Vulnerability Mapping in Oceania

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Policy Research Project on Disaster Risk Reduction in Oceania

Directed by Dr. Joshua Busby

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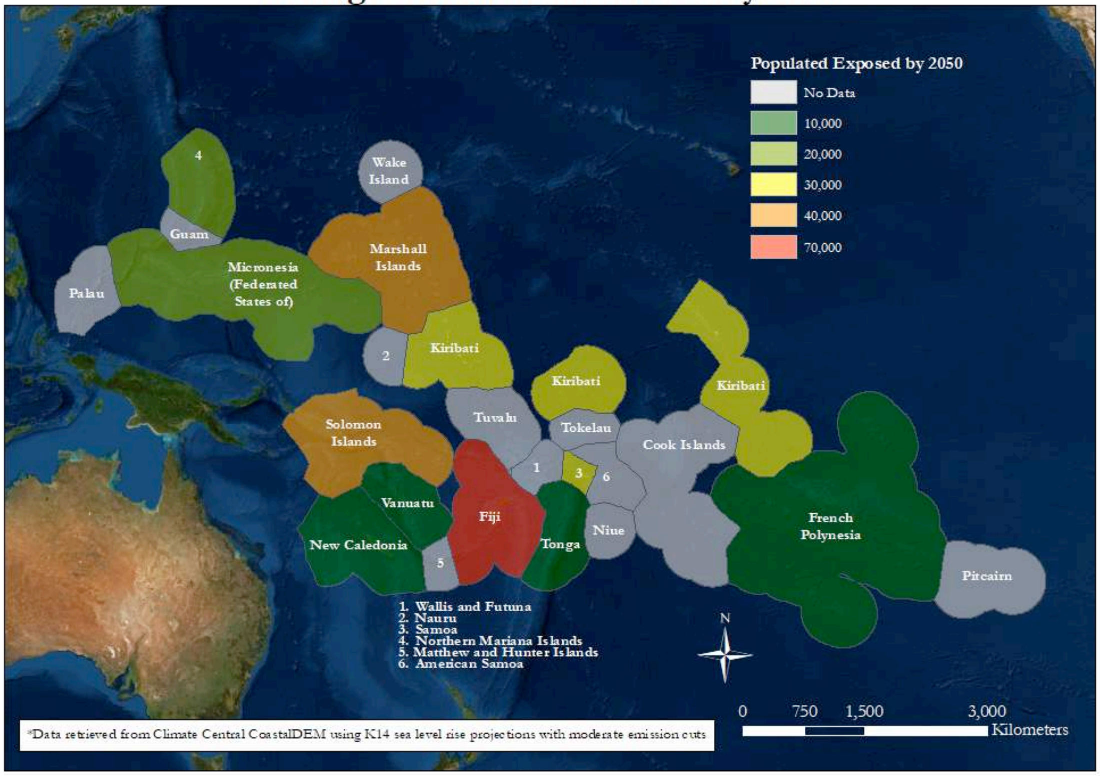
Population Living in Areas Below Annual Average Coastal Flood Levels by 2050



*Data retrieved from Climate Central CoastalDEM using K14 sea level rise projections with moderate emission cuts

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About Climate Security in Oceania

This research was conducted by master’s students at the LBJ School of Public Affairs for their capstone policy research project. The students were supervised by Professor Joshua Busby on behalf of the Center for Excellence in Disaster Management and Humanitarian Assistance.

About the Center for Excellence in Disaster Management &Humanitarian Assistance (CFE-DM)

The Center for Excellence in Disaster Management and Humanitarian Assistance reports directly to the US Indo-Pacific Command. Its goal is to support preparation for humanitarian crises and increase response capacity and in the Asia-Pacific region.

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Executive Summary

The small Pacific island states of Oceania are some of the most vulnerable countries in the world to climate change. The purpose of this research project is to anticipate and minimize climate vulnerability in these small-island states by identifying priority action areas for the US Indo-Pacific Command.[1]

Vulnerability in the study area is the result of a variety of factors. Geographically, the study area consists solely of islands which are naturally more likely to face existential threats related to flooding and sea level rise. Furthermore, isolated geography, changing weather patterns, and highly dispersed populations make vulnerability localized, which is difficult to predict and minimize. Economically, countries in our study area depend heavily on imported essential remittances and international aid. They are not equipped to handle climate related hazards on their own.

Based on these factors, this report illustrates action areas through a series of maps that focus on three aspects of climate-related vulnerability and risk: Island Geology, Population Vulnerability to Coastal Flooding, and Infrastructure Vulnerability to Coastal Flooding. These maps are meant to be easily consumable visual aids to help audiences quickly understand climate related vulnerability and risks in the study area. This report also provides context and background to explain the relevance and limits of each series of maps.

Key Findings

Islands Geology: Low lying islands, especially atolls and other reef islands are the most vulnerable to climate change and are the most common island type. Reef islands are predominant in Solomon Islands, Micronesia, Marshall Islands, Tuvalu, Tokelau, and French Polynesia but are common throughout the region. Their low profiles leave them vulnerable to risks related to climate change due to several factors including: coastal flooding, saltwater intrusion into drinking water, and erosion from wave energy.

Population Vulnerability to Coastal Flooding: We use the highest resolution, freely available satellite imagery from Climate Central's Socioeconomic Data and Applications Center to identify 484,000 people living within one meter of elevation above mean sea-level and thus

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[1] The project includes only American Samoa, Cook Islands, Federated States of Micronesia, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Nauru, New Caledonia, Niue, Northern Mariana Islands, Palau, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, and Wallis and Futuna. We exclude Papua New Guinea because it alone has a population of seven million with different vulnerabilities than Oceania's small-island states.

potentially vulnerable to coastal flooding. This is about 18% of Oceania's estimated population, nearly 90% of the populations of Tokelau and Marshall Islands, and 50% of Tuvalu. We discuss the limitations and variation in vulnerability modelling to explain the different population vulnerability estimates in Oceania and suggest collecting high resolution satellite imagery and bathymetry data on seafloor topography to refine these estimates.

Infrastructure Vulnerability to Coastal Flooding: This report identifies airports, health sites, and power plants at risk of coastal flooding on Fiji, Solomon Islands, Tuvalu, and Tonga. Only Fiji had power plants at risk of flooding, with 12% of plants (2/17) at risk. Solomon Islands had the most at risk sites, with 28% (7/25) of airports and 33% (2/6) of health sites, followed by Fiji with 16% (3/19) airports and 3% (1/34) of health sites. Tonga only had 22% (2/9) health sites at risk and no airports or power plants. Tuvalu had no sites at risk.

Informal Settlements: This report identifies informal settlements as a key area for further research. Informal settlements are often in marginal, naturally vulnerable areas, with poor quality housing, and limited essential services. Informal settlements are growing in Oceania's cities, though comprehensive information does not exist on the magnitude and locations of this growth. While this report identifies an increase in informal settlements in Suva (Fiji), Honiara (Solomon Islands), Port Vila (Vanuatu), Tarawa (Kiribati), and Majuro (Marshall Islands), it is essential to develop datasets on the scope of informal settlements across all Oceania states to effectively plan for climate events.[2]

Limitations

Data availability was a key limiting factor for all three sections. This limited both the number of maps this report could produce as well as the reliability of the maps. Reliable, complete, granular data sets on Oceania are rare, leaving large gaps in our ability to analyze vulnerability in the region. Information as simple as population is not readily available at the resolution required to assess individual islands, satellite imagery is not available in high enough resolution to accurately predict coastal flooding or shifting coastlines, and comprehensive infrastructure datasets do not exist. Each section explains its respective data limitations and how they are key to understanding the information our maps convey.

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[2] Paul Jones, *The Emergence of Pacific Urban Villages: Urbanization Trends in the Pacific Islands* (Mandaluyong City, Metro Manila, Philippines: Asian Development Bank, 2016).

Recommendations

This report makes five key recommendations for future research. All are related to collecting more accurate and detailed data that would enable future climate-related vulnerability mapping efforts in Oceania. We also identify potential partners for each recommendation who we believe have shared interests or relevant subject matter expertise. Future research should:

1. **Create freely available high-resolution satellite imagery to enable remote sensing possibilities and allow for more detailed coastal flooding maps.** Potential partners include FRANZ Agreement allies (France, Australian and New Zealand), the United States Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), and the US Navy and Air Force.

2. **Collect bathymetry data to understand local variation in sea level rise and flood risks.** Potential partners include FRANZ Agreement allies, USGS, NOAA, and the US Navy and Air Force.

3. **Collect detailed infrastructure data, especially related to power generation and distribution, to provide a clear picture of infrastructure at risk.** Potential partners include FRANZ Agreement allies, the Pacific Islands Forum (PIF), the Pacific Community (SPC) and its Pacific Data Hub, the Multinational Planning Augmentation Team (MPAT), and regional universities such as the University of the South Pacific (USP).

4. **Identify informal settlements in the region through remote sensing, as informal settlements are extremely vulnerable to flooding risks and likely growing in Oceania.** Potential partners include FRANZ Agreement allies, USAID, Department of State, PIF, SPC, MPAT, and regional universities.

5. **Include plans to ground-truth data to identify and understand any data deficiencies.** Potential partners include FRANZ Agreement allies, USAID, local governments, regional universities, Fulbright scholars, and Peace Corps volunteers.

Introduction

Scope of Work

Our research focuses on a subset of the UN-defined Oceania.[3] This subset includes eleven UN member states (Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, Palau, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu), two sovereign nations that are not UN member states (Cook Islands and Niue), and seven dependent territories, of which three are associated with France (French Polynesia, New Caledonia, and Wallis and Futuna), three with the United States (American Samoa, Guam, and Northern Mariana Islands), one with New Zealand (Tokelau), and one with the United Kingdom (Pitcairn Islands). This study does not include Australia, Papua New Guinea, and New Zealand, the three largest and most populous countries in UN-defined Oceania.[4]

Including the Pacific Ocean space, Oceania has a land surface area of about 3.3 million square miles – roughly the surface area of the continental United States (3.1 million square miles).[5,6] Australia (2.7 million square miles), Papua New Guinea (178,000 square miles), and New Zealand (103,000 square miles) make up 93% of Oceania's land mass and are excluded from this study's target countries.

The total land area for the target countries, therefore, is roughly 38,000 square miles, about the size of Indiana. These 38,000 miles are not contiguous; rather, they are spread over 1,287 islands. Each state or territory consists of 64 islands on average. In contrast, the total water area of our target countries, using their exclusive economic zones for measurement, is roughly 10.5 million square miles, larger than the entire land area of North America.

Oceania's population tells a similar story. Including Australia, Papua New Guinea, and New Zealand, about 39 million people live in Oceania.[7] 24.3 million of them live in Australia, 7.6 million in Papua New Guinea, and 4.4 million in New Zealand. This leaves about 2.7 million

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[3] "UNSD — Methodology," accessed May 7, 2020, https://unstats.un.org/unsd/methodology/m49/.

[4] "Non-Self-Governing Territories | The United Nations and Decolonization," accessed May 7, 2020, https://www.un.org/dppa/decolonization/en/nsgt.

[5] "Oceania," IUCN, February 4, 2017, https://www.iucn.org/commissions/commission-ecosystem-management/regions/oceania.

[6] "What Are The Contiguous United States?," WorldAtlas, accessed May 7, 2020, https://www.worldatlas.com/articles/what-are-the-contiguous-united-states.html.

[7] "Oceania."

people in the study area, about one third of the population of Indiana and roughly 0.03% of the world's total population.[8,9,10]

Considering only land area, the target countries have a population density of about 72 people per square mile. Taking the water area into account, the study area has a population density of 0.27 people per square mile – slightly more than one person every 4 square miles. For reference, Wyoming, the most sparsely populated US state in the contiguous United States, had 5.8 people per square mile in the 2010 census, and Alaska had 1.2 people per square mile.[11] This study's area of focus, therefore, has a combined land mass the size of Indiana, with one third of the population, spread over an area the size of North America.

The study area is not economically equipped to handle large scale disasters. Estimates of the study area's total GDP ranges from $11 billion to $24 billion, between 0.01% and 0.03% of the $85.9 trillion global GDP in 2019.[12] The economies of the study area depend heavily on imports for food stuffs, services, industrial equipment, industrial material, and manufactured products.[13] Some exports exist and are vital for the region's economic growth but are narrowly tailored to agricultural products such as sugar, palm oil, and fish. Only New Caledonia, Fiji, and Nauru export minerals. Fiji and Western Samoa have some manufacturing capacity, but it is focused on garments, and has only modest ability to manufacture essential goods. Accordingly, states do not have the capacity to manage and recover from climate related disasters nor the resources to collect data to optimize their disaster resiliency plans.

Data Challenges

A lack of accurate, current information on our target subset of Oceania limits our ability to meaningfully identify areas of climate vulnerability, risk, and opportunity in the region. While some data sets exist, Oceania's size, dispersed geography, low population, and varied

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[8] "UNdata | Record View | Population by Sex and Urban/Rural Residence," accessed May 7, 2020, http://data.un.org/Data.aspx?d=POP&f=tableCode%3a1.

[9] US Census Bureau, "Search Results," The United States Census Bureau, accessed May 7, 2020, https://www.census.gov/search-results.html.

[10] "World Population Clock: 7.8 Billion People (2020) - Worldometer," accessed May 7, 2020, https://www.worldometers.info/world-population/.

[11] US Census Bureau, "Population and Housing Unit Counts: 2010," The United States Census Bureau, accessed May 7, 2020, https://www.census.gov/library/publications/2012/dec/cph-2.html.

[12] "GDP (Current US$) | Data," accessed May 7, 2020, https://data.worldbank.org/indicator/NY.GDP.MKTP.CD.

[13] Dr. Te'o Fairbairn, "Pacific Islands Economies: Trade Patterns and Some Observations on Trade Policy Issues," Nautilus Institute for Security and Sustainability, September 26, 1994, https://nautilus.org/trade-and-environment/pacific-islands-economies-trade-patterns-and-some-observations-on-trade-policy-issues-4/.

government capacity make data sets extremely challenging to create and maintain.[14] As a result, data on Oceania – particularly this study's research area – are often outdated and do not accurately reflect the region's geographic and demographic realities.

Given the small percentage of the global population living in our study area and relatively small economic influence, the region is unlikely to naturally attract detailed collection efforts from international organizations or external states. Creating and regularly maintaining data sets that capture variation between sub-national islands is prohibitively difficult for an external data collector to accomplish.

Without an established network, someone must collect and record the data on the ground. Travel to collect and record data in the study area, however, is time consuming and expensive. For example, airfare from New York City to Tarawa, Kiribati's main island costs approximately $1500 and takes 26 hours.[15] Kiribati has 33 islands, many of which are not accessible by regular commercial flights.[16] While visiting all 33 islands would not necessarily be essential to accurately collecting demographic data, visiting enough to gather representative data would be extremely expensive and time consuming. Kiribati is just one of 20 countries in the study area and has fewer islands than average.

The alternative is for countries to collect data themselves, but state capacity to collect accurate, regular data varies in the region. Some of the target states are independent and responsible for collecting data themselves, while others are territories and have access to the resources of high capacity countries such as France, the United States, and New Zealand. As a result, many independent states also face the same challenges in visiting their own remote islands to collect data as independent researchers. Many states consist of few large, populous islands and many islands with relatively small populations. For example, 34,000 people live in Kiribati's capital Tarawa, roughly one third of Kiribati's total population. Spending the time and resources to collect data from remote islands is challenging for governments with limited capacity.

The result of these challenges is a set of disparate, often outdated data sets that do not accurately reflect Oceania's geographic and demographic realities. Without consistent,

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[14] "SDG Indicators," SDG Indicators United Nations Global SDG Database, accessed May 7, 2020, https://unstats.un.org/sdgs/indicators/database/.

[15] "Google Flight," Google Flights, accessed May 7, 2020, https://www.google.com/travel/explore?curr=USD&gl=us&hl=en&authuser=0&origin=https%3A%2F%2Fwww.google.com&tfc=ciMKDwoNCgkvbS8wMl8yODYQBBIOCgwKCC9tLzA0N3RfEAYgAHIjCg4KDAoIL20vMDQ3dF8QBhIPCg0KCS9tLzAyXzI4NhAEIAAYASoECAQQApABADABOgIIAQ&tfs=CBsQAxoNagsIAhIHL20vMHZ6bRoNcgsIAhIHL20vMHZ6bXACggENCP___________wEQAkABSAGYAQE.

[16] "Getting Here – Kiribati For Travellers – Kiribati National Tourism Office," Government Agency, Kiribati National Tourism Office, accessed May 7, 2020, https://www.kiribatitourism.gov.ki/kiribati-pacific-ocean-location/getting-here/.

accurate information, it is challenging to evaluate climate change-related disaster preparedness in detail, making it difficult to prioritize action areas in the region. This limits our ability to create and display maps with granular detail. Accordingly, data availability and accuracy played a major role in limiting our findings.

Island Geology and Risk

Geography and geology form the foundations of disaster risk for Oceania's island states. Accordingly, it is important to recognize the difference between geology and geography of Oceania's islands and their associated risk factors to understand vulnerability in Oceania. First, while interrelated, geology does not mesh perfectly with geography. Geology "deals with the earth's physical structure and substance, its history, and the processes that act on it."[17] In other words, it deals with the formation of islands rather than their composition. Geography builds on geological foundations to describe the "physical features of the earth and its atmosphere, and of human activity as it affects and is affected by these, including the distribution of populations and resources, land use, and industries."[18]

Oceania islands fall into three main geological types: high islands, low islands, and continental islands. As explained by the maps and charts through this section, these islands have geographic sub-categories depending on where they are in the weathering process (i.e. high/low,).[19] Figure A1 illustrates the current proportion of island types per nation in the study area. Figure A2 uses the same data to illustrate the predominant island type by country, mapped by their exclusive economic zones. Orange represents reef islands in both figures, which are the type of island most vulnerable to climate disasters in Oceania. Figure A3 presents the same data is a percentage of islands by type within each country and Figure A4 provides a graphical representation of the different island types.

Based on an island's geological and geographical characteristics, the associated climate change disaster risks are different. For example, volcanic high islands face risks from changing rain patterns and flash flooding. However, reef islands such as atolls face more immediate challenges from sea level rise and shoreline destruction. Accordingly, it is essential to understand Oceania's geology and geography to assess and mitigate climate-related vulnerability in the region.

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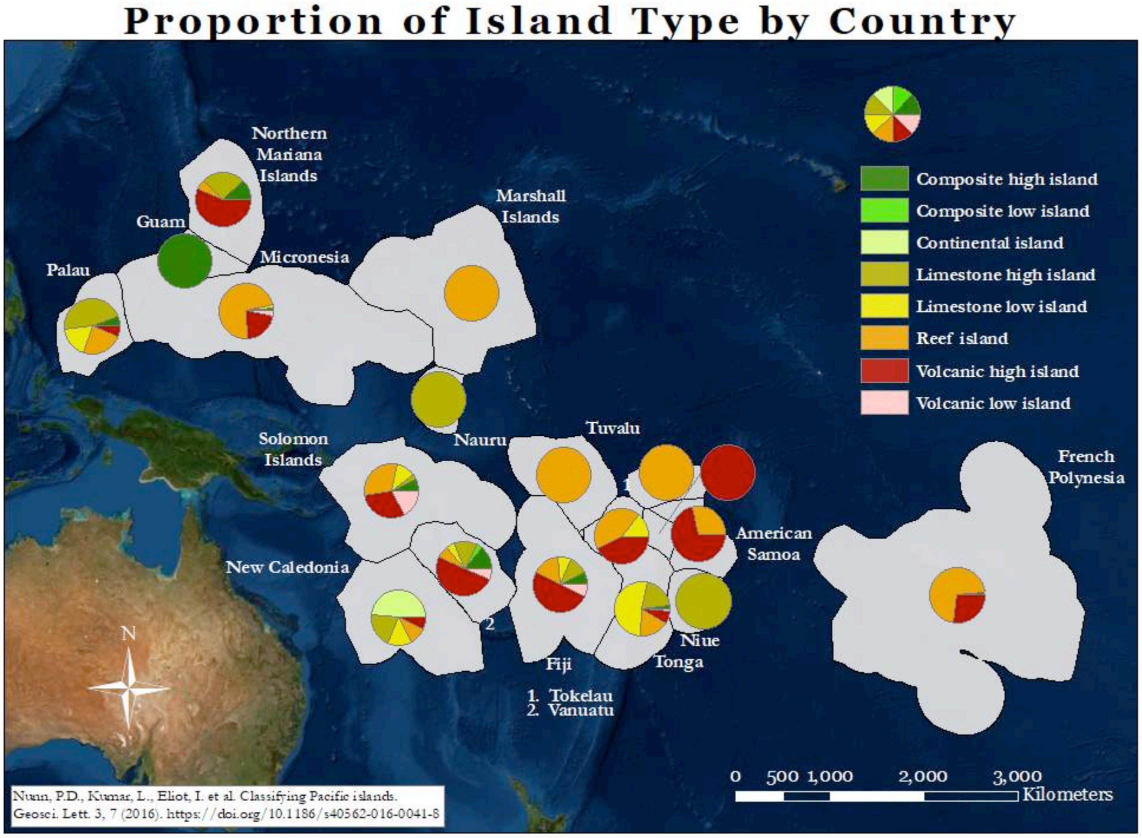
[17] "Geology, n.," in *OED Online* (Oxford University Press), accessed May 7, 2020, http://www.oed.com/view/Entry/77768.

[18] "Geography, n.," in *OED Online* (Oxford University Press), accessed May 7, 2020, http://www.oed.com/view/Entry/77757.

[19] Ken Rubin, "Hawaii Center for Volcanology | Formation of the Hawaiian Islands," accessed May 7, 2020, https://www.soest.hawaii.edu/GG/HCV/haw_formation.html.



Nunn, P.D., Kumar, L., Eliot, I. et al. Classifying Pacific islands. Geosci. Lett. 3, 7 (2016). https://doi.org/10.1186/s40562-016-0041-8

Figure A1: Proportion of each island time by state/territory.[20]

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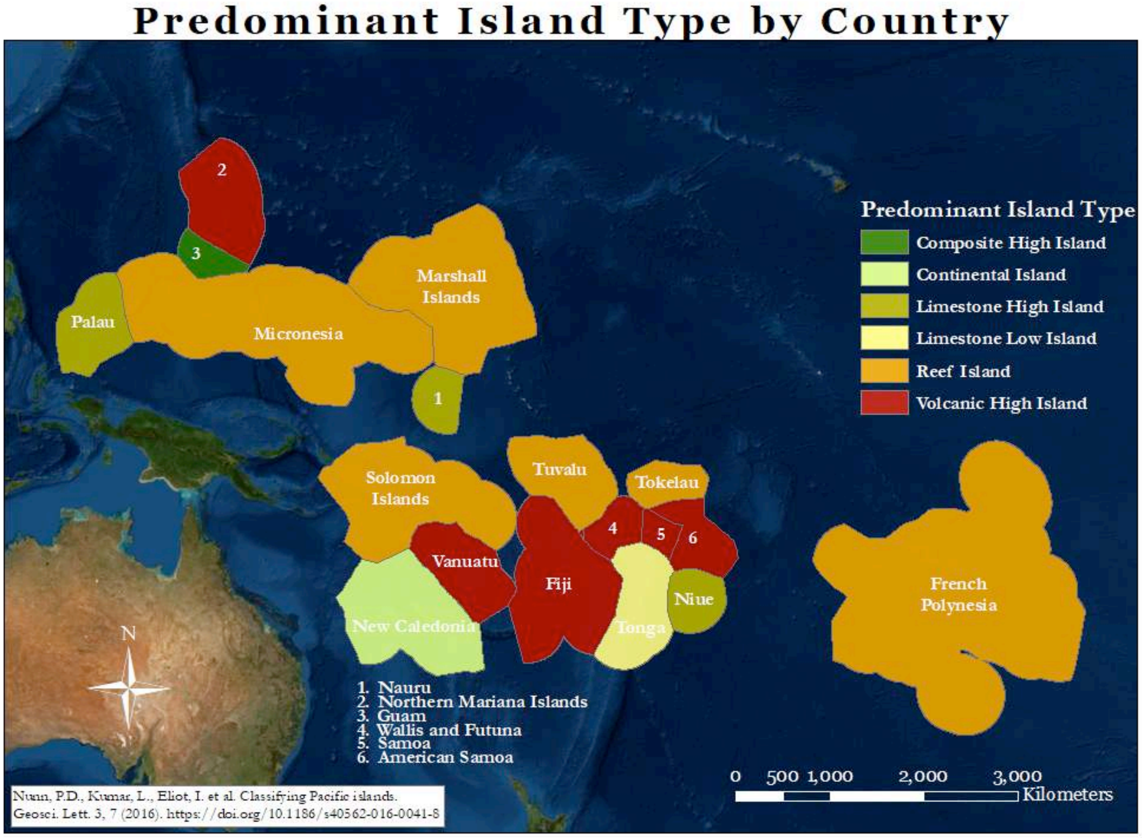
[20] Patrick D. Nunn et al., "Classifying Pacific Islands," *Geoscience Letters* 3, no. 1 (March 2, 2016): 7, https://doi.org/10.1186/s40562-016-0041-8.



Nunn, P.D., Kumar, L., Eliot, I. et al. Classifying Pacific islands. Geosci. Lett. 3, 7 (2016). https://doi.org/10.1186/s40562-016-0041-8

Figure A2: Oceania states by predominant island type.[21]

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[21] Nunn et al.

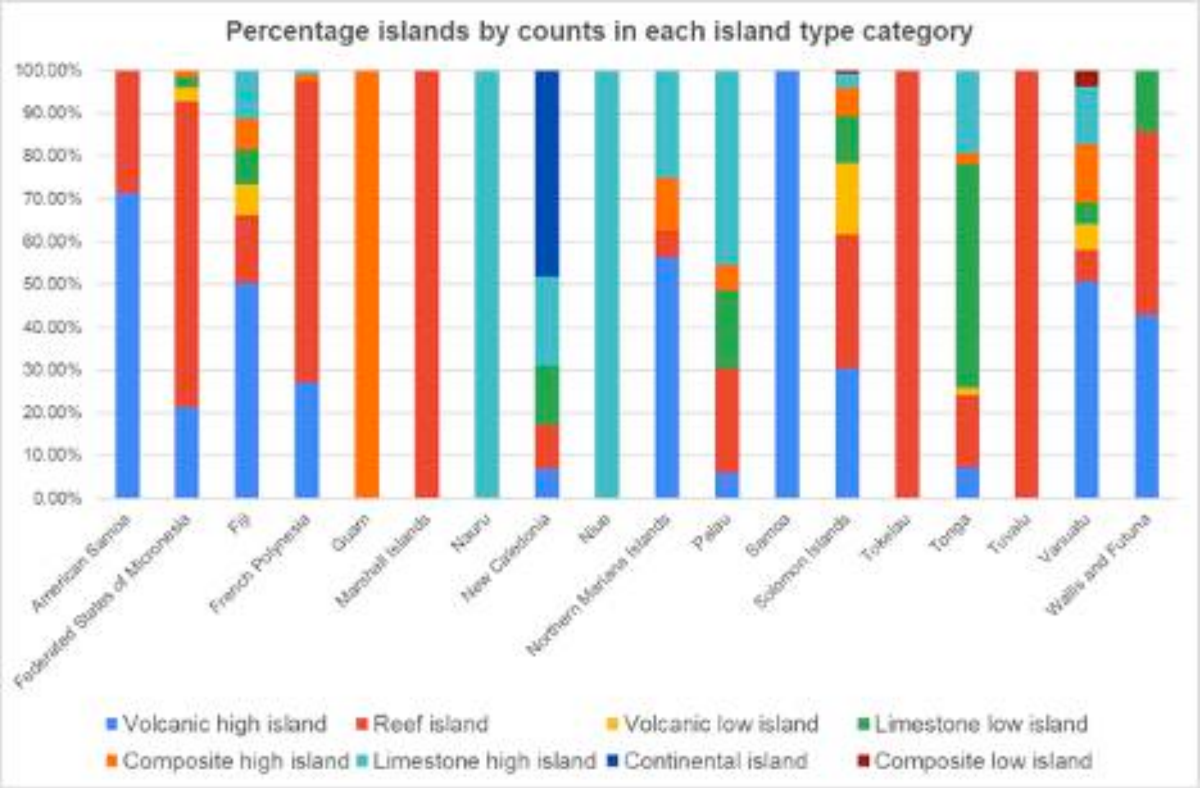

Figure A3. Island type count distribution expressed as a percentage.[22]

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[22] Patrick D. Nunn and Ian Eliot, "Regional Coastal Susceptibility Assessment for the Pacific Islands: Technical Report" (Commonwealth of Australia, 2015), https://www.pacificclimatechange.net/document/regional-coastal-susceptibility-assessment-pacific-islands-technical-report.

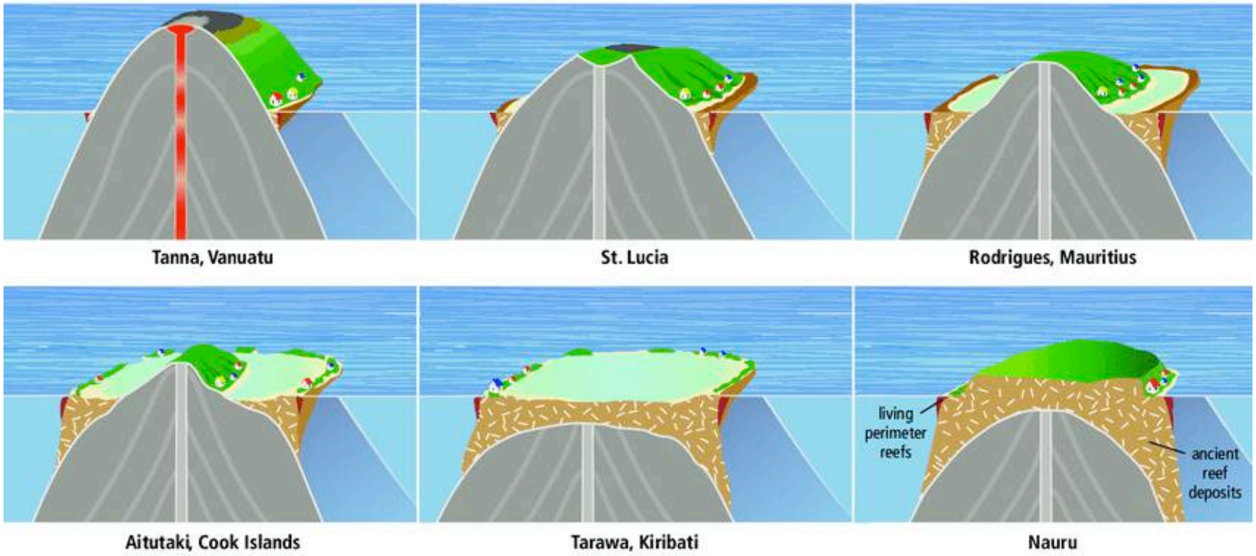

Figure A4: From top left: A young, active volcanic island and limited living perimeter reefs (red zone at outer reef edge), through to an atoll (center bottom), and raised limestone island (bottom right) dominated by ancient reef deposits (brown + white fleck). Atolls have limited, low-lying land areas but well-developed reef/lagoon systems. Continental Islands are not included in this figure.[23]

Weathering from High to Low

Island geography is not a static state. Rather, once a volcano is no longer active, high islands begin to erode into low islands. The Hawaiian Archipelago expresses the relationship between time and island type. The Big Island of Hawaii represents the latest installment of an island-building event that extends 2,400 km to the Kure Atoll. Every island in between represents the various types of islands over the course of geological time (Figure A5). Kauai for example, formed 5 million years ago, is the oldest of the main islands. It has lost over 3,5000 ft in elevation and 1,000 square miles since its peak formation. Eventually, Kauai may become an atoll or some other iteration of low island as its volcanic core weathers beneath the ocean's surface.

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[23] L.A. Nurse et al., "Small Islands. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change" (Cambridge, United Kingdom and New York NY, USA: Cambridge University Press, March 2014), https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap29_FINAL.pdf.

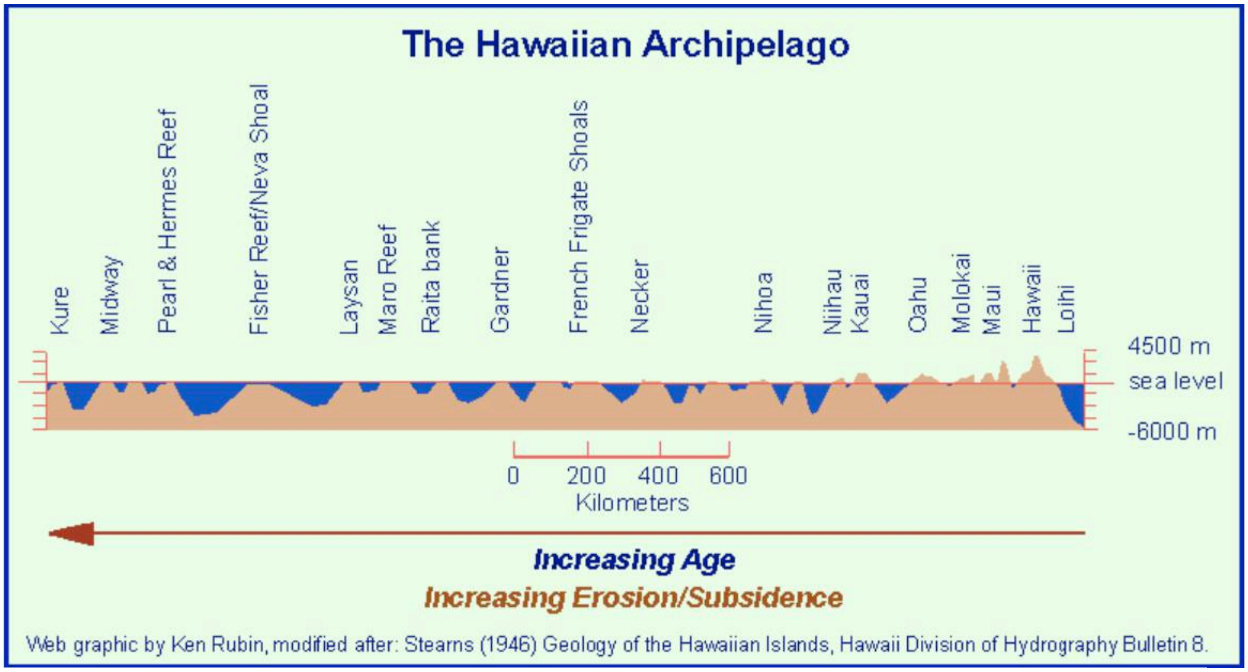

Figure A5: Cross Section of the Hawaiian Archipelago depicting the relationship of time and island weathering.[24]

Volcanic Islands

Volcanic islands are islands that are at least 80% igneous rock.[25] They originate from underwater eruptions where the magma has cooled and built up over time. The volcanic activity creates a steep peak with ridges radiating outward from the peak. Volcanic islands are the result of relatively recent volcanic activity causing basalt outcrops to rise above the ocean surface. Figure A2 above divides volcanic islands into volcanic high and low islands. Geologically, these islands are both still composed of 80% igneous rock. The distinguishing difference is that volcanic low islands do not rise above 30 meters. As a part of the "Ring of Fire", a string of volcanoes bounding the Pacific Ocean, Melanesian island states of Fiji and Vanuatu are largely composed of these island types.

Depending on where a volcanic island is in development, the danger of volcanic eruptions is a very real threat. Many island nations have at least one active submarine volcano, but also may have populations located on volcanoes considered geologically active. The island of Niuafoʻou in the Kingdom of Tonga is considered volcanically active and has a population of 650 people. An eruption of any sort may displace this population and require substantial island nation resources.

Despite being generally mountainous and having substantial elevation, volcanic high island types may be more prone to flash flooding disasters. The problem is twofold. First, populations tend to concentrate in the low-lying coastal areas because that is where economic

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[24] Rubin, "Hawaii Center for Volcanology | Formation of the Hawaiian Islands."
[25] Nunn et al., "Classifying Pacific Islands."

activity flourishes most easily.[26] Second, volcanic high islands' mountainous topography causes water to flow along streams and rivers. During periods of extreme rainfall, these catchments are overwhelmed, resulting in powerful water flows that destroy infrastructure and cause death.[27] The island of Tahiti in French Polynesia dealt with these issues as recently as 2017 and climate change may only increase the frequency of such events.[28]

Limestone Islands

Limestone islands are 80% calcareous rock, or rock composed of calcium carbonate. Limestone low islands are often the result of volcanic activity and ancient reefs weathered over geological time. As volcanic islands begin to weather away and flatten out, coral skeletons and sedimentation are deposited on top. These deposits may present themselves as atolls with low lying sedimentary formations and shallow lagoons in the core. They may similarly weather down to sedimentary island types.

This study also divides limestone islands into high and low islands based on typology. Limestone high islands, such as Nauru, rise to an elevation of 30 m above sea level. It is important to note that the weathering process on limestone islands is different from the conventional weathering process in that they often are the result of tectonic uplift where an oceanic plate is being pushed over another plate along convergent plate boundaries.[29]

Limestone low islands rarely rise more than 7 to 8 meters above sea level at their zenith. Like other low lying islands, limestone low islands have little topographical diversity. Rising sea levels thus put limestone low lying islands at risk of being completely inundated in the next 100 years. As outlined in Figure A6, only about 30% of low islands are 2 meters above mean sea level and less than 10% above 3 meters. If the worst-case projections by NOAA are true, sea levels could rise 2 meters by 2100, leaving only 10% of islands above water and likely rendering them uninhabitable.[30]

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[26] Patrick D. Nunn and Nobuo Mimura, "VULNERABILITY OF SOUTH PACIFIC ISLAND NATIONS TO SEA-LEVEL RISE," *Journal of Coastal Research*, 1997, 133–51.

[27] Lucie Pheulpin et al., "Extreme Floods Regionalisation in the Tropical Island of Tahiti, French Polynesia," *E3S Web of Conferences* 7 (2016): 01014, https://doi.org/10.1051/e3sconf/20160701014.

[28] Cecile Lefort, "Residents Evacuated, Airport Closed and Power Cut off in Tahiti Flooding," *Reuters*, January 23, 2017, https://www.reuters.com/article/us-tahiti-floods-idUSKBN157074.

[29] Nunn et al., "Classifying Pacific Islands."

[30] John A. Church and Neil J. White, "Sea-Level Rise from the Late 19th to the Early 21st Century," *Surveys in Geophysics* 32, no. 4–5 (September 2011): 585–602, https://doi.org/10.1007/s10712-011-9119-1.

Atoll or Archipelago	**% above 2 m above MSL**	**% above 3 m above MSL**
Cocos (Keeling) Islands (Costa Rica)	33	8
Maldives (Indian Ocean)	4	1
Chagos (Indian Ocean)	18	7
Marakei (Gilbert Islands, Oceania)	32	8
Gilbert chain/Tuvalu (Oceania)	34	7

Figure A6: A global sampling of low island elevations above mean sea level based on cross sections.[31]

More broadly, limestone islands do not typically have large freshwater reserves or pools to support them, relying instead on regular rain capture for water supply. Those islands that are lucky enough to have freshwater reserves may find them endangered by seawater contamination from rising sea levels or storm surges. A study sponsored by the USGS found that increased wave activity and wave run up would result in over wash that could contaminate the subsurface freshwater lens (Figure A7).[32]

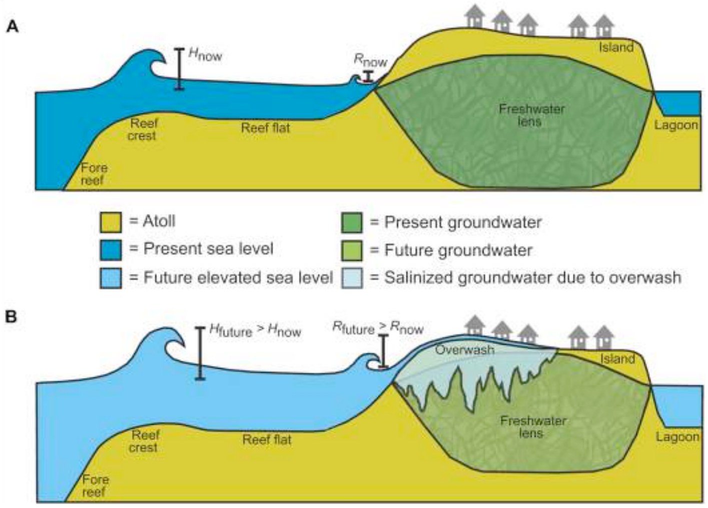

Figure A7: A diagram showing the impact of sea level rise wave activity. A) shows the current level and B) shows the impact of sea water over wash from rising sea levels.[33]

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[31] Colin D. Woodroffe, “Reef-Island Topography and the Vulnerability of Atolls to Sea-Level Rise,” *Global and Planetary Change* 62, no. 1 (May 1, 2008): 77–96, https://doi.org/10.1016/j.gloplacha.2007.11.001.

[32] Curt D. Storlazzi et al., “Most Atolls Will Be Uninhabitable by the Mid-21st Century Because of Sea-Level Rise Exacerbating Wave-Driven Flooding,” *Science Advances* 4, no. 4 (April 1, 2018): eaap9741, https://doi.org/10.1126/sciadv.aap9741.

[33] Storlazzi et al.

Reef Islands

While they share some topographical similarities with limestone islands, reef islands are composed of 80% unconsolidated sediments that have accumulated on a shallow shoal.[34] The shoals on which they accumulate are often the submerged sides of volcanic islands or other reef islands. Reef islands typically rise no more than 3m above sea level and have dynamic shorelines that change position much faster than more geologically structured island types, making them the most transient of island types.

Reef islands include barrier reefs, atolls, and fringing reefs and suffer from many of the same risk profiles as limestone low islands. They are particularly prone to being wiped out by storm surge or rising sea levels because of their unconsolidated geological structure. In other words, because the sediments are not bound together like igneous rocks and calcareous rocks, the sediments can be carried off by the water. This effect can be seen on Paava and Fualifeke in Tuvalu (Figures A8 and A9).

Continental Islands

While there are no continental islands in our study area, important regional partners New Zealand and Australia are both continental islands. Continental islands are simply un-submerged pieces of the continental shelf.[35] They tend to be much larger and are not formed through volcanic activity like high and low islands. While continental islands do not face the same threats as the islands in our research area, an increased likelihood of drought or significant damage to coastal infrastructure could limit the ability of continental islands to support Oceania at large. Additionally, it is important to consider the effect of climate change on these major islands because they will likely play a role in managing any climate crisis and refugees in the region.

The In-Between: Composite Islands

Composite islands represent the various in-between states of islands over the course of geological time.[36] Composite islands are less than 80% igneous rock, less than 80% calcareous rock, and 80% unconsolidated sediments. As with many of the other islands described, composite high islands are those that are at least 30 m above sea level and Composite low islands are less than 30 m above sea level. Composite high and low islands are often found together since they are typically the result of alternating periods of volcanism (volcanic), uplift (limestone), and weathering (sediments).

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[34] Nunn et al., "Classifying Pacific Islands."

[35] "Island | Definition, Types, Examples, & Facts," Encyclopedia Britannica, accessed May 7, 2020, https://www.britannica.com/science/island.

[36] Nunn et al., "Classifying Pacific Islands."

Data and Geology: Erosion and Accretion on Atoll Islands

Not only are islands uniquely vulnerable to climate-related risks based on their weathering and age, but they also have varying vulnerability due to changing erosion and accretion rates. One island type of particular interest is atolls, a type of reef island that will be especially vulnerable to sea level rise. Micronesia, The Marshall Islands, The Solomon Islands, Tokelau French Polynesia and Tuvalu are all comprised primarily of reef islands. More research needs to be done to better understand the land changes that sea level rise will bring.

Figures A8 and A9: From left: The shift of an atoll (Paava and Fualifeke) in Tuvalu over time due to erosion and accretion; Vegetation growth on the new land decreasing from I to III.[37]

While erosion is a commonly understood aspect of shoreline change, accretion, the process by which sediments are deposited, is equally important for understanding atoll formation and vulnerability. As sediment is eroded and becomes suspended in water, it is transported through waves and currents to a new location. One study in Tuvalu tracked these dynamics over time.[38] Figures A8 and A9 help visualize the relationship between erosion and accretion. In Figure A8, you can see the change of part of an atoll over a twenty-year period. In Figure A9, it is easy to see the accretion of the land over time, visible by the height of the vegetation getting shorter from I-III.

Thus, accretion complicates sea-level rise impact analyses, challenging the existing paradigm that islands are static and will respond to sea level rise similarly. A survey of the 101 islands of Tuvalu, ranging in size from 0.1 hectares to over 500 hectares, found an average net increase in the total land area of 2.9% despite local sea levels rising at twice the global average rate (~3.90 +/- 0.4 mm.yr).[39] However, not every island in the country grew. 74%

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[37] Arthur Webb, *Coastal Change Analysis Using Multi-Temporal Image Comparisons- Funafuti Atoll*, 2006.
[38] Webb.
[39] Fairbairn, "Pacific Islands Economies."

increased in size while the remaining 27% decreased. This dichotomy shows the relationship between sea-level rise and inhabitable land is not a straightforward application of average data. Similar to what is seen in figure 1a above, the majority of islands in the study area show both erosion and accretion on different parts of the coastline.[40]

Research has yielded important information to consider when evaluating the impact of sea-level rise on atoll islands. First, the greatest erosion happens on the outer rim of the largest atolls. There is also a trend of atolls developing new land "lagoon-ward" (or inward) as outer sediment is transferred to the middle of the island (Figure A10).[41] Finally, research indicates that although medium and larger islands saw accretion, smaller islands saw increased erosion on average and an overall loss of land. This is significant for future studies on vulnerability as smaller islands should be prioritized in data collection for long term modeling.

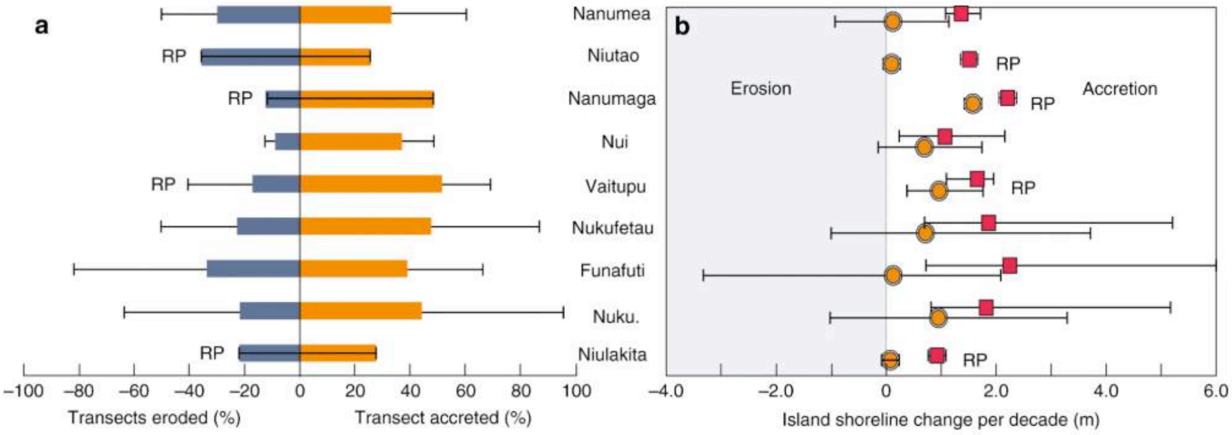

Figure A10: (a) Percentage of shorelines experiencing erosion (blue bars) and accretion (orange bars) aggregated at the atoll scale. Error bars represent maximum transect erosion and accretion in each atoll. (b) Net rate (orange circles) and gross rate (red squares) of shoreline movement per decade aggregated at the atoll scale. Error bars represent minimum and maximum rates within each atoll.[42]

Ocean Dynamics and Atoll Vulnerability

Waves and currents are another factor that should be considered when evaluating the future vulnerability of Oceanic islands. Much of the accretion seen in Tuvalu is likely a result of reef breakdown from increased wave energy. Wave energy, or wave power, is the

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[40] Paul S. Kench, Murray R. Ford, and Susan D. Owen, "Patterns of Island Change and Persistence Offer Alternate Adaptation Pathways for Atoll Nations," *Nature Communications* 9, no. 1 (February 9, 2018): 1–7, https://doi.org/10.1038/s41467-018-02954-1.

[41] Kench, Ford, and Owen.

[42] Kench, Ford, and Owen.

transference of the energy from the wind into ocean surface motion, and has increased globally (likely due to climate change) at a rate of 0.4% per year.[43] This increased movement in the ocean has coincided with the faster destruction of reef formations surrounding Oceania's islands, resulting in short term accretion from sedimentary deposits.

These reef formations are critical because they slow down the impact of waves to atoll islands. The longer and more coral-dense the reef, the larger the area of wave friction and the more energy the wave will lose before it reaches the shore. As ocean movement increases, waves break down reef formations surrounding atolls more rapidly. The area of wave friction will shrink as the reef shrinks and less energy will dissipate from waves before they reach the shoreline of atoll islands. This leads to increased erosion over the long term.[44] This dynamic can be seen in Figure A11, where the reef structure (in brown) dissipates incoming waves over the length of area 3 (marked "wave friction").

This process is especially evident during disaster events like large storms, which can cause major erosion damage to atolls without effective reef protection. Since new coral reefs can take up to 10,000 years to form from a group of larvae, it is essential to protect existing reefs to prevent drastic erosion of atolls in Oceania.

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[43] Borja G. Reguero, Iñigo J. Losada, and Fernando J. Méndez, "A Recent Increase in Global Wave Power as a Consequence of Oceanic Warming," *Nature Communications* 10, no. 1 (January 14, 2019): 1–14, https://doi.org/10.1038/s41467-018-08066-0.

[44] Murray Ford, "Shoreline Changes Interpreted from Multi-Temporal Aerial Photographs and High Resolution Satellite Images: Wotje Atoll, Marshall Islands," *Remote Sensing of Environment* 135 (August 1, 2013): 130–40, https://doi.org/10.1016/j.rse.2013.03.027.

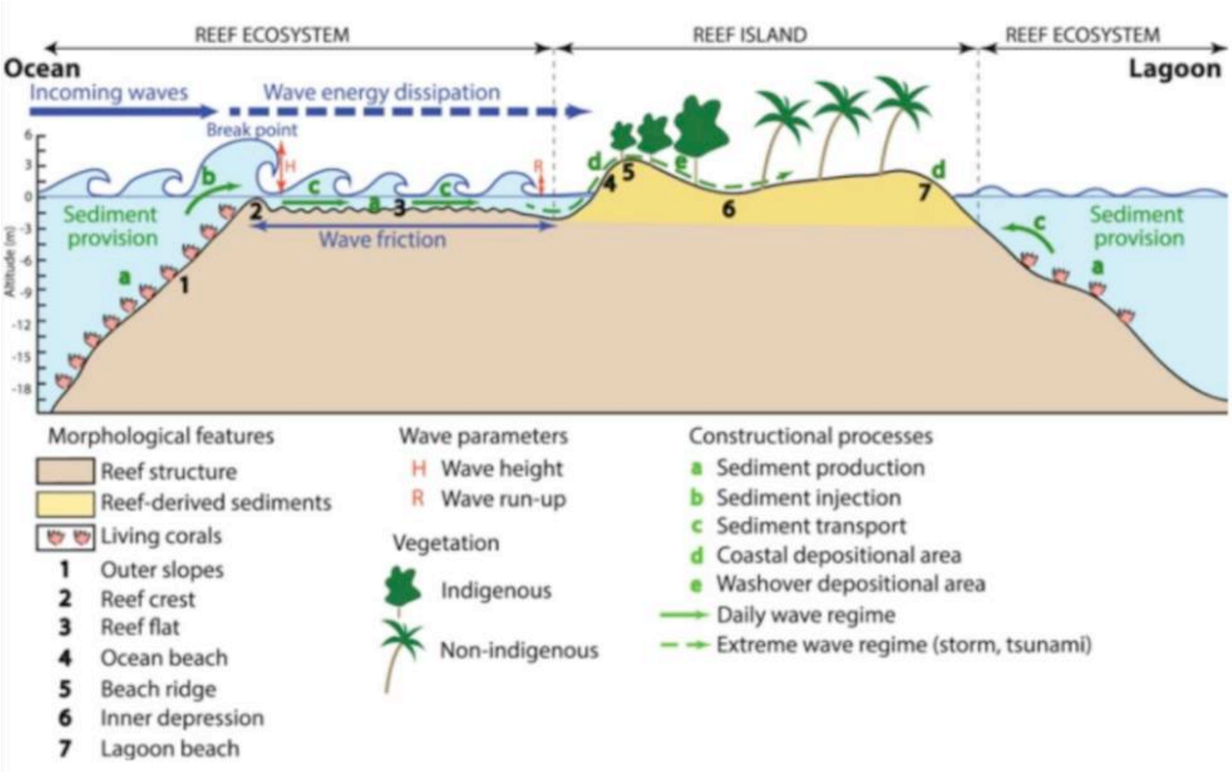

Figure A11: Overview of the atoll erosion process. The reef structure in brown dissipates the energy of incoming waves over the length of section 3, thereby limiting the erosive force waves reaching the shoreline.[45]

These studies demonstrate the critical need to monitor shorelines, geology and reef structures in order to identify the Oceanic islands that are most at-risk. The government of Tuvalu, in partnership with the United Nations Development Programme (UNDP), announced a program to collect bathymetry in order to better understand the country's vulnerability.[46] Ultimately, although our maps can help identify hot-spots for risk, they cannot account for these varying ocean dynamics. Sea-level rise and climate change will not have a similar impact on every island and any climate resiliency or risk preparedness measures must take local variation into account.

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[45] Virginie K. E. Duvat and Alexandre K. Magnan, "Rapid Human-Driven Undermining of Atoll Island Capacity to Adjust to Ocean Climate-Related Pressures," *Scientific Reports* 9, no. 1 (October 22, 2019): 1–16, https://doi.org/10.1038/s41598-019-51468-3.

[46] "Advanced Topographic and Bathymetric Survey to Support Tuvalu's Adaptation Efforts - Tuvalu," ReliefWeb, accessed May 7, 2020, https://reliefweb.int/report/tuvalu/advanced-topographic-and-bathymetric-survey-support-tuvalu-s-adaptation-efforts.

Freshwater Availability and Saltwater Intrusion

Saltwater intrusion into the study area's freshwater reserves is another key vulnerability related to climate events in the region. Water shortages and seasonal variability in rainfall are common in Oceania, forcing residents to turn to existing freshwater reserves to survive.[47] If saltwater contaminates these reserves, routine variation in rainfall has the potential to create a series of existential climate disasters on islands across the region. In 2016, for example, a combination of drought and the contamination of freshwater reserves through saltwater intrusion on the Marshall Islands caused over 16,000 people to suffer from extreme water shortages, leaving thousands to drink from coconuts for survival. To reduce vulnerability to such crises, governments work to limit the saltwater intrusion into freshwater reserves and prepare for seasonal droughts.

Saltwater Intrusion

For most islands in Oceania, freshwater is available from wells that tap into the land's natural freshwater lens (Figure A12). Because saltwater weighs more than freshwater, rainfall that leaches through the ground "floats" on top of the seawater creating two layers of water with a 'transition zone' where they meet. On atolls, the freshwater lens is very thin, making those who live on these islands particularly vulnerable to water shortages. The size of the freshwater lens on atoll islands is generally a function of rainfall, recharge, land permeability, and island width, including the reef flat plate (Same Figure A12). [48]

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[47] Webb, *Coastal Change Analysis Using Multi-Temporal Image Comparisons- Funafuti Atoll*.

[48] Ferdinand K. J. Oberle, Peter W. Swarzenski, and Curt D. Storlazzi, "Atoll Groundwater Movement and Its Response to Climatic and Sea-Level Fluctuations," *Water* 9, no. 9 (September 2017): 650, https://doi.org/10.3390/w9090650.

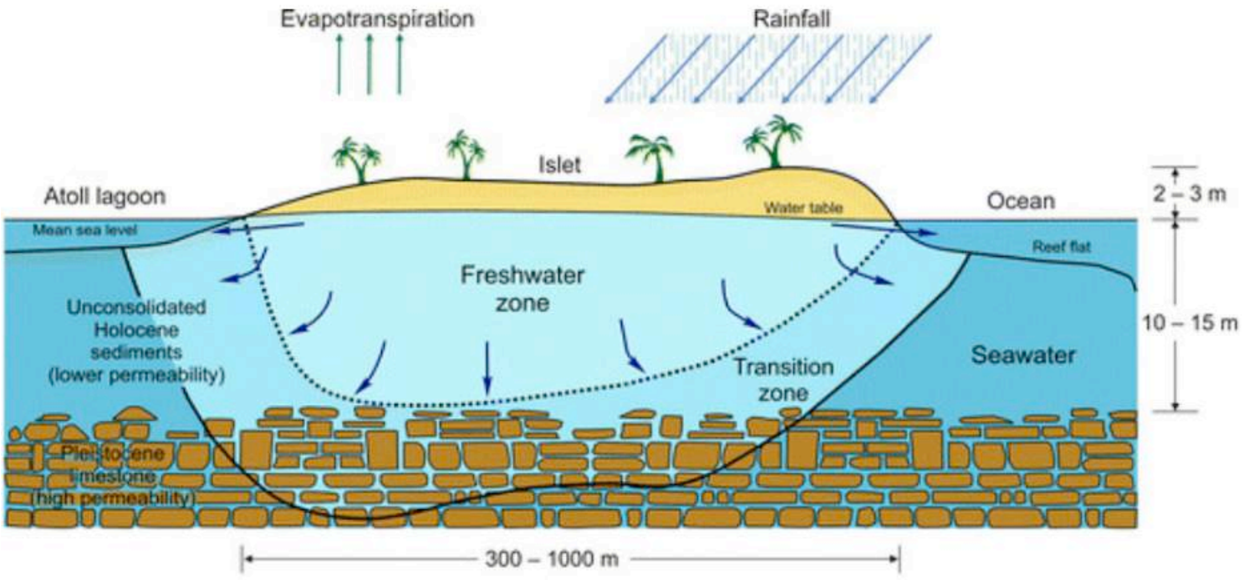

Figure 2: The structure of a freshwater lens on an atoll island.[49]

Saltwater intrusion is the process of seawater mixing with and eventually consuming the freshwater lens. When waves of the heavier saltwater over wash on the island (Figure A14), the saltwater leeches down into the freshwater lens and increases the salinity of the island's drinking water. The heavier saltwater will eventually separate back downward, though the freshwater lens' recovery speed depends on the amount of saltwater over washed and the permeability of the land.[50] Sea level rise speeds up this process, as it increases wave energy and causes more waves to wash over islands (Figure A7). These stronger waves also break down the reef crest and reef flat, which used to keep the waves from over washing. Without the reef crest and reef flat, waves are even more likely to reach the shore and contaminate the freshwater lens.

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[49] James Terry, Ting Fong May Chui, and Anthony Falkland, "Atoll Groundwater Resources at Risk: Combining Field Observations and Model Simulations of Saline Intrusion Following Storm-Generated Sea Flooding.," vol. 7, 2013, 247–70, https://doi.org/10.1007/978-94-007-5648-9.

[50] Storlazzi et al., "Most Atolls Will Be Uninhabitable by the Mid-21st Century Because of Sea-Level Rise Exacerbating Wave-Driven Flooding."

Population Vulnerability and Coastal Flooding

Numerous sea level rise forecasts and models exist. The Intergovernmental Panel on Climate Change (IPCC) currently estimates that the mean sea level rise for the globe will fall between 52 and 98 centimeters by 2050.[51] Local variations in topography, wind patterns, ocean temperature, currents, and general model uncertainty contribute to this range of values.

Methods of determining population vulnerability due to coastal flooding fall into two categories. The first method estimates the total population living within a specific distance of the coast. The Pacific Community (SPC), originally the South Pacific Commission, conducted this analysis to determine the number of people living within 1, 5, and 10 kilometers of the coast for 19 countries in the region.[52] Their work shows that over 41% of the population of 17 of these countries live within 1 kilometer of the coast (Appendix B). This method, while useful to measure vulnerability in many regions, is ineffective in the study area because of the small size of most of the islands. Often, simply living on the island puts you within 1 kilometer of the coastline. A more accurate measure of vulnerability to coastal flooding is thus required in the study area and requires an analysis of the local topography and elevation for each island. This resource-intensive second method more accurately identifies low lying coastal areas that are most likely to flood from sea level rise, storm surges, and tides.

Climate Central recently released a digital elevation model (DEM) that reduces the vertical error and bias in the Shuttle Resource Topography Mission (SRTM) DEM, the previous global standard for elevation data. Using neural networks and open source LIDAR data in the United States and Australia, Climate Central reduced the vertical bias in the SRTM DEM to the decimeter scale. The Climate Central DEM, known as CoastalDEM, predicts that 190 million people (150 - 250 million at the 90% confidence interval) currently live in areas that are projected to be below the high tide lines in 2100.[53] This is 80 million more people than in the previous estimate.

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[51] John A. Church et al., "Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," International Government Agency (Intergovernmental Panel on Climate Change, 2013), https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter13_FINAL.pdf.
[52] "Pacific Coastal Populations- Pacific Community," Pacific Coastal Populations, accessed May 7, 2020, https://www.arcgis.com/apps/MapJournal/index.html?appid=2b5cad0e20e642de96db85b377fc128c.
[53] Church et al., "Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change."

Figure B1 and B2 showcase Climate Central's results for the region. These figures show the population for each country that lives within areas projected to be below annual average coastal flood levels by 2050 given moderate emissions cuts. This is an estimate of the number of people that will be affected by the new high tide line due to sea level rise as well as within the range of annual storm surges. It is necessary to identify the population affected by more than just mean sea level rise because resources will be required to combat all sources of coastal flooding, especially as more people become exposed.

This report expands on the work of Climate Central by using their DEM and gridded population estimates from the Socioeconomic Data and Applications Center (SEDAC) to estimate historic exposure from 2000 to 2020.[54] Figure B3 shows these estimates for 21 nations and territories in the region. These exposure estimates look at the total population per country that lives within 1 meter of coastal flooding. This estimate looks at all populations that live within a one-meter elevation rise from mean sea level. It therefore incorporates all coastal flooding sources (mean sea level rise, tides, storm surge) that raise ocean levels by 1 meter.

To estimate flooded areas, we utilized the CoastalDEM data to map elevation along shorelines in Oceania. We identified all the areas with an elevation less than 1 meter above sea level. We chose a value of 1 meter because it represents both mean sea level rise and areas subject to annual coastal flooding based on global estimates.[55] For population estimates, we used NASA SEDAC gridded population data from 2000 to 2020. Using zonal statistics tools in ArcGIS software, we determined the population overlapping within each country as well as population overlapping with flooded areas. For a complete list of data sources, see Appendix A.

Our final estimate for the region suggests that approximately 484,000 people currently live within an area that falls below a one-meter elevation rise from mean sea level, based on 2020 population estimates (Figure B3). This is approximately 18% of the total estimated population for the region. This includes nearly 90% of the total population of Tokelau and the Marshall Islands as well as nearly 50% of Tuvalu. This differs from the Climate Central reported value, where they estimate that 290,000 people will be exposed to average coastal flood levels by 2050, given moderate emissions cuts (Appendix C). The differences between these two estimates can be traced to a variety of sources, most notably the Climate Central reported data only analyzed 12 countries in the region (11% of the population of these countries subjected to coastal flooding), compared to the 21 that we analyzed. While their

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[54] "Socioeconomic Data and Applications Center | SEDAC," accessed May 7, 2020, https://sedac.ciesin.columbia.edu/.

[55] Scott A. Kulp and Benjamin H. Strauss, "New Elevation Data Triple Estimates of Global Vulnerability to Sea-Level Rise and Coastal Flooding," *Nature Communications* 10, no. 1 (October 29, 2019): 1–12, https://doi.org/10.1038/s41467-019-12808-z.

estimates chose to look at average coastal flooding by 2050, we identified areas within an elevation less than 1 meter above sea level by 2020.

Research articles are continually being published that estimate the population that will be exposed to sea level rise. These estimates vary greatly from study to study because of the factors at play. Some studies take into account regional variability in sea level rise, others look at a mean sea level rise. Some studies further predict population growth in countries, while others choose to ignore this. And finally, some studies choose to include areas further inland that will be forced to migrate even if they are not directly affected by sea level rise while others do not.[56] Our estimates were derived from using the highest resolution and publicly available global elevation dataset as well as the standard for world population estimates to reduce uncertainty that is inherent in other more complicated models. All sea level rise exposure models have value and serve a purpose to identify specific uncertainties and vulnerabilities and should be aggregated and considered as a whole.

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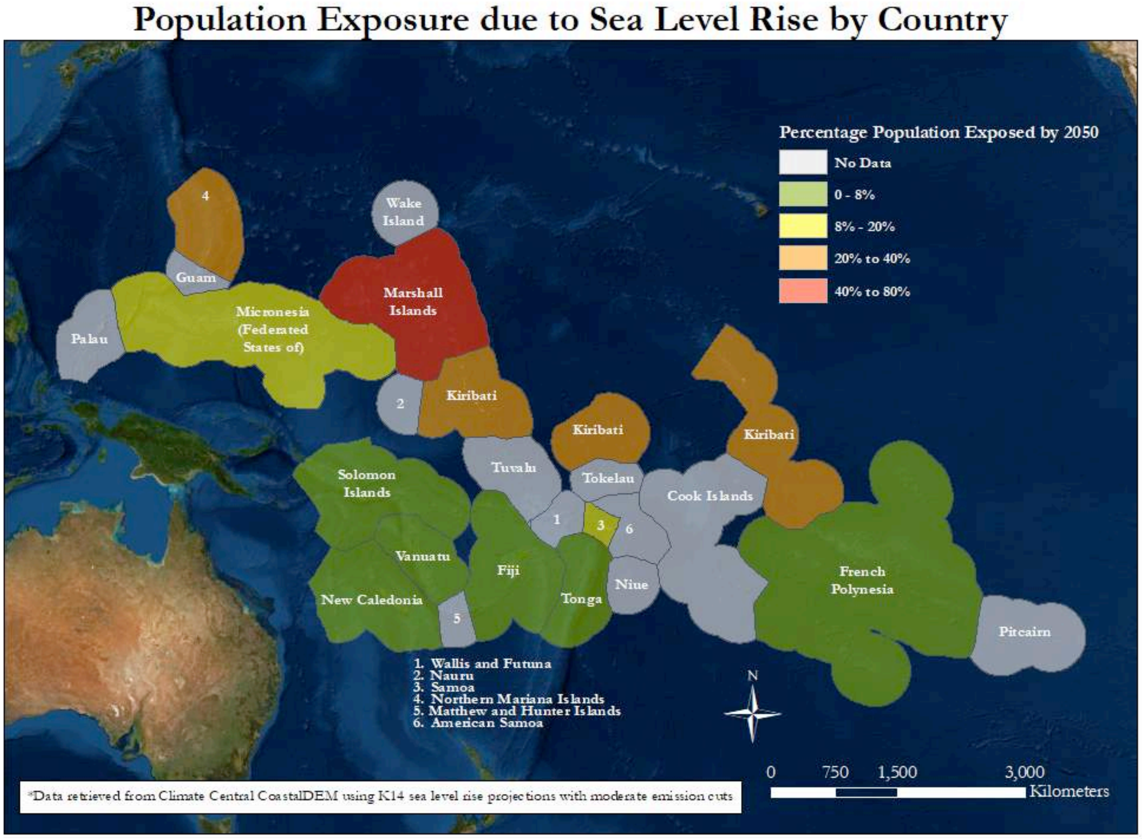
[56] Storlazzi et al., "Most Atolls Will Be Uninhabitable by the Mid-21st Century Because of Sea-Level Rise Exacerbating Wave-Driven Flooding."



*Data retrieved from Climate Central CoastalDEM using K14 sea level rise projections with moderate emission cuts

Figure B1: Estimated population percentage per country that lives in areas below projected annual average coastal flood levels by 2050 with moderate emissions cuts.

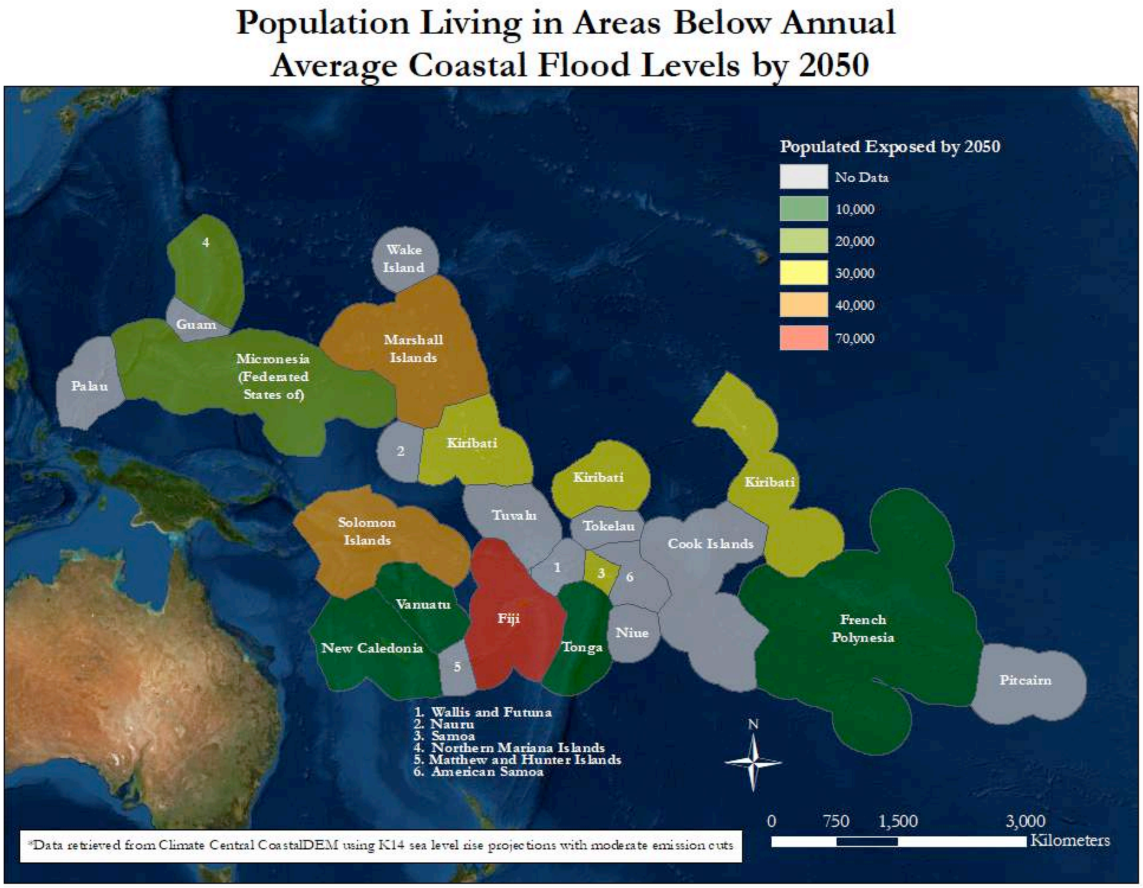


Figure B2: Estimated population per country that lives in areas below projected annual average coastal flood levels by 2050 with moderate emissions cuts

Total Population for Countries < 100,000

Estimated Population Exposed to 1-meter Sea Level Rise

Estimated Percentage of Country Exposed to 1-meter Sea Level Rise

Total Population for Countries > 100,000

Estimated Population Exposed to 1-meter Sea Level Rise

Estimated Percentage of Country Exposed to 1-meter Sea Level Rise

Figure B3: Exposure estimates by country from 2000 to 2020.

Vulnerability and the consequences of sea level rise

Projecting a global average sea level rise onto the elevation of coastal areas fails to show the true vulnerability of specific coastal regions, as it excludes local factors affecting the vulnerability of specific coastal areas. In reality, a coastal area's vulnerability to sea level rise depends on a variety of local factors, including topography, bathymetry, wind speed and direction, ambient temperature, and ocean currents. For example, an island that is in the path of a major ocean current will see higher sea level rise than an island place that is not, as the currents force water further inland. Sea level rise will not be uniform across the globe and will likely affect Oceania more than other regions of the world.

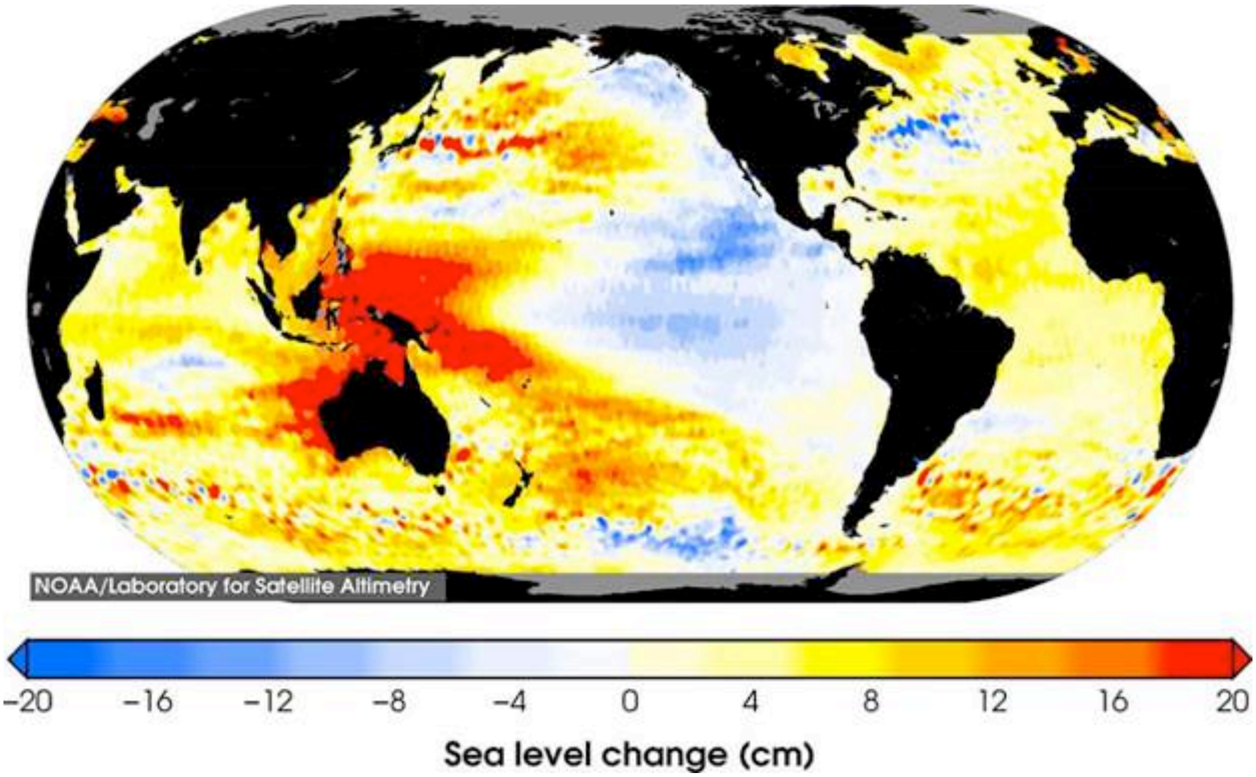


Figure B4: Global variability in sea level rise since 1993, showing a greater relative increase in Oceania/South Pacific.[57]

Furthermore, the disaster implications of sea level rise are not limited to water intrusion and reduced shorelines. Studies show that sea level rise exacerbates the effects of storm surges

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[57] NOAA, "Is Sea Level the Same All across the Ocean?," National Ocean Service-National Oceanic and Atmospheric Administration, November 13, 2019, https://oceanservice.noaa.gov/facts/globalsl.html.

and tides.[58] As sea levels rise, tides and storm surges move further inland, causing more erosive forces in areas that were previously protected and further allows the ocean to encroach inland. The graphics in figure B5 illustrate this compounding process known as shoreline retreat.

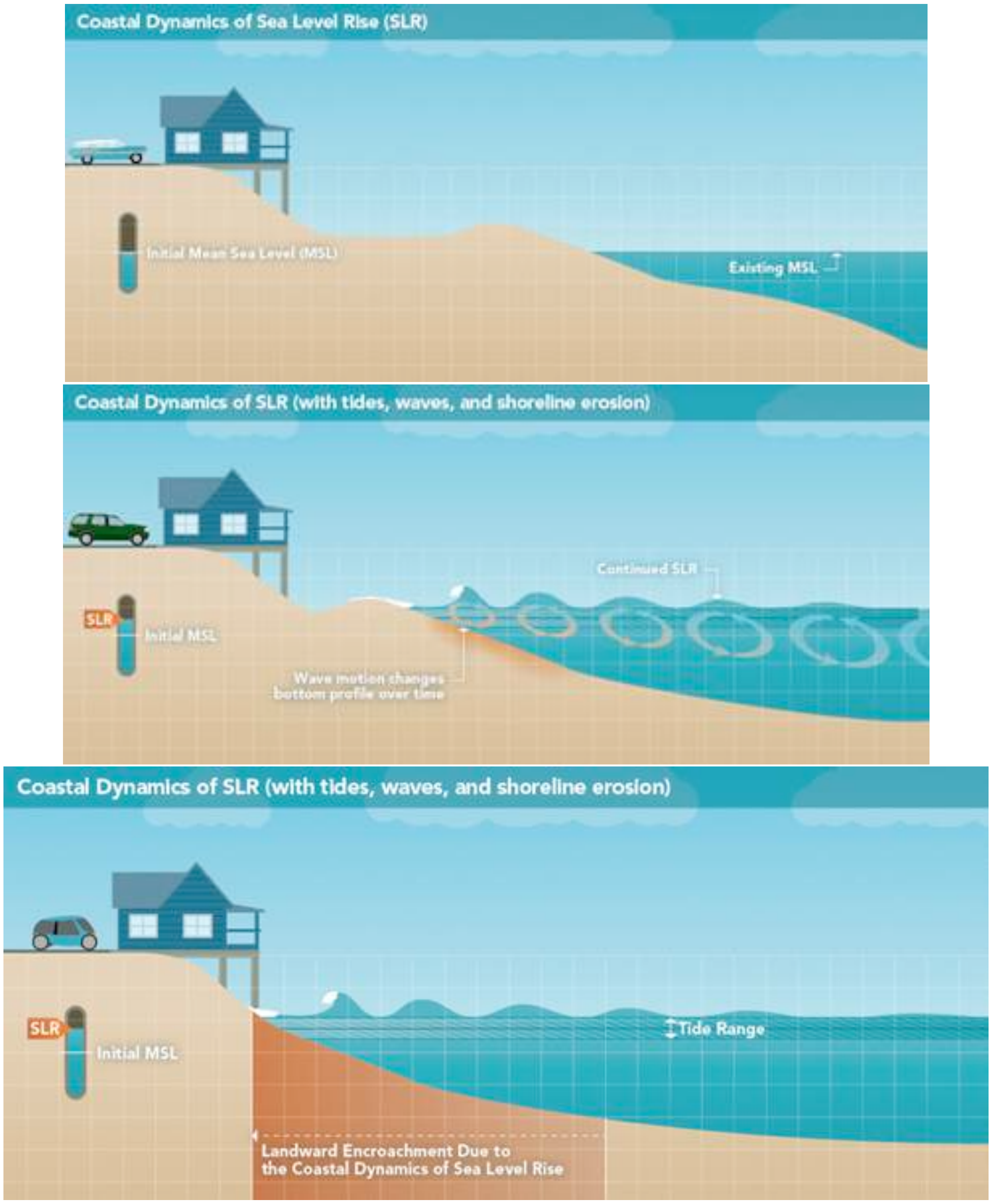

Figure B5: Mean sea level (MSL) combined with sea level rise (SLR) contribute to tidal encroachment inland Meaning sea level rise is more than just water levels rising but also physically removing land.[59]

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[58] Davina L. Passeri et al., "Dynamic Modeling of Barrier Island Response to Hurricane Storm Surge under Future Sea Level Rise," *Climatic Change* 149, no. 3 (August 1, 2018): 413–25, https://doi.org/10.1007/s10584-018-2245-8.

[59] "Coastal Dynamics of Sea Level Rise: Simulated Storm Surge," accessed May 7, 2020, https://www.arcgis.com/apps/MapJournal/index.html?appid=964181e11b4d4736ac85d7ecd33104ab.

Our population vulnerability maps are therefore not based on a simple calculation of average sea level rise compared to the number of people who live within a certain distance of the coast. To avoid underrepresenting the risk sea level rise poses to countries in the study area, our maps reflect the interaction of coastal topography and local geomorphology to more accurately predict the vulnerability in each target country to sea level rise.

Our coastal flooding maps still face inherent limitations. First, there is limited bathymetry data available on the structure of Oceania's ocean floor, which is critical to understanding erosion, reef breakdown, and inundation. The only way to accurately model erosion is to track bathymetry data over time. Unfortunately, only 1% of the world's ocean floor is mapped precisely enough to accurately model erosion. Our understanding of the remaining 99% of the ocean floor, which includes our study area, is approximated using satellite imagery to shape the seafloor through relatively imprecise gravitational measurement tools. It is impossible to model erosion with this imprecise data, which is the only bathymetry data available in Oceania. Our maps therefore cannot account for island-specific erosion patterns, making it difficult to precisely predict the severity of coastal flooding and vulnerability.

Second, high resolution satellite imagery is difficult to find for Oceania. In 2000, the United States conducted the Shuttle Resource Topography Mission (SRTM) to measure the elevation of the globe.[60] Prior to 2015, this unique and widely used global-elevation dataset had a resolution of 90 meters, meaning every 90 square meters was given a single elevation value. In 2015, the United States released an updated global SRTM dataset with a 30-meter resolution, which is the most accurate global elevation dataset freely available.

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[60] Tom G. Farr et al., "The Shuttle Radar Topography Mission," *Reviews of Geophysics* 45, no. 2 (May 19, 2007): RG2004, https://doi.org/10.1029/2005RG000183.

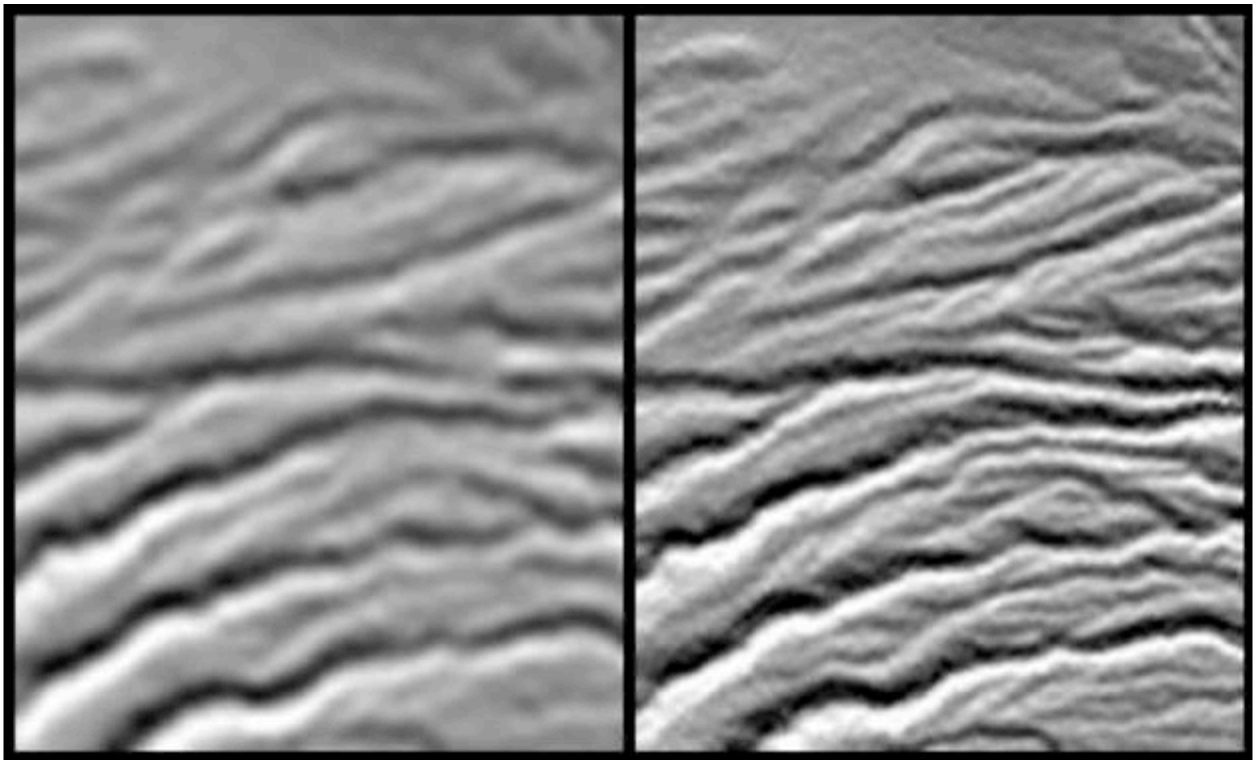

Figure B6: Difference between the 90-meter and 30-meter Shuttle Resource Topography Mission (SRTM) Data[61]

The 30-meter resolution SRTM dataset is still not perfect, as it underestimates population exposure compared to higher resolution data sets. This is in part because coastlines are dynamic features that are manipulated by anthropogenic and natural processes (i.e. dredging, construction, erosion, etc). It is also because the intertidal zone, the area between the range of high and low tides, is constantly changing, making it impossible to identify the precise location at which land becomes ocean. For example, the 30-meter SRTM underestimates population exposure due to sea level rise by up to 60% relative to the 3-meter resolution data in the United States.[62] Some global studies predict that SRTM data underestimates global exposure to sea level rise by a factor of three.[63] Until global data exists at a resolution comparable to the 3-meter imagery available of the United States, it will be impossible to predict the vulnerability of coastal regions without underrepresenting the risk.

This is particularly challenging in Oceania, where all nations share extensive natural boundaries with the ocean. Combined, these features are difficult for the 30-meter SRTM data to capture accurately and would be extremely time consuming and expensive to capture

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[61] Farr et al.

[62] Scott Kulp and Benjamin H. Strauss, "Global DEM Errors Underpredict Coastal Vulnerability to Sea Level Rise and Flooding," *Frontiers in Earth Science* 4 (2016), https://doi.org/10.3389/feart.2016.00036.

[63] Kulp and Strauss, "New Elevation Data Triple Estimates of Global Vulnerability to Sea-Level Rise and Coastal Flooding."

at a higher resolution. Accordingly, the coastline and vulnerability maps in this paper likely under-represent the vulnerabilities of coastal areas and should be considered with the inherent data limitations in mind.

Vulnerability beyond coastal flooding

Compound Flooding

Island nations are also vulnerable to flooding disasters from causes other than rising sea levels, including other types of coastal flooding, fluvial flooding, pluvial flooding, and the compounding of multiple types of simultaneous floods. Unfortunately, data on these compound flood risks does not exist for much of Oceania and the maps in the paper thus do not depict regional compound flooding vulnerability. Any resiliency or disaster preparedness planning efforts should recognize this limitation and consider localized compound flooding risks beyond sea level rise. This is particularly true in urban areas where large populations are likely to be at risk.

The three principal mechanisms for compound flooding are coastal, fluvial, and pluvial flooding. Coastal flooding includes the inundation of land areas from the combination of sea level rise, storm surge, and tides. Fluvial flooding, more commonly known as river flooding, occurs when water extends over the typical boundaries of rivers, lakes, streams, and dams caused by increased rainfall upstream. Pluvial flooding is when extreme rainfall causes water to pool anywhere and does not necessarily occur near an existing body of water. Coastal, fluvial, and pluvial flooding can compound on each other, particularly during an extreme precipitation event, thus increasing the severity of the resulting inundation.

The complexity of these compounding flooding mechanisms converge is difficult to model and forecast in coastal areas. Accordingly, risk planning often excludes compound flooding risks.[64] This is particularly dangerous for urban settings, which tend to be located downstream on rivers and where stormwater infrastructure cannot withstand compound flooding events. This results in major flooding events in urban areas thought to be sufficiently resilient. This is particularly dangerous in Oceania, where 68% of the population lives in coastal urban areas.[65] Cyclone Winston provides a good example of the potential effects of compound flooding in

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[64] Andrea Thompson, "Extreme Flooding from Florence Likely, Due to a Convergence of Threats," Scientific American, September 12, 2018, https://www.scientificamerican.com/article/extreme-flooding-from-florence-likely-due-to-a-convergence-of-threats1/.

[65] "68% of the World Population Projected to Live in Urban Areas by 2050, Says UN," UN DESA | United Nations Department of Economic and Social Affairs, May 16, 2018, https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html.

Oceania, as storm surges carried water 600 feet inland while saturated rivers overflowed with rain, leading to record inundation levels.[66,67]

Extreme precipitation events like Cyclone Winston are likely to be more common in Oceania. Globally, the number of hydrometeorological disasters has increased exponentially between 1950 and 2000.[68] Regionally, there have been numerous studies to forecast the climate changes. While there is a high degree of uncertainty around rainfall patterns, projections suggest that the dry season will get dryer and the wet season wetter.[69,70] While annual rainfall may stay constant, precipitation events will be more intense, creating a major compound flooding threat.

Saltwater Intrusion

Each island in Oceania is unique and climate change will affect them differently. For example, freshwater lens recovery times vary from one month to 26 months.[71] Over wash severity also will vary as some islands see increased coral reef breakdown with increasing wave energy. Given this variation, saltwater intrusion will change the salinity of freshwater lenses at different rates throughout the region. To effectively protect freshwater lenses and thus ensure adequate alternate freshwater resources, we must understand how to model saltwater intrusion.

Modeling saltwater intrusion requires geographic data, collecting bathymetry data over time as well as measuring the recovery time of the freshwater lens after an over wash event. Collecting this data can help us more accurately predict and prevent freshwater scarcity. Unfortunately, many saltwater intrusion models have historically focused on sea level rise and failed to incorporate climate change. Specifically, increased wave energy will have a large impact on how quickly islands will face saltwater inundation. Recent studies that incorporate increased wave energy paint a vastly different picture than previous predictions.

A study of the Marshallese atoll island Roi Namur found that traditional models for each RCP climate change scenario (Figure B7) underestimated the percentage of the island inundated over

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[66] Fane Ravula-Dinono, “Cyclone Winston Survey Sets New Baseline for Damage Data - Fiji,” ReliefWeb, April 1, 2016, https://reliefweb.int/report/fiji/cyclone-winston-survey-sets-new-baseline-damage-data.

[67] “Fiji: UN Warns of Flooding as Cyclone-Battered Country Braces for Another Storm,” UN News, April 6, 2016, https://news.un.org/en/story/2016/04/526102-fiji-un-warns-flooding-cyclone-battered-country-braces-another-storm.

[68] Tom Beer, “Climate Variability and Change: A Perspective from the Oceania Region,” *Geoscience Letters* 1, no. 1 (March 6, 2014): 5, https://doi.org/10.1186/2196-4092-1-5.

[69] Fiji Meteorological Service, Australian Bureau of Meteorology, CSIRO, “Current and Future Climate of the Fiji Islands | Pacific Climate Change Portal” (CSIRO, Australian Bureau of Meteorology, 2015), https://www.pacificclimatechange.net/document/current-and-future-climate-fiji-islands-0.

[70] “What Is Pacific Climate Futures v2.1?,” Government Agency, Pacific Climate Change Science Climate Futures, September 24, 2018, https://www.pacificclimatefutures.net/en/.

[71] Oberle, Swarzenski, and Storlazzi, “Atoll Groundwater Movement and Its Response to Climatic and Sea-Level Fluctuations.”

time.[72] Unlike traditional approaches that only account for sea level rise, the study implemented sophisticated modeling techniques to incorporate wave energy into their projections. The study combined bathymetry, topological data, oceanographic, and hydrogeologic models with climate change and sea-level rise projections to model saltwater intrusion. The study calibrated its models with salinity data from a real inundation event to make the results more accurate. This study was expensive and therefore difficult to replicate at scale, as it required Roi Namur's unique profile, including baseline saltwater intrusion data and its specific geographic profile. The results were vastly different from traditional sea level rise models and showed saltwater inundation at close to 100% by the year 2100. This study could be used as a model for how future research can more accurately predict the extent of saltwater intrusion for high risk islands.

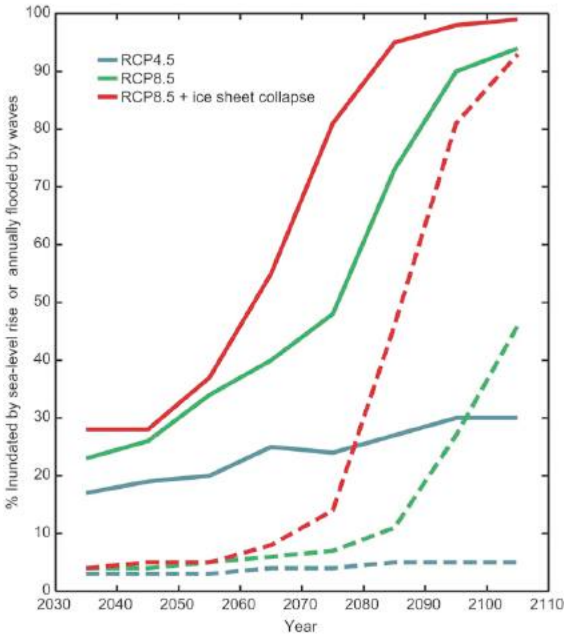

Figure B7: The results of a study on salt water inundation over time from the Marshall Island Roi Namur. The dashed lines depict inundation levels only considering sea level rise, while solid lines depict inundation levels incorporating flooding, varying climate change scenarios and increased wave energy. [73]

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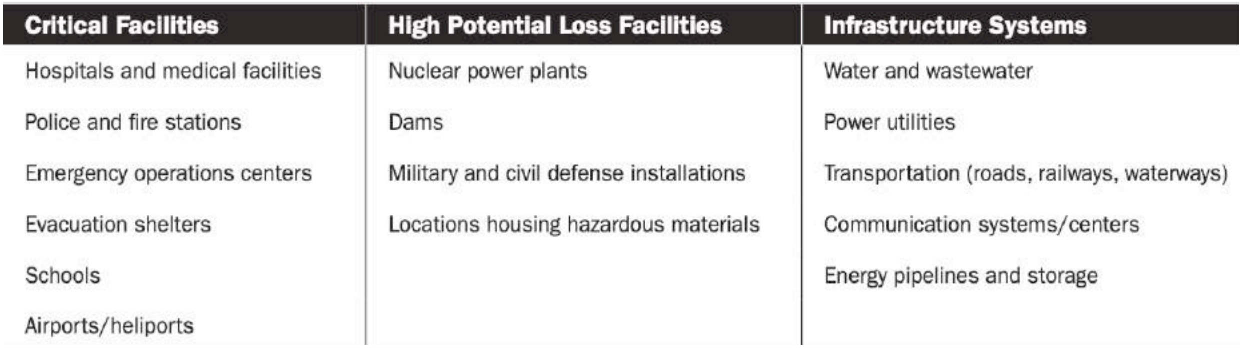
[72] Storlazzi et al., "Most Atolls Will Be Uninhabitable by the Mid-21st Century Because of Sea-Level Rise Exacerbating Wave-Driven Flooding."

[73] Storlazzi et al.

Infrastructure Vulnerability

Information on critical infrastructure is vital to emergency response and planning for resilient communities. Successful risk assessments should include geospatial data on roads, utilities, health centers, shelters and other essential facilities.[74] The ability to determine which key assets are vulnerable to climate related disaster allows stakeholders to mitigate risk and reduce the consequences of future emergencies. In particular, sea level rise will undoubtedly affect Oceania's infrastructure. Our maps aim to highlight some of the vulnerable critical facilities, demonstrate the issues that prevent a region-wide analysis of infrastructure vulnerability, and reinforce the need for complete datasets to properly map the area.

In the Federal Disaster Mitigation Act of 2000, the United States mandated local governments to develop and adopt a Multi-Hazard Mitigation Plan (MHMP). One of the major tasks of local leaders is to conduct a risk assessment and identify vital infrastructure in their communities. Figure C1 shows the infrastructure the MHMP identified as vital to creating risk assessment plans.



Critical Facilities	High Potential Loss Facilities	Infrastructure Systems
Hospitals and medical facilities	Nuclear power plants	Water and wastewater
Police and fire stations	Dams	Power utilities
Emergency operations centers	Military and civil defense installations	Transportation (roads, railways, waterways)
Evacuation shelters	Locations housing hazardous materials	Communication systems/centers
Schools		Energy pipelines and storage
Airports/heliports		

Figure C1: Infrastructure vital to risk assessment plans under the Federal Disaster Management Act of 2000.[75]

Ideally our maps would include all of these important features of Oceania's built environment; however, datasets on the location of these facilities in Oceania are virtually non-existent. As a result, we had to build datasets for transportation, healthcare, and energy infrastructure to create the maps below. While all facilities in the MHMP are important to understanding the long term implications of sea level rise on the study area, this paper cannot

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[74] "Lesson Summary," Government Agency, Federal Emergency Management Administration, accessed May 8, 2020, https://emilms.fema.gov/is922/GIS0103summary.htm.

[75] "Local Mitigation Planning Handbook | FEMA.Gov," Government Agency, Federal Emergency Management Administration, March 1, 2013, https://www.fema.gov/media-library/assets/documents/31598.

display that information because the data does not exist and collecting it for the entire region is prohibitively time consuming. Future research should be sure to include other critical infrastructure in the area. For example, during Cyclone Pam, some islands' water infrastructure and resources were wiped out, leaving them without water for days.[76] Future efforts to map critical infrastructure should include water facilities, which necessitates on the ground data collection in the area.

Airports

Sea level rise is putting airports in Oceania at risk and airports are critical facilities because they provide transportation services and deliver essential goods for their communities.[77] During disaster events, access to medical equipment, food, water and other necessary items is critical because island resources are insufficient to meet the additional strain. Additionally, airports will be necessary for residents to evacuate during an emergency. Planning to relocate airports or mitigate climate risks at current airports will be essential to disaster planning in Oceania, especially given the region's limited land resources.

Healthcare Facilities

Healthcare facilities are similarly essential in an emergency as they serve as the front lines for assisting those in need. Sea level rise could threaten these sites, as water inundation will necessitate the relocation of buildings and equipment. Knowing which facilities are most at risk will assist planners, saving time, expenses, and lives.

Power Plants

Primarily powered by diesel generators, power plants in Oceania play an important role in communities, providing electricity to homes and important facilities.[78] Maintaining power plants' functionality during disasters is imperative for transportation, connectivity and basic utility. Sea level rise may threaten these plants as well and mapping their locations to see which might be at risk can help planners decide on the future of their locations.

Findings

Ultimately our results identified multiple airports, health sites, and power plants that could be affected by one-meter worth of coastal flooding. The specific results shown here highlight four specific countries and their vulnerability. Holistically, rising sea levels will affect some infrastructure on most all of the islands. As the chart below demonstrates, the Solomon

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[76] Joshua Robertson, "Cyclone Pam: Aid Agencies Report Widespread Devastation in Vanuatu," *The Guardian*, March 15, 2015, sec. World news, https://www.theguardian.com/world/2015/mar/15/cyclone-pam-vanuatu-more-deaths-water-shortages-storm.

[77] "Runways Underwater: Rising Seas Threaten 80 Airports | ENS," Environment News Service, February 8, 2020, https://ens-newswire.com/2020/02/08/runways-underwater-rising-seas-threaten-80-airports/.

[78] UN Women Pacific, "Gender and Energy in the Pacific" (United Nations Entity for Gender Equality and the Empowerment of Women (UN Women), 2014), https://asiapacific.unwomen.org/en/digital-library/publications/2015/1/gender-and-energy-in-the-pacific.

Islands in particular stands to lose nearly a third of its airports and healthcare facilities in the absence of adaptation.

However, an important takeaway from this data is the disparate impact across different islands within the same nation. While most of Fiji's infrastructure remains intact, the island of Lovoni will likely lose its main power supply and a medical facility (Figure C3). Similarly, while the airport and power station are safe from sea water rise in Tuvalu, virtually all of its residential areas are subject to inundation by 2050 with a quarter of its medical structure (Figure C6).

Infrastructure Vulnerability on Selected Islands

Country	Number of Airports	Airports Affected	Number of Health Sites	Health Sites Affected	Number of Power Plants	Power Plants Affected
Fiji	19	3 (16%)	34	1 (3%)	17	2 (12%)
Solomon Islands	25	7 (28%)	6	2 (33%)	4	0 (0%)
Tuvalu	1	0 (0%)	1	0 (0%)	1	0 (0%)
Tonga	6	0 (0%)	9	2 (22%)	8	0 (0%)

Figure C2: Airports, health sites, and power plants at risk on Fiji, Solomon Islands, Tuvalu, and Tonga due to sea level rise.

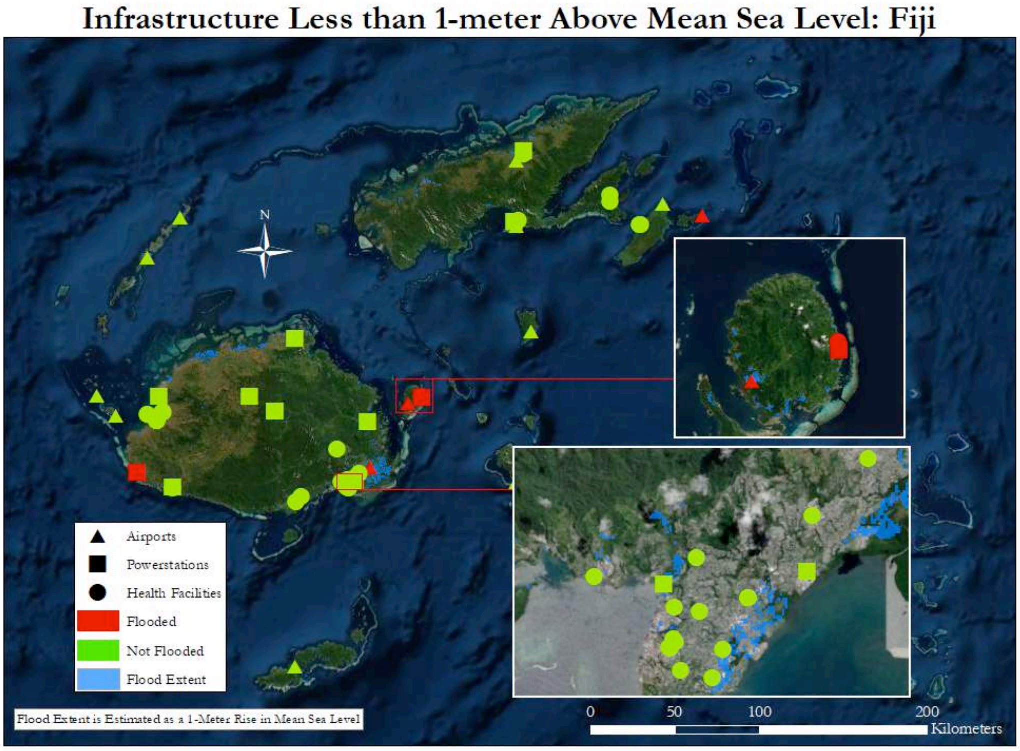


Figure C3: Infrastructure vulnerable to a 1-meter rise in sea level in in Fiji.

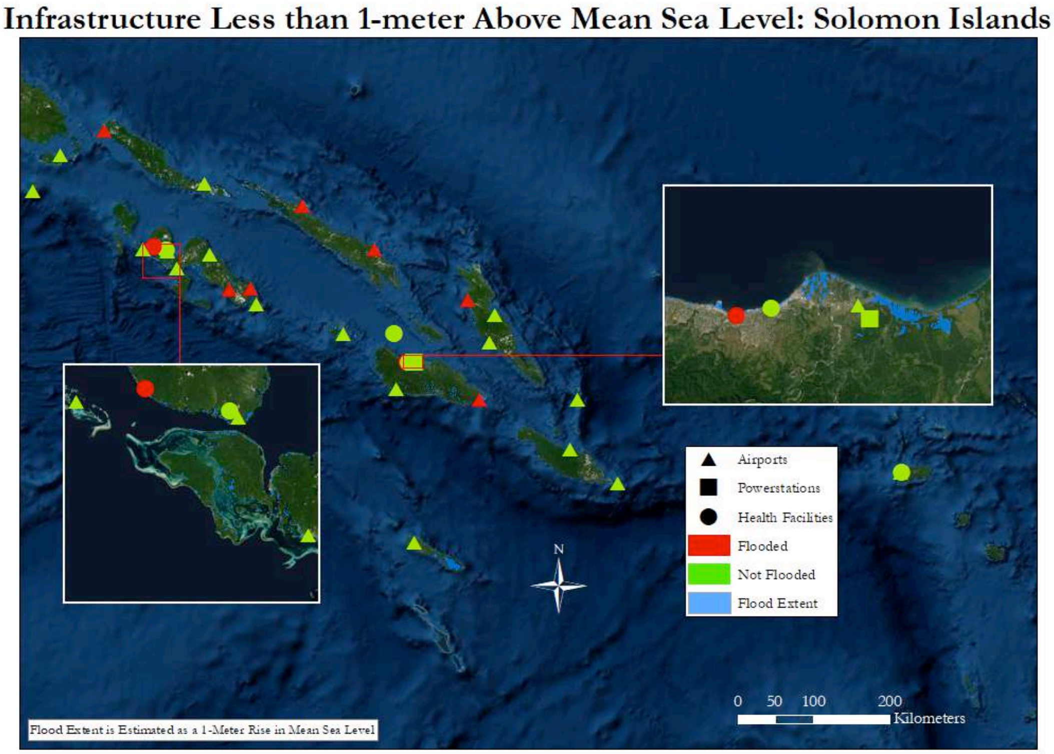


Figure C4: Infrastructure vulnerable to a 1-meter rise in sea level in Solomon Islands.

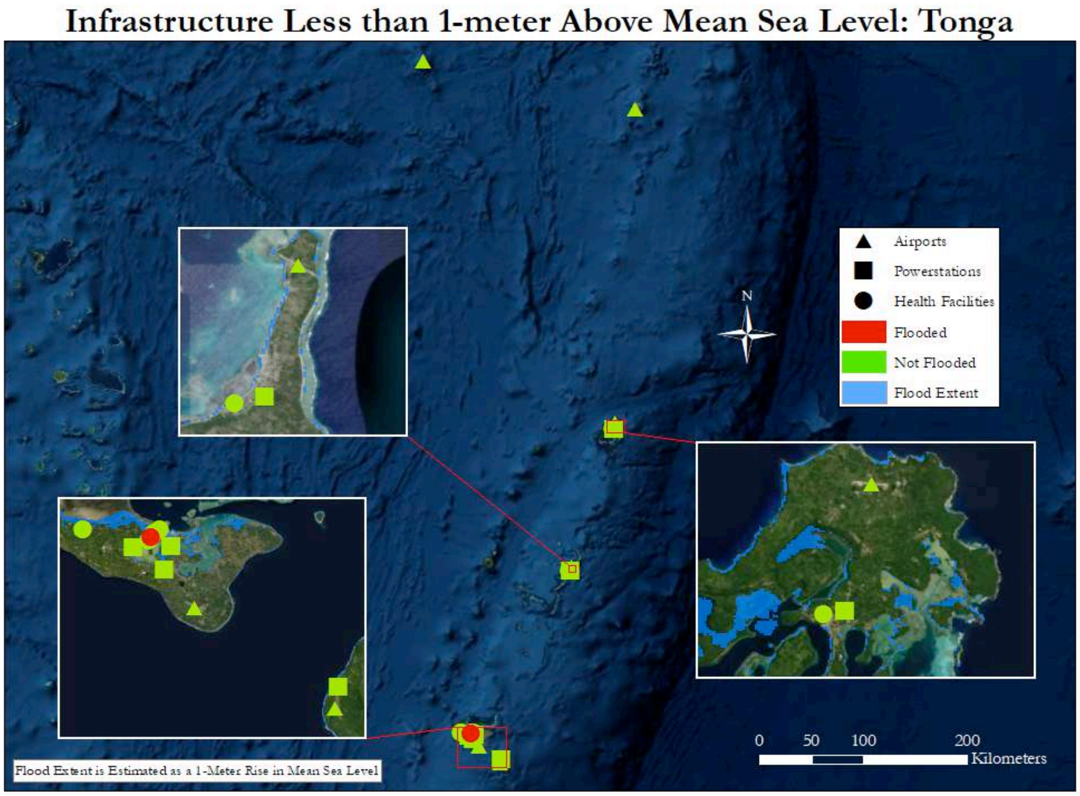
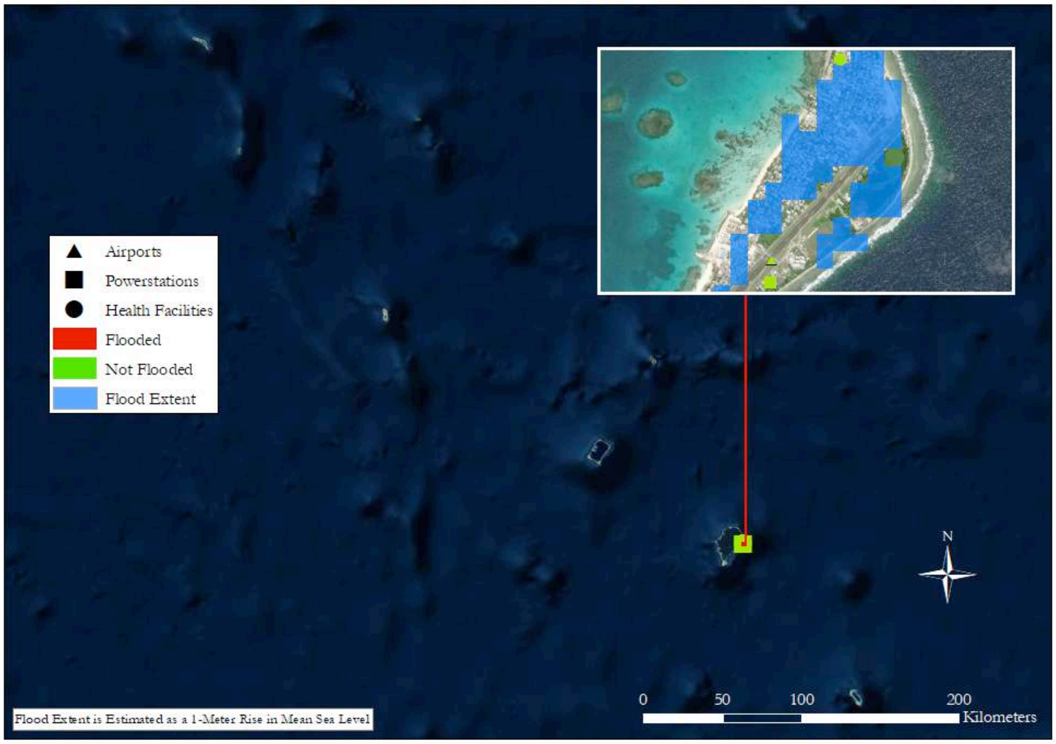


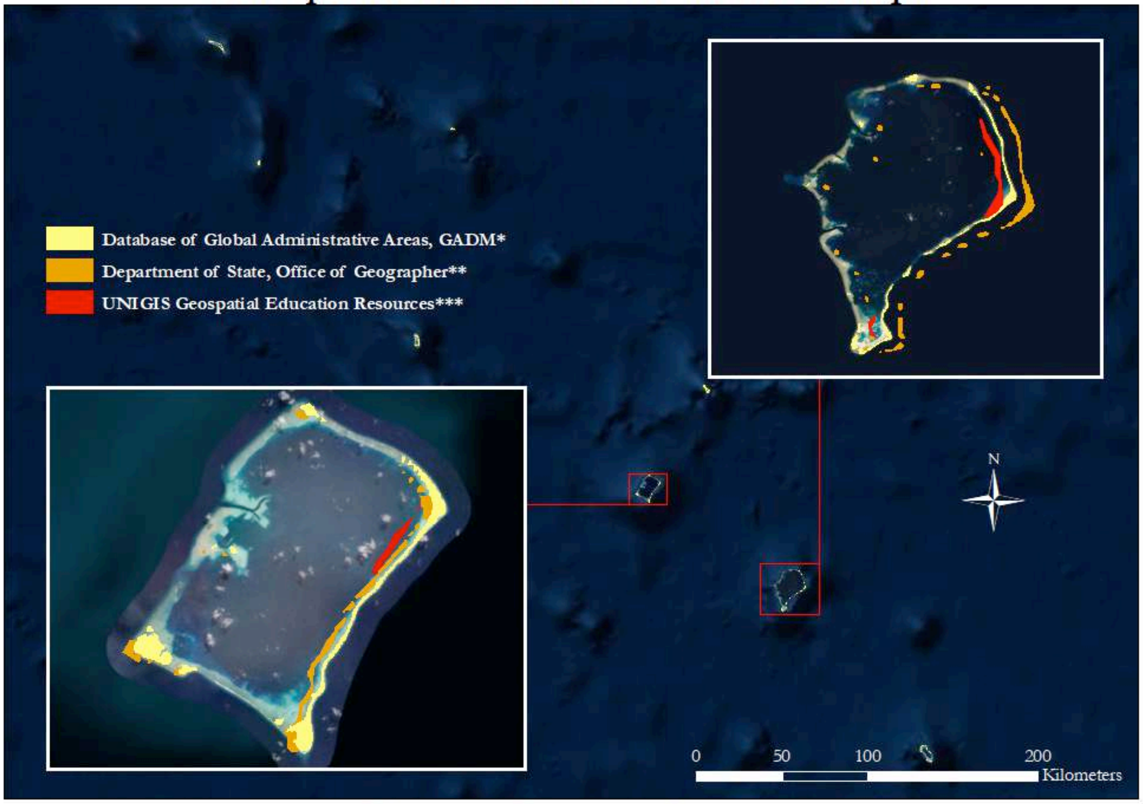
Figure C5: Infrastructure vulnerable to a 1-meter rise in sea level in Tonga.



Infrastructure Less than 1-meter Above Mean Sea Level: Tuvalu

Figure C6: Infrastructure vulnerable to a 1-meter rise in sea level in Tuvalu.

Discrepancies with Datasets: Tuvalu Example



*Accessed Through UC Davis **Accessed through Stanford Univeristy ***Accessed through ESRI Online Resources

Figure C7: Tuvalu as an example of data discrepancies in Oceania

As previously discussed, data on Oceania is lacking compared to other parts of the world. Not only are datasets difficult to find, the reliability of data from widely used sources can contain errors. For example, three separate shapefiles of Tuvalu showcase the discrepancies that exist between datasets. All three shapefiles have the same general shape of the island chain. The red shapefile comes from the ESRI online repository, a go to for GIS resources. This shapefile is also oversimplified and fails to recognize many of the islands. The orange shapefile comes from the Department of State's Office of Geographer (accessed through Stanford University's online portal). It is less generalized but again fails to align with satellite imagery (all shapefiles shown have the same map projection). The third and final shapefile shown, from the Database of Global Administrative Areas (accessed through UC Davis' online portal), is the most accurate and aligns properly with the satellite imagery. Small discrepancies like this are inconsequential for larger countries but play a major role in spatial analysis for small island nations where being by a matter of meters can miss the entire island.

Areas for future research

Informal settlements

Informal settlements are unplanned residential areas that typically exist on the peripheries of existing urban areas. They are splintered throughout Oceania's cities and present a major opportunity to identify large, growing populations of vulnerable people in Oceania and include them in disaster preparedness efforts. Informal settlements are often highly vulnerable, as they grow haphazardly in areas naturally exposed to hazards. Furthermore, preparedness efforts often exclude these unofficial settlements because of their informal nature, making residents more susceptible to climate disasters than their formal neighbors. Finally, given the challenges to identifying and mapping informal settlements at a regional level, no comprehensive information on these vulnerable populations exist in Oceania.

Informal settlements are highly vulnerable and present an array of challenges related to disaster preparedness. They are often located in marginal areas exposed to environmental hazards such as low-lying coastal areas, flood plains, riverbanks, and steeply sloped hills. Housing is typically poor quality and less durable than permanent structures. Furthermore, those living in informal settlements are generally underserved by water, sanitation, and hygiene infrastructure. Finally, informal settlements are often centers for migration to urban areas and have higher rates of poverty and domestic violence.

Evidence from specific countries and urban areas suggest that informal settlements are growing in the study area. Informal settlements in Honiara, Solomon Islands, are growing at 12% per year and now include around 40% of Honiara's population.[79] The situation in Fiji's greater Suva area is similar. 494,252 people, half of Fiji's population, lives in the Suva area, which has grown 16% since 2007.[80] Much of this growth has been on the border of developed urban areas in splintered, informal settlements.[81] Estimates on the number of people currently living in these informal settlements range from 76,613 to 98,850, with the actual number of informal settlements in the Suva area ranging from 72 to 172.[82,83,84]

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[79] Meg Keen and Luke Kiddle, "Priced out of the Market: Informal Settlements in Honiara, Solomon Islands," *Devpolicy Blog from the Development Policy Centre* (blog), January 16, 2017, https://devpolicy.org/priced-out-of-the-market-informal-settlements-in-honiara-solomon-islands-20160117/.

[80] "Fijian Government - Fiji Bureau of Statistics Releases 2017 Census Results," Government Agency, The Fijian Government, October 1, 2018, https://www.fiji.gov.fj/Media-Centre/News/Fiji-Bureau-of-Statistics-Releases-2017-Census-Res.

[81] N. S Rao and South Pacific Regional Environment Programme, *An Economic Analysis of Ecosystem-Based Adaptation and Engineering Options for Climate Change Adaptation in Lami Town, Republic of the Fiji Islands: Technical Report*, 2013, http://www.sprep.org/publications/lami-town-fiji-ebatechnical-report.

[82] UN Habitat, "Fiji – Informal Settlement Situation Analysis | Advisory Center for Affordable Housing ACASH," accessed May 8, 2020, https://center4affordablehousing.org/topics/fiji-informal-settlement-situation-analysis-4/.

[83] ACROS Fukuoka, "UN-Habitat Regional Office for Asia and the Pacific (ROAP)," n.d., 2.

The situations in Fiji and the Solomon Islands are not unique in Oceania. As of 2015, an estimated 40% of Kiribati's capital Tarawa, 30% of Vanuatu's capital Port Vila, and 10% of Tonga's capital Nuku'alofa lived in informal settlements.[85] Urban populations are likely to grow rapidly across the region, at least in part due to increased rural-urban migration as a consequence of climate change and Oceania's informal settlements are likely to continue to grow.

Unfortunately, the exact location of Oceania's informal settlements and the scope of their population growth is difficult to determine. As with other information in the region, there is no comprehensive data set on informal settlements. The limited data that do exist are disparate and without context. For example, the three data points available through the Sustainable Development Goal's open database are for the entirety of Oceania in 2000 and 2016 and for Fiji in 2016.[86] The lack of data on the study area is expected given the inherent challenges to collecting and maintaining datasets in the study area.

The Challenge of Identifying Informal Settlements

Informal settlements do not exist on maps and are and are not easily identifiable using remote mapping tools. In the map of Suva (Figure D1), the estimated informal settlement areas are in pink.[87] This helps visualize the challenge of identifying informal settlements as they are dispersed throughout developed Suva in irregular patterns.

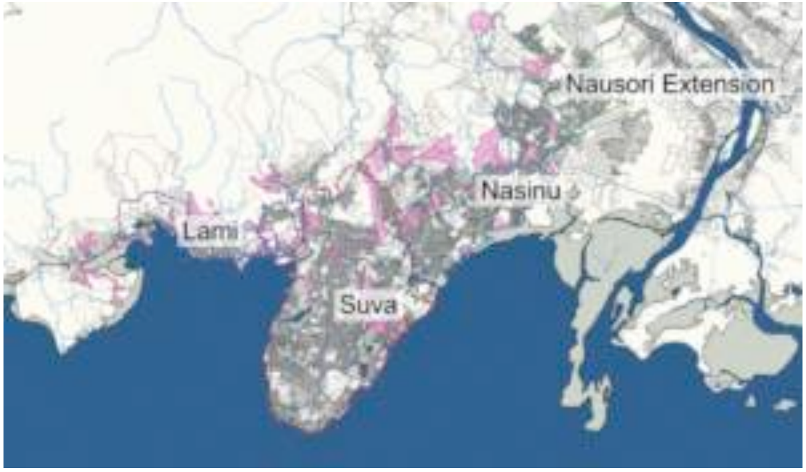

Figure D1: Information settlements (pink) in the greater Suva area, Fiji.[88]

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[84] Asian Development Bank, "Pilot Fragility Assessment of an Informal Urban Settlement in Fiji" (Asian Development Bank, March 1, 2013), Fiji, https://www.adb.org/publications/pilot-fragility-assessment-informal-urban-settlement-fiji.

[85] Jones, *The Emergence of Pacific Urban Villages*.

[86] "SDG Indicators."

[87] UN Habitat, "Fiji – Informal Settlement Situation Analysis | Advisory Center for Affordable Housing ACASH."

[88] UN Habitat.

For example, Lami Town, a settlement on the edge of Suva, is bordered by mangrove forests and prone to flash flooding and inundation during heavy rainfall. Informal settlements in Lami Town, particularly the one noted by the dotted red box (Figure D2), are in the areas of Lami Town most vulnerable to flooding and other climate risks (Figure D3). Satellite imagery of Lami Town in Figure D4 highlights the practical challenge of remotely identifying and delineating informal settlements. There are no clear boundaries between the formal city and informal areas.

Figure D2: Informal settlements in Lami Town, outside of Suva, Fiji.[89]

Figure D3: Hotspot map of flooding and climate risks in Lami Town, outside of Suva, Fiji.[90]

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[89] UN Habitat.

[90] UN Habitat.

Figure D4: Satellite image of Lami Town, outside of Suva, Fiji.[91]

Getting accurate data for informal settlements

At varying levels of expense, commitment, and technology, there are several ways to improve data about informal settlements and their populations. One promising method is using Convolutional Neural Networks (CNNs) for Image Identification. CNNs are neural networks that can process images and identify objects within them. Although these methods of machine learning have been around for a long time, it is only within the past 10 years that the error of image classification was reduced to 15%, leading many companies and researchers to adopt these methods for data collection and image processing.

CNNs have been used successfully to map informal settlements in other parts of the world. One study used freely available satellite imagery from the European Commission's Sentinel-2 satellite to locate informal settlements and estimate the number of people who live in a certain area.[92] This technology could allow us to get a more accurate estimate of the population that is vulnerable to sea level rise.

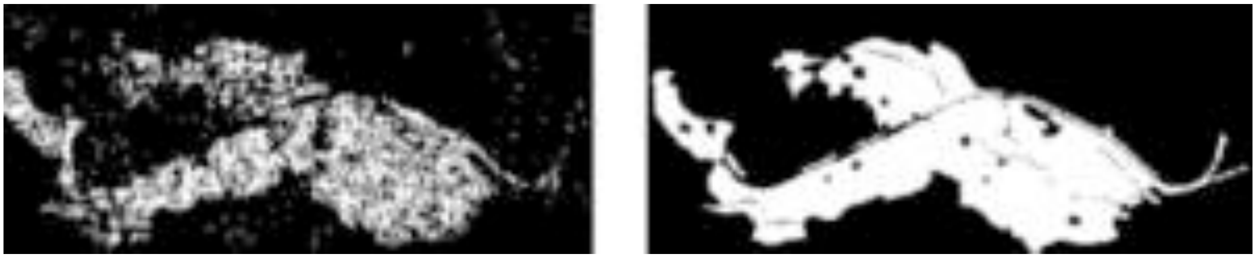

Figure D5: *Left*: Predicted informal settlements in white pixels in Kibera, Nairobi. *Right*: Ground-truth map of Kibera, Nairobi.[93]

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[91] UN Habitat.

[92] Bradley Gram-Hansen et al., "Mapping Informal Settlements in Developing Countries Using Machine Learning and Low Resolution Multi-Spectral Data," *Proceedings of the 2019 AAAI/ACM Conference on AI, Ethics, and Society*, January 27, 2019, 361–68, https://doi.org/10.1145/3306618.3314253.

[93] Gram-Hansen et al.

This method shows significant promise for Oceania, as it allows researchers to map informal settlements without visiting them; however, this method is not a perfect solution. Refining it to accurately analyze Oceania would require a coordinated technological effort and should include on-the-ground verification of initial data. This verification could be costly, but it is not required; the estimates produced by CNNs can still be useful for planning and modeling purposes.

Accurate CNNs are also dependent on the availability of open-source satellite data. If the open-source satellite imagery is unavailable or not detailed enough, the replacement higher resolution satellite imagery can cost hundreds of thousands of dollars.

The greatest benefit of CNNs is their ability to collect data remotely, which could eliminate the costs and time required by traditional methods of data collection. Most alternatives to this machine learning approach suffer the same pitfall: they require localized, intense effort and resources, including technical skill. While such methods may help identify and map informal settlements in specific areas, they are too resource intensive to replicate in bulk across Oceania's disparate, remote islands. The company Picterra bridges this gap and offers a promising potential solution to collect image data through CNNs.[94] Critically, Picterra allows users to train an artificial intelligence platform to recognize features for free, which is cheaper and requires less technical expertise than other current CNN mapping platforms.

Using remote sensing to create more reliable data sets

Gathering data on Oceania is integral to disaster planning, however there are many challenges to acquiring large datasets in isolated areas because of limited connectivity. One promising tool that should continue to be explored is using remote sensing to identify key features of the area. From topographic data to the locations of more vulnerable buildings and populations, remote sensing can fill the gaps on collecting important planning information. Data that historically was collected on a localized basis can now be extracted from satellite imagery on a large scale.

Defining remote sensing

Remote sensing is data collection from a distance, typically from an aircraft or satellite. Notably, it does not require on-the-ground data collection efforts that present major data challenges in Oceania. Remote sensing can provide complete, accurate data sets that, when integrated with climate modeling and emergency management, allow for more effective disaster planning and preparedness.[95] Recent advances in technology allow remote sensing to move beyond traditional land change monitoring tools to more advanced health, enforcement,

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[94] "Picterra - Geospatial Imagery Analysis Made Easy," Picterra, accessed May 16, 2020, https://picterra.ch/.

[95] Jun Yang et al., "The Role of Satellite Remote Sensing in Climate Change Studies," *Nature Climate Change* 3, no. 10 (October 2013): 875–83, https://doi.org/10.1038/nclimate1908.

and prediction tools that can be used to identify specific at-risk populations at higher resolutions over larger areas. Convolutional Neural Networks (CNNs), discussed above, are a tool that can be used to enhance remote sensing by recognizing and identifying objects in an image. These methods could be particularly helpful in filling the data availability gaps in Oceania.

Traditional Applications of Remote Sensing

Satellite remote sensing has traditionally been used to track changes in land use over time by using satellite imagery going back decades.[96] Land use (or land cover) change is useful to assess urbanization, deforestation, agricultural productivity. This is particularly true for Oceania as these countries have limited land resources. Figures D6 and D8 depict the same shoreline on Vanuatu before and after Cyclone Pam struck the island in 2015.[97] As made evident by the new water line, swaths of the shore were wiped away. Similarly, the islands in Figures D8 and D9 were so vulnerable that they were completely swept away from a strong weather event.[98]

Figure D6: Shoreline on Vanuatu before Hurricane Pam in 2015.[99]

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[96] Michino Hisabayashi, John Rogan, and Arthur Elmes, “Quantifying Shoreline Change in Funafuti Atoll, Tuvalu Using a Time Series of Quickbird, Worldview and Landsat Data,” *GIScience & Remote Sensing* 55, no. 3 (May 4, 2018): 307–30, https://doi.org/10.1080/15481603.2017.1367157.

[97] Simon Elvery and Tim Leslie, “Before and after: Cyclone Pam’s Impact on Vanuatu - ABC News (Australian Broadcasting Corporation),” accessed May 8, 2020, https://www.abc.net.au/news/2015-03-17/cyclone-pam-before-after/6325222?nw=0.

[98] “An Island Disappears,” accessed May 8, 2020, https://earthobservatory.nasa.gov/images/144346/an-island-disappears.

[99] Elvery and Leslie, “Before and after: Cyclone Pam’s Impact on Vanuatu - ABC News (Australian Broadcasting Corporation).”

Figure D7: Shoreline on Vanuatu after Hurricane Pam in 2015.[100]

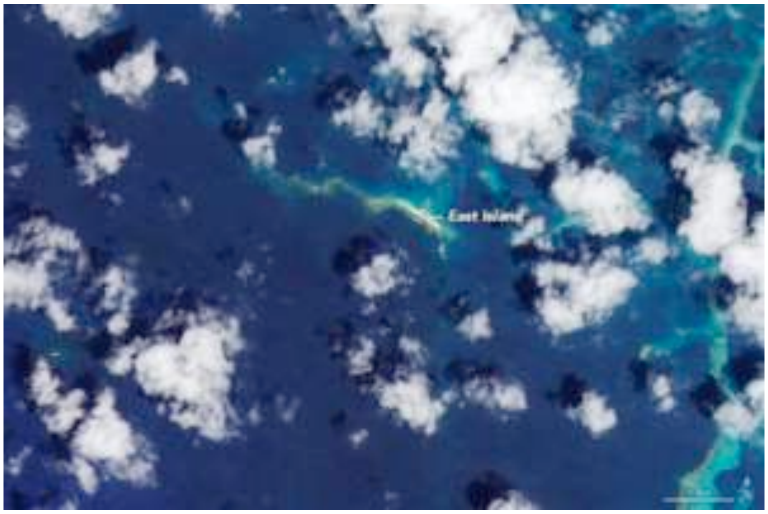

Figure D8: Vanuatu’s East Island before Hurricane Pam in 2015.[101]

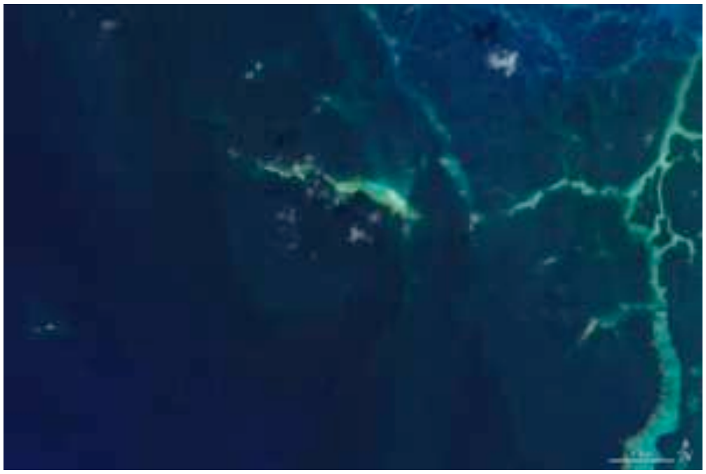

Figure D9: Vanuatu’s East Island, now underwater, after Hurricane Pam in 2015.[102]

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[100] Elvery and Leslie.

[101] Elvery and Leslie.

In the long term, satellite imagery provides scientists and stakeholders with an arsenal of knowledge to better predict and prepare for extreme events caused by climate change.[103] It is important for communities to have baseline data when planning for these events, and for the community to understand how to use this data for their benefit. Local knowledge, combined with quantitative data from remote sensing, can provide a powerful tool in addressing risk and vulnerability.

Advancements in the Application of Remote Sensing

Artificial intelligence (including CNNs), higher resolution imagery, and new sensors are just some of the new technologies revolutionizing what can be studied through remote sensing. Specifically, remote sensing can provide high resolution satellite imagery which would allow for a more accurate assessment of vulnerability related to sea level rise.

The CoastalDEM data that this report uses was created by reducing uncertainty and vertical bias from the shuttle resource topography mission (SRTM), which provided the first complete elevation model of the entire world with a spatial resolution of 30 meters.[104] CoastalDEM has is also more accurate than SRTM in coastal regions. Landsat imagery, which has been around since 1972, boasts the same resolution.[105] It is possible, however, to create higher resolution satellite images of Oceania, though no freely available high resolution data exists.[106, 107] Higher resolution images are critical to conduct accurate analysis of the consequences of climate change and sea level rise to Oceania's island nations. at a scale appropriate for their land size.

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[102] Elvery and Leslie.

[103] Yang et al., "The Role of Satellite Remote Sensing in Climate Change Studies."

[104] Farr et al., "The Shuttle Radar Topography Mission."

[105] "Landsat Image Gallery," accessed May 8, 2020, https://landsat.visibleearth.nasa.gov/.

[106] "Satellite Imagery and Archive," Planet, April 29, 2019, https://planet.com/products/planet-imagery/.

[107] "See How @DigitalGlobe 30 Cm Imagery, the New Gold Standard in Satellite Imagery, Is Changing the Game.," DigitalGlobe 30 cm, accessed May 8, 2020, https://www.digitalglobe.com/30cm/.

Figure D10: A canal in Venice, Italy, at 10-meter resolution.[108]

Figure D11: The canal in Figure 10 from Venice at 50-centimeter resolution.[109]

Limitations and the future of remote sensing in Oceania

Despite the advancements in remote sensing, it still has limitations. Because Oceania is mostly composed of small islands, remotely sensed data will have to have a high spatial resolution. While resolution exists today, it is prohibitively expensive. Therefore, leveraging strategic partnerships is necessary. One example is the United Nations program Common

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[108] "Satellite Data: What Spatial Resolution Is Enough for You?," Earth Observing System, April 12, 2019, https://eos.com/blog/satellite-data-what-spatial-resolution-is-enough-for-you/.
[109] "Satellite Data: What Spatial Resolution Is Enough for You?"

Sensing through the UNOSAT office and many other remote sensing partnerships are possible.[110]

Furthermore, remote sensing cannot completely replace localized efforts. Qualitative data such as access to health services, poverty levels, or affordable housing options cannot be measured from space. Rather, satellite imagery should supplement local knowledge and qualitative data to build accurate, dynamic monitoring and preparedness tools. For example, marine habitat mapping is possible because of collaboration between local communities, remote sensing engineers, and policy makers on a scale that would be impossible for any one group to accomplish.[111] Furthermore, there are important metrics that cannot be seen with satellites. New tools are looking into metrics to estimate such parameters with satellite imagery, but the quality of such data is not yet clear.[112]

Moving forward, stakeholders can continue to leverage remote sensing to quantify and visualize the dangers posed by climate related disasters. Vulnerability mapping that incorporates remotely sensed data will continue to be a critical aspect of climate planning. However, mapping alone will not be enough to combat the future negative effects. Interpreting the data into meaningful actions will require the combined efforts of policy makers, local communities and scientists.

Advancements in bathymetry data collection

Bathymetric data, or the topographic data of the sea floor, is integral to assessing risk for Oceanic Islands. Modeling the seafloor is important in understanding their future erosion and risk, but complete, precise bathymetry data is not available for this area of the world. Efforts to collect bathymetric data have been increasing in Oceania, though collecting accurate data is expensive.[113] Future researchers should understand the importance of bathymetric data in modeling and planning for disasters.

Topographic mapping of the earth's surface uses Light Detection and Ranging (LIDAR) technology, which is a remote sensing method that uses a laser to pulse light and measure ranges. This can be done using satellites, helicopters, and aircraft.[114] While LIDAR sensing methods utilizing planes and satellites can easily measure the top surface of the ocean, they

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[110] "CommonSensing: Building Climate Resilience in Small Island Developing States (SIDS) | UNITAR," United Nations Institute for Training and Research, June 21, 2019, https://unitar.org/about/news-stories/news/commonsensing-building-climate-resilience-small-island-developing-states-sids.

[111] Matthew Lauer and Shankar Aswani, "Integrating Indigenous Ecological Knowledge and Multi-Spectral Image Classification for Marine Habitat Mapping in Oceania," *Ocean & Coastal Management* 51, no. 6 (January 1, 2008): 495–504, https://doi.org/10.1016/j.ocecoaman.2008.04.006.

[112] Tilottama Ghosh et al., "Using Nighttime Satellite Imagery as a Proxy Measure of Human Well-Being," *Sustainability* 5, no. 12 (December 2013): 4988–5019, https://doi.org/10.3390/su5124988.

[113] "Advanced Topographic and Bathymetric Survey to Support Tuvalu's Adaptation Efforts - Tuvalu."

[114] National Oceanic and Atmospheric Administration US Department of Commerce, "What Is LIDAR," Government Agency, National Ocean Service-National Oceanic and Atmospheric Administration, accessed May 8, 2020, https://oceanservice.noaa.gov/facts/lidar.html.

cannot be used in a water column, where electromagnetic energy dissipates too quickly for accurate measurement.

To get around this constraint, bathymetry data has historically been collected by utilizing sound waves, which allow us to map bathymetry similar to how we currently map land topography. Ships emit sonar beams that bounce back to a sensor on the ship. The intensity of their reflection is measured and analyzed to stitch together a picture of the ocean floor (Figure D12). Since this method cannot be done by distant satellites or aircraft, it requires substantial financial resources and time to get a wide, complete picture.

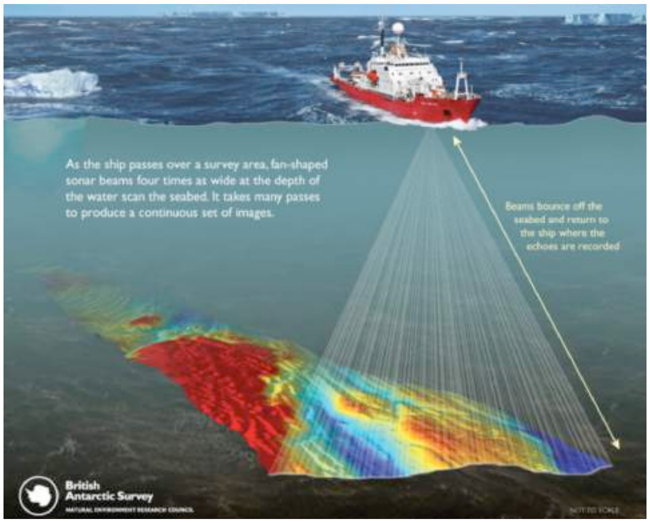

Figure D12: Ship-based bathymetry data collection.[115]

Ship-based sonar in shallow waters also has its limitations. Sonar beams are only able to measure a limited area of the ocean floor at a time, because beam lengths are limited and can only be collected along specific ship pathways (See Figure D13).[116] To make a complete image, ships would have to make many passes on a similar route. The larger the ship, the wider the area it can cover in one sweep. However, since large ships are confined to deep water, it is difficult for them to get close to shore to measure bathymetry close to the land.

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[115] "Multibeam Echosounder - British Antarctic Survey," accessed May 8, 2020, https://www.bas.ac.uk/polar-operations/sites-and-facilities/facility/rrs-james-clark-ross/multibeam-echosounder-2/.

[116] "Bathymetric Data Viewer," accessed May 8, 2020, https://maps.ngdc.noaa.gov/viewers/bathymetry/.

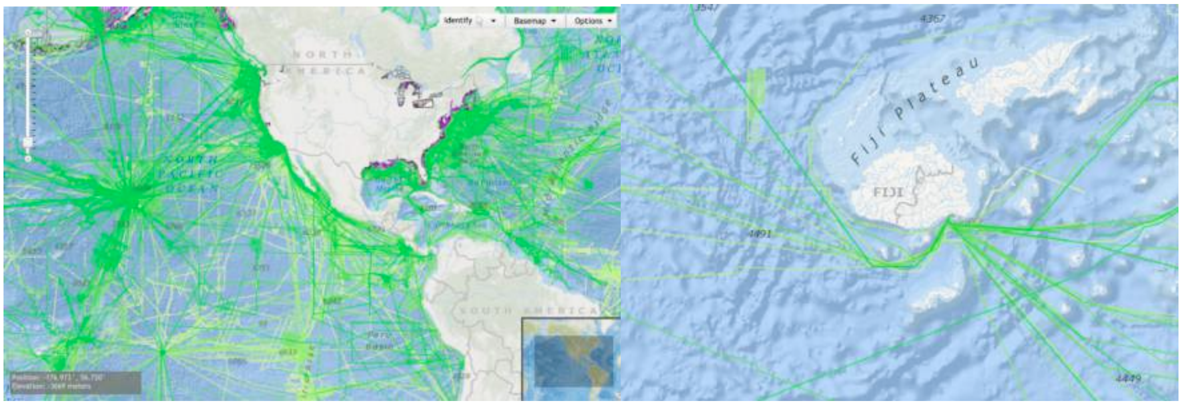

Figure D13: Current extent of bathymetry data from NOAA (2020).[117]

Recent Developments in Near-Shore Bathymetry Data Collection:

Many scientists are interested in collecting accurate bathymetry data close to shore to study vulnerability and erosion, leading to a data gap where boats cannot reach, and aircraft LIDAR cannot penetrate through the water. Thankfully, a few recent developments have allowed for the estimation of bathymetry data with high degree of accuracy.

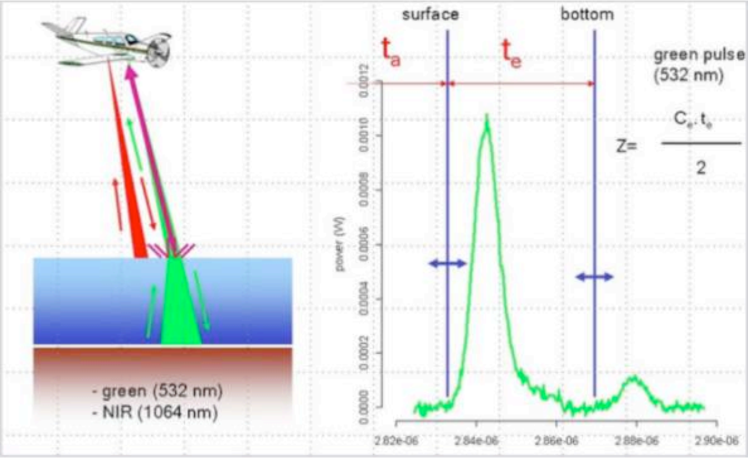

Figure D14: Airborne Laser Hydrography.[118]

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[117] "Bathymetric Data Viewer."

[118] Arnaud Abadie, Marie Lamouret, and Viala Christophe, *Cartographie Au Lidar de La Limite Des Herbiers de Posidonies*, 2019, https://www.researchgate.net/publication/337831409_Cartographie_au_lidar_de_la_limite_des_herbiers_de_posidonies.

One promising method for bathymetry data collection is Airborne Laser Hydrography, which was recently used to collect bathymetry data in Tuvalu (Figure D14). This method combines infrared light that scatters off the surface with water-penetrable green light (usually at 532nm) that scatters at the seafloor. The plane's sensor measures the time it takes between the infrared and green lights to quantify the depth of the survey area.[119]

Although this method cannot be used accurately for depths over approximately 50 meters, this is a fast and comparably economical method for gathering near-shore data. These images can be combined with traditional sonar wave measurements from boats to paint an accurate picture of the bathymetry close to the shore.

Figure D15: Satellite-derived Near-shore Bathymetry (SDB).[120]

Unfortunately, air and ship data collection methods also come with a hefty price tag. The average price for ship-collected data is approximately $1,000 per ship, per hour. It is unlikely that these measurement techniques will be able to be implemented across the globe, much less for all the vulnerable areas that need it. More feasible for tracking bathymetry economically over time is satellite-derived near-shore bathymetry or SDB.[121] A recent study on atolls in the Marshall islands used SDB spectral band ratio-based techniques (commonly called the natural logarithm approach) that produced highly accurate results at depths of 6

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[119] Jacques Populus, "Use of Lidar for Coastal Habitat Mapping - MarineSpecies Introduced Traits Wiki," World Register of Introduced Marine Species, 2019, http://www.marinespecies.org/introduced/wiki/Use_of_Lidar_for_coastal_habitat_mapping.

[120] Populus.

[121] Sandra K. Poppenga et al., "Evaluating the Potential for Near-Shore Bathymetry on the Majuro Atoll, Republic of the Marshall Islands, Using Landsat 8 and WorldView-3 Imagery," USGS Numbered Series, *Evaluating the Potential for Near-Shore Bathymetry on the Majuro Atoll, Republic of the Marshall Islands, Using Landsat 8 and WorldView-3 Imagery*, vol. 2018–5024, Scientific Investigations Report (Reston, VA: U.S. Geological Survey, 2018), https://doi.org/10.3133/sir20185024.

meters.[122] This method of analyzing images for light and color and predicting water turbidity could be a promising alternative to costly air-based and ship-based data collection methods.

It is unrealistic to expect every country in the study area facing high climate vulnerability to be able to map their bathymetry with high precision. Therefore, advancements in SDB techniques could provide a cost-effective means to gather bathymetry data on a large scale.

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[122] Poppenga et al.

Conclusion

Studying climate vulnerability in Oceania at scale comes with limitations. Risk related to sea level rise and flooding depend on natural attributes that are unique to individual islands and cannot be modeled accurately without comprehensive datasets for each individual island. Such datasets do not currently exist for the study area. Despite these challenges, we were still able to estimate infrastructure and populations that are most at risk as starting point for future research on vulnerability in Oceania.

Our models found 484,000 people, about 18% of the total population, living within one meter of mean sea level and thus vulnerable to coastal flooding. The countries with 50,000+ people at risk of one-meter sea level rise are: the Marshall Islands, Kiribati, French Polynesia, the Solomon Islands, and Fiji. Nearly 90% of the populations in Tokelau and Marshall Islands and 50% of the populations of Tuvalu and Kiribati are at risk. Our models also found that the Solomon Islands has a large percentage of at-risk infrastructure, with 33% of health sites and 28% of airports vulnerable to one meter of sea level rise, though comprehensive infrastructure data are necessary to assess regional risks.

Moving forward, advances in artificial intelligence and remote sensing will allow planners to collect more accurate regional data to improve these vulnerability maps. Specifically, convolutional neural networks for image identification will allow for more accurate population estimates, including informal settlements, and will provide a cost-effective method to collect near-shore bathymetry data. High quality data also must involve local verification, which requires at least some on-the-ground effort. Prioritizing data collection and risk assessments for coastal populations and critical infrastructure like health sites, transportation and power generation will help policy makers understand the extent of the vulnerability and prepare for hazards as climate change threatens their homes.

Recommended Action Items

To better understand vulnerability and prepare for climate disasters in Oceania, we recommend the below steps. While we suggest partners for each recommendation, this report does not explore the specific capabilities of each partner nor the feasibility of a partnership. Rather, the partners we suggest are based on partners' existing relationships with potential shared interest or overlapping technical capability that we believe would facilitate each recommendation. Our recommendations are:

1. **Create freely available high-resolution satellite imagery to enable remote sensing possibilities and allow for more detailed coastal flooding maps**. Potential partners include FRANZ Agreement allies (France, Australian and New Zealand), the United States Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), the US Navy, and the US Air Force.

2. **Collect bathymetry data to understand local variation in sea level rise and flood risks.** Potential partners again include FRANZ Agreement allies, USGS, NOAA, the US Navy, and the US Air Force.

3. **Collect detailed infrastructure data, especially related to power generation and distribution, to provide a clear picture of infrastructure at risk**. Potential partners include FRANZ Agreement allies, the Pacific Islands Forum (PIF), the Pacific Community (SPC) and its Pacific Data Hub, The Multinational Planning Augmentation Team, and regional universities such as the University of the South Pacific (USP).

4. **Identify informal settlements in the region through remote sensing, as informal settlements are extremely vulnerable to flooding risks and likely growing in Oceania.** Potential partners include FRANZ Agreement allies, USAID, Department of State, PIF, SPC, local governments, and regional universities.

5. **Include plans to ground-truth data to identify and understand any data deficiencies.** Potential partners include FRANZ Agreement allies, USAID, local governments, regional universities, Fulbright scholars, and Peace Corps volunteers.

Appendix A: Data Sources and Available Data Files

Dataset	Source	Spatial Resolution	Temporal Resolution
Population	SEDAC[123]	1km	2000, 2005, 2010, 2015, and 2020 estimates
Country Location and Shape	GADM[124] ESRI[125] DoS[126]	Varies	NA
Health Sites	United Nations[127]	NA	Last Updated March 6th, 2020
Elevation	CoastalDEM[128]	90 meter	Published October, 2019
Airports	Developed by students from Google Maps.	NA	Data Collected April, 2020
Powerplant Data	Developed by students from Google Maps.	NA	Data Collected April, 2020

Data Package:

The data package put together contains all of the raster and shapefile data that was used, collected, or created throughout the course of this research.

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[123] "Socioeconomic Data and Applications Center | SEDAC."

[124] "GADM," accessed May 8, 2020, https://gadm.org/.

[125] "Countries WGS84," accessed May 8, 2020, https://hub.arcgis.com/datasets/a21fdb46d23e4ef896f31475217cbb08_1.

[126] "Detailed World Polygons (LSIB), Oceania, Malaysia, Antarctica, 2013 in EarthWorks," accessed May 8, 2020, https://earthworks.stanford.edu/catalog/stanford-dt465jv7171.

[127] "The Centre for Humanitarian Data – Connecting People and Data to Improve Lives," accessed May 8, 2020, https://centre.humdata.org/.

[128] "Climate Central," accessed May 8, 2020, https://go.climatecentral.org/coastaldem/.

Appendix B: Pacific Community Estimates of Population Within 1km of Coastline

Country	Population within 1km[129]	Percentage of Total Population
American Samoa	33,618	61%
Cook Islands	13,588	91%
Fiji	227,984	27%
French Polynesia	211,092	79%
Guam	48,219	30%
Kiribati	109,693	100%
Marshall Islands	53,158	100%
Micronesia	91,059	89%
Nauru	9,206	93%
New Caledonia	153,615	57%
Niue	360	25%
Northern Mariana Islands	37,243	69%
Palau	16,510	93%
Samoa	114,834	61%
Solomon Islands	335,613	65%
Tonga	84,859	84%
Tuvalu	10,640	100%
Vanuatu	149,967	67%

Data derived from Pacific Data

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[129] “Pacific Coastal Populations- Pacific Community.”

Appendix C: Climate Central Population Exposure Estimates

Country	Population Exposed to Coastal Flooding by 2050[130]	Percentage of Total Population Exposed
Fiji	70,000	8.14%
Solomon Islands	40,000	7.84%
New Caledonia	10,000	4.00%
Vanuatu	10,000	5.26%
French Polynesia	10,000	3.57%
Samoa	30,000	15.79%
Marshall Islands	40,000	80.00%
Tonga	10,000	8.33%
Kiribati	30,000	30.00%
Micronesia (Federated States of)	20,000	20.00%
Northern Mariana Islands	20,000	40.00%

Climate Central estimates of population exposure to coastal flooding by 2050

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[130] "Climate Central," accessed May 8, 2020, https://go.climatecentral.org/coastaldem/.

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