only 2.8% of sites have been surveyed for more than 15 years. Such sites are essential for understanding long-term changes occurring on coral reefs. There is a great need to increase available resources and finances to maintain monitoring programs, as well as increase the use and adoption of technologically-advanced protocols such as artificial intelligence that may help reduce part of the resource burden to monitor coral reefs.

Third, monitoring programs should expand beyond benthic cover to include additional biological indicators such as fish biomass. New technologies like eDNA and photogrammetry can make this expansion of indicators more feasible. In addition, monitoring the stressors affecting coral reefs such as Crown-of-Thorns starfish or nutrient concentrations would also help inform and assess the effectiveness of management measures at local scales.

Finally, facilitating data access and reuse is essential. Most datasets lack compliance with the FAIR (Findable, Accessible, Interoperable, Reproducible) data principles, limiting their utility. Data owners are encouraged to publish datasets in online repositories, use global data standards, and include comprehensive metadata. Open access and better data practices will facilitate improved collaborations and inform environmental policies faster.

Conclusions

By using 50 datasets on benthic coral reefs monitoring, we estimated the temporal trends in the benthic cover of seven benthic categories. We also calculated how certain threats to coral reefs of the Pacific have changed over the last decades. Our results show a complex situation.

The overall stability in hard coral cover can be seen as a signal of hope in a context of global decline of hard coral cover. We have put forward various hypotheses, which are not mutually exclusive, to explain this result. Importantly, the benthic cover of coralline algae increased from 1990 to 2022, which may have benefited the recruitment of hard corals.

However, our results show an increase in macroalgae cover, which can be the result of depletion in herbivore fish population due to fishing or an increase in nutrient runoff. As macroalgae compete with hard corals for space, this increase may have negatively impacted coral reef accretion. In addition, we show that the composition of the hard coral assemblage has changed over the period. The hard coral families with the most complex skeletons have declined, partly in favour of families with massive skeletons that provide less shelter for reef organisms such as fish. Finally, we have shown that the average sea surface temperature of coral reefs in 2022 was warmer by 0.82°C than in 1990 due to the effects of climate change.

Because of the large geographical extent of the Pacific region, these regional results may differ from trends at the individual country or territory scale. It is also important to note that our findings capture only a portion of the long-term trajectories of Pacific coral reefs in the Anthropocene, and significant ecological shifts may have taken place prior to the period covered by our analysis. Furthermore, we relied on a limited set of indicators to assess changes in coral reef conditions, which may not encompass the full complexity of ecosystem dynamics. For these reasons, the continued development and strengthening of comprehensive monitoring programs is essential to improve our understanding of coral reef changes, support early detection of emerging threats, and inform effective conservation and management strategies.

INTRODUCTION

Context and objectives of the GCRMN

Coral reefs of the Anthropocene are increasingly threatened by a range of human-induced stressors from anthropogenic local drivers of loss including overfishing, pollution, and coastal development, to regional stressors such as climate change and ocean acidification. The cumulative impacts of these stressors have significantly altered the structure, function, and composition of coral reef ecosystems worldwide (Hughes et al., 2017). One of the most documented consequences is the sustained decline in hard coral cover exacerbated by mass bleaching events driven by anomalously high sea surface temperatures such as those recorded in 1998, 2010, and 2014-2017 (Skirving et al., 2019), and most recently during the Fourth Global Mass Bleaching Event (Reimer et al., 2024). Beyond these ecological changes, coral reef degradation undermines the ability of these ecosystems to provide vital services to human populations including coastal protection, food security through fisheries, and income from tourism (Woodhead et al., 2019).

To halt the global decline of coral reefs, many countries have adopted national strategies and committed to international environmental agreements such as the Convention on Biological Diversity (CBD). The Kunming-Montreal Global Biodiversity Framework, adopted in 2022, sets ambitious targets for 2030 and 2050, many of which are directly relevant to coral reef conservation (CBD, 2022; ICRI, 2024). However, achieving these goals requires robust, quantitative data collected at large spatial scales to monitor progress and inform adaptive management. Long-term, standardized monitoring of coral reefs is essential to detect changes, understand underlying drivers, and support timely and effective conservation responses tailored to regional and national contexts (Orr et al., 2022).

Established in 1995 as an operational network of the International Coral Reef Initiative (ICRI), the Global Coral Reef Monitoring Network (GCRMN) plays a central role in global coral reef monitoring efforts. Working through ten regional nodes - including the Pacific - the GCRMN produces regular syntheses of the status and trends of coral reefs based on harmonized scientific data. The network's mission is to improve understanding of reef health, support evidence-based policy and management, and build the technical and human capacity for reef monitoring at local, national, and regional levels. The GCRMN's global and regional reports are designed for policymakers, managers, researchers, and international organizations to guide conservation strategies and help countries meet their national and international biodiversity commitments. In combining science, capacity building, and policy relevance, the GCRMN is a cornerstone of efforts to safeguard coral reefs in an era of accelerating environmental change.

Since its establishment, the GCRMN has published six global reports, most of which were released between 1998 and 2008. The most recent - "Status of Coral Reefs of the World: 2020" (Souter et al., 2021) - was the first global report based on a comprehensive quantitative analysis and was published in 2021. Alongside these global assessments, the GCRMN has produced numerous regional and thematic reports focusing on the status and trends of coral reefs in specific areas, such as the Caribbean (Jackson et al., 2014), the Western Indian Ocean (Obura et al., 2017), the Pacific (Moritz et al., 2018), and the East Asian Seas (Kimura et al., 2022). Unlike global reports, regional GCRMN reports offer more detailed insights at the level of individual countries and territories.

History of GCRMN reports

Key Milestones in GCRMN History

1995

GCRMN is officially launched as a global framework under ICRI to coordinate coral reef monitoring and data collection

1998

The first global coral bleaching event occurs, highlighting the need for improved reef monitoring

2000-2010

GCRMN expands its network to regional nodes, publishing periodic global "Status of Coral Reefs of the World" reports

2016

The network is restructured to enhance collaboration with regional monitoring initiatives and standardize data collection methods

2021

The latest GCRMN Global Report is published, providing a comprehensive analysis of coral reef trends over the past 40 years based on data from more than 300 organizations and 12,000 monitoring sites worldwide

The 2018 GCRMN Pacific report

The "*Status and Trends of Coral Reefs of the Pacific*", published in 2018, was the most recent report of coral reef health across the Pacific region prior to this current report. It presented the status and long-term trends of percent cover of hard coral and macroalgae and herbivorous fish biomass from 1989 to 2016 (Moritz et al., 2018). The main findings of the 2018 report were the stability of average hard coral cover at the scale of the Pacific region with an average hard coral cover across all islands and all years of 25.6%, as well as an increase in macroalgae cover over this period. A gradual change in hard coral assemblage was also observed with a decline of the genus *Pocillopora* and an increase in the genus *Porites*, suggestive of a reduction in reef structural complexity. A decline in herbivorous fish biomass was also observed across the sampling period, likely driven by the unsustainable exploitation of *Acanthuridae* fishes.

Objectives of the current report

Since the 2018 GCRMN Pacific report concentrated on temporal trends between 1989 and 2016, it did not account for events after 2016. Notably, the global bleaching event of 2014–2017 which was documented at local and national scales by various researchers, has yet to be addressed in a Pacific regional synthesis. To address this gap, the editors produced the current report, "*Status and Trends of Coral Reefs of the Pacific: 1980–2023*", which provides an updated overview of the state of coral reefs in the region and incorporates the most significant changes observed over the past several years.

The objectives of the current report are to describe the changes that have occurred on shallow-water coral reefs of the Pacific from 1980 to 2023. In particular, the report aims to answer two major questions: 1) How has the percentage cover of benthic categories changed from 1990 to 2022? and 2) How have threats to coral reefs of the Pacific changed between 1980 and 2023? We answered these questions by using two categories of indicators.

Firstly, the temporal trends of four biological indicators associated with coral reef benthic organisms were reported: the benthic cover of hard coral, macroalgae, turf algae, and coralline algae. Contrary to the previous GCRMN global report, the algae cover indicator was disaggregated into macroalgae, turf algae, and coralline algae to better describe changes that occurred on coral reefs of the Pacific. In addition, three major hard coral families (Acroporidae, Pocilloporidae, and Poritidae) were assessed to understand broad changes in the regional hard coral assemblages.

Secondly, we used indicators associated with threats to coral reefs of the Pacific. Indicators related to human populations living near coral reefs were used as a broad proxy of direct human impacts to these ecosystems. In addition, two indicators, the thermal regime over coral reefs of the Pacific, and the long-term trend in Sea Surface Temperature (SST) and daily SST anomalies, were reported. Finally, we provided the trajectories of cyclones within 100 km from a coral reef within the region, and the intensities of these cyclones in terms of maximum sustained wind speed.

Structure of the current report

Similar to all GCRMN reports, the current report is divided into two main parts. The first part of the report corresponds to a synthesis of coral reef temporal trends at the scale of the entire Pacific region (see Part 1 - Synthesis for the Pacific region). This part is divided into four sections, with a general description of coral reefs of the region, the main threats they face, the temporal trends in percentage cover of benthic categories, and a set of recommendations to improve the collection and usefulness of monitoring data.

The second part of the report includes the syntheses of coral reef temporal trends for each country and territory of the Pacific region (see Part 2 - Syntheses for countries and territories). Each of these chapters includes a brief introduction, a quantitative description of the thermal regime and cyclones over coral reefs of the country or territory, as well as a more qualitative evaluation of the other threats. These chapters also include a section about the temporal trends in benthic cover of major benthic categories. However, contrary to the first part of the report, the temporal trends in benthic cover of major hard coral families were not included within country and territory syntheses. For some chapters, case studies were provided by national experts/contributors to further contextualise particular aspects of their coral reefs. In particular, socioeconomic case studies are included in some chapters where data and resources allowed, marking a critical step forward in including human dimensions data alongside biophysical monitoring data.

In addition, further details expanding on the results discussed in the report can be found in the Supplementary Materials, along with a comprehensive description of the Materials and Methods used to collect and analyse the data.

PART

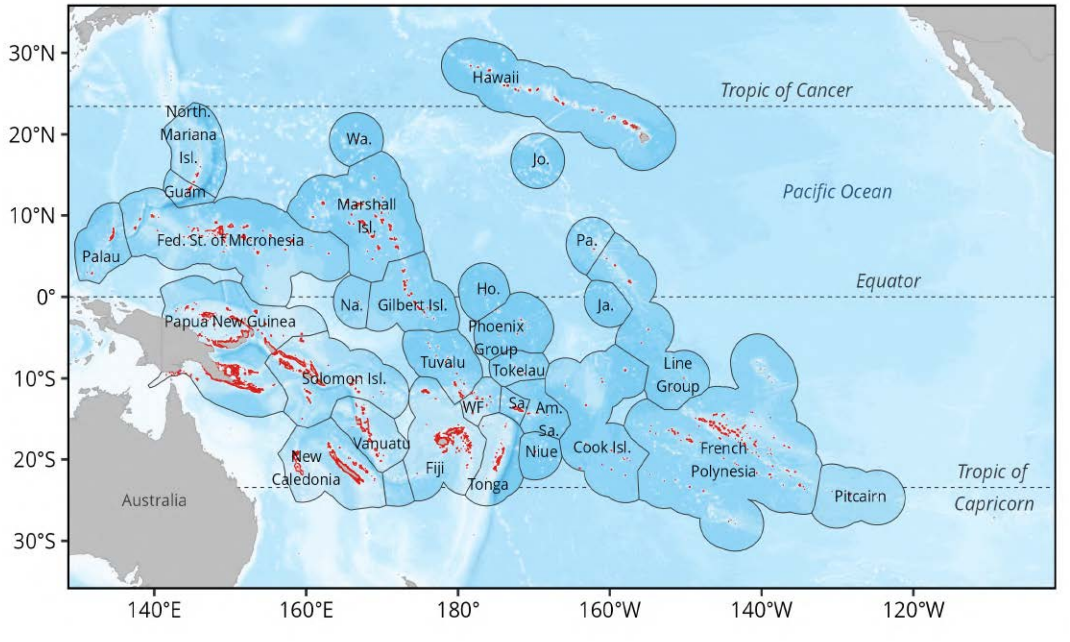
1

Synthesis for the Pacific Region

Coral reefs of the Pacific

Distribution and extent

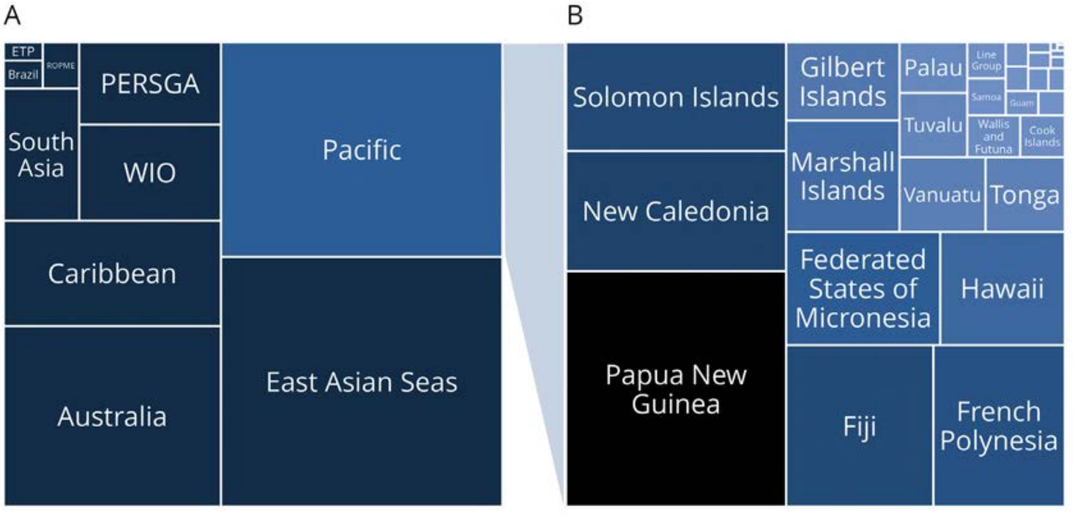
The GCRMN Pacific region (hereafter simply called the Pacific) ranges from Palau to Pitcairn on a longitudinal axis over 11,000 km, and from Hawaii to French Polynesia on a latitudinal axis over 7,200 km (Figure 1.1.1). After the East Asians Seas region, the Pacific has the second highest coral reef extent of GCRMN regions (Figure 1.1.2 - A). Its 65,255 km² of coral reefs, which represent 26.13% of the world's coral reefs, reside within 30 economic exclusive zones, corresponding to as many countries and territories (Figure 1.1.1).



▲ **Figure 1.1.1.** Map of the economic exclusive zones (EEZ) of the Pacific GCRMN region (hereafter called countries and territories). The unlabelled economic exclusive zone represents the overlapping claimed area of Matthew and Hunter Islands by both France and Vanuatu. Am. Sa. = American Samoa, Ho. = Howland and Baker islands, Ja. = Jarvis Island, Jo. = Johnston Atoll, Na. = Nauru, Pa. = Palmyra Atoll, Sa. = Samoa, Wa. = Wake Island, WF = Wallis and Futuna. Isl. = Islands. The distribution of coral reefs is represented in red.

Although most of the countries within the region constitute a unique territory, three countries have non-adjacent territories, namely the Republic of Kiribati, the United States, and France (Figure 1.1.1). The Republic of Kiribati includes three territories of the Gilbert Islands, the Line Group, and the Phoenix Group. The United States integrates several states and territories with the Hawaiian archipelago, Guam, the Commonwealth of the Mariana Islands, American Samoa, and seven islands referred to as the Pacific Remote Island Areas (Howland, Baker, Jarvis, Kingman, Palmyra, Johnston atoll, and Wake island). Finally, France aggregates three territories in the Pacific which are French Polynesia, New Caledonia, and Wallis and Futuna.

The extent of coral reefs varies greatly from one country or territory to another, ranging from 14,592 km² for Papua New Guinea (22.36% of coral reef of the Pacific) to 6 km² for Jarvis Island (0.01% of coral reefs of the Pacific) (Table 1.1.1). Papua New Guinea, New Caledonia, Solomon Islands, and Fiji represent more than half of the region's coral reef extent (Figure 1.1.2 - B).



▲ **Figure 1.1.2.** Relative coral reef extent between GCRMN regions (A) and between countries and territories within the GCRMN Pacific region (B). The area of each polygon is proportional to the relative coral reef extent of the associated region. The absolute values of coral reef extent for countries and territories of the Pacific are provided in Table 1.1.1. In subfigure A, ETP is the acronym for Eastern Tropical Pacific and WIO for Western Indian Ocean. PERSGA (Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden) and ROPME (Regional Organization for the Protection of the Marine Environment) regions correspond to the Red Sea and Gulf of Aden, and Arabian/Persian Gulf, respectively.

Diversity

With the notable exception of Papua New Guinea and New Caledonia, most of the Pacific landmass derives from volcanism activity, through two major geological processes (Goldberg, 2018). First, subduction zone volcanism is behind the formation of islands located where the Australian and Pacific plates meet, like those from Fiji, Tonga, and Solomon Islands (Neall and Trewick, 2008). Second, hotspot volcanism is responsible for the formation of islands located within the Pacific plate, such as the Hawaiian archipelago and the Society Islands, in French Polynesia (Neall and Trewick, 2008). Over time, reef organisms have formed fringing reefs on the flanks of volcanic islands by accumulating calcium carbonate. Under their own weight, these islands gradually sank, while coral reef organisms continued to accumulate carbonates. Eventually, this process has led to the formation of a barrier reef, separated from the island by a lagoon. When the original volcanic island has completely disappeared beneath the surface, the barrier reef surrounds only the lagoon, forming an atoll (Figure 1.1.3 ; Steibl et al., 2024). In addition to these three main types of islands, which vary widely in size and shape, are special formations such as closed atolls and submerged reefs. Estimates of the total number of islands in the GCRMN Pacific region ranged from around 2,600 (Goldberg, 2018) to 3,400 (Maragos and Williams, 2011), depending on the definition used to characterize an island. The reef formations on these islands can in turn be subdivided into different geomorphic zones, such as reef slope, reef crest, or patch reef (Kennedy et al., 2021).

In addition to these differences in geological characteristics, coral reefs of countries and territories of the Pacific also develop under different environmental conditions. Gove et al. (2013) have found a large spatial heterogeneity across United States Pacific coral reefs in terms of SST, wave energy, and irradiance. The authors also found that the long-term average in chlorophyll-a concentration, a proxy for nutrient concentration, was 1.8 to 3.4 greater in coral reefs near the Equator compared to the other United States coral reefs of the Pacific. These environmental differences between coral reefs of countries and territories of the Pacific are not only reflected in long-term average, but also by acute climatic disturbances such as marine heatwaves (see section Thermal regime) or cyclones (see section Cyclones). Finally, currents across the region have important impacts on connectivity between coral reef communities of the Pacific (Siedler et al., 2013).

Numerous species have adapted to this wide range of environmental conditions. We estimated that around 600 hard coral species are present in the Pacific, which correspond to 70% of the world's hard coral species. Hard coral species richness was the highest for countries and territories closest to the coral triangle, in agreement with previous studies (Veron et al., 2015). Papua New Guinea hosts the greatest diversity of hard coral species, whereas Hawaii and Pitcairn hosts the lowest. This spatial pattern in species richness was also obtained for coral reef fishes, which was consistent with previous studies (Parravicini et al., 2014). Experts believe that most coral reef species have yet to be discovered and/or named, except for certain taxa such as Scleractinia or Pisces, for which the taxonomic inventory is deemed mostly complete (Fisher et al., 2015). Indeed, the poor accessibility of certain reefs, coupled with the cryptic nature of many taxa makes an exhaustive inventory difficult. This is particularly true for the Pacific where coral reefs are scattered over thousands of square kilometers, often far from research facilities.

▲ **Figure 1.1.3.** Aerial photograph of the atoll of Reao, in the south of the Tuamotu archipelago, French Polynesia. Credit: Gilles Siu.

▼ **Table 1.1.1.** Comparison of coral reef extent indicators between countries and territories of the GCRMN Pacific region. Since the values for "Kiribati" and "Pacific Remote Island Area" rows correspond to the sum of their associated territories, they were not used to calculate the total for the entire Pacific region.

Countries and territories	Absolute extent (km²)	Extent rel. to the Pacific (%)	Extent rel. to the world (%)
American Samoa	129	0.20	0.052
Cook Islands	528	0.81	0.211
Federated States of Micronesia	4,925	7.55	1.972
Fiji	6,704	10.27	2.685
French Polynesia	5,981	9.17	2.395
Guam	224	0.34	0.090
Hawaii	3,978	6.10	1.593
Kiribati	3,041	4.66	1.218
Gilbert Islands	2,498	3.83	1.000
Line Group	389	0.60	0.156
Phoenix Group	153	0.23	0.061
Marshall Islands	3,558	5.45	1.425
Nauru	15	0.02	0.006
New Caledonia	7,450	11.42	2.983
Niue	44	0.07	0.018
Northern Mariana Islands	181	0.28	0.073
Pacific Remote Island Areas	248	0.38	0.099
Howland and Baker islands	12	0.02	0.005
Jarvis Island	6	0.01	0.002
Johnston Atoll	100	0.15	0.040
Palmyra Atoll	105	0.16	0.042
Wake Island	26	0.04	0.010
Palau	966	1.48	0.387
Papua New Guinea	14,598	22.37	5.846
Pitcairn	64	0.10	0.026
Samoa	402	0.62	0.161
Solomon Islands	6,743	10.33	2.700
Tokelau	155	0.24	0.062
Tonga	1,662	2.55	0.665
Tuvalu	1,231	1.89	0.493
Vanuatu	1,803	2.76	0.722
Wallis and Futuna	626	0.96	0.251
Entire Pacific region	**65,256**	**100.00**	**26.132**

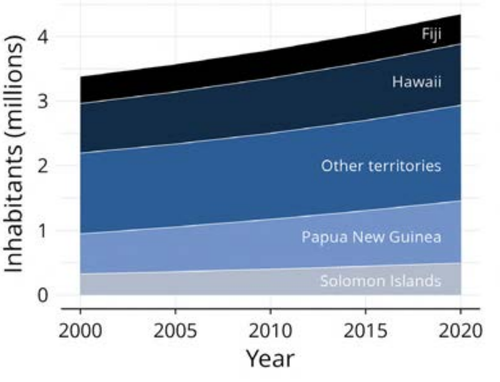
Human population

Compared to the other GCRMN regions and given its large area, the Pacific region hosts a relatively low human population, with a total of only 14,196,000 inhabitants in 2020 (see Materials and Methods for details). This population is unevenly distributed between the countries and territories of the region, ranging from 9,232,500 inhabitants for Papua New Guinea, which represent 65% of the total human population of the Pacific region, to uninhabited territories such as Palmyra Atoll.

In addition to the high variability in the distribution of the human population between countries and territories of the Pacific, there is also a high variability within them. Indeed, the human population tends to be clustered in some islands and in some cities within these islands. For example, in 2022 almost 70% of the population of French Polynesia was living on the island of Tahiti, where most of the population lives in Papeete, the regional capital of the territory (INSEE, 2023). Economic opportunities are among the main factors explaining this aggregated distribution of human population across the Pacific (Andrew et al., 2019).

Due to the small land areas of the countries and territories of the Pacific, their fragmentation into multiple islands, and the extensive presence of coral reefs in the region, a large proportion of the human population is living within 5 km from a coral reef. We estimated that 4,354,718 inhabitants were living within 5 km from a coral reef in 2020, representing 30% of the total human population of the Pacific. However, this percentage reached almost 70% when Papua New Guinea was excluded. Andrew et al. (2019) estimated that 90% of the total human population of the Pacific lived within 5 km from a coral reef, Papua New Guinea and Hawaii excepted. The Pacific is the region of the world with the highest proportion of the human population living within 5 km from coral reefs (Sing Wong et al., 2022). Notably, twelve countries and territories have their entire human population living within 5 km from coral reefs (Table 1.1.2).

Overall, we estimated that there was an increase of 28.7% in the number of inhabitants living within 5 km from coral reefs between 2000 and 2020 (Figure 1.1.4). This regional value hides a wide range of multi-decadal trends from territories with net loss of population over the period (e.g. Northern Mariana Islands) to territories showing a net gain in their population (e.g. Palau) (Table 1.1.2).



▲ **Figure 1.1.4.** Change in the human population living within 5 km from a coral reef between 2000 and 2020 for countries and territories of the GCRMN Pacific region.

The number of inhabitants living close to coral reefs is frequently used as a proxy of cumulative direct human stressors on these ecosystems (Smith et al., 2016; Williams et al., 2015). However, it can also be seen as a proxy for the dependence of human populations on coral reefs (Sing Wong et al., 2022).

▼ **Table 1.1.2.** Comparison of human population indicators between countries and territories of the GCRMN Pacific region. The column "Human pop. 2020" corresponds to the total number of inhabitants living within 5 km from coral reefs of the country or the territory in 2020. The column "Change in human pop." corresponds to the relative change in the number of inhabitants (in %) living within 5 km from coral reefs of the country or the territory between 2000 and 2020. The column "Percentage of total human pop." corresponds to the percentage of total human population (in %) of the country or the territory living within 5 km from coral reefs in 2020.

Countries and territories	Human pop. 2020	Change in human pop. (%)	Percentage of total human pop.
American Samoa	56,439	-1.49	100.00
Cook Islands	18,049	-0.23	100.00
Federated States of Micronesia	102,646	-3.11	99.13
Fiji	468,453	10.84	50.52
French Polynesia	226,292	32.98	73.88
Guam	164,276	7.00	99.27
Hawaii	952,086	23.84	62.27
Kiribati	133,754	58.75	100.00
Gilbert Islands	122,305	62.02	100.00
Line Group	11,448	30.66	100.00
Phoenix Group	0	0.00	0.00
Marshall Islands	55,833	9.63	100.00
Nauru	10,244	0.83	100.00
New Caledonia	133,824	13.62	46.86
Niue	1,232	-23.38	88.61
Northern Mariana Islands	41,990	-39.33	100.00
Pacific Remote Island Areas	0	0.00	0.00
Howland and Baker islands	0	0.00	0.00
Jarvis Island	0	0.00	0.00
Johnston Atoll	0	0.00	0.00
Palmyra Atoll	0	0.00	0.00
Wake Island	0	0.00	0.00
Palau	27,219	45.10	95.68
Papua New Guinea	964,040	55.02	10.44
Pitcairn	81	76.41	100.00
Samoa	114,921	14.57	57.96
Solomon Islands	494,831	52.44	73.59
Tokelau	1,317	-14.18	100.00
Tonga	103,479	6.09	97.52
Tuvalu	12,235	30.39	100.00
Vanuatu	260,982	59.85	87.15
Wallis and Futuna	10,494	-34.14	100.00
Entire Pacific region	**4,354,718**	**28.70**	**30.68**

Ecosystem services

Coral reefs provide numerous ecosystem services to human populations (Moberg & Folke, 1999; Woodhead et al., 2019). These services, that are defined as benefits that human population derive from the presence of coral reefs, are usually divided into provisioning, regulating, and cultural services (Woodhead et al., 2019).

Provisioning services are defined as the products obtained from ecosystems (Woodhead et al., 2019). Fishing is probably the most important provisioning service provided by coral reefs. Although coral reef fishes are the most targeted taxon, human populations harvest a wide range of organisms such as seaweed, clam, trochus, and various crayfish (Albert et al., 2015). Because of limited arable lands, fishing supplies the main source of protein and micronutrients for human populations from the countries and territories of the Pacific (Bell et al., 2009). The population of most of these countries and territories consumes several times more kilograms of fish per year than the global average (Gillett and Fong, 2023). In addition to the importance of fisheries for food security, this activity also provides livelihoods and income for coastal populations. Teh et al. (2013) have estimated the total number of reef fishers in the Pacific to be around 450,000. Outside to live catches, human populations also harvest coral sand and rubble that are used as construction materials (Albert et al., 2015). Finally, recent and ongoing research suggests that many promising pharmaceuticals are derived from cnidarians (including corals) and sponges, and other coral reef-associated organisms that could be used to treat inflammation, cancer, bone repair, dental deformities, neurological deficits, and hypertension (Cooper et al., 2014).

Regulating services are the benefits resulting from the regulation of ecosystem processes (Woodhead et al., 2019). Notably, coral reefs play a critical role in the protection of coastal populations and infrastructures from waves and storm surge (Figure 1.1.5). Indeed, coral reefs can reduce wave energy by 97% and wave height by 84% on average (Ferrario et al., 2014). This role is particularly important during extreme events such as cyclones or tsunamis. For example, following the tsunami induced by the Hunga Tonga-Hunga Ha'apai volcanic eruption, the reef system reduced wave heights from 18 m to less than 2 m on the island of Tongatapu (Purkis et al., 2023). Burke and Spalding (2022) have estimated that 41% of hazard-exposed people living along coasts of the Pacific are protected from flooding through the protection of coral reefs.

Cultural services encompass cognitive and experiential benefits (Woodhead et al., 2019) that play a significant role in many Pacific social and cultural customs, especially in the expression of relationships, hospitality, spirituality and identity. This type of ecosystem services also include tourism, which can be either directly (e.g., snorkeling and diving) or indirectly linked to the presence of coral reefs (e.g., fine sand beaches; calm clear waters). Coral reef tourism is highly aggregated in space, particularly in the Pacific, due to the numerous remote islands and atolls (Spalding et al., 2017). The main tourist destinations linked to coral reefs are located in Hawaii, Guam, Fiji, and the Northern Mariana Islands (Spalding et al., 2017). In countries and territories where there is development, coral reef tourism can bring more than 1 million US dollars per km^2 in tourist expenditure (Spalding et al., 2017). Coral reef tourism provides employment and income for numerous inhabitants of the Pacific, and contributes to the inflow of foreign currency for countries and territories of this region. For example, Spalding et al. (2017) estimated that coral reefs of Palau support 64% of all tourist expenditures and 43% of Palau's GDP.

Despite all the services that coral reefs provide, anthropogenic activities exert various negative impacts on these ecosystems, that are more or less direct. By threatening coral reefs, these impacts are affecting ecosystem services and may compromise livelihoods of human populations of the Pacific (Hughes et al., 2017).

▲ **Figure 1.1.5.** Barrier reef in Faa'a, Tahiti, French Polynesia. The accretion of the reef creates a barrier that breaks the waves and protects the island's coastline. Credit: Gilles Siu.

Threats to coral reefs of the Pacific

Thermal regime

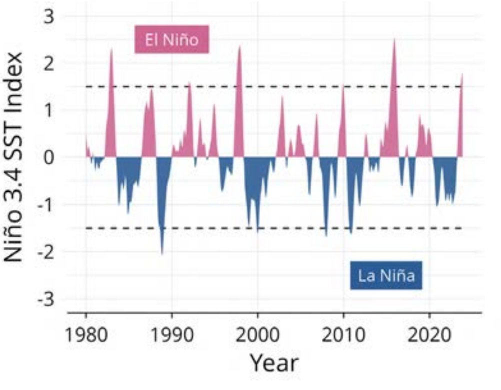
The atmospheric concentration of greenhouse gases has increased over the last century, and dramatically over the last decades, due to anthropogenic activities. Particularly, atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased by 47%, 156%, and 23%, respectively, since 1750 (IPCC, 2023). These increases are mainly due to the combustion of fossil fuels, industrial processes, and land use (IPCC, 2023). The accumulation of greenhouse gases in the atmosphere has led to an energy imbalance by decreasing the amount of energy lost to space in the form of reflected sunlight and thermal radiation (IPCC, 2021). This process is responsible for climate change, which has already increased global surface temperature by 1.19°C compared to the time period between 1850-1900 (Forster et al., 2024). Climate change has major consequences for marine ecosystems including coral reefs (Doney et al., 2012). Notably, climate change modifies the thermal regime over coral reefs with long-term changes in sea surface temperatures and changes in the intensity and frequency of marine heatwaves (Laufkötter et al, 2020).

Long-term trend in SST

We estimated that sea surface temperatures (SST) over coral reefs of the Pacific have increased by 0.82°C between 1985 to 2023, on average. This corresponds to a warming rate of 0.22°C per decade, a value consistent with the one obtained by Heron et al. (2016). Almost all countries and territories of the Pacific showed an increase in SST over coral reefs from 1985 to 2023 (Figure 1.2.1). Only coral reefs of Jarvis Island showed a slight decrease of their SST over this period. Average long-term changes in SST over coral reefs were the highest in Hawaii, Fiji, and Tonga with an increase of more than 1°C between 1985 to 2023 (Figure 1.2.1). Coral reefs from countries and territories located on the Eastern part of the tropical Pacific, such as the Line Group, Phoenix Group, and Howland and Baker Islands are those for which SST has increased the least on average during the time period 1985-2023 (Figure 1.2.1). However, SST over coral reefs of these countries and territories are characterized by a high interannual variability (Supplementary Figure 1), associated with El Niño Southern Oscillation (ENSO).

▲ **Figure 1.2.1.** Comparison of average changes in SST of coral reefs between Pacific countries and territories over the period 1985 to 2023. Bars to the left of the vertical black line correspond to countries and territories with an average decrease of SST over the period, whereas bars to the right correspond to countries and territories with an average increase in SST. See Table 1.2.1 for values. The value for the "Global Ocean" (*i.e.* 0.97°C) was obtained from Forster et al. (2024)[1] and provided for comparison purposes. However, it must be noted that this value corresponds to the average SST change from 1850-1900 to 2014-2023 and not to the average SST change from 1985 to 2023.

ENSO is characterized by two phases, separated by a neutral phase, which occur on an irregular cycle of two to seven years. During the La Niña phase, SST are lower than average in the Central and Eastern tropical Pacific Ocean. On the contrary, during the El Niño phase, SST are higher than average in the Central and Eastern tropical Pacific Ocean. Although ENSO is a natural climatic phenomenon that takes place in the Pacific Ocean, it has global consequences on atmospheric circulation and notably impacts precipitation regime and currents. From 1980 to 2023, strong El Niño phases occurred in 1982-1983, 1997-1998, and 2015-2016 (Figure 1.2.2).



▲ **Figure 1.2.2.** El Niño Southern Oscillation (ENSO) index from 1980 to 2023. Values are the 3-month moving average of the Niño 3.4 SST Index, pink areas are El Niño phases while blue areas are La Niña phases of ENSO. Dashed lines indicate threshold for strong El Niño and La Niña phases.

[1] We preferred this value to the SST change value of 0.88°C between 1850–1900 and 2011–2020, provided by the IPCC AR 6 (IPCC, 2021; chapter 9, page 1214) because it coincided more closely with our study period.

▼ **Table 1.2.1.** Comparison of thermal regime indicators between countries and territories of the GCRMN Pacific region. The column "Long-term SST average" corresponds to the long-term average of Sea Surface Temperature (SST) from 1985 to 2023 over coral reefs of the country or the territory. The column "Change in SST" corresponds to the change in SST from 1985 to 2023 over coral reefs of the country or the territory. The column "Annual rate of change" corresponds to the annual rate of change in SST from 1985 to 2023, and was calculated as the long-term SST trend value divided by 38 (the number of years from 1985 to 2023).

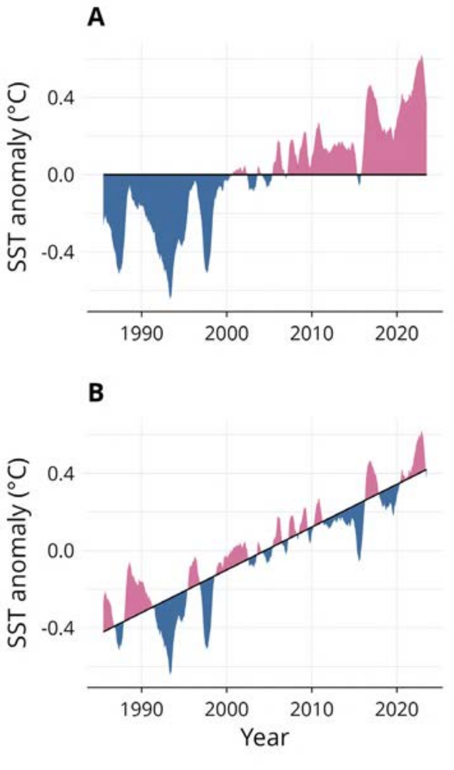
Countries and territories	Long-term SST average (°C)	Change in SST (°C)	Annual rate of change (°C.year^{-1})
American Samoa	28.57	0.83	0.022
Cook Islands	27.52	0.55	0.014
Federated States of Micronesia	29.01	0.89	0.023
Fiji	27.51	1.06	0.028
French Polynesia	27.31	0.25	0.007
Guam	28.67	0.93	0.024
Hawaii	24.87	1.07	0.028
Kiribati	28.79	0.33	0.009
Gilbert Islands	28.93	0.37	0.010
Line Group	27.71	0.05	0.001
Phoenix Group	28.70	0.07	0.002
Marshall Islands	28.47	0.80	0.021
Nauru	29.13	0.44	0.012
New Caledonia	25.41	0.75	0.020
Niue	26.88	0.85	0.022
Northern Mariana Islands	28.56	0.86	0.023
Pacific Remote Island Areas	27.76	0.39	0.010
Howland and Baker islands	28.28	0.13	0.003
Jarvis Island	27.19	-0.08	-0.002
Johnston Atoll	26.72	0.68	0.018
Palmyra Atoll	28.28	0.24	0.006
Wake Island	27.58	0.98	0.026
Palau	29.01	0.86	0.023
Papua New Guinea	28.55	0.96	0.025
Pitcairn	24.50	0.18	0.005
Samoa	28.70	0.81	0.021
Solomon Islands	29.20	0.92	0.024
Tokelau	29.26	0.51	0.014
Tonga	26.27	1.05	0.028
Tuvalu	29.11	0.88	0.023
Vanuatu	27.63	0.92	0.024
Wallis and Futuna	28.82	0.92	0.024
Entire Pacific region	**27.69**	**0.82**	**0.022**

Marine heatwaves

In addition to long-term increases in daily average SST over coral reefs, climate change is also responsible for changes in the marine heatwave regime (Laufkotter et al., 2020). Marine heatwaves are periods of extreme warm sea surface temperature that persist for days to months and can extend up to thousands of kilometers (Frolicher et al., 2018). Marine heatwaves can have significant impacts on marine organisms, and particularly on hard corals (Smale et al., 2019). Indeed, exposure to anomalously high SST for long periods of time causes a breakdown in the relationship between hard coral and their symbiotic algae living inside their tissues. The expulsion of these symbiotic algae causes the white coral skeleton to become visible through the translucent tissue, a phenomenon called coral bleaching (Figure 1.2.3, van Woesik et al., 2022). Because symbiotic algae bring most of the energetic resources of the coral host, their loss can lead to the death of the coral colony by starvation. Even if a hard coral colony doesn't die following a marine heatwave, the disruptive effect of bleaching on the metabolic process of energy acquisition can have delayed impacts by decreasing the survivorship, growth, and reproductive outputs of hard corals (Briggs et al., 2023). Finally, because the dissolution of atmospheric oxygen in water is inversely proportional to temperature, marine heatwaves can also exacerbate hypoxia phenomena (Hughes et al., 2020; Li et al., 2024).

▲ **Figure 1.2.3.** Bleached hard corals at Moorea, French Polynesia, in 2019. Credit: Yannick Chancerelle.

In the GCRMN Pacific region, marine heatwaves occurred in 1987, 1998, 2014-2017, and 2023 (Figure 1.2.4B). Most of the marine heatwaves that have occurred in the Pacific since 1980 arose during El Niño phases (Figure 1.2.2 and Figure 1.2.4, Holbrook et al. (2019)). While the impacts of the 1982-1983 strong El Niño event on coral reefs of the Pacific were poorly quantified (Coffroth et al., 1990), those of the marine heatwaves associated with the strong El Niño events of 1998 and 2014-2017 have been subject of more studies. For example, Hédouin et al. (2020) have shown the 2016 bleaching event led to contrasting patterns in hard coral cover mortality across French Polynesia, ranging from less than 1% in Moorea, to 71% in Tuamotu Archipelago. From 2013 to 2016, an unprecedented marine heat wave known as "the Blob" dominated the northeastern Pacific. Characterized by SST rising up to 2.5°C above average, this marine heatwave upended ecosystems across a huge swath of the Pacific Ocean. In Hawaii, surveys revealed that approximately 47% of corals in Hanauma Bay exhibited bleaching, with nearly 10% mortality observed in affected areas (Ku'ulei et al., 2017). More recently, in 2023, a fourth global mass bleaching event occurred (Reimer et al., 2024). However, quantification of its impacts on coral reefs of the Pacific is beyond the scope of the present report, since several years will be necessary to gather the data necessary to assess the long-term impacts of this recent bleaching event (see Case study on the 4th Global Bleaching Event - NOAA Coral Reef Watch).



▲ **Figure 1.2.4.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of the Pacific. Data used for the subplots A and B are the same, but the reference lines are different. On subfigure A, the black line is the long-term average in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term average), and values above this line are positive SST anomalies (*i.e.* warmer than long-term average). On subfigure B, the black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend).

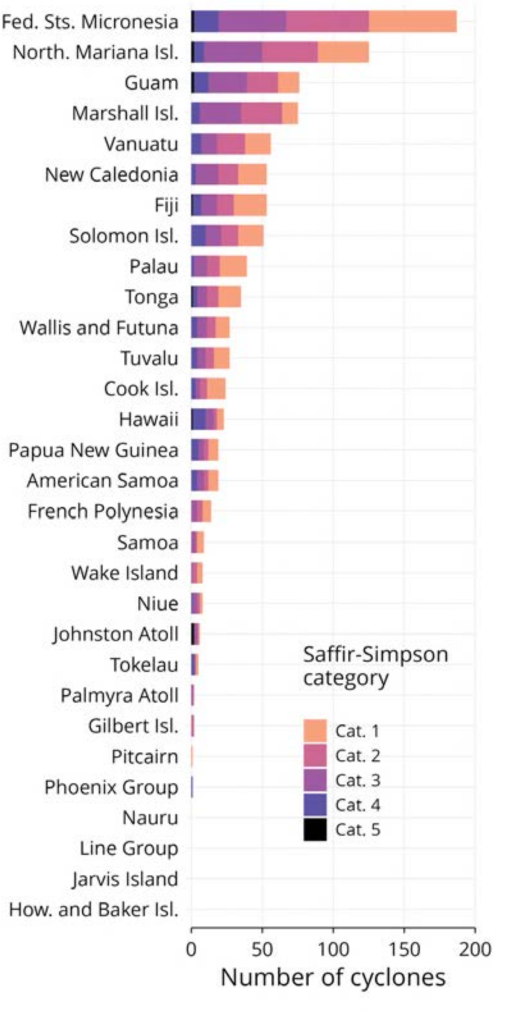
The intensity, frequency, and duration of marine heatwaves have increased over the past decades, and this trend is predicted to continue over the century due to climate change (Frolicher et al., 2018 ; Oliver et al., 2018 ; IPCC, 2023). Some evidence of apparent increases in hard coral community resistance to bleaching have been observed in the Pacific over the last years. For example, Donner and Carilli (2019) showed that the extent of the 2009-2010 bleaching event over Kiribati was limited compared to the one that occurred in 2004-2005, due to a shift in the hard coral community from sensitive to more thermally tolerant species. In Palau, Lachs et al. (2023) showed less severe bleaching impacts in 2017 compared to 1998, despite similar heat stress levels, suggesting an increase in the thermal tolerance. However, adaptation and acclimatization of organisms to new environmental conditions are limited by genetic diversity and physiological limits. In addition, the loss of thermally sensitive hard coral species will impact the ecological functioning of coral reefs of the Pacific (Darling et al., 2019 ; Richards, 2015). In the absence of a drastic reduction in greenhouse gas emissions, the marine heatwaves will increasingly impact coral reefs and will lead to profound societal impacts (Smith et al., 2025).

Cyclones

Cyclones (also called hurricanes or typhoons) are meteorological phenomena characterized by a central zone of low pressure surrounded by circular winds whose speed exceeds 33 $m.s^{-1}$ (~ 119 $km.h^{-1}$). Cyclonic winds can generate waves greater than 8 m in height, which release considerable energy when they hit the coast. In addition, the low-pressure zone at the center of the cyclone causes a storm surge of several meters above the tidal level. Cyclones are categorized into five levels on the Saffir-Simpson scale according to their maximum sustained wind speed, with level five corresponding to the most intense cyclones (see Table 3.1). The passage of a cyclone is generally associated with heavy rains that can increase turbidity and decrease salinity in coastal waters. These abrupt changes in hydrographic conditions have multiple impacts on coral reef communities (Harmelin-Vivien, 1994).

Cyclone-induced waves can lead to physical damage to benthic organisms that range from tissue abrasion due to suspended particles, to the complete dislodging of the organism (Fabricius et al., 2008). Pascoe et al. (2021) showed that the cyclone Walaka had catastrophic consequences on the structural complexity of the coral reef of Lalo, in the Northwestern Hawaiian Islands. The passage of this category 5 cyclone transformed the habitat from a reef dominated by tabulated *Acropora* hard corals to a coral rubble area colonized by turf algae. However, damage induced by cyclones are usually spatially variable across a reef system (Gouezo et al., 2015). Indeed, the impacts of cyclones on coral habitats and reef organisms depend on multiple factors associated with cyclone characteristics (e.g., maximum wind speed, direction of the cyclone, distance from the reef), reef geomorphology (e.g., depth), and community composition (e.g., massive or branching corals) (Beeden et al., 2015; Madin et al., 2014).

Since coral reefs are present over a large area of the Pacific, trajectories of cyclones regularly pass over these ecosystems (Puotinen et al., 2020). We found that a total of 945 cyclones passed within 100 km from a coral reef in the GCRMN Pacific region from 1980 to 2023. The disparity in cyclone occurrence between countries and territories of the Pacific was high, ranging from 0 to 187 (Figure 1.2.5). Particularly, countries and territories exposed to the greatest number of cyclones that have passed within a 100 km radius from a coral reef were those from the Northwestern Pacific (e.g., Federated States of Micronesia, Northern Mariana Islands, Marshall Islands), followed by those from the Southwestern Pacific (e.g., Vanuatu, New Caledonia, Fiji) (Figure 1.2.5). On the contrary, for some countries and territories, no or very few cyclones have passed within 100 km of a coral reef between 1980 and 2023 (Figure 1.2.5). This is the case for countries and territories located near the equator, where the coriolis force is zero (Figure 1.2.6). Between 1980 and 2023, the most powerful cyclones to pass within 100 km of coral reef of the Pacific were the cyclones Winston in Fiji in 2016, with sustained wind speed of 268 km.h^{-1}, and Pam in Vanuatu in 2015, with sustained wind speed of 246 km.h^{-1}. The breaking waves generated by cyclones of this intensity can exceed 8 m in height (Gouezo et al., 2015).



▲ **Figure 1.2.5.** Comparison of the number of cyclones that passed within 100 km of a coral reef between countries and territories of the Pacific from 1980 to 2023.

CASE STUDY

4th Global Bleaching Event - NOAA Coral Reef Watch

Authors

Morgan W. Pomeroy, Blake Spady, Derek Manzello

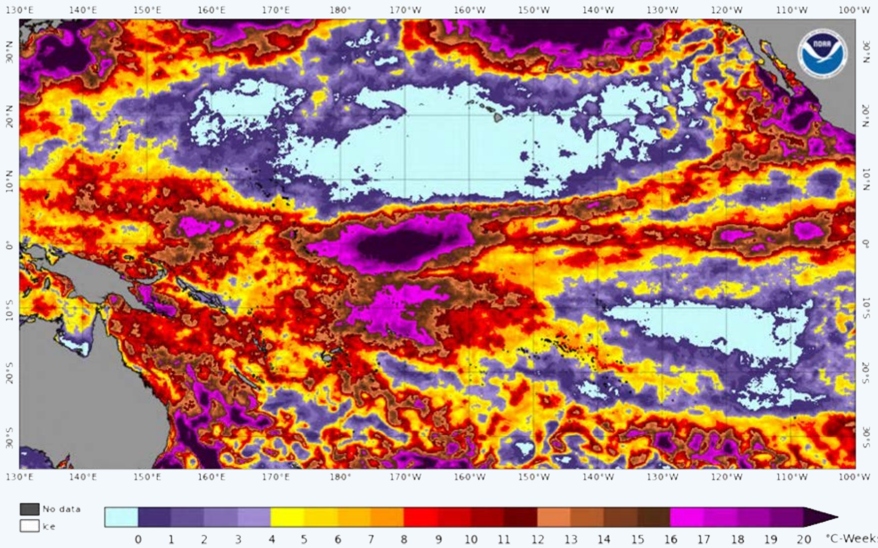
In April 2024, the U.S. National Oceanic and Atmospheric Administration's Coral Reef Watch program announced the development of the fourth global coral bleaching event. During this ongoing global event, the extent and intensity of accumulated heat stress, measured by Degree Heating Weeks (DHW; °C-weeks), within the Pacific Island region has exceeded the previous record highs achieved during the third global coral bleaching event (2014–2017). Between 1st January 2023 and 30th September 2024, 38.7% of all 0.05 x 0.05-degree (5 km) satellite reef pixels within the GCRMN Pacific region experienced DHW accumulation greater than ever recorded before within the satellite record (1985-present) (Figure 1).

Across the Pacific Island region, the highest 2024 DHW values accumulated in the Samoan Islands, Wallis and Futuna, and the Northern Cook Islands. Here, heat stress intensity approached ~18 to 19 °C-weeks; these locations experienced little heat stress (DHW < 4) during 2023. In 2023, areas of the Pacific Remote Island Area (Howland and Baker) and Kiribati (Phoenix Islands) were among the areas of highest heat stress accumulation, with maximum DHW values of ~22 to 23. While the Phoenix Islands were again exposed to extreme heat stress accumulation in 2024 (~15 °C-weeks), Howland and Baker escaped repeated bleaching-level heat stress (BLHS, defined as DHW > 4°C-weeks). Certain areas in the Pacific Islands region experienced moderate to high levels of heat stress intensity (> 8 °C-weeks) in both 2023 and 2024 (e.g. Papua New Guinea, Fiji, Vanuatu, and South Tonga), whereas other areas escaped BLHSs entirely in both years (e.g. the Hawaiian Archipelago, Wake Atoll, Johnston Atoll, and some areas of French Polynesia).

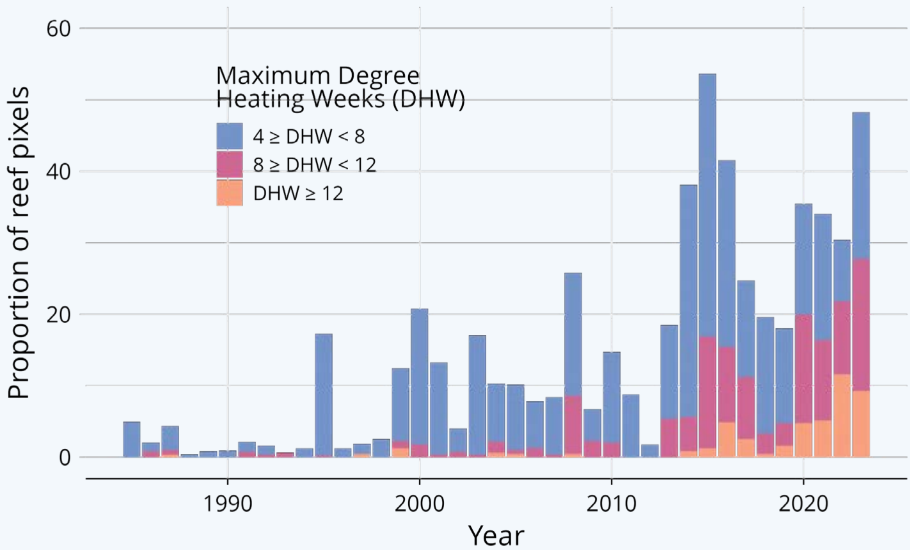
From 1st June 2023 to 31st May 2024, 57.4% of all Pacific Island reef pixels were exposed to ≥ 4 ˚= °C-weeks, surpassing the previous record set during from 2015–2016 (54.7%) (Figure 2). Three of the past four annual (1st June–31st May) periods had record-high extent of DHW ≥ 8 °C-weeks, with 27.7% of reef pixels experiencing these values in 2023–2024. While the extent of DHW ≥ 12°C-weeks slightly decreased from 11.4% in 2022–2023 to 9.2% during 2023–2024, this exposure area still nearly doubled from the extent of 4.9% observed in 2016–2017.

Locations of thermal reef refugia, defined as reef pixels with all-time maximum DHW < 4 °C-weeks, have been declining within the Pacific Islands over the past decade, when heat stress accumulation during 2015–2017 resulted in a ~62% decrease of these areas. Since 2017, there have been further declines on average of 7.5% per year of remaining refugia; from January to September 2024 alone, there was a 22% decrease. While 4,360 possible refugia existed in the Pacific Island region as of 31st December, 2014, there are currently only 920 refugia remaining (as of 14th September, 2024). Of the remaining thermal reef refugia, the highest concentrations are within the Solomon Islands and French Polynesia.

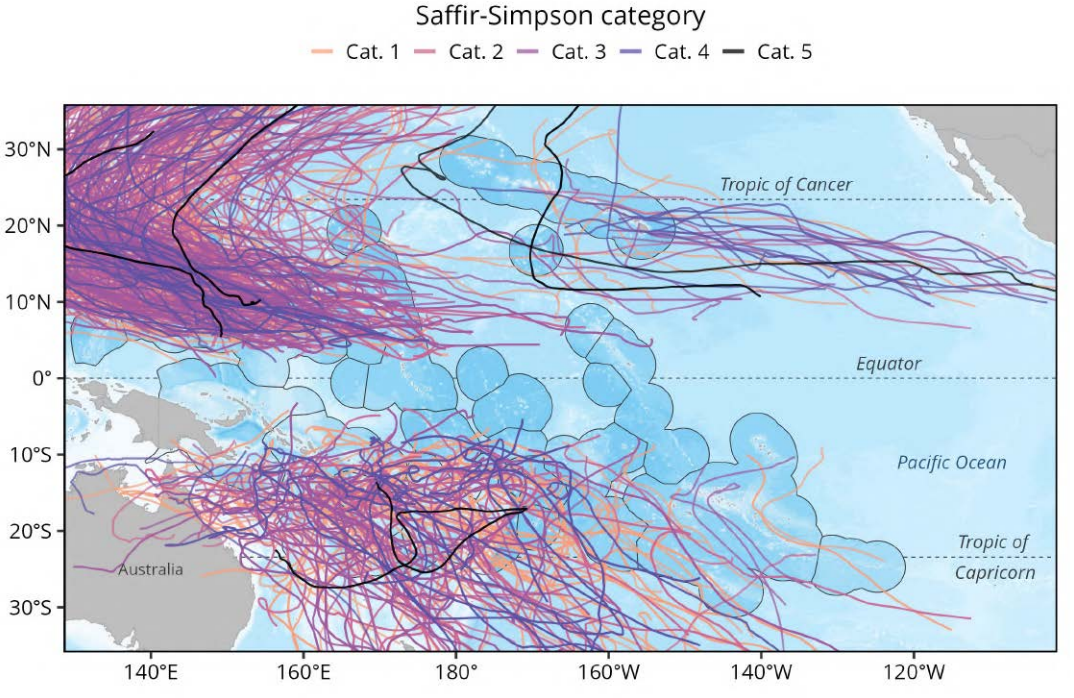
The greatest discrepancies in DHW experienced during 2023–2024 when compared to past heat stress events occurred in Tuvalu, Wallis and Futuna, the Samoas, Gilbert Islands, and parts of the Solomon Islands where DHWs were near 10-12 °C-weeks higher than ever previously recorded. Maximum sea surface temperatures between January 2023 and September 2024 were the highest within the satellite record on 11.7% of Pacific reefs—upwards of 0.7°C higher than 1985–2022 records. These record highs primarily occurred on reefs within Micronesia, Papua New Guinea, Fiji, Tuvalu, Solomon Islands, and French Polynesia. Thus far, preliminary bleaching observation data has confirmed the presence of mass bleaching within 11 of the GCRMN Pacific countries or territories during the 2023–2024 event (American Samoa, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, New Caledonia, Samoa, Tuvalu, Vanuatu, Wallis & Futuna), while localized bleaching has been observed in Federated States of Micronesia and Republic of Palau.



▲ **Figure 1.** Maximum Degree Heating Weeks (DHW, °C-weeks) experienced across the Pacific region from 1st January 2023 to 30th September 2024.



▲ **Figure 2.** Proportion of Pacific reef pixels per annual survey period (1st June - 31st May) experiencing annual maximum Degree Heating Weeks (DHW, °C-weeks) of 4 ≥ DHW < 8, 8 ≥ DHW < 12, and DHW ≥ 12.



▲ **Figure 1.2.6.** Trajectories of cyclones that passed within 100 km of a coral reef of the Pacific between 1980 and 2023. Polygons represent economic exclusive zones. Saffir-Simpson categories were derived from the maximum cyclone wind speed over its entire track.

Characteristics of cyclones are predicted to change by the end of the century under the effects of climate change (IPCC, 2021). Notably, the frequency of cyclones has decreased over the 20th century (Chand et al., 2022 ; Zhao et al., 2024), and this frequency is predicted to remain stable or decrease over the 21st century (IPCC, 2021; Knutson et al., 2010). However, the intensity of cyclones, measured in terms of maximum wind speed, is predicted to increase in the future, as well as precipitation associated with these meteorological phenomena (IPCC, 2021; Knutson et al., 2010). In other words, it is predicted that there will be fewer cyclones in the coming decades, but that cyclones that do occur will be more intense (Walsh et al., 2019). In particular, the South Pacific region is prone to this intensification with a high probability of an increase in category-3 cyclones (Bloemendaal et al., 2022). In anticipation of the increase in the number of more intense cyclones, some scientists have suggested adding a sixth category to the Saffir-Simpson scale (Wehner & Kossin, 2024). Finally, Shan et al. (2023) have shown that intense cyclones have occurred early in the cyclonic season, particularly in some zones of the South and Northwestern Pacific, due to higher SST earlier in the hot season. The change of cyclones' regimes over the 21st century is likely to have profound consequences for coral reefs (Cheal et al., 2017; Puotinen et al., 2020).

Ocean acidification

Since the industrial revolution, the atmospheric concentration of CO_2 has increased from approximately 280 parts per million (ppm) to over 400 ppm (Ripple et al., 2023). These increases in atmospheric CO_2 have driven corresponding increases in dissolved surface CO_2 in the ocean. Dissolved CO_2 in the ocean reacts with seawater to increase hydrogen ions thereby increasing seawater acidity, through a process called ocean acidification. Since 1750, the pH of the global ocean has decreased from 8.2 to 8.1 (IPCC, 2021). Because the pH scale is logarithmic, this change represents an approximately 30% increase in acidity. Seawater is projected to drop another 0.3–0.4 pH units by the end of this century (IPCC, 2021).

This change in acidity ultimately changes the availability of ions in the seawater that calcifying organisms like corals need to build their skeletons or shells (Hoegh-Guldberg et al., 2007). This is because the structural complexity of coral reefs largely depends on calcium carbonate ($CaCO_3$) production by calcifying organisms such as hard corals and coralline algae. These organisms build their skeletons by using calcium (Ca^{2+}) and carbonate ions (CO_3^{2-}) dissolved in seawater. However, the dissolution of CO2 in seawater decreases seawater pH (increase in hydrogen ion concentration (H^+)), which causes a reduction in the number of carbonate ions (CO_2^{-3}) available. A reduction in the number of carbonate ions available makes it more difficult and/or requires marine calcifying organisms to use more energy to build calcium carbonate skeletons or shells ($CaCO^3$). This reduction in carbonate ion concentration also leads to a reduction in calcium carbonate saturation state (Ω), which also has significant impacts on marine calcifiers by making carbonate dissolution more chemically favorable than carbonate accretion. Hence, ocean acidification makes both the production of calcium carbonate more difficult for coral reef organisms, while also making its dissolution easier (Doney et al., 2020). Ocean acidification has been described as an invisible but pervasive threat to coral reefs (Anthony, 2016).

In a study using long-term coral reef monitoring data across the U.S. Pacific Islands between 2010-2019, Barkley et al. (2022) showed that net carbonate accretion rates demonstrated significant sensitivity to declining Ω, and coral reef net carbonate accretion is a critical tool for monitoring the long-term impacts of ocean acidification that may not be visible by assessing benthic cover and composition alone.

Crown-of-Thorns Starfish

Hard corals are preyed on by several species including some species of butterflyfish (*Chaetodon* spp.), gastropods (*Drupella* spp.), and Crown-of-Thorns Starfish (COTS). Most of these predators have a limited impact on corals as they generally consume only a small fraction of the coral colony's tissue (Rice et al., 2019). However, predators can consume corals on entire reef sections during population outbreaks, particularly those of COTS (Rotjan & Lewis, 2008). The occurrence of COTS outbreaks is due in part to the ability of juvenile COTS to primarily be herbivorous, allowing them to wait until the benthic cover of hard corals, their prey when they reach adulthood, becomes sufficient. For this reason, Deaker et al. (2020) designated the accumulation of juveniles that precedes the occurrence of an outbreak on a reef as a "hidden army". Although COTS outbreaks may have always been a major natural disturbance affecting coral reefs, it is difficult to demonstrate this using sedimentary records (Greenstein et al., 1995). Rather, it has been suggested that COTS outbreaks may have been exacerbated by anthropogenic activities (Pratchett et al., 2017). The "predator removal" hypothesis states that the depletion of COTS predators due to overfishing and habitat destruction has facilitated the occurrence of population outbreaks (Cowan et al., 2017). A second hypothesis called the "nutrient enrichment" hypothesis suggests that deforestation, mining, and agricultural activities have enhanced nutrient supply to reefs through rivers (Brodie et al., 2005). This enrichment may increase the concentration of phytoplankton that larval COTS feed on, and therefore increase the frequency of outbreaks (Fabricius et al., 2010). Although the ecological mechanisms leading to the outbreak or retention of COTS populations remain largely unelucidated it is likely to be a combination of different drivers (Pratchett et al., 2017).

Several population outbreaks of the COTS *Acanthaster spp.* (Figure 1.2.7) have been reported throughout the Pacific over the last decades (Dumas et al., 2020, Uthicke et al., 2024). During these population outbreaks, densities of COTS can exceed 1,000 individuals per hectare, whereas in non-outbreaks they are of the order of one individual per hectare (Kayal et al., 2012; Pratchett et al., 2017). On the coral reefs of Moorea, French Polynesia, a COTS outbreak led to a decrease in hard coral cover from 40% in 2005 to less than 5% in 2010 (Kayal et al., 2012). In addition to reducing coral cover, COTS also changed the composition of the coral assemblage from one dominated by *Acropora* and *Pocillopora*, their favorite prey, to one dominated by Porites. This selective feeding was also observed in Bootless Bay, Papua New Guinea following an outbreak that occurred in 2006 (Pratchett et al., 2009). Pratchett et al. estimated that the outbreak caused hard coral cover to decline from 42.4% to 19.1% within a year. In another example from Guam, it took 12 years for hard corals species richness, cover, and composition to return to levels comparable to those before the 1968-1969 COTS population outbreaks (Colgan, 1987). Since hard corals are primarily responsible for the structural complexity of coral reefs, COTS outbreaks have major impacts on the structure, composition, and function of these ecosystems (Kayal et al., 2012).

▲ **Figure 1.2.7.** Crown-of-Thorns Starfish eating hard corals on a South Tuamotu atoll, French Polynesia, in 2021. Credit: Yannick Chancerelle.

Although climate change will likely have various impacts on the different developmental stages of COTS, the changes that will take place in the frequency and intensity of outbreaks in the coming decades remain highly uncertain, as are their impacts on coral reefs of the Pacific (Byrne et al., 2023; Pratchett et al., 2017).

Unsustainable fishing

Unsustainable fishing can have major consequences for coral reefs and have detrimental impacts on the local economies that depend on them. Examples of unsustainable fishing may include fishing for small sizes, where young fish are removed from the population before they can reproduce, or conversely, fishing for very large fecund fish whose removal is also detrimental for population reproduction (Barneche et al, 2018). Additionally, certain fishing techniques can have major impacts on coral reef organisms. For example, blast fishing can transform hard coral colonies into a field of rubble (Hampton-Smith et al, 2021). Finally, fishing for certain trophic groups can have more negative impacts on coral reef structure and functioning than others. For example, herbivorous fishes play a critical role on the reef in that they consume macroalgae and keep algal overgrowth in check. Indiscriminate fishing for herbivores reduces the ability of these fish to control algal growth and can contribute to an unbalanced benthic ecosystem where algal growth dominates coral growth (Edwards et al, 2014).

Fishing is critical for food security and income for populations of countries and territories of the Pacific (Bell et al, 2009), and plays an important social and cultural role for coastal human communities (Moberg and Folke, 1999). Teh et al. (2013) have estimated that there would be around 450,000 reef fishers within the region, which would correspond to 68% of the coastal rural population who were engaged in artisanal or subsistence fishing. In 2010, subsistence fishing represented almost 70% of total fishing catches of small-scale fisheries within the Pacific (Zeller et al, 2015). Although fishes are the most heavily fished group, numerous reef organisms are also targeted, such as crustaceans and molluscs (Albert et al, 2015 ; Campbell et al, 2024). Estimating the level of sustainability of a fishery is challenging, since the biomass of fish and other targeted organisms depends on multiple environmental factors (Richards et al., 2012). However, Zeller et al. (2015) have shown that small-scale fisheries catches have declined between 2000 to 2010. Assuming a constant fishing effort over the period, it is likely that biomasses have declined over the last decades because of fishing pressure. This conclusion is supported by different studies who found fish biomasses sometimes an order of magnitude lower around populated areas, compared to atolls far from human populations (Zeller et al, 2015). However, the level of sustainability of fisheries on most coral reefs of the Pacific seems to be higher than those of other regions (Newton et al, 2007). It is difficult to estimate the impacts of unsustainable fishing on the structure and functioning of coral reefs at the scale of the Pacific, given the diversity of species fished and the complexity of coral reefs trophic networks (Guillemot et al., 2014). Nonetheless, local scale studies can provide information on the nature of these impacts. For example, Dulvy et al. (2004) showed that COTS densities increased along a fishing gradient on coral reefs sites of the Lau Islands Group, in Fiji. They concluded that the depletion of fish predators by fishing resulted in an increase in COTS, which led to a change in benthic communities from hard corals to filamentous algae (see section "Crown-of-Thorns starfish"). This spatial pattern between fishing and COTS outbreaks has since been confirmed by several studies (Sweatman, 2008; Mellin et al., 2016). The impact of overfishing is not limited to coral reef fishes, and the depletion of other reef organisms can have major consequences for coral reefs through cascading effects. For example, sea cucumbers (*i.e.* beche-de-mer) have been over-harvested in many coral reefs of the Pacific (Eriksson et al, 2018), and some authors have suggested that this may have increased the occurrence of diseases affecting hard corals (Clements et al. (2024), see section "Diseases").

Estimating unsustainable fishing is difficult because coral reef fish catches are not consistently monitored by countries and territories in the region. Moreover, while national statistics on the number of fishing vessels or tons of fish landed may exist, they are not generally specific to coral reef fisheries. Finally, these national statistics often cannot capture non-commercial fishing catches (e.g. subsistence and recreational fishing, Zeller et al., 2006). However, available data suggest that some coastal fisheries stocks in the Pacific islands region may be overfished or subject to overfishing (Prince et al., 2019). Unsustainable fishing is associated with multiple socio-economic factors such as rapid human population growth, increased population demand for fish-based products, the use of more efficient fishery technologies, and inadequate management and enforcement laws. Hence, if these factors increase in the future, it is likely that unsustainable fishing will also increase in the coming decades, which will have consequences for the coral reefs of the region.

Nutrients and sediments

Most coral reefs of the Pacific are growing in oligotrophic waters, where the concentrations of inorganic nutrients is limited, and the water clarity is high due to low concentration of suspended sediments. Hard corals have adapted to these conditions and are efficient at recycling nutrients, and indirectly carry out photosynthesis, through their symbiosis with zooxanthellae. However, changes in land use and higher use of fertilizer have largely contributed to the increase in sediment and nutrients in coral reefs of the Pacific Ocean. For example, it has been estimated that the mean annual load of sediments, nitrogen and phosphorus to the Great Barrier Reef lagoon increased by 5.5, 5.7, and 8.9 respectively, since the European settlement, two centuries ago (Kroon et al, 2012).

Elevated concentrations in nutrients can promote the development of turf algae and macroalgae, competing with corals for space, and thus modify the composition of the benthic assemblage (Brodie et al., 2019). In 1977-1978 wastewater discharges were diverted outside of Kaneohe Bay, in Hawaii. As a result, the benthic cover of a green algae decreased by 75% while hard coral cover doubled from 1978 to 1983 (Hunter and Evans, 1995). Although nutrient and sediment inputs sometimes have the same origins, they affect coral communities differently. Suspended sediments decrease light availability for benthic organisms while sedimentation can decrease coral recruitments (Fabricius, 2005). Golbuu et al. (2011) showed that hard coral cover in Ngermeduu Bya, in Palau, was negatively correlated with the concentration of suspended sediments. Mining activities can deliver high loads of sediment, as well as associated heavy metal, to coastal waters. For example, at the Lihir Island Group, in Papua New Guinea, it has been observed that coral reefs located less than two kilometres from a gold mine waste disposal site were characterized by a lower hard coral species richness and an hard coral cover 15 times lower than control sites (Haywood et al., 2016).

To our knowledge there are no studies that have directly quantified long-term temporal changes in nutrient and sediment concentrations on coral reefs of the Pacific. However, it is likely that these have increased in recent decades due to a wide range of factors. Changes in land-use such as deforestation, agriculture practices (e.g., fertilizer use, livestock grazing), and urbanization, have exacerbated soil erosion and terrestrial runoff, and thus contributed to higher concentration of nutrients and sediments in coastal areas (Carlson et al, 2019 ; Fong et al., 2020). Other factors are also likely to have adversely affected the quality of coastal waters. Nutrient concentrations may have increased over the last few decades as a result of the growth in the coastal human population and poor wastewater management (Kuempel et al., 2024) while coastal development (including dredging activities) may have contributed to the increased load of suspended sediments (Carlson et al, 2019).

Pollution

Human populations are responsible for releasing a variety of debris in the marine ecosystem. Plastics, including those related to fishing activities (e.g., longlines, ghost gillnets), represent most of the marine anthropogenic debris found on coral reefs (Pinheiro et al., 2023). Hard corals are particularly impacted by marine debris that can cause physical damage (Nama et al., 2023), as well as an increased risk of diseases (Lamb et al., 2018). In addition to this visible pollution, coral reefs are also impacted by numerous chemical substances released by human activities, such as heavy metals, pesticides, and pharmaceuticals (Nalley et al, 2021).

Fujita et al. (2014) measured the concentrations of seven heavy metals in coastal sediments of the Funafuti atoll, in Tuvalu and reported concentrations in cadmium and lead to be 13 and 21 times higher in sediments from densely populated sites compared to those of a site located in an uninhabited area. Although Pacific coral reefs are not on the major shipping routes (Wang et al., 2023), they can be affected by oil spillage resulting from ship's grounding. For example, the grounding of a fishing vessel in Rose Atoll in American Samoa in October 1993 released 379 tonnes of diesel fuel (Haapkylä et al, 2007). The spillage has resulted in a massive die-off of coralline algae and many reef-dwelling invertebrates. Finally, some coral reefs of the Pacific have been polluted by radioactive elements such as those caused by nuclear testing conducted by the United States on Bikini Atoll (Marshall Islands) from 1946 to 1958 (Richards et al., 2008), and by France on Mururoa Atoll (French Polynesia) from 1966 to 1996 (Morrison et al., 2013). While coral reefs appeared relatively resilient to the physical impacts of these nuclear explosions, the long-term impacts of radioactive emissions on coral reef biodiversity remains largely unknown (Richards et al., 2008).

The concentrations of pollutants in marine waters are costly to estimate, in particular because of the wide variety of molecules. In addition, their impacts on coral reef organisms are difficult to quantify since they may have sublethal effects and act synergistically through a cocktail effect (Brodie et al., 2019). However, the sources of the pollutants are often well known (Diarra and Prasad, 2021). These include defective waste treatment systems for plastics (Jambeck et al., 2015), agriculture and antifouling paint for pesticides, industry, mining, and domestic wastewater for heavy metals, pathogens, and endocrine disruptors (Fujita et al., 2014 ; Wear and Thurber, 2015; Diarra and Prasad, 2021). In a context of growing human populations (Figure 1.1.3.) and without the development of appropriate regulatory measures, it is likely that the impact of pollution on Pacific reefs will increase in the coming years. However, the concentration of the pollution near urban centers may facilitate the monitoring of measures implemented to limit pollutants affecting coral reefs (Morrison et al., 2013).

Non-native species

Many coral reef organisms have a larval life phase which allows them to disperse before recruiting on the appropriate substrate, sometimes several dozen kilometers from the reef where they originated (Graham et al., 2008). Larval stage duration and the intensity and direction of currents are usually the major limiting factors for species to colonize new coral reefs via transportation of larvae in the water column (Graham et al., 2008). Nonetheless, currents transport floating objects which may facilitate the movement of species over great distances. For example, pumice rafts produced by volcanic eruptions can be used by benthic organisms to travel across the pelagic realm (Bryan et al., 2012).

Additionally, the quantity of plastic waste entering the ocean has significantly increased over the last decades (Jambeck et al., 2015), which has potentially provided additional ways of dispersal for marine species. For example, the tsunami that hit the coast of Japan in 2011 caused many anthropogenic objects to be carried out to sea, enabling coastal marine species to move thousands of kilometers across the Pacific (Carlton et al., 2017). However, although these examples are striking, international shipping is predominantly responsible for the dispersal of species over long distances through ballast waters and hull fouling (Molnar et al., 2008).

Species occurring outside their natural range and dispersal potential whose presence and dispersal is due to intentional or unintentional human action are called non-native species (Walther et al., 2009). Hawaii accounts for most of the non-native marine species occurrences observed across the Pacific (Alidoost Salimi et al., 2021). Non-native species that have been reported in the Hawaiian archipelago belong to different taxa such as algae, sponges, and fishes (Coles & Eldredge, 2002). For example, *Gracilaria salicornia*, a red alga, was intentionally introduced on O'ahu in the 1970s for aquaculture of the agar industry (Smith et al., 2004). *G. salicornia* forms mats up to 8 cm thick that reduce irradiance, increase sedimentation, and modify oxygen concentration for native benthic communities developing underneath (Martinez et al., 2012). In reef areas where *G. salicornia* is present, it can cover up to 50% of the substratum, negatively impacting native benthic communities (Smith et al., 2004).

Overall, the occurrence and impacts of non-native species on coral reefs of the Pacific are poorly understood (Alidoost Salimi et al., 2021; Coles & Eldredge, 2002). Since most non-native species have been reported in well-studied regions, it is likely that these observations are dependent on the sampling effort and that the actual number of non-native species may be largely underestimated (Molnar et al., 2008). Yet, early identification of non-native species is essential to avoid these species becoming invasive and limit their impacts on coral reefs. One of the main challenges of research on non-native species is the ability to identify cryptogenic species, such as parasites, that can cause diseases to native coral reefs species (Alidoost Salimi et al., 2021).

Diseases

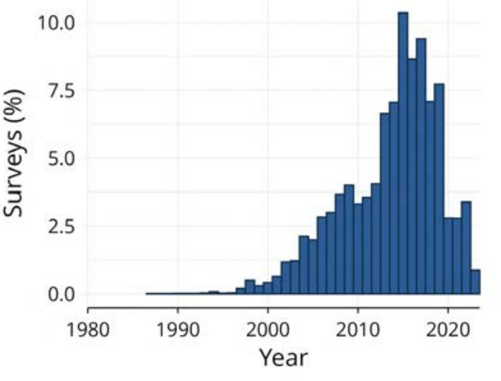
Similarly to terrestrial organisms, marine organisms, including those living on coral reefs are prone to diseases that can lead to mass mortalities (Harvell et al, 1999). A total of 22 diseases have been reported to affect hard coral species at the global scale (Morais et al., 2022). Coral mortality in the Pacific seems to have been less affected by diseases than in other parts of the world, particularly compared with the Caribbean region (Alvarez-Filip et al, 2022). For example, Vargas-Ángel and Wheeler (2009) has shown a limited prevalence of hard coral diseases in the U.S. Pacific territories, with values ranging from 1.3% to 11.7% of coral colonies affected, although the prevalence varied depending on the disease and the species considered. Other organisms than hard corals can also be affected by diseases, which can lead to changes in reef structure and functioning. For example, Vargas-Ángel (2010) identified a total of five diseases affecting coralline algae in the U.S. Pacific territories. As coralline algae promote hard coral recruitment (Gouezo et al., 2020) and contribute to carbonate production (Cornwall et al., 2023), such diseases can indirectly affect the physical structure of the reef. However, because of a lack of consistent monitoring programs, as well as the challenging nature of identifying marine pathogens, knowledge about the occurrence and impacts of diseases on coral reefs of the Pacific remains limited (Morais et al., 2022).

Several studies have shown that the risk of disease is exacerbated by other coral reefs threats such as water quality (Redding et al., 2013), plastic pollution (Lamb et al., 2018), and overfishing (Clements et al., 2024). For example, Clements et al. (2024) showed that the removal of detritivore sea cucumbers increased tissue mortality by 370% in *Acropora pulchra* coral colonies in Moorea, French Polynesia. By ingesting large amounts of sediments, detritivore sea cucumbers reduce the bacterial and organic load on coral reefs. However, sea cucumbers have been overharvested in coral reefs of the world, including in countries and territories of the Pacific (Purcell et al., 2011). This depletion may have led to an increase in the bacterial load in sediments and thus a higher risk of disease to coral reef organisms (Clements et al., 2024). Although it is extremely complicated to predict how the prevalence of diseases affecting coral reef organisms will change over the coming decades, it is reasonable to assume that as long as the factors exacerbating these diseases increase, so will their prevalence.

Temporal trends in benthic cover

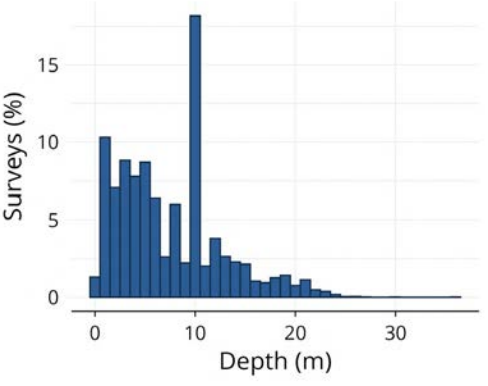
Spatio-temporal distribution of monitoring

The estimation of temporal trends in benthic cover of major benthic categories and three major hard coral families was achieved through the integration of 50 datasets (Supplementary Table 1). Together, these datasets represent a total of 8,193 monitoring sites, on which 15,482 surveys were conducted between 1987 and 2023 (Table 1.3.1). Although early benthic cover surveys were conducted in 1987, most surveys were conducted after 2003 (Figure 1.3.1). The increase in the number of surveys after 1998 and 2010 is likely due to an increase in funding for coral reef monitoring to assess the impacts of the mass bleaching events that occurred in those years (Lachs et al, 2023). The large number of surveys conducted between 2013 and 2019 (Figure 1.3.1) is mainly due to the inclusion of datasets from the National Coral Reef Monitoring Program conducted by the National Oceanic and Atmospheric Administration (NOAA) from the United States. Indeed, this monitoring program is based on stratified random surveys, consisting of monitoring numerous random sites over time. We interpreted the low number of surveys conducted in 2020 and 2021 as impacts from the COVID-19 pandemic which limited coral monitoring and travel due to stay-at-home restrictions that were implemented in some countries and territories. Finally, a limited number of surveys were conducted in 2023. A low number of surveys conducted the years directly preceding the end of data collection has been observed for previous GCRMN reports (Moritz et al., 2018; Souter et al., 2021). This may be due to the time required by people in charge of coral reef benthic monitoring to process raw data. For example, while photo-quadrat monitoring method enables raw data (*i.e.* photography) to be acquired rapidly, additional time is needed to derive the coverage of benthic categories from photographs.



▲ **Figure 1.3.1.** Percentage of coral reefs surveys conducted from 1980 to 2023 in the GCRMN Pacific region.

The surveys were conducted between 0 and 30 m depth (Figure 1.3.2). This distribution corresponds to the distribution of shallow coral reefs. The skewed distribution toward 0 can be explained by the increasing time needed to acquire data at great depths, due to the diving levels. This can also be explained by the fact that certain reef types, such as lagoon, are limited in depth by nature. The present report doesn't describe the status and trends of mesophotic coral reefs, which occur between 30 and 150 m depth (Rocha et al, 2018). Because of their depth, mesophotic coral reefs are less accessible and they were therefore subject to a limited number of surveys. Moreover, their depth also makes it impossible to derive information from satellite measurements. For this reason, the distribution of mesophotic coral reefs is poorly known and quantifying the impacts they suffer is more difficult than for shallow coral reefs.

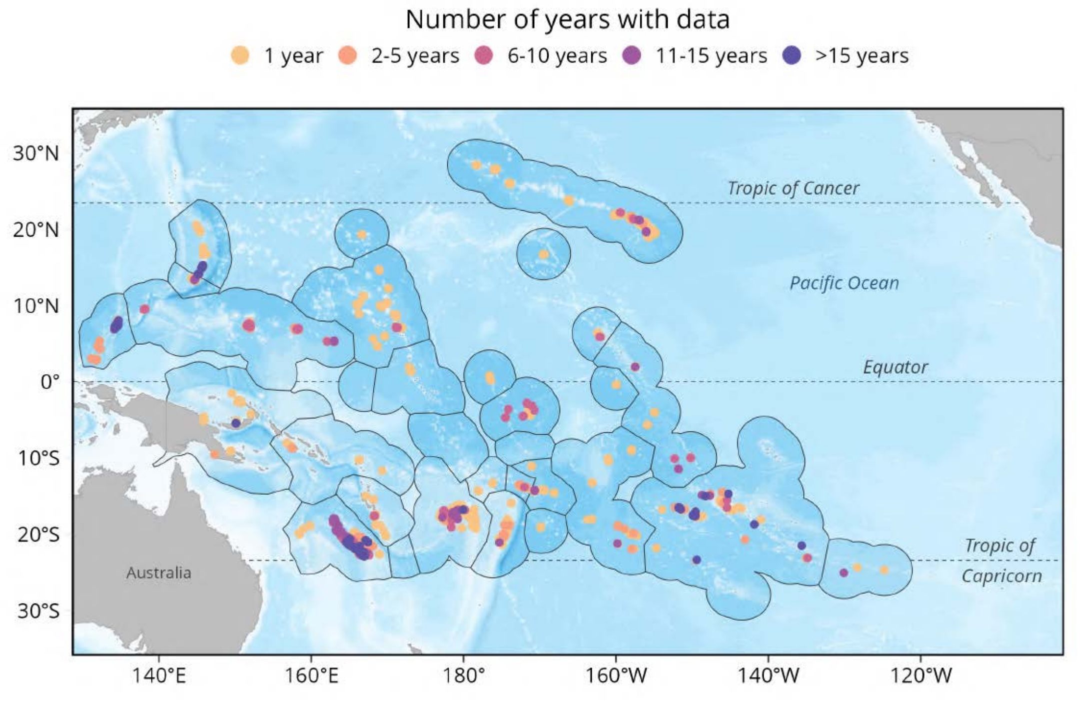


▲ **Figure 1.3.2.** Percentage of surveys conducted by depth in the GCRMN Pacific region.

The countries and territories with the highest number of monitoring sites and surveys of benthic cover were Hawaii, American Samoa, and New Caledonia. No benthic cover monitoring data were available for Nauru, Tokelau, and Tuvalu (Table 1.3.1). While it is possible that data exist for these countries and territories that we did not integrate into this report, it also may be that no benthic cover monitoring has been carried out in these countries and territories. Indeed, the development and maintenance of a coral monitoring program is costly and can be difficult to implement for small island developing states.

▼ **Table 1.3.1.** Comparison of benthic cover monitoring indicators between countries and territories of the GCRMN Pacific region. Columns “Sites” and “Surveys” correspond to the number of monitoring sites and surveys assessed within the country or the territory. The column “Datasets” correspond to the number of individual datasets with at least one survey from the country or the territory. Columns “First year” and “Last year” are respectively the first and last year where a survey has been conducted within the country or territory. The values reported in the table are provided for all benthic categories combined.

Countries and territories	Sites	Surveys	Datasets	First year	Last year
American Samoa	1,039	1,219	4	1997	2019
Cook Islands	191	246	5	2005	2023
Federated States of Micronesia	217	555	3	2000	2020
Fiji	650	997	12	1997	2023
French Polynesia	229	2,173	8	1987	2023
Guam	391	545	4	1997	2021
Hawaii	2,019	2,405	4	1997	2021
Kiribati	173	266	6	2009	2023
Gilbert Islands	18	18	2	2011	2018
Line Group	97	125	3	2009	2023
Phoenix Group	58	123	1	2009	2018
Marshall Islands	147	174	3	2002	2020
Nauru	0	0	0		
New Caledonia	798	3,541	8	1997	2023
Niue	7	7	1	2011	2011
Northern Mariana Islands	680	924	3	1999	2020
Pacific Remote Island Areas	758	862	2	2009	2019
Howland and Baker islands	150	150	1	2015	2017
Jarvis Island	222	222	1	2015	2017
Johnston Atoll	46	46	1	2015	2015
Palmyra Atoll	194	298	2	2009	2019
Wake Island	146	146	1	2014	2017
Palau	112	381	3	1997	2022
Papua New Guinea	91	267	4	1998	2019
Pitcairn	6	12	2	2009	2023
Samoa	50	90	4	2012	2022
Solomon Islands	78	176	4	2005	2021
Tokelau	0	0	0		
Tonga	470	516	6	2002	2022
Tuvalu	0	0	0		
Vanuatu	75	114	3	2004	2023
Wallis and Futuna	12	12	1	2019	2019
Entire Pacific region	**8,193**	**15,482**	**50**	**1987**	**2023**



▲ **Figure 1.3.3.** Spatio-temporal distribution of benthic cover monitoring sites across the GCRMN Pacific region. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years.

Across 8,193 sites included within the synthetic dataset, 84.7% were monitored once and percentages decreased progressively for the other time-span categories, declining to 5.9% for the 2-5 years' category to only 2.8% for sites surveyed for more than 15 years. The allocation of resources available for monitoring is a trade-off between space and time. Some monitoring programs have focused their resources on spatial representativeness by surveying numerous, different sites each year (random survey design), whereas other monitoring programs have focused their resources on temporal representativeness by surveying a limited number of the same sites each year (fixed survey design).

Trends in major benthic categories

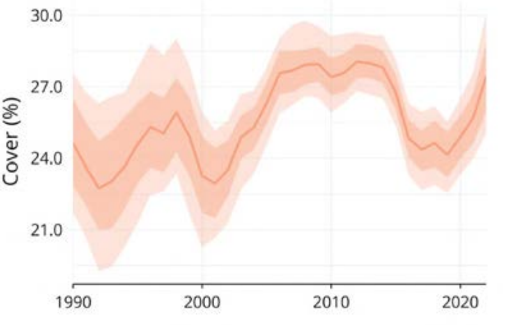
The distribution of coral reef benthic cover monitoring sites was not homogeneous over space and time within the Pacific region (see section "Spatio-temporal distribution of monitoring"). Hence, plotting the average cover for benthic categories per year from coral reef monitoring data at the regional scale poses the risk of obtaining estimates of benthic cover trends that are not representative of coral reefs of the region, but only reflect changes occurring on areas that are the most surveyed (e.g. Hawaii, New Caledonia). To overcome this issue, we estimated the temporal trends in benthic cover of major benthic categories (i.e. hard coral, coralline algae, macroalgae, and turf algae) using machine learning models. In particular, machine learning (ML) models rely on the relationship between observed data and multiple predictors to predict benthic cover on a set of generated sites, that can be considered as representative of coral reefs of the Pacific (see Materials and Methods).

Although we have run the ML models over the period from 1980 to 2023, we have chosen to represent the temporal trends only from 1990 to 2022. This period covered virtually all the observed data, guaranteeing greater robustness of the estimated trends. Nonetheless, the model estimates over the period 1990 to 2000 must be interpreted cautiously because few data were available in these years to train the ML models (Figure 1.3.1). Moreover, the year 1990 must not be taken as a baseline of pristine coral reefs, since human activities have affected coral reefs of the Pacific before this year (e.g. Zeller et al, 2015). Finally, the temporal trends estimated by the ML models for the entire GCRMN Pacific region often differed from the temporal trends estimated for countries and territories, a pattern well known in large-scale ecological syntheses (e.g. Shlesinger and van Woesik, 2023). Temporal trends in major benthic categories for each country and territory are provided in the second part of this report (see Part 2 - Syntheses for countries and territories).

Hard coral cover

We defined hard corals as warm-water calcifying species from the order Scleractinia as well as some species from Milleporidae and Helioporidae, which also have the ability to build a calcium carbonate skeleton (Stoddart, 1969). Hard corals are foundation species that are predominantly responsible for the structural complexity and the accretion of coral reefs of the Pacific (Ellison & Degrassi, 2017).

The estimation of temporal trends in hard coral cover across coral reefs of the Pacific was assessed using 24,460 observations as training data and 8,154 observations as testing data for the ML model. The Root Mean Square Error (RMSE, see section "Models evaluation") value was 10.10%, indicating a good average predictive performance of the ML model (Supplementary Table 2). However, the error in estimation was not constant over the predicted range, and the ML model tended to slightly underestimate observed values when greater than 25% and to overestimate when below this value (Supplementary Figure 5 - A).



▲ **Figure 1.3.4.** Modeled temporal trends for hard coral benthic percentage cover in the Pacific from 1990 to 2022. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively.

The model estimated that the long-term average in hard coral cover across coral reefs of the Pacific was 25.5% (80% CI [24.3% - 26.5%]) between 1990 to 2022 (Figure 1.3.4), a value consistent with previous studies (Vroom, 2011 ; Moritz et al, 2018). The long-term trend in hard coral cover slightly increased from 1990 to 2022 (Mann-Kendall test, $\tau = 0.273$, p-value = 0.026), but the weak statistical significance suggests a trend close to stability. This result aligns with previous studies conducted in the Pacific (Moritz et al., 2018) and in the neighboring East Asian Seas region (Chan et al., 2023). However, it contrasts with the findings of other studies (Souter et al., 2021; Tebbett et al., 2023), which can be due to differences in the geographic areas and time periods considered. From 1990 to 2022, the time-series can be broken into seven periods:

- The first period showed a decline in hard coral cover from 24.6% (80% CI [22.8% - 26.5%]) in 1990 to 23.0% (80% CI [21.0% - 25.1%]) in 1993, representing an absolute loss of 1.6% in the average percentage cover. This first period of decline is concomitant with a high SST anomaly (Figure 1.2.4) and the 1991-1993 El Niño event (Figure 1.2.2 ; Kessler and McPhaden, 1995). However, since we only estimated hard coral cover a year before the start of the El Niño event, it is possible that the decline was actually slightly higher, as it may have started earlier.
- The second period corresponds to an increase in hard coral cover from 23.0% (80% CI [21.0% - 25.1%]) in 1993 to 25.9% (80% CI [24.2% - 27.3%]) in 1998, representing an absolute gain of 2.9% in the average percentage cover.

- The third period showed a decline in hard coral cover from 25.9% (80% CI [24.2% - 27.3%]) in 1998 to 23.5% (80% CI [22.4% - 24.7%]) in 2002, representing an absolute loss of 2.4% in the average percentage cover. This second period of decline occurred following a strong El Niño event (Figure 1.2.2) and is concomitant with an extended period of high SST anomaly (Figure 1.2.4). The 1998 El Niño event led to the first recorded global scale mass bleaching event (Eakin et al, 2019).

- The fourth period corresponds to an increase in hard coral cover from 23.5% (80% CI [22.4% - 24.7%]) in 2002 to 27.9% (80% CI [27.2% - 28.6%]) in 2009, representing an absolute gain of 4.4% in the average percentage cover.

- The fifth period showed an overall stability of hard coral cover from 2009 to 2013 at around 27.8% (80% CI [27.0% - 28.5%]). This stability is probably due to low peaks of SST anomaly over the period (Figure 1.2.4). However, the slight decrease in hard coral cover around 2010 is likely associated with the El Niño event that occurred this year (Figure 1.2.2).

- The sixth period corresponds to a decline in hard coral cover from 28.0% (80% CI [27.3% - 28.7%]) in 2013 to 24.3% (80% CI [23.5% - 25.1%]) in 2017, representing an absolute loss of 3.7% in the average percentage cover. This third period of decline is concomitant with a strong El Niño event (Figure 1.2.2) and the 2014–2017 global bleaching event (Eakin et al, 2019).

- Finally, the last period showed an increase in hard coral cover from 24.3% (80% CI [23.5% - 25.1%]) in 2017 to 27.4% (80% CI [25.9% - 28.8%]) in 2022, representing an absolute gain of 3.1% in the average percentage cover.

The overall stability in hard coral cover in the Pacific from 1990 to 2022 can be perceived as a signal of hope in the context of increasing threats to coral reefs of the world. Several hypotheses, which are not mutually exclusive, can be put forward to explain this result.

First, the 65,256 km² of Pacific coral reefs are spread out along a longitudinal axis of 11,000 kilometers and a latitudinal axis of 7,200 km. Due to this immense area, all coral reefs across the region do not experience the same conditions at the same time. While some reefs experience conditions that promote an increase in hard coral cover, others are exposed to stressors that lead to decline. Such asynchrony in hard coral cover trajectories has notably been shown across French Polynesia (Vercelloni et al., 2019). Because of these local variations in hard coral cover dynamics, long-term relative stability is more likely to be observed at the regional scale than a strong long-term trend, compared to smaller regions.

Building on the previous point, acute stressors that affect a large proportion of the Pacific at the same time are more likely to lead to a regional scale decrease in hard coral cover. This theoretical point is corroborated by our result which shows that abrupt declines in hard coral cover occurred following El Niño events, which led to a high SST anomaly. As a result, a cyclical pattern emerges: a decline following an El Niño event, a subsequent increase, and sometimes a stabilization phase. Since our analysis spans only 32 years - a relatively short period for an ecosystem - and the more recent phase corresponded to an increase in hard coral cover, we observed an overall stability. If the most recent phase had been one of decline, it is possible that the long-term trajectory would have been a decline. Likewise, if the study period had included the years preceding 1990, it is likely that a greater portion of the initial decline phase would have been captured, potentially revealing a long-term trajectory even closest to stability.

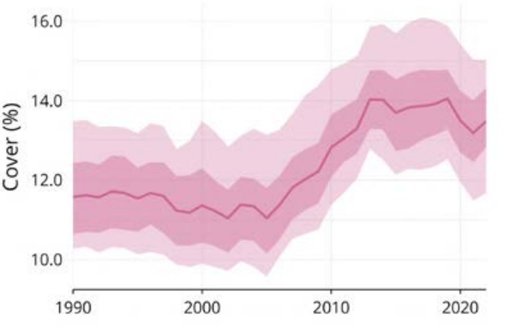
The impacts of direct anthropogenic stressors - such as unsustainable fishing, nutrient and sediment runoff, and chemical pollution (e.g., pesticides, heavy metals) - add to the impacts of climate-related disturbances on coral reefs. Unlike large scale climatic events (e.g. El Niño), these direct anthropogenic stressors are typically chronic in nature, occurring at relatively low intensity but persisting over extended periods. Moreover, their impacts are generally spatially confined, affecting specific reefs rather than large areas. Due to the region's low human population and the high number of remote reefs, Pacific coral reefs experience relatively limited direct anthropogenic stressors compared to other regions worldwide. This may explain why our results do not show a downward trend on a regional scale for hard coral cover, even though localized anthropogenic stressors may be driving declines in specific areas.

Apart from climatic and direct anthropogenic stressors, which are extrinsic factors, the absence of a regional decline in hard coral cover may also be related to intrinsic factors. In accordance with the diversity-stability hypothesis (McCann, 2000), the high specific diversity of hard corals in the Pacific compared with other regions of the world could contribute to the stability of the coral cover observed (but see Zhang et al., 2014). Moreover, it has been shown a growing resistance of hard coral cover to heat stress in Gilbert Islands (Donner and Carilli, 2019) and Palau (Lachs et al., 2023), for which mechanisms of acclimatisation, adaptation or change in the composition of the coral assemblage could be at the origin. Finally, our results show that the hard coral cover is resilient to the impacts of large-scale marine heatwaves, and returns to its long-term term average value of 25.5% in around 6 years.

Coralline algae cover

We defined coralline algae as species belonging to the order of Corallinales. Coralline algae are encrusting red algae that produce calcium carbonate and contribute to the cementation of carbonate materials produced by hard corals, hence contributing to the persistence of coral reef structure over time (Vargas-Ángel, 2010 ; Cornwall et al, 2023). Coralline algae are also known to promote hard coral recruitment (Gouezo et al., 2020).

The estimation of temporal trends in coralline algae cover across coral reefs of the Pacific was assessed using 17,366 observations as training data and 5,789 observations as testing data for the ML model. The RMSE value was 6.18%, indicating a good average predictive performance of the ML model (Supplementary Table 2). However, the error in estimation was not constant over the predicted range, and the ML model tended to slightly underestimate observed values when greater than 12.5% and to overestimate when below this value (Supplementary Figure 5 - B.



▲ **Figure 1.3.5.** Modeled temporal trends for coralline algae benthic percentage cover in the Pacific from 1990 to 2022. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively.

The ML model estimated that the long-term average in coralline algae cover across coral reefs of the Pacific was 12.3% (80% CI [11.5% - 13.1%]) between 1990 to 2022 (Figure 1.3.5), a value relatively similar to the one found by Vroom (2011) for United States Pacific territories. The long-term trend in coralline algae cover increased from 1990 to 2022 (Mann-Kendall test, τ = 0.5, p-value = 4.6 x 10-5). Over this time range, the time-series can be broken into three periods:

- The first period showed a slight decrease in coralline algae cover from 11.6% (80% CI [10.6% - 12.4%]) in 1990 to 11.0% (80% CI [10.1% - 11.8%]) in 2005, representing an absolute loss of 0.6% in the average percentage cover.
- The second period corresponds to an increase in coralline algae cover from 11.0% (80% CI [10.1% - 11.8%]) in 2005 to 14% (80% CI [13.3% - 14.8%]) in 2013, representing an absolute gain of 3% in the average percentage cover.
- The third period showed a slight decline in coralline algae coral cover from 14% (80% CI [13.3% - 14.8%]) in 2013 to 13.5% (80% CI [12.8% - 14.3%]) in 2022, representing an absolute loss of 0.5% in the average percentage cover.

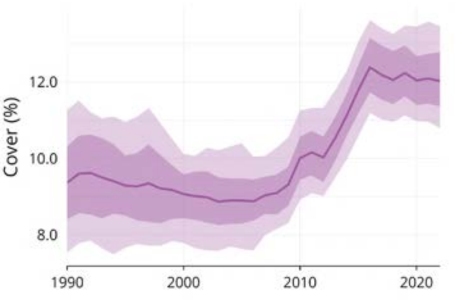
Macroalgae cover

We defined macroalgae as species belonging to the classes Phaeophyceae, Florideophyceae (but not from the order of Corallinales), and Ulvophyceae, that have not been identified by data contributors as turf algae. For example, species belonging to the genera *Sargassum, Dictyota, Halimeda,* and *Padina* were included within macroalgae. Hence, it must be noted that under the broad term of macroalgae are multiple species with different biology and ecology (Cannon et al, 2023).

The estimation of temporal trends in macroalgae cover across coral reefs of the Pacific was assessed using 19,816 observations as training data and 6,606 observations as testing data for the ML model. The RMSE value was 5.66%, indicating a very good average predictive performance of the ML model (Supplementary Table 2). However, the error in estimation was not constant over the predicted range, and the ML model tended to slightly underestimate observed values when greater than 10% and to overestimate when below this value (Supplementary Figure 5 - C).

The ML model estimated that the long-term average in macroalgae cover across coral reefs of the Pacific was 10.0% (80% CI [9.4% - 10.8%]) between 1990 to 2022 (Figure 1.3.4 - C), a value consistent with Tebbett et al (2023). The long-term trend in macroalgae cover increased from 1990 to 2022 (Mann-Kendall test, τ = 0.386, p-value = 0.001). Both the timing and the order of magnitude of macroalgae cover increase are consistent with previous studies (Moritz et al., 2018 ; Souter et al., 2021 ; Tebbett et al., 2023). From 1990 to 2022, the time-series can be broken into three periods:

- The first period showed a slight decrease in macroalgae cover from 9.3% (80% CI [8.4% - 10.3%]) in 1990 to 8.9% (80% CI [8.4% - 9.4%]) in 2006, representing an absolute loss of 0.4% in the average percentage cover.
- The second period corresponds to an increase in macroalgae cover from 8.9% (80% CI [8.4% - 9.4%]) in 2006 to 12.4% (80% CI [11.7% - 13.1%]) in 2016, representing an absolute gain of 3.5% in the average percentage cover.
- The third period showed a slight decline in macroalgae coral cover from 12.4% (80% CI [11.7% - 13.1%]) in 2016 to 12.0% (80% CI [11.3% - 12.8%]) in 2022, representing an absolute loss of 0.4% in the average percentage cover.

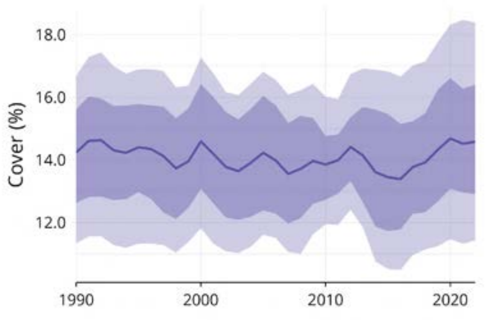


▲ **Figure 1.3.6.** Modeled temporal trends for macroalgae benthic percentage cover in the Pacific from 1990 to 2022. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively.

Turf algae cover

We defined turf algae as short (< 2cm height) filamentous algae growing on soft or hard substrate. It must be noted that the use of the term turf algae is a matter of debate in the scientific community, because of the different definitions used by the people in charge of monitoring programs (Connell et al, 2014 ; Tebbett and Bellwood, 2019). However, we considered it informative to report the temporal trend of turf algae since it is a separate category from macroalgae and coralline algae from a reef functioning perspective.

The estimation of temporal trends in turf algae cover across coral reefs of the Pacific was assessed using 19,327 observations as training data and 6,443 observations as testing data for the ML model. The RMSE value was 9.43%, indicating a good average predictive performance of the ML model (Supplementary Table 2). However, the error in estimation was not constant over the predicted range, and the ML model tended to slightly underestimate observed values when greater than 32.5% and to overestimate when below this value (Supplementary Figure 5 - D).



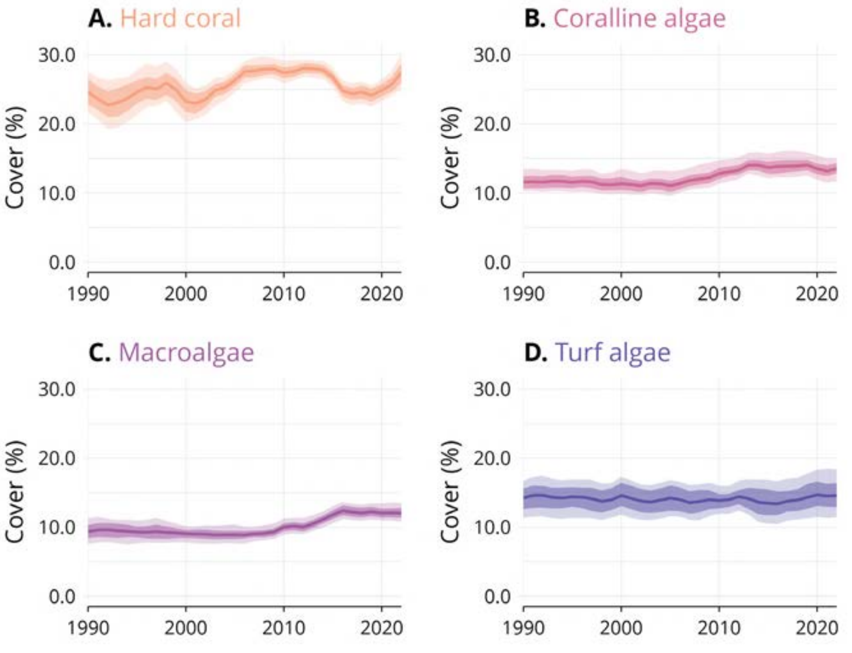
▲ **Figure 1.3.7.** Modeled temporal trends for turf algae benthic percentage cover in the Pacific from 1990 to 2022. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively.

The ML model estimated that the long-term average in turf algae cover across coral reefs of the Pacific was 14.1% (80% CI [12.5% - 15.6%]) between 1990 to 2022 (Figure 1.3.4 - D). The benthic cover of turf algae showed no significant trend from 1990 to 2022 (Mann-Kendall test, τ = -0.17, p-value = 0.16).

Changes in benthic assemblage

Our results indicate that hard corals were the predominant benthic organism on coral reefs of the Pacific from 1990 to 2022 (25.5% of long-term average), followed by turf algae (14.1%), coralline algae (12.3%), and macroalgae (10.0%) (Figure 1.3.8). The sum of the long-term average percentage cover of the four major benthic categories from 1990 to 2022 reached 61.9%, and not 100%. This indicates that we have only described part of the temporal dynamic of coral reef benthic communities. Indeed, the benthos on coral reefs can be covered by other organisms than those reported here, such as sponges and bryozoans, and also by abiotic substrate such as sand or coral rubble (e.g. Gouezo et al, 2019). Sessile benthic organisms are in competition for space in coral reefs, and free hard substrates are rapidly colonized. Hence, temporal trends of benthic cover can be seen as a zero-sum game, where the decrease in cover of one benthic category is followed by a gain in cover of another category. This gain corresponds to the colonization by organisms of one benthic category of the substrate left vacant by another benthic category, generally following the death of these organisms.

From 1990 to 2010, the decline and the recovery of hard coral cover was not concomitant with changes of the same magnitude in the benthic cover of the three other categories (Figure 1.3.8). It is possible that the limited amount of observed data for coralline algae, macroalgae, and turf algae over the 1990-2005 period prevented the ML models from identifying a more refined pattern. It is also possible that the decline and the recovery of hard coral cover could have been accompanied respectively by an increase and a decrease of the cover of benthic categories that have not been described here (e.g., sponges, bryozoans, abiotic substrate, etc.). On the contrary, in the period 2013 to 2019, the decrease in hard coral cover matched the increase in coralline algae and macroalgae cover.



▲ **Figure 1.3.8.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) benthic percentage cover in the Pacific from 1990 to 2022. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively.

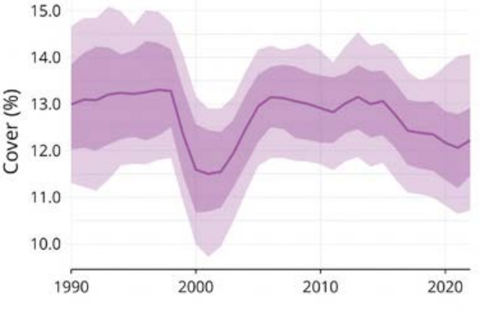
Trends in major hard coral families

Using the same predictors as those used to estimate temporal trends of major benthic categories in coral reefs of the Pacific (see section "3.2 Trends in major benthic categories"), we estimated the temporal trends of three major hard coral families, namely *Acroporidae*, *Pocilloporidae*, and *Poritidae*. These families were selected because they account for a large proportion of the total hard coral cover in coral reefs of the Pacific (e.g. Adjeroud et al, 2018).

Acroporidae

Acroporidae is a family of Scleractinian hard corals that encompasses around 216 species in the Pacific, which represent approximately 36% of all hard coral species present in the region.

The estimation of temporal trends in the benthic cover of *Acroporidae* across coral reefs of the Pacific was assessed using 17,076 observations as training data and 5,693 observations as testing data for the ML model. The RMSE value was 6.70%, indicating a good average predictive performance of the ML model. However, the error in estimation was not constant over the predicted range, and the ML model tended to slightly underestimate observed values when greater than 10% and to overestimate when below this value (Supplementary Figure 6 - A).



▲ **Figure 1.3.9.** Modeled temporal trends of the benthic percentage cover of *Acroporidae* in the Pacific from 1990 to 2022. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively.

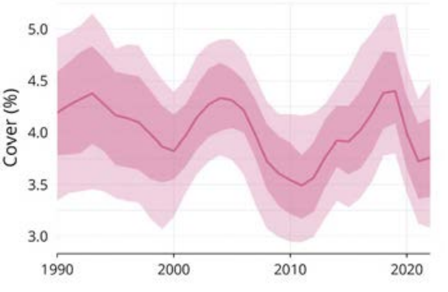
The ML model estimated that the long-term average in the benthic cover of *Acroporidae* across coral reefs of the Pacific was 12.7% (80% CI [11.9% - 13.5%]) between 1990 to 2022 (Figure 1.3.9 - A). The long-term trend in *Acroporidae* benthic cover showed a decline from 1990 to 2022 (Mann-Kendall test, τ = -0.242, p-value = 0.04). Over this time range, the time-series can be divided into four periods:

- The first period showed a slight increase in *Acroporidae* cover from 13.0% (80% CI [12.0% - 13.8%]) in 1990 to 13.3% (80% CI [12.3% - 14.3%]) in 1998, representing an absolute gain of 0.3% in the average percentage cover.
- The second period corresponds to a steep decline in *Acroporidae* cover from 13.3% (80% CI [12.3% - 14.3%]) in 1998 to 11.5% (80% CI [10.7% - 12.4%]) in 2001, representing an absolute loss of 1.8% in the average percentage cover. It is likely that this decline was due to the strong El Niño event that occurred in 1998 (Figure 1.2.2), which was associated with high SST anomalies and widespread coral bleaching (Figure 1.2.4).
- The third period showed a recovery of the *Acroporidae* cover, from 11.5% (80% CI [10.7% - 12.4%]) in 2001 to 13.1% (80% CI [12.5% - 13.8%]) in 2006, representing an absolute gain of 1.6% in the average percentage cover.
- The fourth period corresponds to a progressive decline in *Acroporidae* cover from 13.1% (80% CI [12.5% - 13.8%]) in 2006 to 12.2% (80% CI [11.4% - 12.9%]) in 2022, representing an absolute loss of 0.9% in the average percentage cover. Interestingly, the decline in the benthic cover of *Acroporidae* after the strong El Niño event that occurred in 2015-2016 (Figure 1.2.2), was much more limited than the one that occurred in 1998.

Pocilloporidae

Pocilloporidae is a family of Scleractinian hard corals that encompasses around 24 species in the Pacific, which represent approximately 4% of all hard coral species present in the region.

The estimation of temporal trends in the benthic cover of *Pocilloporidae* across coral reefs of the Pacific was assessed using 13,733 observations as training data and 4,578 observations as testing data for the ML model. The RMSE value was 3.80%, indicating a very good average predictive performance of the ML model. However, the error in estimation was not constant over the predicted range, and the ML model tended to slightly underestimate observed values when greater than 4% and to overestimate when below this value (Supplementary Figure 6 - B.



▲ **Figure 1.3.10.** Modeled temporal trends of the benthic percentage cover of *Pocilloporidae* in the Pacific from 1990 to 2022. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively.

The ML model estimated that the long-term average in the benthic cover of *Pocilloporidae* across coral reefs of the Pacific was 4.0% (80% CI [3.7% - 4.4%]) between 1990 to 2022 (Figure 1.3.9 - B). The long-term trend in *Pocilloporidae* benthic cover showed a decline from 1990 to 2022 (Mann-Kendall test, τ = -0.25, p-value = 0.04). Over this time range, the time-series can be divided into five periods:

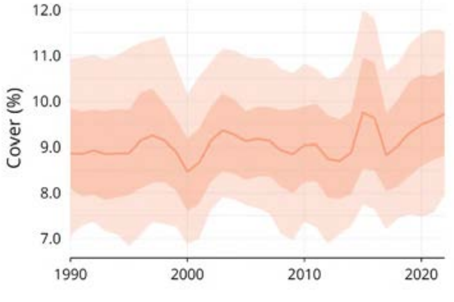
- The first period showed a decrease in *Pocilloporidae* cover from 4.2% (80% CI [3.8% - 4.6%]) in 1990 to 3.8% (80% CI [3.5% - 4.2%]) in 2000, representing an absolute loss of 0.4% in the average percentage cover.
- The second period corresponds to an increase in *Pocilloporidae* cover from 3.8% (80% CI [3.5% - 4.2%]) in 2000 to 4.3% (80% CI [4.0% - 4.7%]) in 2004, representing an absolute gain of 0.5% in the average percentage cover.
- The third period showed a decline in *Pocilloporidae* cover from 4.3% (80% CI [4.0% - 4.7%]) in 2004 to 3.5% (80% CI [3.2% - 3.8%]) in 2011, representing an absolute loss of 0.8% in the average percentage cover.
- The fourth period corresponds to an increase in *Pocilloporidae* cover from 3.5% (80% CI [3.2% - 3.8%]) in 2011 to 4.4% (80% CI [4.1% - 4.7%]) in 2019, representing an absolute gain of 0.9% in the average percentage cover.

- Finally, the last period, showed a decline in *Pocilloporidae* cover from 4.4% (80% CI [4.1% - 4.7%]) in 2019 to 3.8% (80% CI [3.4% - 4.1%]) in 2022, representing an absolute loss of 0.6% in the average percentage cover.

Poritidae

Poritidae is a family of Scleractinian hard corals that encompasses around 56 species in the Pacific, which represent approximately 9% of all hard coral species present in the region.

The estimation of temporal trends in the benthic cover of *Poritidae* across coral reefs of the Pacific was assessed using 13,586 observations as training data and 4,529 observations as testing data for the ML model. The RMSE value was 5.94%, indicating a very good average predictive performance of the ML model. However, the error in estimation was not constant over the predicted range, and the ML model tended to slightly underestimate observed values when greater than 9% and to overestimate when below this value (Supplementary Figure 6 - C).



▲ **Figure 1.3.11.** Modeled temporal trends of the benthic percentage cover of *Poritidae* in the Pacific from 1990 to 2022. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively.

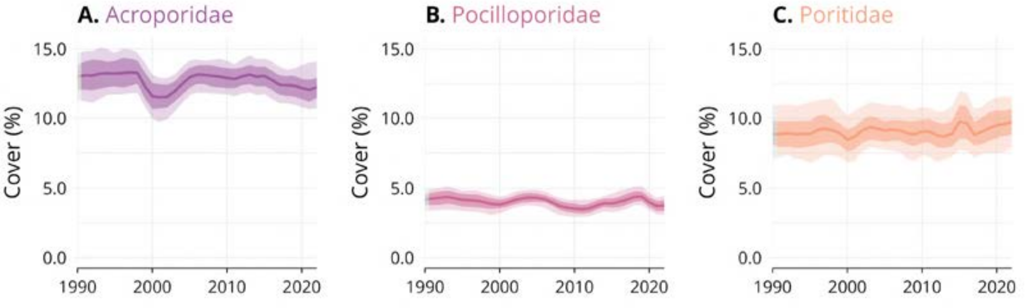
The ML model estimated that the long-term average in the benthic cover of *Poritidae* across coral reefs of the Pacific was 9.0% (80% CI [8.2% - 10.0%]) between 1990 to 2022 (Figure 1.3.9 - C). The benthic cover of Poritidae showed no significant trend from 1990 to 2022 (Mann-Kendall test, $\tau = 0.197$, p-value = 0.110). However, the benthic cover of Poritidae declined abruptly in 1998 and 2015-2016, with an absolute loss of around 1%. These two periods of steep decline are probably due to the two strong El Niño events that occurred in these years (Figure 1.2.2) and which were associated with high SST anomaly (Figure 1.2.4).

Changes in hard coral assemblage

Acroporidae represented most of the hard coral cover of coral reefs of the Pacific from 1990 to 2022 (12.7% of long-term average), followed by *Poritidae* (9.0%), and *Pocilloporidae* (4.0%).

Our results suggest that while hard coral cover remained relatively stable from 1990 to 2022 at the scale of the Pacific (Fig. 1.3.8), there was a slight change in the composition of the hard coral assemblage (Fig. 1.3.12). Particularly, the benthic cover of *Acroporidae*, a family representing most hard coral branching species, decreased and may have been partially replaced by *Poritidae*, encompassing most of massive hard coral species. This finding is consistent with the result of the previous GCRMN Pacific report, which describe a decrease in the percentage cover of the genus *Acropora* and an increase in the percentage cover of the genus *Porites* (Moritz et al., 2018).

It must be highlighted that our results only partially reflect changes occurring in coral reef communities. We were only able to estimate temporal trends in three main hard coral families, but it is very likely that complex changes in benthic composition have also occurred within other families at the taxonomic level.



▲ **Figure 1.3.12.** Modeled temporal trends of the benthic percentage cover of *Acroporidae* (A), *Pocilloporidae* (B), and *Poritidae* (C) in the Pacific from 1990 to 2022. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available.

Recommendations

Monitoring coral reefs is essential for the effective implementation of conservation and management plans, and reporting on and implementing national policies, regional targets, and international commitments. Regular and long-term monitoring allows scientists and managers to detect early signs of stress, such as coral bleaching, coral mortality, incidents of disease or declining fish populations. Data collected through monitoring provides a scientific basis for making informed decisions and quantifies the effectiveness of management actions. Without accurate and up-to-date information, conservation efforts risk being ineffective or too late to prevent damage. Therefore, monitoring programs must be capable of generating data of sufficient quality and quantity to track changes in key biological indicators of coral reefs. However, our findings reveal that coral reef monitoring across the Pacific is inconsistent in both spatial and temporal coverage. Furthermore, our experience in producing this report highlights that the data collected is often insufficiently standardized, limiting the ability to perform large-scale analyses efficiently. For this reason, we propose four recommendations to improve coral reef monitoring in the region and improve the utility of data collected.

Improve spatial representativeness

Coral reef benthic monitoring is unevenly distributed across countries and territories of the Pacific (Figure 1.3.3). Most of the monitoring efforts in the region have been from the United States (e.g., Hawaii) and French overseas territories (e.g., French Polynesia). However, these territories represent only 28.5% of coral reefs of the Pacific. On the contrary, while Papua New Guinea hosts 22% of the coral reef extent of the Pacific (Table 1.1.1), the number of surveys assessed in this country only represent 1.7% of the total number within the region from 1980 to 2023 (Table 1.3.1). In addition, we were unable to include benthic cover data from Nauru, Tokelau, and Tuvalu (Table 1.3.1). Although it is possible that we were unable to obtain the data, it is also possible that no benthic cover data has been collected in these countries. These numbers show that coral reefs in countries and territories of the Pacific are not monitored in proportion to their extent. It is likely that other factors, like the Gross Domestic Product (GDP), remoteness of reefs, or distance from research facilities, are associated with benthic monitoring effort. The limited amount of data available for some places in the Pacific limits our capacity to produce robust estimates of coral reefs trajectories within the region. This also represents a major barrier to identifying the reefs that are most resilient to the impacts of climate change (van Woesik et al., 2012).

Several solutions can be considered to remedy, at least partially, this problem of spatial representativeness. Firstly, funding organizations must be encouraged to direct part of their funding towards implementation of monitoring programs in the accessible areas where little monitoring has been carried out so far. Secondly, in inhabited areas far from research centres, citizen science may contribute to alleviate the spatial gaps. Scientists can provide citizens with simplified protocols for taking photos or videos, which can then be analysed using artificial intelligence tools, such as ReefCloud, to extract the percentage cover of benthic categories. The inclusion of local organisations and communities in monitoring their reefs empowers the custodians of marine resources, with many Pacific nations operating under local customary systems. Finally, large ocean-going research and monitoring expeditions, such as those previously carried out by the Living Oceans Foundation (Purkis et al, 2018), can help to collect data on the most remote reefs of the region. However, these expeditions must involve people from the countries and territories where the surveys are being done, and the sharing of data and findings to avoid parachute science (Stefanoudis et al., 2021).

Maintain monitoring over time

Long-term monitoring sites, defined as sites that have been surveyed for at least 15 years, represented only 2.8% of monitoring sites in the Pacific from 1980 to 2023. In addition, these sites are aggregated in a restricted number of countries and territories in the region, mainly in Fiji, French Polynesia, Palau, and New Caledonia. Yet, long-term monitoring sites are essential to describe and understand the changes that have occurred in coral reefs. For example, in Moorea, long-term monitoring sites have made it possible to describe the changes that have taken place in the composition of benthic communities and to distinguish different trajectories between inner and outer reefs (Moritz et al., 2021). In addition to their importance for research, long-term monitoring sites are also essential for management. In Hawaii, Guam, and American Samoa, the data collected by the U.S. National Park Service as part of monitoring programs were used to direct culling efforts of COTS and to inform mitigation of land-based pollution (Brown et al., 2016).

Despite their importance for both research and management, the maintenance of long-term monitoring programs is often challenging (Vucetich et al., 2020). Notably, long-term monitoring may not be seen as a priority by funding agencies that may prefer to fund shorter term projects or active interventions like coral restoration. Maintaining a long-term monitoring site may also be called into question when the trend is stable over several years, particularly when a site remains degraded, or, on the contrary, remains in good condition. However, the value of the data acquired from long-term monitoring sites increases as the time series gets longer (Lindenmayer et al., 2012). Hence, we recommend that funding organizations direct funding to the maintenance (or implementation) of long-term monitoring programs.

Monitor additional indicators

Benthic cover indicators alone are insufficient to capture the full complexity of changes occurring on Pacific coral reefs. For instance, the percentage of hard coral cover may remain stable, while the richness of hard coral species declines. In such cases, relying solely on this indicator may lead to the mistaken conclusion that reef condition is stable, whereas other indicators would reveal a decline. Therefore, it is essential that coral reef monitoring programs include additional biological indicators alongside benthic cover data.

Whenever possible we recommend fish size and density to be monitored by species, which makes it possible to derive fish biomass. Estimating changes in total fish biomass over time can provide information on how the capacity of reefs to provide a key ecosystem service, through fishing, is changing. This can also provide an indication about the sustainability of fishing, as a decrease in the total biomass of fish could indicate unsustainable fishing. In addition, herbivorous fish biomass provides information about the level of herbivory, which is a key function helping to regulate the amount of certain algae on the reef, which can compete for space with hard corals (Williams et al., 2019).

More specific biological indicators can be included in coral reef monitoring programs depending on the objectives. For example, monitoring a particular species abundance is needed to estimate the effectiveness of management measures implemented to protect it. However, monitoring programs also have a role to play outside of measuring conservation successes or failures. In particular, coral reef monitoring is crucial to rapidly identify emerging threats, such as diseases or invasive species (Morais et al., 2022).

The development of new technology over the last few decades will facilitate the processing of coral reef monitoring data. For example, artificial intelligence is used by ReefCloud to automate the estimation of the coverage of benthic organisms on photoquadrats. By decreasing the human and financial costs of the monitoring, such technologies could allow time and funding to be allocated to the acquisition of additional indicators. Some new technologies like eDNA and photogrammetry might be used to measure additional biological indicators such as relative species richness or structural complexity (e.g. West et al., 2020). Although certain technologies reduce the reliance on divers, general underwater observations will remain necessary to provide qualitative information that complement quantitative measurements.

Facilitate better use of data

The estimation of temporal trends in the benthic cover of the categories considered was made possible by the collection and standardisation of 50 datasets (see Data integration). This data integration work alone accounted for about a quarter to a third of the time needed to produce this report. Part of this time was spent researching existing datasets and contacting their owners, then signing data sharing agreements with those who wanted to share them. A significant part of the time spent on data integration was also dedicated to standardizing the collected datasets, a step which included discussions with data owners, particularly when certain metadata were missing. Our experience, through the production of this report shows that most of the benthic cover datasets do not follow the FAIR (Findable, Accessible, Interoperable, Reusable) data principles (Wilkinson et al., 2016). This makes the re-use of the data for purposes other than those for which they were initially collected more complicated. Yet, facilitating the use of data collected by coral reefs monitoring programs in the region would make it possible to drive conclusions more rapidly to inform policy makers and implement effective management solutions. Based on the FAIR data principles, we identified several areas to increase the usefulness of coral reef monitoring data.

First, we recommend that people leading monitoring programs make their datasets findable on the internet. This can be achieved by publishing the dataset on a data repository, which can be institutional (e.g. National Centers for Environmental Information), regional (e.g. Pacific Data Hub), or general (e.g. Zenodo). Another solution is to upload datasets on a data management platform such as MERMAID. Nonetheless, the ideal solution is to publish the dataset alongside a data paper (e.g. Tanner and Connell, 2022). Although longer to set up, this last option makes it possible to group together the data, their associated metadata, and a narrative on how to correctly use the data (Costello et al., 2013). The three options listed above usually allow attribution of a Digital Object Identifier (DOI) to the dataset, which makes the dataset citable by future users.

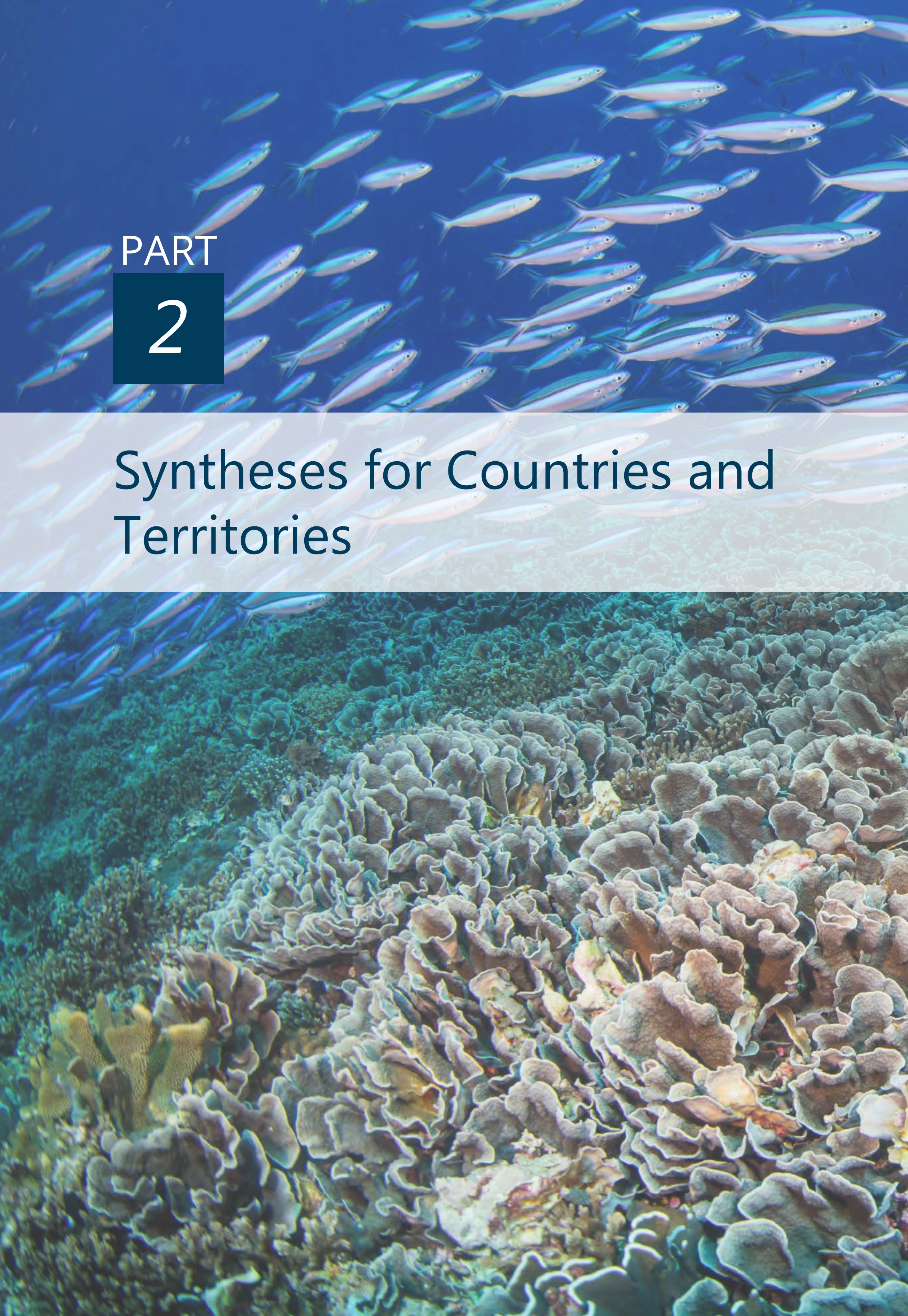
The publication of the dataset can be done by restricting access to data. This way, potential users know that the dataset exists, but must contact the data owner for permission to use the data. Such an approach can be considered when confidentiality or sovereignty issues are a factor. However, whenever possible we recommend datasets be published open access so that the data is freely accessible to potential users. We recognize that the implementation of such a practice for benthic coral reef monitoring datasets may be at odds with a data management culture focused on controlling the use of the data. For example, people leading monitoring programs can be reluctant to share their dataset because of fear it may be used inappropriately, potentially leading to incorrect conclusions (Gomes et al., 2022). They may also fear that their dataset will be used to publish a scientific article by other scientists before they have had a chance to do so themselves (Gomes et al., 2022). On the contrary, we argue that people leading monitoring programs can earn more citations and recognition for their work by publishing their dataset. This also helps to strengthen participation in international research groups. Thirdly, we recommend the people leading monitoring programs follow data standards, such as the Darwin Core (Wieczorek et al., 2012). The adoption of data standards improves interoperability, which means that the dataset can be more easily combined with other datasets (Poisot et al., 2019). In concrete terms, following data standards consists of using standardized variables names (i.e. column header), units (e.g. meters rather than feet), and data structure (e.g. long format rather than wide format).

Finally, the data must be accompanied by sufficient metadata to be re-used. We therefore recommend that people leading monitoring programs associate their dataset with a file with a description of each variable, including units used. We also recommend including the site coordinates, coordinate reference system used (CRS), equivalences of benthic categories codes, and date of the surveys if these information are not directly included in the data. Additional information can also be provided in the metadata file such as the citation to be used for the dataset and contacts of people who own the dataset.

PART

2

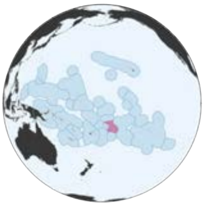
Syntheses for Countries and Territories



AMERICAN SAMOA

Co-authors[1]

Erica K. Towle, Sheila McKenna, Graham J. Edgar, Lizzi Oh, Rick D. Stuart-Smith, Jan Freiwald, Jenny Mihaly



Introduction

Maritime area	405,830 km²
Land area	216 km²
Mean land elevation	173 m
Coral reef extent	129 km²

The U.S. territory of American Samoa consists of five volcanic islands and two atolls (Rose Atoll and Swains Island) and is located in the central South Pacific Ocean. It is the U.S.' southernmost jurisdiction (Allen et al. 2023). The five volcanic islands, Tutuila, Aunu'u, Ofu, Olosega, and Ta'u, are the major inhabited islands (Hile et al. 2024). Tutuila is the largest island and the center of government. Ofu, Olosega, and Ta'u are collectively referred to as the Manu'a Islands. Twenty-five percent of the coral reefs in American Samoa are designated under either federal or territorial management, and 7% of the coral reef area are no-take (NOAA CRCP, 2018).

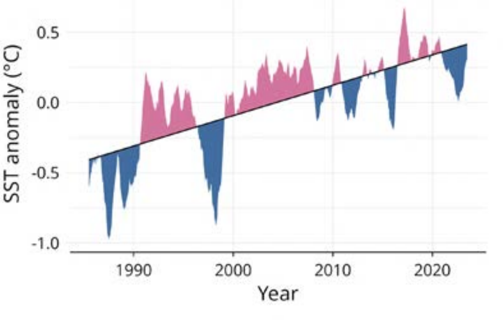
Coral reefs of American Samoa cover approximately 129 km², which represent 0.20% of the total coral reef extent of the GCRMN Pacific region, and 0.052% of the world's coral reef extent.

We estimated the human population of American Samoa living within 5 km from coral reefs to be 56,439 inhabitants in 2020. This represents 100.00% of the total human population of American Samoa living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has decreased by 1.49% between 2000 and 2020.

Threats

Thermal regime

The long-term average of SST on coral reefs of American Samoa between 1985 and 2023 was 28.57°C (Supplementary Figure 1). SST over coral reefs of American Samoa have increased by 0.83°C between 1985 and 2023, which corresponds to a warming rate of 0.022°C per year (Supplementary Figure 1).



▲ **Figure 2.1.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of American Samoa. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

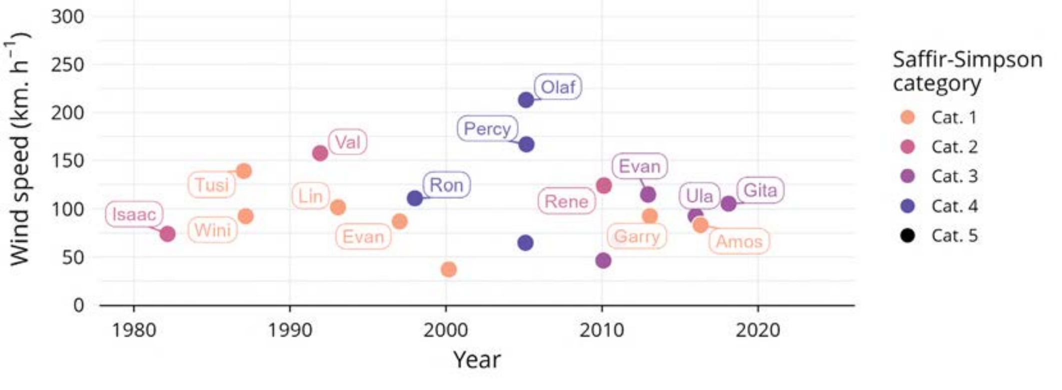
Cyclones

Between 1980 and 2023, a total of 31 tropical storms passed within 100 km distance from a coral reef of American Samoa, and of these 10 were characterized by sustained wind speed greater than 100 km.h^{-1} (Figure 2.1.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Olaf in 2005, which passed 26 km from a coral reef with sustained wind speed of 213 km.h^{-1}.

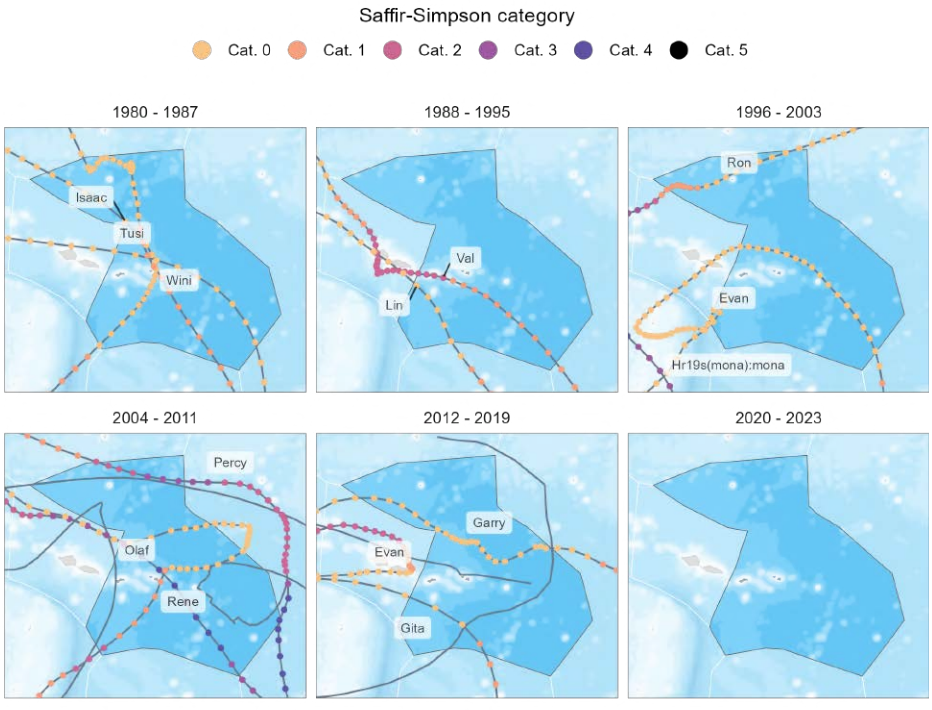
Other threats

In addition to thermal stress and cyclones, the islands of American Samoa are vulnerable to other climate change impacts such as ocean acidification, increased storm surge, and heavy rainfall events (NOAA CRCP, 2018). Additionally, one of the most notable threats to the coral reefs in American Samoa is sea level rise resulting from climate change and the continued subsidence of the islands from the 2009 earthquake, resulting in a rate of sea level rise approximately five times the global average (Han et al., 2019).

Crown of thorns sea star (COTS, *Acanthaster spp.)* outbreaks have also been a major challenge in the past few decades in American Samoa. COTS consume the coral tissue, leaving behind bare coral skeleton. In low densities, COTS have little effect on coral reefs. However, when they aggregate and form large densities or outbreaks, they can decimate the amount of live coral on the reef, change the reef structure, create space for algal growth, and affect fish populations (De'ath et al. 2012; Fabricius 2013). In 2012, the COTS population began to explode. Land-based pollution and the subsequent runoff of nutrients like nitrogen and phosphorus are believed to cause COTS outbreaks. However, another theory links the COTS outbreak to a 2009 tsunami, which may have dislodged sediments and stirred up nutrients from the ocean floor (NOAA).



▲ **Figure 2.1.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in American Samoa. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h^{-1}). Note that cyclones passing more than 100 km away from coral reefs of American Samoa are not represented, although they may have had an impact.

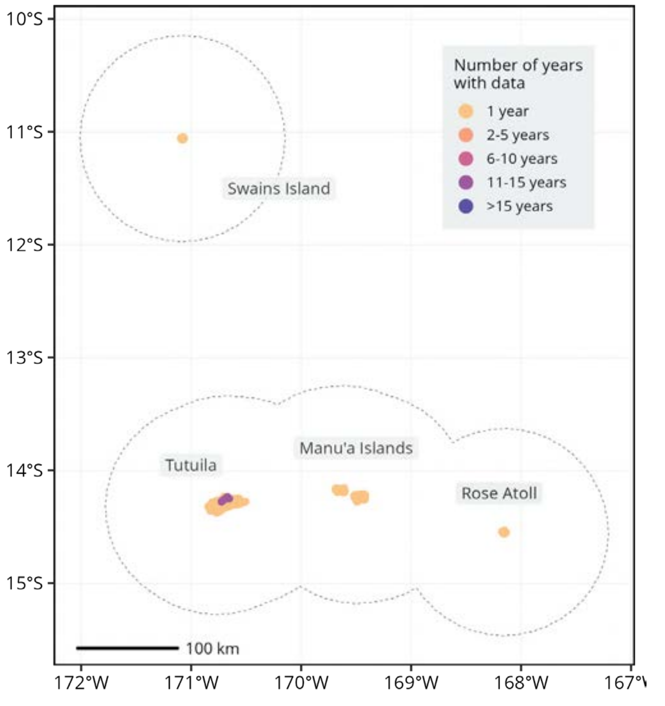


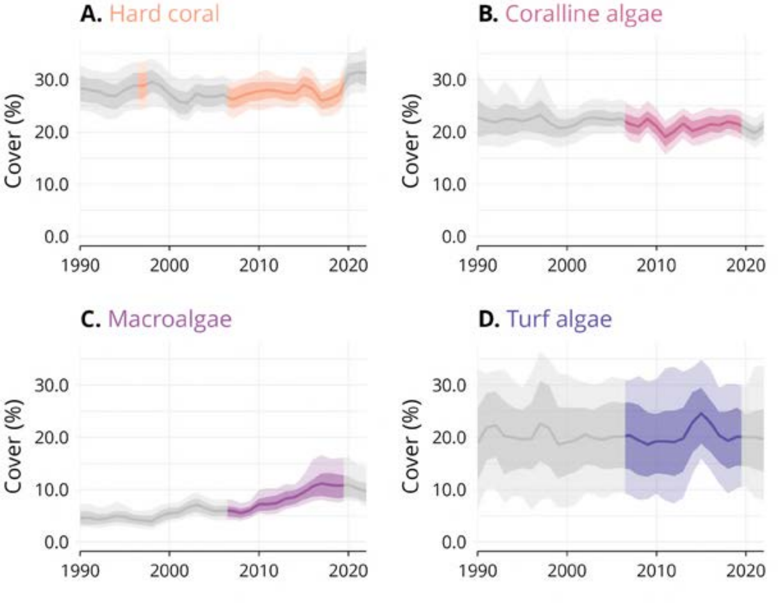
▲ **Figure 2.1.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in American Samoa. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (i.e. subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in American Samoa was achieved through the integration of 4 datasets (Supplementary Table 1). These datasets represent a total of 1,039 monitoring sites, on which 1,219 surveys were conducted between 1997 and 2019.

▸ **Figure 2.1.4.** Spatio-temporal distribution of benthic cover monitoring sites across American Samoa. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories.





▲ **Figure 2.1.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in American Samoa. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

CASE STUDY

Trends in Human Connections to Coral Reefs in American Samoa

Author

Mary Allen[1]

Socioeconomic monitoring is critical to understanding the connections between humans and coral reef ecosystems. This is important because coral reefs provide a variety of benefits to people such as recreation, tourism, seafood, cultural heritage, and much more. Likewise, people play a central role in protecting coral reef ecosystems to sustain these benefits, while fostering their relationships with nature. Recognizing that people are an integral part of the ecosystem, NOAA's National Coral Reef Monitoring Program (NCRMP) is one of the few programs in the world that integrates human dimensions into coral reef ecosystem monitoring. As a whole, NCRMP provides a holistic understanding of the status of coral reefs and the coastal communities who depend on these ecosystems.

The Socioeconomic Component of NCRMP collects and monitors socioeconomic data in seven U.S. coral reef jurisdictions, including American Samoa. The territory consists of seven islands including the inhabited islands of Tutuila, Aunu'u, and Manu'a (Ta'u, Olosega, Ofu). In 2020, American Samoa had a population of 49,710 people[1] , with the majority living on the main island of Tutuila. Tutuila is the only island with villages classified as 'urban'. The remaining islands are less developed, largely due to having fewer inhabitants.

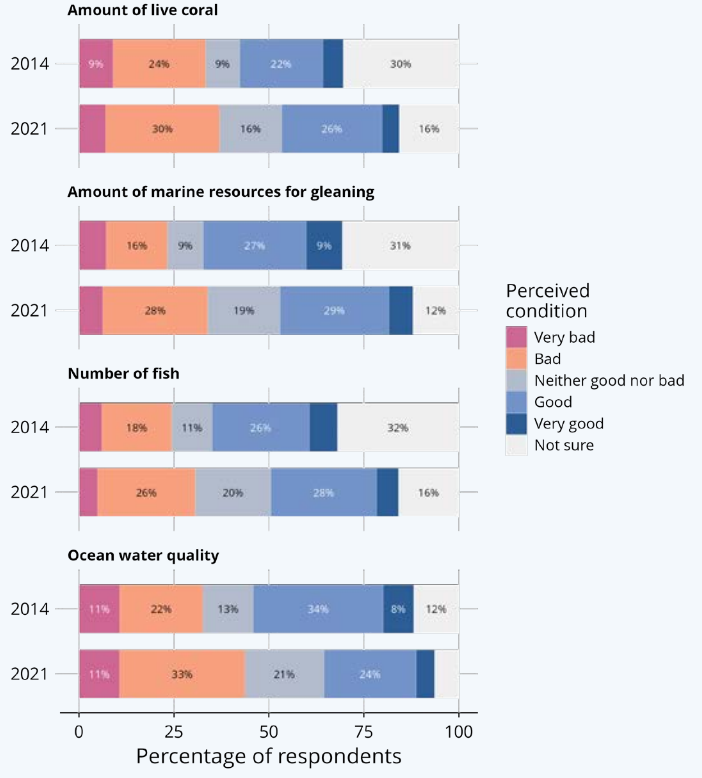
The people of American Samoa have strong cultural ties to the ocean. Samoan culture, or *Fa'a Samoa*, is the foundation of life in these islands and remains extremely important in modern times. With two coral atolls and shallow water coral reef habitats surrounding all of the islands, American Samoa's coral reef ecosystem has high biodiversity with over 2,700 species to include corals, invertebrates, fishes, and mammals. This ecosystem is critical to maintaining customs and traditions, as well as American Samoa's ocean economy which employs about 40% of the territory's people (NOAA OCM 2022). However, this ecosystem and its dependent population are at risk to a number of threats, such as the invasive crown-of-thorns starfish, coral bleaching, coastal construction, pollution, algal outbreaks, among others.

To assess the status of socioeconomic conditions related to coral reefs, surveys are conducted with household residents every 5-7 years. The surveys collect data on measures such as human use of coral reef resources, knowledge, attitudes, and perceptions of coral reefs and management. These data inform the human connections to coral reefs and people's relationships with coral reefs may be changing over time. Two monitoring cycles have been completed in American Samoa so far, with surveys conducted with residents in 2014 (n = 448) and 2021 (n = 1,318). Results are representative of the resident population of American Samoa as a whole, as well as five strata: rural villages, semi-rural villages, urban villages, Aua village, and the Manu'a Islands.

[1] This value differs from the one given in the American Samoa chapter as a result of different data sources

The 2021 results showed a general consensus that American Samoa's coral reefs are important to culture, coastal protection, the local economy, and food for coastal communities. Swimming/wading, beach recreation, and waterside/beach camping were primary activities for American Samoa residents in both 2014 and 2021, but frequency of participation in all activities declined in 2021. Additionally, most resident households consumed seafood on a weekly basis, and nearly all residents ate local seafood from coral reefs at least once a month.

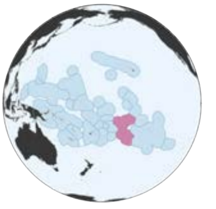
Residents believed that the overall marine ecosystem in American Samoa had become worse or not changed over the past ten years, but most believed that resource conditions may improve in the future. In 2021, the conditions of ocean water quality and amount of live coral were particular concerns (Figure 1). Ocean water quality was perceived as being in the worst condition, relative to other resources, and the percentage of residents who rated water quality as "bad" increased by 11% in 2021. In general, there was a decrease in the percentage of residents who were "not sure" about these conditions, suggesting residents were more confident in their perceptions.



▲ **Figure 1.** American Samoa resident perceptions of resource conditions in 2014 and 2021.

Residents were familiar with a variety of threats to coral reefs. They were most familiar with climate change, hurricanes, and pollution as threats, but least familiar with ocean acidification. Residents generally supported a range of potential marine management policies and regulations, such as incorporating traditional Samoan practices into coral reef management, improving law

COOK ISLANDS



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Introduction

Maritime area	1,969,553 km²
Land area	257 km²
Mean land elevation	52 m
Coral reef extent	528 km²

The Cook Islands are a collective of 15 islands across an EEZ of nearly 2 million square kilometers. Of the 15 islands, 12 are inhabited, with most of the population living on the island of Rarotonga (approximately 11,000 people). The islands are divided into the northern group, composed of mostly coral atolls and the southern group which are mostly raised coral islands, with two atolls (Palmerston and Manuae) and the "almost-atoll" of Aitutaki. The uninhabited islands of Suwarrow, Manuae, and Takutea represent important reef habitats that are less exploited for reef resources than the inhabited islands.

Coral reefs of Cook Islands cover approximately 528 km², which represent 0.81% of the total coral reef extent of the GCRMN Pacific region, and 0.211% of the world coral reef extent.

We estimated the human population of Cook Islands living within 5 km from coral reefs to be 18,049 inhabitants, in 2020. This represents 100.00% of the total human population of Cook Islands living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has decreased by 0.23% between 2000 and 2020.

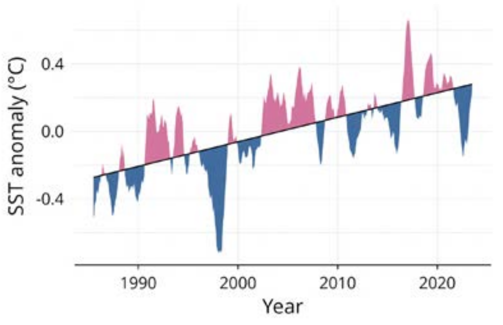
Threats

Thermal regime

The long-term average of SST on coral reefs of Cook Islands between 1985 and 2023 was 27.52°C (Supplementary Figure 1). SST over coral reefs of Cook Islands have increased by 0.55°C between 1985 and 2023, which corresponds to a warming rate of 0.014°C per year (Supplementary Figure 1).

Severe bleaching events have been observed in the Cook Islands corresponding to El Niño events (Rongo, 2016). Coral bleaching, particularly in lagoon areas, has also been observed during calm periods with extreme low tides where corals in shallow areas become exposed (Rongo and van Woesik, 2013; Rongo, 2016). Bleaching events are generally more severe in the northern group islands, where temperatures are warmer on average than the southern group.

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

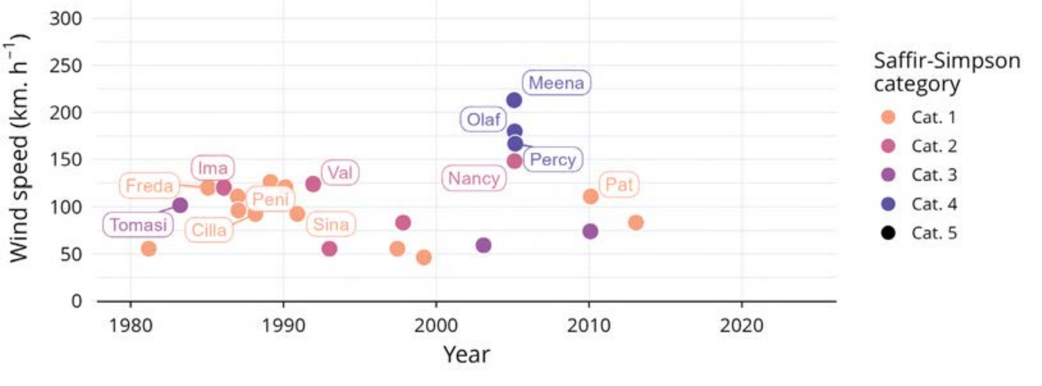


▲ **Figure 2.2.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Cook Islands. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Cyclones

Between 1980 and 2023, a total of 59 tropical storms passed within 100 km distance from a coral reef of Cook Islands, and of these 14 were characterized by sustained wind speed greater than 100 km.h^{-1} (Figure 2.2.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Meena, in 2005, which passed 35 km from a coral reef with sustained wind speed of 213 km.h^{-1}.

Due to multiple stressors and the challenges of surveying remote reefs, the direct impact of cyclones on coral reefs has been difficult to assess (Rongo et al., 2017). Notably, however, during 2005-2016 there were no cyclones experienced in Rarotonga, which allowed reefs there to recover from previous damage (Rongo, 2017).



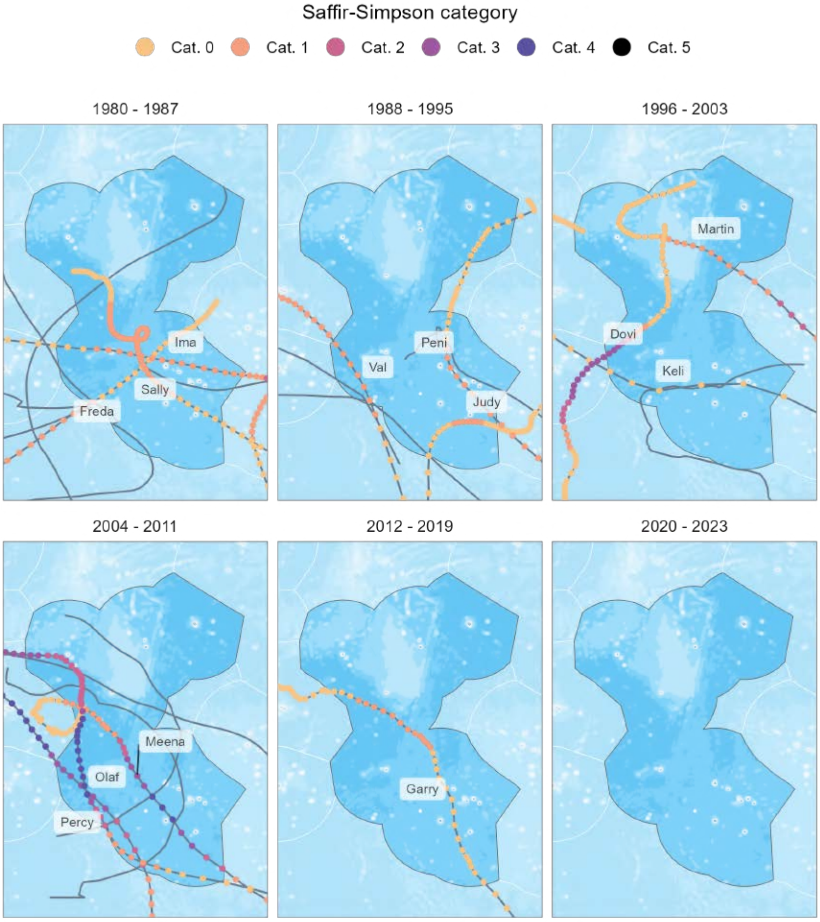
▲ **Figure 2.2.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Cook Islands. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h^{-1}). Note that cyclones passing more than 100 km away from coral reefs of Cook Islands are not represented, although they may have had an impact.

Other threats

Crown of Thorns starfish (*taramea*, *Acanthaster spp.*) are a key threat to coral reefs in the Cook Islands. Multiple outbreaks of taramea have been documented in Rarotonga and the southern group islands (e.g. Rongo, 2016; Parrish and Morejohn, 2021). Not all islands are equally affected by COTS, and significant removal efforts are made by local organisations to control outbreaks, particularly in Rarotonga.

Sedimentation from land-based activities, coastal development and terrestrial runoff threaten reefs on inhabited islands. Agricultural runoff can also cause nutrient enrichment in coastal areas, leading to excessive algae growth, particularly in lagoons (Tait et al., 2014, Erler et al., 2018).

Overfishing is a concern for reefs in the Cook Islands, particularly for prized species such as giant clams (*Tridacna spp.*). Removal of fish and invertebrates from reefs may disrupt reef ecosystems and impact coral health. This includes the harvesting of the natural predators of COTS, the *maratea* (humphead wrasse; *Cheilinus undulatus*) and *Pū* (triton's trumpet; *Charonia tritonis*).

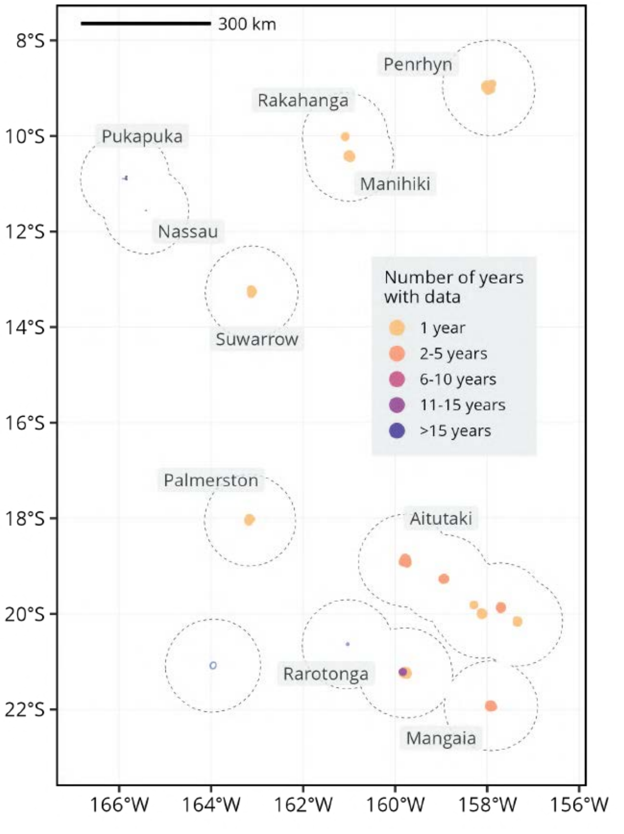


▲ **Figure 2.2.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Cook Islands. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

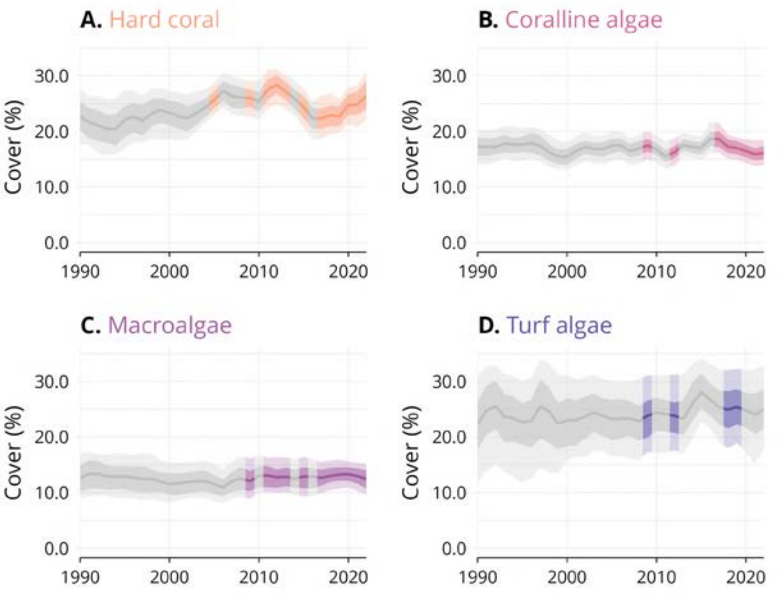
Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Cook Islands was achieved through the integration of 5 datasets (Supplementary Table 1). These datasets represent a total of 191 monitoring sites, on which 246 surveys were conducted between 2005 and 2023.

There is a paucity of time series data for most islands within the Cook Islands, with Rarotonga being the only island with longer term data sets. Overall hard coral cover appears to be increasing in recent years, following a decline corresponding to the 2015/2016 El Nino event. Coralline algae and macroalgae cover have not changed significantly across the last 5 years of monitoring, with low variability across the dataset, despite data being drawn from both the Northern and Southern group islands.

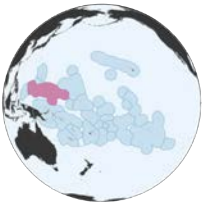


▲ **Figure 2.2.4.** Spatio-temporal distribution of benthic cover monitoring sites across Cook Islands. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.2.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Cook Islands. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

FEDERATED STATES OF MICRONESIA



Co-authors[1]

Peter Houk, Nicole Pedersen, Beverly French, Stuart Sandin, Jan Freiwald, Jenny Mihaly

Introduction

Maritime area	3,007,718 km^2
Land area	760 km^2
Mean land elevation	99 m
Coral reef extent	4,925 km^2

The four states that comprise the Federated States of Micronesia (FSM) account for a large part of tropical western Pacific ocean (1 to 10 degrees N, 138 to 162 degrees E). This represents over 2,700 kilometers in linear distance crossing the states of Kosrae, Pohnpei, Chuuk, and Yap (east to west, respectively) (Figure 1). In terms of area, the FSM economic exclusive zone accounts for around 3 million km2 of the western Pacific Ocean, representing the 14th largest in the world, despite having only 760 km2 of land. While there are 607 islands across the FSM, 65 are inhabited. Human populations are centered on the main four islands of each state which have volcanic origins, significant agriculture, extensive freshwater resources, and diverse coral-reef habitats. In contrast, the outer atolls have limited amounts of land and often limited freshwater resources, although extensive reef structures exist.

Coral reefs of Federated States of Micronesia cover approximately 4,925 km^2, which represent 7.55% of the total coral reef extent of the GCRMN Pacific region, and 1.972% of the world coral reef extent.

We estimated the human population of Federated States of Micronesia living within 5 km from coral reefs to be 102,646 inhabitants, in 2020. This represents 99.13% of the total human population of Federated States of Micronesia living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has decreased by 3.11% between 2000 and 2020. Inhabitants spread across the main islands of Yap (7,300), Chuuk (36,000), Pohnpei (36,000), Kosrae (6,700), and the sparse but significant populations on the numerous outer atolls (27,000).

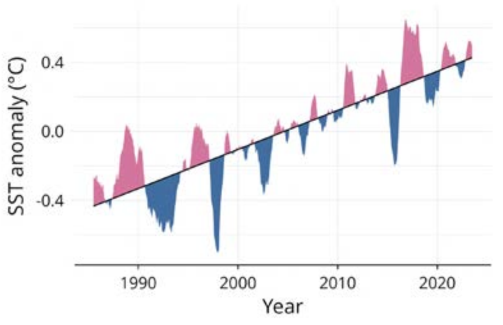
Threats

Thermal regime

The long-term average of SST on coral reefs of Federated States of Micronesia between 1985 and 2023 was 29.01°C (Supplementary Figure 1). SST over coral reefs of Federated States of Micronesia have increased by 0.89°C between 1985 and 2023, which corresponds to a warming rate of 0.023°C per year (Supplementary Figure 1).

Within FSM, there have been significant spatial differences in the frequency and magnitude of heat stress to the oceans. The recent 2015 to 2017 ENSO event caused heat stress to the FSM ocean, however, many remote atolls near Chuuk experienced up to three times the amount of heat stress compared to remote Yap atolls. Unfortunately, the frequency and magnitude of climate disturbances continues to rise, and FSM was again impacted in 2020 and the 2023 to 2024 ENSO as well.

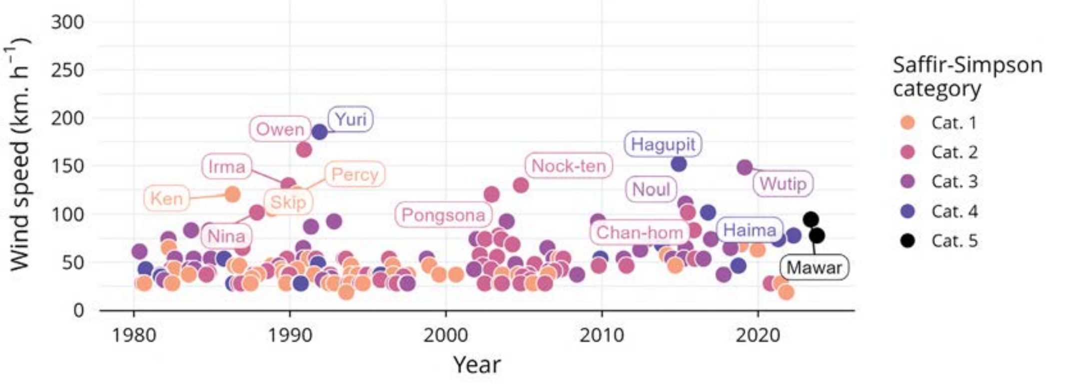
[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.



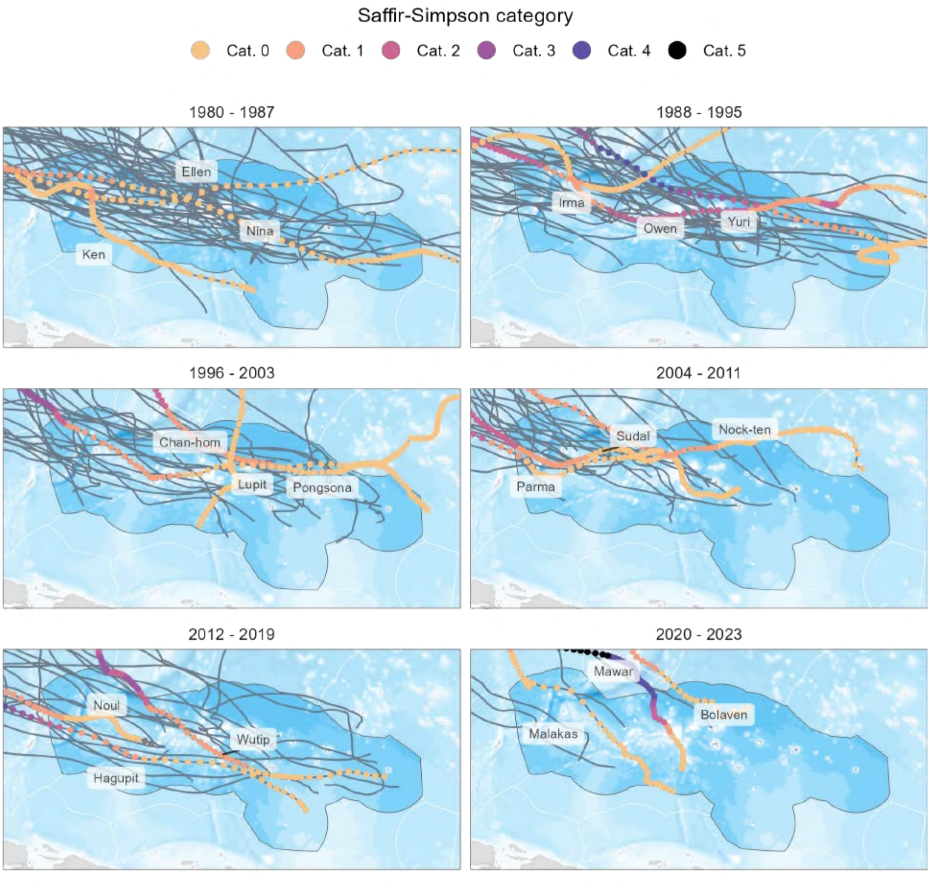
▲ **Figure 2.3.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Federated States of Micronesia. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Cyclones

Between 1980 and 2023, a total of 307 tropical storms passed within 100 km distance from a coral reef of Federated States of Micronesia, and of these 15 were characterized by sustained wind speed greater than 100 km.$^{h-1}$ (Figure 2.3.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Yuri, in 1991, which passed 52 km from a coral reef with sustained wind speed of 185 km.h^{-1}.



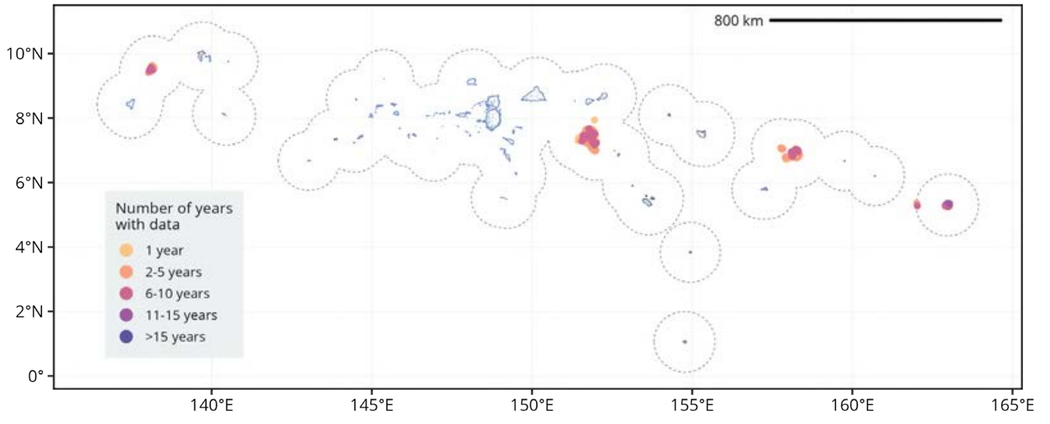
▲ **Figure 2.3.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Federated States of Micronesia. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h^{-1}). Note that cyclones passing more than 100 km away from coral reefs of Federated States of Micronesia are not represented, although they may have had an impact.



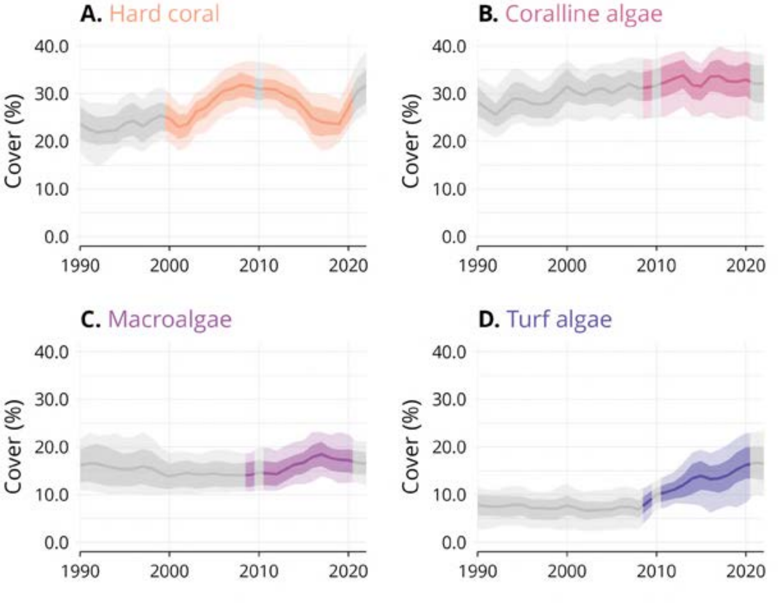
▲ **Figure 2.3.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Federated States of Micronesia. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Federated States of Micronesia was achieved through the integration of 3 datasets (Supplementary Table 1). These datasets represent a total of 217 monitoring sites, on which 555 surveys were conducted between 2000 and 2020.



▲ **Figure 2.3.4.** Spatio-temporal distribution of benthic cover monitoring sites across Federated States of Micronesia. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories.The distribution of coral reefs is shown in light blue.



▲ **Figure 2.3.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Federated States of Micronesia. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

CASE STUDY

SocMon Case Study: Weloy, Yap State, Federated States of Micronesia

Author

Winfred Mudong

The Federated States of Micronesia (FSM) is composed of four states: Yap, Chuuk, Pohnpei, and Kosrae. These states consist of 607 islands, stretching across approximately 1,700 miles from west to east varying from high mountainous islands to low-lying atolls. The waters of the FSM host 1,221 species of fish, with 1,070 of these species associated with the extensive reef systems. The broader Micronesia region is estimated to contain 4% of the world's coral reefs, with these reefs being a defining feature of the FSM. The corals themselves are highly diverse in the FSM waters, with a significant presence of both soft and hard/stony corals. According to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, there are 427 species of coral in the FSM's waters, of which 100 are considered vulnerable and three endangered.

Yap State is located in the western most part of the FSM, and has a population of approximately 11,000 people spread across the main island of Yap and its outer islands. Weloy municipality is centrally located on the main island of Yap, with both east- and west-facing coastlines. The traditional leaders of Okaw and Kaday villages formally endorsed the Nimpal Channel Marine Conservation Area (NCMCA) to address overharvesting in the Nimpal Channel. This initiative, along with other community-led natural resource management activities, aims to ensure the sustainability and productivity of local fishing grounds and to enhance marine biodiversity conservation in the area. A public declaration of the NCMCA by the respective communities and their leadership is an exercise of traditional rights and ownership recognized by Yap State. This declaration allows the people of Kaday and Okaw villages, within Weloy municipality, to protect and regulate the use of marine resources in the Nimpal Channel according to their customs and traditions. This area holds special significance due to its abundant marine resources and the culturally important fish it has historically supplied to families in Weloy.

In 2018, the SEM-Pasifika (SocMon) assessment was initiated by the Kaday and Okaw communities of Weloy. The assessment was fully supported by the Weloy leaderships, the Micronesia Conservation Trust, the NOAA Pacific Islands Fisheries Science Center (PIFSC), and the Pacific Island Managed and Protected Area Communities (PIMPAC). Combining science with traditional and local knowledge, the SEM-Pasifika team included local representatives from Weloy, the Micronesia Challenge Socioeconomic Monitoring Regional Coordinator, trained members of the SEM-Pasifika Micronesia Challenge core teams, and social scientists from University of Hawaiʻi, and the U.S. National Oceanic and Atmospheric Administration.

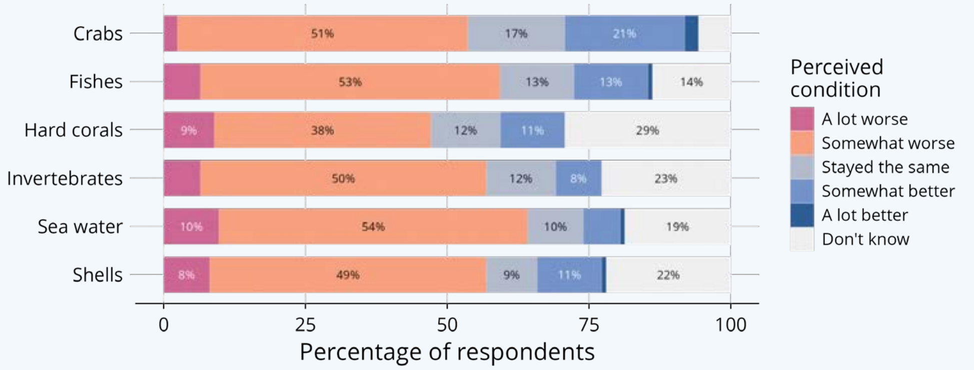
To collect socioeconomic data, a household survey was administered in person by trained enumerators. Stratified sampling was employed to guarantee that the sample was representative of Weloy's population distribution across its villages, which is organized based on traditional fishing rights. Weloy has a total of 177 households. To achieve a standard 95% confidence interval with a 5% margin of error, the target sample size was set at a minimum of 123 households. The selection of households was stratified into three subgroups, each based on the village of origin. This stratification was crucial because the traditional rights and responsibilities of the households vary depending on their village of origin. This sampling design ensured that each subgroup was proportionately represented, reflecting the true demographic and social structure of Weloy Municipality.

The objectives of this socioeconomic survey were to understand community natural resource use in Weloy, including: (1) the types and ways of utilizing marine and coastal resources such as fish, corals, and shellfish; (2) household dependence on natural resources for sustenance and income; (3) perceived conditions of natural resources; and (4) perceived threats and priorities concerning key marine, coastal, and terrestrial resources.

All households surveyed in Weloy engaged in some form of natural resource use for sustenance, income, or cultural purposes. Most households utilized marine resources such as fish, shellfish, and invertebrates primarily for household use. A smaller proportion used these resources for both household use and sale. Specifically, 91% of households used fish, with 72% using it exclusively for household purposes and 19% using it for both household consumption and income.

Regarding fishing locations, 73% of households fished or harvested marine resources in seagrass beds, 62% in blue holes (marine sinkholes), 53% on reef flats, 52% in channels, 39% in mangroves, and 31% on the outer reef. The primary reasons for fishing included feeding or supporting their family (73%), giving to extended family or friends (55%), special occasions (52%), recreation (27%), selling (21%), and less than 10% for feeding livestock or agricultural use.

Despite their heavy dependence on marine resources, over 50% of households perceived these resources to be in poor or very poor condition, with the exception of corals (Figure 1). Furthermore, the majority believed that the condition of these resources had deteriorated over the past ten years, although about one-third were unaware of the changes. However, over 75% of households agreed that the Nimpal Channel Marine Conservation Area (MCA) had positively impacted the populations of important food fish and invertebrates, both within and outside the MCA, and had improved coral reef health in the area. They also believed the MCA helped maintain cultural and customary fishing practices and would ensure food security for future generations.

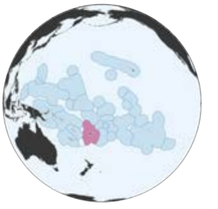


▲ **Figure 1.** Weloy household perceptions of the condition of natural resources, *n* = 123.

Key recommendations from the survey included improving outreach, information flow, and awareness, as most households were willing to support conservation but were unaware of ongoing activities in their communities. These social data provide natural resource managers and leaders with better insights into community perceptions of conservation. This information can help develop effective adaptive management plans for natural resource conservation and sustainability and improve communication with community members. Based on the positive sentiment towards protected areas, there is potential to expand such community projects or initiatives to neighboring communities.

The results of this assessment represent a baseline socioeconomic status that can be monitored over time in concert with biophysical and climate monitoring of coral reef ecosystems. Socioeconomic information, coupled with biophysical and climate information, allows researchers and planners to examine a holistic system, encompassing both natural and social aspects when making informed natural resource management and conservation decisions.

FIJI



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Introduction

Maritime area	1,302,114 km²
Land area	18,904 km²
Mean land elevation	210 m
Coral reef extent	6,704 km²

Located in the south central Pacific, the Republic of Fiji comprises 332 islands and 522 islets with a total land area of 18,904 km2 and an exclusive economic zone of 1.3 million km². Fiji's coral reefs cover approximately 6,704 km², which represent 10.27% of the total coral reef extent of the GCRMN Pacific region, and 2.68% of the global coral reef extent. A wide variety of coral reefs are found in Fiji including fringing, platform, pinnacles, submerged, barrier, oceanic ribbon, atolls, near-atoll, and drowned reefs. At least 342 species of scleractinian corals, and 1075 reef-associated fish species have been documented in Fiji (Mangubhai et al., 2019).

Around 100 of Fiji's islands are inhabited, with more than 50% of Fiji's the population (total estimated population 864,132) residing in urban areas (477,500) (Fiji Bureau of Statistics, 2021). Indigenous Fijians (iTaukei) contribute to around 62% of the total population, followed by Indo-Fijians (34%), and other ethnic groups (4%). We estimated the human population of Fiji living within 5 km from coral reefs to be 468,453 inhabitants, in 2020. This represents 50.52% of the total human population of Fiji living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 10.84% between 2000 and 2020.

Fiji's land-sea tenure system is deeply rooted in customary ownership, where iTaukei communities have ownership rights over land and access rights to adjacent marine areas (Veitayaki, 2000). Nearshore coral reefs fall within iTaukei customary fishing grounds (qoliqoli) which extend from the foreshore to the outer edge of the reef, are subject to a dual system of management under both customary and statutory laws, whereby communities have access rights and stewardship over their resources and the ownership of the seabed and overlying resources rests with the State (Sloan and Chand, 2016). There are 411 registered qoliqoli areas in Fiji covering approximately 30,011 km², with several coastal communities sharing access rights to the same fishing grounds. The state retains authority over the seabed and marine resources, and therefore all commercial uses of marine waters (including in qoliqoli areas), requires a licence. This dual management system presents challenges for regulating inshore fisheries and in balancing resource use, biodiversity conservation and protecting customary rights.

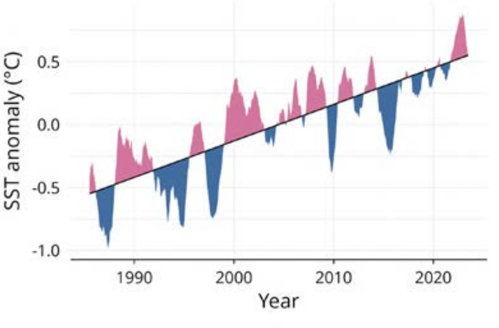
Threats

Thermal regime

The long-term average of SST on coral reefs of Fiji between 1985 and 2023 was 27.51°C (Supplementary Figure 1). SST over coral reefs of Fiji have increased by 1.06°C between 1985 and 2023, which corresponds to a warming rate of 0.028°C per year (Supplementary Figure 1). In Fiji, the highest SSTs occur in December to March each year (Supplementary Figure 2).

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

Widespread coral bleaching and associated mortality (estimated 40–80% of corals) were documented across the archipelago in the 2000 during a La Niña event (Cumming et al., 2006). Smaller, more localised bleaching events have often been reported regularly since during the warmest months (February-April), without strong evidence of significant bleaching-related mortality (Mangubhai et al., 2019). In 2019, SSTs in Fiji ranged from 27–31°C between the months of January to May, with the highest levels of coral bleaching were recorded in March and April, primarily in the Yasawa (40%), Taveuni (>40%) and Beqa (>40%), and 5–20% recorded along the Coral Coast (WCS 2019). However, bleaching did not persist and most corals had returned to normal by May and June as SSTs dropped.



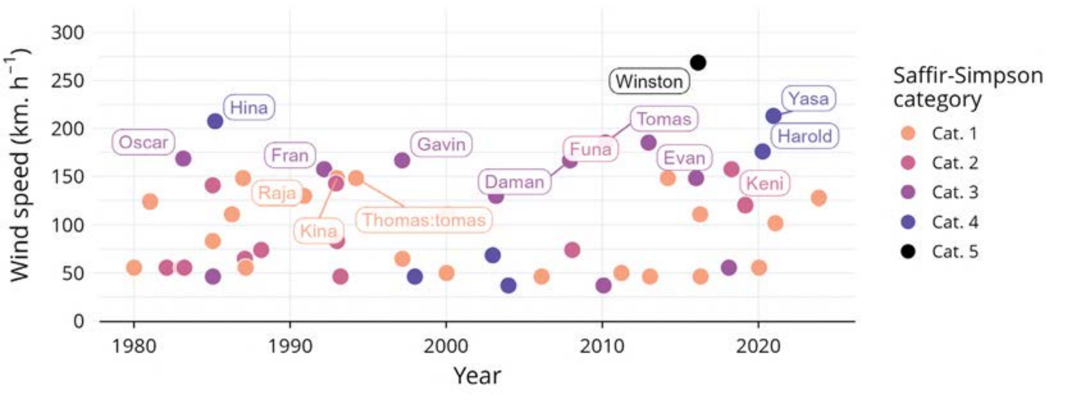
▲ **Figure 2.4.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Fiji. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Fiji's reefs have generally displayed high resilience to disturbances, and reduced bleaching impact may be in part explained by the warmer months coinciding with the cyclone season, which can act to dissipate temperature stress (Mangubhai et al., 2019). For example coral bleaching was documented in 2016 in the weeks leading up to Tropical Cyclone Winston, with in situ temperatures on inner reef flats along the Coral Coast reaching a high of 35°C (Mangubhai, 2016). Rapid assessments in the Vatu-i-Ra Seascape in March 2016 indicated that the average percentage of bleached corals was highest at Gau (20.2±8.6%) and reefs in the Eastern Bligh Waters (7.0±4.8%). Immediately following the cyclone, SSTs in Fiji dropped by 1-2°C and satellite imagery showed hot spots and temperature anomalies dissipating.

Cyclones

Between 1980 and 2023, a total of 112 tropical storms passed within 100 km distance from a coral reef of Fiji, and of these 29 were characterized by sustained wind speed greater than 100 $km.h^{-1}$ (Figure 2.4.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Winston, in 2016, which passed 0 km from a coral reef with sustained wind speed of 269 $km.h^{-1}$.

Tropical cyclone Winston - a category 5 storm on the Saffir-Simpson scale - generated waves up to 30 standard deviations higher than routine wave conditions in some areas (Price et al., 2021) and caused significant damage to corals and the reef matrix down to 30 m depth in 2016 (Mangubhai, 2016). Some reefs lost up to 90% of their hard coral following the cyclone, primarily driven by losses of branching and tabulate Acropora spp., but substantial recovery was documented already by 2020 (Ford et al., in review). Tropical cyclone Yasa that made landfall in 2020 was a slow-moving category 4 storm that also resulted in extensive damage to some areas of reef (e.g. in the Somosomo Strait), with evident dislodgement and breakage of corals and increased rubble following the cyclone (Aitken et al., 2021). The other recent category 4 cyclone was Harold, which occurred in 2021 during the COVID-19 lockdown. While there is no documentation of the impact of this cyclone on coral reefs, anecdotal reports suggest it had a significant impact on southern reefs (e.g. around Kadavu Province).



▲ **Figure 2.4.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Fiji. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 $km.h^{-1}$). Note that cyclones passing more than 100 km away from coral reefs of Fiji are not represented, although they may have had an impact.

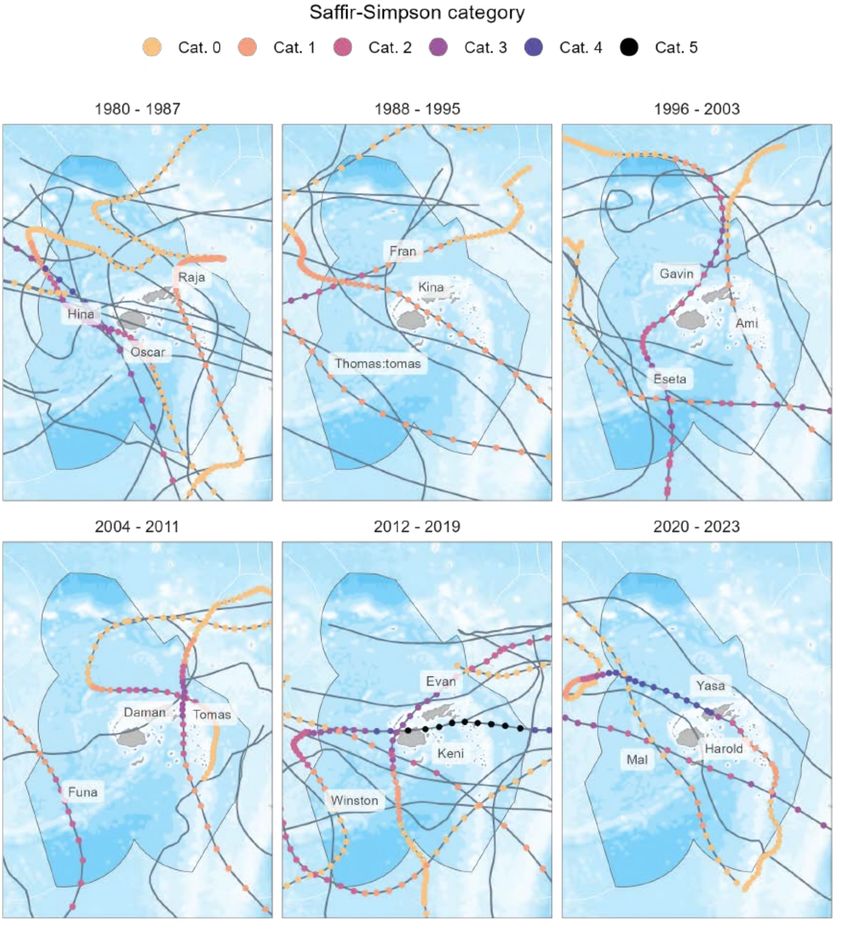
Other Threats

Fiji's coral reefs face a range of compounding and intersecting local threats stemming from anthropogenic activities, including pollution (land and sea-based), sediment, nutrient and chemical runoff, destructive fishing (e.g. duva, a traditional poison), overfishing and poorly planned coastal development (Mangubhai et al., 2019). These stressors can directly damage coral structures, disrupt ecosystems, and impact water quality, leading to reduced coral health and reef resilience (McLeod et al., 2019).

Benthic cyanobacterial mats are an issue on several of Fiji's reefs, covering up to 50% of the substrate at some reefs during surveys (Ford et al., 2021), with a large study of 150 sites in Fiji revealing that 20% have >10% cyanobacterial coverage (Ford et al., unpubl. data). The mats have been linked to rising temperatures and declining water quality (Ford et al., 2018) and can negatively impact corals, coral recruitment, and herbivory processes (Ford et al., 2021), thus likely reducing system resilience. Many survey protocols do not record mats, lumping them together with other groups or recording the abiotic substrate underneath them, limiting large-scale and long-term comparisons in their coverage.

Corals are vulnerable to predators such as crown-of-thorns starfish (COTS) (*Acanthaster planci*) and *Drupella* snails (Mangubhai et al., 2019) and diseases such as white syndrome, ulcerative white spot syndrome and brown band diseases. However, other signs of stress response, such as pigmentation response and growth anomalies, are commonly sighted on Fijian reefs (Nand, 2020). A study from 38 sites across Fijian reefs in 2013 showed that disease prevalence rates varied across locations, reef types (barrier and fringing reefs) and habitats (fore reefs and reef flats). It also showed that barrier reef systems and forereefs (<10%) recorded higher signs of disease lesions on corals than fringing reefs and reef flats (<3%), respectively. Disease prevalence also varied with coral assemblage and locations (difference between dry and wet sides of the larger islands). Diseases in corals are important as a driver of reef degradation, and there is a need to invest resources to assess long-term trends, seasonal and spatial variations of disease prevalence and incidence across Fijian reefs. The correlation between coral disease and other disturbances such as tropical cyclones, flood events, pollution, sedimentation, coastal development, and tourism is poorly understood in the region (Beeden et al., 2015; Ruiz-Moreno et al., 2012; Haapkyla et al., 2013).

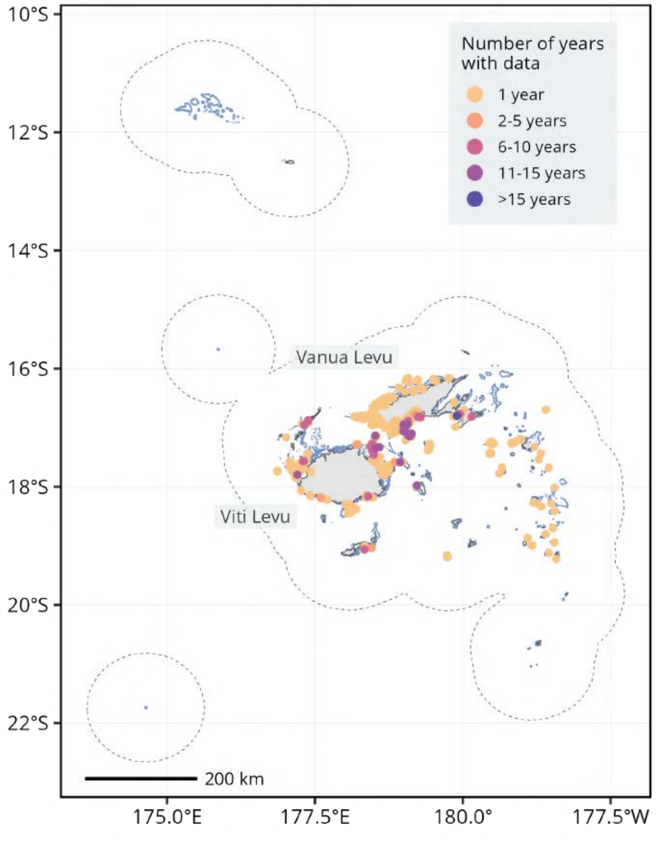
Pollutants including but not limited to sedimentation, nutrients, sewage, heavy metals, (micro)plastics, and pharmaceuticals have been increasingly well-documented in coastal areas in Fiji, revealing concerning levels in sediments, water and biota at some areas, particularly those close to urban centres and rivers (e.g. Pratap et al., 2020; Dehm et al., 2021; Singh et al., 2009). Although coastal pollution is widely acknowledged as a national issue, there has been little to no research on the direct impacts of different pollutants on coral reefs in Fiji. However, research has suggested that some corals near the urban centre of Suva remain adapted to their environment, exhibiting recruitment rates comparable to those in less polluted areas (Lal et al., 2018). Furthermore, comparisons with historical navigational charts suggest that the overall coral reef area has been maintained over time (Lawson et al., 2021), though community changes and degradation have likely occurred.



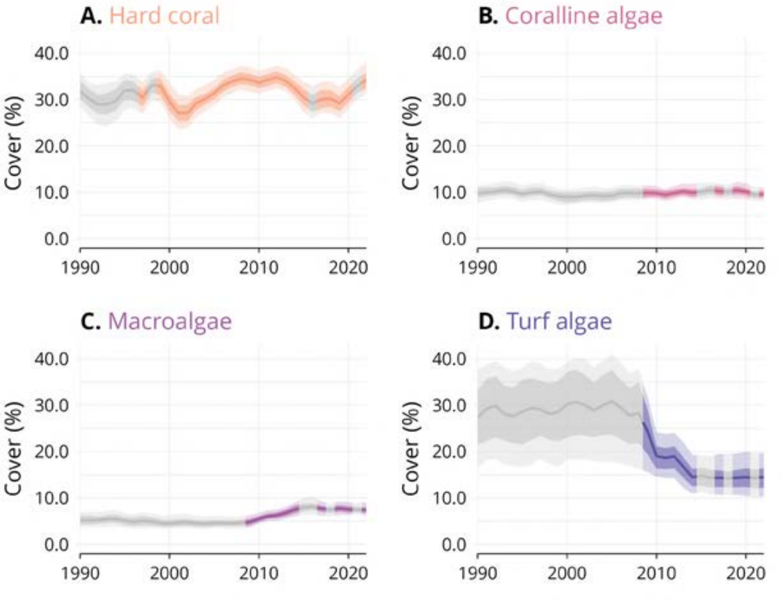
▲ **Figure 2.4.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Fiji. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Fiji was achieved through the integration of 12 datasets (Supplementary Table 1). These datasets represent a total of 650 monitoring sites, on which 997 surveys were conducted between 1997 and 2023. Long-term monitoring has documented the impact and recovery of coral reefs to bleaching, cyclone events and local stressors at different sites (see Figure 35.9 in Mangubhai et al., 2019). High rates of recovery have been documented post-bleaching (Mangubhai et al., 2019) and post-cyclones (Ford et al. *in review*).

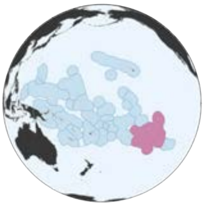


▲ **Figure 2.4.4.** Spatio-temporal distribution of benthic cover monitoring sites across Fiji. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.4.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Fiji. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

FRENCH POLYNESIA



Co-authors[1]

Yannick Chancerelle, Gilles Siu, Mehdi Adjeroud, Mohsen Kayal, Graham J. Edgar, Lizzi Oh, Lucie Penin, Rick D. Stuart-Smith, Serge Planes, Jan Freiwald, Jenny Mihaly

Introduction

Maritime area	4,766,689 km²
Land area	3,894 km²
Mean land elevation	198 m
Coral reef extent	5,981 km²

French Polynesia is a French Overseas collectivity located in the Southern hemisphere, which is bordered by three countries and territories, with Cook Islands on the West, Kiribati (Line Group) on the North, and Pitcairn on the Southeast. With 4,766,689 km², the economic exclusive zone of French Polynesia represents a surface greater than the entire European Union. French Polynesia is composed of five archipelagos, namely Tuamotu islands, Austral islands, Society islands, Gambier islands, and Marquesas islands (Figure 2.5.4). These archipelagos bring together 118 high volcanic islands and atolls (Maragos and Williams, 2011).

Coral reefs of French Polynesia cover approximately 5,981 km², which represent 9.17% of the total coral reef extent of the GCRMN Pacific region, and 2.395% of the world coral reef extent.

We estimated the human population of French Polynesia living within 5 km from coral reefs to be 226,292 inhabitants, in 2020. This represents 73.88% of the total human population of French Polynesia living within 5 km from coral reefs. However, the human population is unevenly distributed over the numerous islands and atolls of the territory. Indeed, in 2022 almost 70% of the population of French Polynesia was living on the island of Tahiti, where most of the population lives in Papeete, the regional capital of the territory (INSEE, 2023). We estimated that the human population living within 5 km from coral reefs has increased by 32.98% between 2000 and 2020.

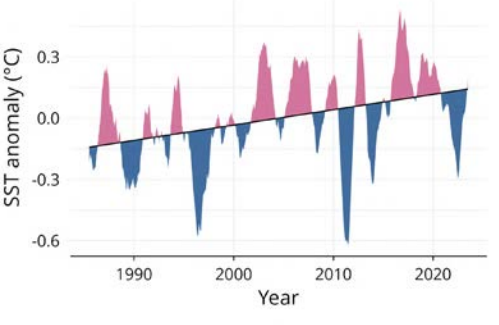
Threats

Thermal regime

The long-term average of SST on coral reefs of French Polynesia between 1985 and 2023 was 27.31°C (Supplementary Figure 1). Due to the distance of French Polynesia from the Equator, there is a substantial seasonal pattern in SST (Supplementary Figure 2). However, because of the wide latitudinal range of French Polynesia, the range of this seasonality in SST differs between the archipelagos and islands of the territory. SST over coral reefs of French Polynesia have increased by 0.25°C between 1985 and 2023, which corresponds to a warming rate of 0.007°C per year (Supplementary Figure 1). This warming rate is lower than the warming rate on coral reefs over the entire Pacific region (*i.e.* 0.022°C per year, Table 1.2.1). Using surface temperature projection models, Van Hooidonk et al (2013) showed that French Polynesia could be one of the regions in the world where annual coral bleaching phenomena would start the latest.

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

From 1985 to 2023, periods of high SST anomalies peaked in 1987, 1991, 1994, 2003, 2005-2007, 2010, 2012, 2016, 2018 and 2020 (Figure 2.5.1). The synthesis conducted by Trapon et al. (2011) shows that the high SST anomalies that occurred from 1987 to 2007 have led to bleaching events and sometimes losses in hard coral cover on reefs of Moorea. More recently, the bleaching events that occurred in 2016 and 2019 led to severe coral mortality, particularly on reefs from the Tuamotu in 2016 and Moorea/Society Islands in 2019, where some reef areas have lost more than half their coral cover (Hédouin et al, 2020; Wyatt et al. 2023). Indeed, the SST anomalies that occurred in 2016 and 2019, due to strong El Niño events (Figure 1.2.2), were significant given their intensity (*i.e.* height of the SST anomaly peak on Figure 2.5.1) and duration (*i.e.* width of the SST anomaly peak on Figure 2.5.1). However, the mortality of hard corals due to heat stress is often heterogeneous over French Polynesian coral reefs, as reported across archipelagoes and at a smaller scale around Moorea (Hédouin et al, 2020; Wyatt et al. 2023). This can be explained by SST anomalies being generally heterogeneous across French Polynesia.



▲ **Figure 2.5.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of French Polynesia. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

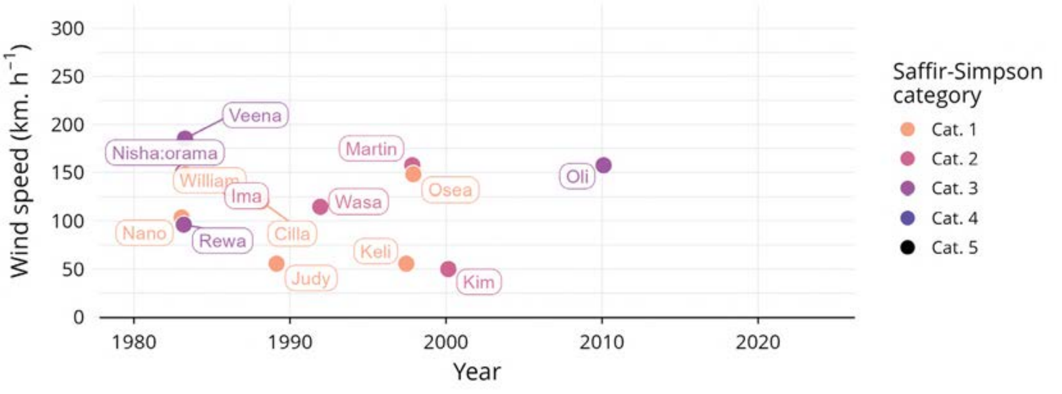
Cyclones

Between 1980 and 2023, a total of 42 tropical storms passed within 100 km distance from a coral reef of French Polynesia, and of these 16 were characterized by sustained wind speed greater than 100 $km.h^{-1}$ (Figure 2.5.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Veena, in 1983, which passed 14 km from a coral reef with sustained wind speed of 185 $km.h^{-1}$.

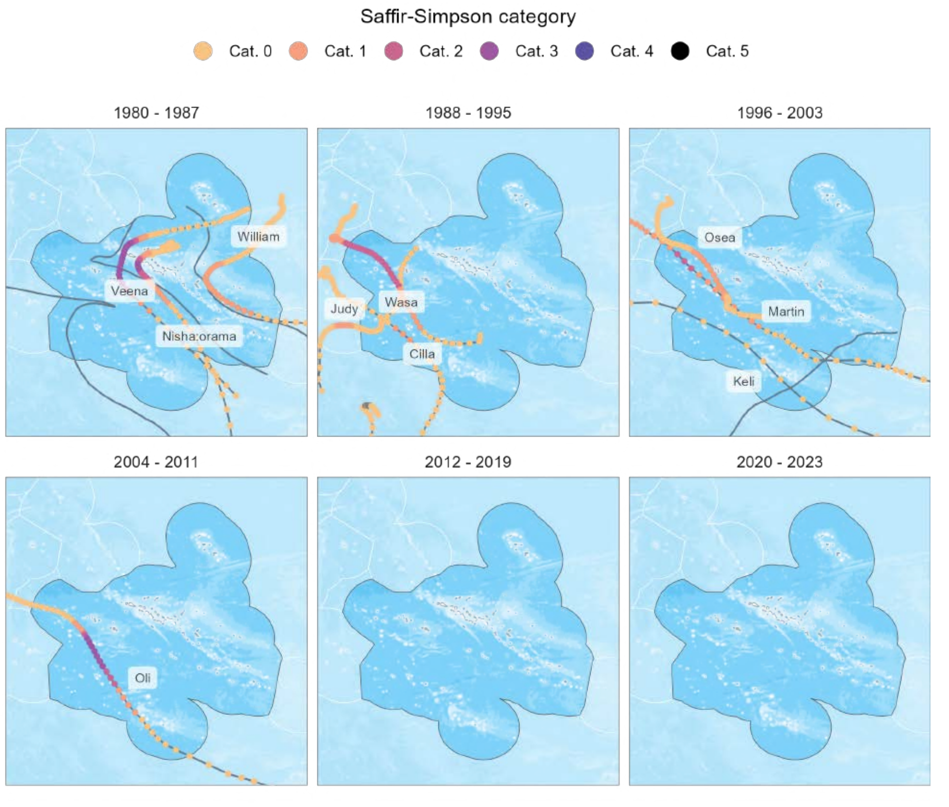
The impacts of some of these cyclones on coral reefs of French Polynesia have been described in the scientific literature. Notably the impacts of cyclones occurring between 1982 and 1983 are detailed in Harmelin-Vivien and Laboute (1986). More recently, Lamy et al (2016) have estimated an absolute loss in hard coral cover of 27.4% at Tiahura, in Moorea, due to the occurrence of the cyclone Wasa in 1991, whereas the impacts of most recent cyclone Oli on live coral cover was largely mitigated by the prior occurrence of an intense episode of COTS outbreak (Kayal et al. 2012; Adjeroud et al. 2018; Pérez-Rosales et al. 2021).

Crown of Thorns Starfish

Although predominantly observed around high volcanic islands, COTS outbreaks have had by far the strongest impacts on live coral cover in French Polynesia (Kayal et al. 2012; Adjeroud et al. 2018; Vercelloni et al. 2019; Pérez-Rosales et al. 2021). Vercelloni et al. (2019) showed that COTS outbreaks led to higher loss in hard coral cover than marine heatwaves and cyclones, on 17 reefs located on 13 different islands across French Polynesia over the period 1994-2008. Around the high volcanic islands of the Society Archipelago such as Tahiti and Moorea, COTS outbreaks have been recorded every ~15-20 years since the 1960's including 1968, 1979-1986, 2003-2010, and 2021-2024 (Kayal et al. 2012; Pellerin et al. in press), and have led to absolute losses in hard coral cover nearing 100% loss in some reef areas (Adjeroud et al. 2018; Vercelloni et al. 2019; Pérez-Rosales et al. 2021). High densities of COTS were recently observed in 2024 in Tikehau, Fakarava, Manihi, and Raiatea (Yannick Chancerelle, *pers. obs.*).



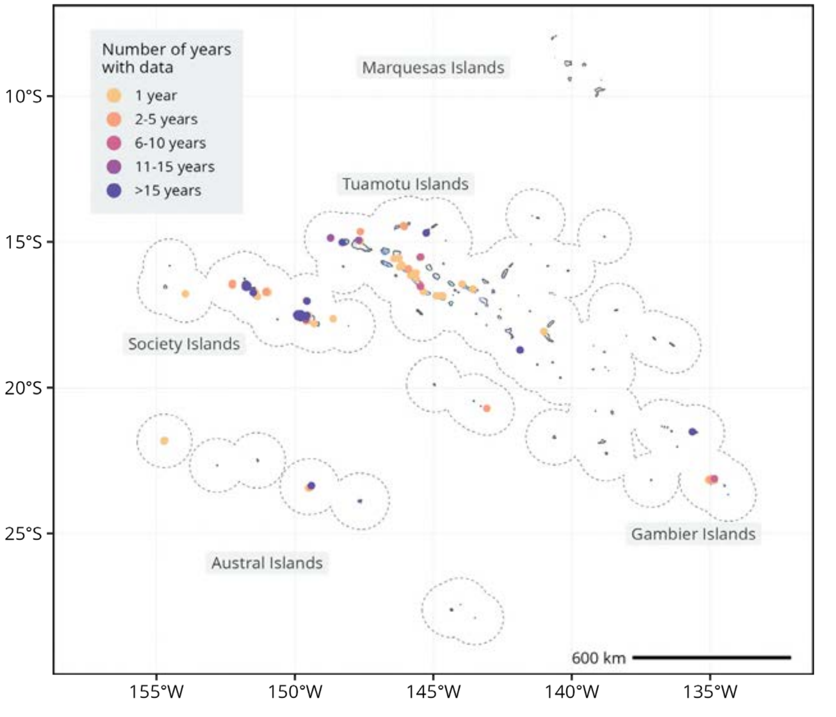
▲ **Figure 2.5.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in French Polynesia. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 $km.h^{-1}$). Note that cyclones passing more than 100 km away from coral reefs of French Polynesia are not represented, although they may have had an impact.



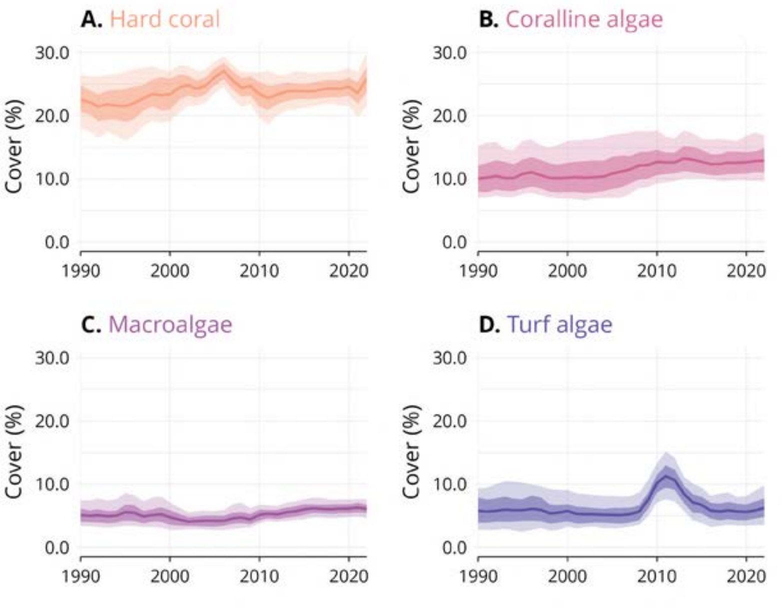
▲ **Figure 2.5.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in French Polynesia. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in French Polynesia was achieved through the integration of 8 datasets (Supplementary Table 1). These datasets represent a total of 229 monitoring sites, on which 2,173 surveys were conducted between 1987 and 2023. The spatial distribution of monitoring sites across French Polynesia was not homogeneous. Indeed, most of the sites were located in Society Islands and Tuamotu Islands archipelagos (Figure 2.5.4).

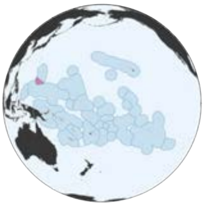


▲ **Figure 2.5.4.** Spatio-temporal distribution of benthic cover monitoring sites across French Polynesia. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue. Although the coral reef distribution dataset from WRI do not indicate a presence of coral reefs on the Marquesas archipelago, there are in fact small isolated reefs, for example on Tahuata Island (Serge Planes, *pers. comm.*).



▲ **Figure 2.5.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in French Polynesia. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

GUAM



Co-authors[1]

Erica K. Towle, Sheila McKenna, Peter Houk, Jan Freiwald

Introduction

Maritime area	208,234 km²
Land area	549 km²
Mean land elevation	99 m
Coral reef extent	224 km²

Guam, a United States unincorporated territory, is the southernmost island in the Mariana Archipelago. Guam is the largest and the most populated island in Micronesia (NOAA, 2018).

Coral reefs of Guam cover approximately 224 km², which represent 0.34 % of the total coral reef extent of the GCRMN Pacific region, and 0.090 % of the world's coral reef extent.

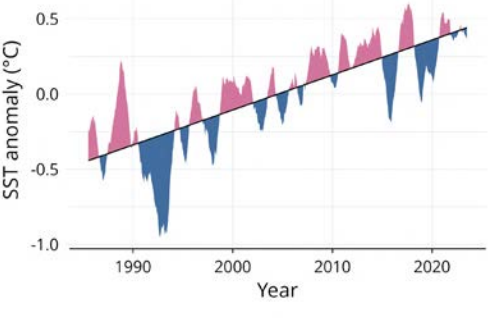
We estimated the human population of Guam living within 5 km from coral reefs to be 164,276 inhabitants, in 2020. This represents 99.27% of the total human population of Guam living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 7.00 % between 2000 and 2020.

Threats

Thermal regime

The long-term average of SST on coral reefs of Guam between 1985 and 2023 was 28.67°C (Supplementary Figure 1). SST over coral reefs of Guam have increased by 0.93°C between 1985 and 2023, which corresponds to a warming rate of 0.024°C per year (Supplementary Figure 1).

Guam's coral reefs experienced bleaching events in 2013, 2014, 2016, and 2017, each lasting several months, which resulted in a decrease in live coral cover by 36% on some reefs in 2017 (Raymundo et al., 2019).



▶ **Figure 2.6.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Guam. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

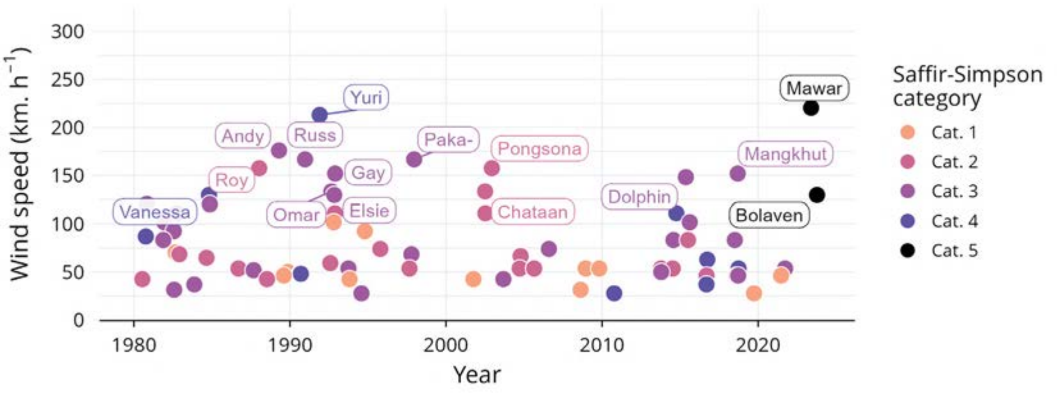
[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

Cyclones

Between 1980 and 2023, a total of 111 tropical storms passed within 100 km distance from a coral reef of Guam, and of these 24 were characterized by sustained wind speed greater than 100 km.h^{-1} (Figure 2.6.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Mawar in 2023, which passed 10 km from a coral reef with sustained wind speed of 220 km.h^{-1}.

Other threats

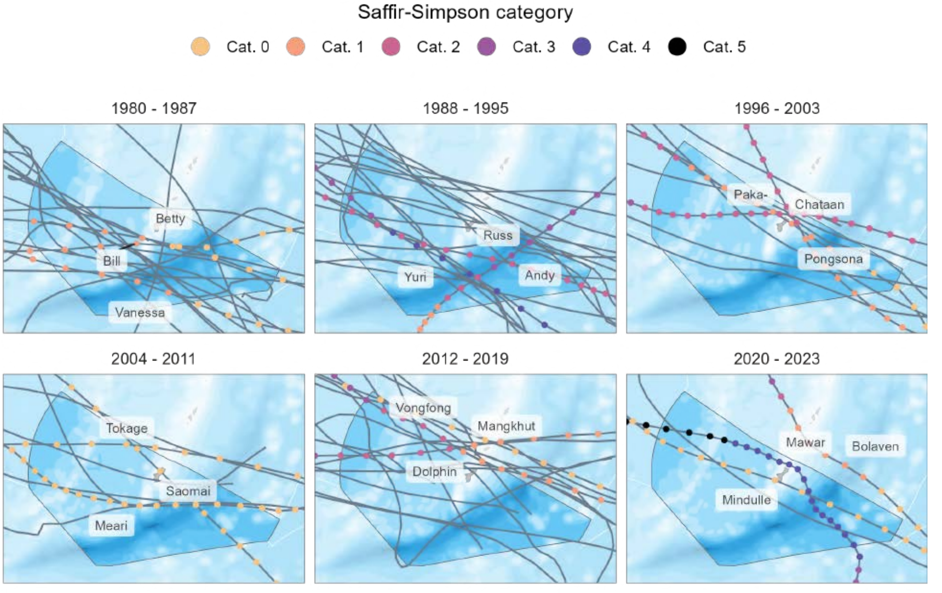
Guam's coral reefs are subject to COTS outbreaks with reports dating back to 1968 (Chesher, 1969). Chronic widespread outbreaks of COTS have been observed on coral reefs of Guam, especially on the east and northwest coasts of the island, since 2003 (Burdick et al., 2008).



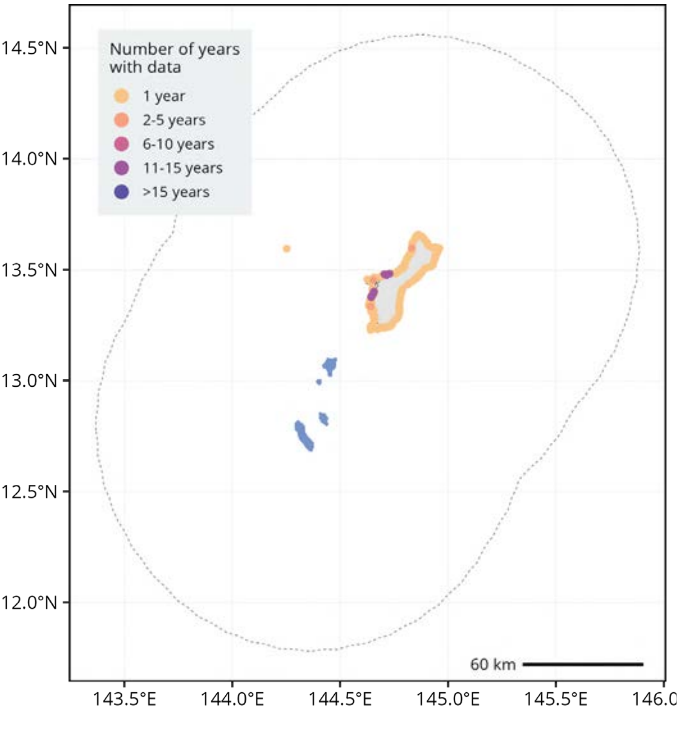
▲ **Figure 2.6.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Guam. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h^{-1}). Note that cyclones passing more than 100 km away from coral reefs of Guam are not represented, although they may have had an impact.

Temporal trends in benthic cover

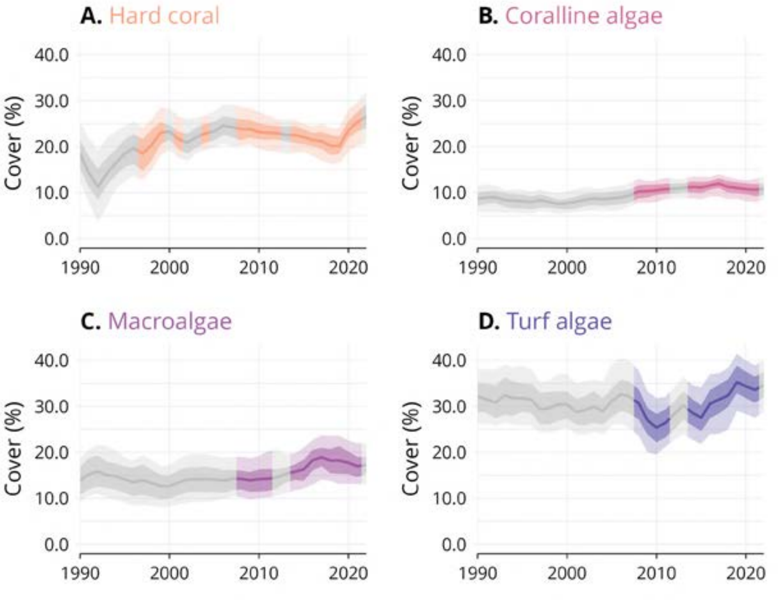
The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Guam was achieved through the integration of 4 datasets (Supplementary Table 1). These datasets represent a total of 391 monitoring sites, on which 545 surveys were conducted between 1997 and 2021.



▲ **Figure 2.6.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Guam. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.



▶ **Figure 2.6.4.** Spatio-temporal distribution of benthic cover monitoring sites across Guam. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.6.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Guam. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

CASE STUDY

Developing a Social-Ecological Systems Framework for Reef Management: A Case Study from the Manell-Geus Habitat Focus Area, Guam

Authors

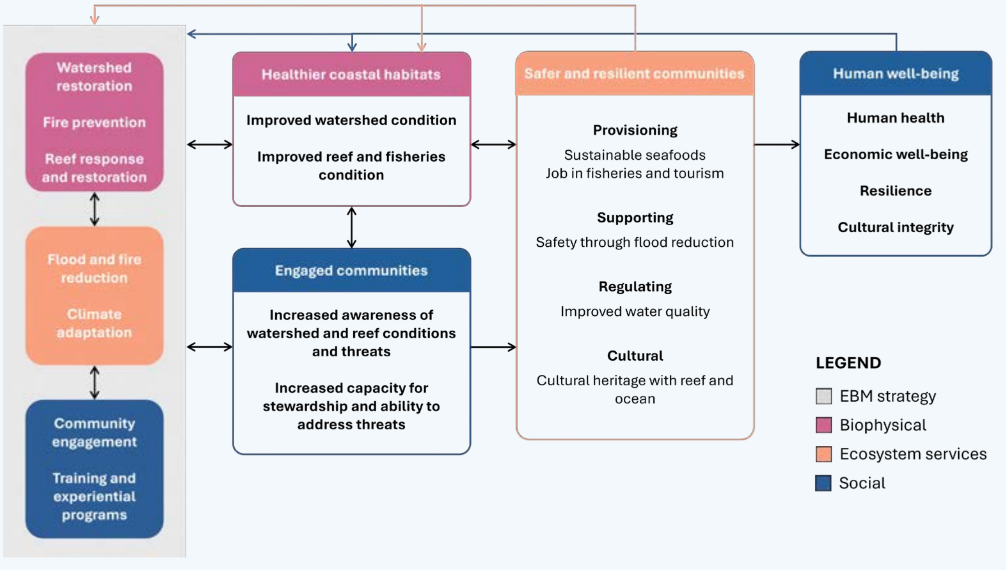
Valerie Brown, Supin Wongbusarakum

Guam, an unincorporated territory of the United States located in the western Pacific Ocean, blends cultural heritage and ecological richness. Guam is one of the most populated islands in the Pacific region with about 170,000 inhabitants, three military bases, and welcomes up to two million visitors each year. Land based sources of pollution, fishing, and tourism associated with this large population, place considerable pressure on the island's coral reefs, which play a crucial role in supporting biodiversity, coastal protection, tourism, as well as the provision of food and income to the local population. Additionally, the original inhabitants, the Chamorro people, have a long-term cultural connection to the reef. Traditional marine resource management was conducted at the village level and fisheries resources were an important component of social interactions through community harvest of seasonal fish and customary catch distribution practices.

In 2014, the Manell-Geus Habitat Focus Area (MGHFA) was established as one of the National Oceanic and Atmospheric Administration's (NOAA) ten inaugural Habitat Focus Areas in the Habitat Blueprint Program. The area contains important coral reef habitats, including the Achang Reef Flat Marine Preserve, the island's only shallow lagoon and barrier reef system, largest seagrass beds, and second largest mangrove forest, all of which support cultural and subsistence harvest. The site is located in the village of Merizo, and the population (ca 1800) is mostly Chamorro. The goals of the effort therefore include both ecological and social goals: (a) improved coral reef ecosystem health and resilience; (b) improved community resilience to climate change impacts; and (c) enhanced community capacity to manage coastal resources. Recognizing the intimate ties between people and ocean resources in this village, the project team employed a socio-ecological systems framework and established an integrated monitoring (IM) program.

The IM team was composed of a diverse set of interdisciplinary experts and employed a range of techniques to assess the social and biophysical conditions of the MGHFA and inform adaptive management (Wongbusarakum et al., 2019). Quantitative methods included in-situ biological and water quality assessment, remote sensing, and spatial analysis to assess biophysical indicators to evaluate ecosystem health; as well as socioeconomic surveys to evaluate knowledge, attitudes, and perceptions and human well-being. The survey indicators were selected and adapted from the NOAA National Coral Reef Monitoring Program, SEM Pasifika/SocMon Guidebook, and Micronesia Challenge socioeconomic indicators (Gorstein et al., 2018; Wongbusarakum & Pomeroy, 2008). The team conducted a household census survey of all 344 households within the project area. These quantitative approaches were complemented by qualitative methods such as stakeholder interviews, key informant interviews, focus group discussions, and participatory mapping exercises, which provide insights into the social dimensions of coastal management, including governance structures, traditional knowledge, and community perceptions. A subset of biophysical indicators was sampled annually and included citizen science initiatives. Interim social data was collected through qualitative approaches as the team engaged with the community throughout the project. Key components of the original monitoring efforts were meant to be repeated in 2020-21, but were preempted by the global pandemic.

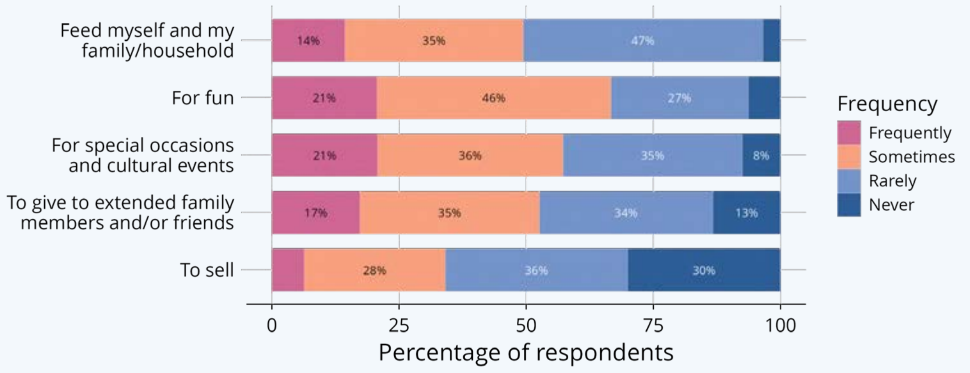
The study identified links and interactions between key social and ecological indicators and informed a model to support adaptive ecosystem-based management that addresses both biophysical and socio-economic conditions in an integrated way. Importantly, the model illustrates the connections between human well-being and ecosystem health while capturing the importance of community engagement in management (Figure 1).



▲ **Figure 1.** Integrated social and ecological model (Brown & Wongbusarakum, 2018).

Integrated monitoring allowed the project team to address threats to coastal ecosystems, while maintaining ecosystem services and human well-being. For example, socioeconomic work indicated that the community was affected by serious flooding during heavy rains. Biophysical research found that invasive bamboo was part of the issue and that it was also increasing sedimentation of reefs due to streambank collapse, so the team worked with local landowners to implement a novel bamboo control project, which reduced flooding in target streams.

This holistic approach also prevented management actions that may have harmed human health. Original scientific advice suggested that implementing harvest restrictions on herbivorous fish in the lagoon would reduce algae cover and facilitate natural recovery of corals. However, social survey data indicated that 53% of Merizo residents fish or gather marine resources, which is significantly higher than the overall Guam average of 29% ($p<0.01$) (Gorstein et al., 2018). Fishing is important in this village and residents fish for a range of reasons, including feeding their family (49%), for cultural purposes (including customary distribution to extended family or elders (52%) and events (56%)), and to sell (34%) (Figure 2). This information was confirmed by key informant interviews. Community members also noted that past military contamination had them worried about contamination. Fish sampling for contaminants indicated that predatory fish had higher levels of PCBs and other toxins and should be avoided to protect human health and that herbivorous fish were a safer target for consumption. Once these pieces were connected and discussed with the community, it was clear that an herbivore ban would expose the village to a higher risk of contaminants and should not be implemented. The project's integrated approach prevented serious impacts to human health and wellbeing that could have occurred without social data and community engagement.

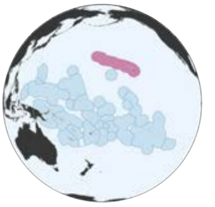


▲ **Figure 2.** Reasons for fishing by respondents that fish or harvest marine resources, *n* = 176.

The socioeconomic surveys and community engagement also provided information that enhanced management actions, including opinions on management options, perceived threats to the ecosystem and human health, as well as demographics and preferred sources of information. The effort also included community perceptions of ecosystem health, which led to some interesting findings. The most startling was the discrepancy between the biophysical data and the community's perceptions of changes in coral cover. Coral cover had declined by an average of 60% on the fore-reef due to seastar predation and coral bleaching in the decade prior to the household survey (Burdick et al. 2023). Yet, 48% of community members reported that coral cover was good or even better than the decade before. Thus, indicating that community members might be interacting less with their ecosystems, or experiencing a "shifting baseline syndrome". Key informants from the fishing community provided information that was more aligned with the biophysical surveys.

This case study highlights the importance of considering cultural and socioeconomic aspects in management actions and provides an example of how integrated monitoring can improve management processes and outcomes. Limiting monitoring to biophysical aspects provides only a partial view of reef status and sources of pressure, whereas the addition of socioeconomic monitoring creates new ways forward for improved management. This is particularly important considering that management interventions target more often human activities than ecological aspects and that community-based approach can be more effective for protecting the reefs. The case study provides a clear framework to apply an interdisciplinary approach to monitoring and management.

HAWAII



Co-authors[1]

Erica K. Towle, Graham J. Edgar, Lizzi Oh, Rick D. Stuart-Smith, Jan Freiwald, Jenny Mihaly

Introduction

Maritime area	2,474,715 km²
Land area	16,709 km²
Mean land elevation	893 m
Coral reef extent	3,978 km²

The Hawaiian Archipelago is a U.S. state in the north central Pacific Ocean. It consists of two regions: eight populated large islands, referred to as the Main Hawaiian Islands (MHI), and 124 mostly uninhabited small islands, atolls, reefs, and submerged banks to the northwest of the MHI, referred to as the Northwestern Hawaiian Islands (NWHI). The eight Main Hawaiian Islands, listed from East to West are: Hawaii, Maui, Kahoolawe, Lanai, Molokai, Oahu, Kauai, and Niihau. All except Kahoolawe are inhabited. The entire archipelago is considered the longest, oldest, and perhaps best-studied archipelago on earth (Grigg et al., 2008). The geographic isolation of these islands has resulted in some of the highest endemism of any tropical marine ecosystem (Kay and Palumbi, 1987; Jokiel, 1987).

Coral reefs of the Hawaiian Archipelago cover approximately 3,978 km², which represent 6.10 % of the total coral reef extent of the GCRMN Pacific region, and 1.593 % of the world's coral reef extent.

We estimated the human population of the Hawaiian Archipelago living within 5 km from coral reefs to be 952,086 inhabitants in 2020. This represents 62.27 % of the total human population of the Hawaiian Archipelago living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 23.84 % between 2000 and 2020.

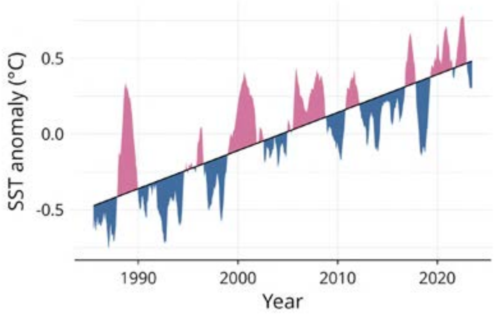
Threats

Thermal regime

The long-term average of SST on coral reefs of the Hawaiian Archipelago between 1985 and 2023 was 24.87°C (Supplementary Figure 1). SST over coral reefs of the Hawaiian Archipelago has increased by 1.07°C between 1985 and 2023, which corresponds to a warming rate of 0.028°C per year (Supplementary Figure 1).

The Main Hawaiian islands experienced back-to-back severe coral bleaching in 2014 and 2015, while parts of the Northwestern Hawaiian Islands experienced severe bleaching in 2014 (NOAA, 2018).

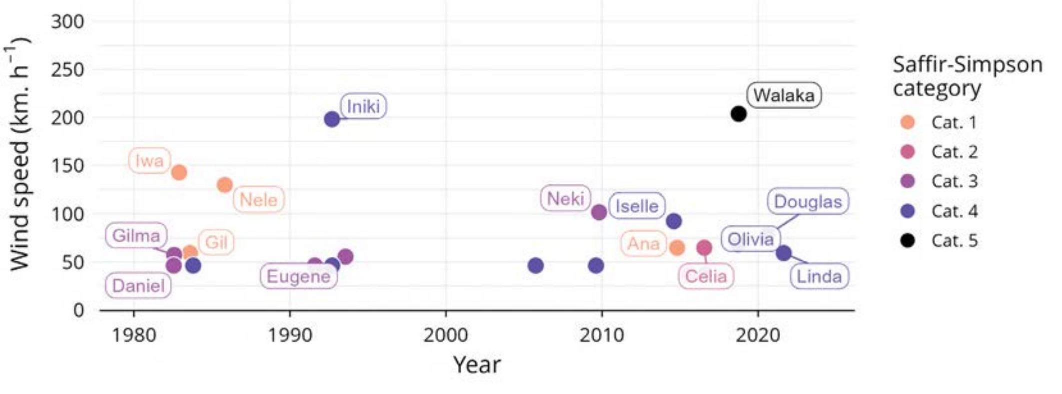
[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.



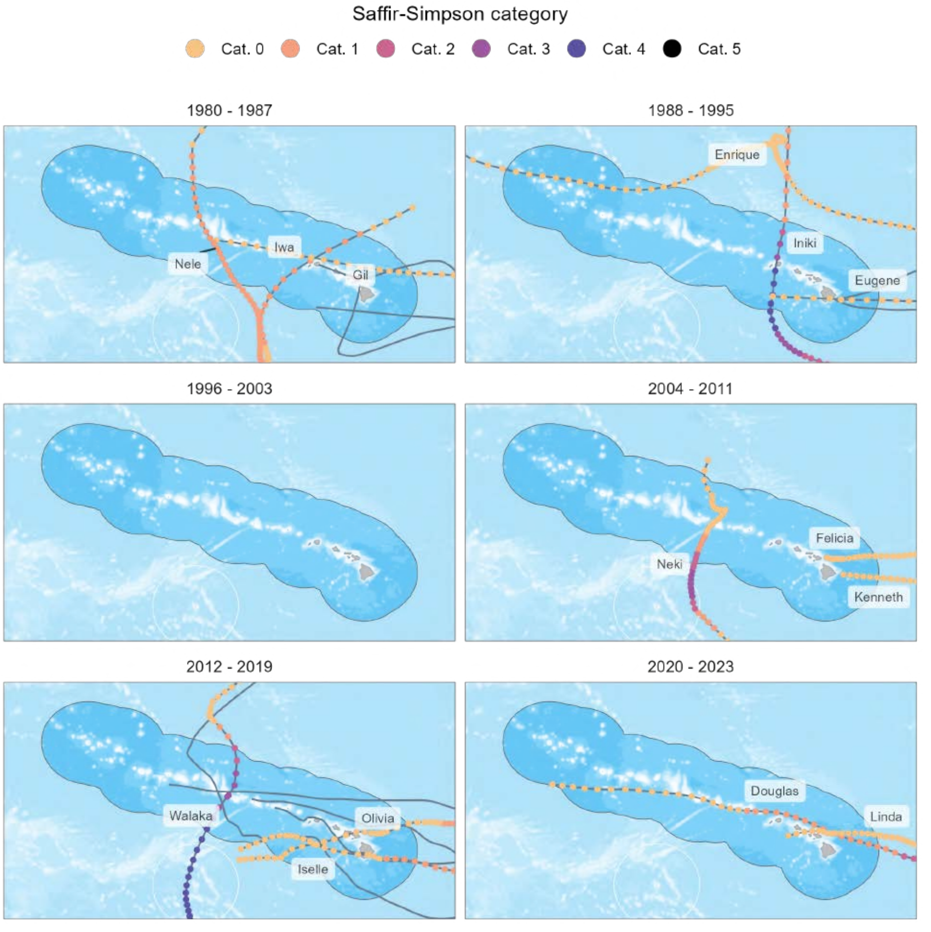
▲ **Figure 2.7.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Hawaii. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Cyclones

Between 1980 and 2023, a total of 34 tropical storms passed within 100 km distance from a coral reef of the Hawaiian Archipelago, and of these 5 were characterized by sustained wind speed greater than 100 km.h^{-1} (Figure 2.7.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Walaka in 2018, which passed 0 km from a coral reef with sustained wind speed of 204 km.h^{-1}.



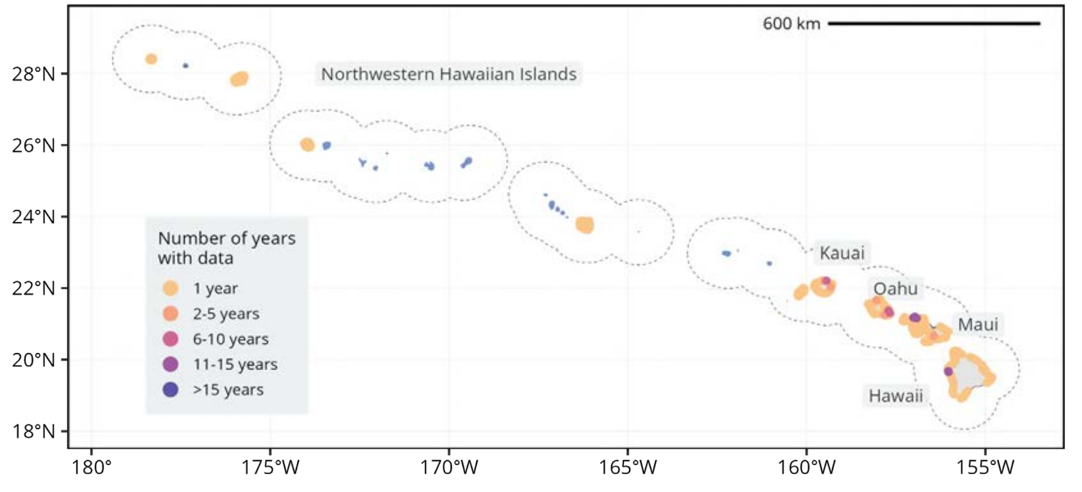
▲ **Figure 2.7.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in the Hawaiian Archipelago. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h^{-1}). Note that cyclones passing more than 100 km away from coral reefs of the Hawaiian Archipelago are not represented, although they may have had an impact.



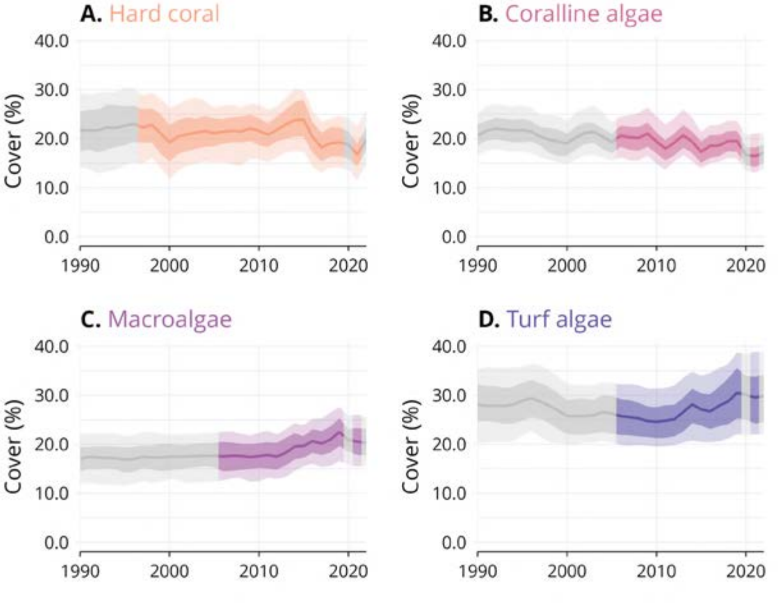
▲ **Figure 2.7.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in the Hawaiian Archipelago. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in the Hawaiian Archipelago was achieved through the integration of 4 datasets (Supplementary Table 1). These datasets represent a total of 2,019 monitoring sites, on which 2,405 surveys were conducted between 1997 and 2021.



▲ **Figure 2.7.4.** Spatio-temporal distribution of benthic cover monitoring sites across the Hawaiian Archipelago. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.7.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in the Hawaiian Archipelago. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

CASE STUDY

Trends in Human Connections to Coral Reefs in Hawai'i

Author

Mary Allen

Socioeconomic monitoring is critical to understanding the connections between humans and coral reef ecosystems. This is important because coral reefs provide a variety of benefits to people such as recreation, tourism, seafood, cultural heritage, and much more. Likewise, people play a central role in protecting coral reef ecosystems to sustain these benefits, while fostering their relationships with nature. Recognizing that people are an integral part of the ecosystem, NOAA's National Coral Reef Monitoring Program (NCRMP) is one of the few programs in the world that integrates human dimensions into coral reef ecosystem monitoring. As a whole, NCRMP provides a holistic understanding of the status of coral reefs and the coastal communities who depend on these ecosystems.

The Socioeconomic Component of NCRMP collects and monitors socioeconomic data in seven U.S. coral reef jurisdictions, including Hawai'i. The Main Hawaiian Islands (commonly called Hawai'i) include Ni'ihau, Kauaʻi, O'ahu, Moloka'i, Lāna'i, Maui, Kaho'olawe, and Hawai'i (or "the Big Island"). All but Kaho'olawe are permanently inhabited. In 2020, the state of Hawai'i had a population of 1.4 million people . Polynesians first settled in the Hawaiian Islands sometime during the 3rd to 6th century AD during the age of transpacific migrations. The socioeconomic connection between Hawaiians and the surrounding ocean environment is imperative for understanding community life in Hawai'i. The islands are relatively small and most cities, towns, and villages are located within the coastal zone. As such, various aspects of local and indigenous history, culture, and society are closely related to the surrounding ocean and use of its resources. As a result, modern culture in Hawai'i is based on a mix of both ancient and newer practices.

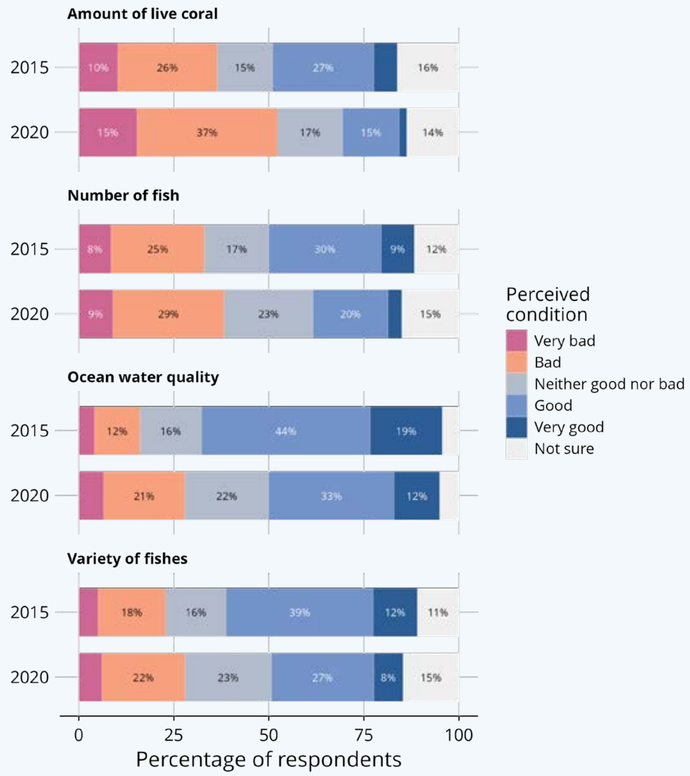
Tourism is an integral part of the Hawaiian economy with visitors contributing $20.8 billion in 2023. Due to Hawai'i's favorable climate and unique cultural and ecological features, the state is a frequently visited tourist destination for domestic and foreign travelers alike. These high rates of tourism, coupled with high population density near the coast, bring even more humans in contact with coral reef ecosystems in the region; thereby creating more opportunities for humans to derive ecosystem services from reefs, but also more opportunities for human-induced stressors to impact reefs.

To assess the status of socioeconomic conditions related to coral reefs, surveys are conducted with household residents every 5-7 years. The surveys collect data on measures such as human use of coral reef resources, knowledge, attitudes, and perceptions of coral reefs and management. These data inform the human connections to coral reefs and people's relationships with coral reefs may be changing over time. Two monitoring cycles have been completed in Hawai'i so far, with surveys conducted with residents in 2015 (n = 2,240) and 2020 (n = 2,700). Results are representative of the resident population of Hawai'i as a whole, as well as the islands of Hawai'i (further stratified by East and West), Kaua'i, Maui, and O'ahu.

The 2020 results showed a general consensus that Hawai'i's coral reefs are important to Hawaiian culture and traditions, offer protection from erosion and natural disasters, attract tourists to the region, and provide economic opportunities and food for coastal communities. Beach recreation, swimming/wading, and snorkeling were primary activities for Hawaiian residents in both 2015 and 2020. Additionally, most resident households consumed seafood on a weekly basis, and nearly 25% of all residents ate locally caught seafood harvested from coral reefs every month.

Residents believed that the quality of marine resources in general had become worse over the past ten years, and that conditions are likely to worsen in the future. In 2020, more residents perceived the amount of live coral, number of fish, variety of fish, and ocean water quality as being in bad condition (Figure 1). Of these four resource conditions, the amount of live coral was perceived as being in the worst condition. Residents had more positive perceptions of ocean water quality. However, the percentage of those who thought this resource was in bad condition increased in 2020. Residents were also more certain about their perception of water quality compared to the other resource conditions.

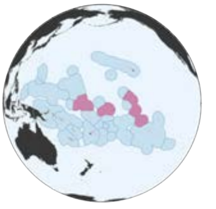
The study identified links and interactions between key social and ecological indicators and informed a model to support adaptive ecosystem-based management that addresses both biophysical and socio-economic conditions in an integrated way. Importantly, the model illustrates the connections between human well-being and ecosystem health while capturing the importance of community engagement in management (Figure 1).



▲ **Figure 1.** Hawai'i resident perceptions of current resource conditions in 2015 and 2020

Residents were familiar with a variety of threats to coral reefs, such as climate change, hurricanes, and pollution, but least familiar with ocean acidification. Residents generally supported a range of potential marine management policies and regulations, such as coral restoration efforts and stricter control of sources of pollution to preserve water quality. In general, the results indicate that residents in Hawai'i have important human connections to coral reefs and rely on these ecosystems for a variety of cultural and socioeconomic benefits. Results also suggest that residents want to see efforts to mitigate threats (e.g., pollution) to coral reefs and prevent resource conditions (e.g., ocean water quality, amount of live coral) from becoming worse. Targeted outreach, particularly about ocean acidification, could help increase awareness of threats to coral reefs and how those threats are linked to ecosystem services and sustained benefits.

KIRIBATI



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Introduction

	Maritime area	Land area	Mean land elevation	Coral reef extent
Gilbert Islands	1,053,245 km²	322 km²	8 m	2,498 km²
Line Group	1,641,193 km²	510 km²	4 m	389 km²
Phoenix Group	745,782 km²	35 km²	4 m	153 km²
Entire Kiribati	3,440,220 km²	867 km²		3,041 km²

The Republic of Kiribati consists of 33 atolls and reef islands across three island chains, the Gilbert Islands, Line Islands and Phoenix Islands, as well as the raised limestone island of Banaba. Atoll coral reefs are the main reef type in Kiribati, supporting a variety of habitats such as patch reefs, microatolls in the lagoons, outer reefs, and submerged reefs. Coral reefs of Kiribati cover approximately 3,041 km², which represent 4.66% of the total coral reef extent of the GCRMN Pacific region, and 1.21% of the world coral reef extent.

We estimated the human population of Kiribati living within 5 km from coral reefs to be 133,754 inhabitants, in 2020. This represents 100% of the total human population of Kiribati living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 58.75% between 2000 and 2020. More than 90% of the population lives in the Gilbert Islands, the ancestral home of the i-Kiribati people, with over half of the population residing in the capital region of South Tarawa (SPC, 2022). The i-Kiribati people have a subsistence lifestyle and receive supplemental support from sale of fisheries and agricultural products (largely copra), and overseas remittances. Kiribati has among the highest per capita consumption of marine products in the world, with fishing for household consumption common even among households in relatively urbanized South Tarawa (72% of households; SPC, 2022). Customary marine tenure is present in the Gilbert Islands but does not exist in the Line and Phoenix Islands where both land and waters belong to the state.

Threats

Thermal regime

The coral reefs of Kiribati are exposed to bleaching-level heat stress more frequently than the majority of coral reefs in the tropics, because of interannual SST variability driven by the El Niño / Southern Oscillation (Obura and Mangubhai, 2011; Mangubhai

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

et al., 2019). The long-term average of SST on coral reefs of Kiribati between 1985 and 2023 was 28.79°C (Supplementary Figure 1). SST over coral reefs of Kiribati have increased by 0.33°C between 1985 and 2023, which corresponds to a warming rate of 0.009°C per year (Supplementary Figure 1).

Coral skeletal records indicate that coral bleaching and bleaching-induced coral mortality was limited or rare in Kiribati before the 2000s, possibly due to long-term adaptation or acclimation of coral populations and communities to episodic low-level heat stress associated with El Niño events (Carilli et al., 2012; Mollica et al., 2019). More severe bleaching-level heat stress led to mass bleaching events across each of the three island chains over the past two decades.

The first documented mass coral bleaching in the Gilberts Group occurred in 2004-2005, with mortality ranging from 25%–66% at Tarawa Atoll and 35%–54% Abaiang Atoll sites (Donner et al., 2010). Subsequent bleaching during a 2009-2010 Central Pacific El Niño event (Teema et al., 2011) was more limited, with a 3% decline in coral cover at Tarawa and Abaiang sites, despite more intense and prolonged heat stress due to cloudy conditions and shifts to more thermally-tolerant taxa (Donner et al., 2019). A lack of observed bleaching during subsequent severe bleaching-level heat stress (e.g. 2014-2015; 2015-2016) is attributed to a possible phase shift toward stress-tolerant communities, particularly at sites most exposed to local human disturbance (Cannon et al., 2021). The stress tolerant encrusting species Porites rus represented 41%-93% of live coral cover at South Tarawa sites in 2023 surveys (Donner, unpublished data).

Major coral bleaching has been documented in the Phoenix Islands in 2002–2003 (Obura and Mangubhai, 2011), 2009–2010 and 2015–2016 (Brainard et al., 2018). The 2002–2003 event resulted in coral mortality of 42%–79% among atolls, with lagoonal and leeward reefs the most impacted (Obura and Mangubhai, 2011). While high recovery rates at some sites (e.g. 52.8% of hard corals in Kanton Lagoon) has been heartening (Mangubhai et al., 2019), recovery to pre-2002 levels has not occurred. However, while 5%–25% of corals were bleached at the peak of the 2015-2016 El Niño, there was little coral mortality observed in 2016 (Brainard et al., 2018).

The 2015-2016 El Niño caused extensive coral bleaching in Kiritimati of the Line Islands Group, resulting in initial loss of 89% of coral cover in forereef surveys (Baum et al., 2023) and declines in reef structural complexity (Magel et al., 2019). Losses were lower for stress-tolerant species, such that massive Porites spp. represented >50% of coral cover in post-bleaching surveys (Baum et al., 2023). Coral communities exposed to poorer water quality due to local disturbance were more bleaching resilient, due to the prevalence of stress-tolerant taxa (Baum et al., 2023), similar to findings in the Gilberts Islands.

Cyclones

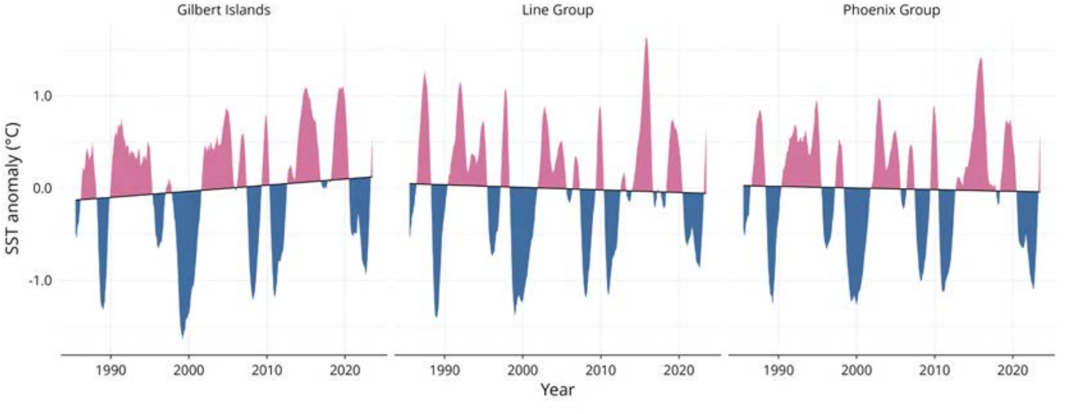
Between 1980 and 2023, no tropical storms passed within 100 km distance from coral reefs of Kiribati. Cyclones rarely occur within 5–10 degrees of the equator, and therefore, rarely affect Kiribati. Distant tropical cyclones and Northern Hemisphere mid-latitude cyclones can cause swell waves and coastal flooding events in the Gilberts Group (Hoeke et al., 2021), but with no documented damage to coral reefs.

Other threats

Kiribati's coral reefs are under local threats from sewage pollution, reef rock mining, unsustainable fishing, and sedimentation due to shoreline manipulation and erosion, all of which are elevated concerns in South Tarawa (Mangubhai et al., 2019) where the population is growing 5% annually since 1990 (SPC, 2022). Sewage and other forms of pollution have been linked to observations of bacteria and pathogens at Kiritimati coral reefs (McDevitt-Irwin et al., 2019). Recent projects to improve sanitation in the urban areas of South Tarawa and Kiritimati have increased access to flush toilets to 75% and 60% households, respectively (SPC, 2022).

Outbreaks of Crown-of-Thorns starfish (COTs) have been recorded in the Gilberts Group since the 1970s. From 2013-2014, a COTs outbreak spread from the northern (Butaritari Atoll) to the central (Abemama) part of the island chain (Kiareti et al., 2013; Cannon et al., 2021). The outbreak disproportionately affected massive Porites spp. which had been less affected by the 2004-2005 and 2009-2010 bleaching events (Cannon, et al. 2021).

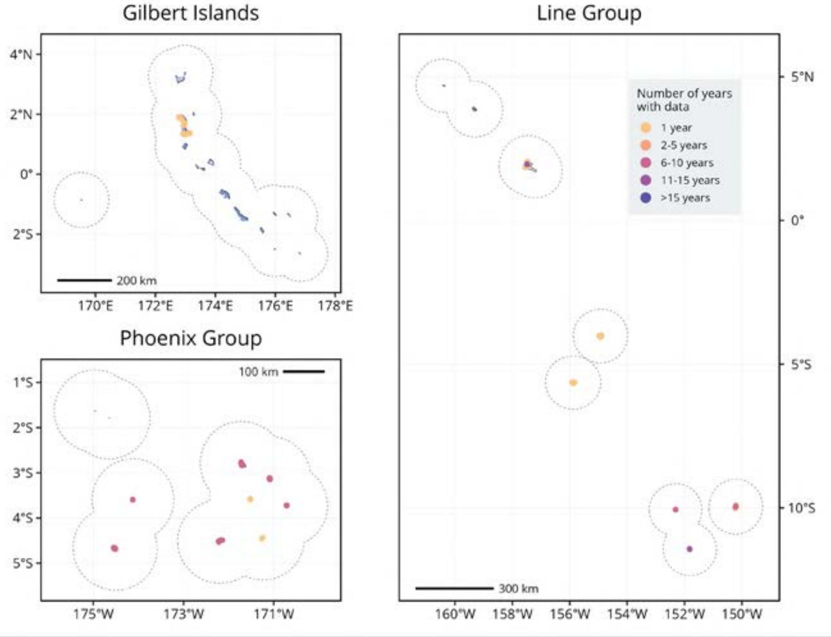
"Black reefs" which are dominated by cyanobacterial mats and devoid of coral and crustose coralline algae and linked to the leaching of iron from shipwrecks on iron-poor coral reefs, is a growing concern for the Line and Phoenix Islands. Black reefs are documented on Tabuaeran in the Line Islands (Kelly et al., 2012), and on Nikumaroro, Enderbury, and McKean in the Phoenix Islands and on Carondelet Seamount (Mangubhai and Obura, 2019; Mangubhai et al., 2024). For example black reef sites in the Phoenix Islands had very low coral cover (4.9%), high cover of cyanobacterial mats and turf algae (79.8%) and low coral recruitment (0.22 recruits per m2) associated with shipwreck debris (Mangubhai and Obura, 2019). Even on reefs such as Nikumaroro with no local anthropogenic threats, black reefs have been expanded with no recovery documented over a decade (2005-2015). South Tarawa reefs sites with similar benthic composition may be linked to the legacy of trace metal leaching from World War II wreckage and metallic debris from abandoned ships and other equipment (Donner et al., 2019).



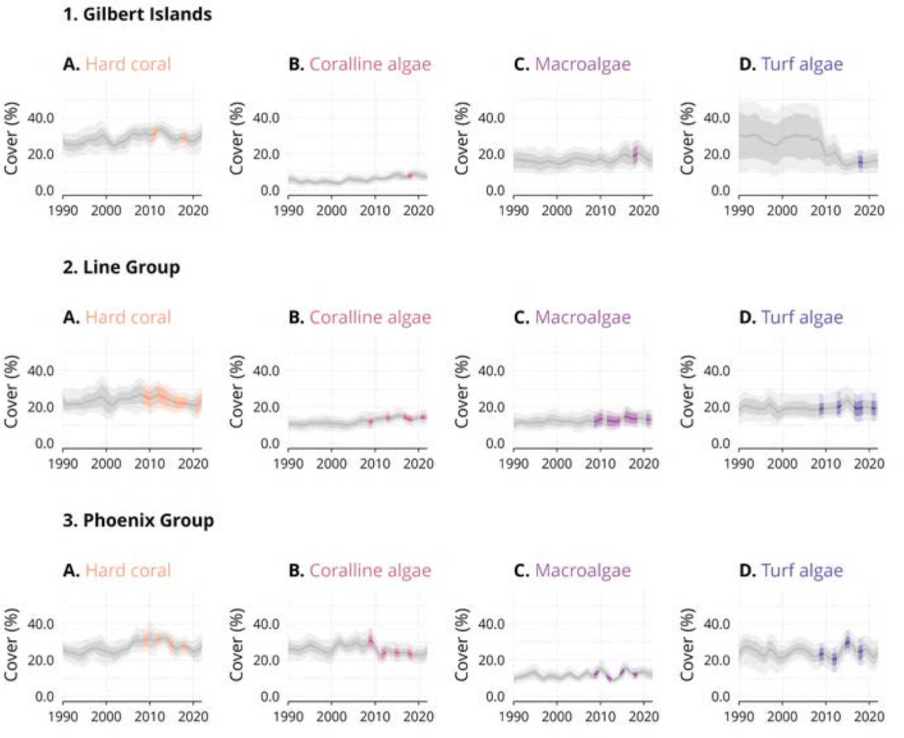
▲ **Figure 2.8.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Kiribati. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Kiribati was achieved through the integration of 6 datasets (Supplementary Table 1). These datasets represent a total of 173 monitoring sites, on which 266 surveys were conducted between 2009 and 2023.



▲ **Figure 2.8.2.** Spatio-temporal distribution of benthic cover monitoring sites across Kiribati. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.8.3.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Kiribati. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

MARSHALL ISLANDS

Co-authors[1]

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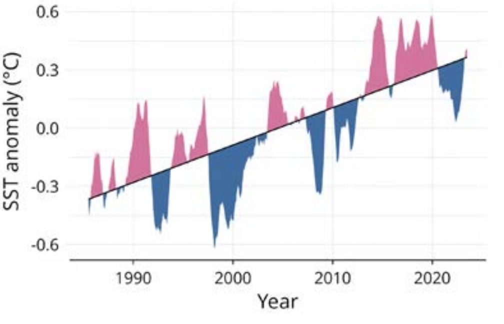
Introduction

Maritime area	2,002,220 km^2
Land area	286 km^2
Mean land elevation	7 m
Coral reef extent	3,558 km^2

Coral reefs of Marshall Islands cover approximately 3,558 km^2, which represent 5.45 % of the total coral reef extent of the GCRMN Pacific region, and 1.425 % of the world coral reef extent.

We estimated the human population of Marshall Islands living within 5 km from coral reefs to be 55,833 inhabitants, in 2020. This represents 100.00 % of the total human population of Marshall Islands living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 9.63 % between 2000 and 2020.



▲ **Figure 2.9.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Marshall Islands. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (i.e. cooler than long-term trend), and values above this line are positive SST anomalies (i.e. warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (i.e. 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Threats

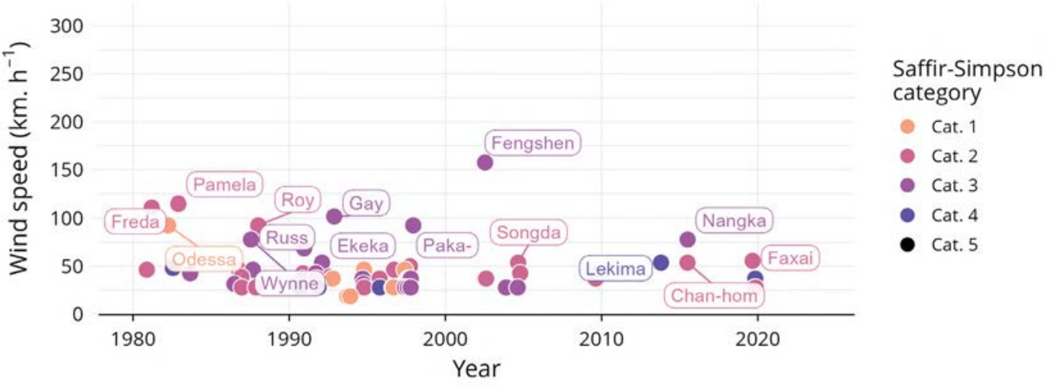
Thermal regime

The long-term average of SST on coral reefs of Marshall Islands between 1985 and 2023 was 28.47°C (Supplementary Figure 1). SST over coral reefs of Marshall Islands have increased by 0.80°C between 1985 and 2023, which corresponds to a warming rate of 0.021°C per year (Supplementary Figure 1).

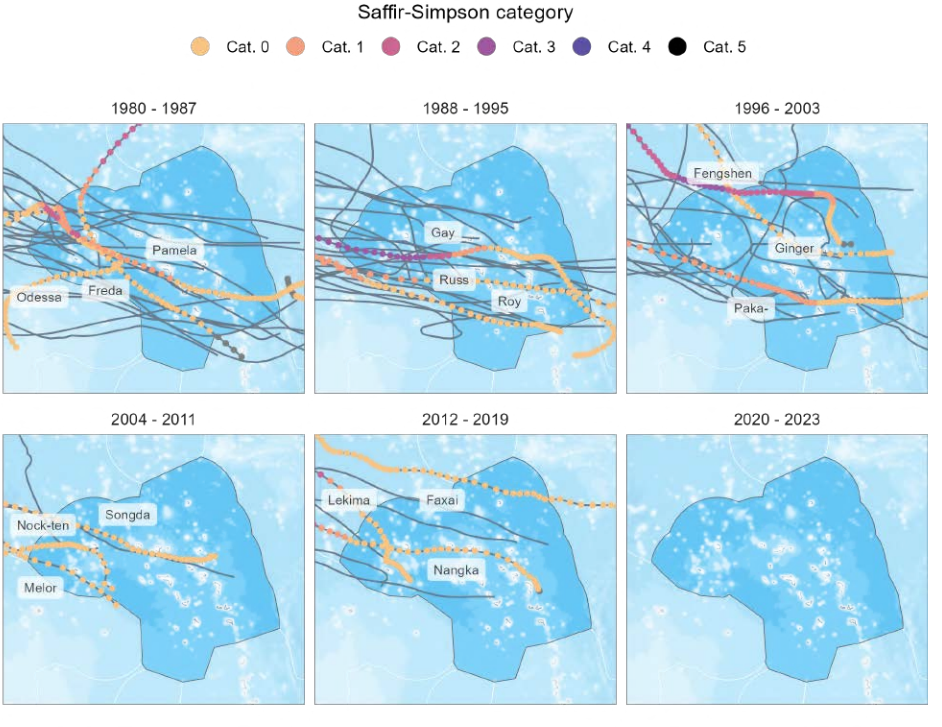
Cyclones

Between 1980 and 2023, a total of 113 tropical storms passed within 100 km distance from a coral reef of Marshall Islands, and of these 4 were characterized by sustained wind speed greater than 100 $km.h^{-1}$ (Figure 2.9.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Fengshen, in 2002, which passed 5 km from a coral reef with sustained wind speed of 157 $km.h^{-1}$.

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.



▲ **Figure 2.9.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Marshall Islands. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h^{-1}). Note that cyclones passing more than 100 km away from coral reefs of Marshall Islands are not represented, although they may have had an impact.

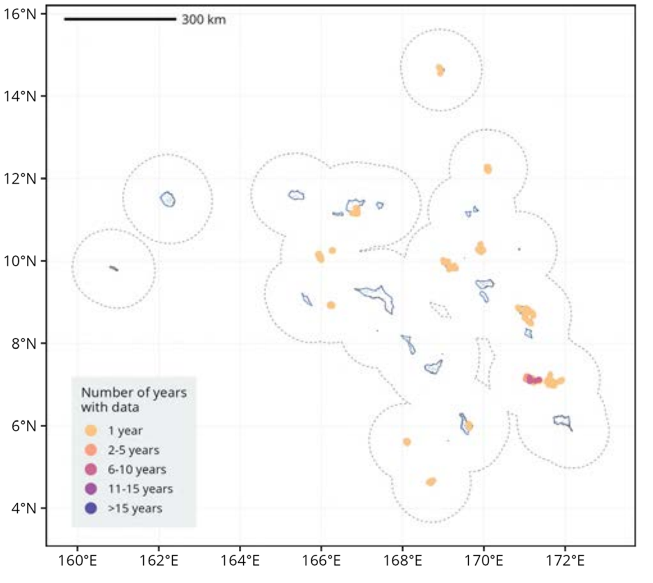


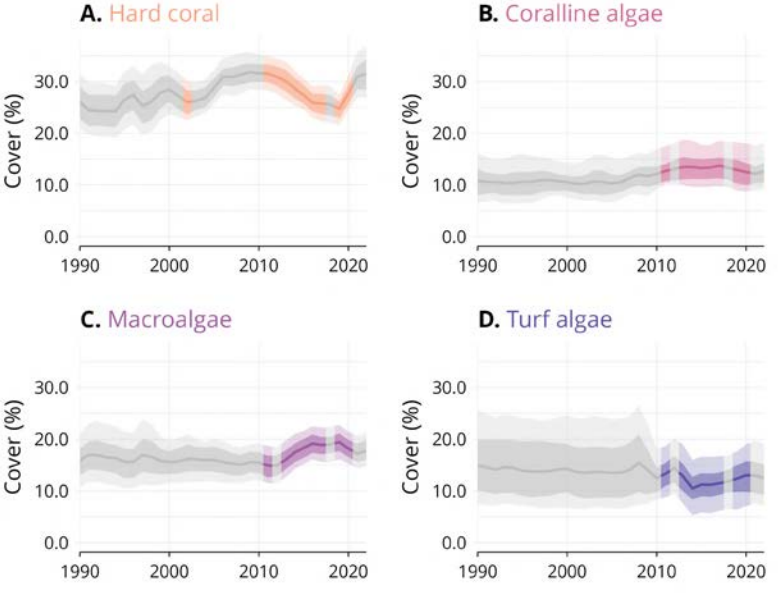
▲ **Figure 2.9.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Marshall Islands. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Marshall Islands was achieved through the integration of 3 datasets (Supplementary Table 1). These datasets represent a total of 147 monitoring sites, on which 174 surveys were conducted between 2002 and 2020.

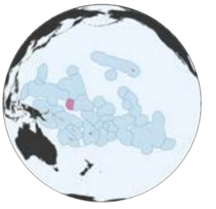
▶ **Figure 2.9.4.** Spatio-temporal distribution of benthic cover monitoring sites across Marshall Islands. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.





▲ **Figure 2.9.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Marshall Islands. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

NAURU



Author

Jérémy Wicquart

Introduction

Maritime area	309,261 km²
Land area	22 km²
Mean land elevation	25 m
Coral reef extent	15 km²

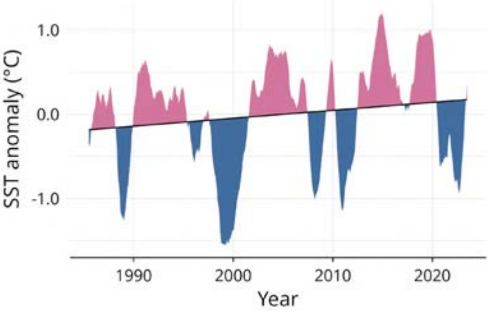
Coral reefs of Nauru cover approximately 15 km², which represent 0.02 % of the total coral reef extent of the GCRMN Pacific region, and 0.006 % of the world coral reef extent.

We estimated the human population of Nauru living within 5 km from coral reefs to be 10,244 inhabitants, in 2020. This represents 100.00 % of the total human population of Nauru living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 0.83 % between 2000 and 2020.

Threats

Thermal regime

The long-term average of SST on coral reefs of Nauru between 1985 and 2023 was 29.13°C (Supplementary Figure 1). SST over coral reefs of Nauru have increased by 0.44°C between 1985 and 2023, which corresponds to a warming rate of 0.012°C per year (Supplementary Figure 1).



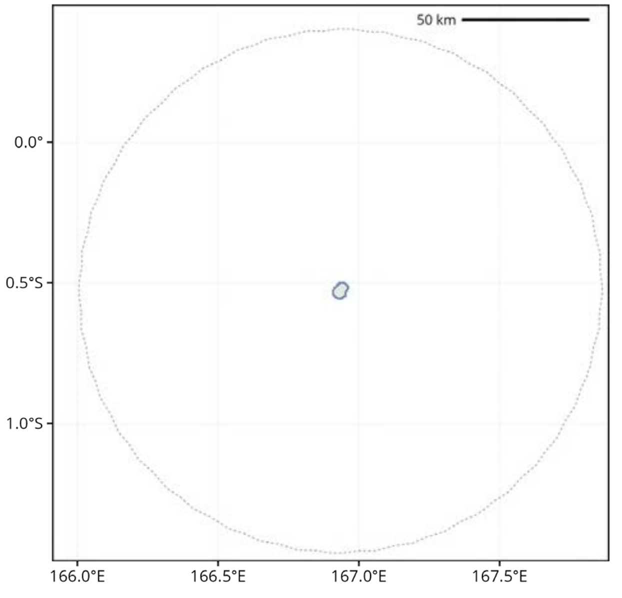
▲ **Figure 2.10.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Nauru. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (i.e. cooler than long-term trend), and values above this line are positive SST anomalies (i.e. warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (i.e. 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Cyclones

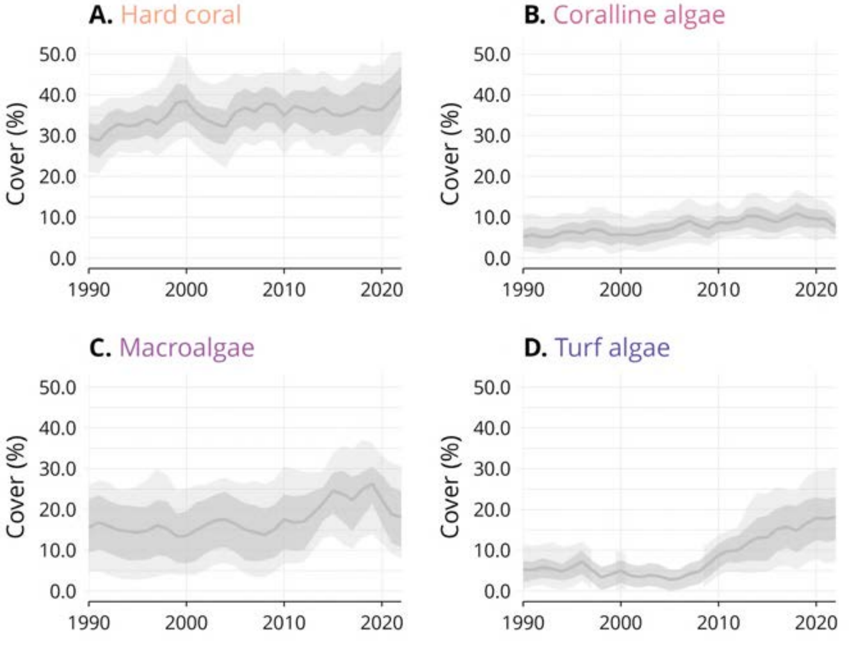
Between 1980 and 2023, no tropical storms passed within 100 km distance from a coral reef of Nauru. This is explained by the location of the country on the equator.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Marshall Islands was achieved through the integration of 3 datasets (Supplementary Table 1). These datasets represent a total of 147 monitoring sites, on which 174 surveys were conducted between 2002 and 2020.

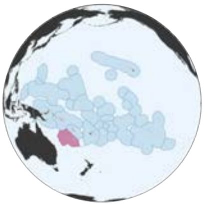


▲ **Figure 2.10.2.** Spatio-temporal distribution of benthic cover monitoring sites across Nauru. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.10.3.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Nauru. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.

NEW CALEDONIA



Co-authors[1]

Sandrine Job, Antoine Gilbert, Nicolas Guillemot, Mohsen Kayal, Tom Heintz, Mehdi Adjeroud, Lucie Penin

Introduction

Maritime area	1,175,971 km²
Land area	18,779 km²
Mean land elevation	250 m
Coral reef extent	7,450 km²

Located in the southwestern Pacific, 1,500 km east of Australia, New Caledonia is part of Melanesia. The archipelago comprises numerous islands, the largest being Grande Terre, the third-largest island in the South Pacific. Grande Terre is surrounded by a nearly continuous barrier reef stretching 1,500 km - the second longest in the world after the Great Barrier Reef - enclosing the world's largest lagoon (23,400 km²). Within this lagoon lie remote islands such as the Belep Archipelago in the north, along with numerous small islands and coral islets encircling Grande Terre. To the east lies the Loyalty Islands archipelago, composed of four coral islands - Lifou, Maré, Tiga, and the atoll of Ouvéa - along with the coral reefs and banks of Durand and Beautemps-Beaupré. The archipelago extends northwards to include the Astrolabe, Gazelle, and Pétrie reefs, and southwards to Walpole Island and Ellet Bank. To the north, the lagoon extends to the Entrecasteaux reefs, which include several atolls - only Huon and Surprise have true emerged landforms, while others (Portail, Grand and Petit Guilbert, Pelotas, and Mérite) are either fully submerged or limited to sparse sandy islets. West of Grande Terre lie the submerged atolls of Fairway and Lansdowne, followed by the Chesterfield Plateau, which hosts two large atolls: Chesterfield and Bellona. Numerous seamounts are also present throughout these offshore areas.

Coral reefs of New Caledonia cover approximately 7,450 km², which represent 11.42 % of the total coral reef extent of the GCRMN Pacific region, and 2.983 % of the world coral reef extent[2] .

We estimated the human population of New Caledonia living within 5 km from coral reefs to be 133,824 inhabitants, in 2020. This represents 46.86 % of the total human population of New Caledonia living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 13.62 % between 2000 and 2020.

Threats

Thermal regime

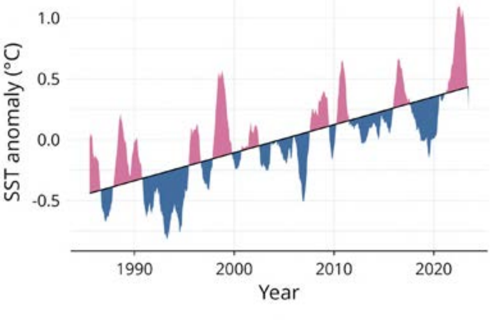
The long-term average of SST on coral reefs of New Caledonia between 1985 and 2023 was 25.41°C (Supplementary Figure 1). SST over coral reefs of New Caledonia have increased by 0.75°C between 1985 and 2023, which corresponds to a warming rate of 0.020°C per year (Supplementary Figure 1).

Since 2003, approximately one hundred reefs across New Caledonia have been monitored annually as part

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

[2] Differences in data sources may lead to variations between our estimate and others. For example, Andrefouet et al. (2009) reported a total coral reef extent of 4,537 km² for New Caledonia.

of the RORC, a territory-wide monitoring program. Until 2016, no coral bleaching events linked to thermal stress had been observed. However, during the austral summer of 2016, an unprecedented marine heatwave occurred, driven by anomalously high sea surface temperatures. Although reefs across all three provinces were affected, bleaching was not uniform: coastal reefs were the most severely impacted, except in the far north of Grande Terre (Poindimié and Ouégoa), where bleaching was equally severe from the coast to the barrier reef. The extent of bleaching also varied depending on coral assemblages, with branching corals - particularly those of the Acroporidae family - being the most vulnerable to heat stress (Job, 2016). Subsequent observations indicated that most reefs began to recover once the heatwave subsided (Job, 2018). Some reefs, notably those in Poindimié and Ouégoa, remain in the recovery phase, while a few have not regenerated due to additional disturbances such as crown-of-thorns starfish outbreaks. In 2022, another marine heatwave struck, which particularly affected reefs of the Loyalty Islands (Job, 2023) and several coastal reefs on Grande Terre (Poum, Mont Dore, and Touho: A. Durbano/Hô-üt and S. Job, *pers. comm.*). These reefs suffered from the combined effects of thermal stress and reduced salinity caused by extreme rainfall, with 2022 recorded as the wettest year to date. As in 2016, the hard coral cover has begun to recover on the majority of reefs, once conditions normalized (Job, 2023).

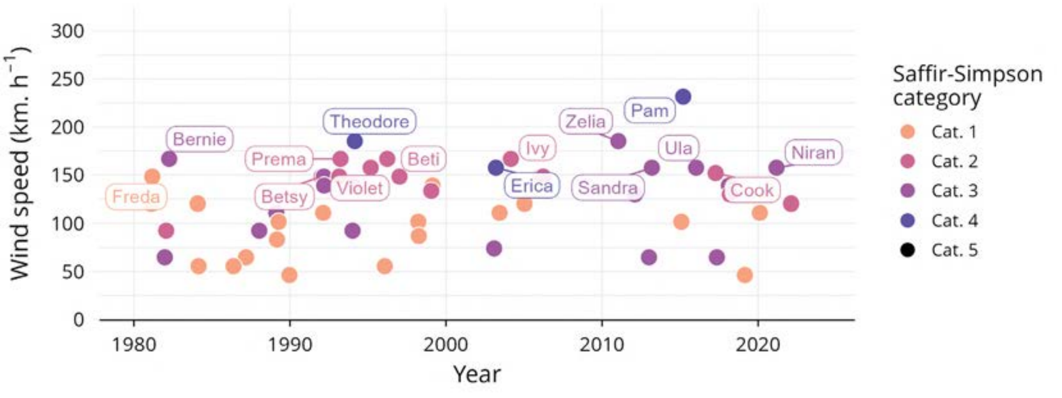


▲ **Figure 2.11.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of New Caledonia. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (i.e. cooler than long-term trend), and values above this line are positive SST anomalies (i.e. warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (i.e. 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

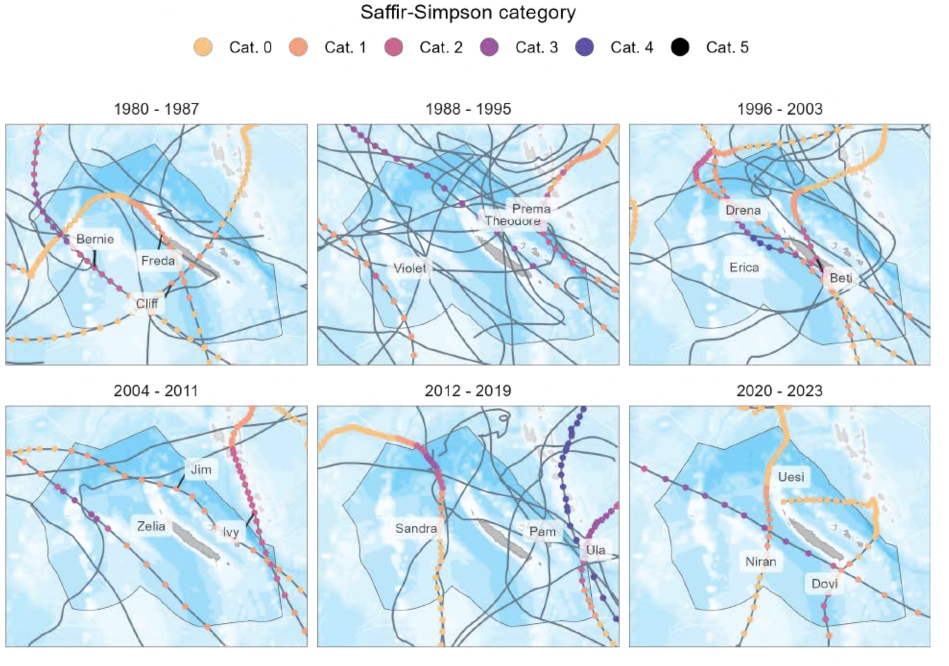
Cyclones

Between 1980 and 2023, a total of 112 tropical storms passed within 100 km distance from a coral reef of New Caledonia, and of these 44 were characterized by sustained wind speed greater than 100 km.h^{-1} (Figure 2.11.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Pam, in 2015, which passed 94 km from a coral reef with sustained wind speed of 232 km.h^{-1}.

Cyclones are one of the major drivers of the long-term dynamics and trajectories of coral reefs in New Caledonia, with impacts that can be locally very significant and long-lasting on exposed reefs. In March 2003, Cyclone Erica caused significant damage to numerous reefs along the western coast of New Caledonia (Wantiez et al., 2006; Guillemot et al., 2010). Subsequent data from three long-term monitoring networks indicated that coral populations on affected lagoon and barrier reefs showed signs of recovery within a decade. More recently, Cyclones Lucas and Niran, which struck just a month apart in February and March 2021, severely impacted coral reefs at Signal Islet (Nouméa), Bonne Anse and Casy Islet (Prony Bay), Akaia (Bourail), Tadine Bay (Maré), and the northern area of Santal Bay (Job, 2022).



▲ **Figure 2.11.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in New Caledonia. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h-1). Note that cyclones passing more than 100 km away from coral reefs of New Caledonia are not represented, although they may have had an impact.



▲ **Figure 2.11.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in New Caledonia. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only

Crown of Thorns Starfish

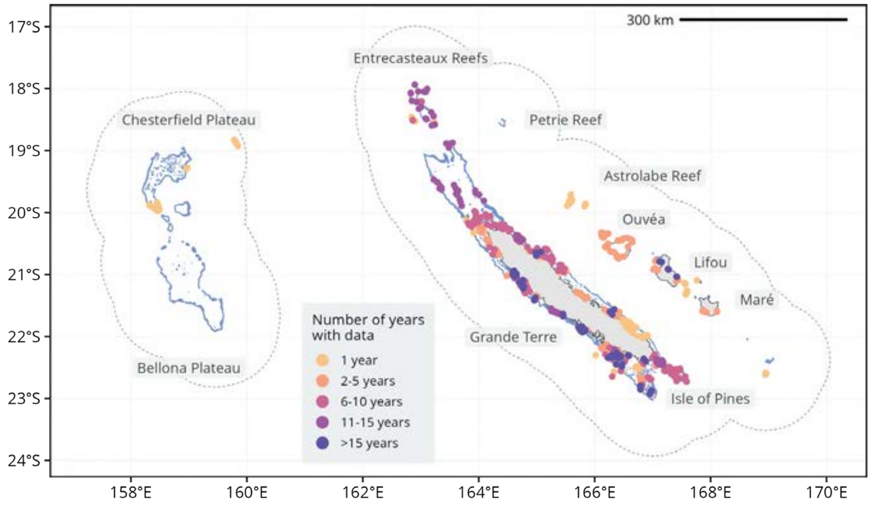
Surveys conducted in 2018 reported elevated densities of Acanthaster spp. in the southern lagoon of Grande Terre, with localized outbreaks observed in Prony Bay, around Ouen Island, and on several offshore reefs near Nouméa (Job, 2019; Dumas et al., 2020). Additional short-term and spatially limited aggregations were documented over the past decade, off Thio in 2011, near Nouméa in 2012–2013 (Maitre Islet and Dumbéa Pass), off Koumac in 2013 (Rat Islet), and near Poindimié in 2014 (Adjeroud et al., 2018). Since 2019, no significant outbreaks have been reported, and the affected sites are either undergoing recovery of hard coral cover or have already recovered.

Sedimentation

Peridotite mountain ranges, rich in metal deposits, cover nearly one-third of Grande Terre's surface. As a result, New Caledonia ranks among the world's leading nickel producers, with numerous open-pit mining sites scattered across the main island. This activity significantly contributes to soil erosion, posing a persistent threat to the marine environment (Fernandez et al., 2006). However, land cover analysis reveals that only 45% of bare, degraded, or human-impacted soils are located in areas of past or ongoing mining. Other major contributors to vegetation loss and subsequent sedimentation in the lagoon include bushfires and invasive species, particularly rusa deer — whose population is the largest globally — as well as feral pigs and wild rabbits (Ifrecor, 2021). These combined pressures result in widespread runoff, especially during the wet season, exposing New Caledonia's coastal waters to high sediment loads. Heintz et al. (2015) demonstrated that although hard coral cover may remain high on fringing reefs along the mainland, many coral colonies show signs of stress and compromised health due to sedimentation and algal overgrowth.

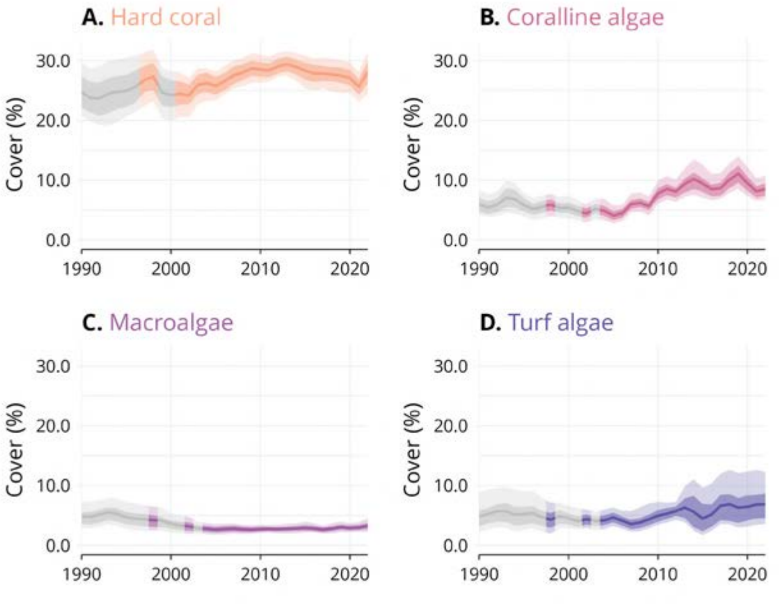
Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in New Caledonia was achieved through the integration of 8 datasets (Supplementary Table 1). These datasets represent a total of 798 monitoring sites, on which 3,541 surveys were conducted between 1997 and 2023.



▲ **Figure 2.11.4.** Spatio-temporal distribution of benthic cover monitoring sites across New Caledonia. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.

Hard coral cover has undergone several distinct phases over the past 25 years (Job, 2023). The decline recorded between the late 1990s and 2004 was attributed to Cyclone Erica in March 2003. From 2004 to 2012, in the absence of major meteorological events or disturbances, monitored reefs experienced a favourable period of coral growth. Starting in 2012, a series of stressors - including localized and temporary higher densities of *Acanthaster* between 2011 and 2014 and again in 2018, prolonged heavy rainfall in 2013 and 2014, and a marine heatwave in 2016 — led to the degradation of some reefs, while others remained unaffected and continued to grow. On average, coral cover remained relatively stable between 2012 and 2020, with a slight declining trend. In 2021, successive storms and cyclones Lucas and Niran caused extensive mechanical damage across many reefs of Grande Terre (Nouméa, Prony, Bourail) and the Loyalty Islands (Tadine and Santal bays). The recent recovery observed over the past two monitoring campaigns highlights the resilience of New Caledonia's reefs, which have so far largely recovered from the various disturbances they have faced. The very low proportion of macroalgae on reefs is a key asset for post-disturbance regeneration, supported by the high abundance of herbivorous species such as parrotfishes, surgeonfishes, rabbitfishes, and sea urchins.



▲ **Figure 2.11.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in New Caledonia. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

CASE STUDY

Effects of the implementation of a marine protected area on commercial reef fish species biomass and richness in Ouano, New Caledonia

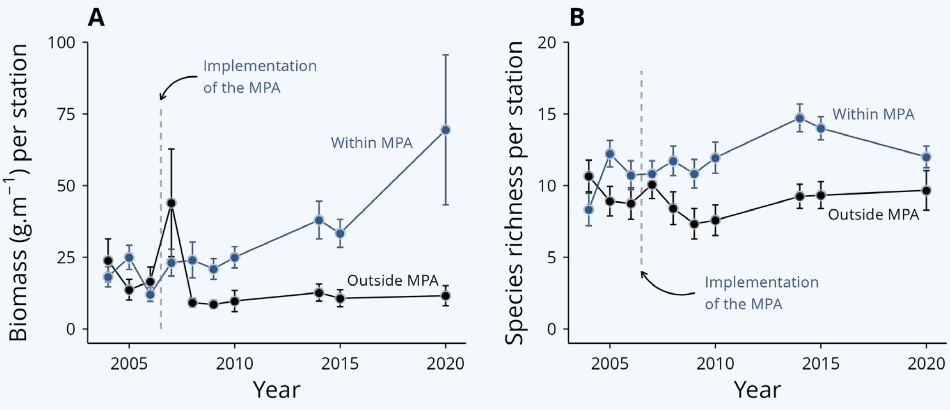
Author

Laurent Wantiez

Ouano Marine Protected Area (3,499 ha) was created in 1989, but the MPA has been implemented and enforced since 2007. The MPA extends from the coastline to the outer slope. The objective of the MPA is the conservation of the lagoon seascape (mangrove, soft-bottom, coral reefs) in the context of sustainable development. Ouano MPA is also included in the *Lagoons of New Caledonia: Reef Diversity and Associated Ecosystems*, a UNESCO world heritage site since 2008. MPA effects were assessed for coral reef fish, macroinvertebrates, and coral habitat using a Before-After Control-Impact Paired Series (BACIPS) design. The sampling network includes two unprotected areas located North and South of the MPA. Three surveys were conducted before enforcement (2004-2006), then 7 surveys after (2007-2020), all during the same season. Each survey consisted of 30 stations sampled on coral reefs (fringing reef, lagoon reef, and inner barrier reef). Eighteen were located within the MPA and 12 outside on unprotected reefs. At each station, the reef flat, the reef crest, and the reef slope were sampled.

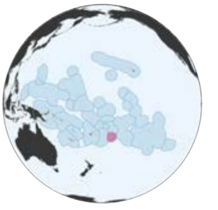
The first significant MPA effects were detected in 2009, three years after enforcement. Then they increased until 2014, and they were still efficient during the last survey in 2020 despite a decrease for several indicators. The commercial fish species increased in the MPA until 2014 while they remained stable outside (Figure 1). The MPA effects are even more significant for the biomass of commercial species, with a constant increase since enforcement, compared to the stability recorded outside the MPA (Figure 1). The main families benefiting from protection are the groupers and the acanthurids. The coral trout (*Plectropomus leopardus*) illustrates these positive effects. The species was observed only once in the unprotected zone and only twice in the MPA before enforcement. Now, the species has been observed in the MPA every survey since enforcement, with maximum densities and biomasses since 2014. Similar patterns are described for the humphead wrasse (*Cheilinus undulatus*) and the bluespine unicornfish (*Naso unicornis*). These three fish species are among the most targeted coral reef fish in the country. Macroinvertebrates also benefited from MPA effects, such as the commercial top shell (*Rochia nilotica*), the giant clams (*Tridacna spp.*), and the lobsters (*Panulirus spp.*). No MPA effect was detected for the coral habitat as the anthropogenic pressure was similar inside and outside the MPA.

However, the level of these positive effects is directly related to the enforcement strategy. A change of the management of the MPA occurred in 2014. Before, the ranger's office in charge of the MPA enforcement was located on top of a hill with a direct view of the entire MPA. Similarly, any person in the MPA could see the office. In 2014, the office was moved to the village of La Foa. The presence of the rangers on the water increased, but they had no view of the MPA from their office anymore. At the same time, we observed a stabilization or a decrease of the MPA effects on several indicators between 2014 and 2020, such as illustrated by the commercial fish species richness (Figure 1). We hypothesize that the presence of the ranger's office in view of the MPA had a significant dissuasive impact on potential poachers. This highlights the importance of the perception of control strategy by the users of the area.



▲ **Figure 1.** Comparison of the temporal trends of biomass (A) and species richness (B) of commercial coral reef fish species within and outside the Marine Protected Area (MPA) of Ouano, in New Caledonia. Points represent the mean between stations within (n = 18) and outside (n = 12) the MPA, and error bars represent the mean ± standard error. The lines between the points are only intended to show the temporal trends and do not rely on data.

NIUE



Co-authors[1]

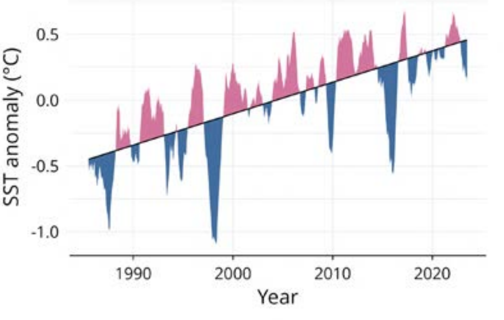
Graham J. Edgar, Lizzi Oh, Rick D. Stuart-Smith

Introduction

Maritime area	318,140 km^2
Land area	266 km^2
Mean land elevation	59 m
Coral reef extent	44 km^2

Coral reefs of Niue cover approximately 44 km^2, which represent 0.07 % of the total coral reef extent of the GCRMN Pacific region, and 0.018 % of the world coral reef extent.

We estimated the human population of Niue living within 5 km from coral reefs to be 1,232 inhabitants, in 2020. This represents 88.61 % of the total human population of Niue living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has decreased by 23.38 % between 2000 and 2020.



▲ **Figure 2.12.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Niue. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Threats

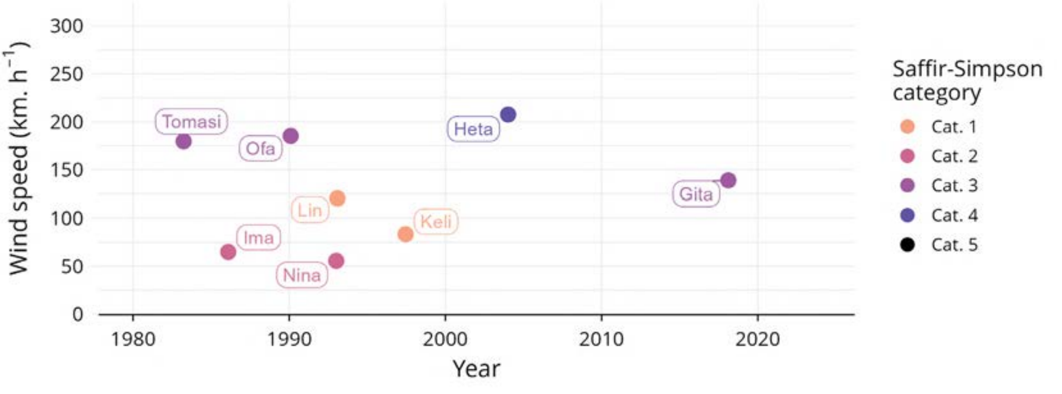
Thermal regime

The long-term average of SST on coral reefs of Niue between 1985 and 2023 was 26.88°C (Supplementary Figure 1). SST over coral reefs of Niue have increased by 0.85°C between 1985 and 2023, which corresponds to a warming rate of 0.022°C per year (Supplementary Figure 1).

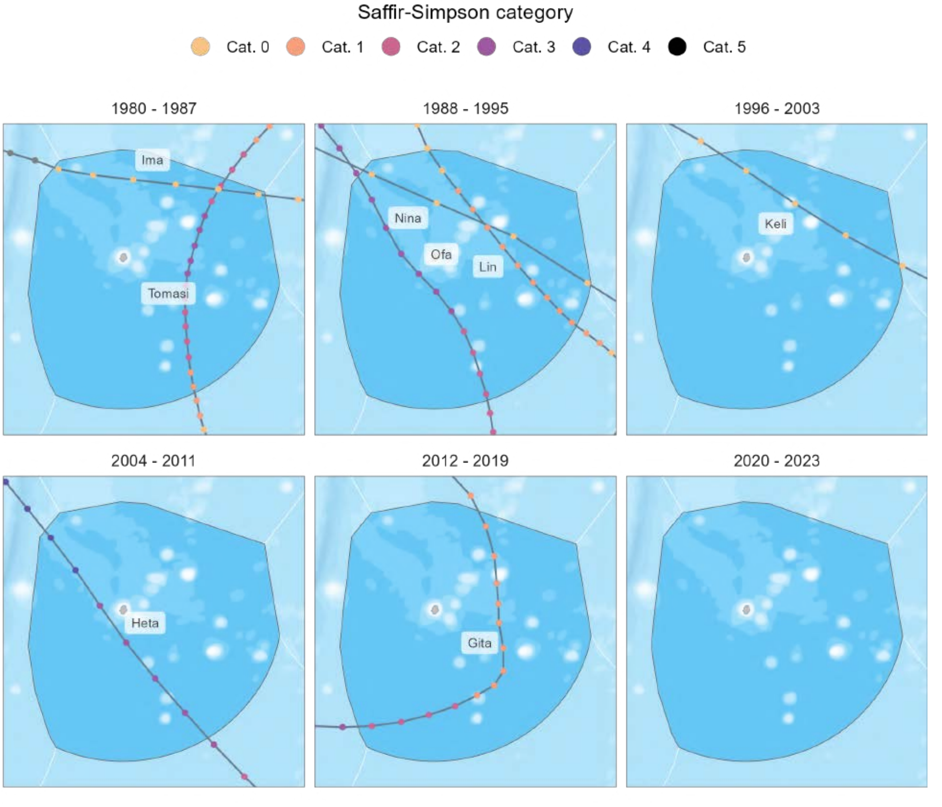
Cyclones

Between 1980 and 2023, a total of 21 tropical storms passed within 100 km distance from a coral reef of Niue, and of these 6 were characterized by sustained wind speed greater than 100 $km.h^{-1}$ (Figure 2.12.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Heta, in 2004, which passed 30 km from a coral reef with sustained wind speed of 207 $km.h^{-1}$.

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.



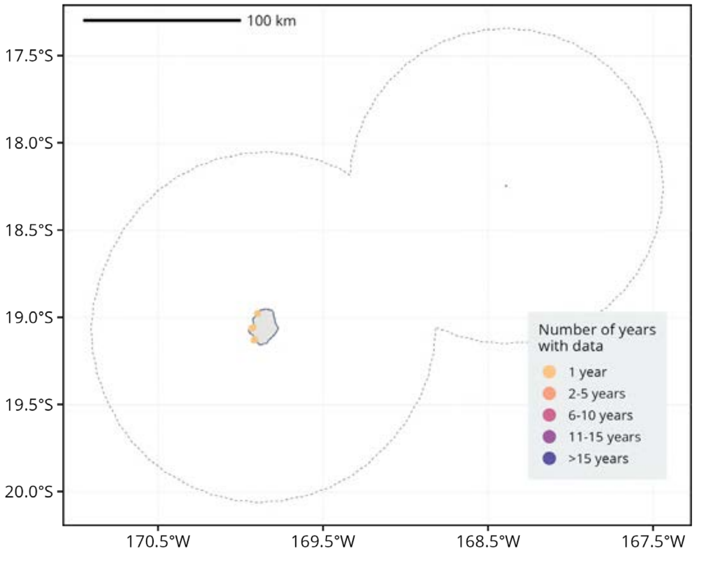
▲ **Figure 2.12.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Niue. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h^{-1}). Note that cyclones passing more than 100 km away from coral reefs of Niue are not represented, although they may have had an impact.



▲ **Figure 2.12.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Niue. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range *(i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

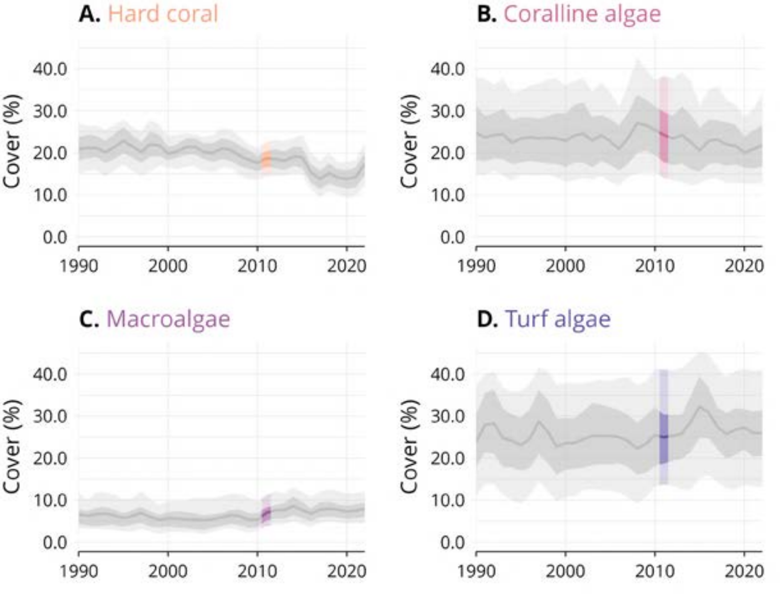
Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Niue was achieved through the integration of 1 dataset (Supplementary Table 1). This dataset represents a total of 7 monitoring sites, on which 7 surveys were conducted in 2011.

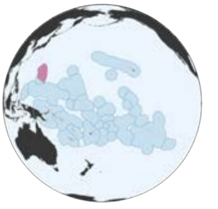


▲ **Figure 2.12.4.** Spatio-temporal distribution of benthic cover monitoring sites across Niue. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.

▶ **Figure 2.12.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Niue. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.



NORTHERN MARIANA ISLANDS



Co-authors[1]

Erica K. Towle, Jan Freiwald, Peter Houk, Jenny Mihaly

Introduction

Maritime area	763,626 km²
Land area	495 km²
Mean land elevation	147 m
Coral reef extent	181 km²

Located north of Guam in the western Pacific, the Commonwealth of the Northern Mariana Islands (CNMI) is a U.S. archipelago consisting of 14 islands. The principal inhabited islands are Saipan, Guguan, Rota and Tinian. The northern, largely uninhabited islands are Farallon de Medinilla, Anatahan, Sariguan, Gudgeon, Alamagan, Pagan, Agrihan, Asuncion, Maug Islands, and Farallon de Pajaro. The majority of the CNMI's residents live on Rota, Tinian, and Saipan, the capital and largest of the Northern Mariana Islands (Gorstein et al., 2019).

Coral reefs of Northern Mariana Islands cover approximately 181 km², which represent 0.28 % of the total coral reef extent of the GCRMN Pacific region, and 0.073 % of the world's coral reef extent.

We estimated the human population of Northern Mariana Islands living within 5 km from coral reefs to be 41,990 inhabitants, in 2020. This represents 100.00 % of the total human population of Northern Mariana Islands living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has decreased by 39.33 % between 2000 and 2020.

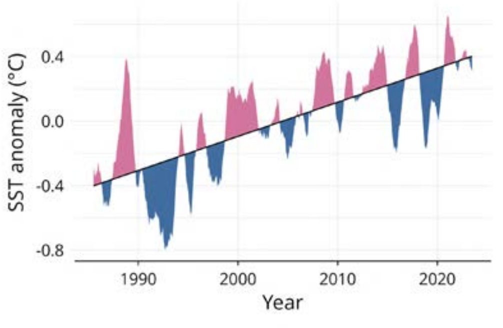
Threats

Thermal regime

The long-term average of SST on coral reefs of Northern Mariana Islands between 1985 and 2023 was 28.56°C (Supplementary Figure 1). SST over coral reefs of Northern Mariana Islands have increased by 0.86°C between 1985 and 2023, which corresponds to a warming rate of 0.023°C per year (Supplementary Figure 1).

From 2013-2017, the coral reefs of the Northern Mariana Islands experienced multiple thermal stress events resulting in unprecedented coral bleaching and mortality across the archipelago. Over this four-year period, most coral species were affected across all islands and reef zones, down to at least 20 meters depth (NOAA, 2018).

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

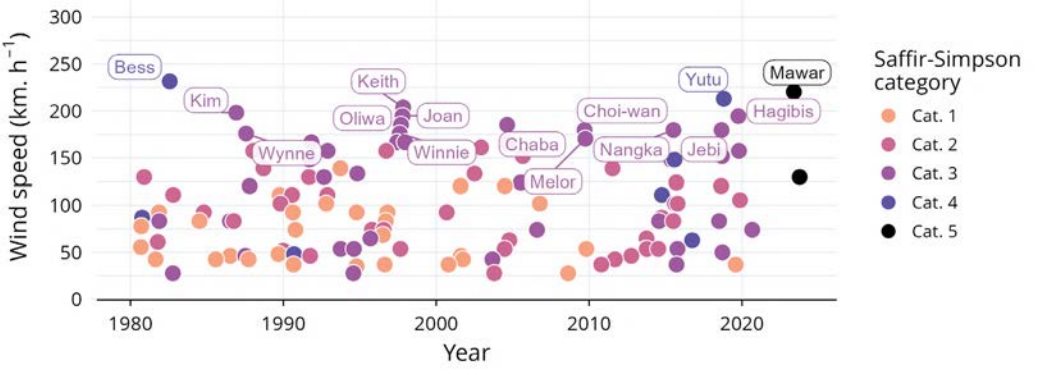


▲ **Figure 2.13.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Northern Mariana Islands. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

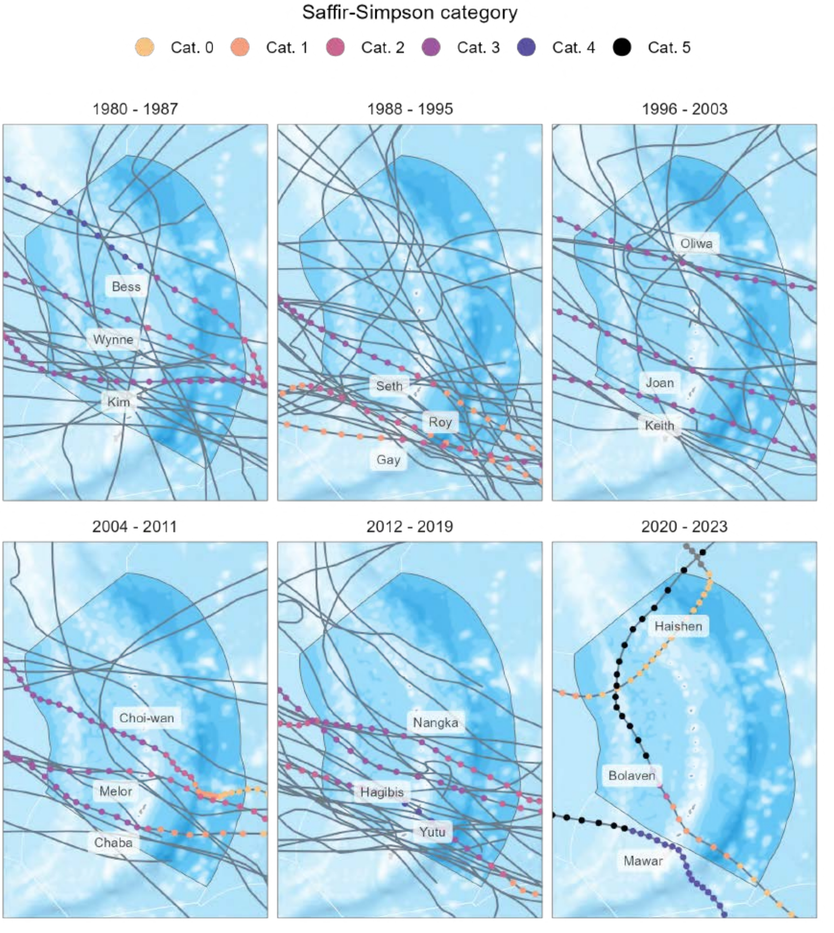
Cyclones

Between 1980 and 2023, a total of 186 tropical storms passed within 100 km distance from a coral reef of Northern Mariana Islands, and of these 57 were characterized by sustained wind speed greater than 100 $km.h^{-1}$ (Figure 2.13.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Bess in 1982, which passed 25 km from a coral reef with sustained wind speed of 232 $km.h^{-1}$.

The Northern Mariana Islands experienced direct impacts from two severe typhoons during 2018. In August, Typhoon Mangkhut passed over Rota, leaving significant damage in its wake. And in October, Typhoon Yutu made direct landfall on Tinian and southern Saipan, bringing devastation to people and property, including major population centers on Saipan (Gorstein et al. 2019).



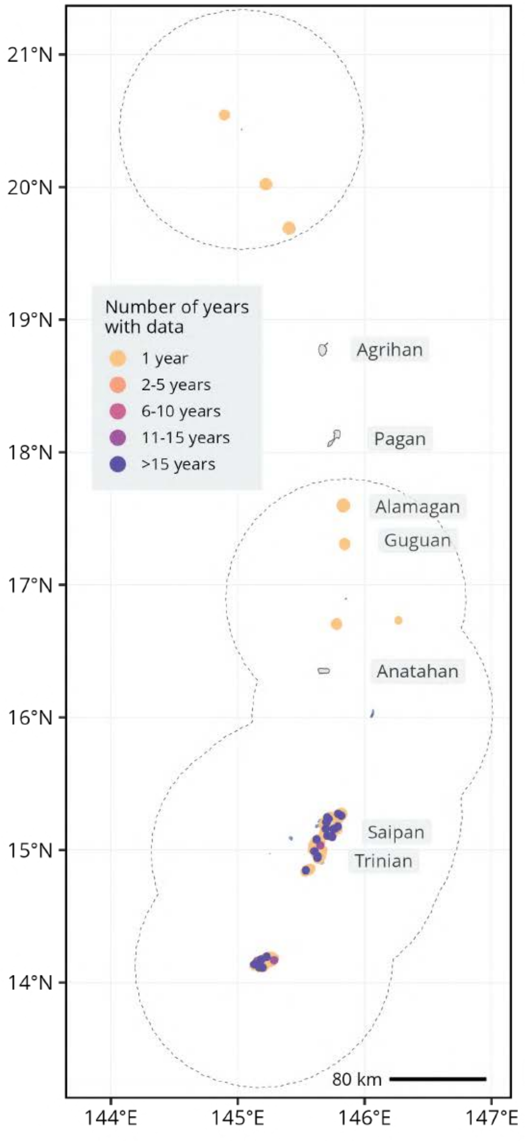
▲ **Figure 2.13.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Northern Mariana Islands. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 $km.h^{-1}$). Note that cyclones passing more than 100 km away from coral reefs of Northern Mariana Islands are not represented, although they may have had an impact.



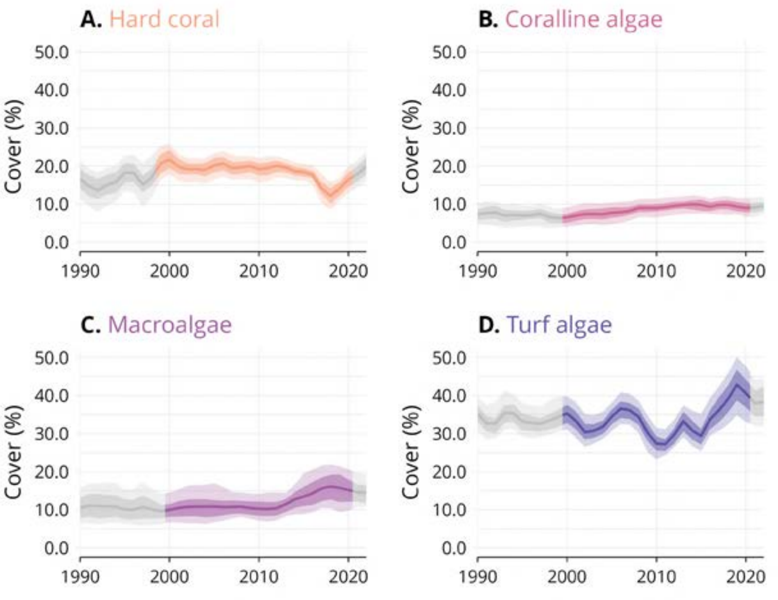
▲ **Figure 2.13.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Northern Mariana Islands. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Northern Mariana Islands was achieved through the integration of 3 datasets (Supplementary Table 1). These datasets represent a total of 680 monitoring sites, on which 924 surveys were conducted between 1999 and 2020.

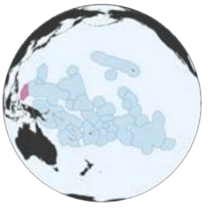


▲ **Figure 2.13.4.** Spatio-temporal distribution of benthic cover monitoring sites across Northern Mariana Islands. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.13.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Northern Mariana Islands. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

PALAU



Co-authors[1]

Victor Nestor, Geraldine Rengiil, Yimnang Golbuu, Beverly French, Nicole Pedersen, Stuart Sandin, Jan Freiwald, Jenny Mihaly

Introduction

Maritime area	616,431 km²
Land area	480 km²
Mean land elevation	54 m
Coral reef extent	966 km²

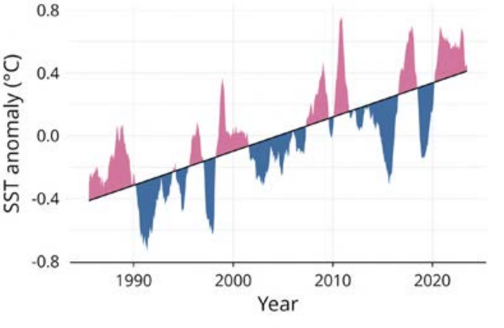
Coral reefs of Palau cover approximately 966 km², which represent 1.48 % of the total coral reef extent of the GCRMN Pacific region, and 0.387 % of the world coral reef extent.

We estimated the human population of Palau living within 5 km from coral reefs to be 27,219 inhabitants , in 2020. This represents 95.68 % of the total human population of Palau living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 45.10 % between 2000 and 2020.

Threats

Thermal regime

The long-term average of SST on coral reefs of Palau between 1985 and 2023 was 29.01°C (Supplementary Figure 1). SST over coral reefs of Palau have increased by 0.86°C between 1985 and 2023, which corresponds to a warming rate of 0.023°C per year (Supplementary Figure 1).

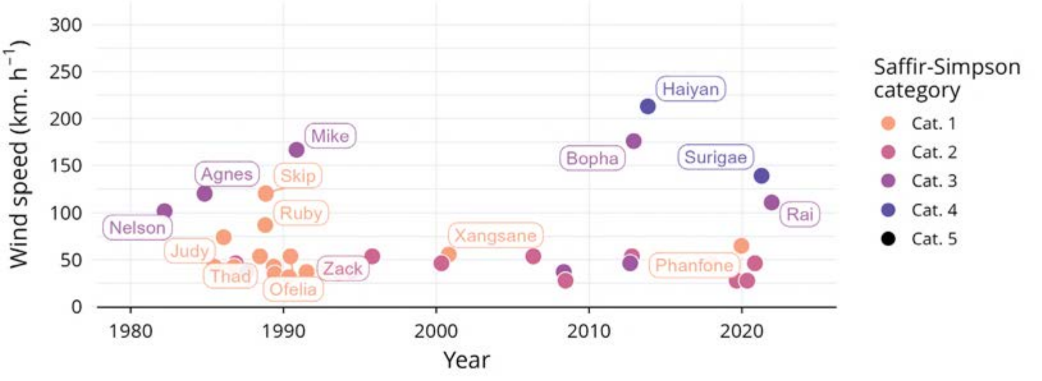


▲ **Figure 2.14.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Palau. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

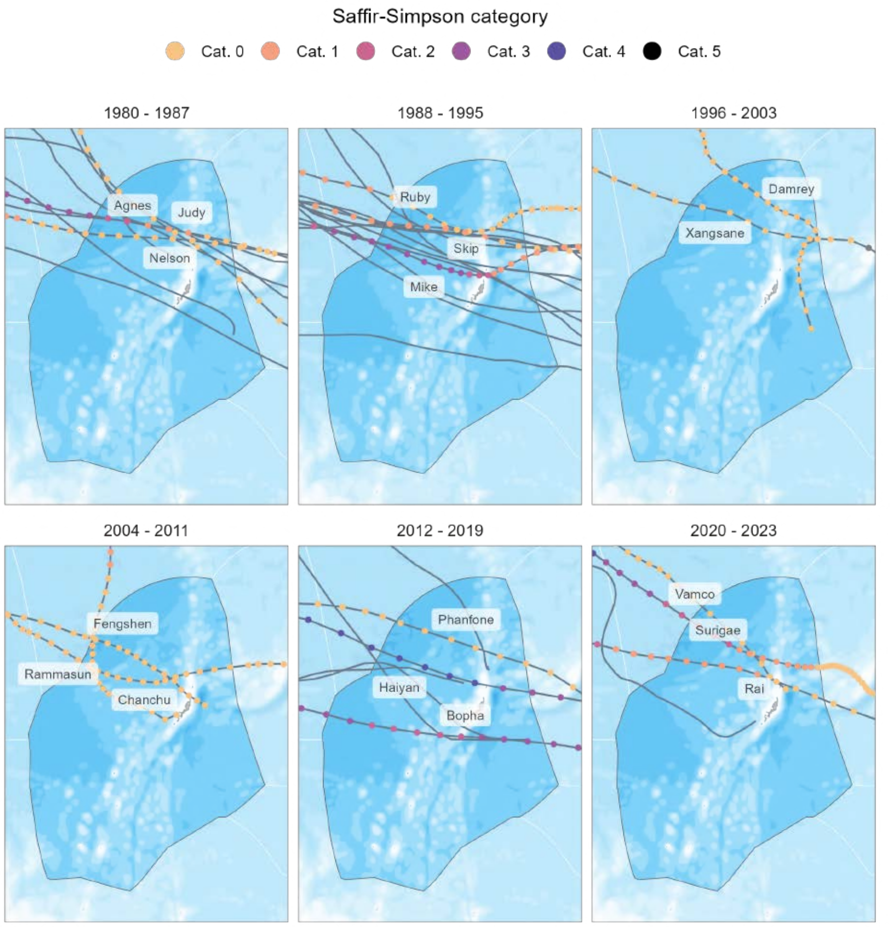
Cyclones

Between 1980 and 2023, a total of 113 tropical storms passed within 100 km distance from a coral reef of Marshall Islands, and of these 4 were characterized by sustained wind speed greater than 100 km.h^{-1} (Figure 2.9.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Fengshen, in 2002, which passed 5 km from a coral reef with sustained wind speed of 157 km.h^{-1}.

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.



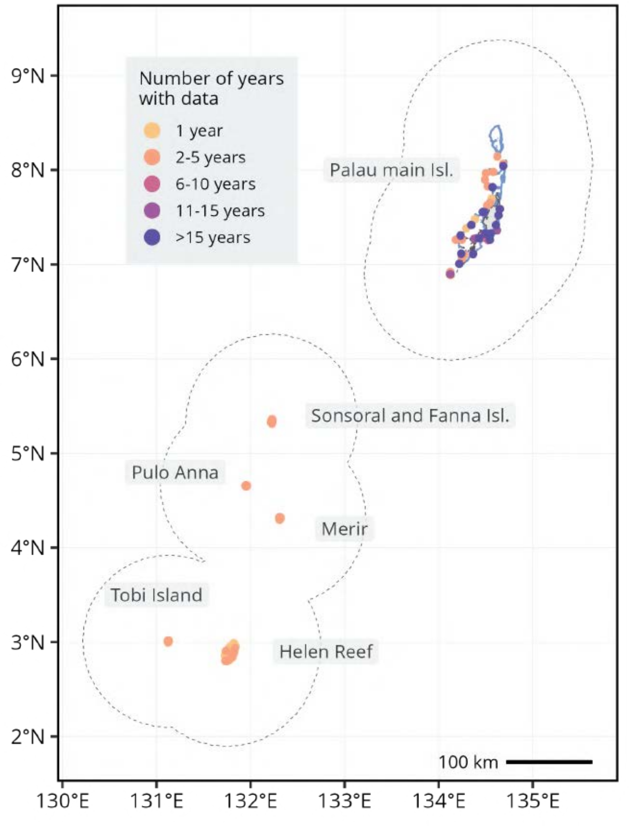
▲ **Figure 2.14.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Palau. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h^{-1}). Note that cyclones passing more than 100 km away from coral reefs of Palau are not represented, although they may have had an impact.



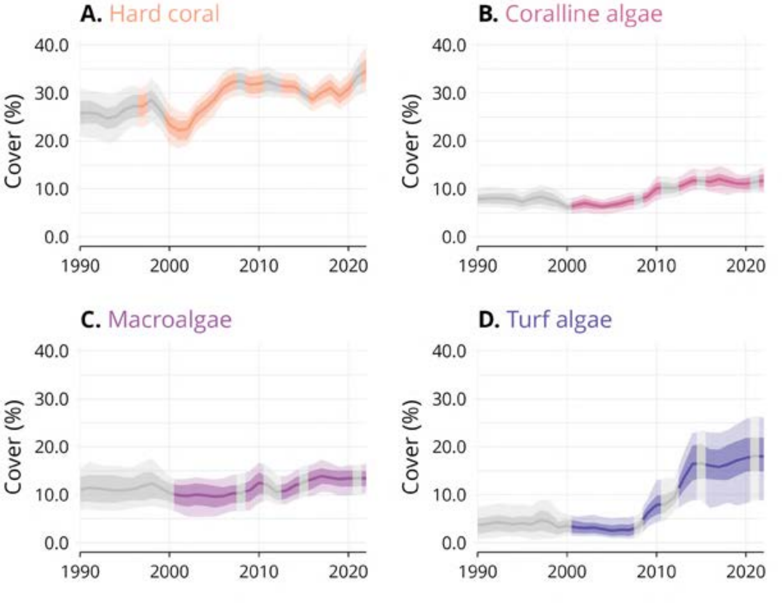
▲ **Figure 2.14.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Palau. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Palau was achieved through the integration of 3 datasets (Supplementary Table 1). These datasets represent a total of 112 monitoring sites, on which 381 surveys were conducted between 1997 and 2022.

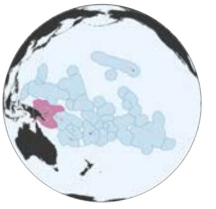


▶ **Figure 2.14.4.** Spatio-temporal distribution of benthic cover monitoring sites across Palau. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.14.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Palau. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

PAPUA NEW GUINEA



Co-authors[1]

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Introduction

Maritime area	2,402,238 km²
Land area	463,249 km²
Mean land elevation	608 m
Coral reef extent	14,598 km²

Coral reefs of Papua New Guinea cover approximately 14,598 km², which represent 22.37 % of the total coral reef extent of the GCRMN Pacific region, and 5.846 % of the world coral reef extent.

We estimated the human population of Papua New Guinea living within 5 km from coral reefs to be 964,040 inhabitants, in 2020. This represents 10.44 % of the total human population of Papua New Guinea living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 55.02 % between 2000 and 2020.

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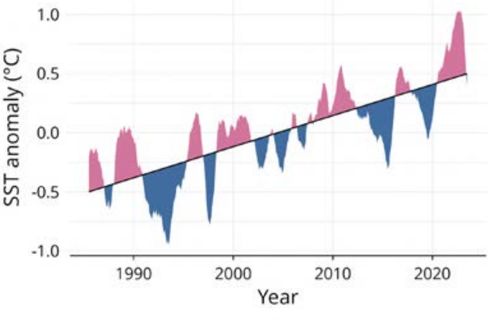


▲ **Figure 2.15.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Papua New Guinea. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Threats

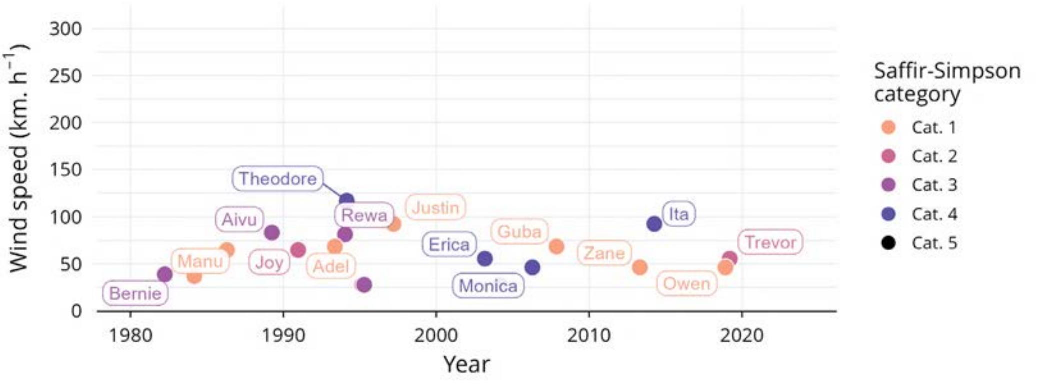
Thermal regime

The long-term average of SST on coral reefs of Papua New Guinea between 1985 and 2023 was 28.55°C (Supplementary Figure 1). SST over coral reefs of Papua New Guinea have increased by 0.96°C between 1985 and 2023, which corresponds to a warming rate of 0.025°C per year (Supplementary Figure 1)

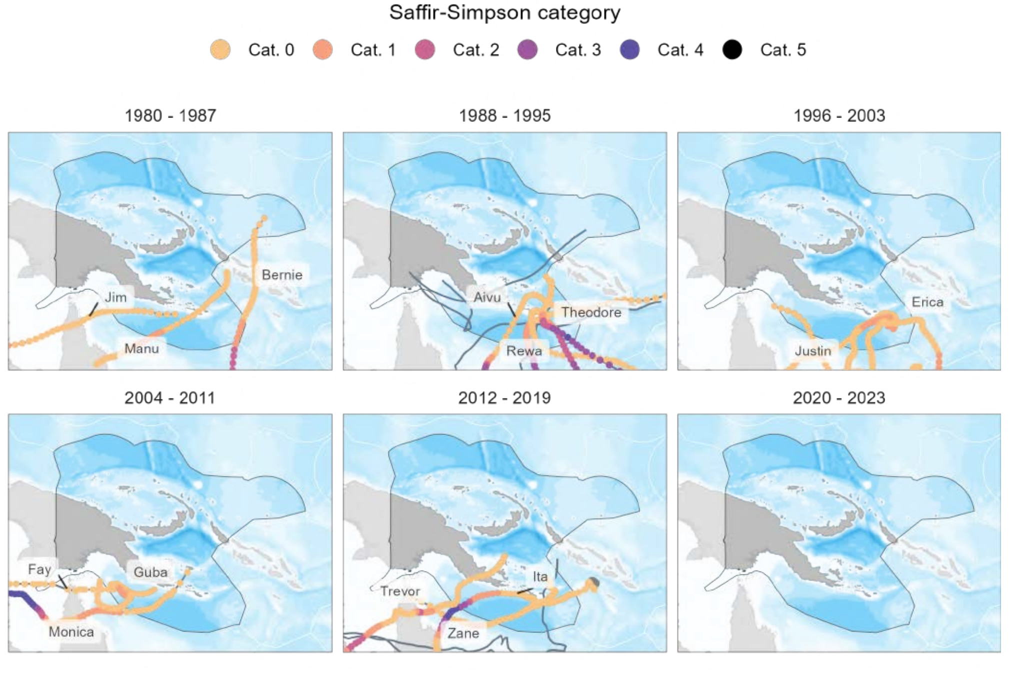
Cyclones

Between 1980 and 2023, a total of 41 tropical storms passed within 100 km distance from a coral reef of Papua New Guinea, and of these 1 were characterized by sustained wind speed greater than 100 km.h^{-1} (Figure 2.15.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Theodore, in 1994, which passed 0 km from a coral reef with sustained wind speed of 117 km.h^{-1}.

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.



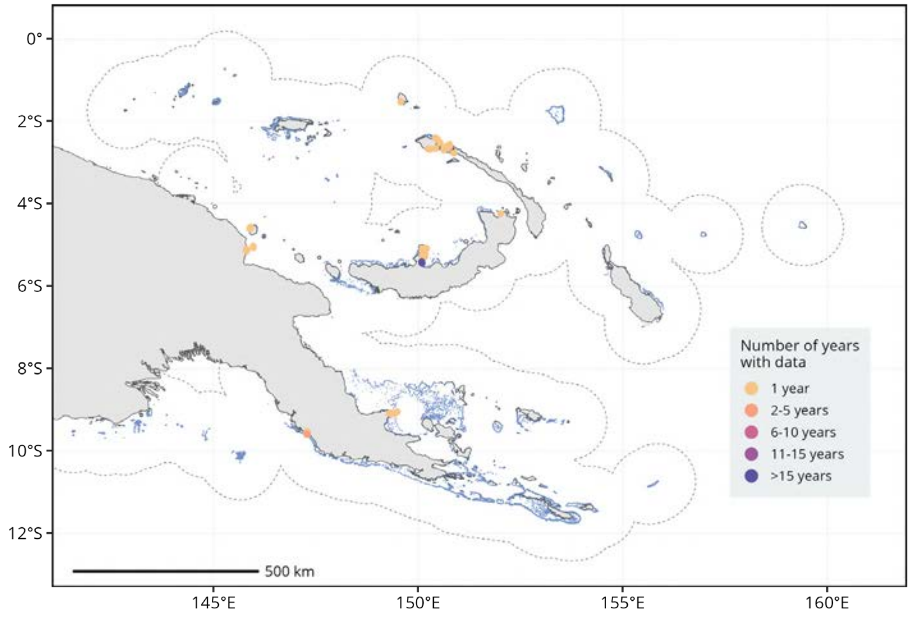
▲ **Figure 2.15.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Papua New Guinea. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h^{-1}). Note that cyclones passing more than 100 km away from coral reefs of Papua New Guinea are not represented, although they may have had an impact.



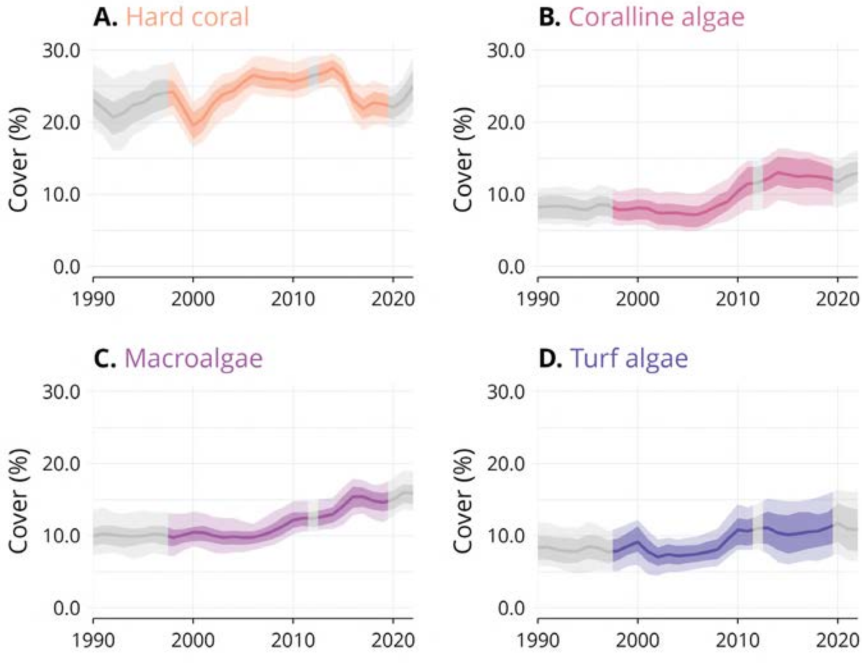
▲ **Figure 2.15.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Papua New Guinea. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Papua New Guinea was achieved through the integration of 4 datasets (Supplementary Table 1). These datasets represent a total of 91 monitoring sites, on which 267 surveys were conducted between 1998 and 2019.

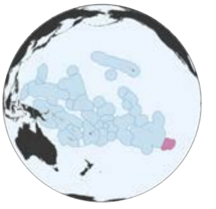


▲ **Figure 2.15.4.** Spatio-temporal distribution of benthic cover monitoring sites across Papua New Guinea. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.15.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Papua New Guinea. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

PITCAIRN



Co-authors[1]

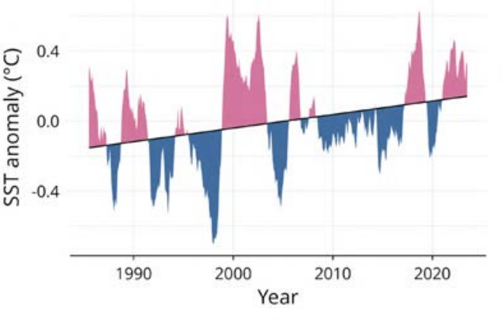
Yannick Chancerelle, Graham J. Edgar, Lizzi Oh, Serge Planes, Gilles Siu, Rick D. Stuart-Smith

Introduction

Maritime area	842,291 km²
Land area	53 km²
Mean land elevation	35 m
Coral reef extent	64 km²

Coral reefs of Pitcairn cover approximately 64 km², which represent 0.10 % of the total coral reef extent of the GCRMN Pacific region, and 0.026 % of the world coral reef extent.

We estimated the human population of Pitcairn living within 5 km from coral reefs to be 81 inhabitants, in 2020. This represents 100.00 % of the total human population of Pitcairn living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 76.41 % between 2000 and 2020.



▲ **Figure 2.16.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Pitcairn. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Threats

Thermal regime

The long-term average of SST on coral reefs of Pitcairn between 1985 and 2023 was 24.50°C (Supplementary Figure 1). SST over coral reefs of Pitcairn have increased by 0.18°C between 1985 and 2023, which corresponds to a warming rate of 0.005°C per year (Supplementary Figure 1).

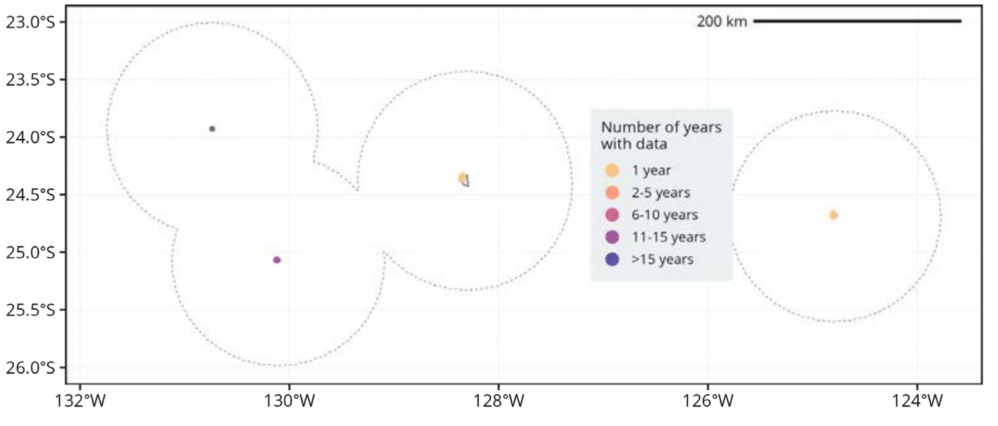
Cyclones

Between 1980 and 2023, no tropical storms passed within 100 km distance from a coral reef of Pitcairn.

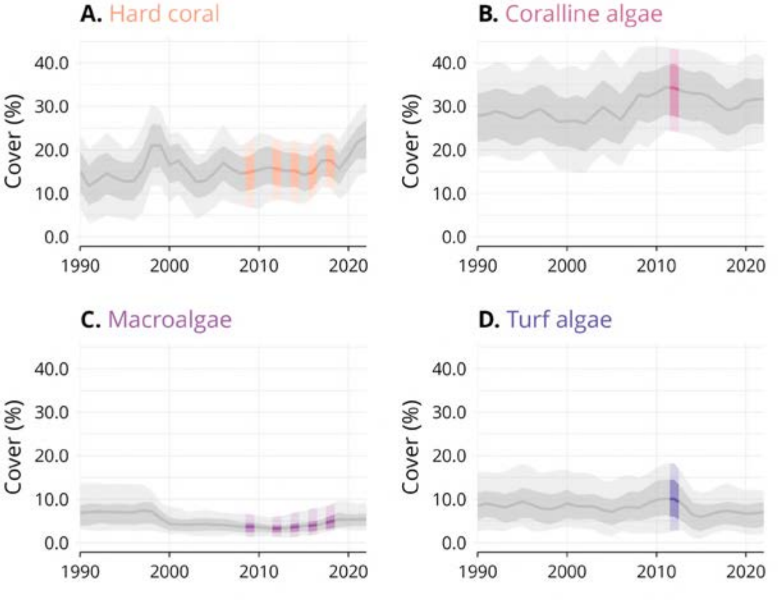
[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Papua New Guinea was achieved through the integration of 4 datasets (Supplementary Table 1). These datasets represent a total of 91 monitoring sites, on which 267 surveys were conducted between 1998 and 2019.

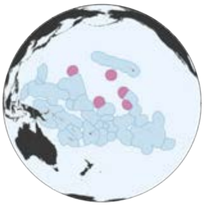


▲ **Figure 2.16.2.** Spatio-temporal distribution of benthic cover monitoring sites across Pitcairn. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.16.3.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Pitcairn. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

PACIFIC REMOTE ISLAND AREA



Co-authors[1]

Erica K. Towle, Adi Khen, Jennifer E. Smith

Introduction

	Maritime area	Land area	Mean land elevation	Coral reef extent
Howland and Baker Islands	434,894 km²	3 km²	6 m	12 km²
Jarvis Island	323,186 km²	< 1 km²	< 1 m	6 km²
Johnston Atoll	442,443 km²	5 km²	8 m	100 km²
Palmyra Atoll and Kingman Reef	353,670 km²	6 km²	9 m	105 km²
Wake Island	406,970 km²	8 km²	6 m	26 km²
Entire PRIA	**1,961,163 km²**	**22 km²**		**248 km²**

The U.S. Pacific Remote Islands, referred to here as the PRIA (Pacific Remote Island Area) encompass islands and atolls scattered across the central Pacific Ocean that represent relatively pristine coral reef ecosystems. Howland, Baker, and Jarvis Islands are geographically situated near the equator. Palmyra Atoll is north of Jarvis Island, and Wake Island and Johnston Atoll are north and west of Palmyra. These islands and atolls are part of a U.S. marine national monument (The Pacific Remote Islands Marine National Monument) established in 2009 and expanded in 2014 (NOAA, 2018).

Coral reefs of the PRIA cover approximately 248 km², which represent 0.38% of the total coral reef extent of the GCRMN Pacific region, and 0.1% of the world coral reef extent. PRIA are mostly uninhabited with the exception of Wake Island. These reef systems are known to have an abundance of top predators, larger-bodied herbivores, and calcifying organisms (Sandin et al., 2008; Williams et al., 2013; Smith et al., 2016). The lack of local stressors such as fishing or pollution makes them an ideal location to study long-term impacts of global change.

Threats

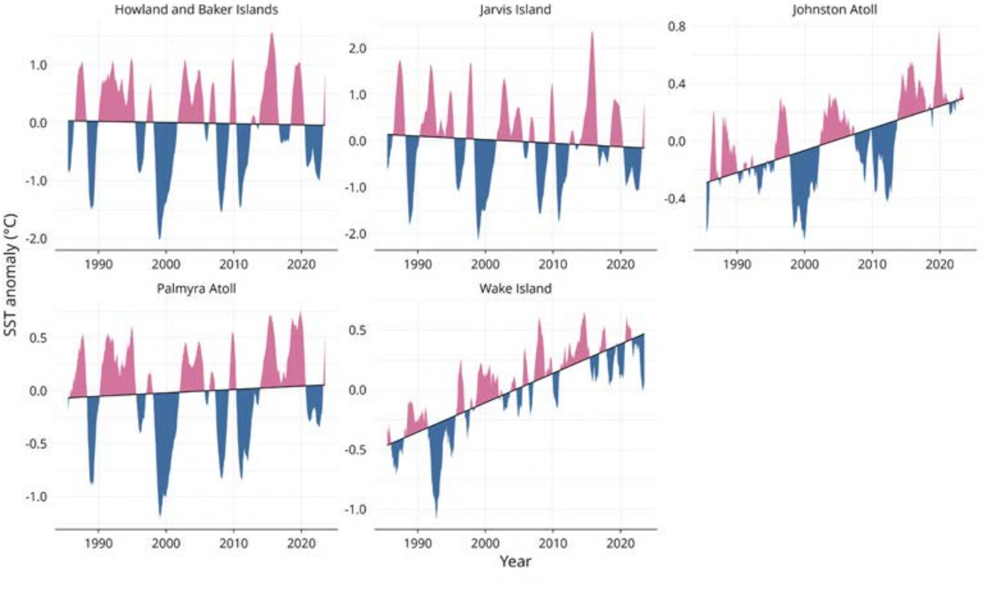
The extreme isolation of reefs in the PRIA and their low elevation make them easy targets for ship groundings. Grounded vessels can physically reduce large areas of healthy reef to rubble when they run aground. In addition, shifts from "healthy" calcifier -dominated reefs to those dominated by fleshy algae, cyanobacterial mats, and corallimorphs (black reefs) have been linked to iron and other nutrients leaching from wrecks (Work et al., 2008; Carter et al., 2019). Another threat is illegal fishing by international fishing boats. While not a

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

current threat, some islands were used for military exercises during World War II which involved lagoon dredging or causeway construction leading to highly altered landscapes, sedimentation, and disrupted hydrodynamics. Management of the Pacific Remote Islands has had positive outcomes due to their federally-protected status, although their remoteness and limited resources and staff present challenges to management (NOAA, 2018). However, the main threat to coral reefs in the PRIA is global climate change including warming seawater temperatures and ocean acidification. For example, widespread and catastrophic coral mortality was reported at Jarvis Island in the aftermath of an exceptionally strong 2015–2016 El Niño warming event (NOAA, 2018). In contrast, Howland and Baker Islands experienced substantially less thermal stress during this event (NOAA Coral Reef Watch) and had reductions in hard coral cover of only around 30% (Brainard et al., 2018). On Palmyra's reefs where accumulated thermal stress was not as severe, post-bleaching recovery and limited coral mortality were observed (Fox et al., 2019; Khen et al., 2022). Other recent threats include crown-of-thorns outbreaks and damage from swells.

Thermal regime

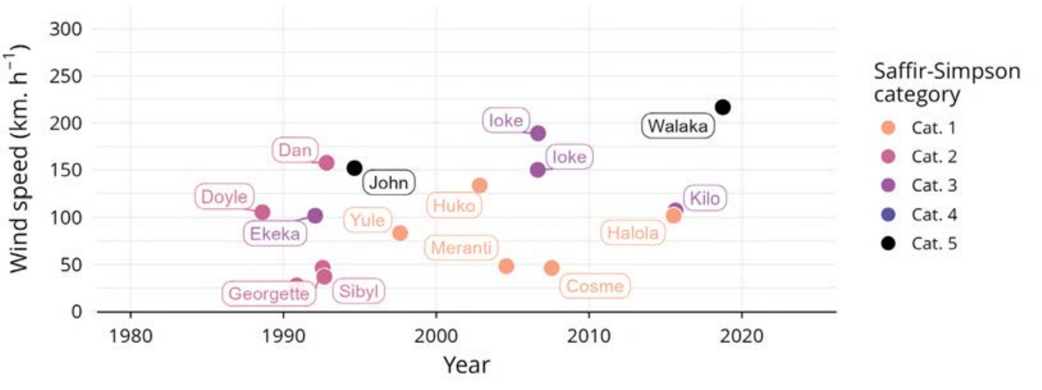
The long-term average of SST on coral reefs of the PRIA between 1985 and 2023 was 27.76°C (Supplementary Figure 1). SST over coral reefs of PRIA have increased by 0.39°C between 1985 and 2023, which corresponds to a warming rate of 0.01°C per year (Supplementary Figure 1).



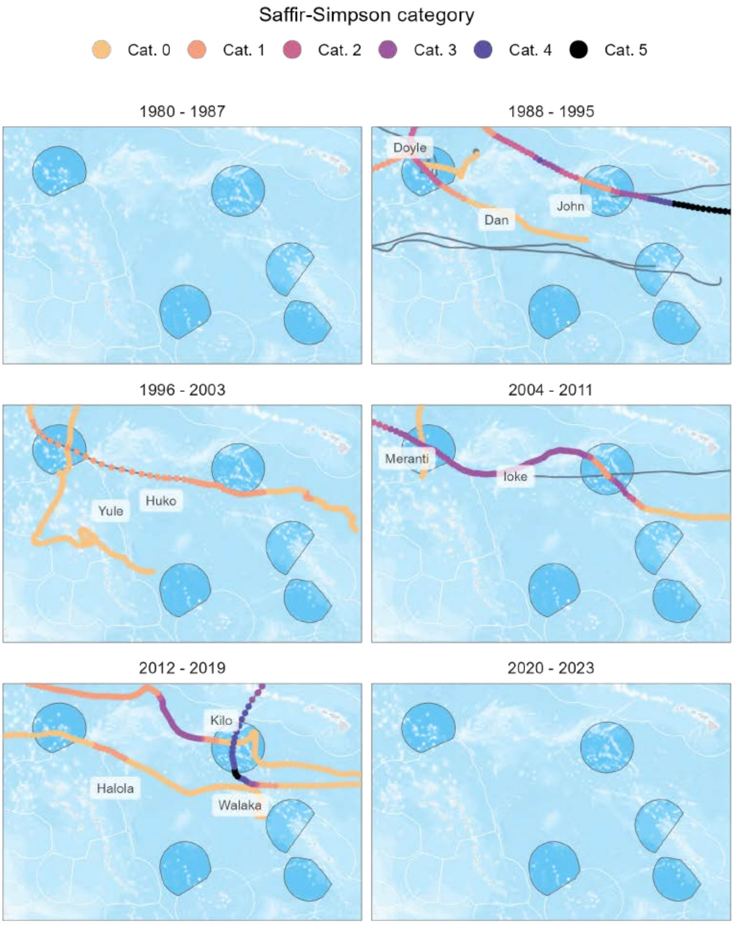
▲ **Figure 2.17.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of the PRIA. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Cyclones

Between 1980 and 2023, a total of 23 tropical storms passed within 100 km distance from a coral reef of the PRIA, mostly in Johnston Atoll and Wake Island (Figure 2.17.3). Among these tropical storms, 10 were characterized by sustained wind speed greater than 100 km.h-1 (Figure 2.17.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Walaka in 2018, which passed 70 km from a coral reef of the Johnston Atoll with sustained wind speed of 216 km.h-1.



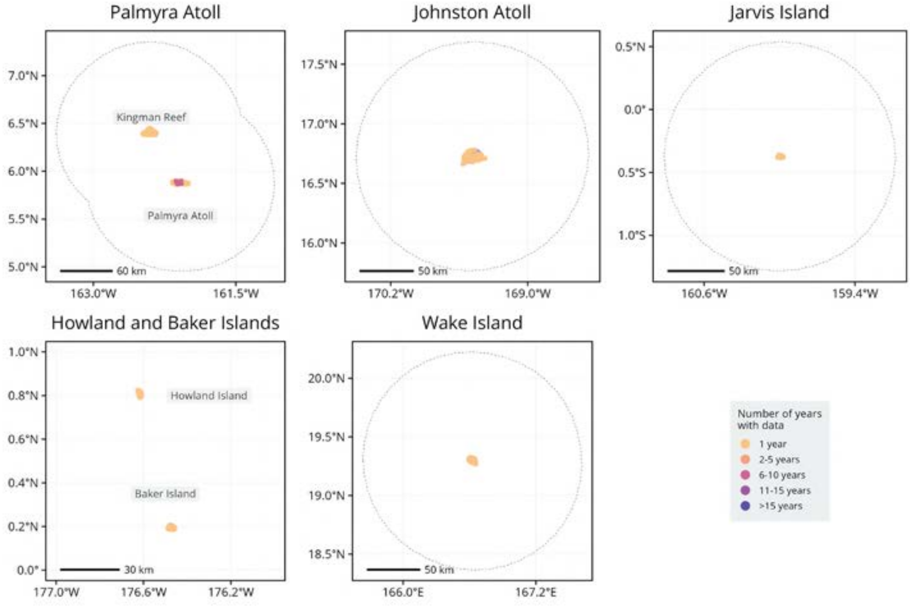
▲ **Figure 2.17.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in the PRIA. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h-1). Note that cyclones passing more than 100 km away from coral reefs of the PRIA are not represented, although they may have had an impact.



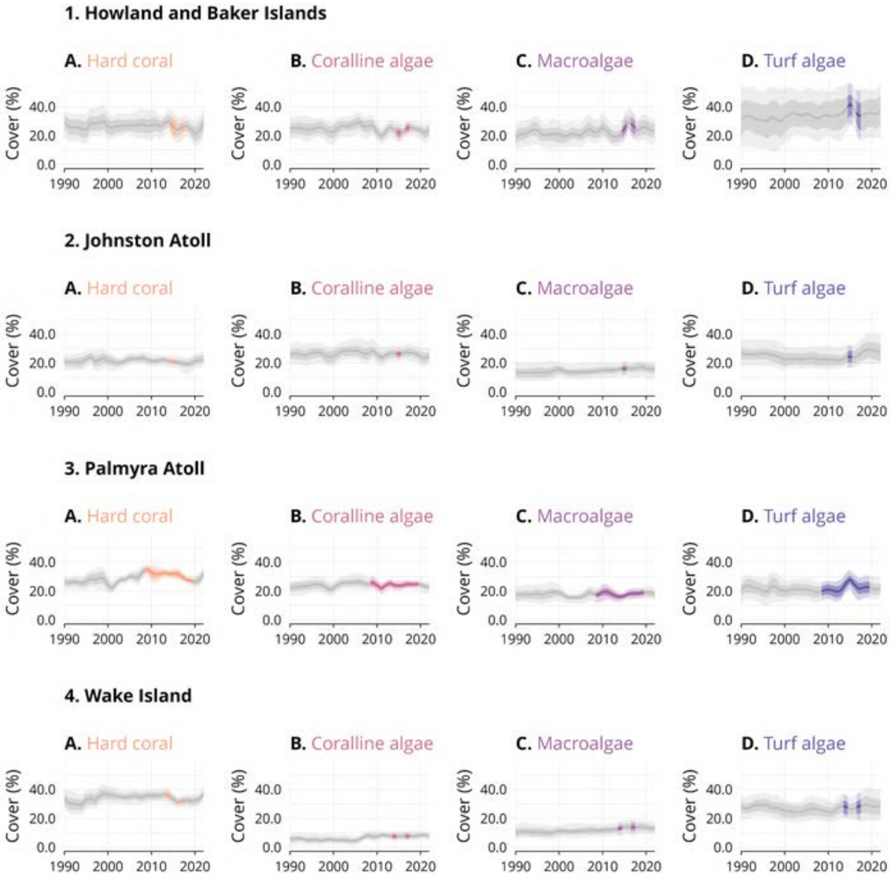
▲ **Figure 2.17.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in the PRIA. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in the PRIA was achieved through the integration of 2 datasets (Supplementary Table 1). These datasets represent a total of 758 monitoring sites, on which 862 surveys were conducted between 2009 and 2019.

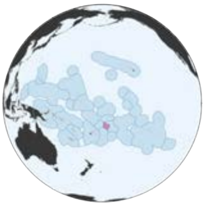


▲ **Figure 2.17.4.** Spatio-temporal distribution of benthic cover monitoring sites across the PRIA. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.17.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in the PRIA. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

SAMOA



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Introduction

Maritime area	130,480 km²
Land area	2,851 km²
Mean land elevation	383 m
Coral reef extent	404 km²

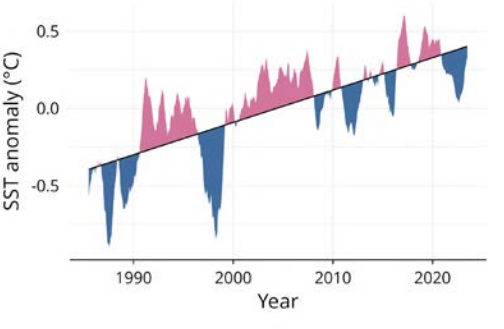
Coral reefs of Samoa cover approximately 402 km², which represent 0.62 % of the total coral reef extent of the GCRMN Pacific region, and 0.161 % of the world coral reef extent.

We estimated the human population of Samoa living within 5 km from coral reefs to be 114,921 inhabitants, in 2020. This represents 57.96 % of the total human population of Samoa living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 14.57 % between 2000 and 2020.

Threats

Thermal regime

The long-term average of SST on coral reefs of Samoa between 1985 and 2023 was 28.70°C (Supplementary Figure 1). SST over coral reefs of Samoa have increased by 0.81°C between 1985 and 2023, which corresponds to a warming rate of 0.021°C per year (Supplementary Figure 1).



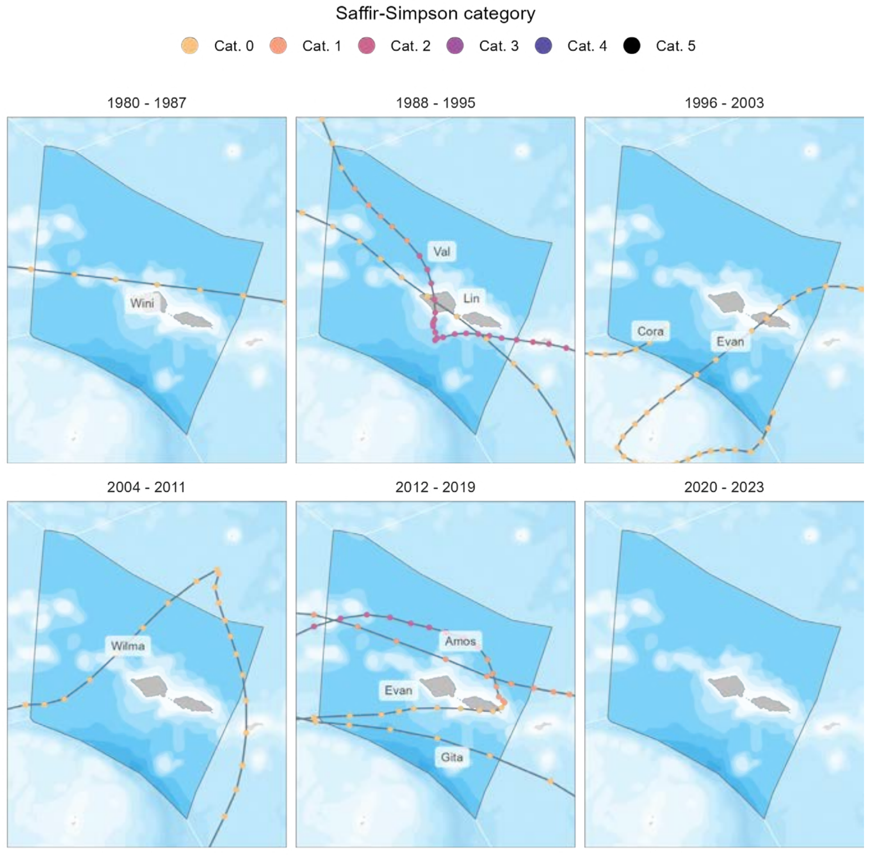
▲ **Figure 2.18.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Samoa. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Cyclones

Between 1980 and 2023, a total of 19 tropical storms passed within 100 km distance from a coral reef of Samoa, and of these 4 were characterized by sustained wind speed greater than 100 km.h^{-1} (Figure 2.18.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Val, in 1991, which passed 0 km from a coral reef with sustained wind speed of 167 km.h^{-1}.

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

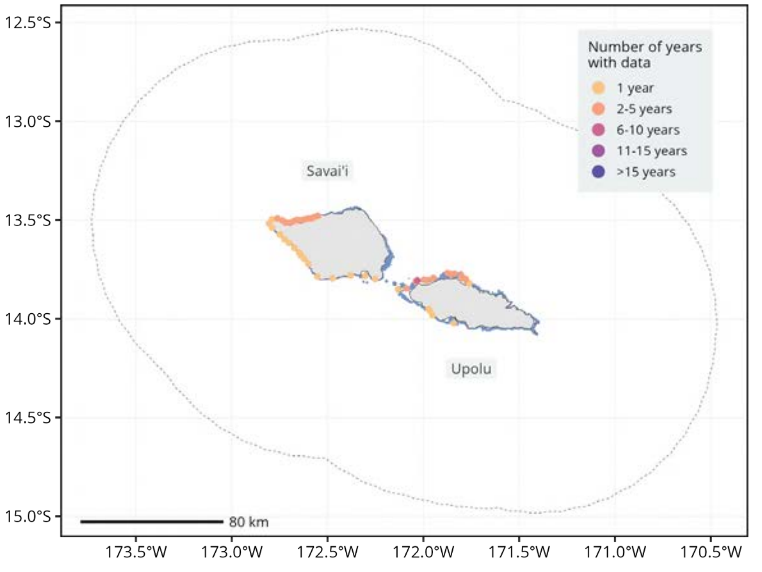
▲ **Figure 2.18.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Samoa. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 $km.h^{-1}$). Note that cyclones passing more than 100 km away from coral reefs of Samoa are not represented, although they may have had an impact.



▲ **Figure 2.18.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Samoa. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

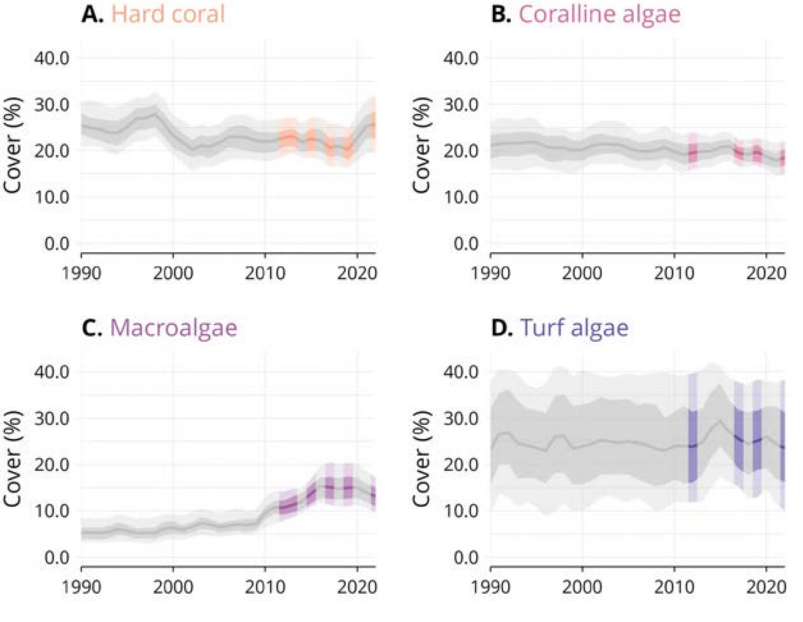
Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Papua New Guinea was achieved through the integration of 4 datasets (Supplementary Table 1). These datasets represent a total of 91 monitoring sites, on which 267 surveys were conducted between 1998 and 2019.

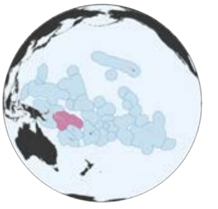


▲ **Figure 2.18.4.** Spatio-temporal distribution of benthic cover monitoring sites across Samoa. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.

▶ **Figure 2.18.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Samoa. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.



SOLOMON ISLANDS



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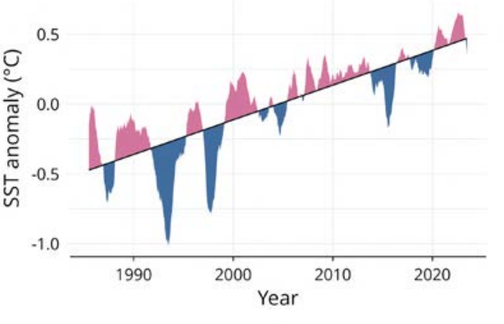
Introduction

Maritime area	1,602,781 km^2
Land area	28,095 km^2
Mean land elevation	239 m
Coral reef extent	6,743 km^2

Coral reefs of Solomon Islands cover approximately 6,743 km^2, which represent 10.33 % of the total coral reef extent of the GCRMN Pacific region, and 2.700 % of the world coral reef extent.

We estimated the human population of Solomon Islands living within 5 km from coral reefs to be 494,831 inhabitants, in 2020. This represents 73.59 % of the total human population of Solomon Islands living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 52.44 % between 2000 and 2020.



▲ **Figure 2.19.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Solomon Islands. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Threats

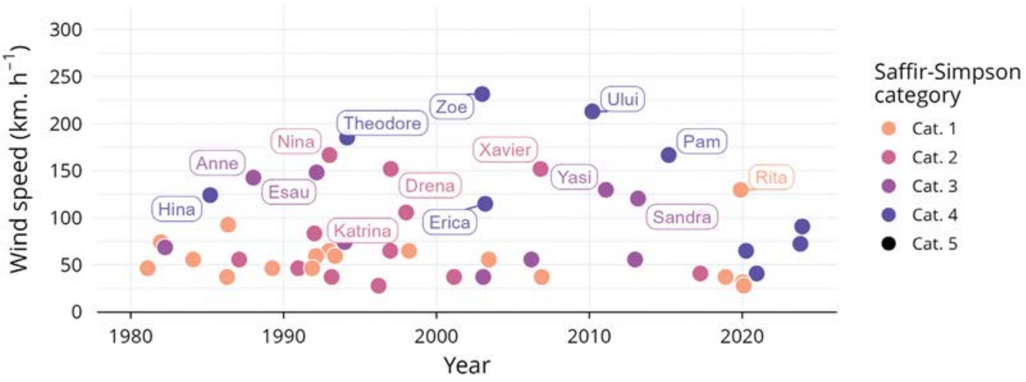
Thermal regime

The long-term average of SST on coral reefs of Solomon Islands between 1985 and 2023 was 29.20°C (Supplementary Figure 1). SST over coral reefs of Solomon Islands have increased by 0.92°C between 1985 and 2023, which corresponds to a warming rate of 0.024°C per year (Supplementary Figure 1).

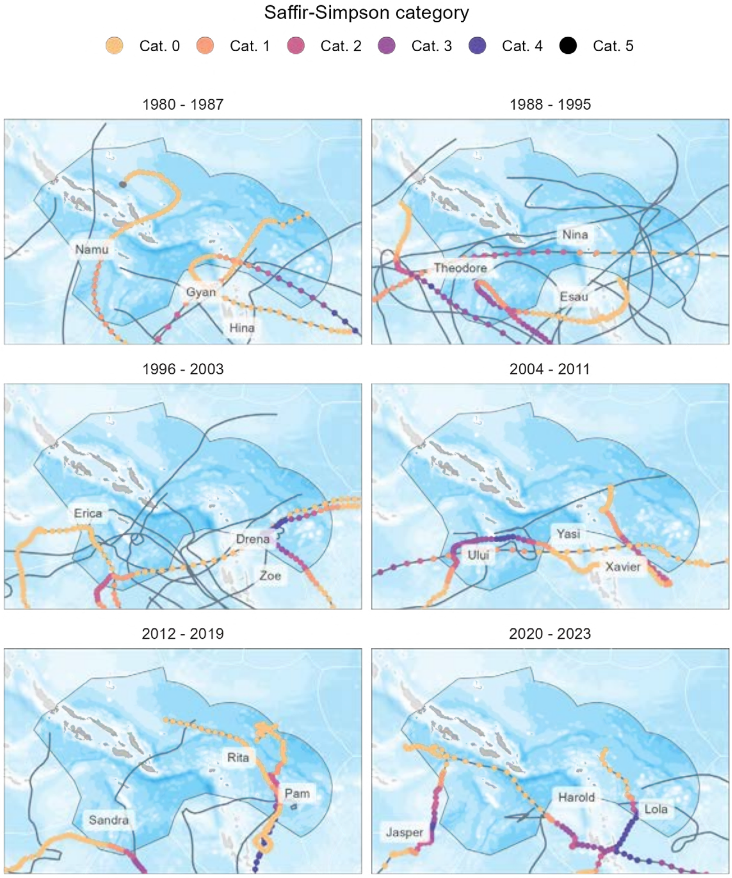
Cyclones

Between 1980 and 2023, a total of 111 tropical storms passed within 100 km distance from a coral reef of Solomon Islands, and of these 16 were characterized by sustained wind speed greater than 100 $km.h^{-1}$ (Figure 2.19.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Zoe, in 2002, which passed 0 km from a coral reef with sustained wind speed of 232 $km.h^{-1}$.

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.



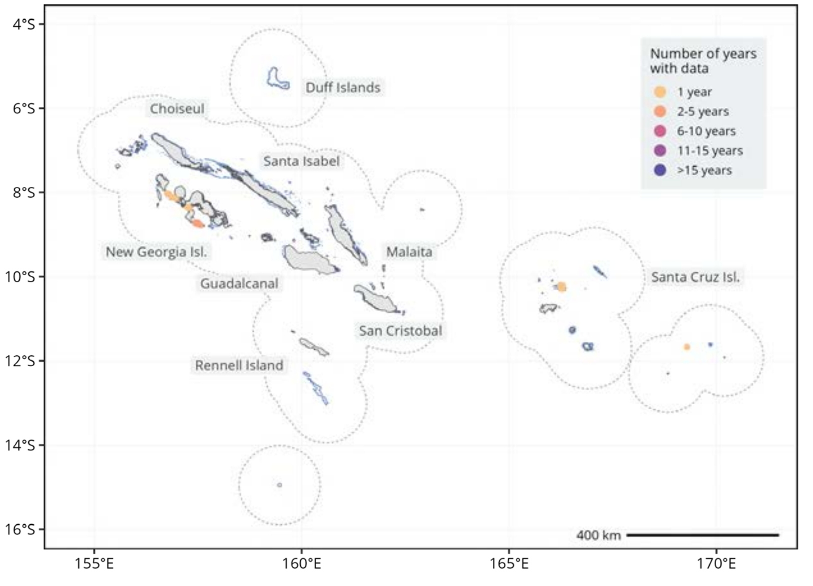
▲ **Figure 2.19.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Solomon Islands. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 $km.h^{-1}$). Note that cyclones passing more than 100 km away from coral reefs of Solomon Islands are not represented, although they may have had an impact.



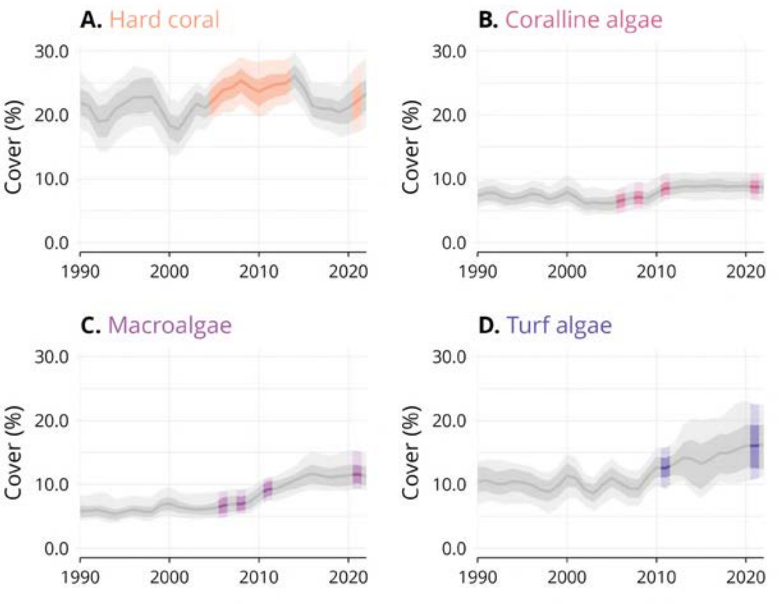
▲ **Figure 2.19.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Solomon Islands. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Solomon Islands was achieved through the integration of 4 datasets (Supplementary Table 1). These datasets represent a total of 78 monitoring sites, on which 176 surveys were conducted between 2005 and 2021.

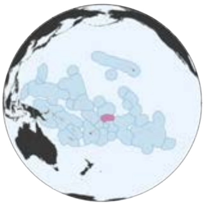


▲ **Figure 2.19.4.** Spatio-temporal distribution of benthic cover monitoring sites across Solomon Islands. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.19.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Solomon Islands. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

TOKELAU



Author

Jérémy Wicquart

Introduction

Maritime area	320,548 km^2
Land area	14 km^2
Mean land elevation	10 m
Coral reef extent	155 km^2

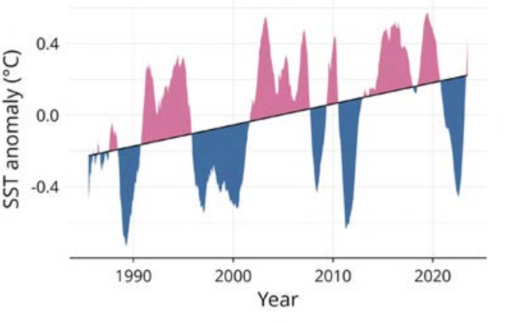
Coral reefs of Tokelau cover approximately 155 km^2, which represent 0.24 % of the total coral reef extent of the GCRMN Pacific region, and 0.062 % of the world coral reef extent.

We estimated the human population of Tokelau living within 5 km from coral reefs to be 1,317 inhabitants, in 2020. This represents 100.00 % of the total human population of Tokelau living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has decreased by 14.18 % between 2000 and 2020.

Threats

Thermal regime

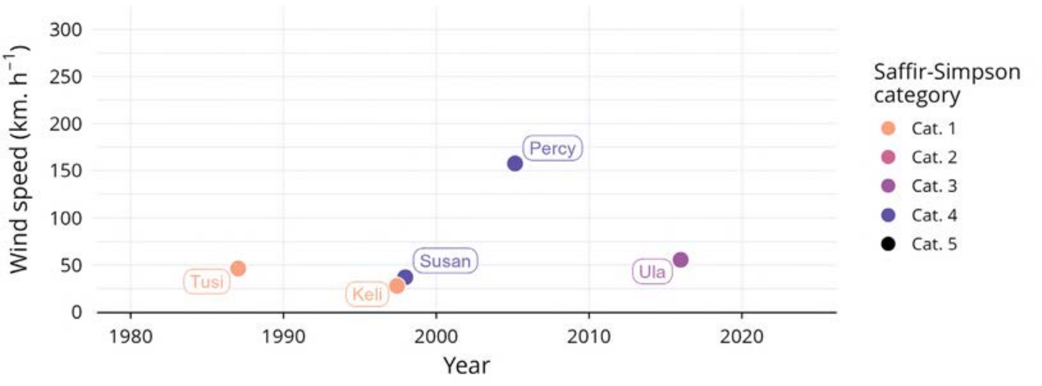
The long-term average of SST on coral reefs of Tokelau between 1985 and 2023 was 29.26°C (Supplementary Figure 1). SST over coral reefs of Tokelau have increased by 0.51°C between 1985 and 2023, which corresponds to a warming rate of 0.014°C per year (Supplementary Figure 1).



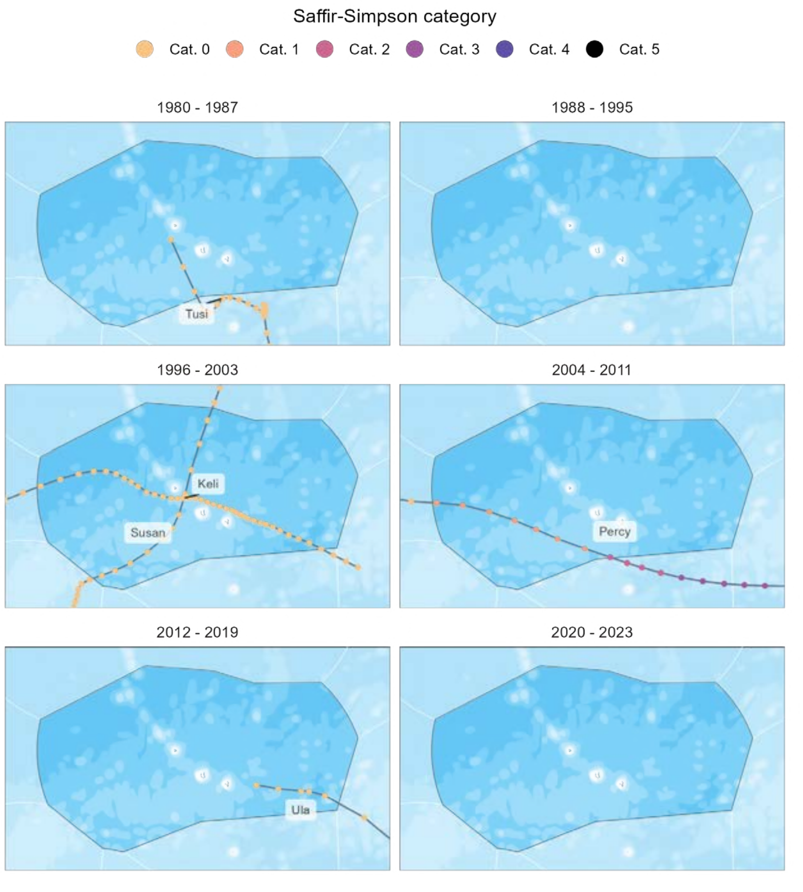
▲ **Figure 2.20.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Tokelau. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Cyclones

Between 1980 and 2023, a total of 5 tropical storms passed within 100 km distance from a coral reef of Tokelau, and of these 1 were characterized by sustained wind speed greater than 100 $km.h^{-1}$ (Figure 2.20.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Percy, in 2005, which passed 94 km from a coral reef with sustained wind speed of 157 $km.h^{-1}$.



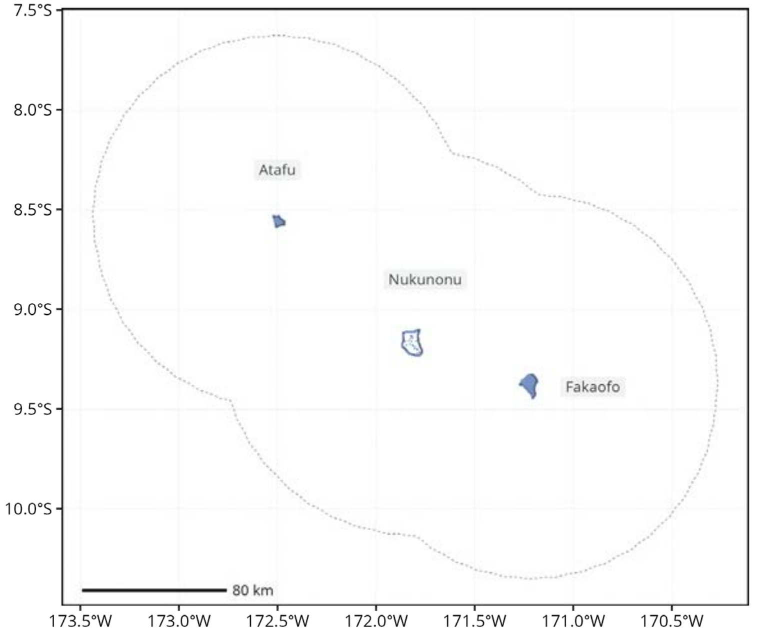
▲ **Figure 2.20.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Tokelau. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 $km.h^{-1}$). Note that cyclones passing more than 100 km away from coral reefs of Tokelau are not represented, although they may have had an impact.



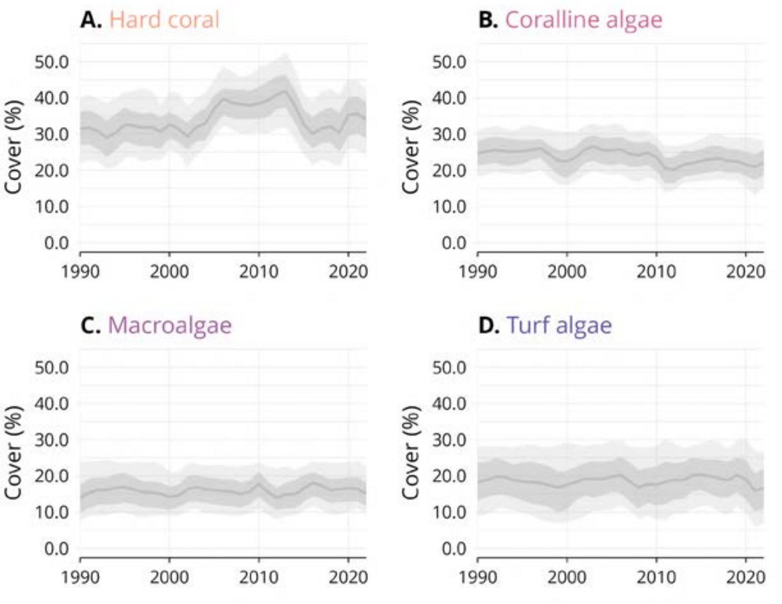
▲ **Figure 2.20.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Tokelau. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

We did not use any monitoring data acquired in Tokelau to model trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae, in that country. Temporal trends were estimated by the models using information provided by the predictors and data from other countries and territories (see Materials and Methods).

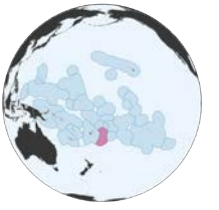


▲ **Figure 2.20.4.** Spatio-temporal distribution of benthic cover monitoring sites across Tokelau. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.20.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Tokelau. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

TONGA



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Introduction

Maritime area	666,052 km^2
Land area	745 km^2
Mean land elevation	61 m
Coral reef extent	1,662 km^2

The Kingdom of Tonga is an archipelago in the South Pacific consisting of 169 islands. Tonga's islands are situated in a geological hotspot, between the Tongan-Kermadec Arc, a volcanic chain of islands lying to the West and the Tongan Trench, the world's second deepest trench, to the East. Tonga is an oceanic nation, with an exclusive economic zone (EEZ) comprising nearly 700,000 km^2 of ocean, 1000 times larger than the country's land area (Tongan Ministry of Fisheries, 2022). Coral reefs of Tonga cover approximately 1,662 km^2, which represent 2.55 % of the total coral reef extent of the GCRMN Pacific region, and 0.665 % of the world coral reef extent.

Tonga is split into four main island groups running from North to South; the Niua Islands, Vava'u, Ha'apai and Tongatapu. The distribution of Tonga's human population is heavily skewed with over 75% of people residing in the capital island group Tongatapu, the remainder live in the elevated islands of Vava'u in the North and in the remote low lying islands of Ha'apai. While the Niua's are the most Northern group comprising three remote volcanic islands with the smallest population (Tonga Statistics Department, 2021). We estimated the human population of Tonga living within 5 km from coral reefs to be 103,479 inhabitants, in 2020. This represents 97.52 % of the total human population of Tonga living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 6.09 % between 2000 and 2020.

Threats

Thermal regime

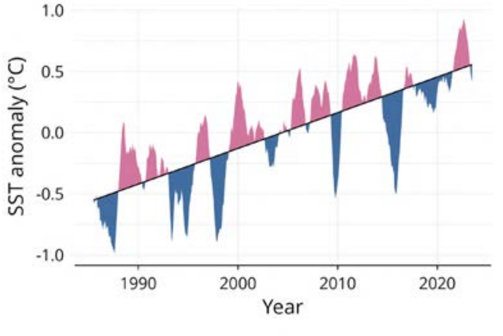
Due to the latitudinal gradient of Tonga's archipelago, there is a natural thermal decrease by 2oC in the southern islands compared to the north. This is reflected in coral cover across the islands. According to data collected between 2016 and 2018, coral coverage in Tongatapu - the southernmost island group - was 2.5 times greater than in Vava'u, the second northernmost group, with respective coverages of 24.9% and 10.4% (Smallhorn-West et al., 2020a).

The long-term average of SST on coral reefs of Tonga between 1985 and 2023 was 26.27°C (Supplementary Figure 1). SST over coral reefs of Tonga have increased by 1.05°C between 1985 and 2023, which corresponds to a warming rate of 0.028°C per year (Supplementary Figure 1).

There is a lack of understanding and data on the frequency and severity of mass bleaching events across the country, due to an absence of

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

dedicated bleaching surveys (Smallhorn-West et al., 2020a). Despite this, there has been anecdotal evidence of bleaching throughout the last few decades. Bleaching was reported in February 2000 in Tongatapu and Ha'apai, with observations of bleaching on the reef slope and lagoonal areas (Lovell and Palaki, 2003). Since then, further coral bleaching events have been observed by both scientists and the local community, in 2012, 2014 and 2016 (Purkis et al., 2017; Smallhorn-West et al., 2020a; Tonga Ministry of Fisheries, 2022; VEPA, 2022). The Rapid Assessment of the Biodiversity of Vava'u in 2014 showed bleaching occurring to depths of 30 meters (Atherton et al., 2014). Signs of recent bleaching in reefs in northern Ha'apai and Vava'u, were also observed between 2016-2018, with mortality of corals observed in reefs composed of dead but in-tact complex structures (Smallhorn-West et al., 2020a). Future dedicated surveys and research is necessary to understand the scale of bleaching impacts in Tonga's coral reefs.

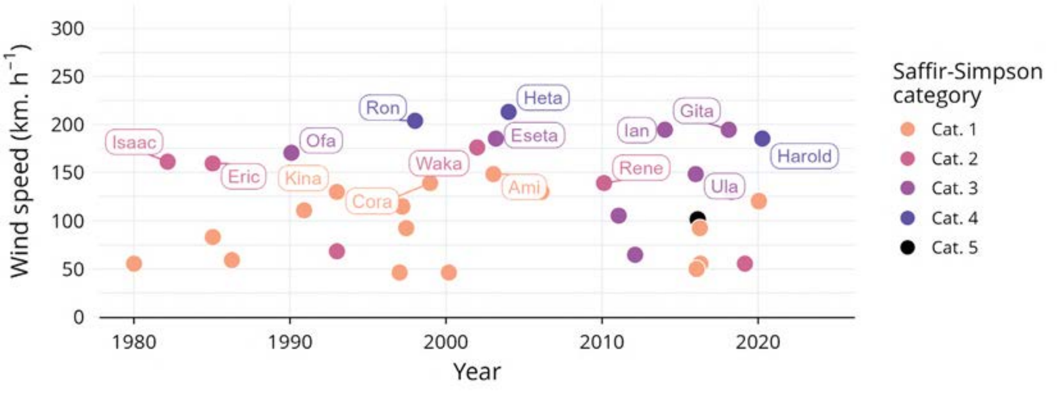


▲ **Figure 2.21.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Tonga. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Cyclones

Similar to neighbouring South Pacific nations, Tonga is increasingly vulnerable to the repeated impacts of tropical storms and cyclones. Between 1980 and 2023, a total of 77 tropical storms passed within 100 km distance from a coral reef of Tonga, and of these 23 were characterized by sustained wind speed greater than 100 km.h^{-1} (Figure 2.21.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Heta, in 2004, which passed 59 km from a coral reef with sustained wind speed of 213 km.h^{-1}.

Cyclone Waka (2001) a category 4 cyclone passed twice over Vava'u and the Niuas. Later, Ian (2014), Winston (2016), and Gita (2018) passed through Ha'apai and Tongatapu, causing storm surges across the region (Adjeroud et al., 2013; Purkis et al., 2017; Smallhorn-West et al., 2020a). Evidence of damage from multiple cyclones has been observed on the western edge of the north-eastern ribbon islands in Ha'apai (Ha'ano, Foa, Lifuka and Uoleva) (Smallhorn-West et al., 2020a). Although it is difficult to retrospectively determine the true extent of impact from these recurrent cyclonic events, it is expected that there was widespread damage across Tonga's coral reefs (Smallhorn-West et al., 2020a).



▲ **Figure 2.21.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Tonga. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h^{-1}). Note that cyclones passing more than 100 km away from coral reefs of Tonga are not represented, although they may have had an impact.

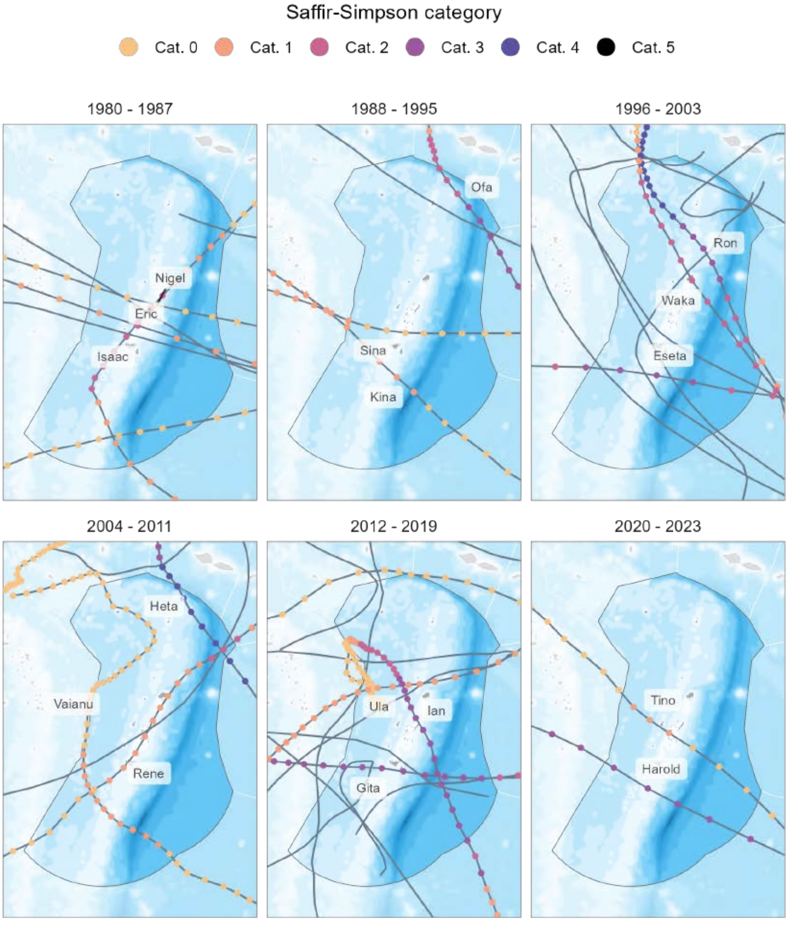
Other Threats

Historically, Tonga has experienced Crown of Thorns outbreaks; occurring in the 1970s, 1980s, and 1992 (Lovell and Palaki, 2003; Adjeroud et al., 2013). However, no official outbreaks have been monitored or recorded in the last decade, with only small numbers observed to have damaged reefs in Vava'u and Ha'apai, in 2011 (Purkis et al., 2017).

Over the past few decades, Tonga's island communities have been hit by numerous disturbances. Tonga is on the front line of climate change and natural disasters, ranking as the 3rd most vulnerable country to disaster risk and 52nd most vulnerable to climate change impacts (Clark et al., 2011). In 2009, the Northern island of Niuatoputapu (Niua group) was impacted by the Samoan earthquake tsunami. There was evidence of damage to the reefs even 6 years after the event (Purkis et al., 2017), with the reefs dominated by algal cover.

More recently Tonga was hit with the largest natural disturbance to have affected their coral reefs in modern history, the Hunga Tonga – Hunga Ha'apai volcanic eruption (January 2022). This eruption triggered a series of tsunamis which inundated and destroyed coastlines in Tonga, and across the Pacific (Purkis et al., 2023).

Initial surveys were conducted a few months after the event, in August 2022, which revealed varied damage between reefs; likely reflecting the relative strength of the tsunami wave at each island and reef (VEPA, 2022). Reefs that were directly exposed to the force of the tsunami were composed of more degraded benthic communities than those sheltered from the impact by the island. Reefs further away from the epicenter of the eruption in Vava'u were also found to be spared, with no observed impact from the tsunami. Whereas, reefs in Ha'apai, Tongatapu, and Eua were found to have coral cover decline since 2017 (VEPA, 2022). Since then, further surveys were conducted, in 2024, to assess reef status over 2.5yrs after the event. Although some signs of recovery were observed, overall, a loss of ~50% of coral cover is estimated across the country (data currently being analyzed). In some islands, reefs were turned to rubble, with large Porites boulders dislodged, while other reefs have incurred large increases in macroalgal beds in areas once void of macroalgae (Lucy Southworth, *pers. obs*).



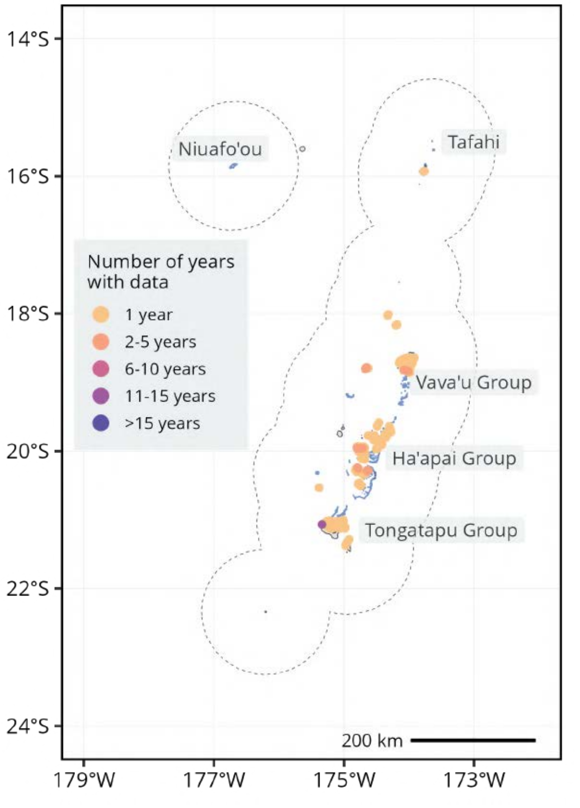
▲ **Figure 2.21.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Tonga. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

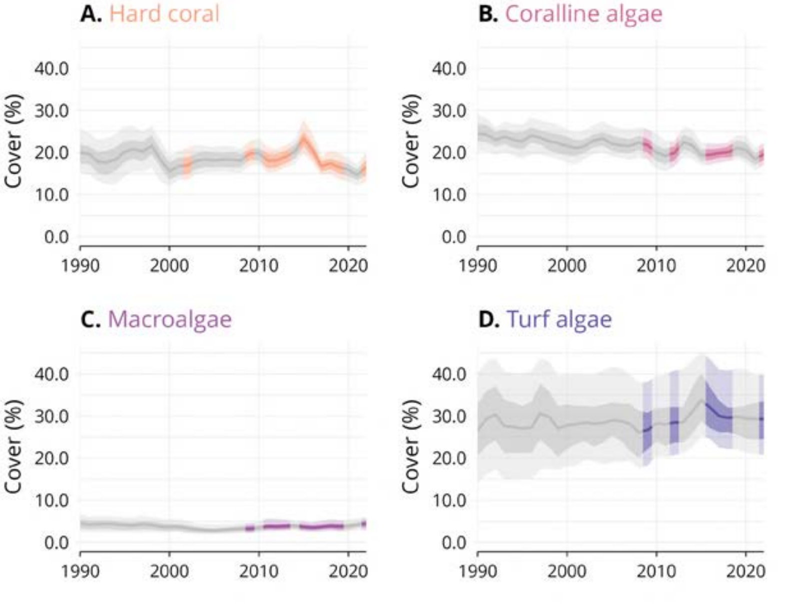
Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Tonga was achieved through the integration of 6 datasets (Supplementary Table 1). These datasets represent a total of 470 monitoring sites, on which 516 surveys were conducted between 2002 and 2022.

Following the impacts from the Hunga Tonga – Hunga Ha'apai eruption in 2022, Tonga's reef communities have incurred huge shifts in coral cover and reef structural complexity. Although some recovery is expected, the current functioning and health of Tonga's reefs has dramatically changed. These shifts will be evident in the following GCRMN report, and management measures will need to be adapted to encourage recovery on Tonga's reef systems.

▸ **Figure 2.21.4.** Spatio-temporal distribution of benthic cover monitoring sites across Tonga. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.





▴ **Figure 2.21.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Tonga. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

CASE STUDY

Ecological impacts of the 2022 Hunga Tonga - Hunga Ha'apai volcanic eruption on Tonga's coral reefs

Authors

Lucy Southworth, Viliami Fatongiatau, Tonga Latu Tuiano, Tevita Havea, Martin Finau, Patrick Smallhorn-West

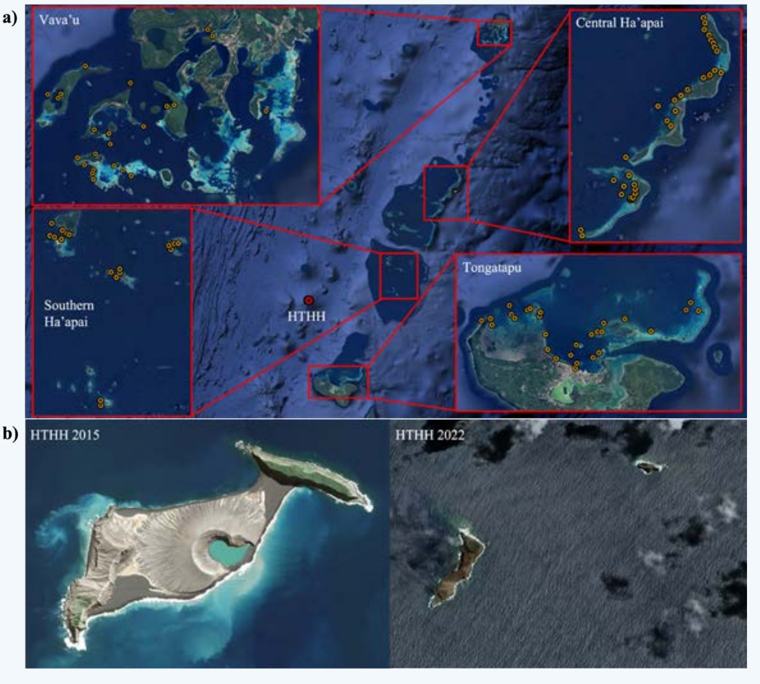
The Kingdom of Tonga is an archipelago situated in the South Pacific comprised of 169 islands, of which 36 are inhabited with 105,000 people (The World Bank 2022). These islands reside at the northern end of the Tonga-Kermadec Arc, sitting on the precipice of the Earth's fastest-converging and most seismically active subjunction zone (Smith and Price 2006; Timm et al. 2013). Home to the highest density of submarine volcanoes (Timm et al. 2013), 35NM (Nautic Miles) west of the inhabited islands lies an arc of >20 volcanic islands (Global Volcanism Program).

On January 15th 2022 the Hunga Tonga - Hunga Ha'apai (HTHH) submarine volcano erupted, likely causing the most powerful natural explosion in over a century (Purkis et al. 2023). The eruption generated atmospheric waves that circled the globe multiple times (Yuen et al. 2022), and an oceanic tsunami that was felt across the Pacific (Proud, Prata, and Schmauß 2022). The capital island Tongatapu suffered tsunami waves up to 17m, while Tofua a neighbouring volcanic island absorbed 45m waves (Purkis et al. 2023). Two thirds of the volcanic material displaced by the eruption was expelled in a volcanic plume to an unprecedented altitude of 55-58 km, reaching Earth's mesosphere (Carr et al. 2022; Proud, Prata, and Schmauß 2022; Taha et al. 2022). This plume expanded into an umbrella cloud almost 600 km diameter, subsequently smothering Tonga's main island groups (Tongatapu, 'Eua, Ha'apai and Vava'u) (Fig. 1a) in a layer of ash up to 50mm thick (The World Bank 2022; Jarvis et al. 2023). The final third of volcanic matter ran down the flanks of the volcano in fast moving pyroclastic flows (hot ash, rock and gas), displacing almost 10 km3 of benthic material, reshaping the seafloor and clearing all life in its path (Amos 2022; Seabrook et al. 2023).

Widespread damage has been inflicted across land and sea both locally in the Tongan archipelago and beyond, with four fatalities in Tonga and two in Peru (Borrero et al. 2023; NCEI 2024). Islands with closest proximity to the volcano in the south incurred the most damage, as the tsunami dissipated with distance, leaving the northern Vava'u group largely unaffected with only a light layer of ash. Whereas further south in Tongatapu and Atata island the inundation of tsunami waves destroyed coastlines, flattening homes and resorts (Borrero et al. 2023). Low-lying islands in Ha'apai including Nomuka Iki, Nomuka, Mango and Fonoifua incurred near total destruction with waves surging over them, causing extreme erosion, stripping away forests, vegetation and buildings, and resulting in the relocation of several island communities (The World Bank 2022; Borrero et al. 2023). Natural resources were also impacted by tsunami inundation and ashfall contaminating agricultural crops. Tsunami impact also destroyed fisheries vessels, engines and infrastructure (HAG, CSFT, and MORDI 2022; The World Bank 2022). However, while damage from the tsunami and ashfall are clearly extensive on land, very little is known about ecological impacts in the ocean, coral reefs and coastal fisheries.

The HTHH eruption provides a unique natural experiment: to understand how huge natural disturbances affect coral reefs and their fisheries. Coral reefs are naturally disturbed systems that have evolved in volcanically active regions, as Darwin theorised coral atolls form on the rim of submerged volcanoes (Darwin, 1842). While there is emphasis globally to focus on the impacts coral reefs endure from increasing climate change and local human stressors, there is also the need to understand how these dynamic systems respond to natural disturbances, in tandem with human pressures.

Through a collaboration between the Tongan Ministry of Fisheries and James Cook University, extensive ecological surveys were conducted across the Tongan archipelago at the same sites prior to and post the 2022 eruption. Sampling was conducted over 107 sites across a range of distances from the volcano in 3 island groups; Vava'u, Ha'apai, Tongatapu, as well as on the flanks of the volcano itself (Fig. 1 and Fig. 2). Each site consisted of 4 x 30m transects spanning depths of 2-9m. Methods used were UVC for reef fish and invertebrate species, photo-quadrats for benthic assemblage, and 3D photogrammetry for reef structural complexity. Additionally, coral cores of Porites colonies were also collected to capture evidence of physiological stress during and after the eruption and tsunami.



▲ **Figure 1.** a) Satellite map of all inhabited island groups and sites surveyed across Tonga in 2024. b) Satellite image illustrating the impact of the Hunga Tonga - Hunga Ha'apai (HTHH) 2022 eruption and 2024 survey sites.

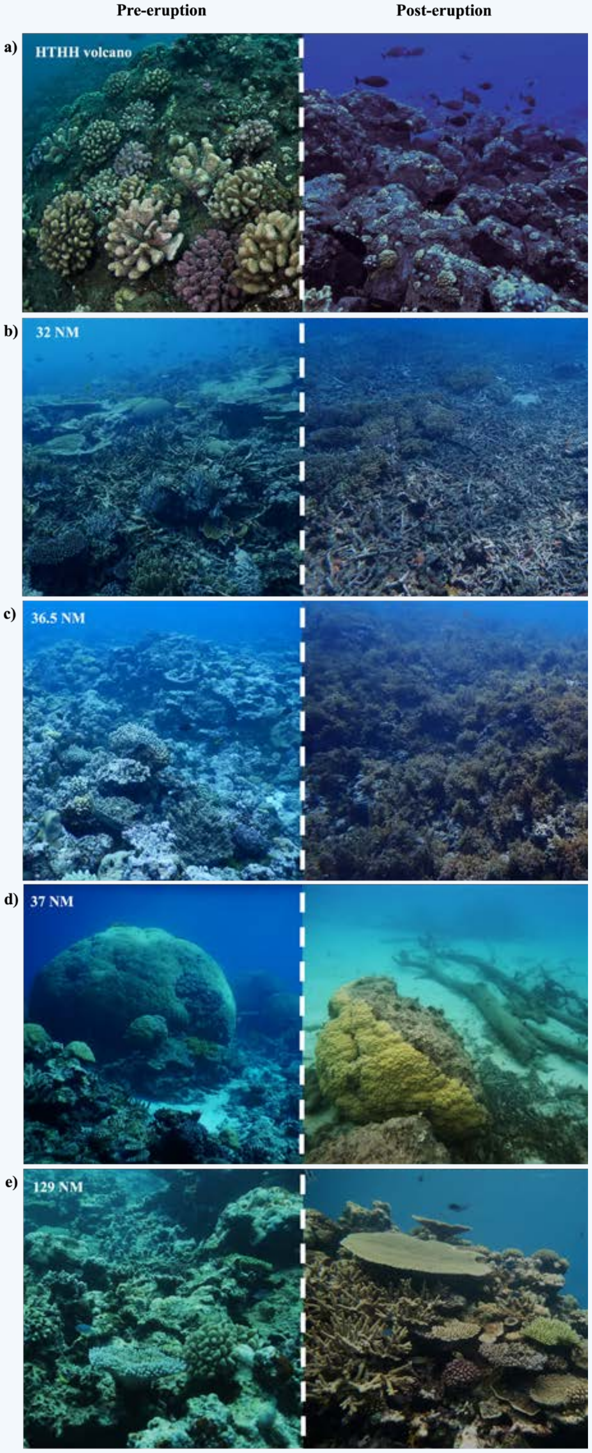
Although analyses are not yet complete, initial observations indicate damage on the reef is extensive, and mostly linear with distance from the volcano epicentre. Most damage has been observed in the southern half of the country, while the reefs further away in the northern island group Vava'u appear unaffected (Ovaka: Fig 2e.). Reefs surveyed in Southern Ha'apai and Tongatapu, in direct exposure to the volcano, have likely experienced ~80-100% loss of coral cover. Evidence of extensive damage includes large scale rubble fields replacing Acropora beds (Atata: Fig 2b.); extensive blooms of macroalgae that have not been observed in Tonga before (Kelefesia: Fig 2c.), and enormous Porites boulders (5-10m in diameter) dislodged and rolled across the reef (Nomuka: Fig 2d.).

This holistic approach also prevented management actions that may have harmed human health. Original scientific advice suggested that implementing harvest restrictions on herbivorous fish in the lagoon would reduce algae cover and facilitate natural recovery of corals. However, social survey data indicated that 53% of Merizo residents fish or gather marine resources, which is significantly higher than the overall Guam average of 29% ($p<0.01$) (Gorstein et al., 2018). Fishing is important in this village and residents fish for a range of reasons, including feeding their family (49%), for cultural purposes (including customary distribution to extended family or elders (52%) and events (56%)), and to sell (34%) (Figure 2). This information was confirmed by key informant interviews. Community members also noted that past military contamination had them worried about contamination. Fish sampling for contaminants indicated that predatory fish had higher levels of PCBs and other toxins and should be avoided to protect human health and that herbivorous fish were a safer target for consumption. Once these pieces were connected and discussed with the community, it was clear that an herbivore ban would expose the village to a higher risk of contaminants and should not be implemented. The project's integrated approach prevented serious impacts to human health and wellbeing that could have occurred without social data and community engagement.

This eruption was not an isolated incident, and in December 2014 a prior eruption caused the two islands to merge, creating one of the Earth's newest volcanic islands (Fig. 1b). (Purkis et al. 2023). Surveys conducted prior to the 2022 eruption found that the HTHH group hosted some of the healthiest reefs in the country (Fig 2a.) (Smallhorn-West et al. 2020). In 2022 the new volcanic island was blown apart and split back into two smaller islands (Fig. 1b). With over two years since the 2022 eruption, despite near complete destruction of the previous reefs, promisingly high levels of coral recruitment were observed colonising the bare volcanic substrate, albeit dominated by few genera (Pocillopora and Acropora) (Fig. 2a). Large schools of Acanthuridae and Labridae fish species are also inhabiting the newly formed reefs – species with no adult pelagic phase and whom therefore must have recruited since the eruption.

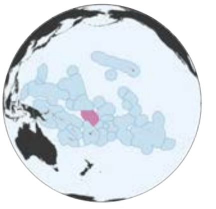
While analyses are ongoing some early conclusions can be raised. First, this unprecedented eruption highlights the need for consistent monitoring of Tonga's coral reefs and fisheries. Without this information it is impossible to grasp the full extent of the ecological impact on the ecosystem and economic status of the reef fisheries. Therefore, we call for the development of a consistent national coral reef monitoring program. Second, the observed extensive damage of the reef in Tonga's low lying islands appears to be set apart from previous events such as the Aceh, Indonesian tsunami (2004) where damage was much less extensive, with no change in shallow reef communities, except in corals growing in unconsolidated substrate (Baird et al. 2005). Thirdly, the recovery and growth of corals appears to be fastest in remote reefs at the volcano, implying chronic human stressors may be inhibiting the reef recovery potential in the inhabited island reefs.

Understanding how these reefs may change following huge disturbances opens a window into how future reefs may function and contribute natural resources to island nations.



▲ **Figure 2.** Images of some of the reefs sites surveyed with comparison images from before the eruption in 2018 (left) and post eruption in 2024 (right) and the distances they are situated from the volcano in nautical miles (NM). Reefs and associated impact are a) the flanks of the Hunga Tonga – Hunga Ha'apai volcano with new coral recruits; b) Atata - rubble fields; c) Kelefesia - macroalgal beds; d)Nomuka – upturned coral boulder; e) Ovaka – Vava'u with no visible damage.

TUVALU



Author

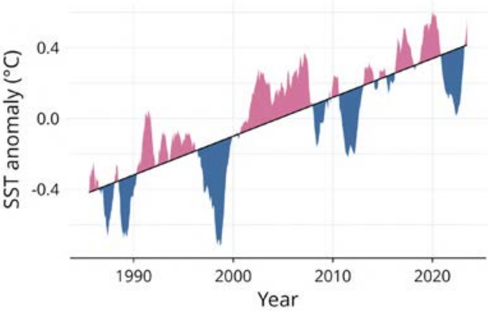
Jérémy Wicquart

Introduction

Maritime area	753,133 km²
Land area	39 km²
Mean land elevation	9 m
Coral reef extent	1,231 km²

Coral reefs of Tuvalu cover approximately 1,231 km², which represent 1.89% of the total coral reef extent of the GCRMN Pacific region, and 0.493% of the world coral reef extent.

We estimated the human population of Tuvalu living within 5 km from coral reefs to be 12,235 inhabitants, in 2020. This represents 100.00% of the total human population of Tuvalu living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 30.39% between 2000 and 2020.



▲ **Figure 2.22.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Tuvalu. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

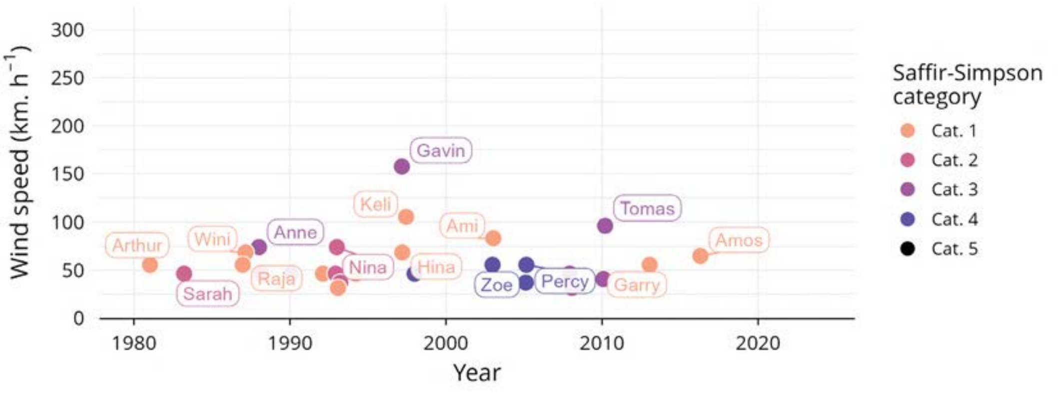
Threats

Thermal regime

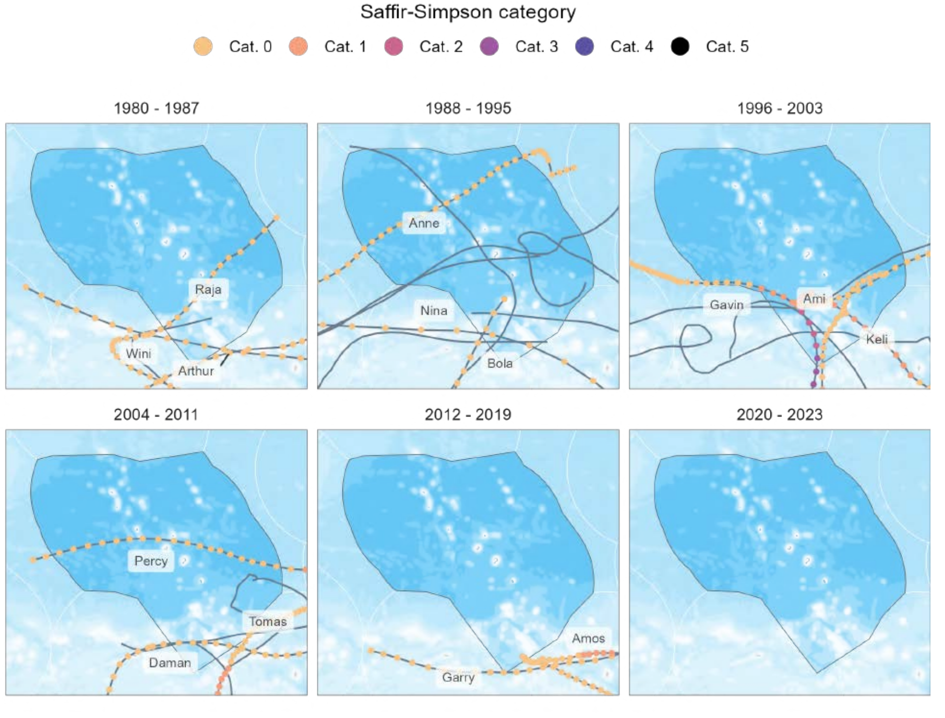
The long-term average of SST on coral reefs of Tuvalu between 1985 and 2023 was 29.11°C (Supplementary Figure 1). SST over coral reefs of Tuvalu have increased by 0.88°C between 1985 and 2023, which corresponds to a warming rate of 0.023°C per year (Supplementary Figure 1).

Cyclones

Between 1980 and 2023, a total of 43 tropical storms passed within 100 km distance from a coral reef of Tuvalu, and of these 3 were characterized by sustained wind speed greater than 100 $km.h^{-1}$ (Figure 2.22.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Gavin, in 1997, which passed 60 km from a coral reef with sustained wind speed of 157 $km.h^{-1}$.



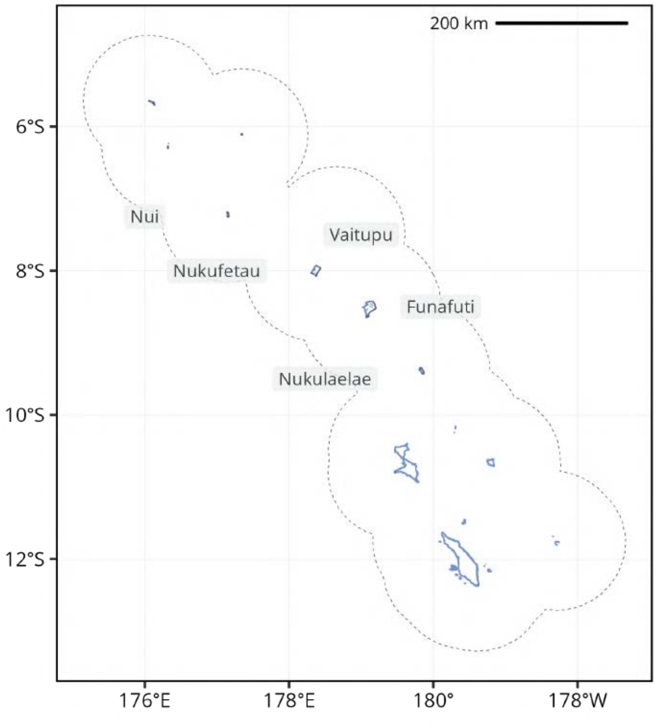
▲ **Figure 2.22.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Tuvalu. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h^{-1}). Note that cyclones passing more than 100 km away from coral reefs of Tuvalu are not represented, although they may have had an impact.



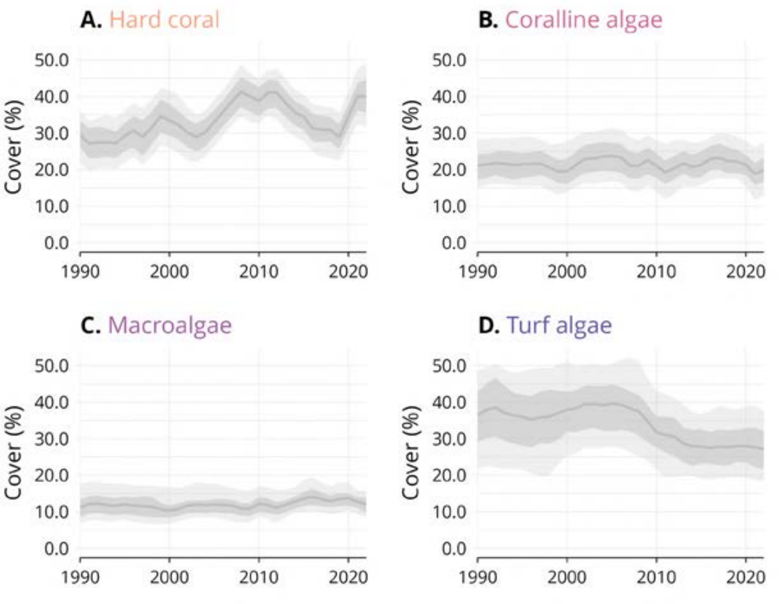
▲ **Figure 2.22.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Tuvalu. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Temporal trends in benthic cover

We did not use any monitoring data acquired in Tuvalu to model trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae, in that country. Temporal trends were estimated by the models using information provided by the predictors and data from other countries and territories (see Materials and Methods).

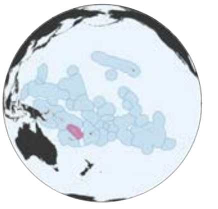


▲ **Figure 2.22.4.** Spatio-temporal distribution of benthic cover monitoring sites across Tuvalu. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.



▲ **Figure 2.22.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Tuvalu. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

VANUATU



Co-authors[1]

Johanna Johnson, Eryn Hooper, Bradley Moore,
Jane Waterhouse, David Welch, Jan Freiwald, Jenny Mihaly

Introduction

Maritime area	625,850 km²
Land area	12,307 km²
Mean land elevation	284 m
Coral reef extent	1,803 km²

The Republic of Vanuatu is an island country consisting of 83 islands (about 65 islands are inhabited) in the Southwest Pacific Convergence zone of the Pacific Ocean in the Melanesian sub-region bordered by Solomon Islands, Fiji and New Caledonia. Vanuatu has extensive marine ecosystems, including pelagic open ocean, seagrass meadows, underwater plateaus with diverse canyons and seamounts, and a variety of coral reef types that support high species biodiversity (Johnson et al., 2018; Johnson and Wabnitz, 2025). Coral reefs of Vanuatu cover approximately 1,803 km², which represent 2.76% of the total coral reef extent of the GCRMN Pacific region, and 0.722% of the world coral reef extent.

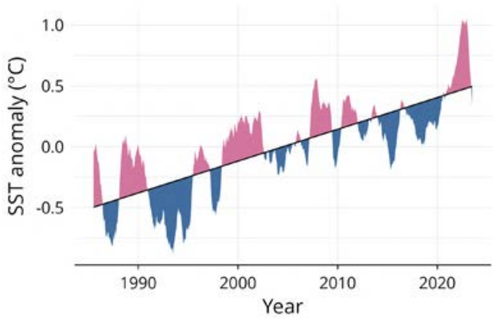
We estimated the human population of Vanuatu living within 5 km from coral reefs to be 260,982 inhabitants, in 2020. This represents 87.15% of the total human population of Vanuatu living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has increased by 59.85% between 2000 and 2020. The population was estimated at 324,085 people in 2024 this population growth is expected to continue, with 530,064 people projected to live on the coast by 2050 (Pacific Data Hub, 2025). As the majority of the population live close to the sea, combined with the small land area and isolated location, there is very high dependence on marine resources to support and many rely on the sea for food and nutrition security, livelihoods, cultural practices and economic revenue (Johnson and Wabnitz, 2025).

Threats

Thermal regime

The long-term average of SST on coral reefs of Vanuatu between 1985 and 2023 was 27.63°C (Supplementary Figure 1). SST over coral reefs of Vanuatu have increased by 0.92°C between 1985 and 2023, which corresponds to a warming rate of 0.024°C per year (Supplementary Figure 1). Observed coral bleaching on fringing reefs around Efate Island in Vanuatu during the 2015-2016 El Nino event recorded high percentages of bleached hard corals, but subsequent recovery of over 90% of colonies (Johnson et al., unpublished data). This pattern of thermal bleaching and recovery has been anecdotally reported from reefs across Vanuatu, and during different marine heatwave years.

[1] The term co-authors encompasses both individuals who contributed to writing the chapter and those who provided data. Therefore, inclusion in this list does not necessarily imply endorsement of the chapter's content. Specific contributions are detailed in the Author Contributions section.

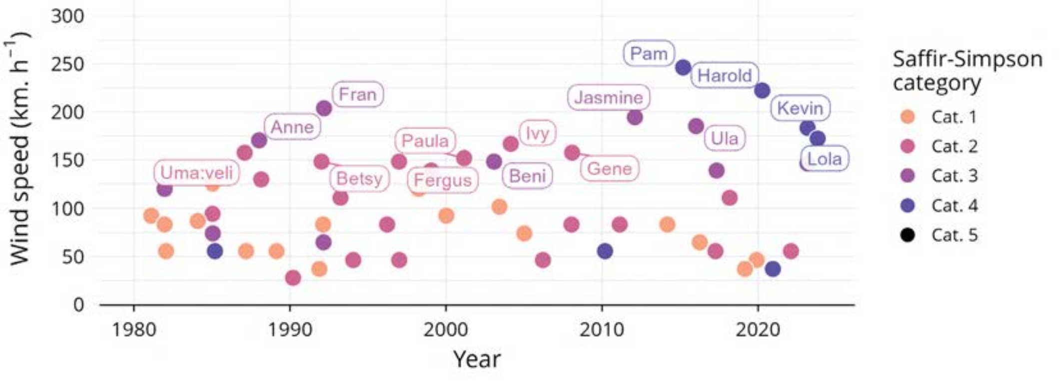


▲ **Figure 2.23.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Vanuatu. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

Cyclones

Between 1980 and 2023, a total of 94 tropical storms passed within 100 km distance from a coral reef of Vanuatu, and of these 29 were characterized by sustained wind speed greater than 100 km.h^{-1} (Figure 2.23.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Pam, in 2015, which passed 5 km from a coral reef with sustained wind speed of 246 km.h^{-1}.

Benthic and finfish surveys in North Efate marine ecosystems after the cyclone Pam documented damage in 2015 and recovery trends until 2023. Cyclone impacts were spatially variable, with reefs exposed to damaging wind and waves experiencing high coral damage while other sites had minimal physical damage. Over time, some reef sites showed limited recovery and remained extremely depauperate, with low hard coral diversity, high macroalgae cover, few high trophic level fish species, and herbivores predominantly represented by a limited number of species (Johnson et al., unpublished data). Recovery at some of these sites remained low in the 2023 surveys, and it is likely that the current fish assemblages will be incapable of either preventing or reversing regime shifts, from coral to algal dominated, that are the result of coral predation and cyclone damage.



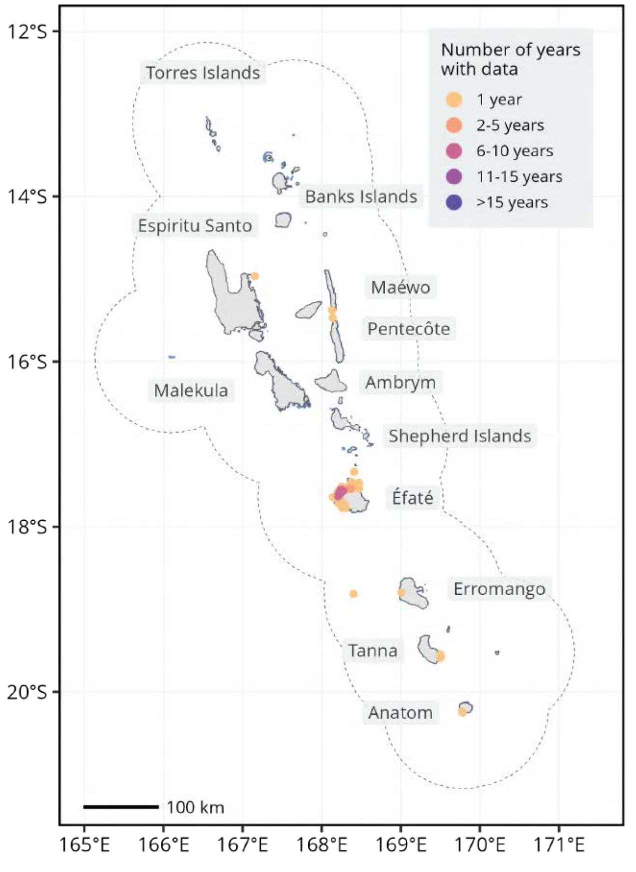
▲ **Figure 2.23.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Vanuatu. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h^{-1}). Note that cyclones passing more than 100 km away from coral reefs of Vanuatu are not represented, although they may have had an impact.

▲ **Figure 2.23.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Vanuatu. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

Other Threats

In Vanuatu, documented reports of COTS observations were as early as 1989-1990 (Done and Navin, 1990), with outbreak densities (commonly recognised as >15 COTS per hectare; Pratchett et al., 2014) reported in 2004 (Espiritu Santo), 2006–2009 (Efate and surrounding islands of Moso, Emao, Nguna and Pele) with peak densities recorded in 2008 (e.g. 4,000/ha on Emao Island), and in 2012–2014 (Efate and surrounding islands of Moso, Emao, Nguna and Pele). COTS outbreaks have also been observed on other islands across the Vanuatu archipelago, including Espiritu Santo, Aore, Malekula and Aniwa (Dumas et al., 2015; Dumas et al., 2020). Patterns of coral cover in north Efate indicates previous COTS impacts from the 2006–2009 and 2012–2014 outbreaks, with highly impacted reefs continuing to have low coral cover (5-12%) and slow recovery (e.g. near Emua and Siviri; Johnson et al., 2016, Johnson et al., unpublished data). Reefs not impacted by COTS have consistently high coral cover (e.g. Lelepa Island with 30-70%; Johnson et al., 2018), which is above the Pacific regional average of 25.5%. Around Efate Island, there has been a 'migrating' COTS outbreak that appears to have started in Vila Harbour in 2017 and moved northeast to Havannah Harbour in North Efate in 2018 and 2019. Since 2020, active locating and culling of COTS (local name *posen sta)* at tourism sites around Efate and surrounding islands of Moso, Lelepa, Emao, Nguna and Pele has expended many dive hours with some signs that the outbreak is dissipating. However, there is no strategic and coordinated approach to COTS control and surveillance, so current status is difficult to report (Johnson et al., 2020).

On 17 December 2024, Vanuatu experienced a 7.3 magnitude earthquake near the capital of Port Vila, 34 km off the coast of Efate Island. Observations in the month after the earthquake recorded significant damage to coral reefs in some locations around the island, including in Vila Harbour, Mele Bay and Havannah Harbour. Earthquake impacts included physical damage to branching hard corals (*Acropora* and *Pocillopora*) and cracking or rolling or large Porites and Favid corals. Benthic surveys conducted three months after the earthquake documented significant coral rubble and recently damaged hard corals at some sites (Johnson, unpublished data).

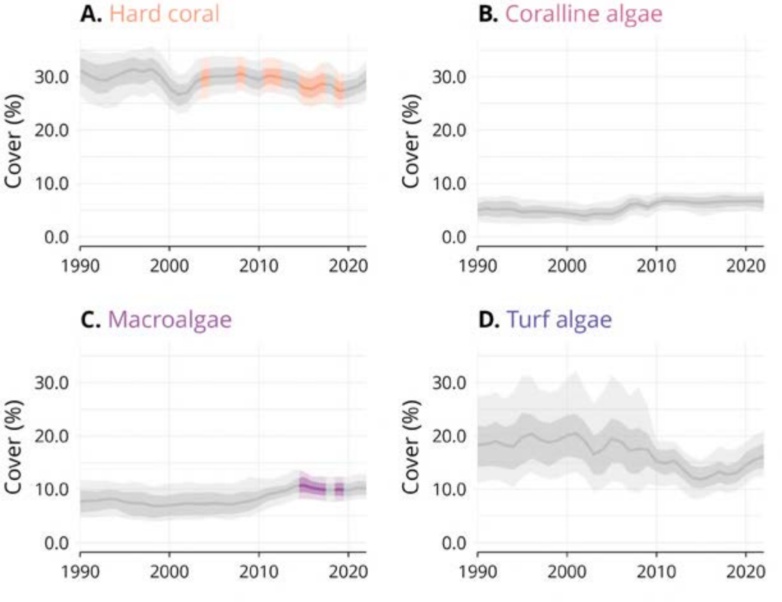


▲ **Figure 2.22.4.** Spatio-temporal distribution of benthic cover monitoring sites across Vanuatu. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.

Temporal trends in benthic cover

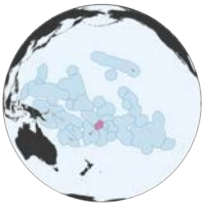
The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Vanuatu was achieved through the integration of 3 datasets (Supplementary Table 1). These datasets represent a total of 75 monitoring sites, on which 114 surveys were conducted between 2004 and 2023.

Hard coral cover has remained relatively stable since 1990 at around 30%, which is consistent with the regional average, and shows some declines around periods of impact, such as tropical cyclones and COTS outbreaks. Macroalgae cover remains stable at below 10%, as does coralline algae cover at 5-8%. Turf algae cover shows the greatest change, with a decline from about 20% in 2010 to about 12% in 2015 and has since steadily increased to almost 20% again. Data are spatially variable across sites and islands.



▲ **Figure 2.23.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Vanuatu. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4.

WALLIS AND FUTUNA



Co-authors[1]

Sandrine Job, Enelio Liufau, Sosefo Malau, Visesio Uluika, Paino Vanai, Didier Labrousse, Florian Le Bail, Ateliana Maugateau

Introduction

Maritime area	250,614 km²
Land area	152 km²
Mean land elevation	87 m
Coral reef extent	626 km²

The territory of Wallis and Futuna, located in the South Pacific, lies within the "Polynesian Triangle." It consists of three islands: the main island of Wallis (Uvea), which hosts the administrative capital Mata Utu, and the Horn Islands (Futuna and Alofi), situated 230 km away. Submerged oceanic banks and atolls of varying size are scattered throughout the EEZ. While Wallis is a low island, Futuna and Alofi are more elevated, with rugged terrain and deeply indented coastlines. Wallis is the only island in the territory with a lagoon, protected by a barrier reef interrupted by four narrow passes. A fringing reef extends along the coastline and connects with the barrier reef in some areas, particularly in the northeast and west, through shallow reef terraces. Numerous coral patch reefs are found within the lagoon, especially in its southern part. Nineteen coral islets are distributed across the lagoon and barrier reef, covering a total of 2 km² of emerged land. Futuna and Alofi are surrounded by narrow fringing reef flats ("platform reefs") that drop off sharply along an outer slope. On Alofi, the fringing reef is discontinuous. Along the northwestern coast of Alofi, facing Futuna, a shallow lagoon-like area has formed. It consists of a broad terrace with sandy bottoms interspersed with coral outcrops (Job and Le Bail, 2021). Coral reefs of Wallis and Futuna cover approximately 626 km², which represent 0.96 % of the total coral reef extent of the GCRMN Pacific region, and 0.251 % of the world coral reef extent.

We estimated the human population of Wallis and Futuna living within 5 km from coral reefs to be 10,494 inhabitants, in 2020. This represents 100.00 % of the total human population of Wallis and Futuna living within 5 km from coral reefs. We estimated that the human population living within 5 km from coral reefs has decreased by 34.14 % between 2000 and 2020.

Threats

Thermal regime

The long-term average of SST on coral reefs of Wallis and Futuna between 1985 and 2023 was 28.82°C (Supplementary Figure 1). SST over coral reefs of Wallis and Futuna have increased by 0.92°C between 1985 and 2023, which corresponds to a warming rate of 0.024°C per year (Supplementary Figure 1).

No monitoring conducted between 1999 and 2019 detected any coral bleaching on the reefs of the three islands of the archipelago (Chancerelle, 2010; Bosserelle et al., 2015; Job, 2023). However, continued FEO monitoring in 2024 revealed a significant loss of coral cover within the Wallis lagoon, linked to a prolonged marine heatwave in early 2024 (Job, *in prep.*).

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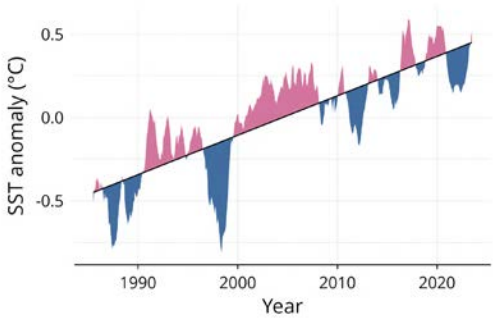
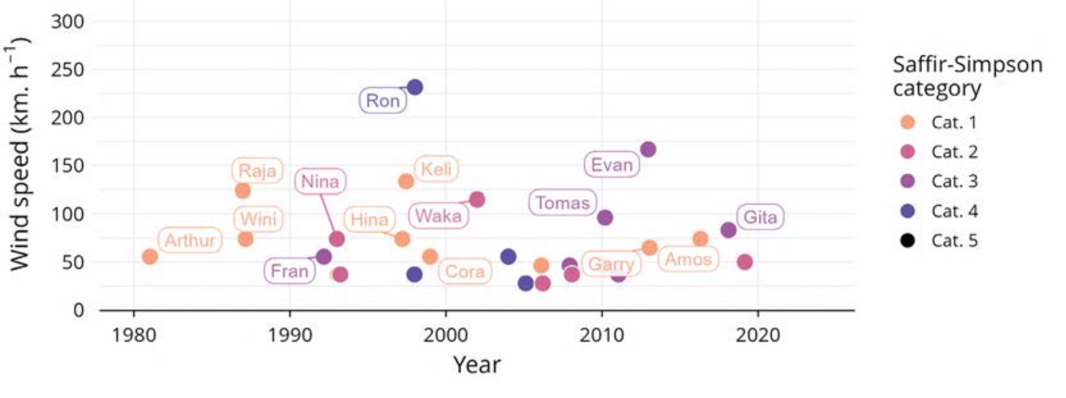


▲ **Figure 2.24.1.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of Wallis and Futuna. The black line is the long-term trend in SST anomaly, values below this line are negative SST anomalies (*i.e.* cooler than long-term trend), and values above this line are positive SST anomalies (*i.e.* warmer than long-term trend). Average Sea Surface Temperature (SST) anomaly with null-SST anomaly (*i.e.* 0) as a reference line, instead of the long-term trend in SST anomaly, are provided in Supplementary Figure 3.

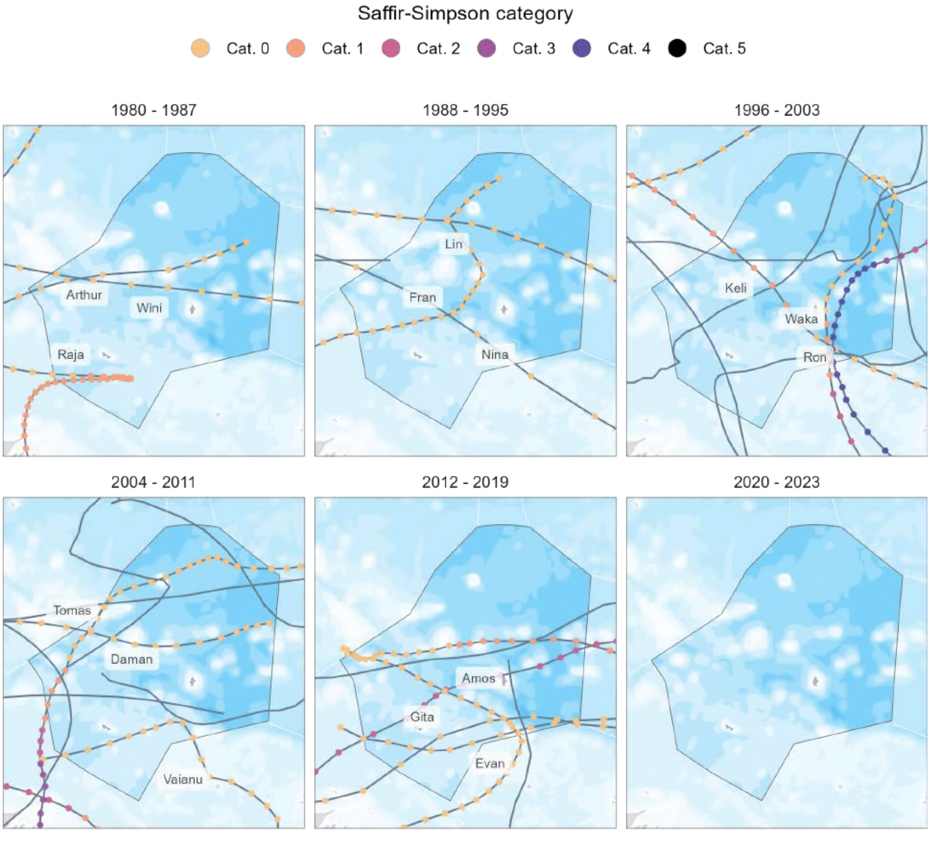
Cyclones

Between 1980 and 2023, a total of 52 tropical storms passed within 100 km distance from a coral reef of Wallis and Futuna, and of these 6 were characterized by sustained wind speed greater than 100 km.h^{-1} (Figure 2.24.2). The cyclone with the highest sustained wind speed over the studied period was the cyclone Ron, in 1998, which passed 8 km from a coral reef with sustained wind speed of 232 km.h^{-1}.

Studies have documented the significant impact of cyclone Tomas in 2010 on the eastern coast of Futuna Island (Chancerelle, 2010) and of cyclone Evan in 2013 on the eastern coast of Wallis Island (Bosserelle et al., 2015). Hard coral cover on these two outer slope reefs declined by approximately 10% following these extreme weather events.



▲ **Figure 2.24.2.** Maximum sustained wind speed of tropical storms passing within 100 km of a coral reef between 1980 and 2023 in Wallis and Futuna. Colors correspond to the cyclone's Saffir-Simpson category along its entire track. However, the values of sustained wind speed are extracted from the nearest tropical storm position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir-Simpson scale (*i.e.* 119 km.h-1). Note that cyclones passing more than 100 km away from coral reefs of Wallis and Futuna are not represented, although they may have had an impact.



▲ **Figure 2.24.3.** Trajectories of cyclones passing within 100 km of a coral reef between 1980 and 2023 in Wallis and Futuna. Points correspond to cyclone positions every 3 hours and are colored depending on the Saffir Simpson scale of the sustained wind speed. Grey points correspond to cyclone positions on which wind speed was not available. For readability, only the three most powerful cyclones are labeled and colored per time range (*i.e.* subplot). The trajectories of other cyclones are represented by gray lines only.

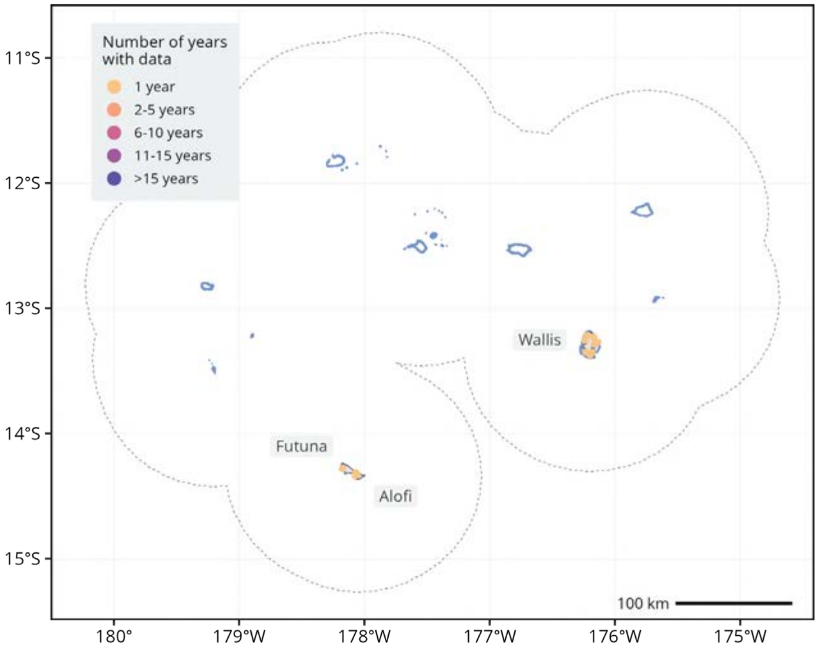
Temporal trends in benthic cover

The estimation of trends in the benthic cover of hard coral, coralline algae, macroalgae, and turf algae in Wallis and Futuna was achieved through the integration of 1 dataset (Supplementary Table 1). This dataset represents a total of 12 monitoring sites, on which 12 surveys were conducted in 2019.

On average across the FEO monitoring network, live coral cover reaches 30%. However, coral cover varies geographically: reefs around Futuna generally show higher values (live coral cover > 40%), moderate levels are observed around Alofi (around 30%), and more variable coral covers are recorded around Wallis, ranging from 6% near the Mata Utu port infrastructures to 51% offshore from the village of Halalo (Job, 2023).

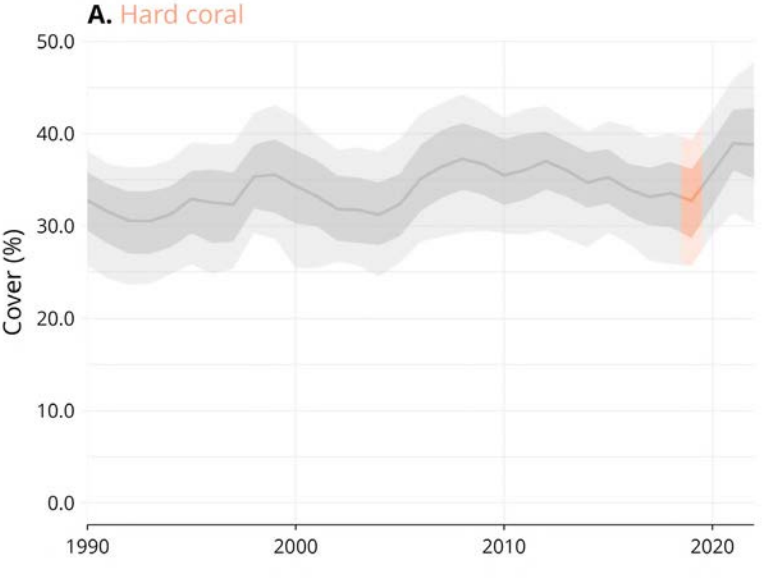
Macroalgae cover is low (<10%) across the entire monitoring network, except at the station located near the Mata Utu port, where it reaches 33%. At this site, green algae of the genus *Halimeda* form dense mats covering several square metres, alongside other algal species (brown, green, red) and mixed algal assemblages.

Turf algal cover is very low, at around 1%, across all stations. These algal patches are maintained by damselfish of the genus *Stegastes* (farmer-fish).



▲ **Figure 2.24.4.** Spatio-temporal distribution of benthic cover monitoring sites across Wallis and Futuna. Sites that were monitored for the longest period of time are represented on top of the sites monitored for fewer years. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the economic exclusive zone. Dashed polygons represent a 100 km buffer around coral reefs. Note that only land and coral reef buffers of the country or territory are represented, not those of adjacent countries and territories. The distribution of coral reefs is shown in light blue.

▶ **Figure 2.24.5.** Modeled temporal trends for hard coral (A), coralline algae (B), macroalgae (C), and turf algae (D) cover from 1990 to 2022 in Wallis and Futuna. The bold line represents the estimated average cover, lighter and darker ribbons represent 95% and 80% confidence intervals, respectively. Gray areas represent periods where no observed data were available. The raw data used to estimate these temporal trends are shown in Supplementary Figure 4



MATERIALS AND METHODS

Background maps

The present report includes multiple maps, either of the Pacific at large or of the different countries and territories of this region. These maps were produced using shapefiles available in open access on different data repositories.

First, the World EEZ v12 data (Flanders Marine Institute, 2023) were used to represent the boundaries of Economic Exclusives Zones (EEZ) of countries and territories of the Pacific. These data were also used further for various spatial analyses. We decided to not include the Matthew and Hunter Islands, which are claimed by both France and Vanuatu. For the maps of the Pacific, these islands were represented, for information, but not labeled (Figures 1.1.1, 1.2.6, and 1.3.3). In addition, this overclaimed area was not used in the analyses, including to derive any geographic information such as the maritime area or the coral reef extent.

Second, we downloaded several datasets from Natural Earth Data v4.1.0 (Natural Earth, 2023), namely "ne_10m_land", which was used to represent land boundaries at the regional scale, "ne_10m_admin_0_countries", which was used to represent land borders between countries, and the "ne_10m_bathymetry_all", which was used to represent the bathymetry within each EEZ. However, because the spatial resolution of Natural Earth Data was insufficient to represent land boundaries at a fine spatial scale, we have used the Global administrative areas v2.8 dataset (Hijmans, 2015) for the maps of countries and territories (e.g. Figure 2.4.1). Finally, municipalities for the island of Yap were obtained from the Digital Atlas of Micronesia (2024).

Geographic indicators

For the second part of the report, we provided different values related to the geography of the countries and territories of the Pacific. These values were obtained using the following data sources and methodologies.

Maritime area

The maritime area was directly obtained from the World EEZ v12 data (Flanders Marine Institute, 2023) by using the values provided in the column "AREA_KM2". As previously mentioned, the overclaimed area of Matthew and Hunter Islands was not included within the maritime area of France nor Vanuatu. We have integrated the Joint regime area Torres Strait Treaty (Papua New Guinea / Australia) into the Papua New Guinea EEZ.

Land area

The land area of each country and territory of the Pacific were derived from the Shuttle Radar Topography Mission (SRTM) digital elevation dataset v4.0 (Farr et al, 2007). These estimates were obtained within Google Earth Engine (GEE, Gorelick et al, 2017) by masking the non-null values of the SRTM dataset by a grid of pixels. Then the values of these pixels, corresponding to the area covered by each pixel (in km^2) were summed up for the EEZ of each country and territory. These estimates can differ from national sources due to the spatial resolution of the SRTM Digital Elevation data *(i.e.* 90 m) but we preferred these later for methodological consistency across countries and territories of the region.

Coral reef extent

The coral reef extent of each country and territory was estimated using the Tropical Coral Reefs of the World data (World Resources Institute, 2011) developed by the World Resources Institute (WRI). These data consist of a shapefile reflecting coral reef locations at a 500 m resolution. By performing a spatial intersection between this shapefile and the World EEZ v12 data (Flanders Marine Institute, 2023), we estimated the total coral reef extent within each EEZ (using the “EPSG:4326” coordinate reference system). Then we calculated the relative coral reef extent of each EEZ to the global coral reef extent, and to the GCRMN Pacific region coral reef extent. This was done using the shapefile of GCRMN regions (GCRMN, 2024). Our estimates can differ from those derived from other coral reefs distribution datasets, mainly due to differences in definition of coral reefs. For example, using the Allen Coral Atlas, Lyons et al. (2024) have estimated the total extent of shallow coral reefs to be 348,361 km² while we estimated this total extent to be 249,713 km² based on the WRI dataset. Particularly, some countries and territories are prone to large differences in estimated coral reefs extent between coral reef distribution datasets. In the Pacific, this is the case of New Caledonia for which coral reef extent can vary from 4,551 km² (Allen Coral Atlas dataset, Lyons et al. (2024)) to 7,450 km² (WRI dataset, our estimate) depending if lagoons are included or not in the definition of coral reefs.

Mean elevation

The mean land elevation of each country and territory of the Pacific were derived from the Shuttle Radar Topography Mission (SRTM) digital elevation dataset v4.0 (Farr et al, 2007). These estimates were obtained within GEE by averaging the SRTM dataset values by the EEZ of each country and territory. Our estimates can differ from national sources due to the spatial resolution of the SRTM Digital Elevation data (*i.e.* 90 m) but we preferred these later for methodological consistency across countries and territories of the region.

Human population

The indicators related to human population were derived from the Gridded Population of the World v4.11 Population Count dataset (CIESIN, 2018), provided at a 30 arc-second resolution (approximately 1 km at the equator). First, we performed a spatial intersection between the Tropical Coral Reefs of the World data (World Resources Institute, 2011) and the World EEZ v12 data (Flanders Marine Institute, 2023), to associate a country or territory to each reef. Using the resulting spatial layer we created a buffer of 5 km from coral reefs of each country and territory of the Pacific, within GEE. Finally, still under GEE, we computed a spatial intersection between each of these buffers and the Gridded Population of the World data, to extract the human population living within 5 km from a coral reef. We also extracted the total human population of each country and territory by computing a spatial intersection between EEZ and the Gridded Population of the World data.

Based on these extracted data, we computed three indicators of human population for each country and territory. First, the number of inhabitants in 2020 living within 5 km from coral reefs. Secondly, the relative change in the number of inhabitants living within 5 km from coral reefs between 2000 and 2020 (Eq. 3.1). Finally, the percentage of total human population of the territory living within 5 km from coral reefs in 2020.

Eq. 3.1 ►

$$Pop.change = \frac{(pop_{2020} - pop_{2000})}{pop_{2000}} * 100$$

Note that the values reported can differ from national population census data (see Andrew et al., 2019). However, we preferred the Gridded Population of the World dataset for methodological consistency across countries and territories of the region, and because of the raster format of this dataset necessary to calculate total population from shapefile layers.

Hard coral species richness

The number of hard coral species from the sections “Diversity” and “Temporal trends in benthic cover” were derived from the “Reef Forming Corals” Red List of Threatened Species v6.3 dataset (IUCN Red List of Threatened Species, 2024) provided by the International Union for the Conservation of Nature (IUCN). We performed a spatial intersection between the "Reef Forming Corals" data and the polygon of the GCRMN Pacific region (GCRMN, 2024), and summed up the number of unique hard coral species. Note that the definition of hard corals used in the "Reef Forming Corals" dataset is consistent to the one used in this report and includes some species from Milleporidae and Helioporidae.

Cyclone indicators

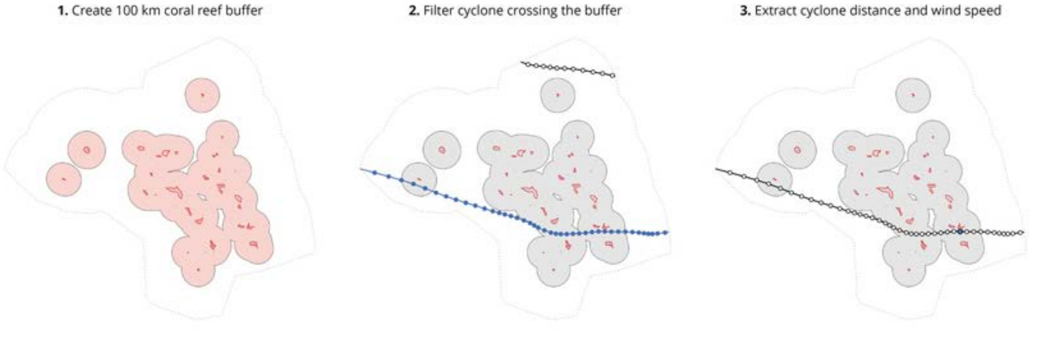
Tropical storms, and more particularly cyclones (also named hurricanes in the Atlantic or typhoons in South East Asia), are major disturbance events affecting coral reefs (Puotinen et al, 2020). To describe the occurrence of such events on coral reefs of the GCRMN Pacific region, over the four last decades, we used the International Best Track Archive for Climate Stewardship (IBCTrACS) dataset v4.00 (Knapp et al. 2010). This dataset provides tropical storms and cyclones positions 3-hourly at a 0.1° spatial resolution (approximately 10 km).

We applied a series of four filters on the IBCTrACS dataset. Firstly, we filtered the data to keep only cyclones, which are climatic events with maximum sustained wind speed greater than 119 $km.h^{-1}$. (*i.e.* category 1 on the Saffir-Simpson scale, see Table 3.1), along the entire trajectory of the phenomenon. However, it must be noted that sustained wind speed could be lower than this threshold at some positions over the cyclone's track. Secondly, we retained only hurricanes occurring after 1980-01-01, to match the period of interest of the report. Thirdly, we removed cyclones for which sustained wind speed was missing for all cyclone positions. Finally, using the coral reef distribution shapefile from the Tropical Coral Reefs of the World data (World Resources Institute, 2011), we created a buffer of 100 km around coral reefs of the Pacific within GEE. We have only kept cyclones for which their paths were crossing this 100 km coral reef buffer, while we recognized that cyclones can have an impact on coral reefs at a greater distance (Beeden et al., 2015; Puotinen et al., 2020).

▼ **Table 3.1.** The different categories of the Saffir-Simpson scale and their associated sustained wind speed. Note that Wehner and Kossin (2024) have recently suggested adding a sixth category to the Saffir-Simpson scale.

Type	Category	Sustained wind speed (km.h-1)
Tropical storm		64 to 118
Cyclone	1	119 to 153
	2	154 to 177
	3	178 to 210
	4	211 to 251
	5	> 251

Following these data filtering steps, we have attributed a Saffir-Simpson scale category (Table 3.1) to each cyclone, based on the maximum sustained wind speed along the entire cyclone track. Then, for each cyclone, we extracted 1) the minimal distance between coral reefs and the cyclone track, and 2) the sustained wind speed at the nearest cyclone position from a coral reef. These extractions were performed for each EEZ using the World EEZ v12 data (Flanders Marine Institute, 2023). Figure 3.1 illustrates the main steps of cyclone data extraction.



▲ **Figure 3.1.** Illustration of the main steps of cyclone data extraction with the example of the Marshall Islands territory (light gray polygon). Coral reefs are represented in red. Points over cyclone tracks are 3-hourly cyclone positions. The last step is repeated for each cyclone crossing the coral reef buffer.

Thermal regime indicators

To describe the thermal regime occurring on coral reefs of the Pacific, we used the CoralTemp v3.1 data products (Skirving et al., 2020) created under the Coral Reef Watch program by the National Atmospheric and Oceanic Administration (NOAA). CoralTemp includes different data products, including daily Sea Surface Temperature (SST), at the global scale with a spatial resolution of 5 km, from 1985 to present. Each of these products consists of one file per day, that we downloaded as NetCDF4 format.

Sea surface temperature

First, we used the SST data product from CoralTemp v3.1 (Skirving et al., 2020). We extracted the SST daily average values over coral reefs using the coral reef distribution shapefile from the Tropical Coral Reefs of the World data (World Resources Institute, 2011). Then, we averaged the extracted values per day and per EEZ, for countries and territories, and all EEZ combined for the entire Pacific region. The time series constituted by these values were used to represent the daily average SST over coral reefs from 1985 to 2023 (see Supplementary Figure 1). In addition, to make it possible to better visualize the intra-annual and the inter-annual average SST variability, we represented the extracted SST time-series by Julian days where months are figured on x-axis instead of the years (see Supplementary Figure 2). We used SST time-series rather than Degree Heating Weeks time-series because SST is raw information that is more easily understood by an uninformed public, since it is expressed in a widely-used unit (*i.e.* °C).

Long-term trend in SST

We used the previously extracted daily SST values and averaged for each country and territory and for the entire Pacific region, to derive long-term trends in SST from 1985 to 2023. For this purpose, we converted the dates of these time-series to a numeric format (e.g. “1985-01-01” was replaced by 1), and we performed linear regressions (Fig. 3.2).

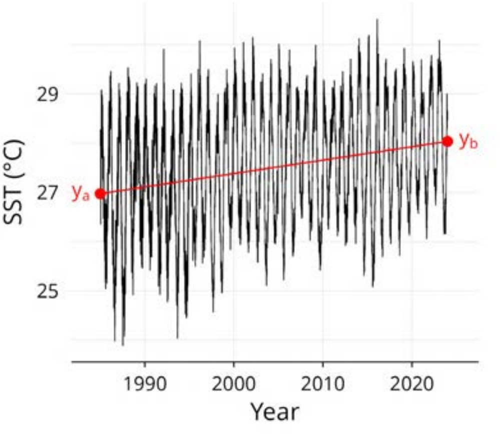


Figure 3.2. Illustration of the linear regression performed on the SST time-series, and the points (y_a = first point of the long-term trend, y_b = last point of the long-term trend) used to estimate the average change in SST and the average annual warming rate. The data used in this example are from Fijian coral reefs.

Then, we used the slope and the intercept of the linear regressions to calculate the first (y_A) and last (y_B) SST values of the long-term trends (Eq. 3.2 and 3.3). The average change in SST between 1985 and 2023 was estimated by subtracting the first SST value to the last SST value (Eq. 3.4). Finally, we estimated the annual rate of change in SST over the period by dividing the average change in SST by 38, which is the number of years between 1985 and 2023 (Eq. 3.5).

Eq. 3.2 ▶ $$y_a = slope \ast x_A + intercept$$

Eq. 3.3 ▶ $$y_B = slope \ast x_B + intercept$$

Eq. 3.4 ▶ $$y_B = slope \ast x_B + intercept$$

Eq. 3.5 ▶ $$Annual\ rate\ of\ change = \frac{y_B - y_A}{2023 - 1985}$$

SST anomaly

In addition to SST that were used to characterize the thermal regime and how it has changed from 1985 to 2023, we used SST anomaly to characterize the occurrence, intensity, and duration of anomalously high SST over the period. To this aim, we used the previously extracted daily SST values from which we have subtracted the long-term SST average from 1985 to 2023 calculated for each EEZ, for syntheses on countries and territories, and for all EEZ combined, for the synthesis on the entire Pacific region. Then, we applied a centered 365 days moving average on the daily SST anomalies values of each country and territory, and the entire Pacific region, to smooth the time series and further enhance data visualization. We represented these time series using a null SST anomaly (*i.e.* 0 value) as a reference line (see Supplementary Figures 3). However, we also represented these time series using the long-term trend in SST anomaly as a reference line (e.g. Figure 2.1.1), to take into account changes in SST over coral reefs, as a result of climate change. Such data visualization makes it easier to distinguish periods of temperature anomalies corrected by the gradual change in SST (*i.e.* using a shifting baseline, see Amaya et al, 2023).

We have used SST anomalies rather than Degree Heating Weeks (DHW), which are a widely used heat stress indicator in coral reef science, for three reasons. First, we were interested in reporting an indicator that can be easily understood by a non-scientific audience, and we believe that this is the case for SST anomalies, which are expressed in a common unit (*i.e.* °C). Second, we wanted to use an indicator for which we could correct the long-term trend in SST. Finally, we were interested in using an indicator of periods of anomalously low SST, and not just high SST, which was necessary in the context of the Pacific, where ENSO generates an alternation of negative and positive SST anomalies.

ENSO

To visualize the alternance between the two phases of the El Niño Southern Oscillation (ENSO) we used the Niño 3.4 SST Index (NOAA, 2024) provided by the National Oceanographic and Atmospheric Administration (NOAA). The Niño 3.4 SST Index corresponds to the SST anomalies averaged over the equatorial box bounded by 58°N, 58°S, 170°W, and 120°W (Bunge and Clarke, 2009). We applied a 3-month moving average to the Niño 3.4 SST Index values to improve readability and align with NOAA's definition (NOAA, 2024).

Benthic cover indicators

In addition to the indicators described above, which are associated with geography and climate regimes on coral reefs of the Pacific, we included seven biological indicators related to benthic cover.

Although numerous ecological indicators are measured and monitored within the world's coral reefs (Flower et al., 2017), the cover of benthic organisms is probably the most widely measured, both spatially and temporally. The main reasons are that most monitoring methods of benthic cover are relatively simple, inexpensive, and require limited skills in taxonomy (Aronson et al., 1994; Hill & Wilkinson, 2004). Early measurements of percentage cover of benthic organisms started before 1980 (Connell et al., 1997; Dustan & Halas, 1987), and new monitoring methods have little impact on comparison with data acquired using historical methods. For example, different methods used to estimate benthic cover, such as point intersect transects and photo-quadrats, lead to similar results (Jokiel et al., 2015).

This comparability of measurements acquired through different methods makes it possible to combine data from multiple monitoring programs to estimate trends of percentage cover of benthic organisms at large spatial scales. This type of analysis, called full data analysis, allows for greater precision in results compared to the other types of synthetic studies, like meta-analysis or systematic review (Spake et al., 2020). A full data analysis thus makes it possible to estimate complex temporal trends rather than a simple slope, as would be the case with a meta-analysis through a meta-effect size (Spake et al., 2020). Moreover, since full data analysis is based on raw data, it allows the use of a greater quantity of information compared to meta-analysis and systematic review, which rely only on published studies.

Among the wide diversity of benthic categories used by monitoring programs, we chose to report hard coral, macroalgae, turf algae, and coralline algae benthic cover. Contrary to the *Status of Coral Reefs of the World: 2020 GCRMN* report (Souter et al., 2021) we decided to separate the algae into three main functional groups, namely macroalgae, turf algae, and coralline algae. This choice was made to better reflect the ecological complexity of coral reefs and the key functional roles of different algae groups (Smith et al., 2016). This choice was also motivated to respond to a criticism addressed after the publication of the *Status of Coral Reefs of the World: 2020 GCRMN* report (Tebbett, Crisp, et al., (2023), page 222). In addition to the four major benthic categories, we also reported the temporal trends in the benthic cover of three major hard coral families, namely Acroporidae, Pocilloporidae, and Poritidae. We selected these families because they account for a large proportion of the total hard coral cover in coral reefs of the Pacific (e.g. Ajeroud et al, 2009).

Data integration

A full data analysis of benthic cover trends in coral reefs is only possible if a homogeneous dataset is available. Since such a dataset was not available in the GCRMN Pacific region, it was necessary to create it by going through a data integration step, before conducting the data analysis in the strict sense. The goal of the data integration was to assemble a homogeneous synthetic dataset on coral reef benthic cover through the aggregation of multiple heterogeneous individual datasets. The data integration was done by using an improved version of the workflow developed by Wicquart et al. (2022) in the frame of the production of the *Status of Coral Reefs of the World: 2020 GCRMN* report (Souter et al., 2021). The main enhancements to the workflow used in the previous GCRMN report, were the addition of quality checks, to provide more reliable assurance of data quality. The data integration workflow used for the present report comprises five main steps, that are illustrated in Figure 3.3 and described in the following sections.

Data collation

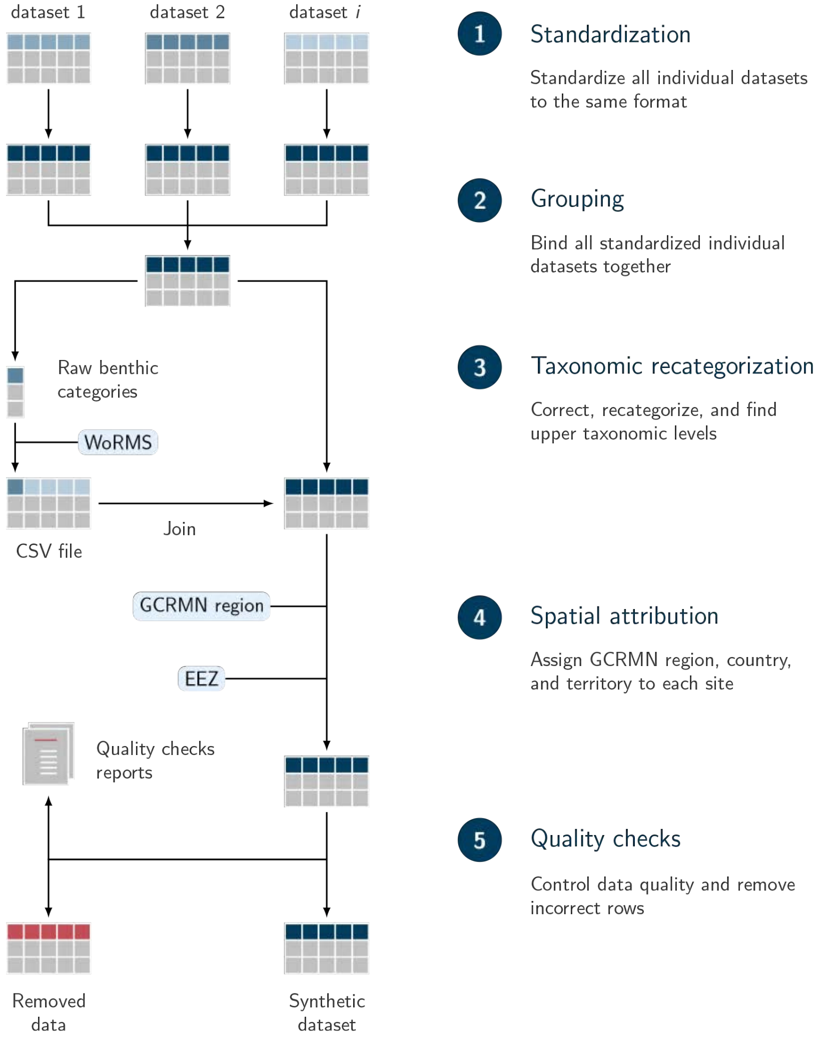
The collation of individual datasets on coral reefs benthic cover was conducted from 2023-01-01 to 2024-03-04. We contacted previous data contributors from the *Status of Coral Reefs of the World: 2020 GCRMN* report (Souter et al., 2021) from the GCRMN Pacific region, to get the authorization to re-use their data and to update the version of datasets previously shared. In addition, we searched for publicly available datasets from data papers, data repositories, and data platforms dedicated to coral reefs. Specifically, we contacted owners of projects stored on ReefCloud (reefcloud.ai) and MERMAID (datamermaid.org). Datasets hosted on the MERMAID platform were downloaded directly to R using the mermaidr package (Gelfand, 2024).

Data standardization

Individual datasets gathered during the data collation step were heterogeneous in data formats (e.g. CSV, Excel), data structure, variable names, and units (e.g. meters vs feet for the depth). For this reason, a standardization step was necessary to enable these individual datasets to be merged into a single synthetic dataset. We created an R script for each individual dataset, and we applied specific modifications to each of them to match the data format and variables we have defined (Table 3.2). These modifications included merging of Excel spreadsheets, joining of the main dataset with its metadata (e.g. site coordinates, benthic codes), selecting and renaming variables, converting units, Coordinates Reference System (CRS) and date formats, deriving benthic cover values from number of points per transect or photo quadrats (Figure 3.3 – Step 1).

All the data standardization was conducted using code, making it possible to keep track of changes made and eventually to apply corrections if errors are identified in the following stages. Since all the R scripts are publicly available, it is also possible for data owners to check the validity of modifications applied to their datasets (see https://github.com/GCRMN/gcrmndb_benthos).

At the end of data standardization, each individual dataset was exported into CSV format. All the CSV files were then merged to create a single raw synthetic dataset (Figure 3.3 – Step 2).



▲ **Figure 3.3.** Illustration of the five main steps of the data integration workflow used to create the synthetic dataset on coral reefs benthic cover. MEOW = Marine Ecoregions of the World (Spalding et al., 2007).

▼ **Table 3.2.** Description of variables included in the gcrmndb_benthos synthetic dataset. Variable names (except region, subregion, ecoregion, category, subcategory, and condition) correspond to DarwinCore terms. Variables 2 to 13 are associated with spatial dimension, variables 14 to 17 are associated with temporal dimension, and variables 20 to 28 are associated with taxonomy.

Nb	Variable	Type	Description
1	datasetID	Factor	ID of the dataset
2	region	Factor	GCRMN region
3	subregion	Factor	GCRMN subregion
4	ecoregion	Factor	Marine Ecoregion of the World (Spalding et al, 2007)
5	country	Factor	Country
6	territory	Character	Territory
7	locality	Character	Site name
8	habitat	Factor	Habitat
9	parentEventID	Integer	Transect ID
10	eventID	Integer	Quadrat ID
11	decimalLatitude	Numeric	Latitude (decimal, EPSG:4326)
12	decimalLongitude	Numeric	Longitude (decimal, EPSG:4326)
13	verbatimDepth	Numeric	Depth (m)
14	year	Integer	Four-digit year
15	month	Integer	Integer month
16	day	Integer	Integer day
17	eventDate	Date	Date (YYYY-MM-DD, ISO 8601)
18	samplingProtocol	Character	Method used to acquire the measurement
19	recordedBy	Character	Person who acquired the measurement
20	category	Factor	Benthic category
21	subcategory	Factor	Benthic subcategory
22	condition	Character	Condition for hard corals
23	phylum	Character	Phylum
24	class	Character	Class
25	order	Character	Order
26	family	Character	Family
27	genus	Character	Genus
28	scientificName	Character	Species
29	measurementValue	Numeric	Percentage cover

Taxonomic re-categorization

During the data standardization step, we stored the raw benthic categories (*i.e.* those used by data owners of the individual datasets) into the temporary variable "organismID". We exported a CSV file of all unique raw benthic categories contained in this variable, and we manually re-categorized each of them into variables 18 to 26 (Figure 3.3 – Step 3).

When the raw benthic category was a broad category not related to taxonomy, we have completed accordingly the variable "category", and the variable "subcategory", where possible. For example, when the raw benthic category was "turf" we attributed the level "Algae" for the variable "category" and the level "Turf algae" for the variable "subcategory".

We were confronted with the following specific cases for the taxonomic re-categorization:

- Mixed categories. In this case we used the lowest common denominator between the mixed categories. For example, when the raw benthic category was "Macroalgae and turf algae" we have used "Algae" for the variable "category".

- Stacked categories. In this case we used the category which covers the other one. For example, when the raw benthic category was "Algae on dead coral" we have used "Algae" for the variable "category".

- Homonym taxa names. In this case we either contacted the data owner to replace the raw benthic category by an unambiguous one during the data standardization step, or we did not complete the variable "category" which later resulted in the removal of the rows concerned. For example, "Turbinaria" is a genus of Scleractinia (coral) but also of Fucales (macroalgae). If the data owner was able to provide clarifying information, the benthic raw category could be replaced by the specific denomination (e.g. "Turbinaria - Coral") during the data standardization step.

- Unrequired or unintelligible categories. In this case we did not complete the variable "category" which later resulted in the removal of the rows concerned. Examples of unrequired or unintelligible raw benthic categories included "Shadow", "Other", or "Unknown".

When the raw benthic category was related to taxonomy (e.g. Acropora) and not to a broad category (e.g. Hard coral), we filled variables 21 to 26. To do so, we first checked the spelling of each raw benthic category using the World Register of Marine Species (WoRMS) website. We also considered updates in taxonomic classification that may have occurred between the data entry by the owners and the data integration process. Then, within the CSV file, we completed the taxonomic level associated with the raw benthic category, and we completed higher taxonomic levels (variables 21 to 26 in Table 3.2). For example, for the raw benthic category "coral acropora" we completed the variable "genus" by "Acropora", the variable "family" by "Acroporidae" and so on until the variable "phylum". We left the category and subcategory variables empty when the raw benthic category was related to taxonomy and not to a broad category. Then we imported the CSV file into R and completed the category and subcategory variables using attribution rules based on variables related to taxonomy (variables 21 to 26 in Table 3.2). These rules were the following ones:

- **Hard coral.** We attributed the level "Hard coral" for the variable "category" when the variable "order" was "Scleractinia" or when the variable "family" was "Milleporidae" or "Helioporidae". When the contributor had used the term "hard coral" but had not provided taxonomic information, then we attributed the level "Hard coral" for the category. Note that the "Hard coral" category has not included dead corals, but may have included partially or fully bleached corals.

- **Macroalgae.** We attributed the level "Algae" for the variable "category" and the level "Macroalgae" for the variable "subcategory" when the variable "Class" was "Phaeophyceae", "Florideophyceae", or "Ulvophyceae" and the variable "order" was not "Corallinales". When the contributor had used the term "Macroalgae" but had not provided taxonomic information, then we attributed the level "Algae" for the variable "category" and the level "Macroalgae" for the variable "subcategory".

- **Coralline algae.** We attributed the level "Algae" for the variable "category" and the level "Coralline algae" for the variable "subcategory" when the variable "order" was "Corallinales". When the contributor had used the term "coralline algae" but had not provided taxonomic information, then we attributed the level “Algae” for the variable “category” and the level “Coralline algae” for the variable “subcategory”.

- **Turf algae.** When the contributor had used the term “turf algae”, then we attributed the level “Algae” for the variable “category” and the level “Turf algae” for the variable “subcategory”.

- **Cyanobacteria.** We attributed the level “Algae” for the variable “category” and the level “Cyanobacteria” for the variable “subcategory” when the variable “phylum” was “Cyanobacteria”.

- **Other fauna.** We attributed the level “Other fauna” for the variable “category” when the variable “phylum” was “Porifera”, “Chordata”, “Echinodermata”, “Bryozoa”, “Annelida”, “Mollusca”, “Arthropoda”, or when the variable “order” was “Actiniaria”, “Alcyonacea”, ”Zoantharia”, “Corallimorpharia”, “Antipatharia”, or when the variable “subclass” was “Octocorallia”.

- **Seagrass.** We attributed the level “Seagrass” for the variable “category” when the variable “phylum” was “Tracheophyta”.

Once the recategorization was done, we joined the table containing the organismID variables and the new variables (variables 18 to 26 in Table 3.2) with the main data table. Finally, we removed the temporary variable “organismID” and we deleted all rows containing missing values for the variable “category”. Note that removing missing values for the variable “category” has no effect on percentage cover values although it reduces the total percentage cover on the sampling unit (e.g. quadrat, transect) below 100%. Finally, we summed up the values of measurementValue by grouping by all other variables, to avoid having duplicated benthic categories on a given sampling unit.

The recategorization of raw benthic categories into standardized categories through variables 18 to 26 of Table 3.2, can be publicly accessed in the file “03_tax-recategorisation.csv” on the gcrmndb_benthos GitHub repository.

Spatial attribution

Using site coordinates, through variables decimalLatitude and decimalLongitude, we added three additional variables to the data, related to the spatial dimension (Figure 3.3 – Step 4). First, we aggregated some of the marine ecoregions of the world from the shapefile built by Spalding et al. (2007) to create a shapefile of the ten GCRMN regions. Then we used this shapefile to associate the GCRMN region (*i.e.* variable higherGeography) to each site. Secondly, we added the country and territory by using the variables SOVEREIGN1 and TERRITORY1 from the World EEZ v12 shapefile (Flanders Marine Institute, 2023). These three variables - higherGeography, country, and territory - were needed for the data analysis step to obtain estimates of benthic cover at different spatial scales.

Quality checks

Large quantities of data should not be pooled without sufficient verification at the risk of loss of data quality. Indeed, previous studies have highlighted the risk of biased interpretations of ecological questions when the quality of large synthetic dataset has not been sufficiently verified (Augustine et al., 2024). For this reason, we added a step dedicated to the assessment of data quality (Figure 3.3 – Step 5). We defined a set of eight quality checks that were inspired by Vandepitte et al. (2015) (Table 3.3). Quality checks take the form of questions associated with one or several variable(s) and can easily be transcribed into code.

Because of rounding decimal places, the sum of the percentage cover of benthic categories within a sampling unit can be slightly greater than 100 (Razak et al, 2024). Hence, to avoid removing too much data, rows for which the sum of the percentage cover of benthic categories within a sampling unit was between 100 and 101 were normalised relative to 100. This step was done before applying the quality check 8 (Table 3.3).

We checked whether the quality checks were “True” or “False”, and we removed all rows with “False” quality checks values. However, it’s preferable to correct errors than to delete them, in order to have a sufficient volume of data for the analysis. For this reason, we exported summary reports for each individual dataset integrated. These individual dataset reports included the percentage of rows deleted of the individual dataset per each quality check. These individual reports were used to identify and correct errors by updating the code of the data standardization (Figure 3.3 – Step 1). For example, one of the common errors that is easily correctable was the inversion of values between variables "decimalLatitude" and "decimalLongitude". The individual dataset reports also included additional information such as the percentage of missing values for each variable, the percentage of rows per benthic category and taxonomic level, and the distribution of observations in space and time.

▼ **Table 3.3.** List of quality checks used for the gcrmndb_benthos synthetic dataset.

Nb	Variable	Question
1	decimalLatitude decimalLongitude	Are the latitude and longitude available?
2	decimalLatitude	Is the latitude within its possible boundaries (*i.e.* between -90 and 90)?
3	decimalLongitude	Is the longitude within its possible boundaries (*i.e.* between -180 and 180)?
4	decimalLatitude decimalLongitude	Is the site within the coral reef distribution area (100 km buffer)?
5	decimalLatitude decimalLongitude	Is the site located within an EEZ (1 km buffer)?
6	decimalLongitude	Is the year available?
7	decimalLatitude	Is the sum of the percentage cover of benthic categories within the sampling unit greater than 0 and lower than 100?
8	decimalLongitude	Is the percentage cover of a given benthic category (*i.e.* a row) greater than 0 and lower than 100?
6	year	Is the year available?
7	year	Is the sum of the percentage cover of benthic categories within the sampling unit greater than 0 and lower than 100?
8	measurementValue	Is the percentage cover of a given benthic category (*i.e.* a row) greater than 0 and lower than 100?

Code availability

The data integration process, which includes data collation, data standardization and data cleaning, was done through the gcrmndb_benthos GitHub repository. This repository serves as a shared resource for GCRMN reports and was not specifically established or maintained for the purposes of the current report. The data integration steps were assessed using R software version 4.4.2 (R Core Team, 2024) and predominantly packages tidyverse (Wickham et al, 2019), mermaidr (Gelfand, 2024), and sf (Pebesma, 2018). The code used for the data integration of benthic cover monitoring data can be accessed at https://github.com/JWicquart/gcrmndb_benthos.

Data analysis

Over the last three decades, multiple studies have estimated temporal trends in the percentage cover of hard corals and other benthic categories at large spatial scales. The authors of most of these studies have aggregated data from different monitoring programs and interpreted temporal trends by plotting the average hard coral cover per year and its associated confidence interval (Gardner et al., 2003; Obura et al., 2017). Other studies have used statistical models to identify the factors associated with temporal trends in percentage cover (Bruno & Selig, 2007; De'ath et al., 2012; Jackson et al., 2014; Moritz et al., 2018 ; Tebbett et al., 2023b).

The main assumption of these approaches is that the data aggregated are representative of coral reefs of the region where they were obtained. However, coral reef monitoring is highly heterogeneous both in space and time (Souter et al., 2021). Indeed, because of their proximity to research facilities, some coral reefs have been intensively monitored (e.g. Moorea, (Moritz et al., 2021)) while others have not been monitored at all due to their remoteness. This issue is particularly striking within the Pacific region, where coral reefs extend over 32 million kilometers squared of ocean (Figure 1.3.3). For example, while New Caledonia and Hawaii hosts only 17.5% of the coral reef extent of the Pacific region, these territories represent 38.4% of surveys assessed from 1980 to 2023 (Table 1.3.1). On the contrary, Papua New Guinea hosts 22.3 % of the coral reef extent of the Pacific region but represented only 2 % of surveys assessed from 1980 to 2023 (Table 1.3.1). Hence, plotting the average hard coral cover per year from coral reef monitoring data at the regional scale poses the risk of obtaining estimates of benthic cover trends that are not representative of coral reefs of the region, but only reflect changes occurring on monitoring sites.

To overcome this issue, the previous global GCRMN report used a Bayesian hierarchical model to weight the estimates of percentage cover based on coral reef extent represented by monitoring sites (Souter et al., 2021). While this type of modeling approach is particularly powerful in providing a measure of uncertainty on the estimated percentage cover, it does not allow predictors to be included easily, limiting the model's ability to provide reliable estimates for regions where little or none data are available. Predictors, also called covariates or explicative variables, are variables that can be used in a statistical model to inform percentage cover values of benthic categories. In other words, by knowing (through the model) the relationship between the percentage cover measured on monitoring sites and a set of predictors' values, it is possible to predict the percentage cover on coral reefs sites from the predictors' values obtained from these sites. Of course, a single predictor does not provide sufficient information to be able to correctly estimate the percentage cover value of a given benthic category. Examples of predictors for benthic cover in coral reefs include sea surface temperature and concentration in chlorophyll a.

For many years, the inclusion of predictors within statistical models for macro-ecological studies was limited by the availability of predictors at the global scale as well as their spatio-temporal resolution. However, over recent years, numerous data products usually produced from satellite measurements have been made freely and publicly available (Gorelick et al., 2017). Coupled with the increase in computational capabilities and improvements in machine learning (ML) algorithms (Rubbens et al., 2023), these make it possible to use numerous predictors to estimate percentage cover of benthic categories. Such ML modeling approaches are increasingly being used in recent coral reef studies (Bakker et al., 2023; T. McClanahan et al., 2024; T. R. McClanahan, 2023; Mellin et al., 2019).

Here, we used a ML approach to estimate the temporal trends of percentage cover of overall hard coral, key coral families Acroporidae, Pocilloporidae, and Poritidae, macroalgae, turf algae and coralline algae, on Pacific coral reefs from 1980 to 2023. The six main steps of the ML approach used are illustrated in Figure 3.4 and detailed in the following sections. These sections were written using the REFORMS checklist developed by (Kapoor et al., 2024), which provides recommendations for ML-based science.

Pre-processing of benthic data

Data selection

We extracted benthic cover monitoring data from the gcrmndb_benthos synthetic dataset (see section "Data integration") that were located within the GCRMN Pacific region. Since the GCRMN regions shapefile was created based on the aggregation of several marine ecoregions (Spalding et al., 2007) and not on EEZ, we removed data from sites falling outside the EEZs covered by this report (e.g. those falling within the Australian EEZ).

Then we filtered data from the years 1980 to 2023, which constitute the period of interest of this report. Although data were available within gcrmndb_benthos synthetic dataset before 1980 and after 2023, we decided to not use them since they were too scarce to be considered sufficiently informative for the model. In addition, most satellite-derived predictor data were not available before 1980, limiting the predictive capacity of the model before this year.

Finally, we removed data associated with datasetIDs "0009" and "0042," corresponding to the Catlin Seaview Survey and the Living Ocean Foundation datasets, respectively. These datasets were initially included in the analyses but were later excluded after the first deployment of the ML models. Notably, they emerged as key predictors in the Variable Importance Plots for several benthic categories (see Model Interpretation), suggesting that their data differed from those of the other datasets. While we were unable to pinpoint the exact source of this discrepancy, it may be linked to differences in monitoring protocols. For instance, the Catlin Seaview Survey dataset was collected using a kilometer long transect, whereas most benthic cover monitoring transects extend only a few dozen meters.

Following these data selection steps, the dataset used for modeling consisted of a total of 49 individual datasets, representing 13,828 surveys acquired on 7,344 sites, spanning from 1987 to 2023 (Table 1.3.1). The list of the individual datasets used within the analyses for the estimation of benthic categories cover trends at the scale of the GCRMN Pacific region is provided in Supplementary Table 1.

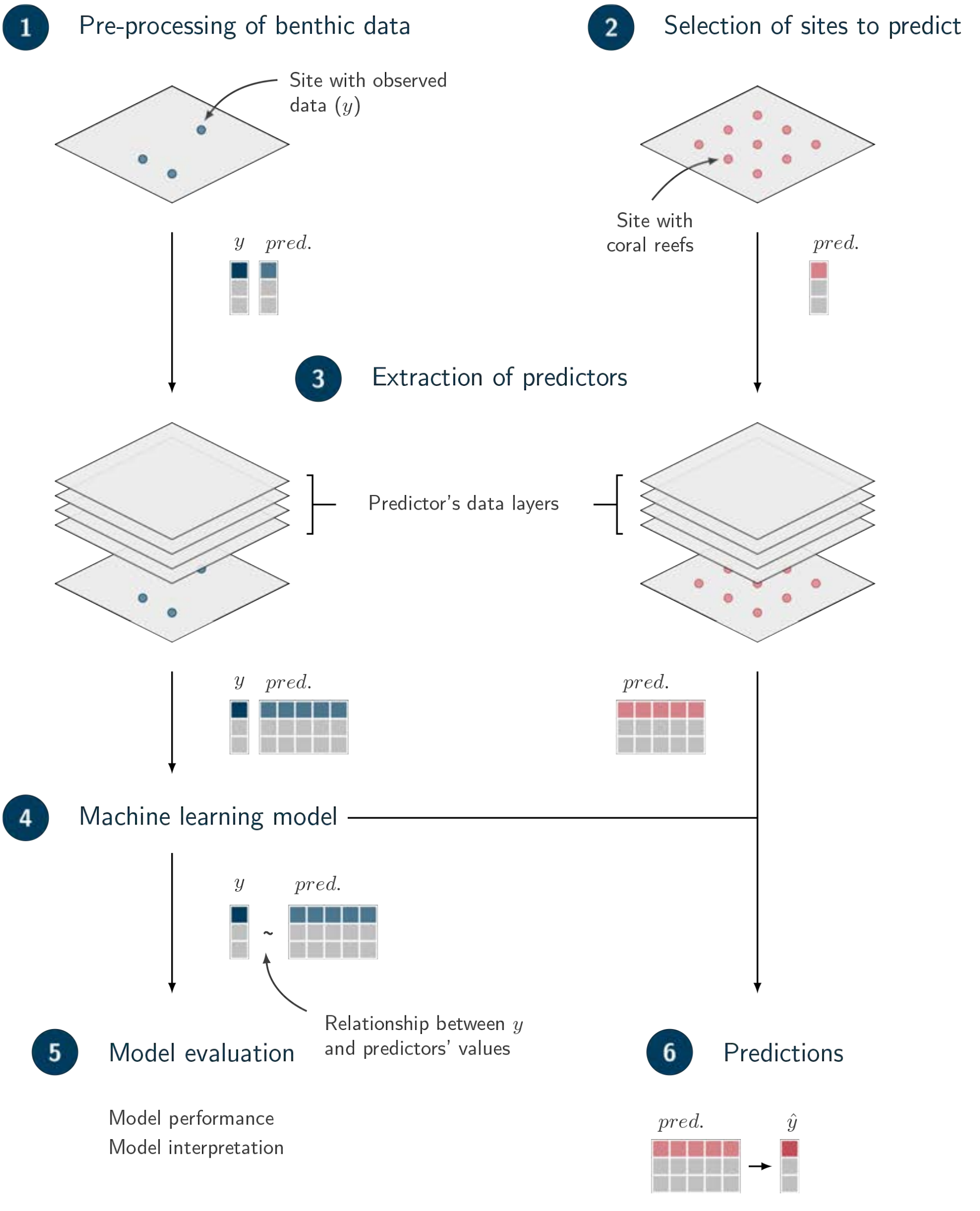
Although our study focused on modeling temporal trends in shallow coral reefs - defined as occurring at depths of 0 to 30 m - we did not apply any filter on the depth. Filtering the data to retain only depths of 30 m or less would have required removing entries with missing depth values, resulting in the loss of 22.9% of the surveys. However, since less than 0.01% of the surveys were conducted at depths greater than 30 m (for those where the depth was recorded), the bias introduced by including mesophotic coral reef data in our analysis of shallow coral reef temporal trends seems to have been limited.

Data transformation

When the number of points used to estimate the percentage cover of benthic categories was low (e.g. around 10), data acquired from the photo-quadrat methodology can be considered pseudo-quantitative and can lead to misleading predictions. For this reason, we summarized the data at the transect level by averaging the values between photo-quadrats. We decided to summarize the data at the scale of a transect, instead of at the site scale, to consider the fine-scale variability in benthic cover within the models. Apart from avoiding pseudo-quantitative data, summarizing the data at the scale of a transect, also reduced the number of observations, hence decreasing the running time of the ML model. Data acquired using Line Intercept Transect (LIT) and Point Intercept Transect (PIT) methods were not affected by this step, since they were acquired at the transect level.

Then for each transect, we summed the percentage cover of the different benthic levels of lower taxonomic rank than the benthic categories of interest (hard coral, coralline algae, turf algae, and macroalgae). For example, for a given transect, we summed up the percentage cover of "*Acropora*", "*Pocillopora*", and so on, to obtain the percentage cover of all hard corals.

The presence or the absence of zero values can have a significant influence on the results of macroecological studies. In the context of coral reefs benthic cover, removing zero values can lead to biased temporal trends, where the value of percentage cover of a given benthic category can be overestimated. Yet, zero values are not always included in coral reefs benthic cover monitoring datasets, zeros were generally included more often when data was structured in a wide format than in a long format. For this reason, we regenerated zero values for each benthic categories of each datasetID. Regenerating zero values per datasetID avoided generating zero values for benthic categories that were not initially present in a given datasetID. For example, a dataset may have included only hard coral cover values and not percentage cover values for other benthic categories. Hence, this step



▲ **Figure 3.4.** Illustration of the main steps of the machine learning modeling approach used to estimate the temporal trends of percentage cover of the four benthic categories (overall hard coral, macroalgae, turf algae, coralline algae); y are the observed values of percentage cover (*i.e.* "measurementValue" in Table 3.2) of a given benthic category; *pred.* is the set of predictors used in the ML model; $\hat{y}$ are the predicted values of "measurementValue" for a given benthic category over coral reef sites. For steps 1 and 2, the predictors ("pred.") include at least latitude, longitude, and year (see section "Extraction of predictors").

ensured that all the benthic categories present in a given dataset were associated with each of the surveys carried out within that dataset, the initially missing combinations being completed by a zero for the percentage cover.

Exploratory data analysis

We conducted an exploratory data analysis on the benthic cover data to identify any inconsistencies that could have led to biased predictions. Specifically, we plotted and visually checked the distribution of percentage cover values (from the variable "measurementValue") for each benthic category per datasetID and per country and territory. We were particularly vigilant that distributions were not truncated at their zero values. Indeed, some contributors may have deleted percentage cover values equal to zero to reduce the size of their dataset, leading to a risk for us to overestimate the actual percentage cover of benthic categories. When different distributions from those observed for the other datasetID were obtained, we systematically came back to the R scripts used for data standardization and verified that the difference was not due to an error made during data integration. With the set of quality checks used during data integration (see section "Quality checks"), this exploratory analysis represented an additional way to verify data quality.

Selection of sites to predict

To be able to get estimations of benthic categories' percentage cover over sites representative of coral reefs of the Pacific, and not on sites where monitoring data were available, it was necessary to select sites on which predictions would be made. To this end, using Google Earth Engine (GEE), we randomly generated 10,000 sites located within the polygons of the Tropical Coral Reefs of the World data (World Resources Institute, 2011) for the GCRMN Pacific region. Although the number of sites selected may seem low, each site was later repeated for each year from 1980 to 2023, which means that the model must have predicted almost half a million rows (see section "Predictions"). Figure 3.5 compares the spatial distribution of sites with observed data with those selected for making predictions using the example of the main islands of Palau.

▲ **Figure 3.5.** Comparison of the spatial distributions of sites with observed data and sites used for making predictions, using the main islands of Palau as an example. Coral reefs are represented in light blue.

Extraction of predictors

We derived a total of 29 predictors, including nine associated with geographic position of the sites, two associated with the temporal dimension, three associated with the cyclone regime, 11 associated with the thermal regime, two associated with water quality, and two with direct human influence. Most of the predictors were used both to build (*i.e.* train and test) the model using the sites with observed data, and to use it for predictions using selected sites (see part "Selection of sites to predict"). However, some predictors were only included for their explicative role and not for their predictive role. For example, the predictor "datasetID" was included to train and test the model, but not to predict percentage cover values. The inclusion of this predictor was motivated by the need to identify potential abnormal influences of certain datasets (see section "Model interpretation"). The full list of predictors included within the modeling framework is provided below, with the data source and the description for their extraction.

1. chl_a_mean

- **Category:** Ecology
- **Data source:** Ocean Color SMI: Standard Mapped Image MODIS Aqua Data
- **Spatial resolution:** 4,616 m
- **Temporal resolution:** Daily (from 2002-07-03 to 2022-02-28)
- **Description:** Average of chlorophyll a concentration (in mg/m3) from a 10 km radius from the site from 2002-07-03 to 2022-02-28.
- **Used for:** Training and prediction
- **Percentage of missing values:** 3.24 % (training) and 2.75 % (prediction)

2. chl_a_sd

- **Category:** Ecology
- **Data source:** Ocean Color SMI: Standard Mapped Image MODIS Aqua Data
- **Spatial resolution:** 4,616 m
- **Temporal resolution:** Daily (from 2002-07-03 to 2022-02-28)
- **Description:** Average standard deviation of chlorophyll a concentration (in mg/m3) from a 10 km radius from the site from 2002-07-03 to 2022-02-28.
- **Used for:** Training and prediction
- **Percentage of missing values:** 3.24 % (training) and 2.75 % (prediction)

3. datasetID

- **Category:** Geographic
- **Data source:** gcrmndb_benthos
- **Spatial resolution:** None
- **Temporal resolution:** None
- **Description:** ID of the individual dataset
- **Used for:** Training
- **Percentage of missing values:** 0 % (training)

4. decimalLatitude

- **Category:** Geographic
- **Data source:** gcrmndb_benthos / Tropical Coral Reefs of the World data (World Resources Institute, 2011)
- **Spatial resolution:** Unknown, but variable / 500 m
- **Temporal resolution:** None
- **Description:** The latitude of the site
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 0 % (prediction)

5. decimalLongitude

- **Category:** Geographic
- **Data source:** gcrmndb_benthos / Tropical Coral Reefs of the World data (World Resources Institute, 2011)
- **Spatial resolution:** Unknown, but variable / 500 m
- **Temporal resolution:** None
- **Description:** The longitude of the site
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 0 % (prediction)

6. dhw_max

- **Category:** Thermal regime
- **Data source:** CoralTemp Version 3.1 (Skirving et al., 2020)
- **Spatial resolution:** 5 km

- **Temporal resolution:** Daily (from 1985-01-01)
- **Description:** Maximum Degree Heating Week (DHW) value on the site for the year i
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 13.75 % (prediction)

7. dhw_max_y1

- C**ategory:** Thermal regime
- **Data source:** CoralTemp Version 3.1 (Skirving et al., 2020)
- **Spatial resolution:** 5 km
- **Temporal resolution:** Daily (from 1985-01-01)
- **Description:** Maximum Degree Heating Week (DHW) value on the site for the year before the year i. This lagged version of the predictor "dhw_ max" was included to take into account the time needed for the percentage cover to be impacted by the event(s).
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 16.02 % (prediction)

8. elevation

- **Category:** Geographic
- **Data source:** Shuttle Radar Topography Mission (SRTM) Digital Elevation Data Version 4
- **Spatial resolution:** 90 m
- **Temporal resolution:** None (one-shot)
- **Description:** Mean (above-sea) elevation from a 10 km radius from the site
- **Used for: Training and prediction**
- **Percentage of missing values: 0 % (training) and 0 % (prediction)**

9. enso

- **Category:** Thermal regime
- **Data source:** Nino 3.4 Index
- **Spatial resolution:** None
- **Temporal resolution:** Monthly
- **Description:** Average Nino 3.4 Index monthly values over the last two years from the year i
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 2.27 % (prediction)

10. gravity

- **Category:** Human
- **Data source:** Cinner et al., (2018)
- **Spatial resolution:** 10 km
- **Temporal resolution:** None (one-shot)
- **Description:** Gravity value on the site. Gravity can be seen as a proxy of direct human impact on coral reefs and is calculated from human population and reef accessibility
- **Used for:** Training and prediction
- **Percentage of missing values:** 29.53 % (training) and 10.63 % (prediction)

11. land

- **Category:** Geographic
- **Data source:** Shuttle Radar Topography Mission (SRTM) Digital Elevation Data Version 4
- **Spatial resolution:** 90 m
- **Temporal resolution:** None (one-shot)
- **Description:** Total land area from a 10 km radius from the site
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 0 % (prediction)

12. month

- **Category:** Temporal
- **Data source:** gcrmndb_benthos
- **Spatial resolution:** None
- **Temporal resolution:** None
- **Description:** Integer month
- **Used for:** Training
- **Percentage of missing values:** 26.12 % (training)

13. nb_cyclones

- **Category:** Cyclone regime
- **Data source:** International Best Track Archive for Climate Stewardship (IBTrACS) Version 4 (Knapp et al., 2010)
- **Spatial resolution:** 0.1° (~10 km)
- **Temporal resolution:** 3 hourly (interpolated, most raw data are 6 hourly)
- **Description:** Number of cyclones passed within 1° (~ 111 km) from the site on the year i

- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 0 % (prediction)

14. nb_cyclones_y5

- **Category:** Cyclone regime
- **Data source:** International Best Track Archive for Climate Stewardship (IBTrACS) Version 4 (Knapp et al., 2010)
- **Spatial resolution:** 0.1° (~10 km)
- **Temporal resolution:** 3 hourly (interpolated, most raw data are 6 hourly)
- **Description:** Number of cyclones passed within 1° (~ 111 km) from the site over the 5 past years from the year i. This lagged version of the predictor "nb_cyclones" was included to take into account the time needed for the percentage cover to be impacted by the event(s).
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 0 % (prediction)

15. parentEventID

- **Category:** Geographic
- **Data source:** gcrmndb_benthos
- **Spatial resolution:** Unknown, but variable
- **Temporal resolution:** None
- **Description:** The ID of the transect
- **Used for:** Training
- **Percentage of missing values:** 9.14 % (training)

16. population

- **Category:** Human
- **Data source:** Gridded Population of the World (GPW) Version 4.11
- **Spatial resolution:** 927.67 m
- **Temporal resolution:** Yearly (for years 2000, 2005, 2010, 2015, and 2020)
- **Description:** Total number of inhabitants living within 5 km from the site on the year i
- **Used for:** Training and prediction
- **Percentage of missing values:** 1.84 % (training) and 45.45 % (prediction)

17. reef_extent

- **Category: Geographic**
- **Data source: Allen Coral Atlas (ACA) Geomorphic Zonation and Benthic Habitat Version 2.0 (Lyons et al., 2024)**
- **Spatial resolution:** 5 m
- **Temporal resolution:** None (one-shot)
- **Description:** Total area of coral reef habitat from a 10 km radius from the site
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 0 % (prediction)

18. sst_max

- **Category:** Thermal regime
- **Data source:** CoralTemp Version 3.1 (Skirving et al., 2020)
- **Spatial resolution:** 5 km
- **Temporal resolution:** Daily (from 1985-01-01)
- **Description:** Maximum annual SST values on the site for the year i
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 11.48 % (prediction)

19. sst_max_y1

- **Category: Thermal regime**
- **Data source:** CoralTemp Version 3.1 (Skirving et al., 2020)
- **Spatial resolution:** 5 km
- **Temporal resolution:** Daily (from 1985-01-01)
- **Description:** Maximum annual SST values on the site for the year before the year i. This lagged version of the predictor "sst_max" was included to take into account the time needed for the percentage cover to be impacted by the event(s).
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 13.75 % (prediction)

20. sst_mean_y1

- **Category:** Thermal regime
- **Data source:** CoralTemp Version 3.1 (Skirving et al., 2020)
- **Spatial resolution:** 5 km
- **Temporal resolution:** Daily (from 1985-01-01)
- **Description:** Mean annual SST values on the site for the year before the year i.
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 13.75 % (prediction)

21. sst_min

- **Category:** Thermal regime
- **Data source:** CoralTemp Version 3.1 (Skirving et al., 2020)
- **Spatial resolution:** 5 km
- **Temporal resolution:** Daily (from 1985-01-01)
- **Description:** Minimum annual SST values on the site for the year i
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 11.48 % (prediction)

22. sst_sd

- **Category:** Thermal regime
- **Data source:** NOAA CDR Optimum Interpolation Sea Surface Temperature (OISST) Version 2.1
- **Spatial resolution:** 27,830 m
- **Temporal resolution:** Daily (from 1981-09-01)
- **Description:** Long-term SST standard deviation on the site, derived from 1981 to 2023 daily SST values
- **Used for:** Training and prediction
- **Percentage of missing values:** 1.96 % (training) and 1.8 % (prediction)

23. sst_skewness

- **Category:** Thermal regime
- **Data source:** NOAA CDR Optimum Interpolation Sea Surface Temperature (OISST) Version 2.1
- **Spatial resolution:** 27,830 m
- **Temporal resolution:** Daily (from 1981-09-01)
- **Description:** Long-term SST skewness on the site, derived from 1981 to 2023 daily SST values
- **Used for:** Training and prediction
- **Percentage of missing values:** 1.96 % (training) and 1.8 % (prediction)

24. ssta_max

- **Category:** Thermal regime
- **Data source:** CoralTemp Version 3.1 (Skirving et al., 2020)
- **Spatial resolution:** 5 km
- **Temporal resolution:** Daily (from 1985-01-01)
- **Description:** Maximum SST anomaly values on the site for the year i
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 11.48 % (prediction)

25. ssta_mean

- **Category:** Thermal regime
- **Data source:** CoralTemp Version 3.1 (Skirving et al., 2020)
- **Spatial resolution:** 5 km
- **Temporal resolution:** Daily (from 1985-01-01)
- **Description:** Mean SST anomaly values on the site for the year i
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 11.48 % (prediction)

26. territory

- **Category:** Geographic
- **Data source:** Flanders Marine Institute (2023)
- **Spatial resolution:** Unknown
- **Temporal resolution:** None
- **Description:** Country or territory associated to the site
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 0 % (prediction)

27. verbatimDepth

- **Category:** Geographic
- **Data source:** gcrmndb_benthos
- **Spatial resolution:** Unknown, but variable
- **Temporal resolution:** None
- **Description:** The depth at which percentage cover measurements were made
- **Used for:** Training
- **Percentage of missing values:** 23.28 % (training)

28. wind_speed_y5

- **Category:** Cyclone regime
- **Data source:** International Best Track Archive for Climate Stewardship (IBTrACS) Version 4 (Knapp et al., 2010)
- **Spatial resolution:** 0.1° (~10 km)
- **Temporal resolution:** 3 hourly (interpolated, most raw data are 6 hourly)
- **Description:** Maximum sustained wind speed of cyclones passed within 1° (~ 111 km) from the site over the 5 past years from the year i
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 0 % (prediction)

29. year

- **Category:** Temporal
- **Data source:** gcrmndb_benthos / Generated
- **Spatial resolution:** None
- **Temporal resolution:** None
- **Description:** The year at which the measurement of percentage cover was done
- **Used for:** Training and prediction
- **Percentage of missing values:** 0 % (training) and 0 % (prediction)

Following the extraction of predictor values for all the sites, we checked the number of missing values and the distribution of values for each predictor.

The performance of GBM models is not affected by the inclusion of non-informative predictors because these models are intrinsically conducting feature selection (Kuhn & Johnson, 2013). Feature selection consists of removing correlated predictors, which can be seen as a redundant set of information (Boehmke & Greenwell, 2020). Although the feature selection was not an essential step, we checked the Pearson correlation coefficients between predictors by performing pairwise linear regressions, and removed predictors with coefficients greater than 0.90 or lower than -0.90. This step has been added to decrease computation time of the models. Following the feature selection step, we removed the predictor "sst_mean", which was the mean annual SST values on the site.

The high predictive capabilities of ML are usually limited by the availability of training data, including the possibility of integrating enough predictors at a sufficient spatio-temporal resolution. All factors known to play a role on the percentage cover of benthic categories cannot be included within the modeling framework due to the lack of available data. For example, while COTS outbreaks are a major driver of hard coral cover in the Indo-Pacific, the limited number of monitoring programs quantifying COTS abundance does not allow this variable to be used as a predictor (Haywood et al., 2019; Pratchett et al., 2017). In addition to the availability of predictors, there is also the problem of their spatio-temporal resolution. Indeed, we have assumed that the values of predictors extracted accurately represented true values, the ones that would have been measured by a probe at a given site on a given date. However, we recognize that the spatio-temporal resolution of some predictors is insufficient to consider small-scale variations. For example, high differences in SST may arise within a pixel of 5 km square (Green et al., 2019), which is the resolution of CoralTemp NOAA data (Skirving et al., 2020). Moreover, by definition, SST data do not take into account temperature variations at depth, even though these can be significant (Leichter et al., 2006).

Machine learning models

ML encompasses a wide range of methods (e.g. support vector machine, random forest) that can be used either for classification or regression (Boehmke & Greenwell, 2020). Among all these methods, we chose to use Gradient Boosting Machine (GBM, also known as Boosted Regression Trees), and more particularly XGBoost (Chen and Guestrin, 2016), for its performance (Boehmke & Greenwell, 2020; Chen & Guestrin, 2016).

The main issue related to ML is overfitting, which is the ability of the model to perform extremely well on the dataset on which it was trained, but poorly on a new dataset (Kuhn & Johnson, 2013). The first solution to limit overfitting is to split the initial dataset into a training dataset and a testing dataset. The training dataset is used to train the model, and the testing dataset is used to test if the model performs well or not on a new dataset. For our analysis, we used a split of 3/4, resulting in 75% of observations from the initial dataset (*i.e.* rows) attributed to the training dataset and 25% to the testing dataset (Table 3.4).

GBM includes different hyperparameters that must be tuned to improve model performance and limit overfitting. More specifically, model tuning consists of finding the best set of hyperparameters that lead to the model with the highest predictive performance. We performed model tuning by testing 30 combinations of four model hyperparameters, namely learning rate, number of trees, tree depth, and minimum observation per leave (Table 3.5). The learning rate hyperparameter (also known as shrinkage) corresponds to how quickly the algorithm proceeds down the gradient descent. The number of trees hyperparameter corresponds to the number of trees in the ensemble. The tree depth hyperparameter is the number of levels of a tree. The minimum observation per leaf hyperparameter corresponds to the minimum number of observations used for a leaf. The 30 combinations of these four model hyperparameters were generated in such a way that all regions of the hyperparameters space have an observed combination (*i.e.* to maximize the entropy). Model performance during hyperparameter tuning was assessed using a 5-fold cross-validation on training data.

▼ **Table 3.4.** Comparison of the number of observations used to train (column "Training") and test (column "Testing") the ML models used to estimate temporal trends for each of the four major benthic categories and the three major hard coral families. The total number of rows of the initial dataset is equal to the sum of values of the two columns for a given category.

	Training	Testing
Benthic categories		
Hard coral	24,460	8,154
Coralline algae	17,366	5,789
Macroalgae	19,816	6,606
Turf algae	19,327	6,443
Hard coral families		
Acroporidae	17,076	5,693
Pocilloporidae	13,733	4,578
Poritidae	13,586	4,529

▼ **Table 3.5.** Comparison of the number of observations used to train (column "Training") and test (column "Testing") the ML models used to estimate temporal trends for each of the four major benthic categories and the three major hard coral families. The total number of rows of the initial dataset is equal to the sum of values of the two columns for a given category.

	Learning rate	Nb trees	Tree depth	Min. obs.
Benthic categories				
Hard coral	0.0844	1997	5	38
Coralline algae	0.0173	1213	11	11
Macroalgae	0.00433	1954	11	8
Turf algae	0.0321	1153	15	20
Hard coral families				
Acroporidae	0.0146	1868	10	11
Pocilloporidae	0.0114	945	12	38
Poritidae	0.0741	1079	12	16

Models evaluation

Once each ML model was fitted, we evaluated it by checking their predictive performance and interpreting their outcomes.

Model performance

The Root Mean Square Error (RMSE) is the most common metric used to evaluate the performance of ML regression models. Since RMSE is expressed in the same unit as the variable predicted, it represents an easy-to-interpret metric (Kuhn & Johnson, 2013). For example, a RMSE value of 5 means that the value predicted by the model differed, on average, by 5 percent of hard coral cover. Hence, the lower the RMSE value, the better the model's predictive performance. We calculated the RMSE as follows:

Eq. 3.6 ▶

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}}$$

where n is the number of observations, y_i is the observed value i, and $\hat{y}_i$ the predicted value i. In addition to the RMSE, we also calculated the R² (also known as R-squared or coefficient of determination), which is a widely used metric in statistics, particularly for linear regression. R² is usually interpreted as the proportion of the information from the data that is explained by the model (Kuhn & Johnson, 2013). For example, an R² of 0.80 indicates that the model explains 80% of the variation of the data. We calculated R² as follows:

Eq. 3.7 ▶

$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2}$$

where n is the number of observations, y_i is the observed value i, $\hat{y}_i$ the predicted value i, and $\bar{y}$ the mean of observed values. RMSE and R² represent two complementary metrics of model performance. Indeed, RMSE describes how well the model performs on average, while R² provides a measure of correlation (Kuhn & Johnson, 2013).

Metrics for regression models such as RMSE and R² are not sufficient alone to estimate the performance of a ML model. Indeed, these metrics provide a single value to evaluate the overall performance of the ML model and can mask poor predictions over certain ranges of variation of the variable to be predicted. For this reason, we plotted predicted versus observed values on the testing dataset (Supplementary Figures 5 and 6).

Model interpretation

Although ML models are sometimes described as "black box" models, there exists in fact different tools to interpret these models (Biecek & Burzykowski, 2021; Boehmke & Greenwell, 2020). We used variable importance plots (VIMP, see page 207 in Kuhn & Johnson, 2013) to compare the relative influence of each predictor on the percentage cover of each of the four major benthic categories and the three major hard coral families. However, we restricted our interpretations of the VIMP to model evaluation rather than using them for their explicative capabilities. For example, having included “datasetID” as a predictor for training the ML models made it possible to identify problematic datasets. Indeed, if a given individual dataset ID is among the predictors with the highest relative importance, this is likely to indicate that the observations in this dataset are different from those of the other datasets. Hence, interpretation of VIMP can also be seen as a third way to control data quality, along quality checks (see “Quality checks”) and exploratory data analysis (see “Exploratory data analysis”).

Predictions

Contrary to other modeling approaches such as Bayesian models, like the one used for the previous GCRMN global report (Souter et al, 2021), ML models are not intrinsically built to consider uncertainty (Rubbens et al., 2023). However, confidence intervals can be estimated for ML models using bootstrap. Bootstrapping consists of sampling randomly the initial dataset with replacement, to produce variability within the new dataset (Boehmke & Greenwell, 2020). This means that the number of initial rows remained the same, but that some rows were either removed, present one time, or duplicated (one or several times) into the new dataset, due to the sampling. We fitted 50 ML models for each of the four major benthic categories and the three major hard coral families, by training the model on a new dataset, generated through bootstrapping, while using the set of tuning parameters of the initial model (Table 3.5). Indeed, the hyperparameters tuning step was not repeated for each new bootstrapped dataset for computation time limit reasons.

We predicted values of percentage cover for each of the four major benthic categories and the three major hard coral families, across 10,000 sites over the Pacific. For each site, values were predicted for 43 years (*i.e.* from 1980 to 2023), resulting in a total of 430,00 predictions of percentage cover values performed by each ML model. These predictions were obtained for the 50 bootstrap iterations. Because we were interested in temporal trends at a higher spatial level than sites, we averaged the predictions per country or territory and over the entire Pacific region, for each year and each bootstrap iteration.

Although we used the models to predict the percentage cover from 1980 to 2023, we filtered only the estimates from 1990 to 2022. This choice was motivated by unreliable estimates outside this period, due to the limited number of observed data (see Figure 1.3.1.) and a large number of missing data for certain key predictors over the 1980s.

We then determined the mean percentage cover for each of the four main benthic categories and the three dominant hard coral families for each year across the 50 bootstrap iterations. Additionally, we estimated the 95% and 80% confidence intervals around the mean by calculating the upper and lower bounds using the 0.95 and 0.05 quantiles, as well as the 0.80 and 0.20 quantiles, respectively.

To assess the presence of trends, we applied Mann-Kendall statistical tests to the mean percentage cover values estimated by the ML models from 1990 to 2022, for each of the four major benthic categories and the three dominant hard coral families. These tests were conducted using a significance level of $\alpha = 0.05$.

Finally, to improve the visualization of temporal trends, we smoothed the mean percentage cover values and confidence intervals using a two-year, center-aligned moving average.

Code availability

All the scripts used to produce values, tables, figures, and maps presented in this report can be consulted at https://github.com/GCRMN/pacific_2023.

Google Earth Engine (Gorelick et al., 2017) was used for some data analysis scripts using the JavaScript language. Machine learning R scripts were run on an RStudio Server hosted on a Google Cloud Virtual Machine of 50 GB storage capacity, 64 GB RAM, and 8 CPU, operated on Ubuntu. All other R scripts were run on a personal computer with a 236 GB storage capacity, 32 GB RAM, and 6 CPU, operated on Windows 11.

Most of the analyses were assessed using R software version 4.4.2 (R Core Team, 2024) and predominantly packages tidyverse (Wickham et al, 2019), tidymodels (Kuhn et al, 2020), terra (Hijmans, 2025), tidyterra (Hernangómez, 2023), patchwork (Perdersen, 2024), sf (Pebesma, 2018). Versions of all R packages used are provided within the README of the GitHub repository (https://github.com/GCRMN/pacific_2023).

AUTHORS' CONTRIBUTIONS

A co-author is defined as any individual who contributed directly or indirectly to the development of this report. To account for variations in the nature and extent of these contributions, we employed a modified version of the Contributor Role Taxonomy (CRediT). We identified 16 distinct types of contributions encompassing the range of activities involved from the inception of the report to its final publication. In the table below, 'Participation in workshop' refers specifically to the in-person attendance of an author at the workshop held in Auckland, New Zealand, from 16 to 18 November 2023 for the kick-off of the production of the report. An 'X' denotes that a co-author engaged in the activity listed in the column header, while 'W' and 'R' indicate that the co-author contributed to the writing or reviewing of the respective section, respectively.

	Funding acquisition	Supervision	Conceptualization	Facilitation	Data acquisition	Data integration	Data analysis	Participation to workshop	Executive summary	Synthesis for the region	Syntheses for count. and terr.	Case studies	Materials and Methods	Supplementary Materials	Layout	Communication
Mehdi **Adjeroud**					X					R	W		R	R		
Mary **Allen**												W				
Abigail **Alling**					X											
Jeanine **Almany**															X	
Phoebe **Argyle**					X			X			W		R			
Mary **Bonin**					X											
Jonathan **Booth**					X											
Tracey **Boslogo**					X											
Valerie **Brown**												W				
Sara **Cannon**					X											
Yannick **Chancerelle**					X						R					
Liam **Clegg**					X											
Anne **Cohen**					X											
Kitty **Currier**					X					R			R	R		
Thomas **Dallison**	X		X	X				X	R	R						X
Emily **Darling**													R			
Alexandra C. **Dempsey**					X			X			W					
Orla **Doherty**					X											
Simon **Donner**					X						W					

	Funding acquisition	Supervision	Conceptualization	Facilitation	Data acquisition	Data integration	Data analysis	Participation to workshop	Executive summary	Synthesis for the region	Syntheses for count. and terr.	Case studies	Materials and Methods	Supplementary Materials	Layout	Communication
Sirilo **Dulunaqio**					X						W					
Janelle **Eagle**					X											
Graham J. **Edgar**					X											
Andy **Estep**					X											
Viliami **Fatongiatau**												W				
Martin **Finau**												W				
Amanda **Ford**											W					
Michael **Fox**					X											
Jan **Freiwald**				X	X											
Beverly **French**					X			X								
Antoine **Gilbert**					X			X								
Yimnang **Golbuu**					X											
Nicolas **Guillemot**					X			X		R	W		R	R		
Tevita **Havea**												W				
Tom **Heintz**					X					R	W					
Eryn **Hooper**					X											
Peter **Houk**					X						W					
Alec **Hughes**					X											
Sandrine **Job**					X			X			W		R	R		
Johanna **Johnson**					X					R	W		R			
Geoffrey **Jones**					X											
Stacy **Jupiter**					X											
Rocky **Kaku**					X											
Malnoa **Karo**					X											
Mohsen **Kayal**					X					R	W		R	R		
Adi **Khen**					X			X			W					
Kelly **Kozar**					X											
Uali **Kula**					X											
July **Kuri**					X											
Didier **Labrousse**					X											
Tonga **Latu Tuiano**												W				
Florian **Le Bail**					X											
Enelio **Liufau**					X											
Katie **Lubarsky**					X											

	Funding acquisition	Supervision	Conceptualization	Facilitation	Data acquisition	Data integration	Data analysis	Participation to workshop	Executive summary	Synthesis for the region	Syntheses for count. and terr.	Case studies	Materials and Methods	Supplementary Materials	Layout	Communication
Sosefo **Malau**					X											
Sangeeta **Mangubhai**					X					R	W					
Derek **Manzello**												W				
Ateliana **Maugateau**					X											
Mark **McCormick**					X											
Sheila **McKenna**					X					R	W		R			
Jenny **Mihaly**				X	X											
Carol **Milner**					X											
Bradley **Moore**					X											
Kirby **Morejohn**					X											
Winfred **Mudong**												W				
Elizah **Nagombi**					X											
Yashika **Nand**					X						W					
Stephen **Neale**					X											
Victor **Nestor**					X			X			W					
Mike **Neuman**					X											
Poasi **Ngaluafe**					X											
David **Obura**					X											
Lizzi **Oh**					X			X					R			
Thomas **Oliver**													R	R		
Julie **Pagot**					X											
Selma **Pamalok**					X											
Michael **Parrish**					X						R					
Nicole **Pedersen**				X	X			X			W					
Lucie **Penin**					X						R					
Serge **Planes**	X	X	X		X			X	W	W			R	R		X
Morgan **Pomeroy**												W				
Lena **Porte**					X											
Geraldine **Rengiil**					X											
Nicolas **Rocle**				X				X								X
Randi **Rotjan**					X											
Stuart **Sandin**					X											
Annisah **Sapul**					X											
Gilles **Siu**					X						R					

	Funding acquisition	Supervision	Conceptualization	Facilitation	Data acquisition	Data integration	Data analysis	Participation to workshop	Executive summary	Synthesis for the region	Syntheses for count. and terr.	Case studies	Materials and Methods	Supplementary Materials	Layout	Communication
Patrick **Smallhorn-West**					X						W	W	R			
Jennifer **Smith**					X						W					
Ada **Sokach**					X											
Lucy **Southworth**											W	W				
Blake **Spady**												W				
Maya **Srinivasan**					X			X								
Francis **Staub**	X	X														X
Karen **Stone**					X						W					
Rick D. **Stuart-Smith**					X											
Heather **Summers**					X											
Helen **Sykes**					X											
Aranteiti **Tekiau**								X								
Erica K. **Towle**		X	X	X	X				W	W	W	R		R		
Visesio **Uluika**					X											
Schannel **van Dijken**					X											
Paino **Vanai**					X											
Laurent **Wantiez**					X			X			W	W	R			
Jane **Waterhouse**					X											
David **Welch**					X											
Jérémy **Wicquart**		X	X			X	X	X	W	W	W	R	W	W		X
Yvonne **Wong**					X											
Supin **Wongbusarakum**												W				
Ute **Zischka**					X											

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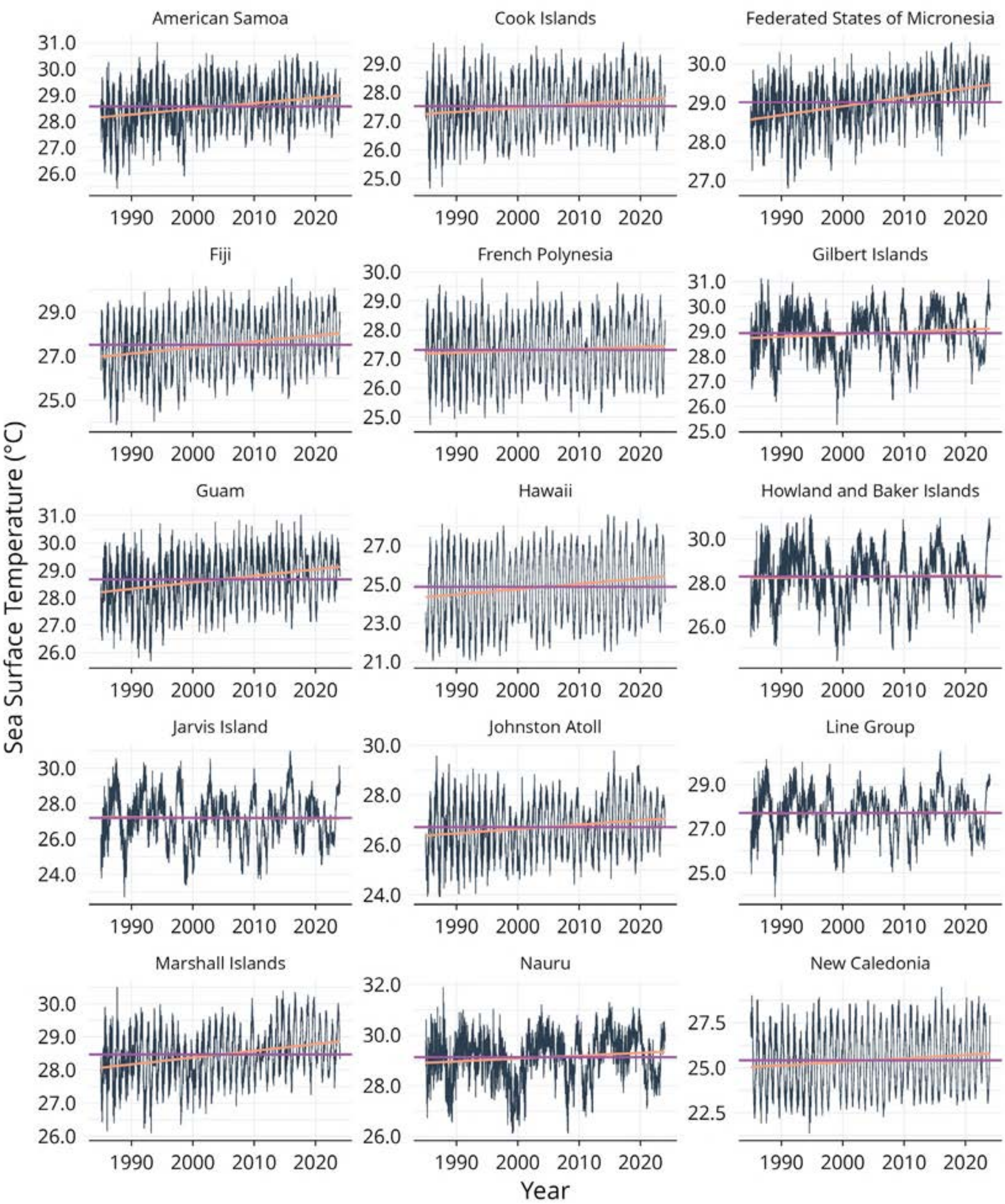
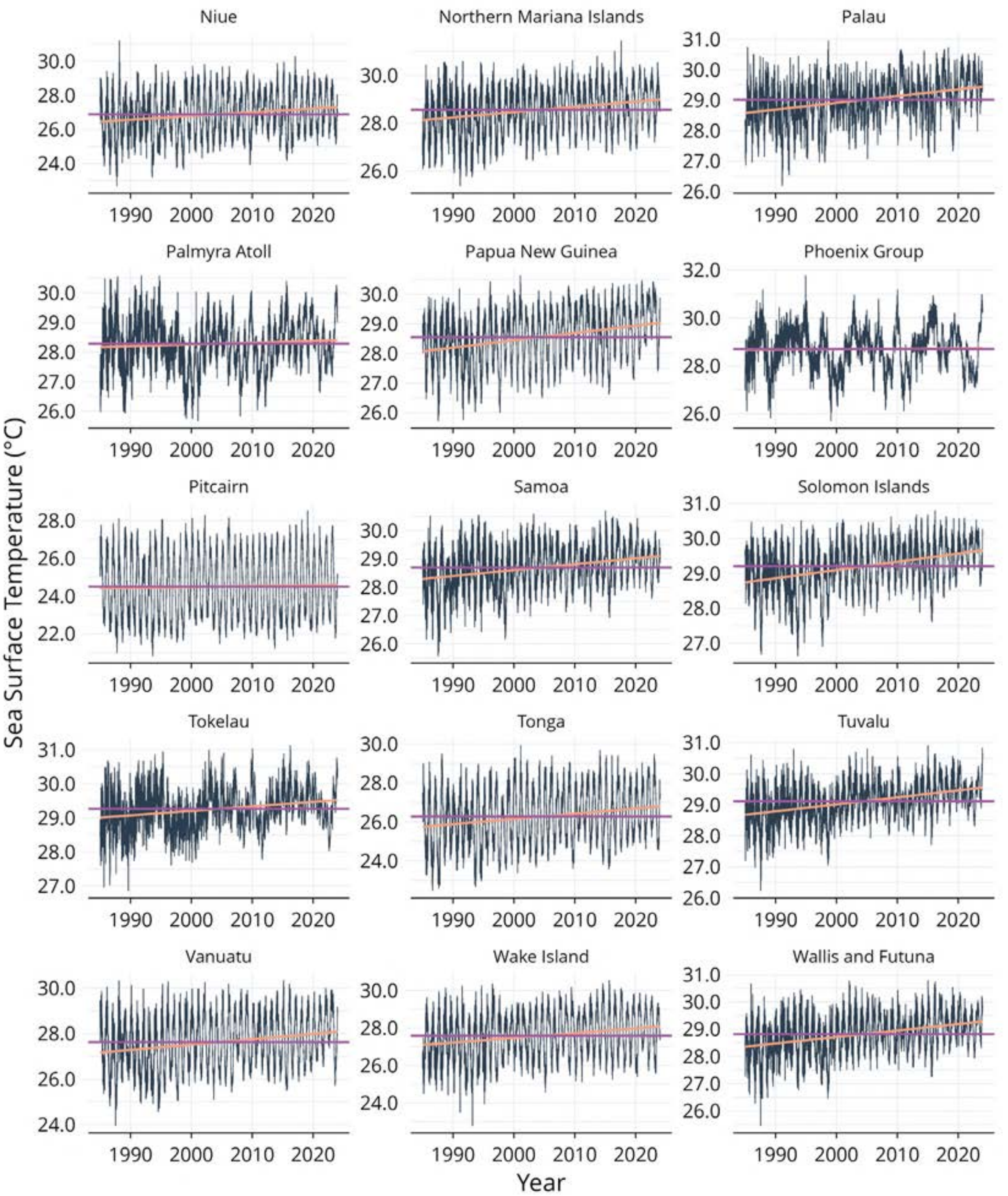
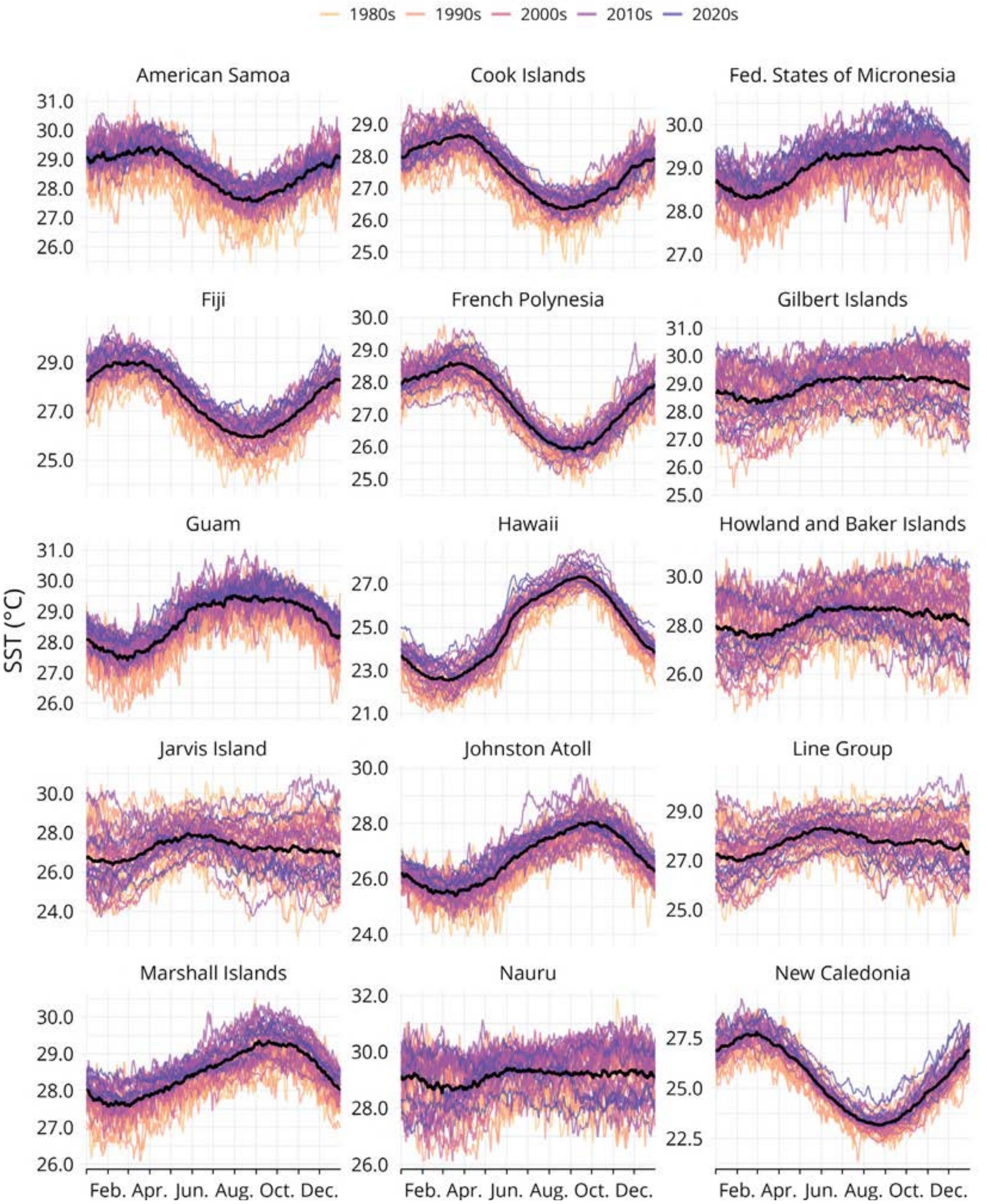
SUPPLEMENTARY MATERIALS



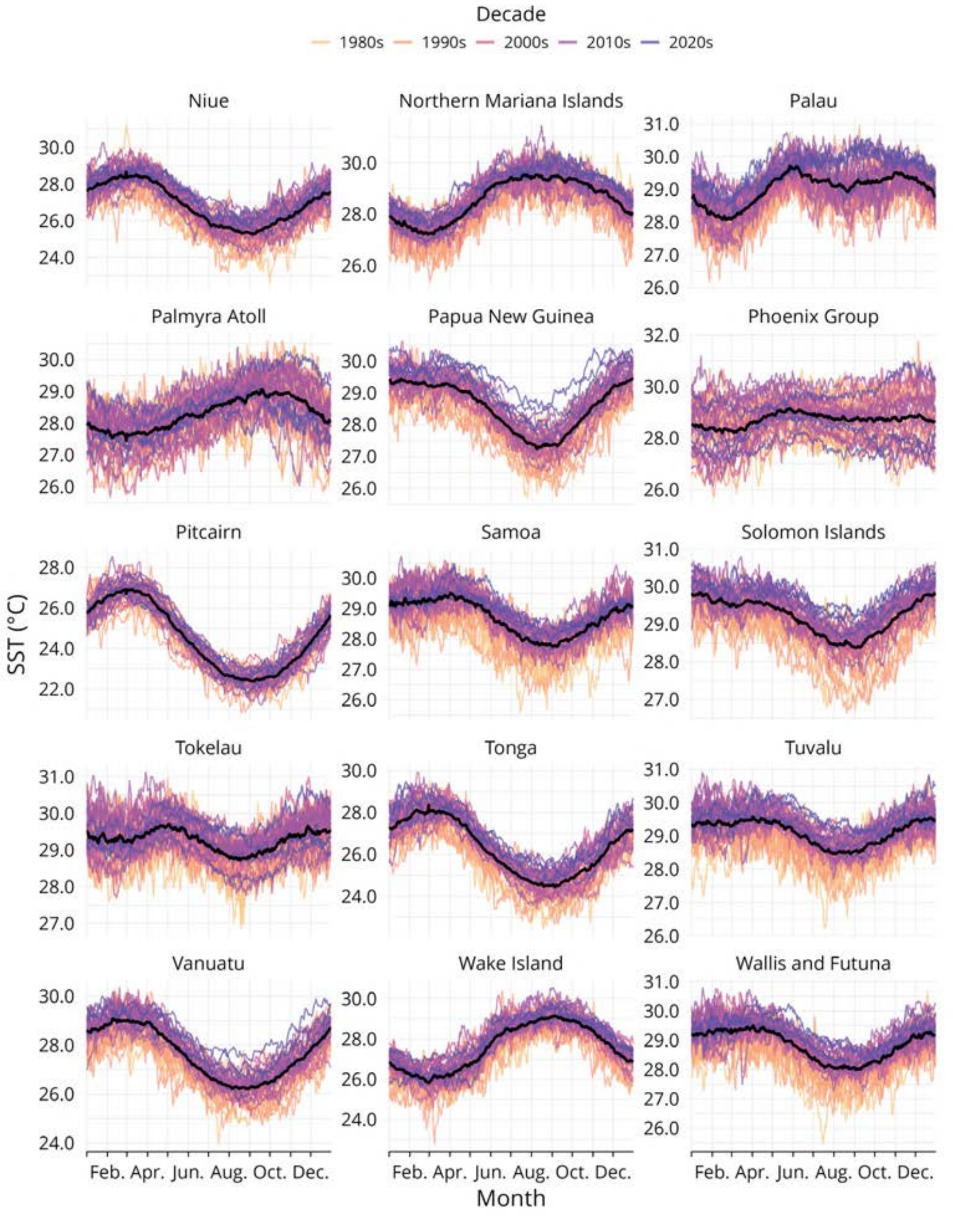
▲ **Supplementary Figure 1.** Average daily sea surface temperature (SST) from 1985 to 2023 over coral reefs of countries and territories of the Pacific. Purple lines represent the average SST over the 1985 to 2023 period, whereas the orange line represents the long-term trend.



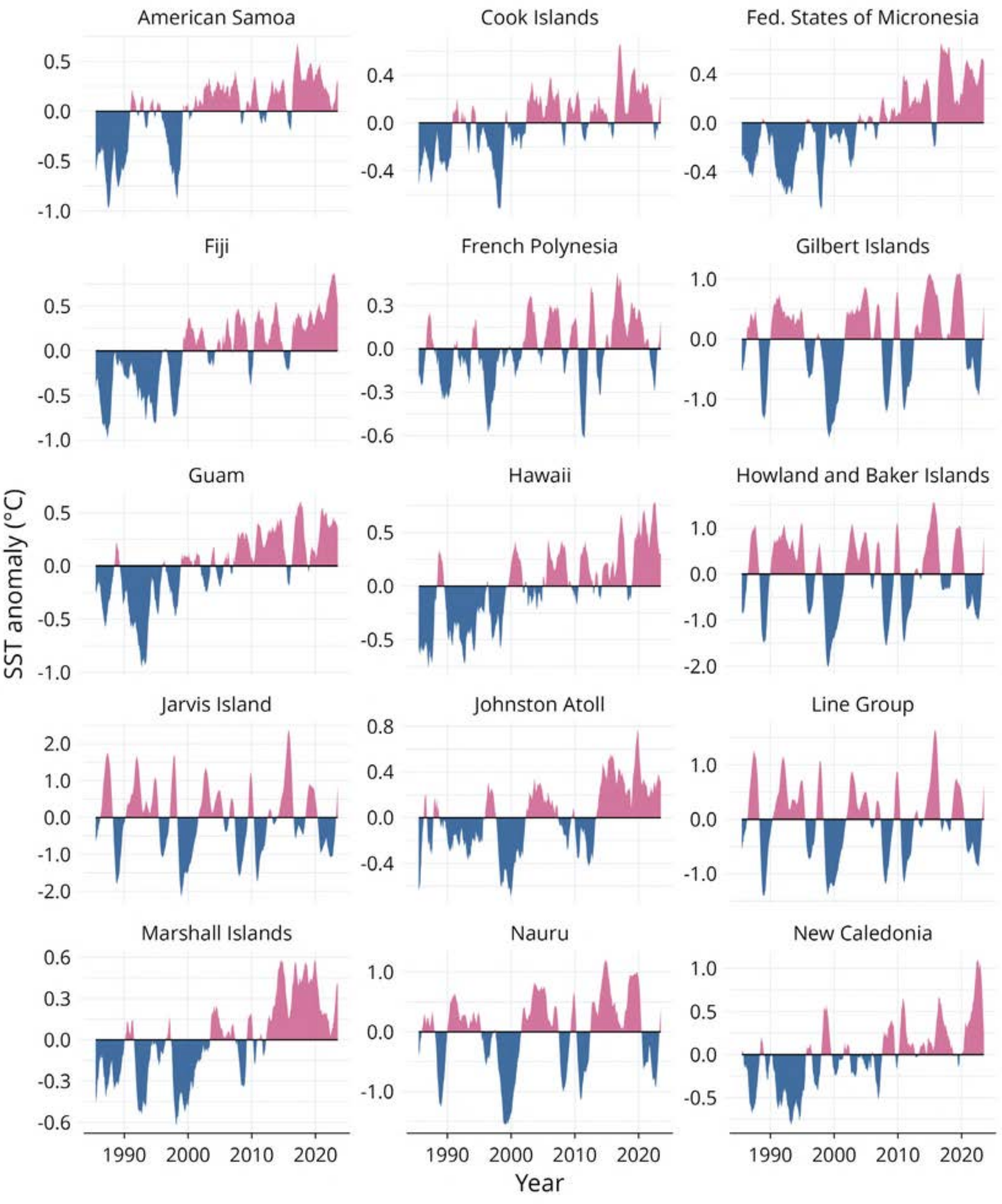
▲ **Supplementary Figure 1 (continuing).** Average daily sea surface temperature (SST) from 1985 to 2023 over coral reefs of countries and territories of the Pacific. Purple lines represent the average SST over the 1985 to 2023 period, whereas the orange line represents the long-term trend.



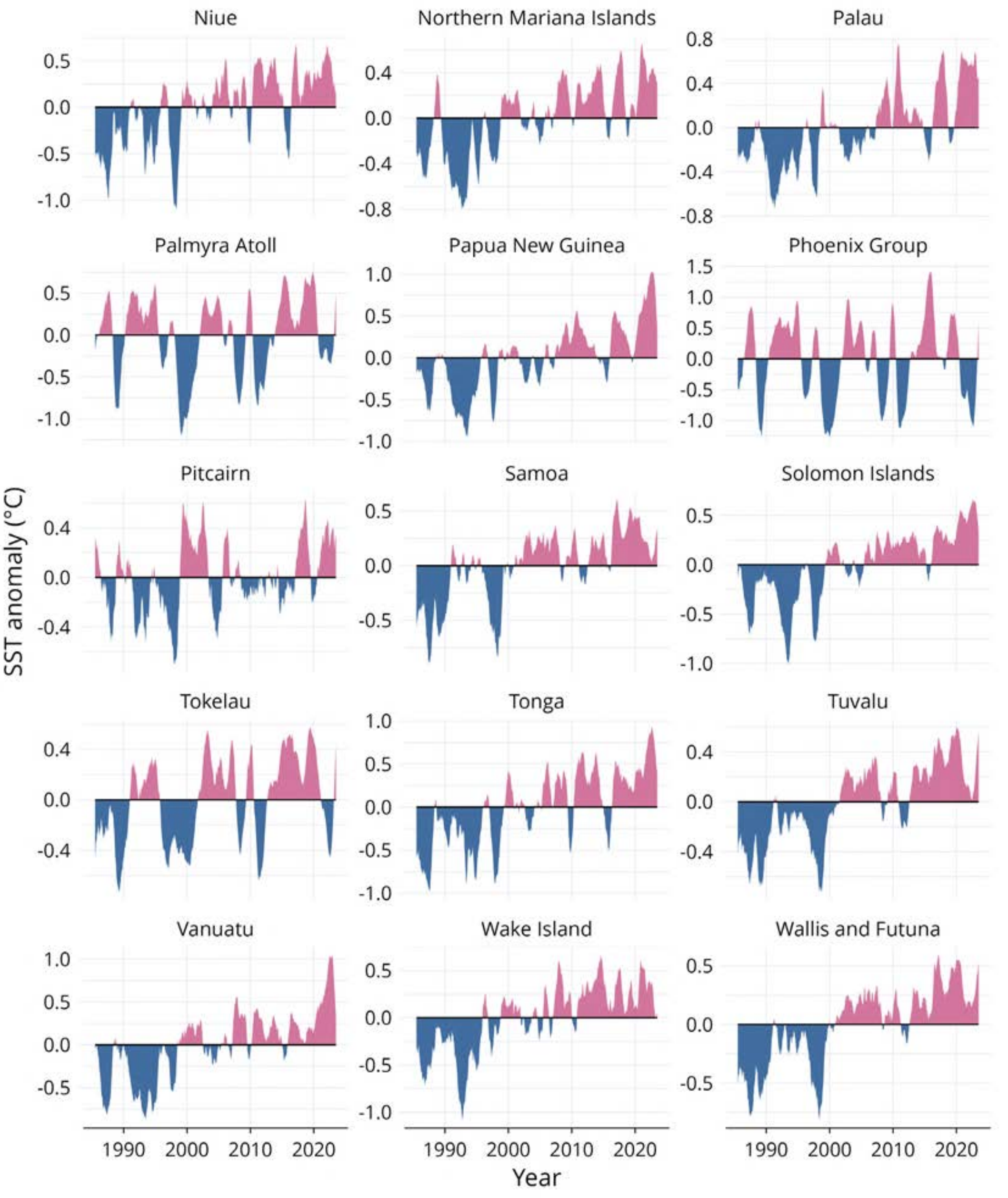
▲ **Supplementary Figure 2.** Annual Sea Surface Temperature (SST) curves from 1985 to 2023 over coral reefs of countries and territories of the Pacific. Each line, color coded by decade, corresponds to a unique year. The black line represents the interannual average SST from 1985 to 2023.



▲ **Supplementary Figure 2 (continuing).** Annual Sea Surface Temperature (SST) curves from 1985 to 2023 over coral reefs of countries and territories of the Pacific. Each line, color coded by decade, corresponds to a unique year. The black line represents the interannual average SST from 1985 to 2023.



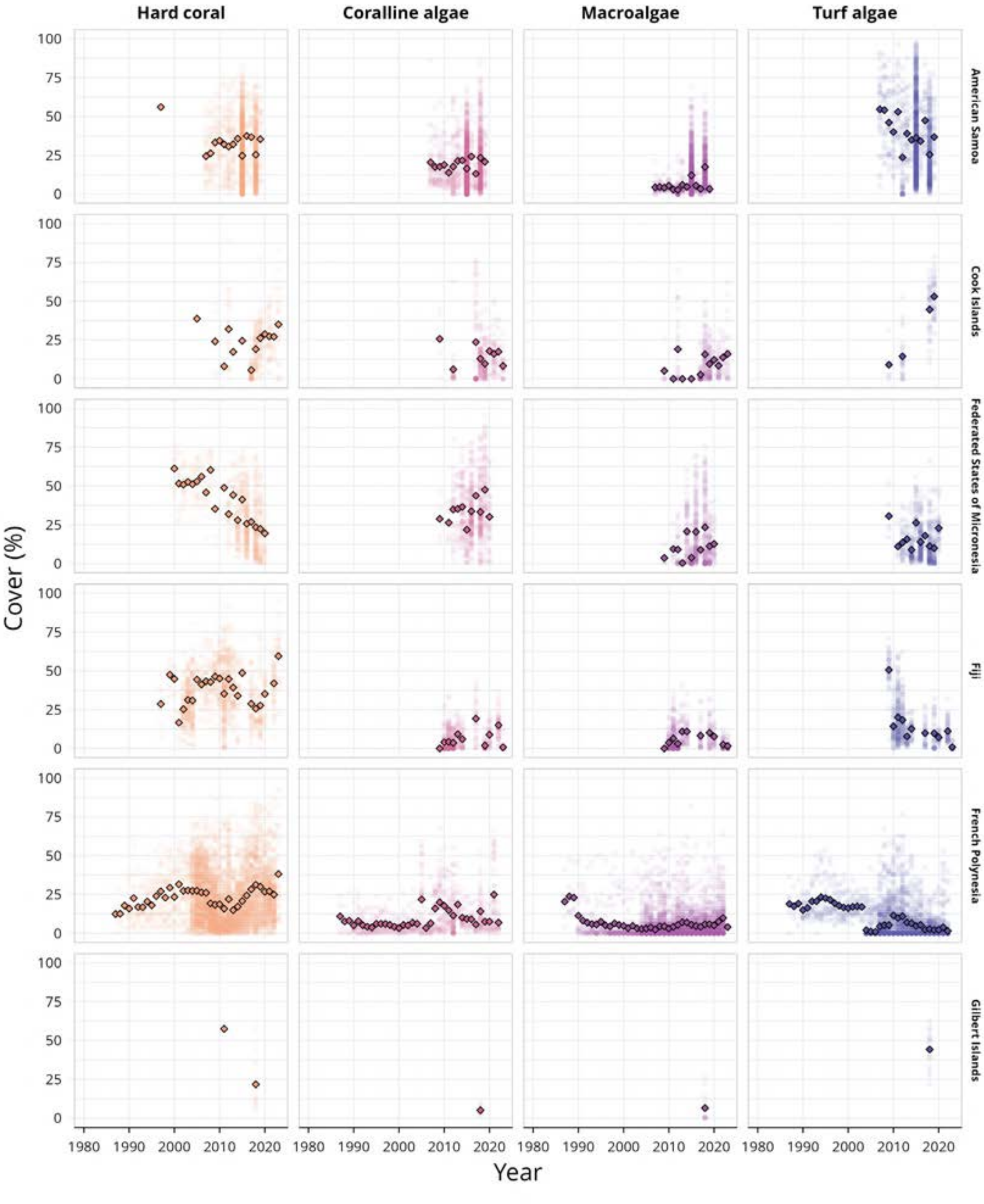
▲ **Supplementary Figure 3.** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of countries and territories of the Pacific. The black line represents a null SST anomaly; values below this line are negative SST anomalies (*i.e.*, cooler than the long-term average), and values above this line are positive SST anomalies (*i.e.*, warmer than the long-term average).



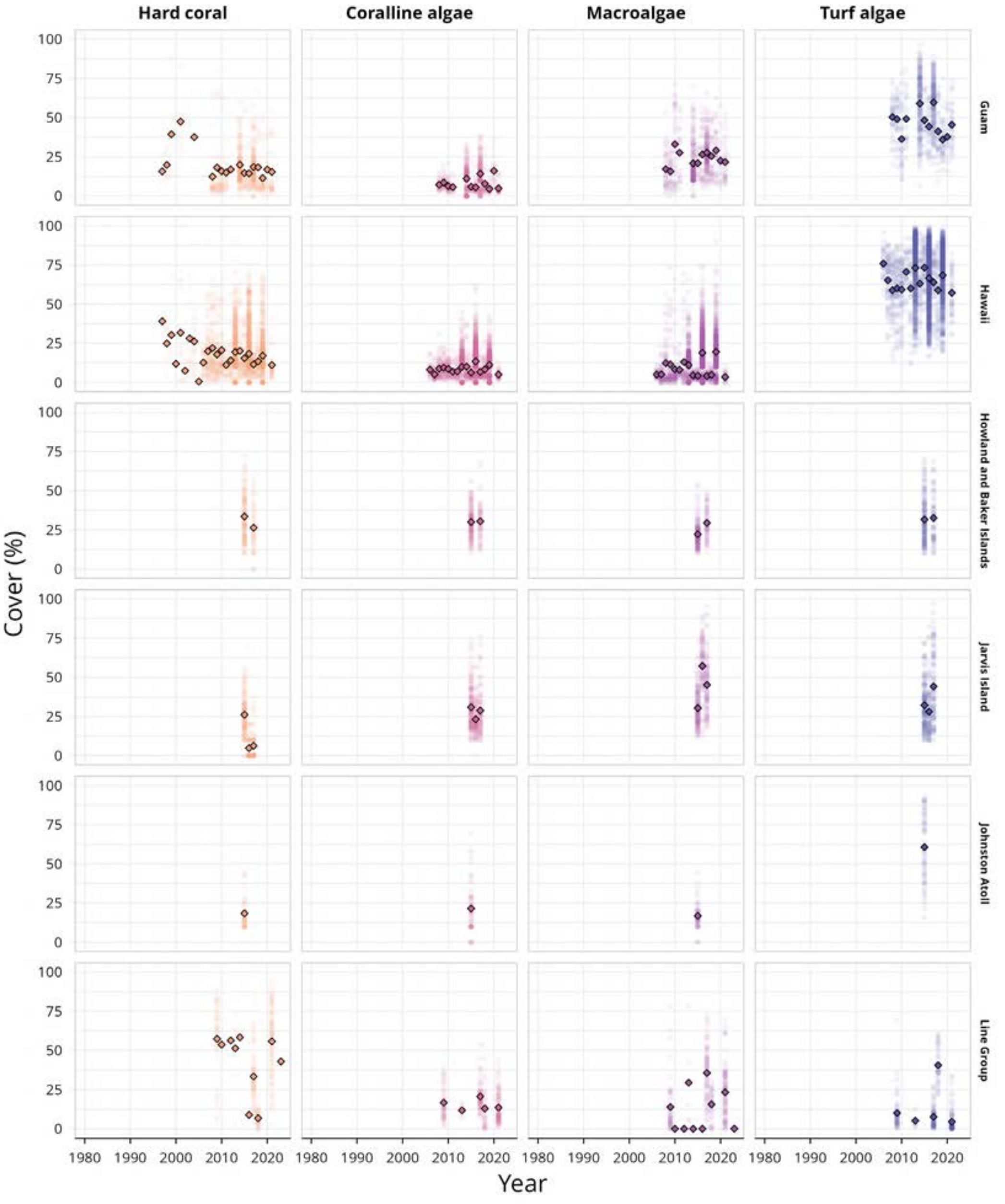
▲ **Supplementary Figure 3 (continuing).** Average Sea Surface Temperature (SST) anomaly from 1985 to 2023 over coral reefs of countries and territories of the Pacific. The black line represents a null SST anomaly; values below this line are negative SST anomalies (*i.e.*, cooler than the long-term average), and values above this line are positive SST anomalies (*i.e.*, warmer than the long-term average).

▼ **Supplementary Table 1.** List of individual datasets used for the analyses of benthic cover for each country and territory. The correspondences of each datasetID are provided in Table 5 of the gcrmndb_benthos.

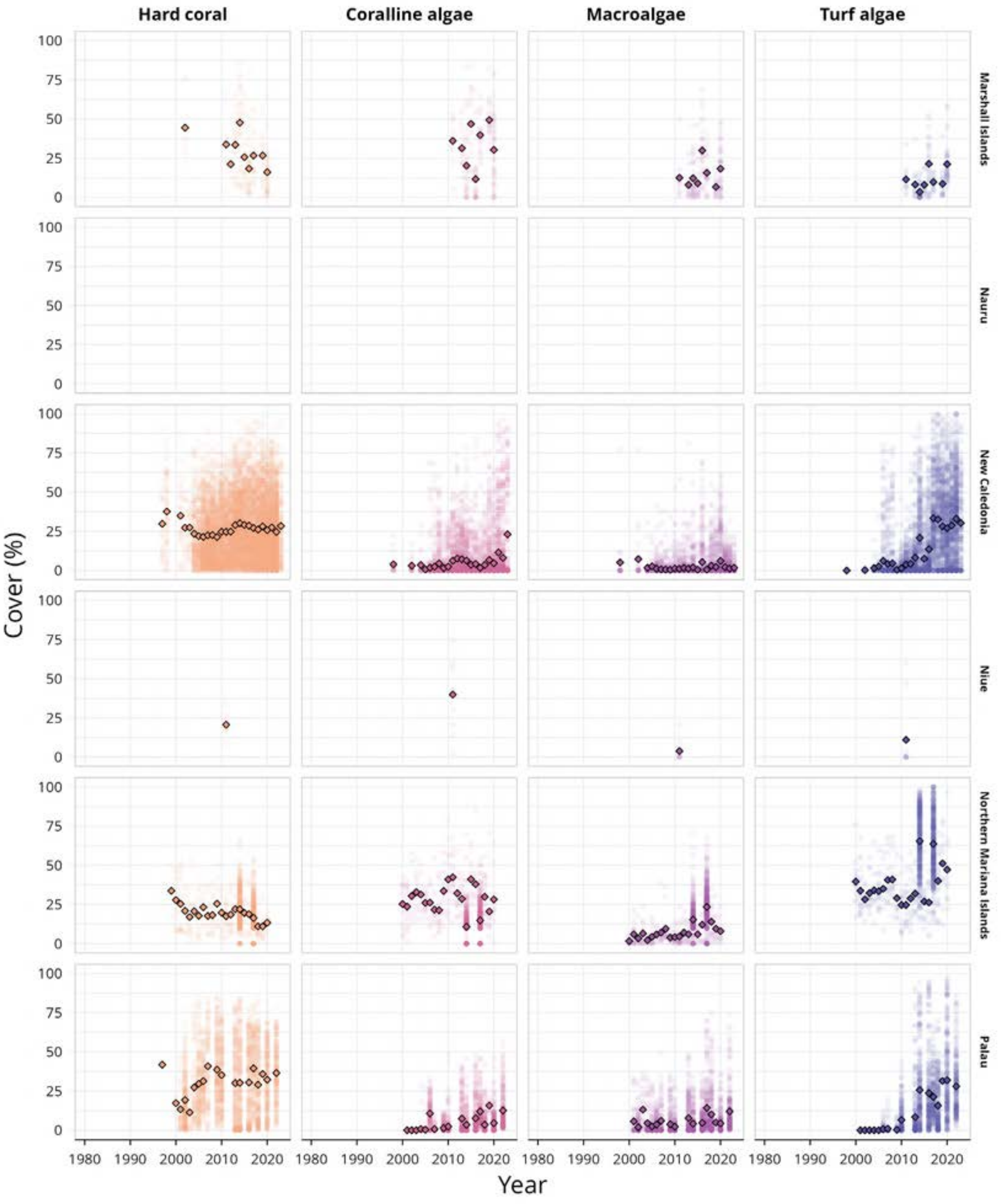
Countries and territories	ID of the datasets
Cook Islands	0011, 0015, 0020, 0038
Federated States of Micronesia	0005, 0015, 0038, 0039, 0043
Fiji	0015, 0022, 0043
French Polynesia	0010, 0015, 0025, 0026, 0027, 0031, 0032, 0033, 0034, 0035, 0045, 0046
Gilbert Islands	0004, 0005, 0006, 0007, 0008, 0015, 0038, 0049
Guam	0015, 0018
Hawaii	0012, 0015, 0020, 0022
Howland and Baker Islands	0013, 0015, 0020, 0038
Jarvis Island	0014
Johnston Atoll	0014
Line Group	0014
Marshall Islands	0005, 0043, 0054
Nauru	
New Caledonia	0015, 0017, 0019, 0021, 0023, 0024, 0041, 0048
Niue	0038
Northern Mariana Islands	0012, 0015, 0022
Palau	0015, 0043, 0044
Palmyra Atoll	0014, 0037
Papua New Guinea	0015, 0029, 0030, 0038
Phoenix Group	0051
Pitcairn	0005, 0038
Samoa	0005, 0038, 0043, 0055
Solomon Islands	0015, 0016, 0036, 0038
Tokelau	
Tonga	0005, 0015, 0038, 0040, 0052, 0053
Tuvalu	
Vanuatu	0015, 0028, 0061
Wake Island	0014
Wallis and Futuna	0050



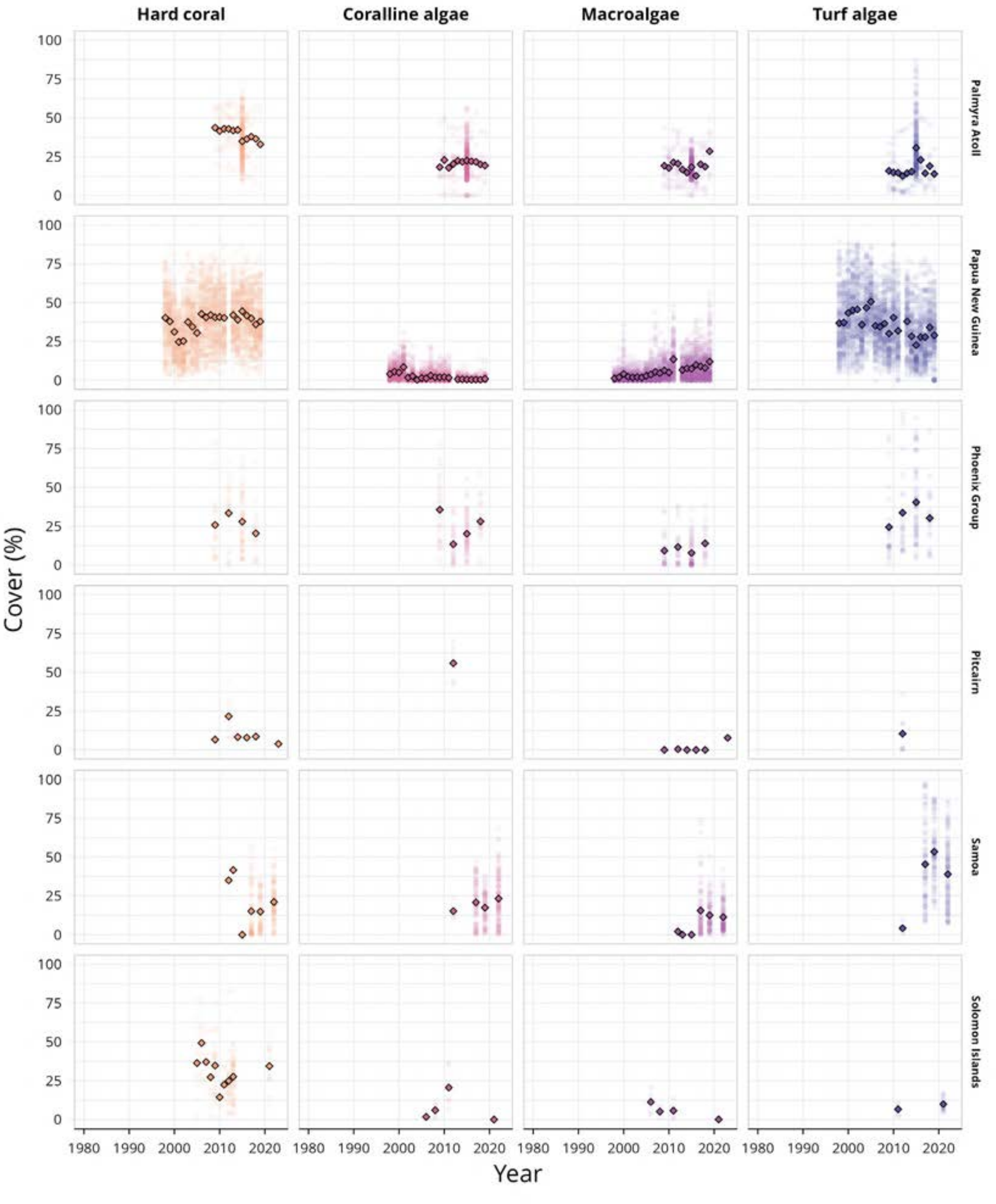
▲ **Supplementary Figure 4.** Raw data of percentage cover per country and territory for each major benthic category. Diamonds represent annual mean of percentage cover.



▲ **Supplementary Figure 4 (continuing).** Raw data of percentage cover per country and territory for each major benthic category. Diamonds represent annual mean of percentage cover.



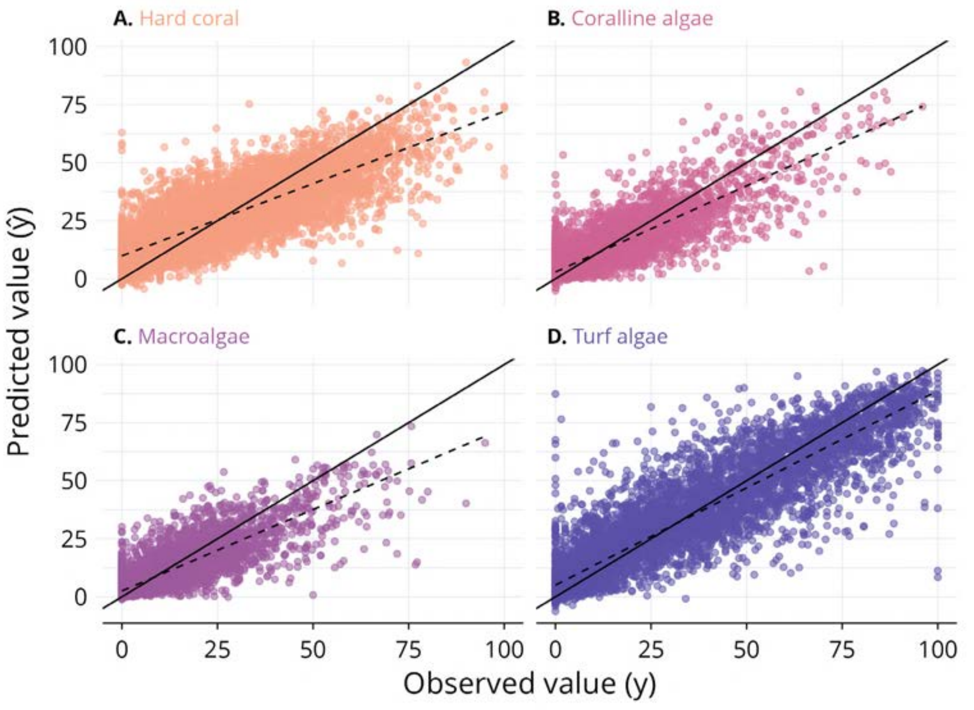
▲ **Supplementary Figure 4 (continuing).** Raw data of percentage cover per country and territory for each major benthic category. Diamonds represent annual mean of percentage cover.



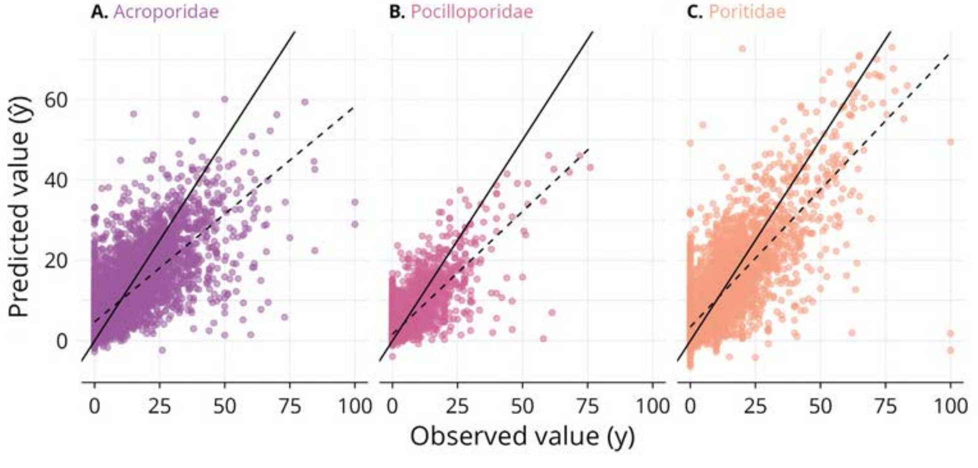
▲ **Supplementary Figure 4 (continuing).** Raw data of percentage cover per country and territory for each major benthic category. Diamonds represent annual mean of percentage cover.

▼ **Supplementary Table 2.** Comparison of Root Mean Squared Error (RMSE) values for major benthic categories for each country and territory.

Countries and territories	Hard coral	Coralline algae	Macroalgae	Turf algae
American Samoa	13.96	10.38	6.79	15.05
Cook Islands	14.32	14.42	8.47	9.24
Federated States of Micronesia	10.81	12.6	7.33	8.62
Fiji	13.9	6.58	6.03	11.12
French Polynesia	9.81	7.59	6.2	5.2
Guam	10.37	5.26	8.2	11.68
Hawaii	9.49	6.41	8.36	12.61
Kiribati				
Gilbert Islands	8.73	3.96	1.27	13.57
Line Group	13.96	7.99	10.07	7.15
Phoenix Group	20.17	15.43	10.51	18.33
Marshall Islands	14.49	14.24	10.23	12.8
Nauru				
New Caledonia	11.32	6.26	4.94	12.28
Niue	7.62	36.19	11.9	12
Northern Mariana Islands	9.91	8.5	8	13.26
Pacific Remote Island Areas				
Howland and Baker islands	14.47	9.81	7.1	12.38
Jarvis Island	10.37	8.43	11.11	11.89
Johnston Atoll	9.96	10.3	5.32	19.05
Palmyra Atoll	9.97	8.07	5.03	11.47
Wake Island	11.25	6.26	7.69	12.43
Palau	10.14	4.62	5.67	7.17
Papua New Guinea	11.25	2.9	4.31	10.77
Pitcairn	8.33	9.61	2.2	13.15
Samoa	7.92	7.03	5.59	9.32
Solomon Islands	13.86	12.63	6.1	5.99
Tokelau				
Tonga	12.07	9.22	5.33	16.5
Tuvalu				
Vanuatu	12.99		11.35	
Wallis and Futuna	10.44			3.85
Entire Pacific region	**10.10**	**6.18**	**5.66**	**9.43**

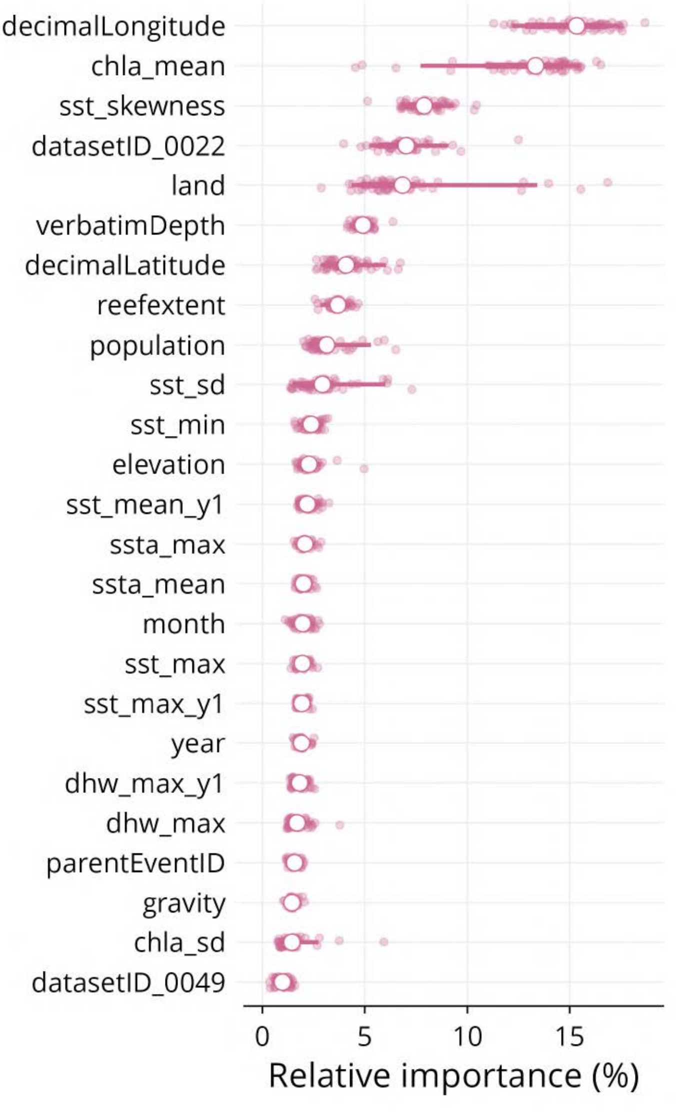


▲ **Supplementary Figure 5.** Observed percentage cover values (*y*) versus values predicted by the ML models (*ŷ*), for the four major benthic categories. The continuous black lines represent the ideal case where all predicted values would have been equal to observed values whereas the dashed black lines represent the linear regression between predicted values and observed values.

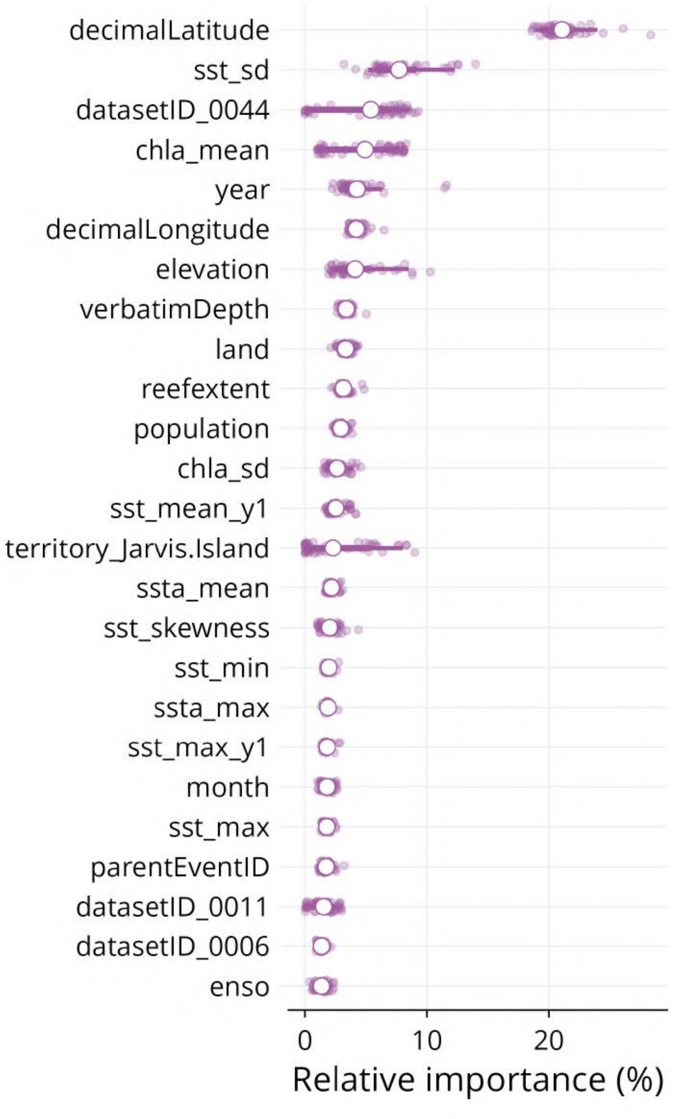


▲ **Supplementary Figure 6.** Observed percentage cover values (*y*) versus values predicted by the ML models (y *ŷ*), for the three hard coral families. The continuous black lines represent the ideal case where all predicted values would have been equal to observed values whereas the dashed black lines represent the linear regression between predicted values and observed values.

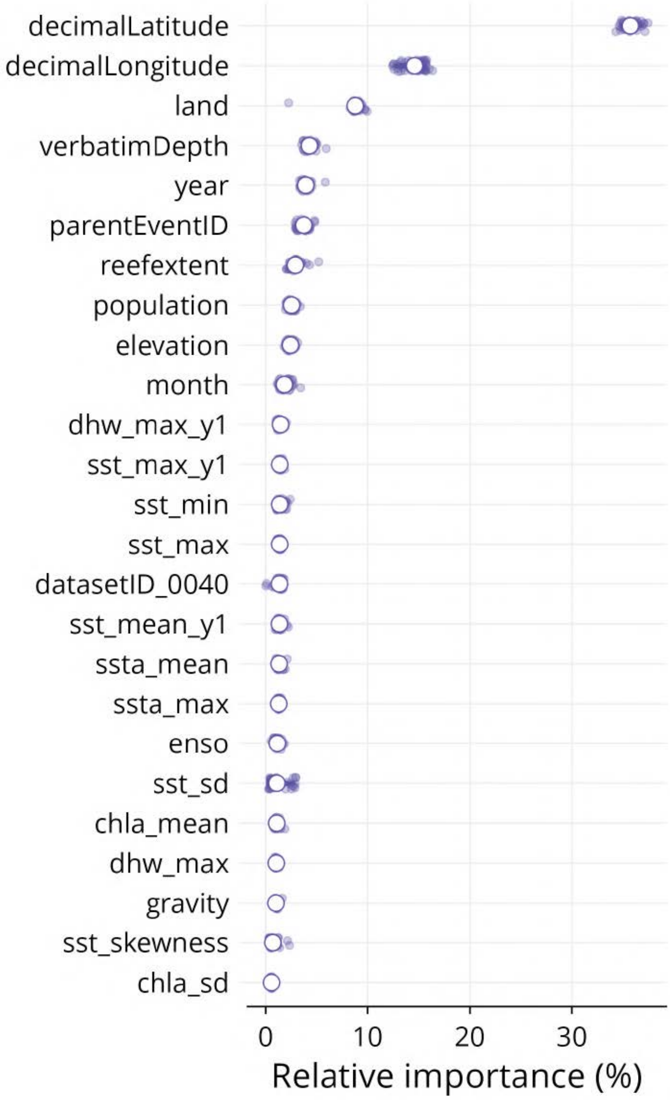
▲ **Supplementary Figure 7.** Variable importance plot for hard coral cover. Each point represents one iteration of the ML model, and white points represent the average of the 50 iterations. Descriptions of each predictor are provided in "6.2.3 Extraction of predictors" of the materials and methods.



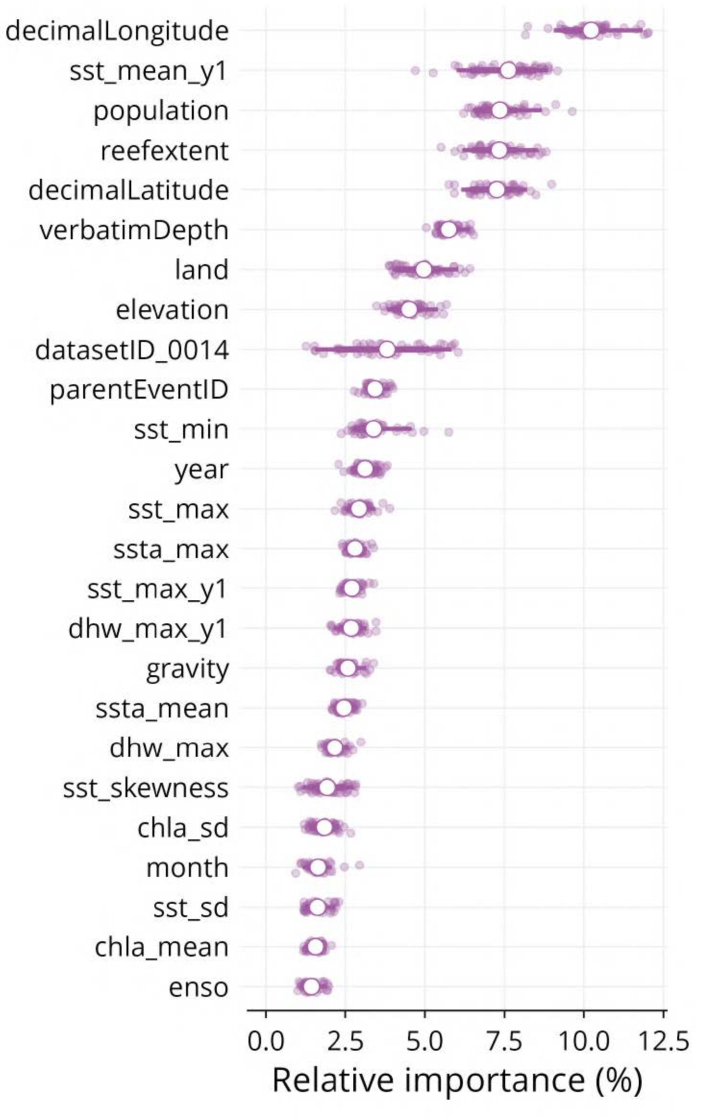
▲ **Supplementary Figure 8.** Variable importance plot for coralline algae cover. Each point represents one iteration of the ML model, and white points represent the average of the 50 iterations. Descriptions of each predictor are provided in "6.2.3 Extraction of predictors" of the materials and methods.



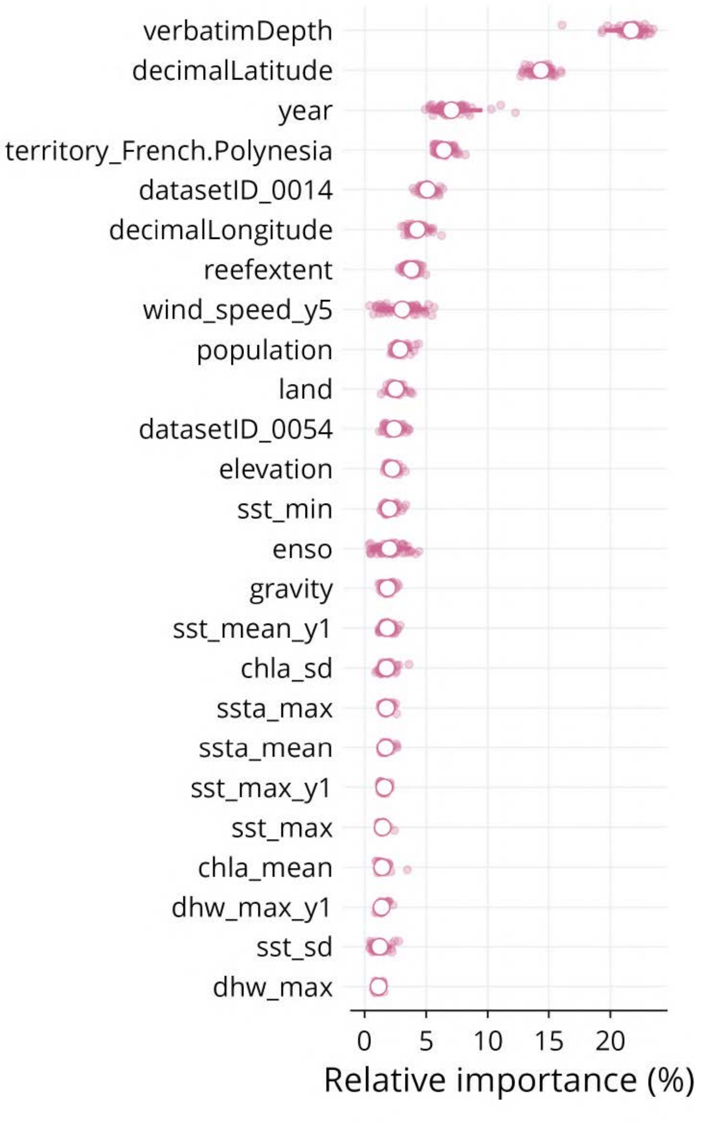
▲ **Supplementary Figure 9.** Variable importance plot for macroalgae cover. Each point represents one iteration of the ML model, and white points represent the average of the 50 iterations. Descriptions of each predictor are provided in "6.2.3 Extraction of predictors" of the materials and methods.



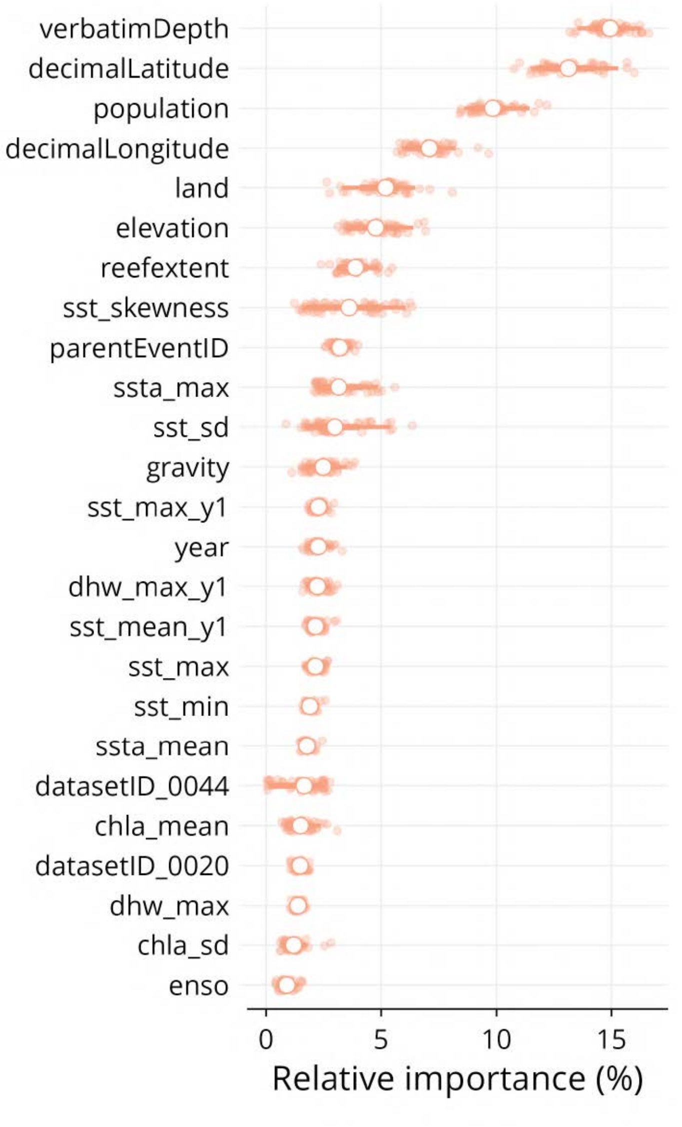
▲ **Supplementary Figure 10.** Variable importance plot for turf algae cover. Each point represents one iteration of the ML model, and white points represent the average of the 50 iterations. Descriptions of each predictor are provided in "6.2.3 Extraction of predictors" of the materials and methods.



▲ **Supplementary Figure 11.** Variable importance plot for *Acroporidae* cover. Each point represents one iteration of the ML model, and white points represent the average of the 50 iterations. Descriptions of each predictor are provided in "6.2.3 Extraction of predictors" of the materials and methods.



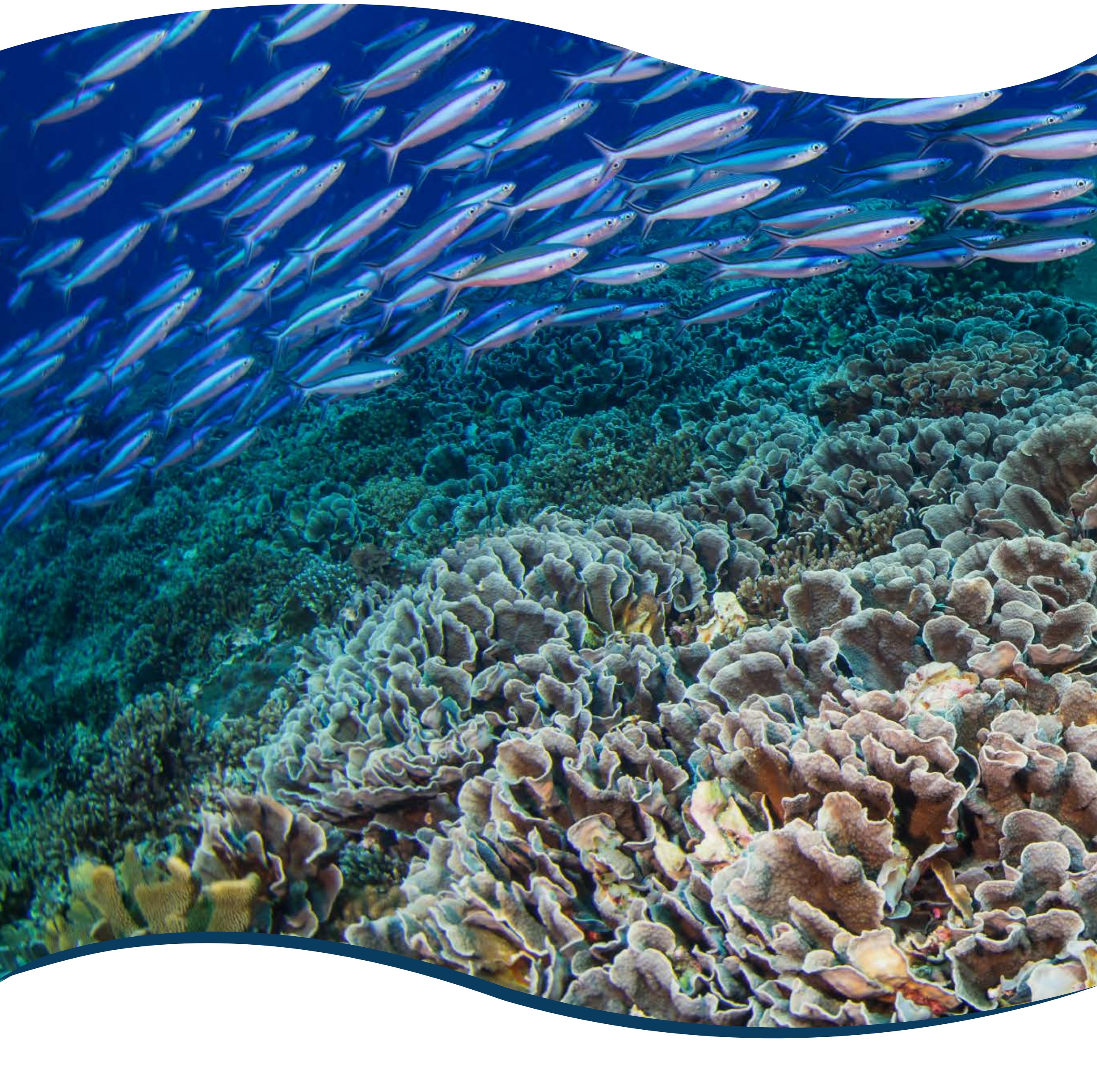
▲ **Supplementary Figure 12.** Variable importance plot for *Pocilloporidae* cover. Each point represents one iteration of the ML model, and white points represent the average of the 50 iterations. Descriptions of each predictor are provided in “6.2.3 Extraction of predictors” of the materials and methods.



▲ **Supplementary Figure 13.** Variable importance plot for *Poritidae* cover. Each point represents one iteration of the ML model, and white points represent the average of the 50 iterations. Descriptions of each predictor are provided in "6.2.3 Extraction of predictors" of the materials and methods.

ICRI
International Coral Reef Initiative

GCRMN
Global Coral Reef Monitoring Network



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