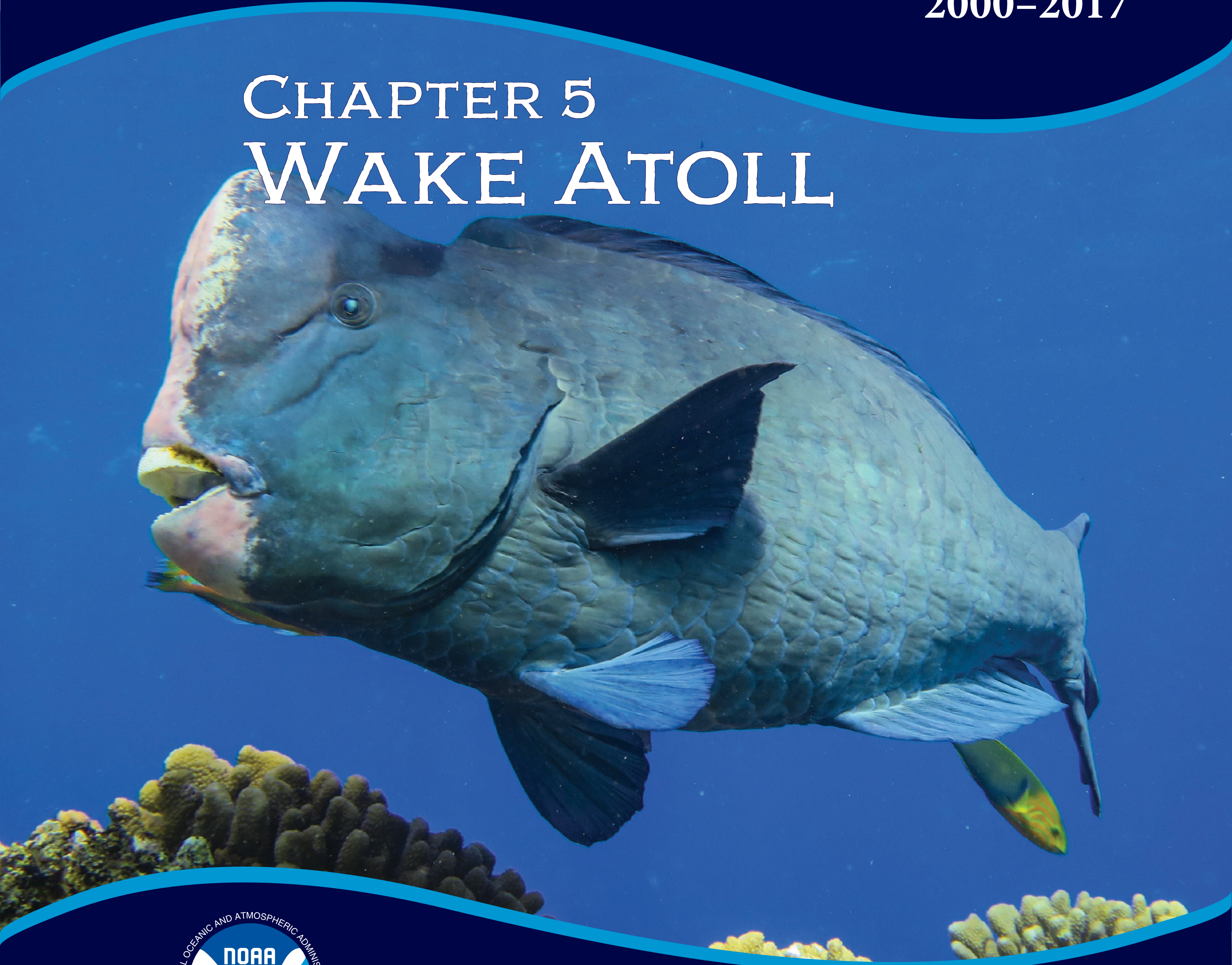
# CORAL REEF ECOSYSTEM MONITORING REPORT FOR THE PACIFIC REMOTE ISLANDS MARINE NATIONAL MONUMENT

2000–2017

## CHAPTER 5

## WAKE ATOLL



NOAA FISHERIES

ECOSYSTEM SCIENCES DIVISION

*Pacific Islands Fisheries Science Center*

# Coral Reef Ecosystem Monitoring Report for the Pacific Remote Islands Marine National Monument 2000–2017

## Chapter 5: Wake Atoll

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## Citations

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Front Cover: Parrotfish (*Bolbometopon muricatum*) at Wake Atoll. Photo: Andrew E. Gray, NOAA Fisheries.

Back Cover: Soldierfish (*Myripristis berndti; Myripristis amaena*) at Wake Atoll. Photo: Andrew E. Gray, NOAA Fisheries.

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# Executive Summary

The work presented within the *Coral Reef Ecosystem Monitoring Report for the Pacific Remote Islands Marine National Monument 2000–2017* is a direct result of nearly 20 years of research in the U.S. Pacific Remote Islands Marine National Monument (PRIMNM) conducted over hundreds of field days aboard National Oceanic and Atmospheric Administration (NOAA) ships by dozens of contributors from NOAA, University of Hawaii–Joint Institute for Marine and Atmospheric Research, and partner scientists. For their efforts, we are eternally grateful and appreciative of their work.

Here, we examine seven islands and atolls within the PRIMNM, using a variety of methods across multiple disciplines in order to gauge how these unique ecosystems have fared through time. In brief, this report describes and highlights the spatial patterns and temporal trends of marine ecosystems associated with Johnston Atoll, Howland Island, Baker Island, Jarvis Island, Palmyra Atoll, Kingman Atoll, and Wake Atoll, along with cross-comparative assessments among the islands, reefs, and atolls of the PRIMNM and other island areas of the U.S. Pacific Islands region in “Chapter 9: Pacific Remote Islands Marine National Monument in the Pacific-wide Context.”

Each island, reef, and atoll chapter, along with the Pacific-wide chapter, is constructed as follows: Introduction, Benthic Characterization, Ocean and Climate Variability, Coral Reef Benthic Communities, Cryptofauna Biodiversity (in the Pacific-wide chapter only), Microbiota, Reef Fishes, Marine Debris, and Ecosystem Integration.

## Key Findings

- Given the wide geographic extent and large variance in oceanographic conditions experienced across the PRIMNM, it is more informative to consider the PRIMNM as three groupings: the northernmost oligotrophic islands of Johnston and Wake Atolls, the central transition islands of Kingman Reef and Palmyra Atoll, and the equatorial upwelling islands of Howland, Baker, and Jarvis Islands.
- Due to the combined effects of equatorial and locally-intense topographic upwelling of the eastward-flowing subsurface Equatorial Undercurrent, Jarvis Island, and to a lesser extent Howland and Baker Islands, are subject to noticeably cooler mean sea surface temperatures (SSTs) than their nearest neighbors (Palmyra Atoll and Kingman Reef). The upwelling routinely experienced by these islands further results in the highest chlorophyll *a* (chl-*a*) concentrations and associated biological productivity measured across the PRIMNM. In contrast, the lower chl-*a* concentrations observed at Wake and Johnston Atolls are similar to concentrations within the Mariana Archipelago and American Samoa, which are located in the oligotrophic gyres of the North Pacific and South Pacific.
- Higher aragonite saturation values correspond to the greater availability of carbonate ions, and thus favor the growth of corals, crustose coralline algae, and other marine calcifiers. The PRIMNM’s northernmost oligotrophic islands (Johnston and Wake Atolls) retained two of the lowest average carbonate accretion rates in the U.S. Pacific Islands, indicating low reef growth over time.

- Jarvis Island experienced a massive decline in coral cover in response to acute thermal stress associated with the 2015–2016 El Niño warming event; Jarvis has shown no substantial recovery in coral cover since. Coral cover at Baker Island and Kingman Reef also declined from 2015 to 2018, reflecting a 13% decline over 3 years at both islands.
- Calcifiers comprised approximately half of the benthic communities at Howland Island, Kingman Reef, and Baker Island. Despite Jarvis's catastrophic decline in coral cover in 2016, the recent proportion of calcifiers at Jarvis Island remains high, likely due to a marked increase in cover of crustose coralline algae (CCA) observed in 2018.
- Across the PRIMNM, the crown-of-thorns sea star (*Acanthaster planci*, COTS) was consistently observed only at Kingman Reef and Johnston Atoll, though densities at these islands fluctuated across survey years. Localized outbreaks that were synchronized in timing across central Pacific reefs appeared to be genetically independent, rather than spread via the planktonic larvae released from a primary outbreak source.
- Mean reef fish biomass varied by a factor of >15 among all U.S. Pacific islands surveyed. The equatorial upwelling and central transition islands of the PRIMNM were among the islands that retained the highest biomass, especially of piscivores and planktivores, although Wake Atoll was an exception to this trend.
- The PRIMNM has also been notable for supporting larger abundances of species listed by the Endangered Species Act (ESA), including the greatest densities of the green sea turtle (*Chelonia mydas*) observed in the U.S. Pacific.

Scientists are increasingly recognizing the magnitude of ongoing and projected effects from global warming and ocean acidification on coral reef ecosystems. As such, this report provides an essential scientific foundation for informed decision making for the long-term conservation and management of the coral reef ecosystems within the PRIMNM. By summarizing trends in ecosystem response across space and time, this report is the first step towards assessing ecosystem resilience and identifying potential underlying drivers that impede or promote such resilience. Understanding these trends can inform the prioritization among candidate areas for management, as well as among the various types of policies and management actions themselves. In conclusion, the individual island, reef, atoll and Pacific-wide comparison chapters give resource managers and policymakers an unprecedented scale of spatial status and temporal trends to examine each ecosystem throughout the PRIMNM, with the hope of protecting and conserving these unique resources for generations to come.

# Acknowledgements

We would like to give credit to all National Oceanic and Atmospheric Administration (NOAA) Pacific Islands Fisheries Science Center (PIFSC) and Research Corporation of the University of Hawaii/Joint Institute for Marine and Atmospheric Research (JIMAR) scientists and staff, and the numerous partners who provided support to the Pacific Reef Assessment and Monitoring Program (Pacific RAMP) during 2000–2017, and contributed to the development of this report. We extend a special thanks to the officers and crews from the NOAA Ships *Townsend Cromwell*, *Oscar Elton Sette*, and *Hiʻialakai* who provided field support for the Pacific RAMP surveys. We further express our sincere appreciation to PIFSC, JIMAR, the NOAA Coral Reef Conservation Program (CRCP), and Pacific Islands Regional Office (PIRO) for funding and providing collaborative resources throughout these efforts.

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Lastly, we are appreciative of Tom Hourigan and Dale Brown of NOAA Fisheries, two of the earliest visionaries in the establishment of the first Pacific long-term, integrated ecosystem-based monitoring program.

PIFSC has been fortunate to work with many partners who contributed to Pacific RAMP and associated efforts, and while this list is by no means comprehensive, we sincerely thank each and every one of you. Your contributions helped make this report possible, and as a result, we have collectively provided valuable inputs to the management and conservation of the coral reef ecosystems of the Pacific Remote Islands Marine National Monument.

# Coral Reef Ecosystem Monitoring Report for the Pacific Remote Islands Marine National Monument

# 2000–2017

## Chapter 5: Wake Atoll

*Aerial view of Wake Atoll from the north looking south.*
*Photo: U.S. Air Force.*

## 5.1 Introduction

### Report Overview

The *Coral Reef Ecosystem Monitoring Report for the Pacific Remote Islands Marine National Monument 2000–2017* provides an overview of key spatial patterns and temporal trends of the environmental and oceanographic conditions, biological resources, and composition of coral reef ecosystems across the seven islands, atolls, and reefs of the Pacific Remote Islands Marine National Monument (PRIMNM). The data compiled for this report are from Pacific Reef Assessment and Monitoring Program (Pacific RAMP) research surveys conducted over the period from 2000 through 2017 by the National Oceanic and Atmospheric Administration (NOAA) Pacific Islands Fisheries Science Center (PIFSC) Ecosystem Sciences Division (ESD) and external collaborating scientists.

This report represents one of many installments of ESD's ongoing efforts to bring resource managers and interested stakeholders the best available, ecosystem-based data to help them make informed decisions about the sustainable use and conservation of the resources they manage, in this case, coral reef ecosystem in the PRIMNM. The information herein serves three main purposes:

- Provide snapshots of the status and condition of coral reef resources around each of the islands, atolls, and reefs in the PRIMNM over the course of the survey periods.
- Provide a foundation of knowledge regarding ecosystem conditions in the PRIMNM for ongoing monitoring of temporal changes to the ecosystem.
- Serve as a resource for stakeholders and resource managers for understanding marine areas of interest and formulating evolving management questions about how to best manage and conserve marine resources in the face of climate and ocean changes.

The report consists of nine chapters. In addition, attached to "Chapter 9: Pacific Remote Islands Marine National Monument in the Pacific-wide Context" are Appendix A, "Total Generic Richness of Hard Corals in the PRIMNM," and Appendix B, "Reef Fish Encounter Frequency in the PRIMNM." For more background information on the report as a whole, operational background, Pacific RAMP methods, and Public Access to Research Results, refer to "Chapter 1: Overview."

### Chapter Overview

Located at 19°17′N, 166°37′E, Wake Atoll is one of the most isolated atolls in the world and the northernmost in the Marshall Islands geological ridge. Wake Atoll is built upon an underwater volcano sitting on perhaps the oldest portion of seafloor in the world (Clouard and Bonneville 2005). Three islands—Peale, the northernmost island; Wake, the main island, and Wilkes—together with a fringing reef on the northwestern side of the atoll enclose a shallow, central lagoon (Figure 1). There is just 7.1 km$^2$ (2.73 mi$^2$) of land at Wake Island, with the highest elevation at 6 m (21 ft) above sea level.

**Figure 1. Satellite image of Wake Atoll, December 5, 2014. (© DigitalGlobe Inc. All rights reserved)**

This chapter consists of sections on “Benthic Characterization,” “Ocean and Climate Variability,” “Coral Reef Benthic Communities,” “Microbiota,” “Reef Fishes,” and “Marine Debris” to assist managers in making informed decisions relating to Wake Atoll and its coral reef ecosystems. Information from these sections is then tied together in the “Ecosystem Integration” section at the end of the chapter to provide a better understanding of the interactions and relationships among the various ecosystem components at Wake Atoll.

To facilitate discussions regarding the spatial patterns of ecological and oceanographic observations that appear throughout this chapter, five geographic regions, hereafter referred to as georegions, were defined for Wake (Figure 2). Most map-based figures throughout this chapter use the basemap template shown in Figure 2, which includes georegions, land features, and the 30 m and 100 m depth contours (isobaths).

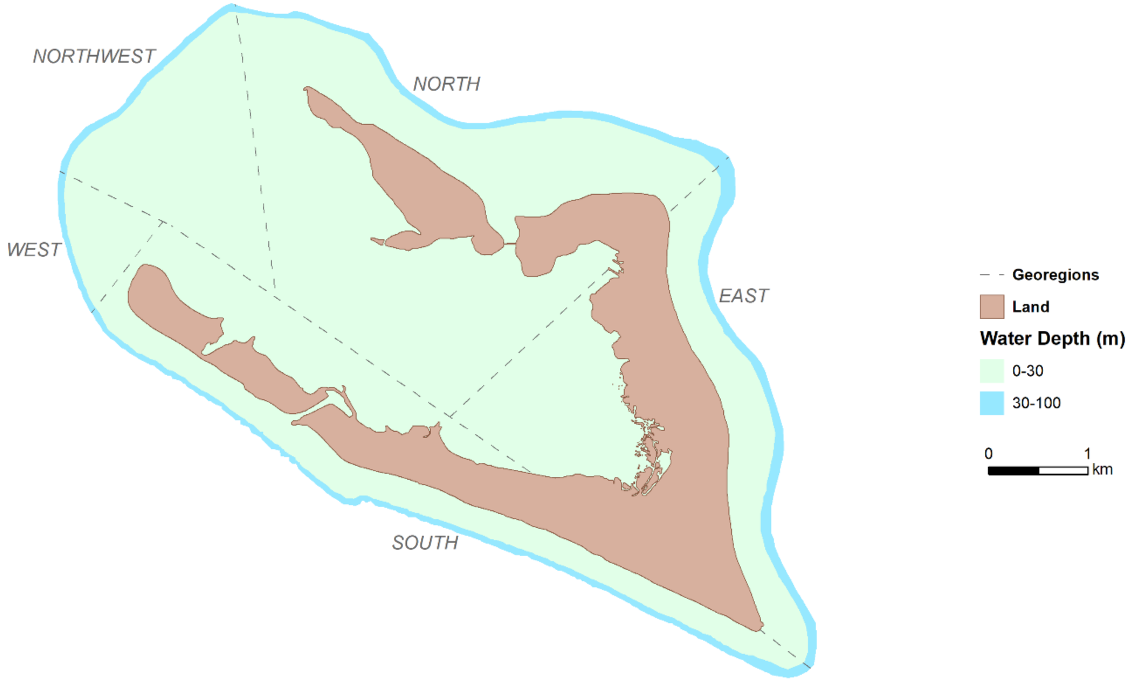


**Figure 2. The five geographic regions, or georegions, for Wake Atoll: West, South, East, North, and Northwest.**

## History and Human Influences

Although there is no archaeological evidence of pre-European human occupation at Wake Atoll, traditional legends and songs reveal that the first visitors to Wake Atoll were likely early Micronesian navigators from the Marshall Islands, who periodically visited and named the atoll *Enen Kio* after the abundant small orange *kio* flower, found only in Wake Atoll.

The first known European sighting of Wake Atoll was in 1568 by Spanish explorer and navigator Álvaro de Mendaña de Neyra; however, the island was named for British sea captain William Wake, who arrived in 1796. Prior to becoming an American possession in 1898, two documented shipwrecks occurred at Wake. In 1866, the 650-ton iron-hulled *Libelle*, hailing from Bremen, Germany, struck the eastern reef of Wake Island during a gale. In 1870, the British tea clipper *Dashing Wave* grounded and broke apart on the reef. Wake was formally claimed by the United States during the Spanish-American War, when it was used as a telegraph cable station and a coaling station for refueling warships. With limited freshwater resources, no harbor, and no plans for development, Wake Island remained a remote Pacific island for most of the early 20th century, with evidence of periodic habitation by Japanese feather hunters collecting seabird feathers for the French millinery trade over the period from 1902 to 1908. In 1935, Pan American Airways (Pan Am) established a seaplane refueling base and 48-room hotel at Wake, housing the atoll’s first known permanent residents.

In 1941, President Franklin D. Roosevelt issued Executive Order 8682 to create naval defense areas in the central Pacific territories. The proclamation established “Wake Island Naval Defensive Sea Area,” which encompassed the territorial waters between the extreme high-water marks and the 3-mile marine boundary surrounding Wake Atoll (President Franklin D. Roosevelt 1941). Later that year on December 11, 1941, the U.S. Marine garrison and 1,200 civilians working to complete construction of a major air and submarine base at Wake were attacked and overwhelmed by Japanese soldiers, who maintained control over the atoll until September 1945. At least two Japanese destroyers, two transport landing craft, and multiple aircraft were lost in the vicinity of Wake Island during the 1941 assault. During the Korean War (1950–1953), Wake airfield and facilities were a key mid-Pacific refueling stop resulting in a heavy increase of air traffic supporting the war effort. The U.S. Navy arrived at Wake Atoll in 1965 to clear the island of the effects of the war and to construct a Naval Air Station. With the resumption of commercial airway passenger service, a runway upgrade was effected in 1964 which included paving concrete over the former coral-based runway, extending it to nearly 3 km (9,800 ft; N1DG 2003).

In 1967, the 18,000-ton oil tanker *SS R.C. Stoner* ran aground on the reef at Wake Atoll spilling an estimated 6 million gallons of refined fuel oil into the small boat harbor and along the southwestern coast of Wake Island. A military-led cleanup and salvage effort removed and burned much of the oil, while explosives were used to flatten and sink the remaining portions of the ship (Gooding 1971).

In the early 1970s, commercial flights discontinued operation to and from Wake Atoll, and responsibility for the civil administration of Wake Atoll was transferred from the Federal Aviation Administration to the U.S. Air Force under an agreement between the Secretary of the Interior and the Secretary of the Air Force. Shortly after, Wake Island was selected as a launch site for the testing of defensive systems against intercontinental ballistic missiles, which has continued under various initiatives to the present. In 1975, Wake was temporarily used as a refugee processing center for evacuees from the Vietnam War, where 15,000 refugees were processed using repurposed infrastructure and field hospitals. Wake Atoll was designated as a National Historic Landmark in 1985 in recognition of its role during World War II.

In 2012, a large rodent eradication effort was undertaken. As part of the project, fish samples from the lagoon were tested for residual rodenticide. Contaminated fish tissue was discovered, resulting in the extension of a prior 2002 seafood consumption advisory for fish caught within the lagoon. Sections of the lagoon and other areas identified with chemical contamination from rodenticide fall under the environmental restoration program of the Air Force and are on the long road to environmental recovery (PACAF Regional Support Center 2015).

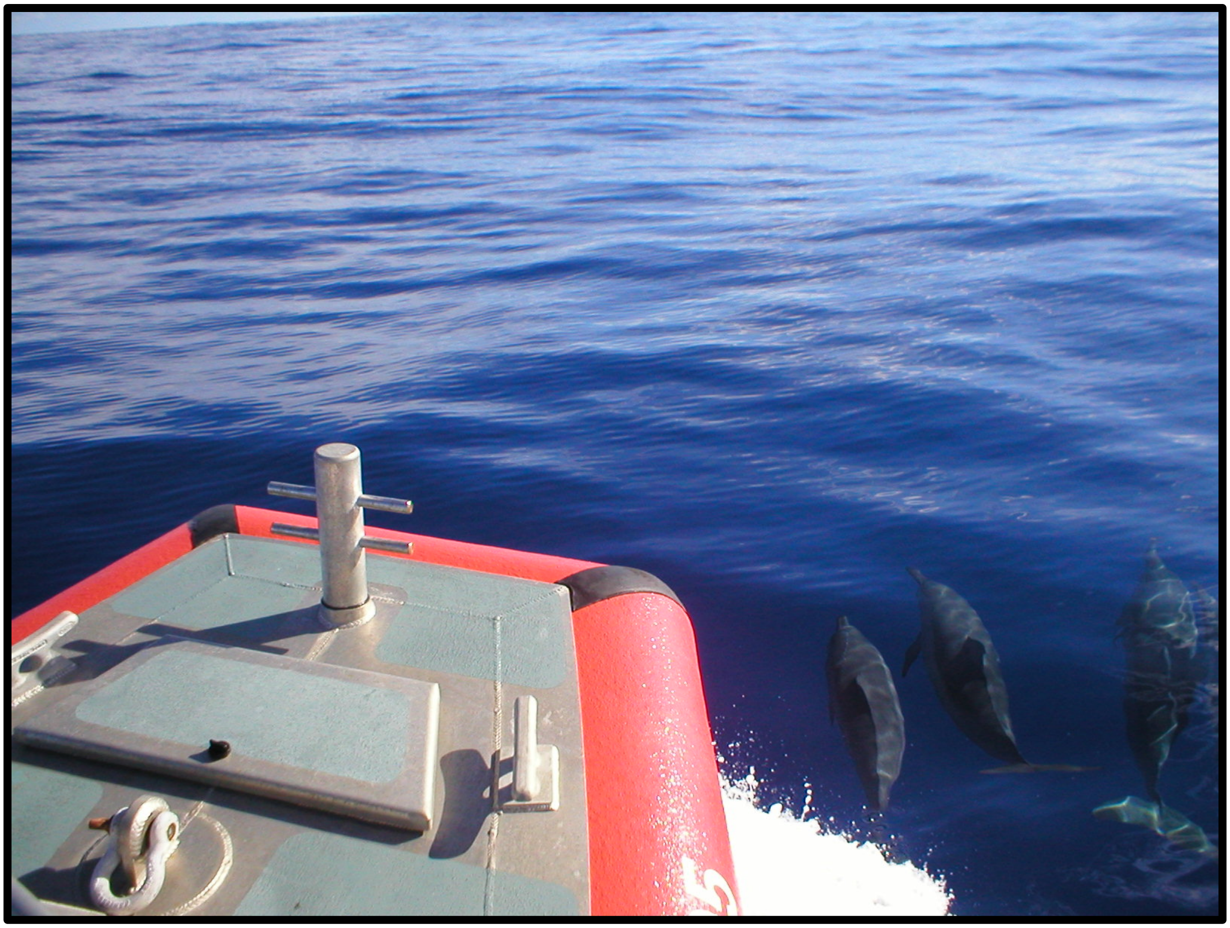
In 2009, President George W. Bush established the PRIMNM to protect and preserve the marine environment around Wake, Baker, Howland, and Jarvis Islands, Johnston and Palmyra Atolls, and Kingman Reef for the care and management of the historic and scientific objects therein (Federal Register 2009). The Proclamation directed the Department of Interior and Commerce to cooperatively manage the waters and submerged and emergent lands from the mean low water lines, seaward to 50 nautical miles, and gave NOAA primary responsibility for managing fishery-related activities from 12 to 50 nautical miles from the island. Managed by the U.S. Fish and Wildlife Service, a Wake Atoll National Wildlife Refuge was also established in 2009 from the mean low water line out to 12 nautical miles. In 2014, President Barack Obama issued Executive Order 9173 to expand the area of the PRIMNM out to the 200 nautical mile U.S. Exclusive Economic Zone boundary for Wake, Johnston, and Jarvis islands. By this proclamation, the area of the monument at Wake Island was increased from 39,069 $km^2$ (15,085 $mi^2$) to 433,398 $km^2$ (167,336 $mi^2$) (Federal Register 2015).

Currently, Wake Atoll is designated as an unincorporated unorganized territory of the United States that is administered by the Department of the Interior, with activities at the atoll conducted by the 11th Air Force and managed from the Pacific Air Force Support Center with the launch support facility being administered by the U.S. Missile Defense Agency. While access is limited, approximately 100 people live on the island to support the 3 km (9,800 ft) runway, the longest strategic runway in the Pacific islands. Infrastructure and maintenance efforts continue at Wake Island Airfield to support mid-Pacific refueling stops for military aircraft and to act as an emergency landing area.

Limited recreational and sustenance fishing are permitted for residents at Wake Atoll under the purview of U.S. Air Force in coordination with U.S. Fish and Wildlife Service refuge management. Research indicates that areas of Wake support a large population of two species of concern, the bumphead parrotfish (*Bolbometopon muricatum*) and the humphead wrasse (*Cheilinus undulatus*), which has resulted in the enactment of Fishing Exclusion Zones. Sustenance pelagic fishing (61 m [200 ft] depth or greater) in waters of Wake Atoll is regulated with quantity limitations. The primary catch is yellowfin tuna (*Thunnus albacares*), skipjack tuna (*Katsuwonus pelamis*), ono (*Acanthocybium solandri*), and mahimahi (*Coryphaena hippurus*; PACAF Regional Support Center 2015).

## Geology and Environmental Influences

Situated in the tropics, Wake experiences mean monthly air temperatures of 24–28 °C (76–83 °F) and is subject to warm sea surface temperatures throughout the year that provide for a diverse coral reef environment. Light seasonal rainfall sustains trees, thick tropic shrub growth, and grasses scattered over the islands. Due to the flat topography and substrate, ground water resources on the islands are extremely limited. Any fresh rainwater that infiltrates into the permeable substrate tends to drain rapidly into the lagoon or the ocean. As a result, ground water is brackish and non-potable. Natural wetlands occur in the intertidal and tidal pools and adjacent ponds along the interior shoreline of central Wake Island, as well as along the south coast of Peale. Some non-historic, manmade containments near the interior shoreline also qualify as wetlands (McAllaster and Davidson 2011). Another important factor in the ecological functioning of the atoll was the construction of a causeway connecting Wilkes and Wake Islands in 1923, which permanently and severely restricted water circulation in the lagoon. Reduced tidal flushing and low levels of dissolved oxygen have been reported in the lagoon. Wake is occasionally subjected to typhoons, but otherwise receives relatively consistent year-round northeast trade winds (Maragos et al. 2008).



*Dolphins swim alongside R/V* AHI *while mapping the benthic habitat.*
*Photo: Megan Moews-Asher, NOAA Fisheries.*

# *Benthic Characterization*

## 5.2 Benthic Characterization

*NOAA Nautical Chart of Wake Atoll.*
*Source: [NOAA, 7th Ed., May 2014]*

In this section, the benthic habitats of Wake Atoll are characterized for the depth range from 0 to 1,000 m, using integrated and synthesized data from numerous sources.

### Survey Effort

NOAA has been collecting benthic habitat mapping data for the nearshore areas around Wake since 2007, using a variety of methods as described in the Benthic Characterization Methods section of “Chapter 1: Overview.” These methods include multibeam bathymetric and backscatter surveys, and single-beam surveys for depth validation.

### *Multibeam Surveys*

Mapping surveys were conducted around Wake during the 2007 Pacific RAMP research cruise using multibeam sonar systems aboard the NOAA Ship *Hiʻialakai* (Simrad EM 300 and EM 3002D) and R/V *AHI* (Reson 8101-ER). Bathymetric and backscatter data were collected for depths between approximately 10 and 3,800 m, including the small boat harbor located between Wake and Wilkes islands, and used to derive mapping products covering approximately 668 km$^2$. Approximately 17.5 km$^2$ of the area remained unmapped because the shallower areas, including the lagoon, were inaccessible to survey with vessel-mounted multibeam systems.

Two of the resulting gridded bathymetric products are a 10 m high-resolution grid of the reefs, banks, shelf, and slope habitats to allow for the identification of fine-scale features to a depth of 800 m and a coarser 50 m mid-resolution grid that includes the full extent of the multibeam bathymetric data collected (Figure 3). The data and supporting documentation are available on the Wake Bathymetry page of the Pacific Islands Benthic Habitat Mapping Center (PIBHMC) website.

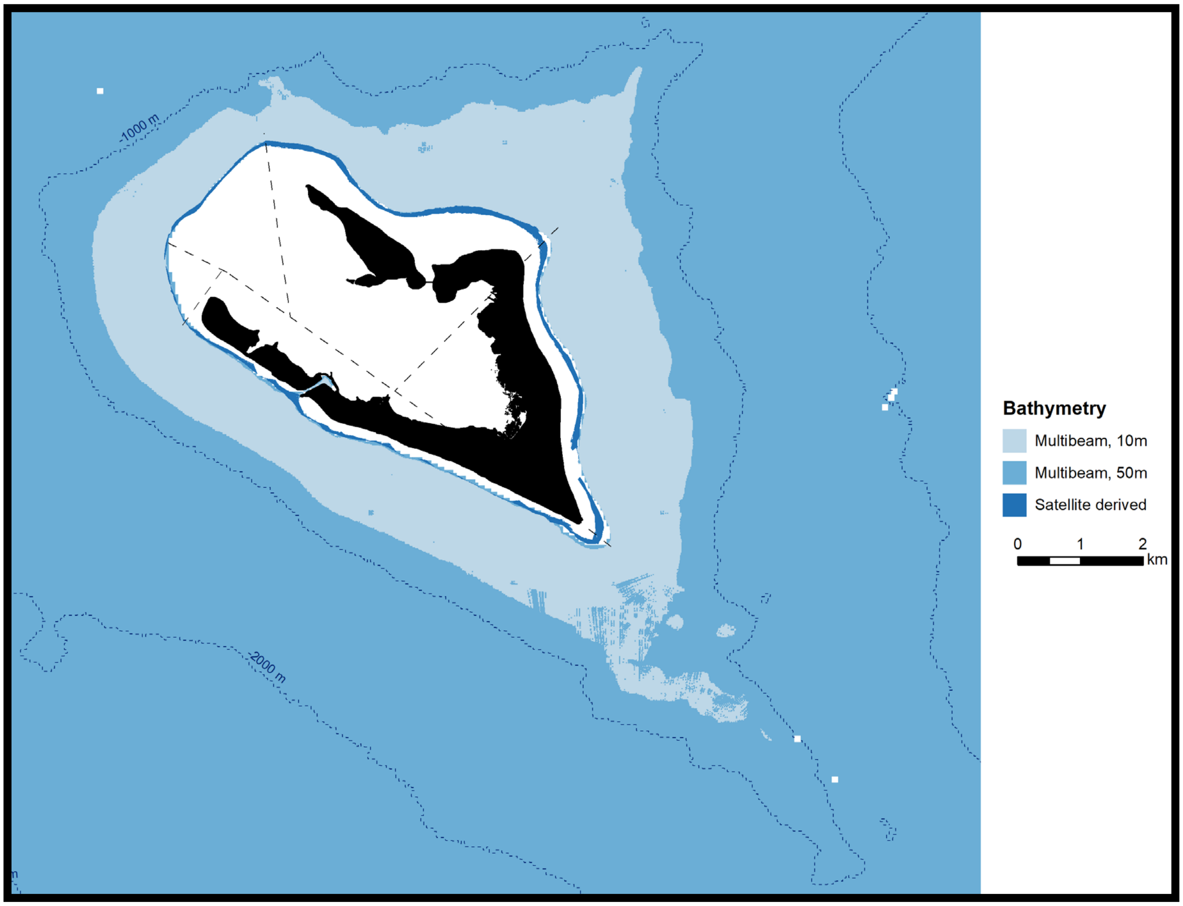


**Figure 3. Bathymetric coverage map for Wake Atoll showing extent of high- (10 m) and mid-resolution (50 m) gridded multibeam data acquired by the Ecosystem Sciences Division (ESD) in 2007 (lighter blues), and estimated bathymetry derived by ESD from satellite imagery (dark blue). The dotted dark blue lines represent 1,000 m interval depth contours. Gaps in bathymetric coverage are shown in white and land features in black. Satellite-derived bathymetry is discussed later in this section.**

The backscatter data from the shallower surveys conducted from the R/V *AHI* were gridded at 1 m resolution, while the data from the deeper surveys conducted from the *Hiʻialakai* were gridded at 5 m resolution. Acoustic backscatter intensities reveal characteristics of the seabed around Wake that can be related to topography and slope. While these data are useful for geomorphology and habitat interpretation, both the shallow and deeper backscatter data have quality issues, including high noise levels and patchiness in the coverage. The data and supporting documentation are available on the Wake Backscatter page of the PIBHMC website.

### Single-beam Surveys

Single-beam sonar data were acquired around Wake from depths between 3 and 300 m in 2014, and between 1 and 1,250 m in 2017 (Figure 4). As ocean conditions varied each year and new survey equipment was introduced in 2017, the errors associated with the two years of data also varied. Soundings error was found to be significantly greater in 2017 (1.92 m compared with 0.19 m in 2014). Therefore, the data collected in 2017 were filtered to exclude depths deeper than 60 m in Figure 4.

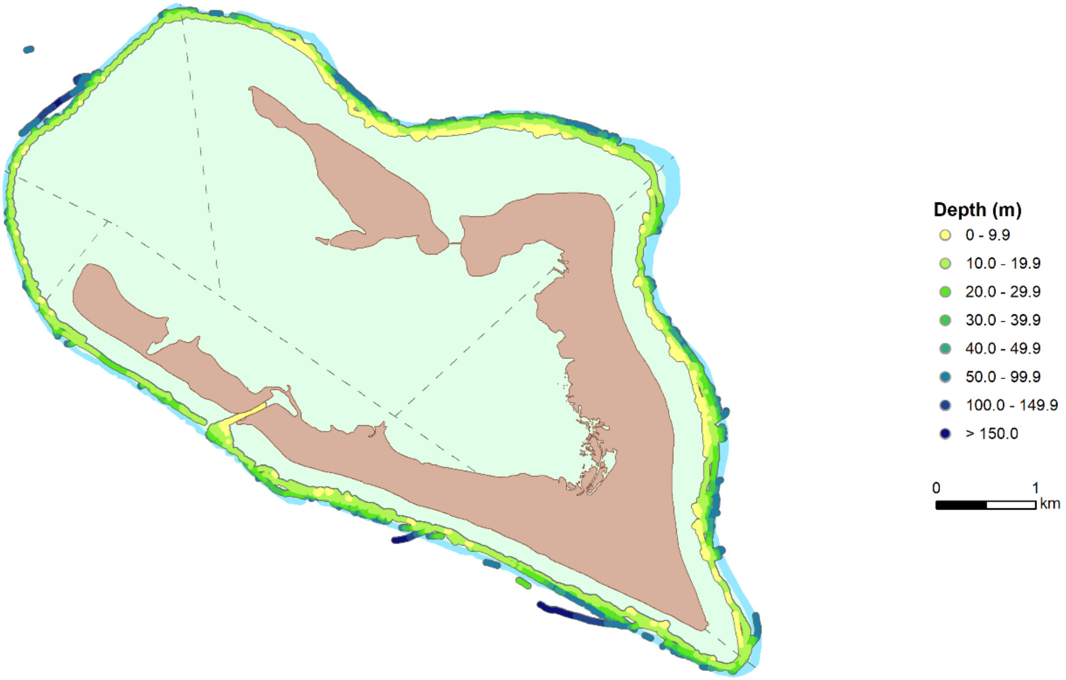


**Figure 4. Depth validation data for Wake Atoll collected by the Ecosystem Sciences Division in 2014 and 2017. Soundings deeper than 60 m have been excluded from the 2017 surveys due to data quality concerns.**

### Towed-camera Surveys

No habitat validation data for habitat mapping purposes were collected at Wake.

## Habitat characterization

### Satellite-derived Bathymetry

ESD derived estimated depths from WorldView-3 satellite imagery acquired in 2014 to fill gaps in the nearshore shallow-water bathymetric coverage around Wake. The coral reefs in the lagoon at Wake were not surveyed during Pacific RAMP missions; therefore, satellite-based bathymetric analysis was not conducted for this area. For areas outside the atoll, only limited estimated depths between 0 and 15 m were derived due to the steep slopes and wide surf zone, which blocked visibility of the seafloor in the satellite imagery (Figure 1). Depth soundings collected in 2014 (Figure 4) were used to validate the satellite-derived depths, resulting in 59% agreement between the overlapping soundings and estimated depths. The data and supporting documentation are available on the Wake Bathymetry page of the PIBHMC website. Though these estimated depths provide useful information for areas with little or no bathymetric measurements, the low depth accuracy limits the use of these data for other mapping purposes. See Figure 3 for the extent of satellite-derived depths generated by ESD that partially filled the bathymetric coverage gap around Wake.

### Digital Elevation Model (DEM)

Two topographic-bathymetric (topobathy) digital elevation models (DEM) were prepared for Wake at different scales (only the higher resolution DEM is of interest here) by the formerly-named NOAA National Geophysical Data Center for use by the NOAA Center for Tsunami Research in tsunami modeling (Grother et al. 2010). Several existing datasets were incorporated into the models, including ESD's multibeam surveys. Shallow-water bathymetric data gaps were addressed using two different methods: 1) depths in the lagoon ranging from 0 m to approximately 5 m were estimated from DigitalGlobe satellite imagery using a method based on ocean color (Figure 5, *right*), and 2) reef depths and areas were digitized from NOAA nautical charts for depths ranging from 0.5 m to 2.5 m (Figure 5, *left*). The existing, estimated, and digitized data were integrated, and any remaining areas without data values (depths or elevations) were interpolated to produce the final surfaces. See NOAA Technical Memorandum (NESDIS NGDC-32) for more information about the data sources, procedures, analyses, and accuracy assessment.

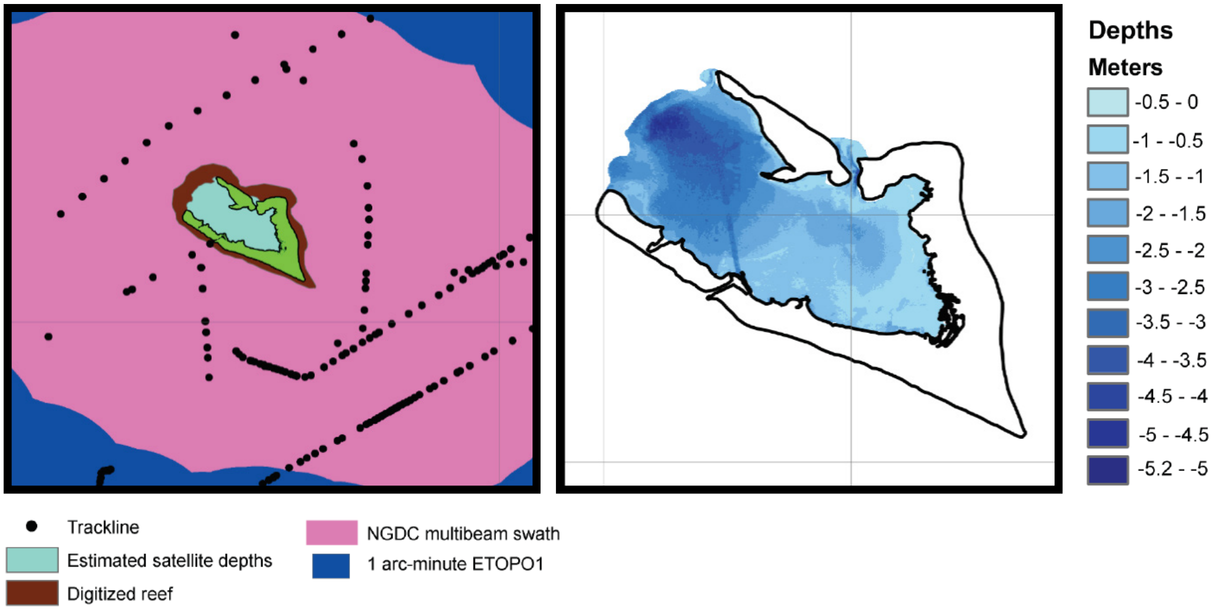


**Figure 5. Figures from (Grother et al. 2010) showing the shallow-water bathymetric data gaps in the reef area and lagoon that were addressed during the development of a topographic-bathymetric digital elevation model for Wake Atoll: the reef area shown in brown was digitized from soundings (left), and estimated depths inside the lagoon were calculated from DigitalGlobe satellite imagery (right).**

### *Integrated Bathymetry*

ESD's multibeam bathymetry and satellite-derived depths and the topobathy DEM were combined to produce an integrated bathymetric map for Wake (Figure 6).

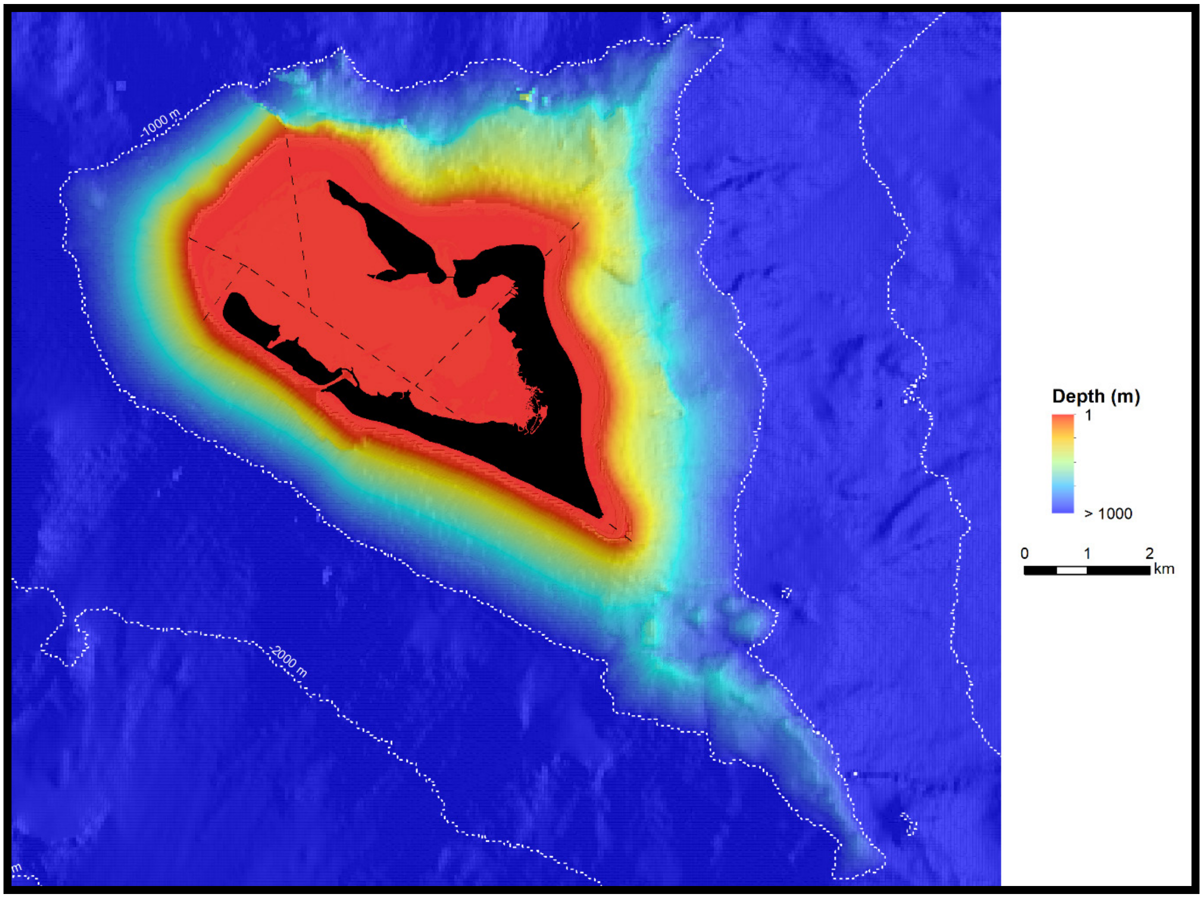


**Figure 6. Integrated bathymetric map focusing on depths from 0 m to ~1,000 m for Wake Atoll. The dotted white lines represent 1,000 m interval depth contours. Land features are shown in black.**

Bathymetric data around Wake indicate an initial flat in depths less than 25 m, followed by steep drop-offs on all sides from 20 to 500 m. No shelf structures occur at depths between 25 and 300 m that would indicate previous sea-level stands. However, the ridge that extends out from the southeast corner of the island has a relatively low slope in depths greater than 500 m and, based on nautical charts, appears to extend over 22 km to the east.

### *Bathymetric Derivatives*

Several geomorphological layers derived from ESD’s multibeam bathymetric grids were developed for Wake Atoll, including slope (i.e., the rate of change in elevation between a location and its surroundings, usually expressed in degrees), rugosity (a measure of the roughness or complexity of the seafloor surface), and bathymetric position index (BPI) zones and structures (i.e., a measure of where a location with a defined elevation is relative to the overall landscape, classified into broad scale and fine scale features, respectively). Similar to the bathymetric grids, each of these layers is available as high- (10 m) and mid-resolution (50 m) gridded products on the Wake Seafloor Characterization page of the PIBHMC website. The mid-resolution slope and BPI zone maps are presented here.

## Slope

Nearshore 50 m resolution gridded slope values around Wake Atoll reflect the steep drop-offs around all sides of the atoll (Figure 7). A mass-wasting area is apparent, as indicated by the gap in the plateau just beyond the upper portion of the South georegion down to 2,000 m depths. Mass wasting—also referred to as submarine mass movement—is the structural failure of the seafloor (e.g., from a submarine landslide along a steep slope) that causes mass movement of sediment deposits.

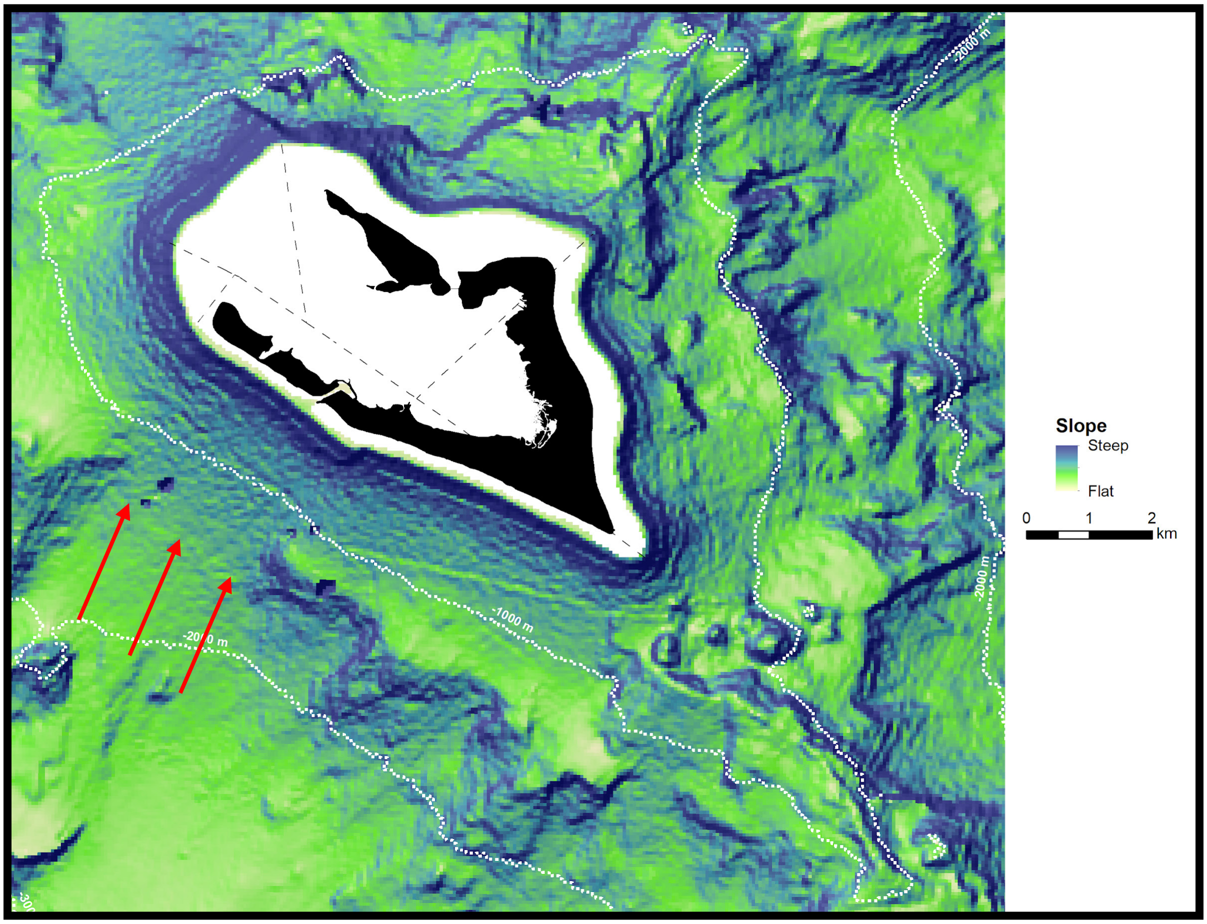


**Figure 7. Slope map for Wake Atoll with data gaps shown in white and land features in black. The dotted white lines represent 1,000 m interval depth contours. Red arrows indicate an example of a mass-wasting area.**

## Rugosity

A 50 m resolution gridded rugosity map (not shown) is available for Wake Atoll. Rugosity, along with a range of other bathymetric derivatives, was tested in the analysis conducted to derive seafloor substrates (discussed later in this section); however, it was highly spatially correlated with slope and therefore did not provide unique information to inform the substrate predictions.

### Bathymetric Position Index (BPI)

The 50 m resolution gridded BPI zones map for Wake Atoll shows that the seafloor landscape around the atoll is predominantly made up of slopes with some broad crests (high points), mostly in the shallower depth ranges, and two discernable ridges (crests) off the northeast and southeast corners (Figure 8). There are few topographic depressions around the atoll, and even fewer flats.

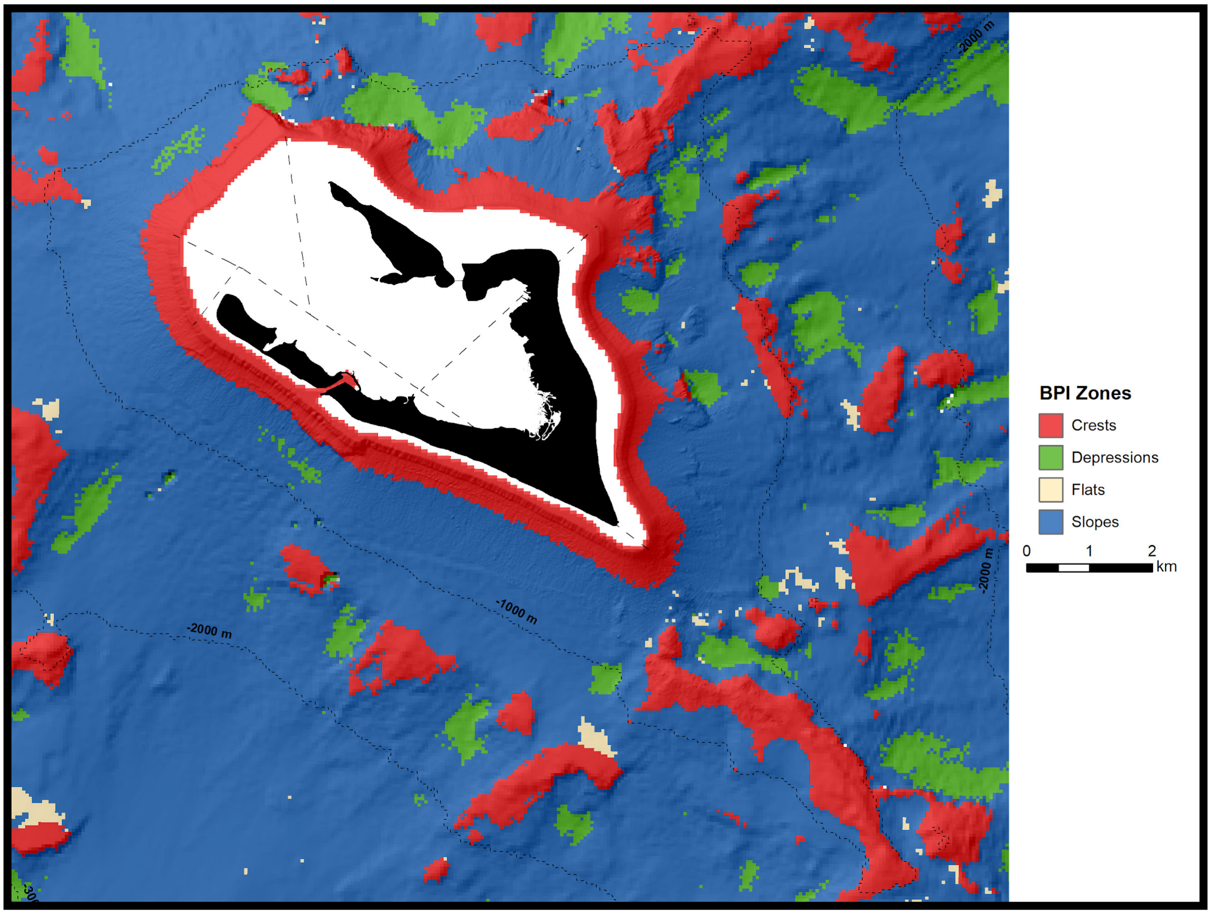


**Figure 8. Map of bathymetric position index (BPI) zones for Wake Atoll with data gaps shown in white and land features in black. The dotted black lines represent 1,000 m interval depth contours.**

The 50 m resolution gridded BPI structures map for Wake Atoll (not shown) shows the finer-scale details of each major BPI zone.

### *Seafloor Substrate*

ESD generated predicted seafloor substrates (i.e., hard or soft bottom) for Wake Atoll in 2018 (Figure 9). The source data used to produce the substrate map for the atoll for water depths to 1,000 m include multibeam bathymetric and backscatter data from the 2007 surveys and satellite imagery acquired in 2014 (WorldView-3) and 2017 (WorldView-2). The data and supporting documentation are available on the Wake Seafloor Characterization page of the PIBHMC website.

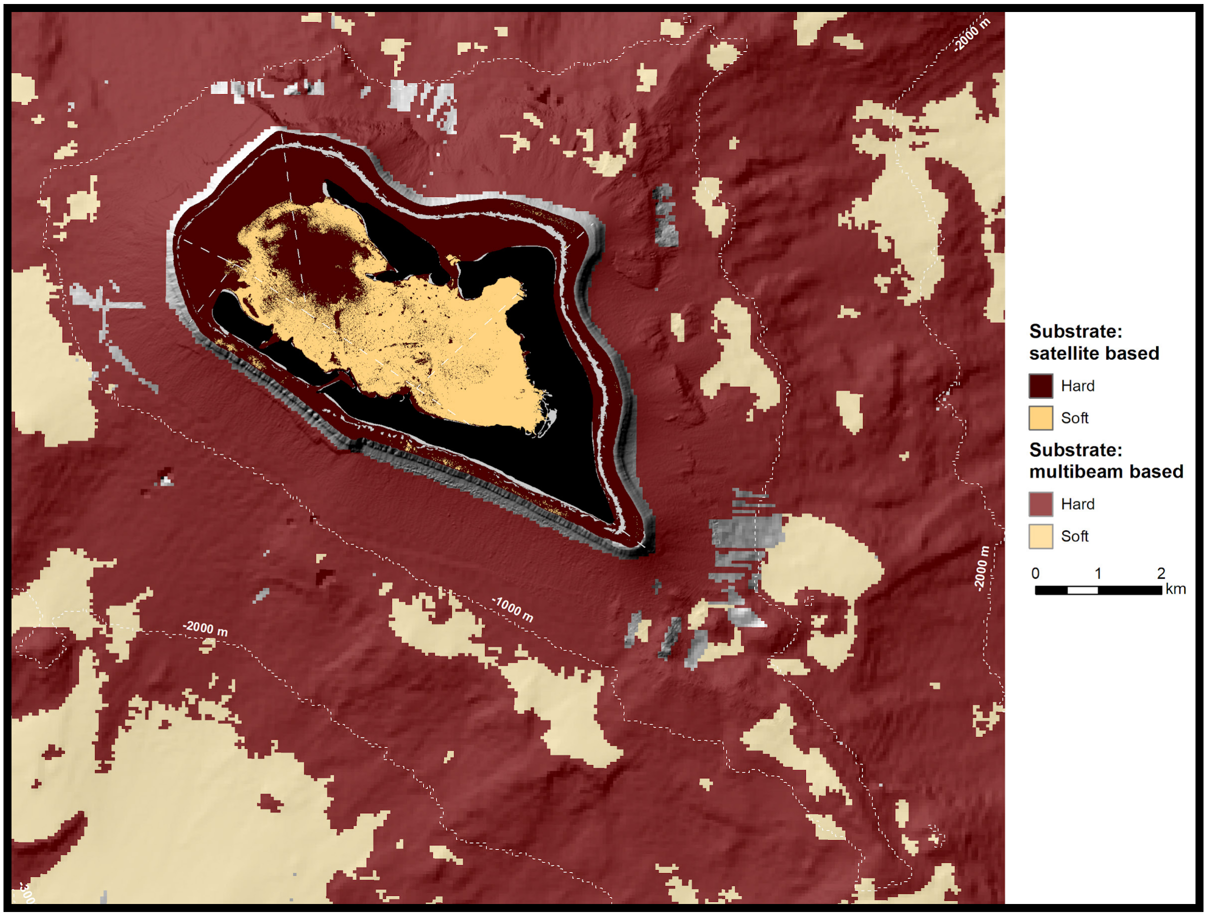


**Figure 9. Seafloor substrate map of Wake Atoll showing hard- and soft-bottom habitats. Depths from ~0 m to 30 m were derived from WorldView satellite imagery, and depths >30 m were based on gridded multibeam bathymetric and backscatter data (50 m and 5 m resolution, respectively). The dotted white lines represent 1,000 m interval depth contours. Gaps in substrate coverage are shown in grey and land features in black.**

Analyses indicate that due to the poor quality backscatter data at Wake Atoll, the bathymetric data more significantly influenced the substrate predictions. The seafloor surrounding Wake (outside of the atoll to 1,000 m depths) is predominantly hard substrate with only relatively small patches of soft-bottom habitat. A possible explanation for the absence of soft-bottom habitat around the atoll could be attributed to the steepness of the slopes and non-existing terraces. The shallow inner lagoon is likely functioning as a sediment trap and shows an accumulation of fine silty sediments resulting from the reduced circulation of waters within the lagoon from the causeway that was constructed in the 1920s (i.e., limited-to-no internal circulation of water within the lagoon or external circulation of lagoon waters with the open ocean). The hard-bottom habitats within the lagoon are primarily composed of coral bommies (large, stand-alone relict reef structures) as shown in Figure 10, which compares the predicted substrate map (*left*) with a satellite image (*right*) for a small area inside the lagoon.

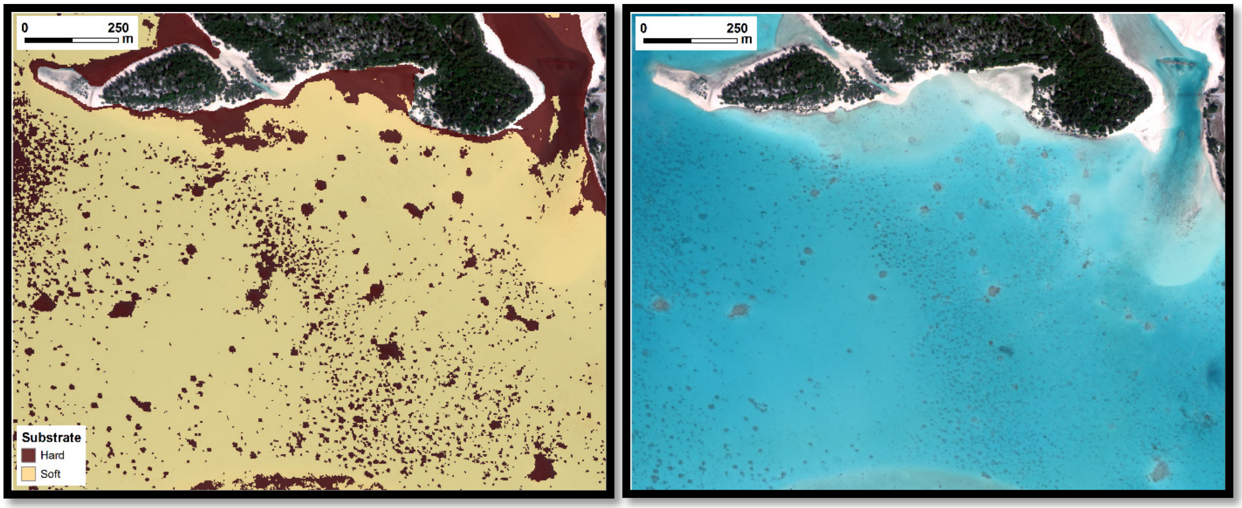


**Figure 10. Satellite-derived substrate predictions (left) compared with a satellite image of the same area (right), demonstrating how the predicted substrates accurately delineate hard features, such as coral bommies, on the seafloor at Wake Atoll.**

## Maps to Inform the Coral Reef Fish and Benthic Monitoring Survey Design

Many biological communities are structured by depth and habitat (i.e., reef zone), often due to differences in associated environmental parameters, such as light, temperature, salinity, and wave energy. The current Pacific RAMP stratified-random survey design restricts monitoring surveys to hard-bottom habitats in the 0 to 30 m depth range, stratified by both depth and reef zone.

### *Depth Strata*

The integrated bathymetry shown in Figure 6 was used to classify depth bins (Figure 11) from 0 to 1,000 m. For the Pacific RAMP surveys, depth strata have been defined as shallow (>0–6 m), mid (>6–18 m), and deep (>18–30 m). Estimated seafloor areas for each of the depth strata are included in Table 1.

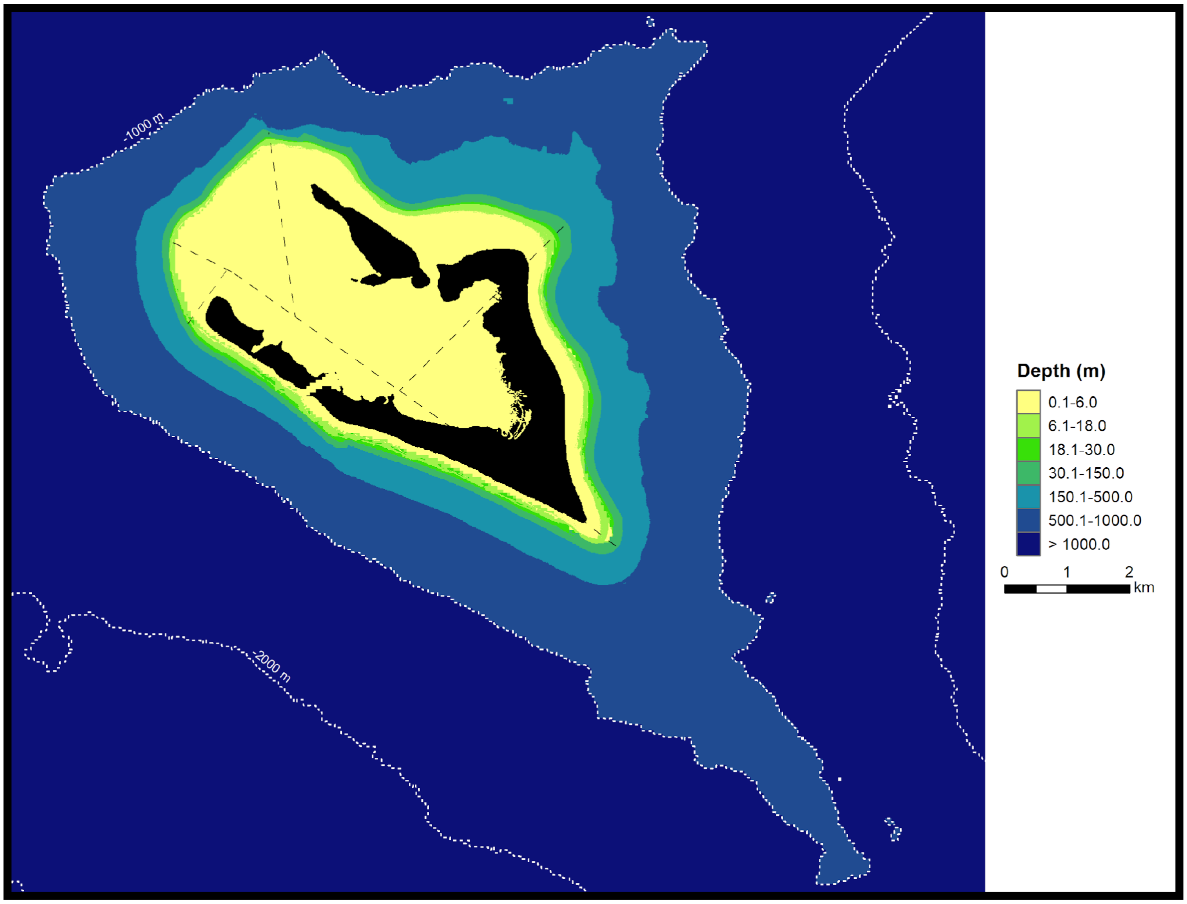


**Figure 11. Depth strata map for Wake Atoll from 0 to 1,000 m.** **The dotted white lines represent 1,000 m interval depth contours. Land features are shown in black.**

The actual mapped seafloor area for the shallowest (>0–6 m) depth strata at Wake Atoll differs from the estimated seafloor area (Table 1). At Wake Atoll, 16% of the seafloor between 0 and 6 m depths was mapped, leaving an approximately 16 km$^2$ gap. The map of the seafloor from 6 to 1,000 m depths was spatially complete.

**Table 1. Land and seafloor area by depth strata from 0 to 1,000 m depths for Wake Atoll. Seafloor area statistics include actual mapped area (km$^2$) and estimated seafloor area (km$^2$) based on the integrated bathymetric map for Wake (excluding the topobathy digital elevation model). Land area is 7.0 km$^2$.**

| Depth (m) | Estimated Seafloor (km$^2$) | Mapped Seafloor (km$^2$) |
|---|---:|---:|
| >0–6 | 16.4 | 0.4 |
| >6–18 | 1.8 | 1.8 |
| >18–30 | 0.8 | 0.8 |
| **Subtotal: >0–30** | **19.0** | **3.0** |
| >30–150 | 2.6 | 2.6 |
| >150–500 | 12.3 | 12.3 |
| >500–1000 | 42.4 | 42.4 |
| **Total: >0–1000** | **76.3** | **60.3** |

### *Reef Zones*

To support the stratified-random design for Pacific RAMP monitoring surveys, reef zones have been delineated for Wake Atoll, including forereef, reef crest/reef flat, backreef, lagoon, and land (Figure 12). Satellite imagery was primarily used to manually digitize the zones. Reef crests/reef flat areas extend from the shoreline out to breaking waves; however, the date of the satellite image may influence the accurate delineation of the reef crest (i.e., due to seasonal changes in wave action).

Only forereef habitats have been surveyed around the atoll because these habitats most commonly occur in coral reef areas. Therefore, results from surveys at Wake can be compared with results from surveys across all coral reefs of the U.S. Pacific Islands. Moreover, hazards navigating near the shallow backreef areas and limited access into the lagoon precluded surveys in these habitats at Wake.

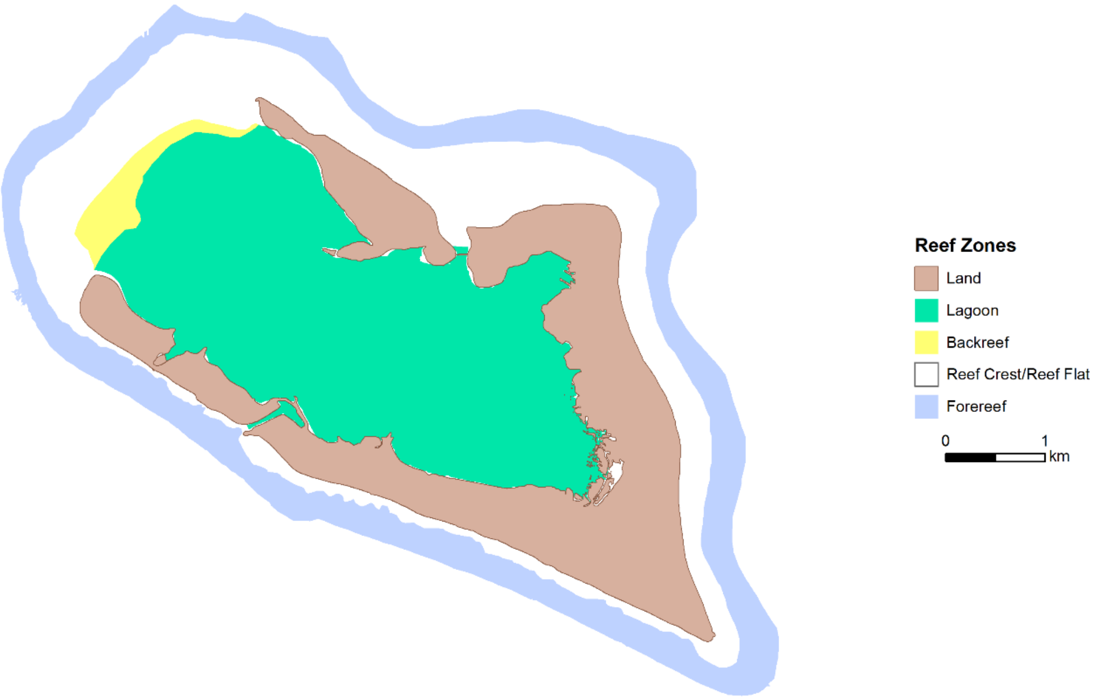


**Figure 12. Reef zones for Wake Atoll digitized from WorldView satellite imagery.**

### *Substrate*

Only hard-bottom substrates were targeted for stratified-random reef fish and benthic monitoring surveys of Pacific RAMP. However, at the time the survey strata were established for Wake Atoll, no substrate information existed. As previously discussed, predicted seafloor substrates have since been developed for the atoll and will be incorporated into the survey strata in advance of the Pacific RAMP surveys at Wake scheduled for 2020. In general, the majority of the seafloor area outside of the atoll is hard bottom, whereas the area within the atoll is primarily soft bottom (Figure 9).

### *Survey Strata*

To date, the survey strata used for the stratified-random fish and benthic surveys were based on depth only (Figure 11). A cursory assessment of the new substrate and reef zone data together with the depth strata indicate a rather narrow area of surveyable seafloor, approximately 2.5 km$^2$, is available within forereef, hard-bottom habitats in the 0 to 30 m depth range at Wake.

*Diver collecting a skeletal core from a* Porites *spp. colony at Wake Atoll.*
*Photo: James Morioka, NOAA Fisheries.*

# *Ocean and Climate Variability*

## 5.3 Ocean and Climate Variability

*Installation of oceanographic instruments at Wake Atoll.*
*Photo: NOAA Fisheries.*

### Survey Effort and Site Information

By virtue of its location, Wake Atoll experiences a relatively stable oceanographic regime. Positioned north of the equator in the western Pacific Ocean, the atoll is removed from the epicenter of the El Niño Southern Oscillation (ENSO) in the eastern and central equatorial Pacific. Wake Atoll is therefore largely sheltered from the dynamic interannual variability in ocean conditions that results from the cycling between warm El Niño events and cool La Niña events every few years. Instead, the atoll's higher latitude creates a stronger seasonal cycle in weather and ocean conditions than is usually observed in the lower latitude reef environments of the PRIMNM, driving intra-annual differences in temperature, salinity, wave exposure, and seawater chemistry that can affect the health and function of coral reef ecosystems.

Documenting baseline conditions and natural variability in coral reef environments is critical under the threat of global climate change, as concentrations of carbon dioxide in the atmosphere are altering the temperature and chemistry of coral reef habitats. Episodic high temperatures, mostly driven by El Niño events, have led to increases in the frequency and intensity of coral bleaching in the past few decades. In addition, the dissolution of carbon dioxide in ocean surface waters sets off a chain of chemical reactions in seawater that decrease pH and make it more difficult for corals and calcifying reef organisms to grow. Understanding the shifts in ocean conditions that are occurring and the sensitivity of coral reef ecosystems to these changes is crucial for projecting their survival under 21st century climate change.

Since 2000, Pacific RAMP efforts have monitored the oceanographic environments of coral reef ecosystems in the PRIMNM. Data were collected on key parameters using: (1) a diverse suite of moored instruments, (2) nearshore conductivity, temperature, and depth (CTD) vertical profiles of water column structure, (3) discrete water samples to assess dissolved nutrients, chlorophyll-*a*, and carbonate chemistry, and (4) estimates of calcium carbonate accretion, bioerosion rates, and coral growth and skeletal density to examine the balance between production and removal of calcium carbonate on the reef (Figures Figure 13, Figure 14, Figure 15,Figure 16, and Figure 17). A summary of the environmental survey efforts around Wake Atoll from 2005 to 2017 is shown in Table 2. Refer to "Chapter 1: Overview" for oceanographic instrumentation specifics and water sample collection methodologies.

Field data collections were complemented by remote sensing data sets and model products to provide the large-scale climate and oceanographic context for our in situ observations. Specifically, the Oceanic Niño Index (ONI, the standard index of ENSO activity), sea surface temperature (SST) anomalies from the Optimum Interpolation SST data set, the Degree Heating Week (DHW) index from Coral Reef Watch, chlorophyll-*a* (chl-*a*, a proxy for primary productivity) anomalies from the Sea-Viewing Wide Field-of-View Sensor and Moderate Resolution Imaging Spectroradiometer Aqua, and global WaveWatch III model output were all used to explore multi-decadal variability in ocean conditions.

**Table 2. Summary of the oceanographic and environmental data collection efforts at Wake Atoll by year over the period 2005 through 2017. The following instruments were deployed: sea surface temperature (SST) buoy, subsurface temperature recorder (STR), Seabird Electronics MicroCAT (SBE-37), ecological acoustic recorder (EAR), acoustic Doppler current profiler (ADCP), calcification accretion unit (CAU), bioerosion monitoring unit (BMU), and autonomous reef monitoring structures (ARMS). Conductivity-temperature-depth (CTD) casts, shallow (near reef) and deep (offshore), have corresponding discrete water samples, shallow (near reef) and deep (offshore). Coral cores were collected from *Porites* spp. Numbers indicate the quantity of instruments deployed (D) and retrieved (R) as D/R, water samples and diurnal suite collections, CTD casts, and coral cores per year.**

| Year | Instruments | | | | | | | | CTD Casts | | Water Samples | | Coral Cores |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SST | STR | SBE-37 | EAR | ADCP | CAU | BMU | ARMS | Shallow | Deep | Shallow | Deep | *Porites* spp. |
| 2005 | 1/- | 7/- | – | – | – | – | – | – | 40 | 12 | 24 | 60 | – |
| 2007 | 1/1 | 8/6 | – | 1/- | – | – | – | – | 26 | 12 | 15 | 60 | – |
| 2009 | 1/- | 12/8 | 6/- | 1/1 | 2/- | – | – | 12/- | 0 | 18 | 11 | 83 | – |
| 2011 | 1/1 | 11/11 | -/6 | -/1 | 1/3 | 25/- | – | 9/9 | 5 | 2 | 10 | 10 | 2 |
| 2014 | -/1 | 14/11 | – | – | – | 25/24 | 20/- | 12/7 | 16 | – | 19 | – | – |
| 2017 | – | 11/11 | – | – | – | 25/21 | 20/15 | 12/11 | 10 | – | 16 | – | – |
| **Total** | **4/3** | **63/47** | **6/6** | **2/2** | **3/3** | **75/46** | **40/15** | **45/27** | **97** | **44** | **95** | **213** | **2** |

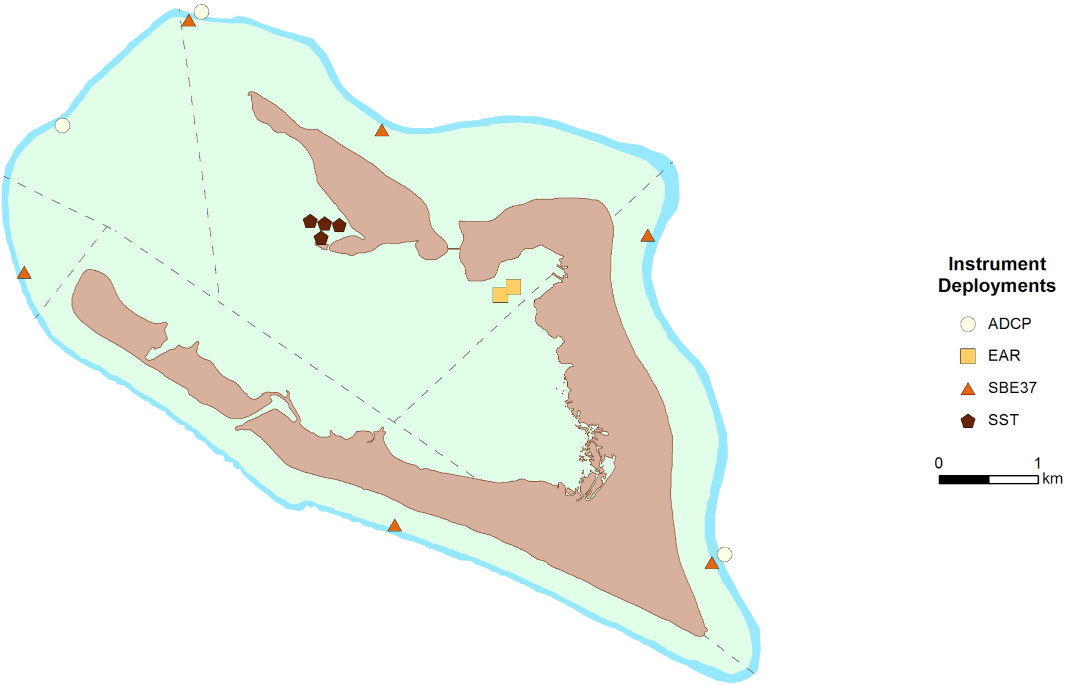


**Figure 13. Deployment locations of Nortek acoustic Doppler current profilers (ADCP), ecological acoustic recorders (EAR), Seabird Electronics MicroCATs (SBE37), and sea surface temperature (SST) buoys around Wake Atoll. Instrument deployments at the same location over multiple years have been plotted adjacent to one another and organized around their shared location on the map.**

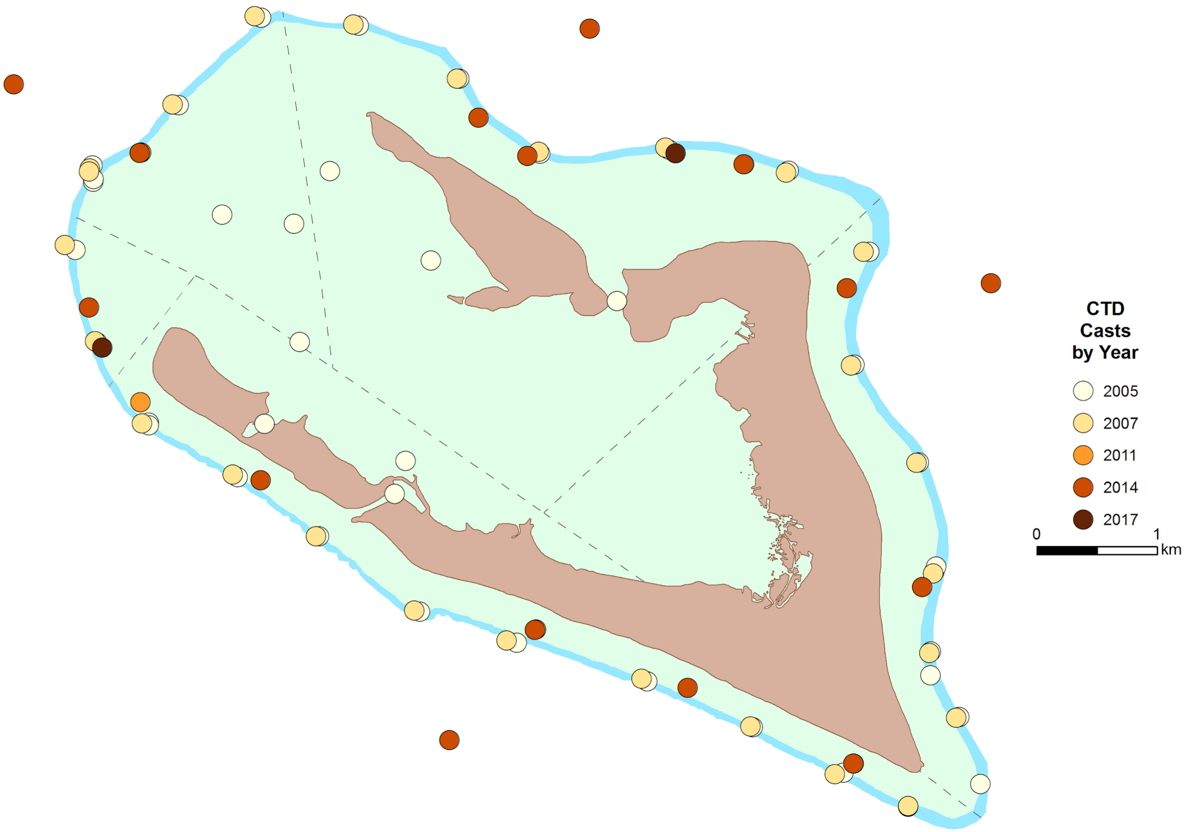


**Figure 14. Locations of nearshore conductivity-temperature-depth (CTD) hydrocasts, measuring water column salinity and temperature from the ocean surface to the seafloor around Wake Atoll. Casts in earlier years (2005–2011) prioritized sampling the entire perimeter of the forereef, while later efforts (2014–2017) focused on permanent instrumentation sites (sites with subsurface temperature recorders, autonomous reef monitoring structures, and/or calcification accretion units).**

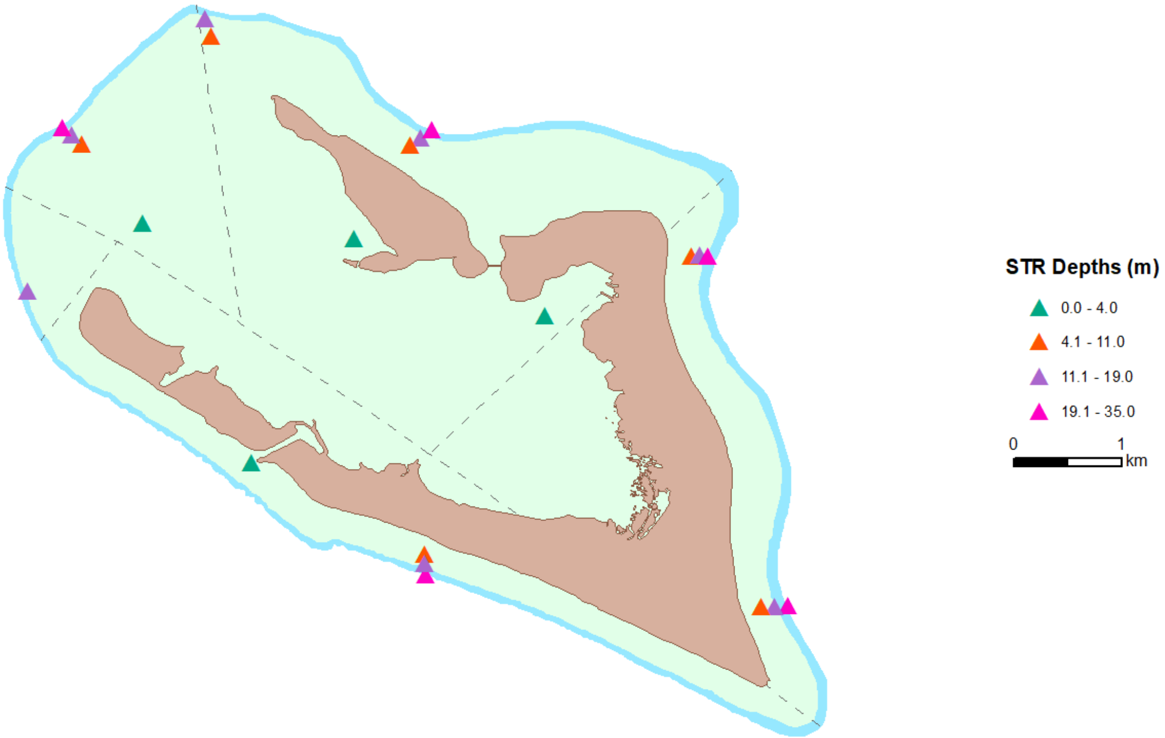


**Figure 15. Locations of subsurface temperature recorders (STRs) deployed on the reef from 1 to 35 m depths around Wake Atoll.**

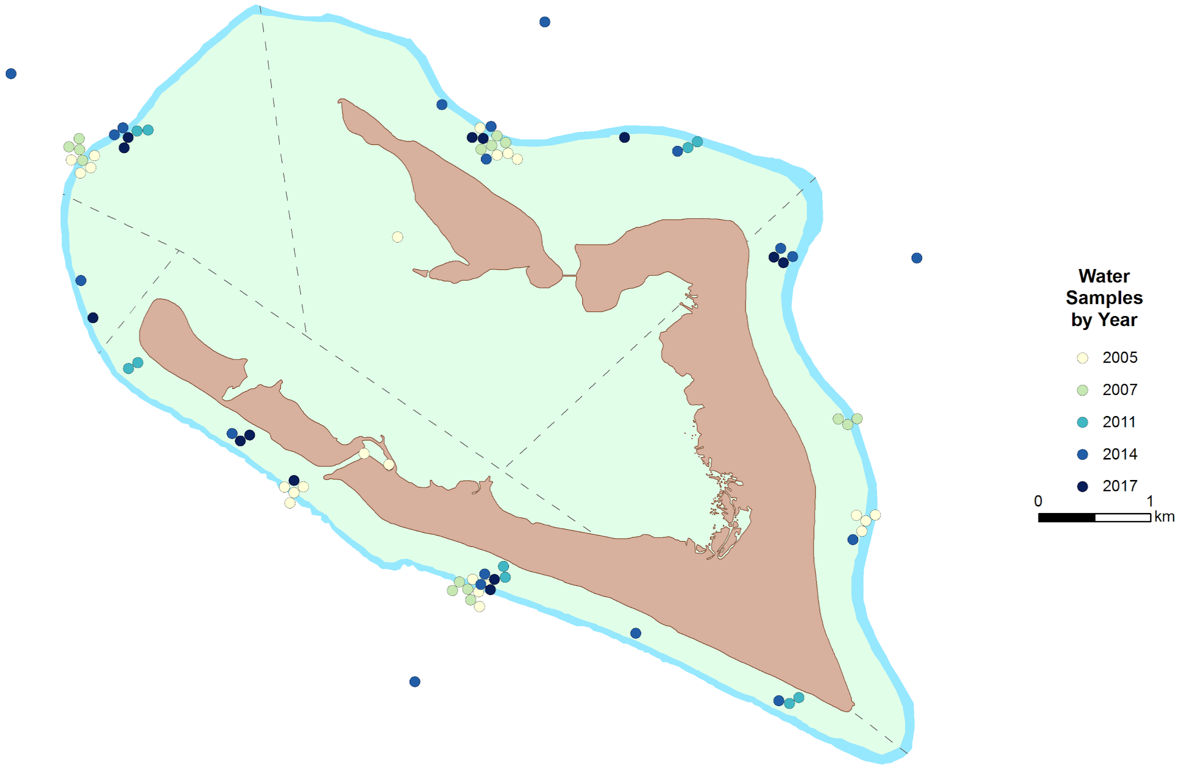


**Figure 16. Locations of discrete seawater sample collections from 1 to 35 m depths around Wake Atoll. Samples evaluated for various analytes: dissolved inorganic carbon, total alkalinity, chlorophyll-*a*, and dissolved inorganic nutrients. Water samples collected at the same location over multiple years have been plotted adjacent to one another and organized around their shared location on the map.**

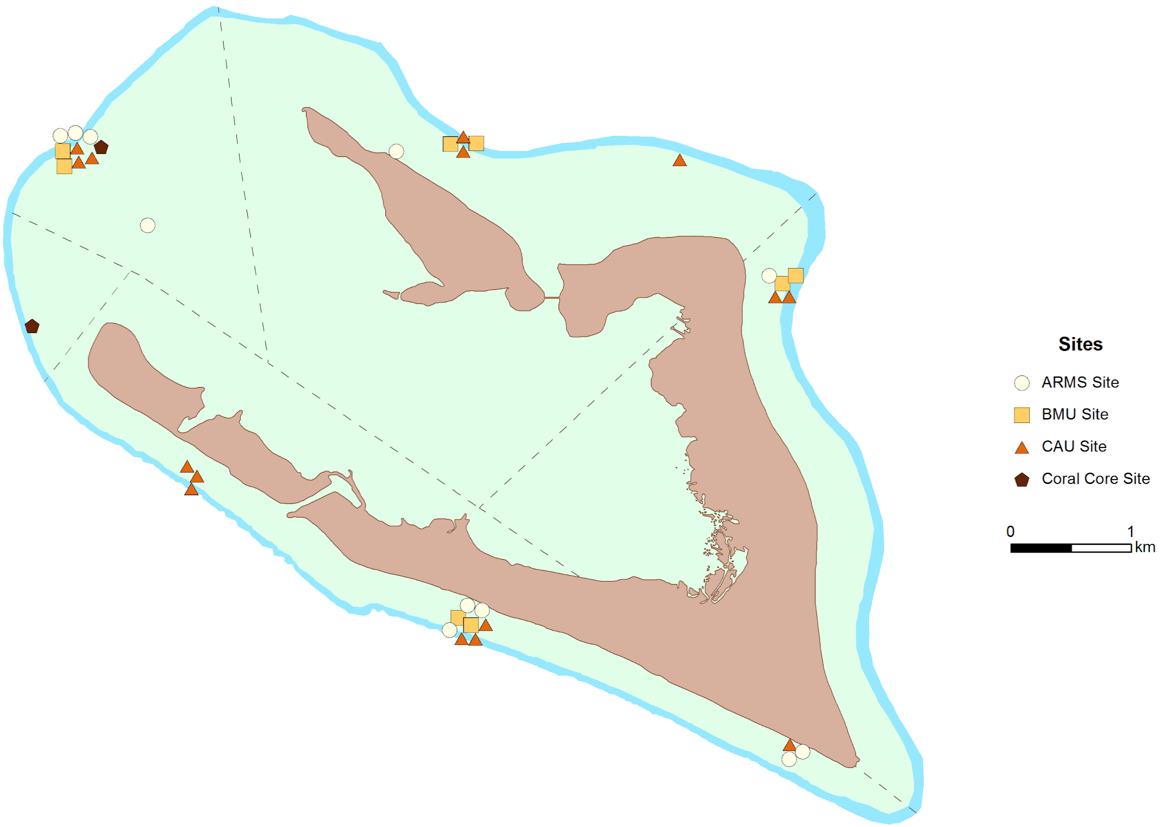


**Figure 17. Locations of autonomous reef monitoring structures (ARMS, 3 units per site), bioerosion monitoring units (BMU, 5 units per site), calcification accretion units (CAU, 5 units per site), deployed on the reef at 15 m depths around Wake Atoll. Coral cores of *Porites* spp. collected opportunistically at depths from 5 to 15 m. Instrument deployments at the same location over multiple years have been plotted adjacent to one another and organized around their shared location on the map.**

## Oceanographic Observations

Oceanographic conditions at Wake Atoll are largely removed from the strong influence of interannual warming and cooling associated with ENSO cycles. The ONI, SST anomalies, DHWs, and chl-*a* anomalies for Wake Atoll from 1981 to 2017 are plotted in Figure 18. The ONI shows the variability and frequency of strong warm (positive, El Niño) and cool (negative, La Niña) SST anomalies in the central equatorial Pacific, with higher SSTs persisting during El Niño warm events and lower SSTs during La Niña cool events (Figure 18a). SST anomalies at Wake are weakly inversely correlated with the ONI (Figure 19a), and water temperatures at Wake cool during El Niño and warm during La Niña events (Figure 18b). While slightly counterintuitive, this pattern is consistent with the cooling that occurs in the western Pacific during El Niño events when the pool of warm water that usually sits in the western Pacific shifts eastward as the trade winds slacken. Wake SST anomalies were also less extreme than the magnitude of temperature change in the central Pacific captured by the ONI, and the severe El Niño warm events of 1982–1983, 1997–1998, and 2015–2016 and La Niña cold events of 1988–1989, 1998–2000, 2007, and 2011 produced only small departures from normal temperatures around the atoll.

Wake coral reefs have experienced relatively few episodes of warming in the past four decades, visualized as DHW in Figure 18c. DHWs estimate the amount of thermal stress that has accumulated in an area over a 12-week period by summing any temperature exceeding the maximum monthly mean by 1 °C. SST anomalies above this threshold can drive significant coral bleaching when sustained for several weeks to months, with moderate bleaching predicted when DHW > 4 °C-weeks and severe bleaching expected when DHW > 8 °C-weeks. The cumulative DHWs since 1985 show a general trend of increase in temperature stress over time (Figure 18c).

Phytoplankton chl-*a* pigment concentrations at Wake are very low and are not strongly correlated with ONI (Figure 19). However, spikes in chl-*a* were observed in 2000, 2001, and 2010 (Figure 18d). These peaks in productivity could relate to transitions from strong El Niño to strong La Niña or could also be driven by more localized oceanographic processes (e.g., increased upwelling or vertical mixing of the water column).

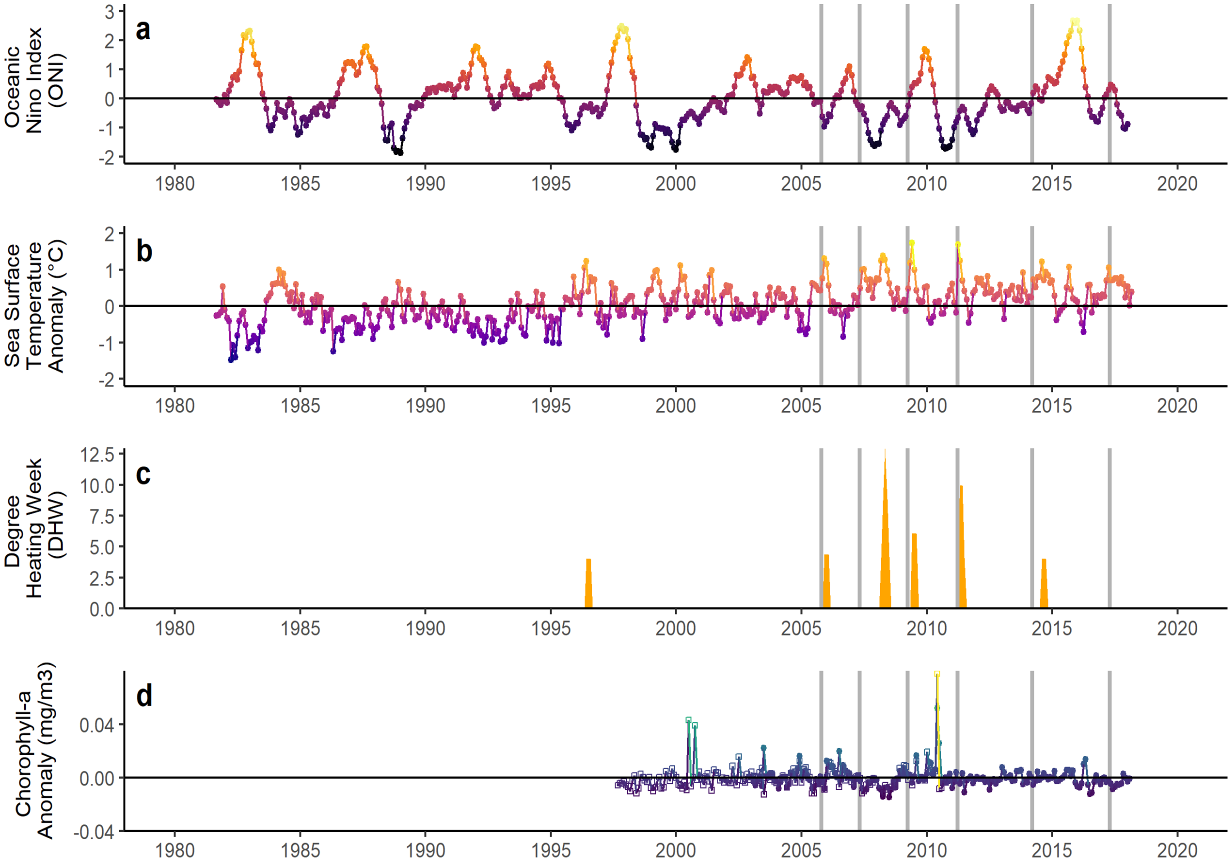


**Figure 18. Time series of oceanographic conditions at Wake Atoll: (a) a 3-month rolling mean of Oceanic Niño Index (ONI) from September 1981 to April 2018 in the El Niño 3.4 region (5°N–5°S, 120°W–170°W), (b) sea surface temperature (SST) anomalies derived from Optimum Interpolation SST data September 1981 to April 2018, (c) Cumulative Degree Heating Week (DHW) derived from the Coral Reef Watch temperature records from 1985 to 2017, and (d) Phytoplankton chlorophyll-*a* pigment (chl-*a*) concentrations from 1997 to 2017. Available data for ONI, Optimum Interpolation SST, DHW, and chl-*a* were extracted for a box around Wake (Latitude North: 19.417938 to 19.175334 and Longitude East: 166.497049 to 166.758215). The grey vertical bars within each time series denote survey missions to Wake.**

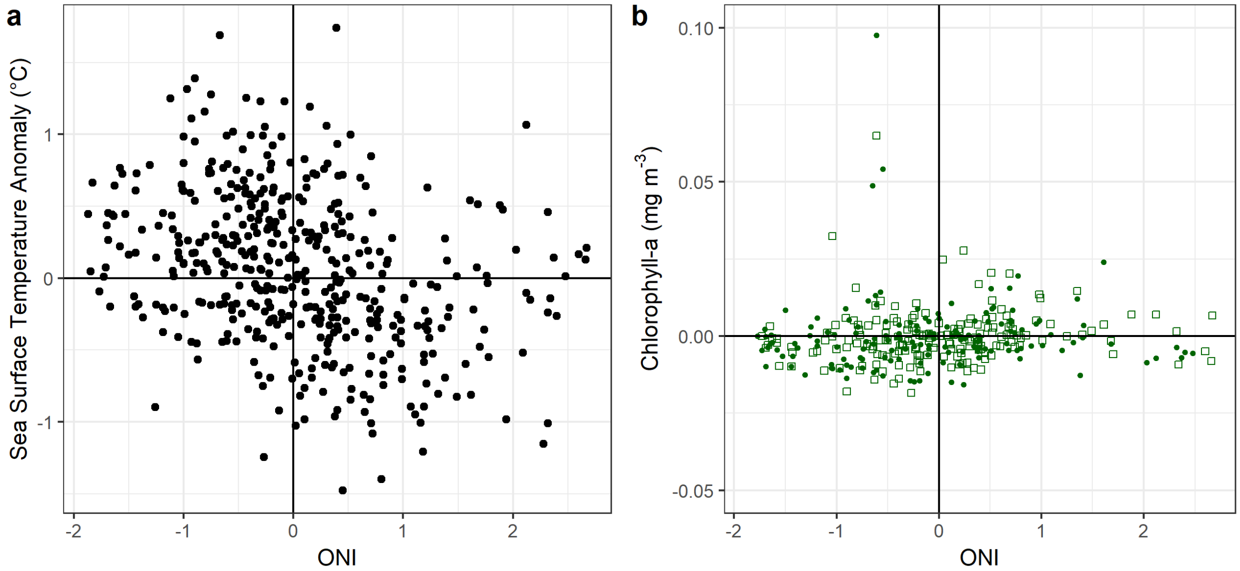


**Figure 19. Relationships between oceanographic conditions at Wake Atoll: (a) Oceanic Niño Index (ONI) vs. sea surface temperature (SST) anomaly, and (b) ONI vs. satellite-derived chlorophyll-*a* (chl-*a*, Sea-Viewing Wide Field-of-View Sensor in boxes and Moderate Resolution Imaging Spectroradiometer in circles) anomaly data. Available data for ONI, SST anomaly, and chl-*a* were extracted for a box around Wake (Latitude North: 19.417938 to 19.175334 and Longitude West: 166.497049 to 166.758215).**

## Water Column Observations

The water column of the nearshore waters surrounding Wake Atoll is generally well-mixed and shows strong seasonal variability in environmental conditions. Figure 20 shows the location of shallow-water CTD casts that were conducted in October 2005 (31 casts) and April 2007 (26 casts). Cast data documented large differences in seawater temperature, salinity, and density profiles between spring (April) and fall (October), with warmer (more than 1 °C) conditions occurring in October and cooler, saltier, and denser seawater observed in April (Figure 21). Temperature, salinity, and density were mostly homogenous throughout the water column in both years, with the exception of a local thermal/salinity inversion of cool, fresher water in the upper 10–15 meters (likely, a signature of recent precipitation) at the northwestern end of the South georegion (sites 28–29) in 2005.

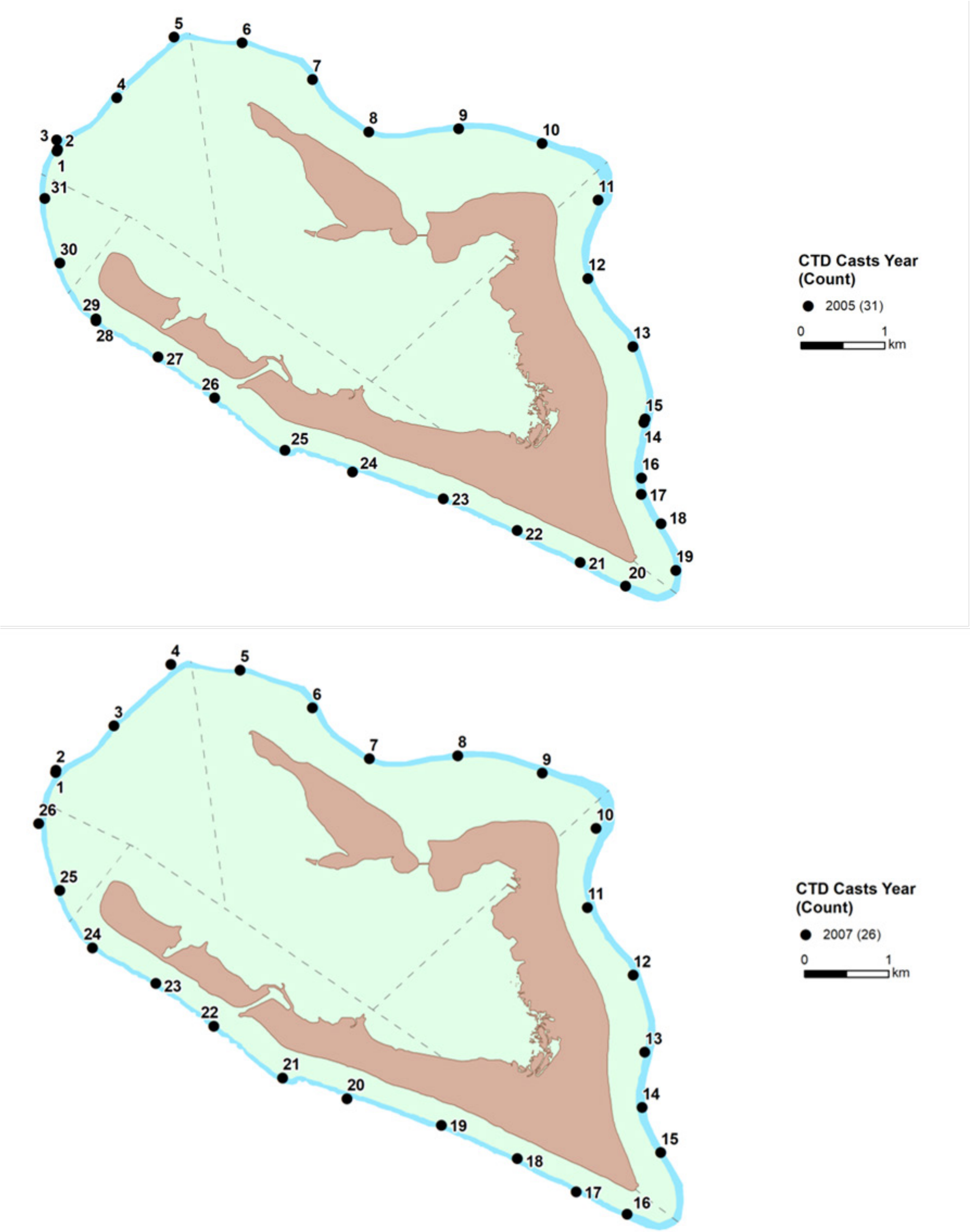


**Figure 20. Shallow-water conductivity-temperature-depth (CTD) sampling locations around Wake Atoll. CTDs were conducted during March of 2005 (31 casts, top) and April 2007 (26 casts, bottom). The casts are numbered sequentially in a clockwise direction around the island.**

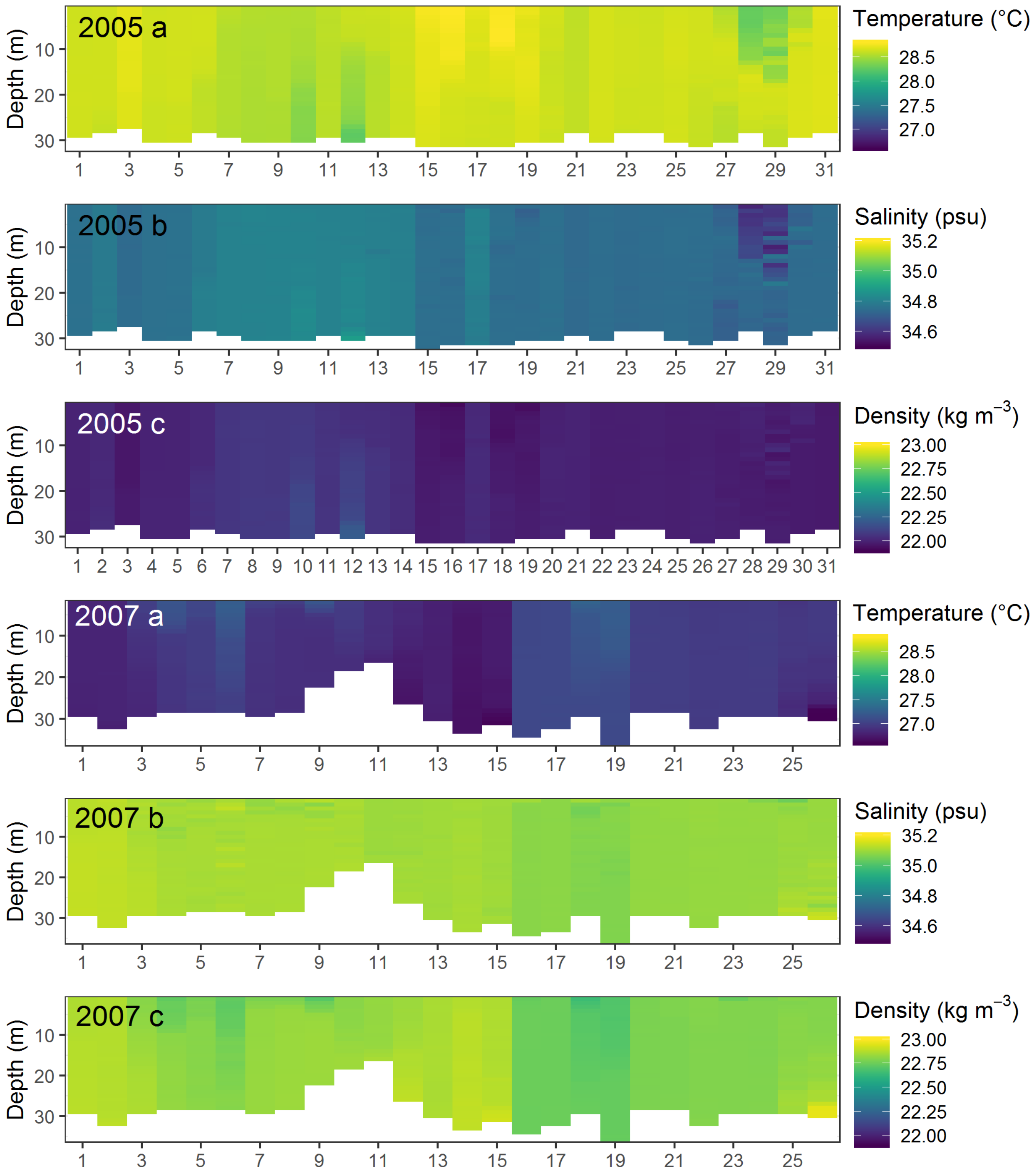


Figure 21. Profiles from shallow-water conductivity-temperature-depth casts around Wake Atoll in October 2005 (top three panels) and April 2007 (bottom three panels) for (a) temperature (°C), (b) salinity (psu), and (c) sigma-t density (density of seawater at atmospheric pressure in kg m-3 - 1,000) from the surface to a depth of 35 m.

Long-term, in situ temperature logger deployments also captured strong seasonal temperature fluctuations in the Wake forereef and lagoon environments. Between 2005 and 2017, a total of 64 moored subsurface temperature recorders were deployed at depths ranging from 1 m to over 26 m (Figure 15). On the forereef, the seasonal range in temperatures was approximately 4 °C between the summer maximum and winter minimum at depths below 4 m, and a larger range in temperatures (up to 8 °C) was observed in the shallows (1 m) on the western side of the atoll (Figure 22). Seasonal swings in temperature were even more exaggerated in the shallow lagoon, where the coldest measured winter temperatures near 21 °C rose to summer temperatures as high as 32 °C. Despite large intra-annual oscillations, interannual variability at Wake Atoll was low during the time period surveyed, and differences in the year-to-year mean and range of temperatures experienced by Wake's coral reefs were minimal.

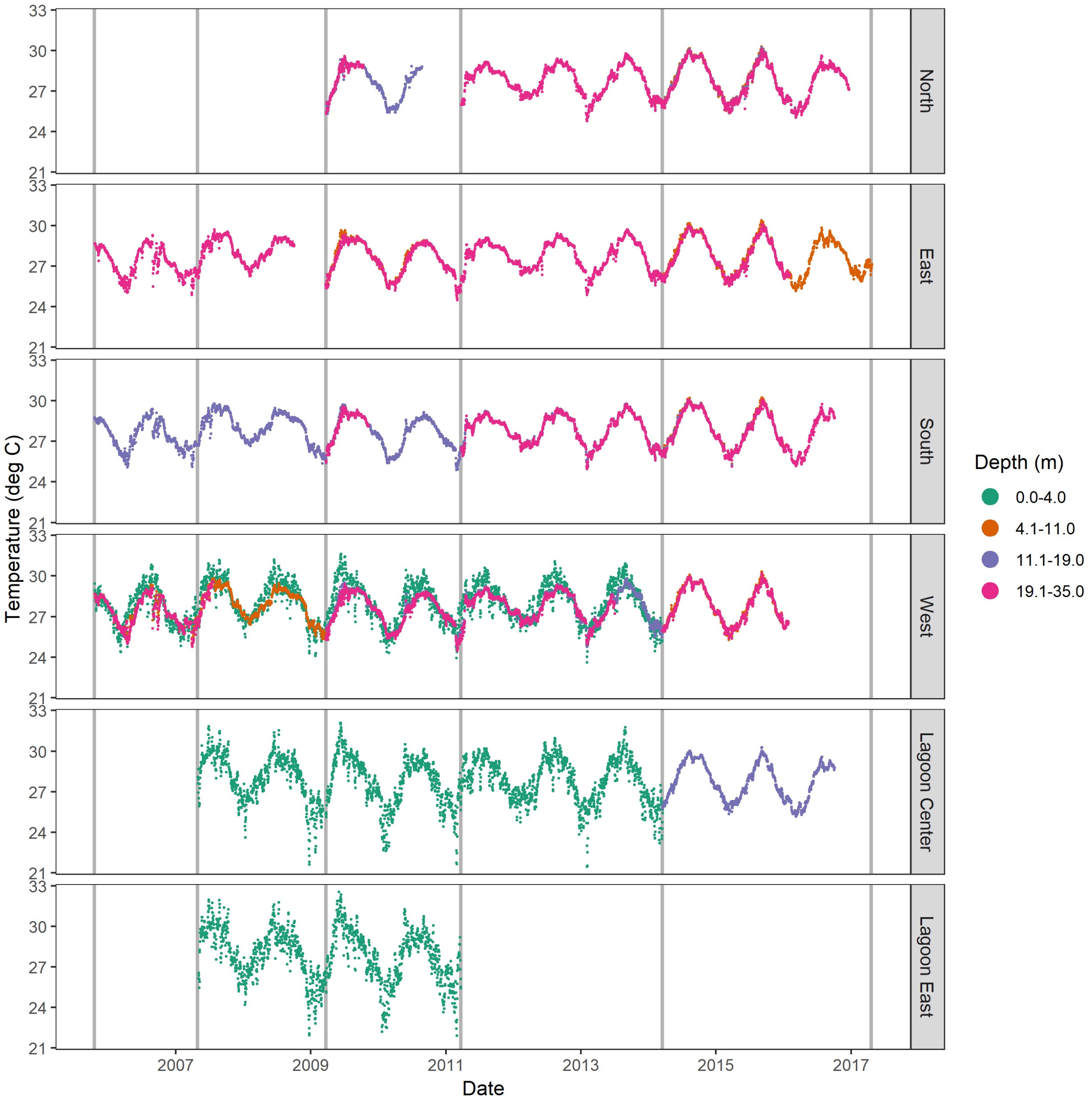


**Figure 22. Daily subsurface temperature recorder time-series observations of temperature over the period between 2005 and 2017, collected around Wake Atoll (North, South, West, and East) and inside its lagoon (Center and East, no data for west side). Four different depth ranges were defined at each of these locations: green (0–4.0 m), red (4.1–11.0 m), blue (11.1–19.0 m), and magenta (19.1–35.0 m). The grey vertical bars within each time series denote survey missions to Wake.**

## Wave Energy

Ocean wave dynamics strongly influence the environmental conditions of coastal habitats. The energy generated by wave activity varies on seasonal time scales, and spatial differences in the direction, magnitude, and frequency of waves around an island or atoll can have significant impacts on the sub-island distribution of coral reef communities. Wave data from 2010 to 2016 are shown in Figure 23 and Figure 24. The northwest side of the atoll experienced the largest number of wave observations with a higher period and wave height from December through February (Figure 23, left panels), while wave observations and height patterns were more evenly distributed around the atoll from July through September (Figure 24, right panels). The mean annual integrated wave power shows that the North and East georegions of the atoll are most impacted by wave patterns (Figure 24).

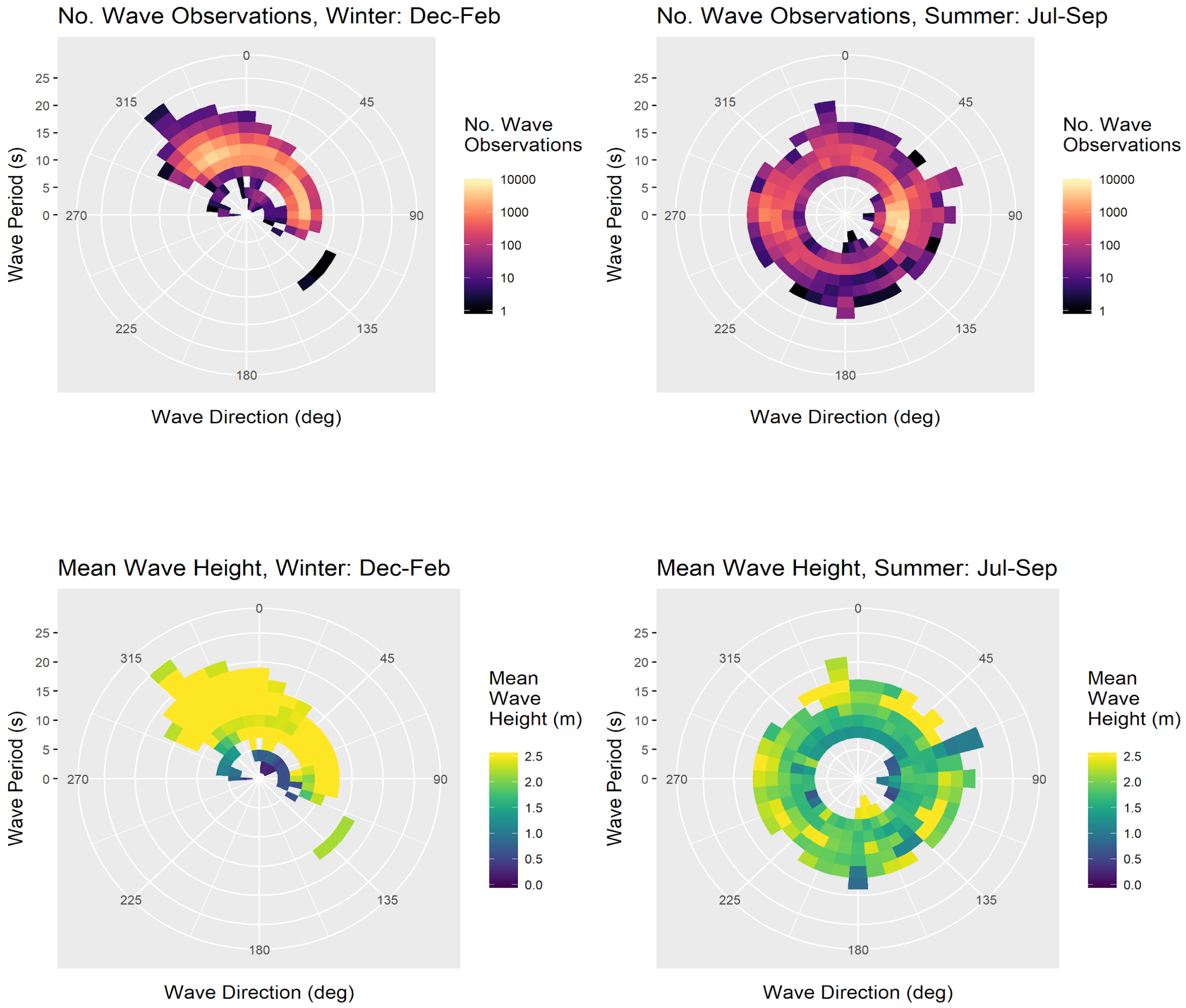


**Figure 23. WaveWatch III data from 2010 to 2016 for the region around Wake Atoll. Top panels: Polar plot of hourly wave data from December to February (left) and July to September (right). Bottom panels: Polar plot of derived mean wave height between December and February (left), and between July and September (right). The position of wave data around the 360-degree circle (in 10-degree bins) displays the direction from which the waves hitting Wake travel. Zero degrees indicates waves arrive from due north and 180 degrees from due south. The height of each directional bin from the center shows the wave period (greater distances from center represent longer wave periods), and the shading shows the number of hourly observations (top) and mean wave height (bottom) for each direction and period.**

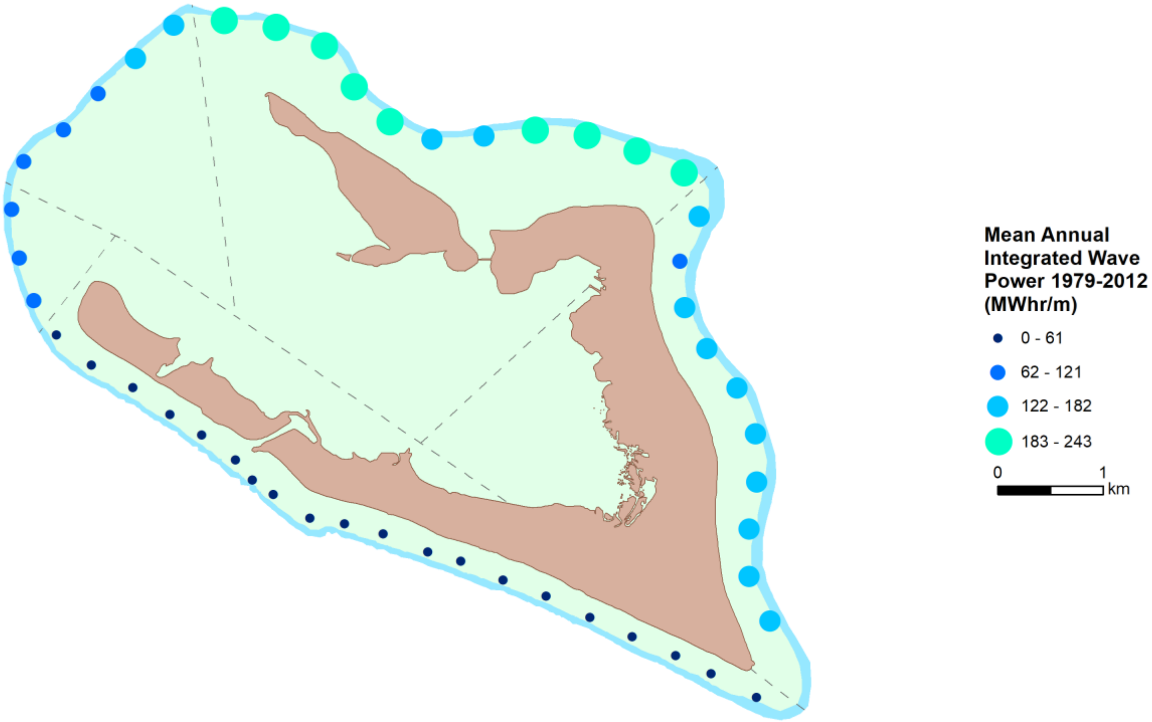


**Figure 24. Mean annual integrated wave power (MWhr/m). Data from 1979 to 2012 correspond to modified WaveWatch III by coastline shadowing using the incident wave swath method (Clark and Oliver, In prep).**

## Carbonate chemistry

Aragonite saturation state ($\Omega_A$) measures the degree to which seawater is saturated with respect to the carbonate mineral aragonite, where $\Omega_A$ values above 1 indicate supersaturated conditions. $\Omega_A$ is often used as a more biologically-relevant alternative to pH because it reflects the availability of the carbonate ion ($CO_3^{2-}$) building blocks which calcifying organisms need in order to construct their calcium carbonate ($CaCO_3$) shells and skeletons. Greater values of $\Omega_A$ correspond to higher $CO_3^{2-}$concentrations and thus favor the growth of corals, crustose coralline algae (CCA), and other reef calcifiers. However, under the process of ocean acidification, with increased dissolution of carbon dioxide in seawater, the seawater pH, $\Omega_A$, and concentrations of $CO_3^{2-}$ all decrease. This makes it more difficult for corals and calcifying reef organisms to grow.

The majority of our discrete water sampling effort at Wake took place at the same time each year (usually in March or April). As a result, it is not possible to describe seasonal patterns in seawater carbonate chemistry. However, interannual variability in $\Omega_A$ between 2011 and 2014 was low, and near-identical median $\Omega_A$ values were observed across the two years (Figure 25). There was also little spatial variability in $\Omega_A$ around the forereef, although a handful of unusually high (3.95 in 2011) and low (3.44 in 2014) $\Omega_A$ values were observed in the South georegion. The anomalous data points could result from small-scale oceanographic or biological processes that alter local carbonate chemistry, differences in the timing of sampling during the day, or (most likely) compromised samples. The homogenous carbonate chemistry conditions around Wake Atoll suggest that forereef waters are relatively well-mixed and well-flushed by offshore oceanic water. $\Omega_A$ and pH values for the atoll were above the median of values observed by ESD across the U.S. Pacific Island region since 2010 (Figure 26).

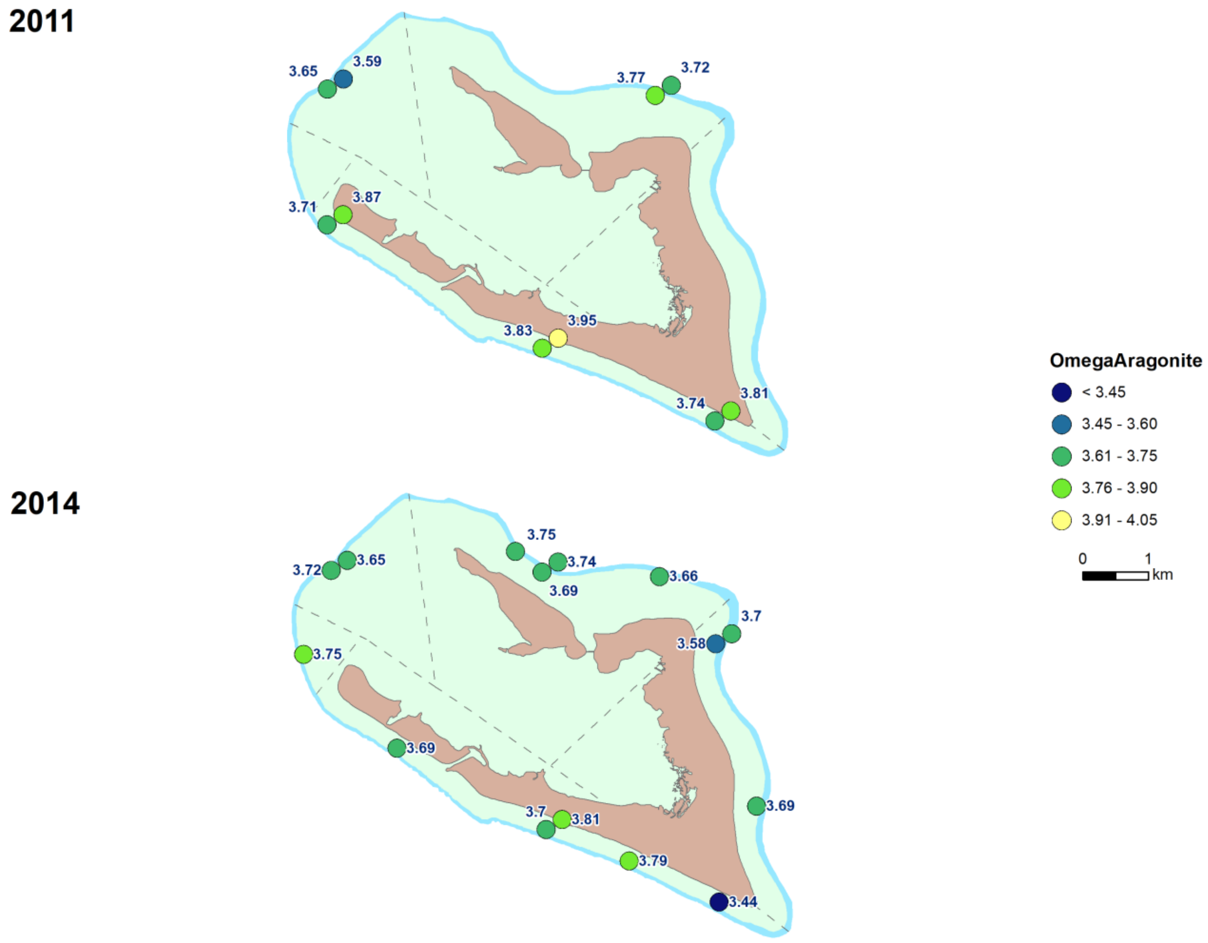


**Figure 25. Spatial distribution of aragonite saturation state, $\Omega_A$, observations during 2011 and 2014 around Wake Atoll.**

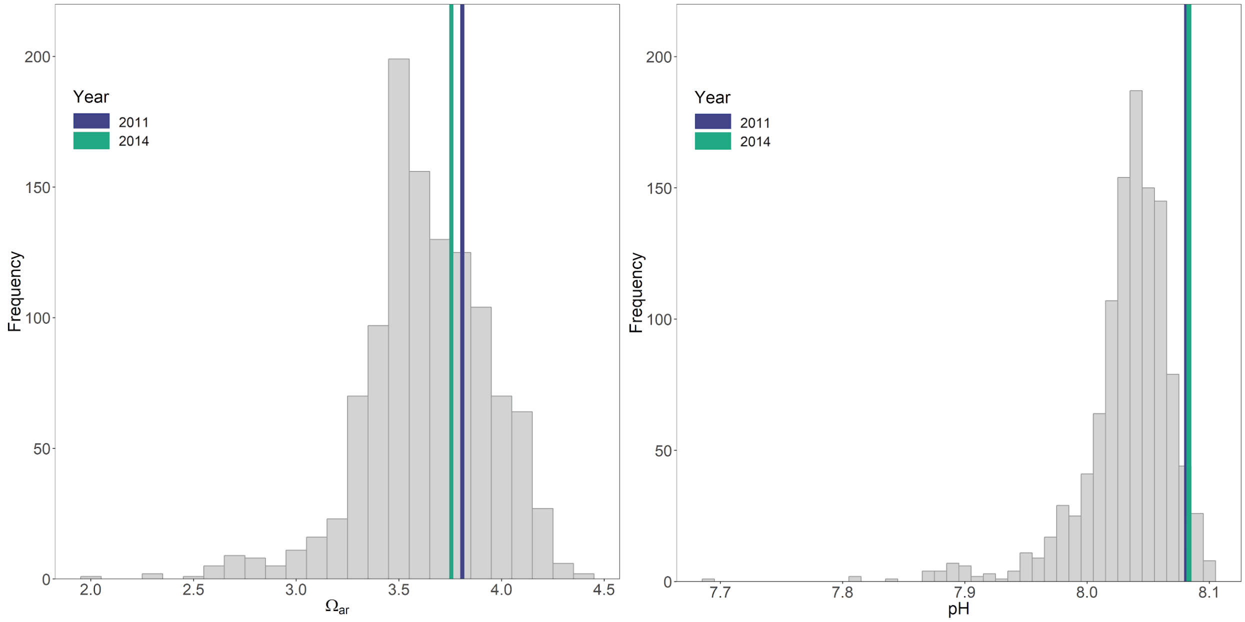


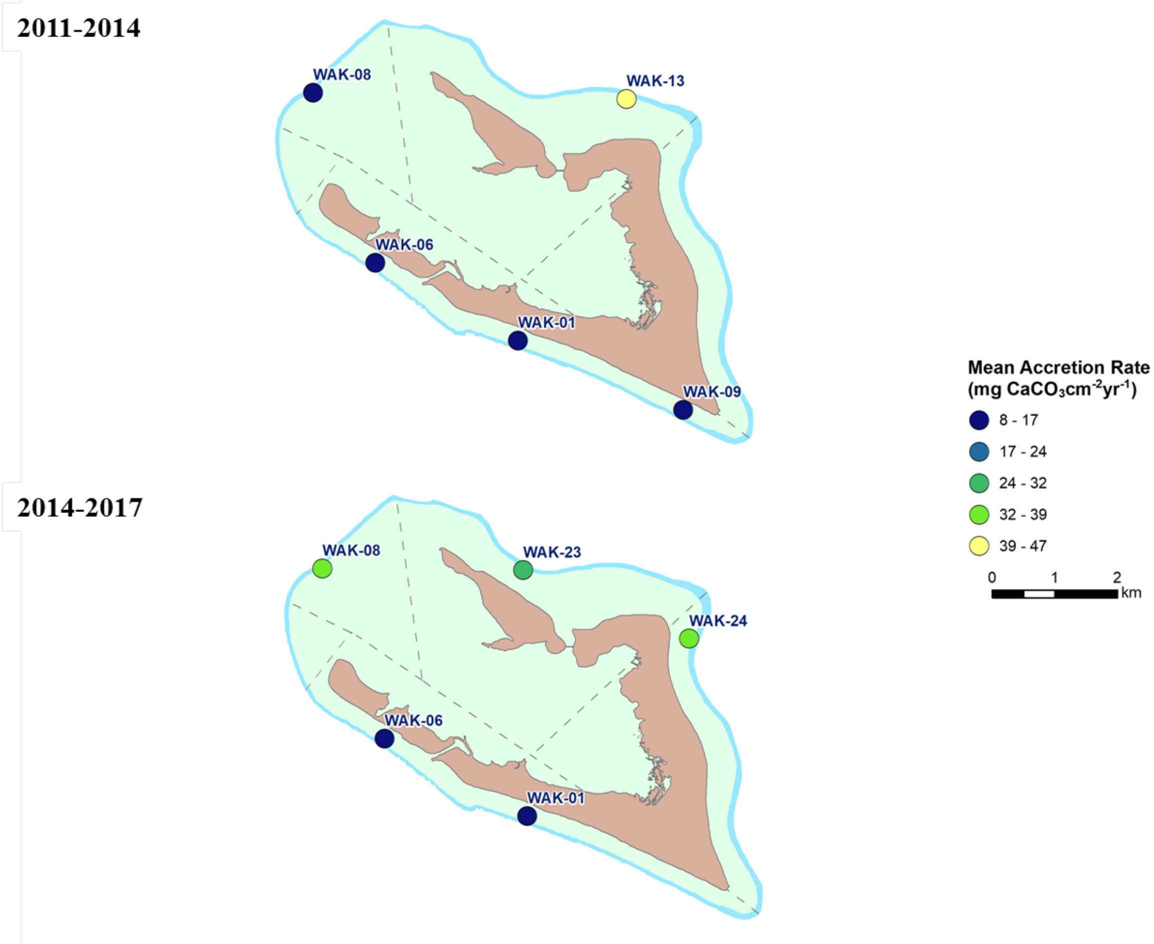
**Figure 26. Histogram of all aragonite saturation state, $\Omega_A$ (left) and pH (right) values measured from discrete seawater samples collected across the U.S. Pacific Islands region from 2010 to 2017 (gray). Overlaid vertical bars show the median values of Wake Atoll data in 2011 (blue) and 2014 (green).**

## Net Carbonate Accretion

Calcification accretion units (CAUs) are simple, two-plate fouling structures that are deployed for 2–3 years and then analyzed for the total weight of $CaCO_3$ accreted by the calcareous organisms that recruit to the plates (largely CCA and hard corals). CAUs provide an assessment of the net rate of $CaCO_3$ formation that results from the competing processes of carbonate precipitation by calcifying organisms and the removal of material by physical (e.g., strong waves) and/or biological (e.g., parrotfish, burrowing bivalves) erosion. $CaCO_3$ accretion is essential for reefs because it builds the structural framework for coral reef ecosystems and provides essential habitat for reef organisms. However, accretion rates are strongly influenced by nearshore environmental conditions. In particular, calcification rates of corals and CCA are sensitive to changes in carbonate chemistry and decrease with decreasing pH and $\Omega_A$ (Pandolfi et al. 2011). Refer to “Chapter 1: Overview” for CAU design specifics and deployment methodologies.

CAUs were deployed from 2011 to 2014 and from 2014 to 2017 around Wake Atoll to assess spatial and temporal variability in accretion (Figure 27). There was little variation in carbonate accretion rates between years, but large spatial differences were observed during both the 2011–2014 and the 2014–2017 deployment periods. Higher accretion rates typically occurred in the north and northeast sites and lower accretion rates were observed at the west and southwest sites. The highest accretion rate was observed in the North georegion over the period 2011–2014, while the lowest carbonate accretion rates were observed during the same period in the South. Spatial variability in $\Omega_A$ is low at Wake Atoll, so it is possible that these patterns are driven by sub-island scale differences in an environmental parameter, such as wave exposure, which is greater at sites with higher net accretion rates.

Despite relatively high pH/ $\Omega_A$, median accretion rates at Wake were very low relative to the rest of the Pacific region (Figure 28). These lower than expected accretion rates are likely also due to the impact of non-$\Omega_A$ physical variables (e.g., light levels, wave energy, or temperature) and/or ecological factors (e.g., predation, competition) on CCA growth. Cooler temperatures and oligotrophic conditions at Wake could limit calcification rates, especially in comparison to the relatively warmer temperatures and/or higher nutrient concentrations found at the lower-latitude islands of the PRIMNM.


2011-2014

2014-2017

**Figure 27. Spatial distribution of mean carbonate accretion rate (mg $CaCO_3$ cm$^{-2}$ yr$^{-1}$) at Wake Atoll during 2011–2014 (top) and 2014–2017 (bottom). The calcification accretion unit sites are shown by location code of WAK and the site number.**

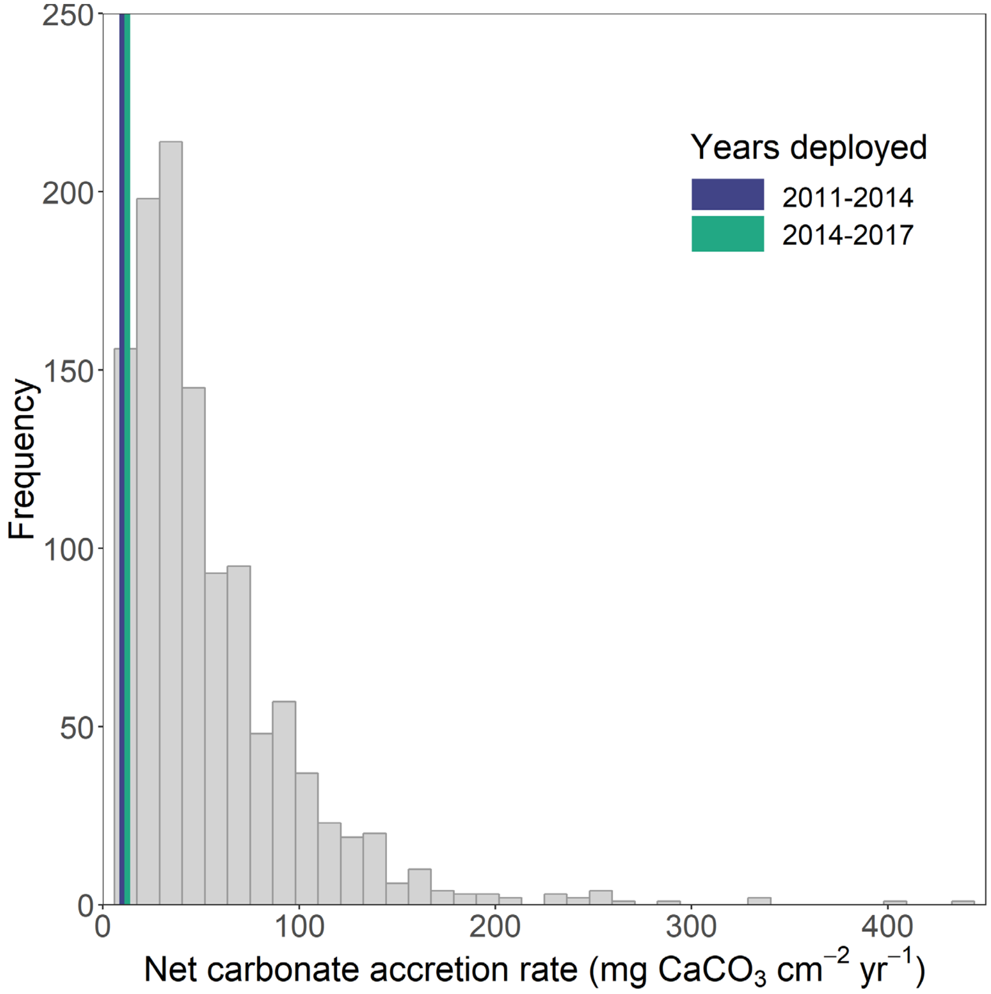


**Figure 28. Net carbonate accretion rate (mg $CaCO_3$ $cm^{-2}$ $yr^{-1}$) as measured using calcification accretion units during the period from 2010 through 2017 for all Pacific-wide samples surveyed as part of the Pacific Reef Assessment and Monitoring Program (gray), and log-transformed median values for Wake Atoll for 2011–2014 samples (blue) and 2014–2017 samples (green).**

*Green sea turtle (*Chelonia mydas*) swimming over a reef at Wake Atoll.*
*Photo: Andrew Gray, NOAA Fisheries.*

# ***Coral Reef Benthic Communities***

## 5.4 Coral Reef Benthic Communities

*Butterflyfish swimming over coral at Wake Atoll.*
*Photo: Andrew E. Gray, NOAA Fisheries.*

### Survey Effort and Site Information

To characterize benthic habitats and the coral populations around Wake Atoll, data were collected using Rapid Ecological Assessment (REA) surveys and towed-diver surveys (TDS) during six survey efforts conducted between 2005 and 2017 (Table 3). REA surveys were primarily performed at repeat sites at mid-depth (>6–18 m) for the four survey efforts between 2005 and 2011. In 2014, a stratified-random sampling (StRS) design was adopted to generate more statistically robust island-scale estimates of coral reef benthic communities. The use of a StRS study design allowed for an allocation of survey effort across multiple depth strata (shallow: >0–6 m; mid: >6–18 m; and deep: >18–30 m). The StRS sites were more widely and evenly distributed around the island than the former repeat sites (Figure 29). Benthic REA surveys implemented the line-point-intercept (LPI) method from 2005 through 2011, and the photoquadrat method from 2014 through 2017 to estimate percent cover of benthic communities. Photoquadrat surveys were also conducted at fish REA sites in 2014 and 2017, yielding greater sample sizes to determine benthic cover. Correspondingly, from 2005 through 2017, the belt-transect (BLT) method was used to estimate the abundance, distribution, condition, and diversity of the coral populations (with progressive updates to the methods detailed in “Chapter 1: Overview”). Benthic TDS were conducted primarily around the island perimeter at predominantly mid-depth forereef habitats to estimate the percent cover of benthic functional groups, the density of ecologically or economically important macroinvertebrates, and occurrences of potentially significant ecological events, such as outbreaks of disease or invasive or nuisance species.

**Table 3. The total number of Rapid Ecological Assessment (REA) survey sites and towed-diver survey (TDS) segments completed by year and strata (if applicable) at Wake Atoll. Numbers in parentheses (bold) indicate the number of surveys conducted at mid-depths (>6–18 m). *Note: In 2014, REA survey methodology shifted from repeat sites to stratified-random sampling (StRS). StRS sites were located across three depth strata: shallow (S), mid (M), and deep (D).**

| **Year** | **TDS** | **REA** | |
|---|---|---|---|
| | | Coral Populations | Benthic Communities |
| 2005 | 149 (**52**) | 8 | 13 (**12**) |
| 2007 | 187 (**108**) | 11 | 12 (**12**) |
| 2009 | 168 (**111**) | 12 | 25 (**12**) |
| 2011 | 147 (**134**) | 11 | 11 (**11**) |
| 2014* | 96 (**94**) | 7 (S)<br>7 (M)<br>6 (D) | 22 (S)<br>22 (M)<br>21 (D) |
| 2017* | 90 (**71**) | 10 (S)<br>12 (M)<br>7 (D) | 24 (S)<br>34 (M)<br>24 (D) |

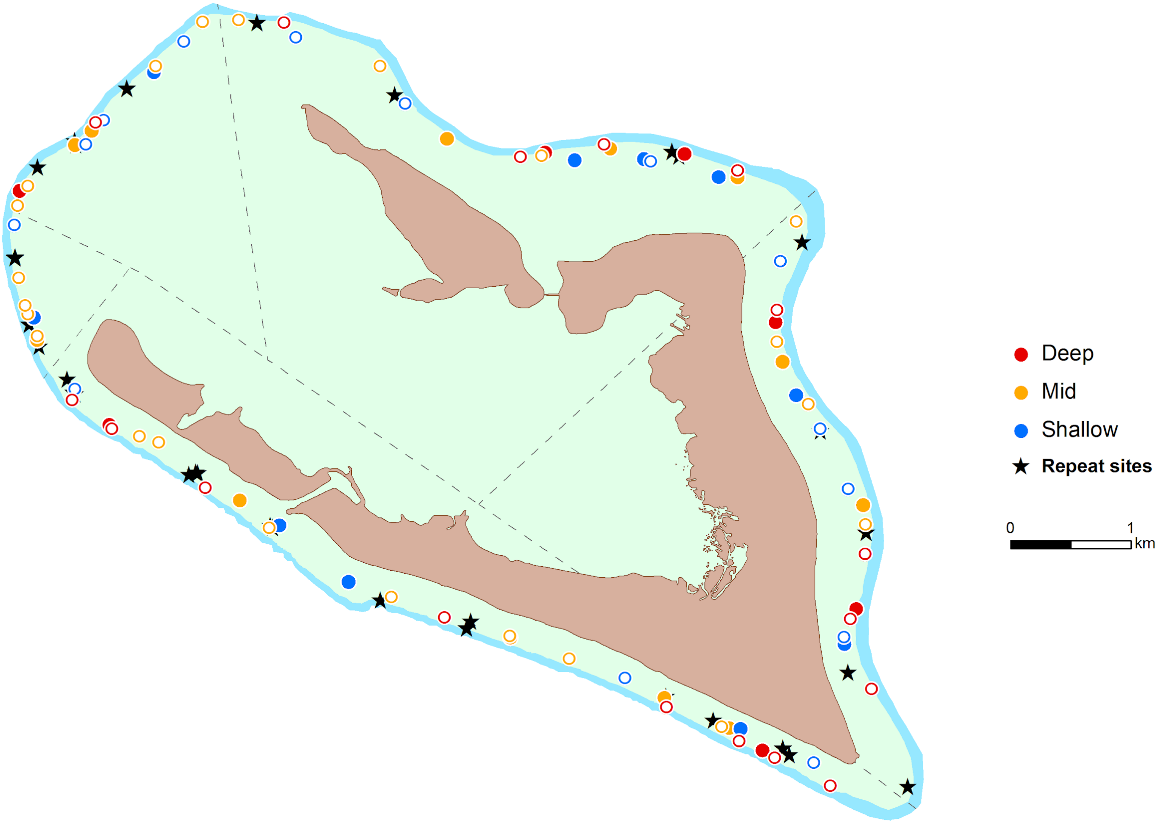


**Figure 29. Wake Atoll benthic Rapid Ecological Assessment surveys locations. Repeat sites (stars) were sampled from 2004 through 2012 and stratified-random sampling (StRS) sites were sampled in 2014 and 2017 (blue, yellow, and red circles for shallow [>0–6 m], mid [>6–18 m], and deep [>18–30 m] depth strata). Photoquadrats for assessing benthic communities were collected at all StRS sites (open circle with white fill and solid circles). Coral population surveys were only conducted at sites indicated by solid circles.**

## Recent State of Benthic Cover

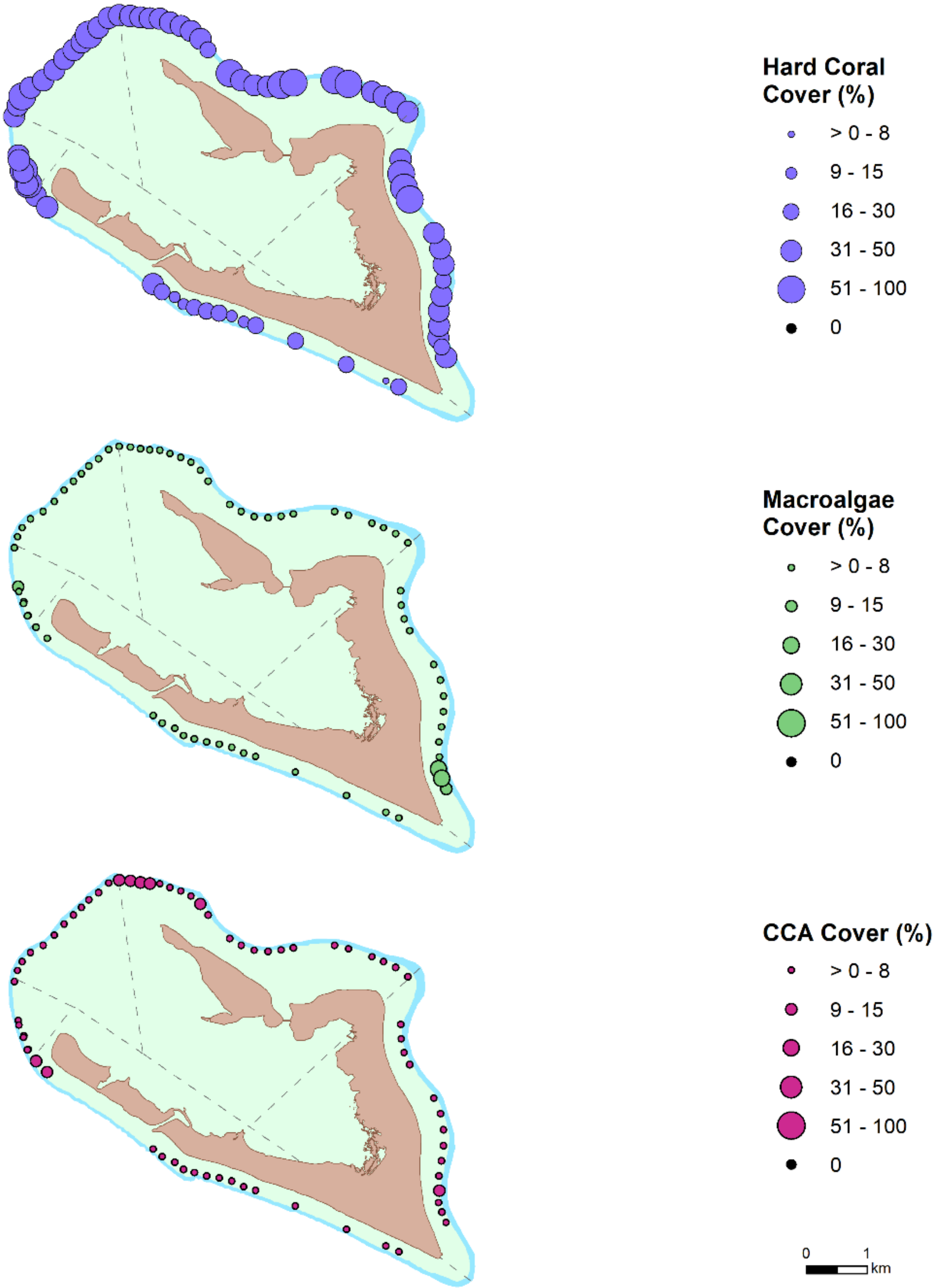


**Figure 30. Visual estimates and spatial distribution of mid-depth (>6–18 m) hard coral, macroalgae, and crustose coralline algae (CCA) cover (%) at Wake Atoll from towed-diver surveys in 2017.**

Hard coral was the dominant benthic functional group observed during mid-depth TDS at Wake Atoll during 2017 (mean = 39% ± 0.8 SE; Figure 30). Relatively low cover of CCA (mean = 3.7% ± 1.4 SE) and macroalgae, including both encrusting and calcified macroalgae (mean = 2.6% ± 0.9 SE), were observed. Hard coral was observed during all TDS segments, with cover per 5-minute tow segment ranging from 8% to 56%. While hard coral cover was overall relatively high (~16–50%) around Wake Atoll, lower values were observed in the South georegion. Macroalgae cover ranged from 0.5% to 25%, but cover values at the majority of TDS segments were less than or equal to 2.5%. Locations of high macroalgae cover were limited to the southeast. Although CCA cover ranged from approximately 0.5% to 8% throughout most of the atoll, low cover values (~0.5%) predominated in the majority of the TDS segments. Only a few instances of 9–15% CCA cover were noted in the East, North, and Northwest georegions.

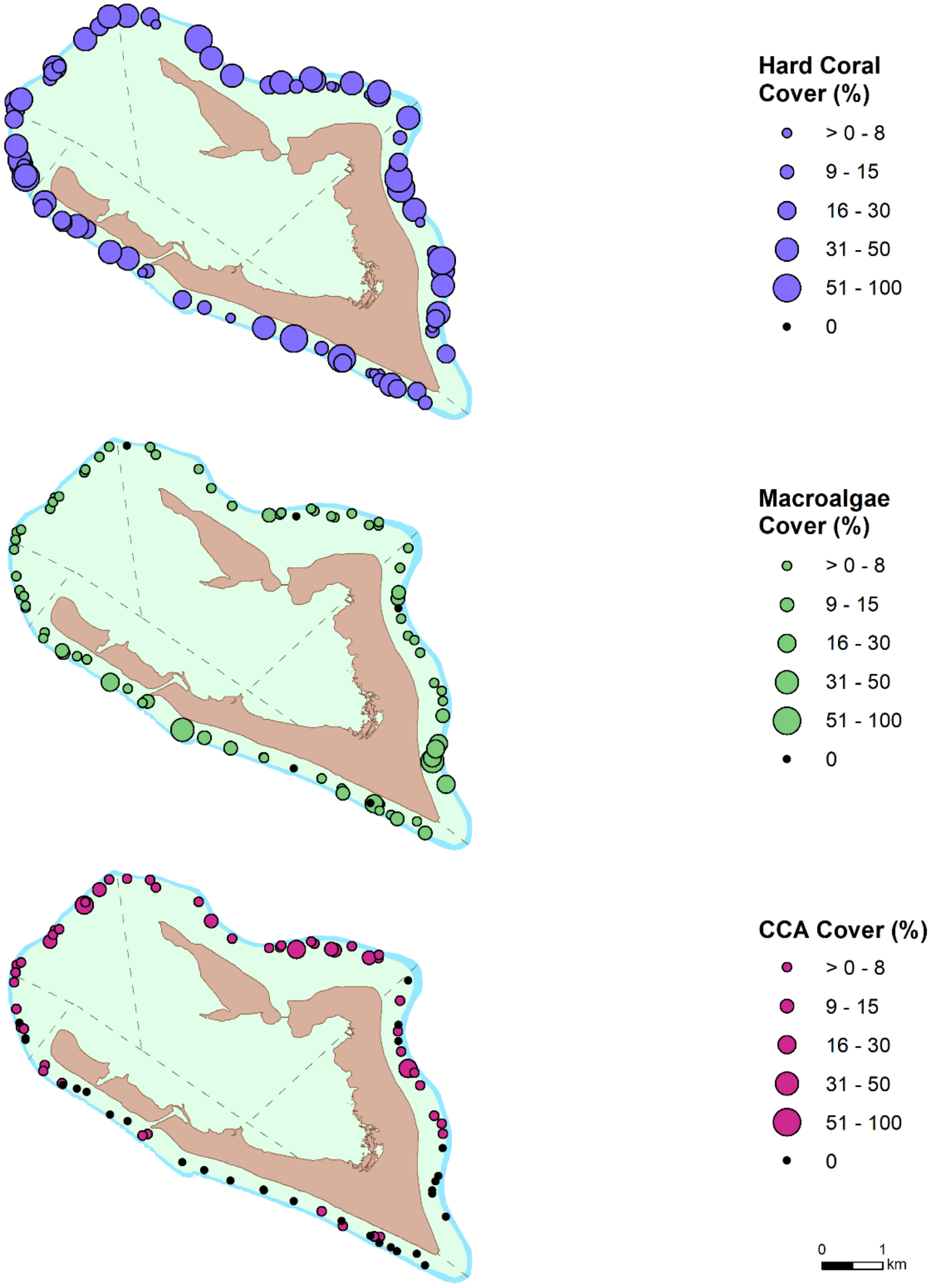


**Figure 31. Site-level estimates of hard coral, fleshy macroalgae (excluding calcified and encrusting macroalgae), and crustose coralline algae (CCA) cover (%) at Wake Atoll from stratified-random sampling photoquadrat surveys conducted at all depth strata combined (>0–30 m) in 2017.**

Cover estimates from StRS photoquadrat surveys show comparable spatial patterns to the TDS, whereby hard coral was the dominant functional group, followed by spatially variable macroalgal cover, and uniformly low CCA cover (Figure 31). Hard coral was present at all StRS sites surveyed at Wake Atoll in 2017, ranging from less than 0.3% to 65%, with nearly 65% of sites exhibiting hard coral cover values greater than 20%. Fleshy macroalgae (excluding calcified and encrusting macroalgae) were largely ubiquitous and variable in percent cover throughout the atoll, with cover ranging from 0 to 39%. Locations with higher macroalgae cover were generally in the South and East georegions. Although CCA cover ranged between 0% and 27%, it was reported absent at 37% of the survey sites and ranged from 0.1% to 5% at nearly 50% of sites. Only a few sites in the North, Northwest, and East georegions exhibited CCA cover in excess 15%.

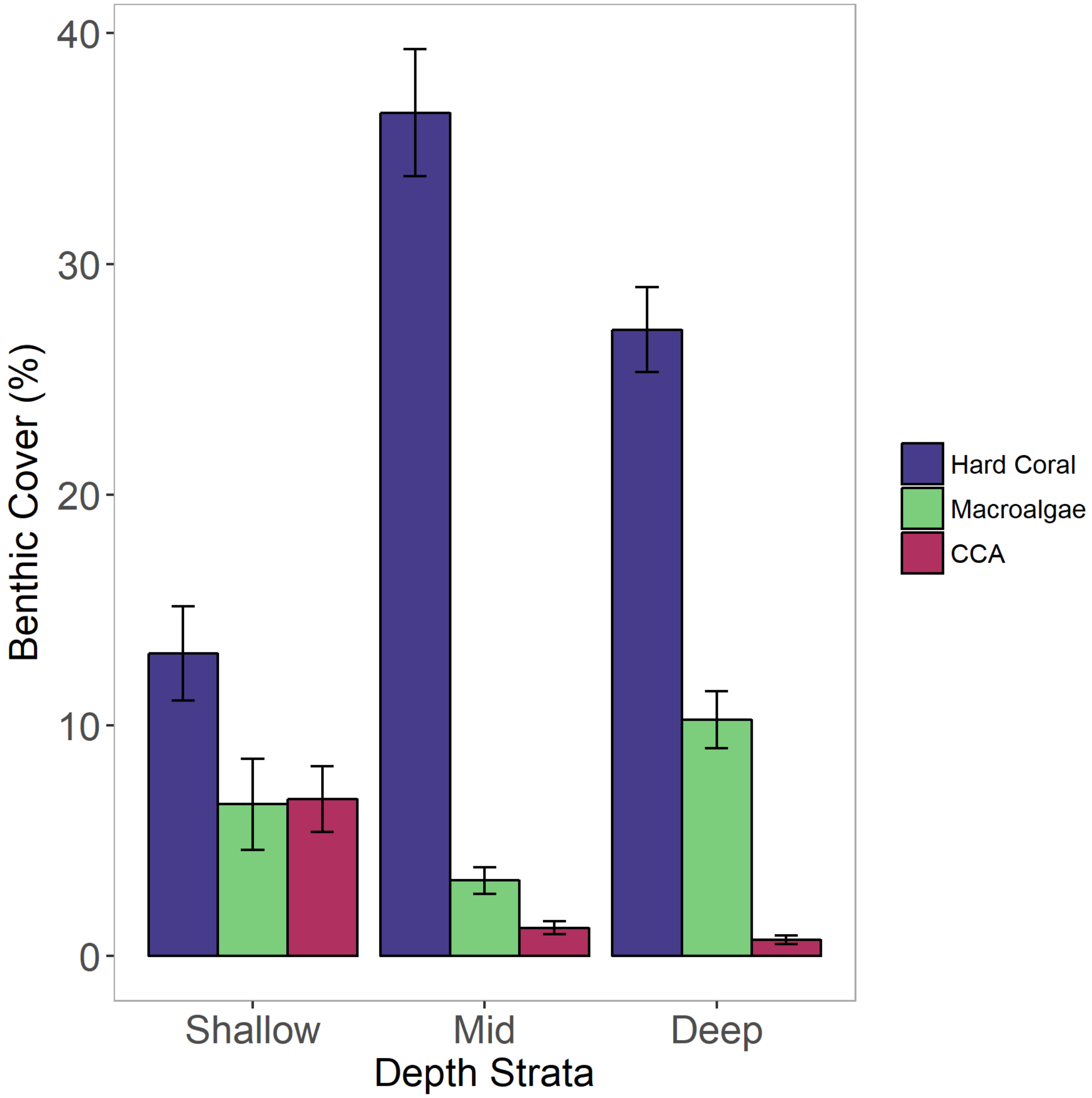


**Figure 32. Strata-level mean benthic cover (±1 SE) at Wake Atoll by benthic functional groups of hard coral, fleshy macroalgae (excluding calcified and encrusting macroalgae), and crustose coralline algae (CCA) for shallow (>0–6 m), mid (>6–18 m), and deep (>18–30 m) depth strata from stratified-random sampling photoquadrat surveys conducted in 2017.**

Based on the 2017 photoquadrat surveys at Wake Atoll, hard coral presented higher percent cover than fleshy macroalgae (excluding calcified and encrusting) and CCA throughout all depth strata (Figure 32). Hard coral cover was highest at mid depths (mean = 36.6% ± 2.7 SE), nearly three times higher than at the shallow-depth stratum (mean = 13.1% ± 2 SE). Lower coral cover observed in shallower stratum may have been associated with exposed, high wave energy environments that may have restricted coral larval settlement and survival. Notwithstanding, compared to the other PRIMNM islands surveyed during 2017 StRS surveys (i.e., Howland, Baker, and Jarvis), Wake Atoll had the overall highest hard coral cover.

Mean CCA cover was greatest (6.7% ± 1.4 SE) in the shallow stratum, likely driven by abundant light levels. Percent cover of CCA was slightly higher than macroalgal cover and about half of that observed for hard coral cover. Conversely, of the three main benthic functional groups studied, CCA exhibited the lowest mean cover values (<1.5%) in mid- and deep-depth stratum. The lowest levels of macroalgal cover were recorded at mid-depth sites (mean = 3.3% ± 0.6 SE) where corals were dominant. Higher levels of macroalgal cover at deep sites (mean = 10.2% ± 1.2 SE) were inverse to a lower preponderance of corals and CCA.

### Time Series of Benthic Cover

Mid-depth (>6–18 m) patterns of benthic cover were dynamic over the period from 2005 through 2017 (Figure 33). Focusing on TDS data, mean hard coral cover decreased by approximately 30% between 2005 and 2007 (from 29.2% to 19.6%), followed by a moderate and continued increase thereafter to an atoll-wide average of 39% (± 3.8 SE) in 2017. Although TDS estimates of mean coral cover were typically lower than the LPI estimates (particularly for 2007 and 2009), the temporal patterns were consistent between both survey methodologies.

Fleshy macroalgal cover, captured by REA surveys, peaked in 2009 and gradually declined in subsequent years. TDS data, which include both fleshy macroalgae and calcified and encrusting algae, also reveal a temporal decline. Benthic cover estimate differences may originate from the nature and spatial coverage of the surveys (TDS vs. LPI), as well as observer biases as corroborated by comparable differences between methods noticed from RAMP surveys at Jarvis Island and Kingman Atoll. In 2014 and 2017, macroalgae cover at Wake Atoll was similar between TDS and photoquadrat estimates. Macroalgae cover was lowest in 2017 for both methods (TDS: mean = 2.6% ± 0.9 SE; PQ: mean = 3.3% ± 0.6 SE).

CCA cover was overall low and quite variable between REA and TDS methods and generally remained below 10%, except for a peak in cover in 2011, which was estimated using LPI surveys (mean = 6% ± 1.2 SE). Neither method exhibited a clear trend in CCA cover over time.

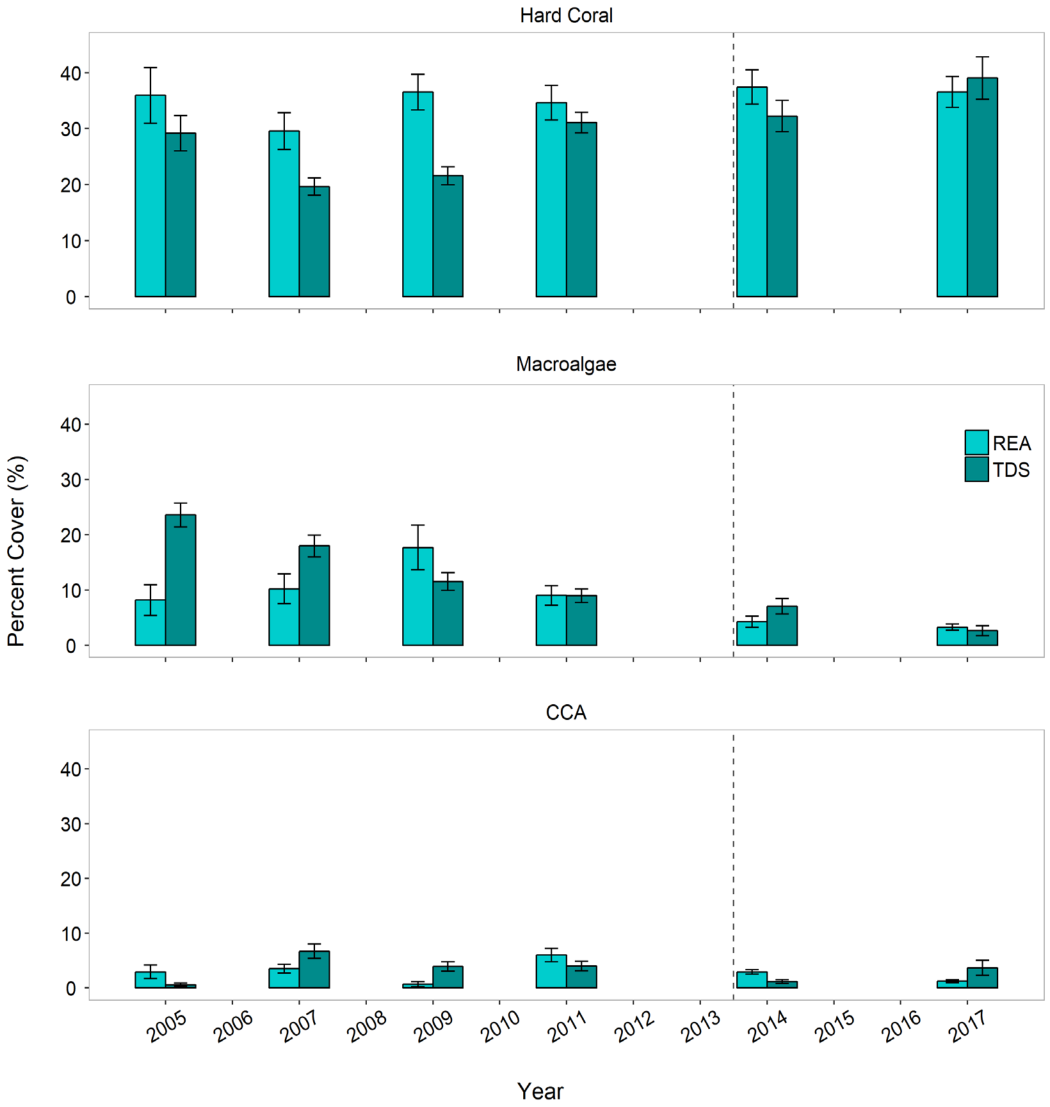


**Figure 33. Time series of mean (±1 SE) hard coral, macroalgae, and crustose coralline algae (CCA) cover (%) at Wake Atoll by survey method (Rapid Ecological Assessment [REA] and towed-diver survey [TDS]) conducted at the mid-depth stratum (>6–18 m) from 2005 through 2017. In 2014 (dashed line), REA survey methodology changed from line-point-intercept at repeat sites to photoquadrat surveys at stratified-random sampling sites to determine benthic cover. *Note: TDS macroalgae data include calcified and encrusting macroalgae; the REA macroalgae data exclude it.**

Averaged across all survey years (2005–2017) and methods (TDS, LPI, and StRS photoquadrats), mean hard coral cover was higher (30–40%) on forereef habitats in the East, North, and West georegions and lower (10–30%) on forereef habitats in the South and Northwest georegions (Figure 34a). The decadal trend analysis presented in Figure 34b illustrates that over time coral cover increased in focal areas along the North, East, and Northwest georegions, interspersed by areas of no change, and decreased mainly along the southeastern boundary of the South georegion. Finally, Figure 34c illustrates how hard coral cover remained stable throughout the survey period (2005–2017), with a slight increasing trend over time in the North georegion.

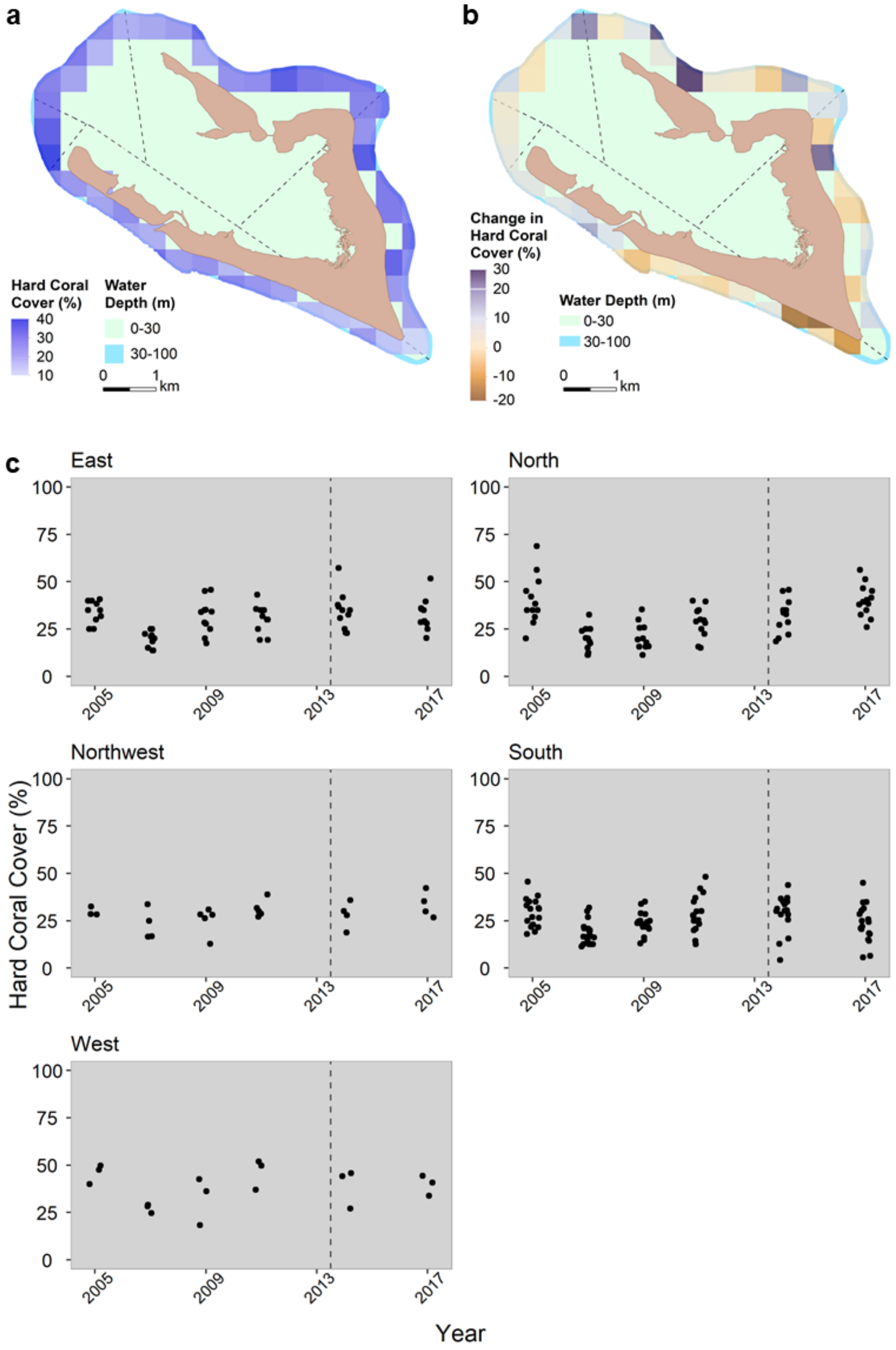


**Figure 34. Spatial patterns and temporal trends of gridded (500 m × 500 m) mean coral cover at Wake Atoll across survey years (2005–2017) and methods (towed-diver survey, line-point-intercept (LPI), and stratified-random sampling (StRS) benthic and fish photoquadrats). (a) Mean hard coral cover per 500 by 500 m grid cell across all survey years; (b) temporal change in hard coral cover per 500 by 500 m grid cell, only including cells with at least a 10-year span of data and at least 3 observation years; and (c) time series of hard coral cover by georegion. In 2014 (dashed line), Rapid Ecological Assessment survey methodology changed from LPI at repeat sites to photoquadrat surveys at StRS sites. See Survey Methods for Coral Reef Benthic Communities in "Chapter 1: Overview" for further details.**

## Time Series of Algal Disease

REA BLT surveys conducted between 2007 and 2017 reported absence of coralline algal diseases during the study period.

## Recent Coral Abundance

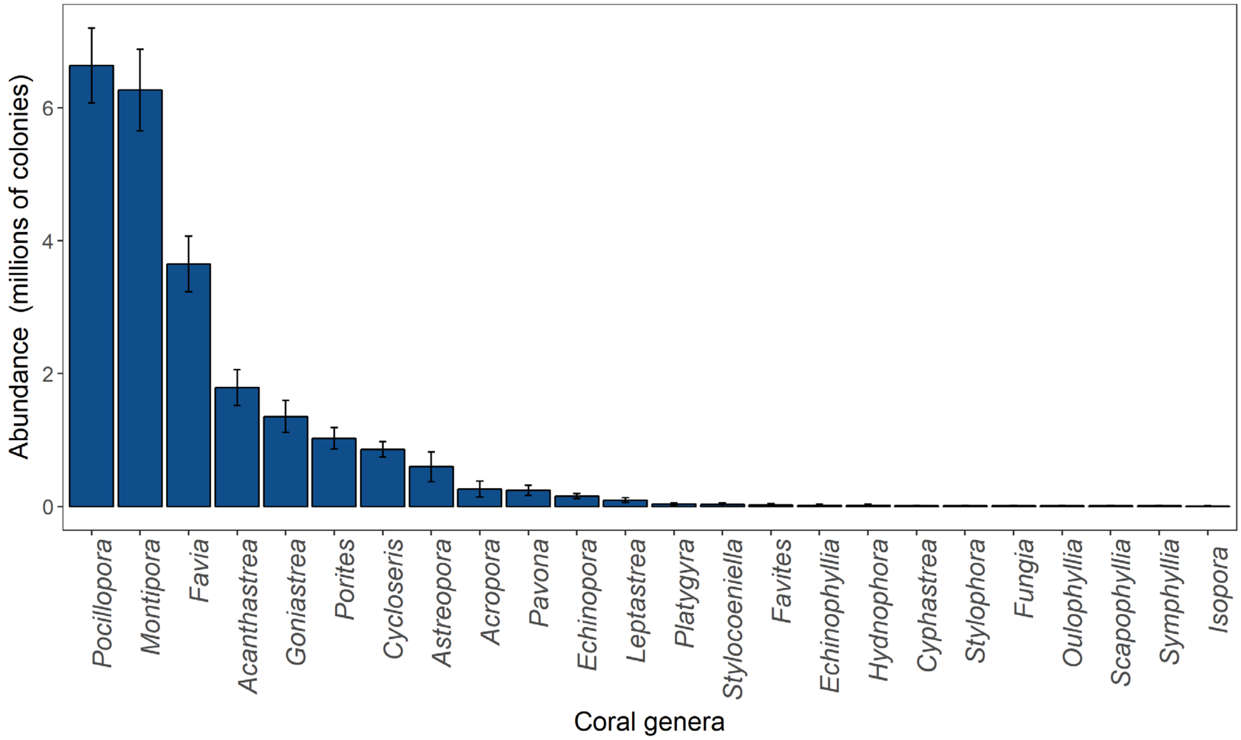


**Figure 35. Island-scale abundance (± 1 SE) estimates by coral genera for all depth strata combined (>0–30 m) at Wake Atoll from Rapid Ecological Assessment surveys conducted in 2017.**

Island-scale abundance estimates for coral genera were extrapolated from the REA transect colony densities over the area of hard bottom habitat found in the survey strata (0–30 m). Across all three depth strata, the coral genera *Pocillopora* and *Montipora* were the most numerically abundant in the 2017 surveys (Figure 35). Despite their numerical similarity, benthic cover of the genus *Pocillopora* was only one half of that of *Montipora* due to their relative smaller colony sizes. Of the 24 total coral genera found, *Favia* was the third most abundant taxon and *Isopora* was the least abundant. A table showing total generic richness of hard corals in the PRIMNM can be found in Appendix A of "Chapter 9: PRIMNM in the Pacific-wide Context."

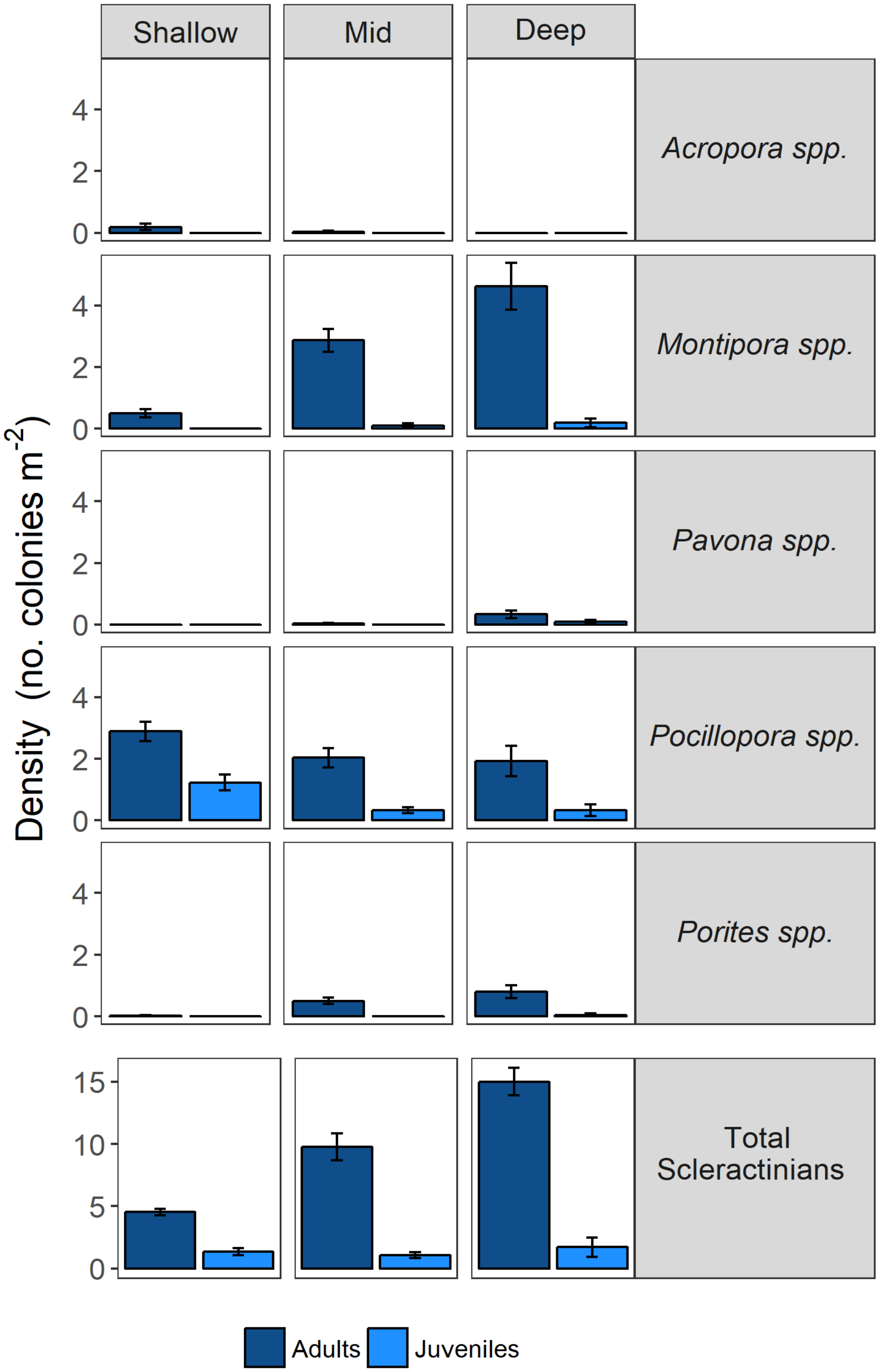


**Figure 36. Mean (± 1 SE) adult and juvenile colony density from Rapid Ecological Assessment surveys conducted at Wake Atoll in 2017 for shallow (>0–6 m), mid (>6–18 m), and deep (>18–30 m) depth strata for total scleractinians and five coral genera abundant in the Pacific Remote Islands Marine National Monument (*Acropora* spp., *Montipora* spp., *Pavona* spp., *Pocillopora* spp., and *Porites* spp.), to facilitate comparison among islands.**

Adult colonies dominated the coral community at Wake Atoll, irrespective of genus and depth. Juveniles (colonies <5 cm) comprised about 30% of the coral population at shallow sites and around 10% on mid and deep sites (Figure 36).

For all genera combined, density of adults increased with depth, while juvenile densities were comparably low across depths. This pattern was driven by the density of adult *Montipora*. Numbers of juvenile colonies of *Montipora* were low across depths, with a narrow increase from shallow (0 colonies/m$^2$) to deep sites (mean = 0.2 ± 0.1 SE colonies/m$^2$).

After *Montipora,* the second most numerically abundant coral genus at Wake was *Pocillopora*; most abundant in the shallow stratum (mean adult = 2.9 colonies/m$^2$ ± 0.3 SE and mean juveniles = 1.2 colonies/m$^2$ ± 0.3 SE, respectively). Adult *Montipora* and *Pocillopora* densities were inversely related across depth, where *Pocillopora* colony densities decreased with depth, while *Montipora* colonies increased (Figure 36). Corresponding patterns were observed on percent cover, with *Pocillopora* ranking the highest in shallow sites (mean cover = 5.5% ± 0.7 SE), while *Montipora* dominated on mid and deep sites (mean cover = 17.7% ± 1.6 SE and 11.3% ± 1.3 SE, respectively). Branching colonies of *Pocillopora* are typically fast growing and thrive in shallow, well-lit habitats; the low density of *Montipora* at shallow sites may be due to space limitation by *Pocillopora* and vice-versa. The juvenile densities of *Montipora* and *Pocillopora* follow the same trends with depth as the adult densities.

*Acropora*, *Pavona*, and *Porites* densities, abundant genera throughout the PRIMNM, were very low (<1 colony/m$^2$) at Wake Atoll in 2017. No juvenile *Acropora* were found at any depth, and the adult *Acropora* density peaked in the shallow stratum with a mean density of 0.2 colonies/m$^2$ (± 0.1 SE). Adult and juvenile *Pavona* were absent from the shallow depth stratum, and both life stages were only present together in the deep stratum (mean adult density = 0.3 colonies/m$^2$ ± 0.1 SE). Juvenile *Porites* were only present in the deep stratum, where the adult *Porites* density was highest (mean = 0.8 colonies/m$^2$ ± 0.2 SE).

These genus-specific differences indicate that community composition varies across survey depths in the forereef habitats around the atoll. These shifts likely reflect differences in the life histories of these genera, which impact their optimal depth range as well as competitive abilities. However, the low colony densities of coral genera at various depths may also imply that larger colonies are present in these areas and not necessarily that the percent cover of coral is lower.

One colony of *Isopora crateriformis*, a species listed as threatened under the Endangered Species Act (National Oceanic and Atmospheric Administration 2005), was reported during the 2017 surveys. No further details are available regarding the sighting of this taxon.

## Time Series of Coral Abundance and Condition

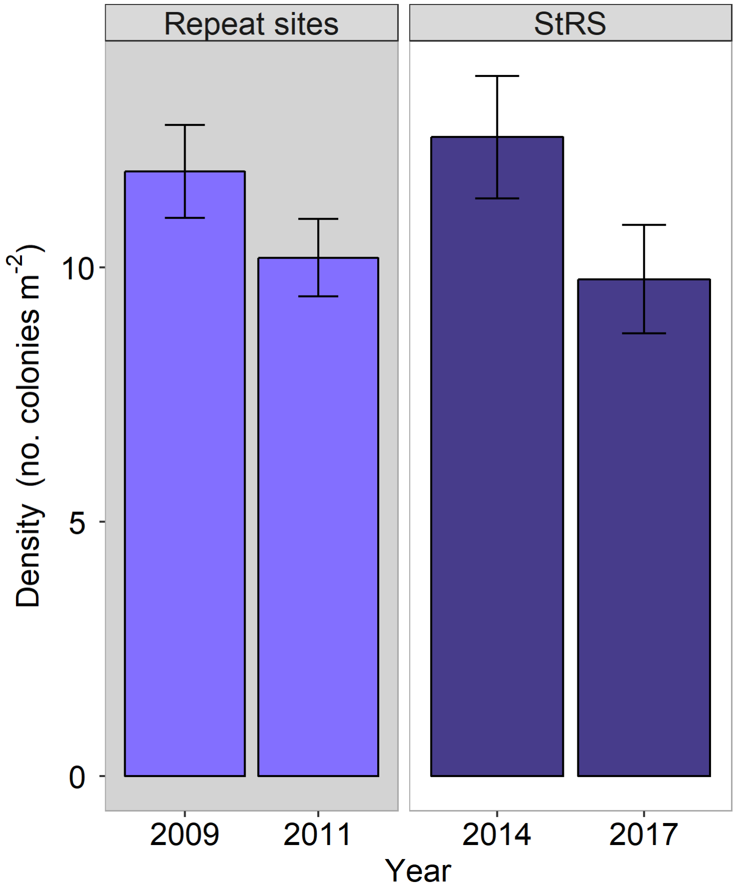


**Figure 37. Time series of mean adult colony density (±1 SE) at Wake Atoll from mid-depth (>6–18 m) strata Rapid Ecological Assessment belt-transect surveys by survey design, repeat sites or stratified-random sampling (StRS), conducted from 2009 through 2017.**

Despite the inherent differences among survey methodologies (repeat sites vs. StRS), coral colony densities around Wake Atoll were dynamic but overall stable from 2009 through 2017 (Figure 37). Based on data collected at repeat sites, mean coral colony density decreased slightly from 2009 to 2011, from 11.9 colonies/m$^2$ (±1.0 SE) to 10.2 colonies/m$^2$ (±0.8 SE). Mean colony density also decreased from 12.6 colonies/m$^2$ (±1.2 SE) in 2014 to 9.8 colonies/m$^2$ (±1.1 SE) in 2017, based on data collected using the StRS design. While the differences in survey design necessitate caution when interpreting differences in data collected at repeat sites and StRS sites, the relatively comparable mean adult colony density across survey years suggests that in the recent past coral populations at Wake have remained relatively stable.

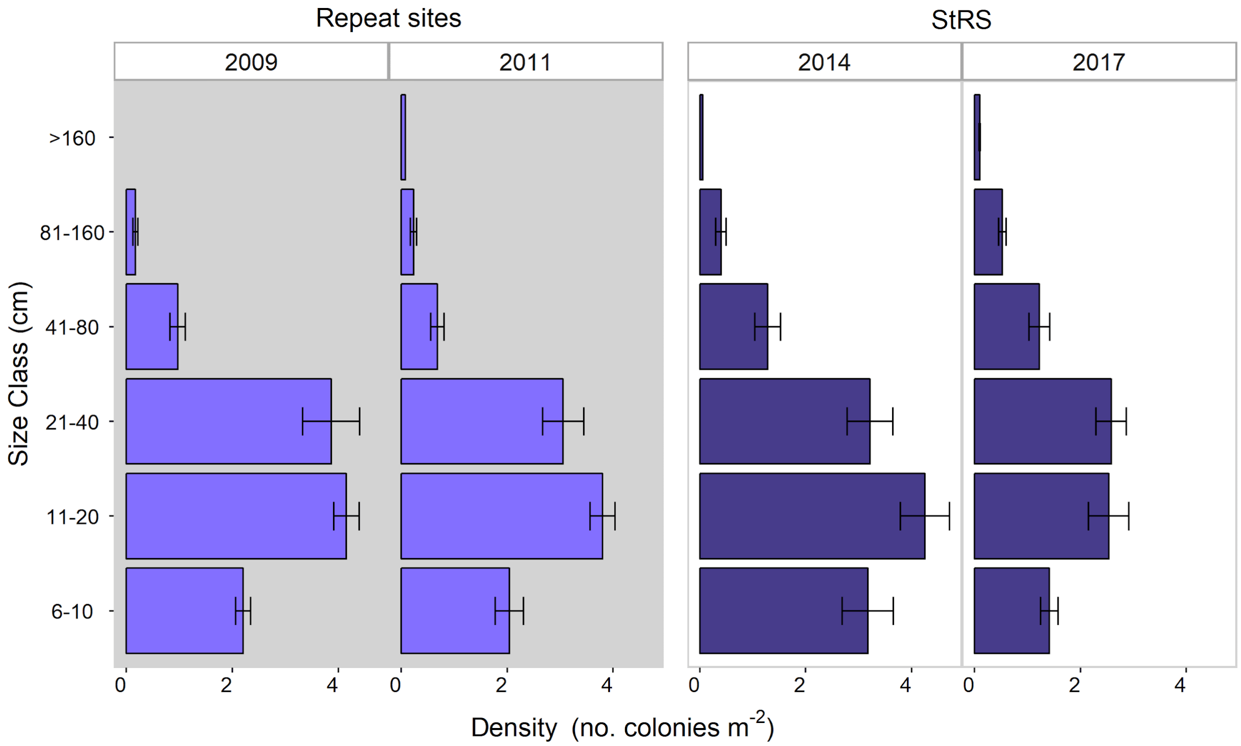


**Figure 38. Time series of mean adult colony density (±1 SE) at Wake Atoll by size class from mid-depth (>6–18 m) strata Rapid Ecological Assessment surveys by survey design, repeat sites or stratified-random sampling (StRS), conducted from 2009 through 2017.**

Two main patterns are evident when reviewing the time series of adult colony densities illustrated in Figure 38. In essence, the coral size frequency distributions have a unimodal pattern where the majority of the colonies are in the moderate size-classes (11–40 cm); smaller (5–10 cm), presumably younger colonies are present, together with a few large (>81 cm) colonies that have survived many decades. Furthermore, despite subtle variations, the unimodal pattern is consistent across years and survey methods. Importantly, coral size-frequency curves exhibiting the above pattern (i.e., skewed to the larger/older colonies) indicate healthy coral populations (Bak and Meesters 1998). In addition, the consistency of this pattern since 2009 suggests some level of stability in the coral population.

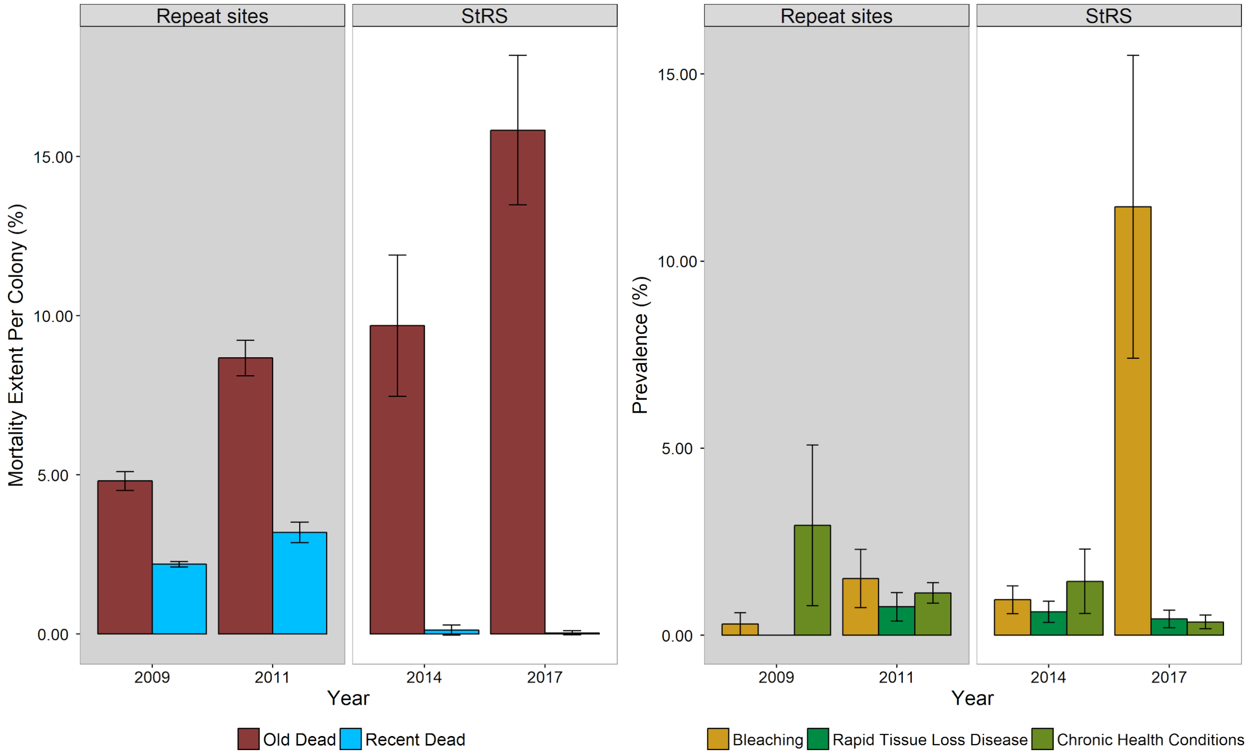


**Figure 39. Time series of mean (± 1 SE) (a) percent partial coral mortality and (b) prevalence of bleaching, rapid tissue loss diseases, and chronic health conditions at Wake Atoll based on mid-depth (>6–18 m) strata Rapid Ecological Assessment surveys by survey design, repeat sites or stratified-random (StRS), conducted from 2009 through 2017.**

Coral partial mortality (expressed as percent of colony exhibiting both recent and old mortality) was greater for old than recent mortality in all survey years (Figure 39). Recent mortality increased from 2009 to 2011, though declined to background levels of less than 1% in 2014 and 2017. Old mortality showed an increasing trend over time, reaching 15.8% (±2.2 SE) in 2017, a 60% increase from 2014. Over this same period, hard coral cover dropped by 13%. Furthermore, while mean bleaching prevalence remained at background levels (0.3–1.5%) from 2009 to 2014, it increased more than tenfold between 2014 and 2017 (mean = 11.4% ± 4.0 SE).

## Benthic Macroinvertebrates

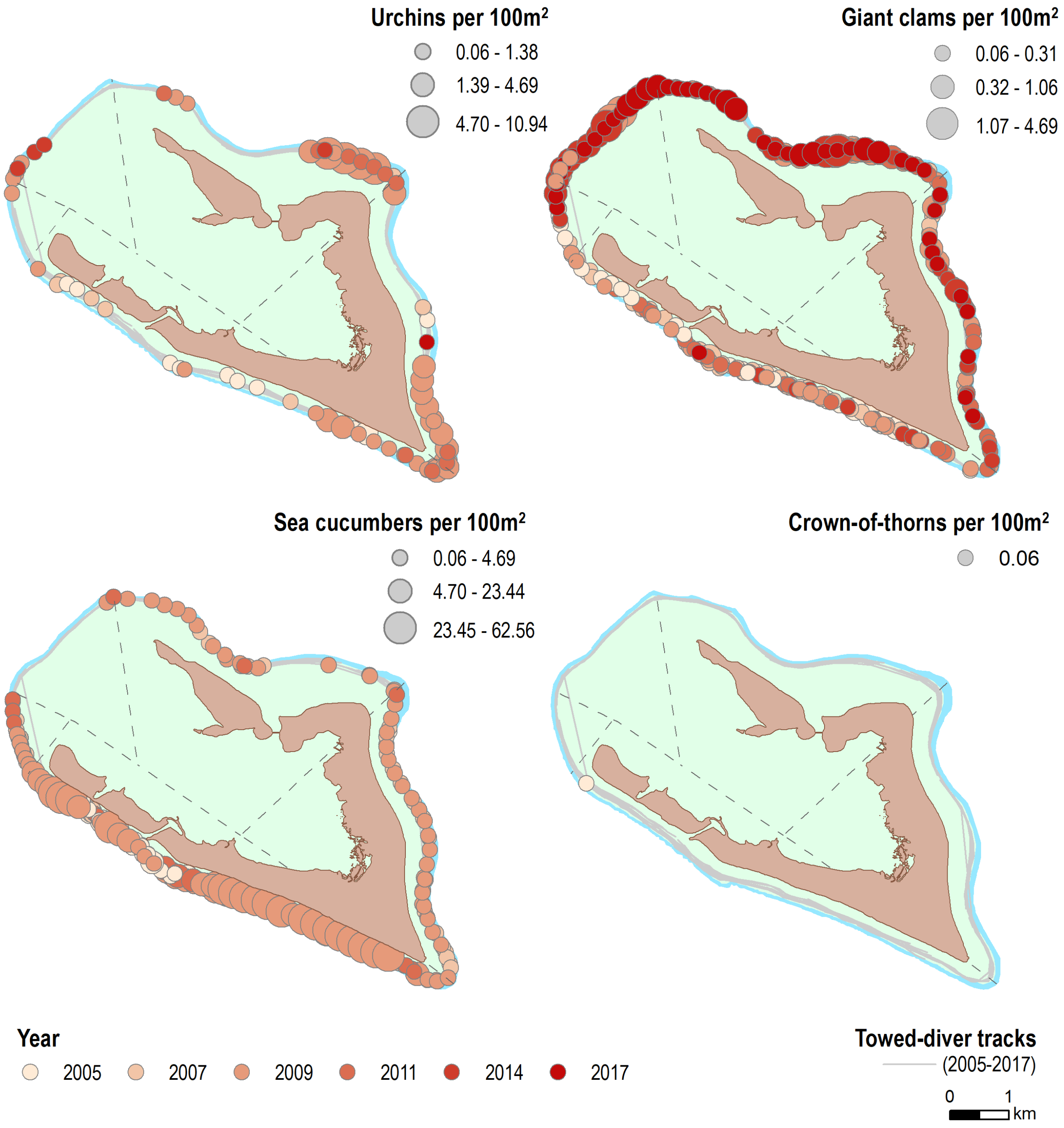


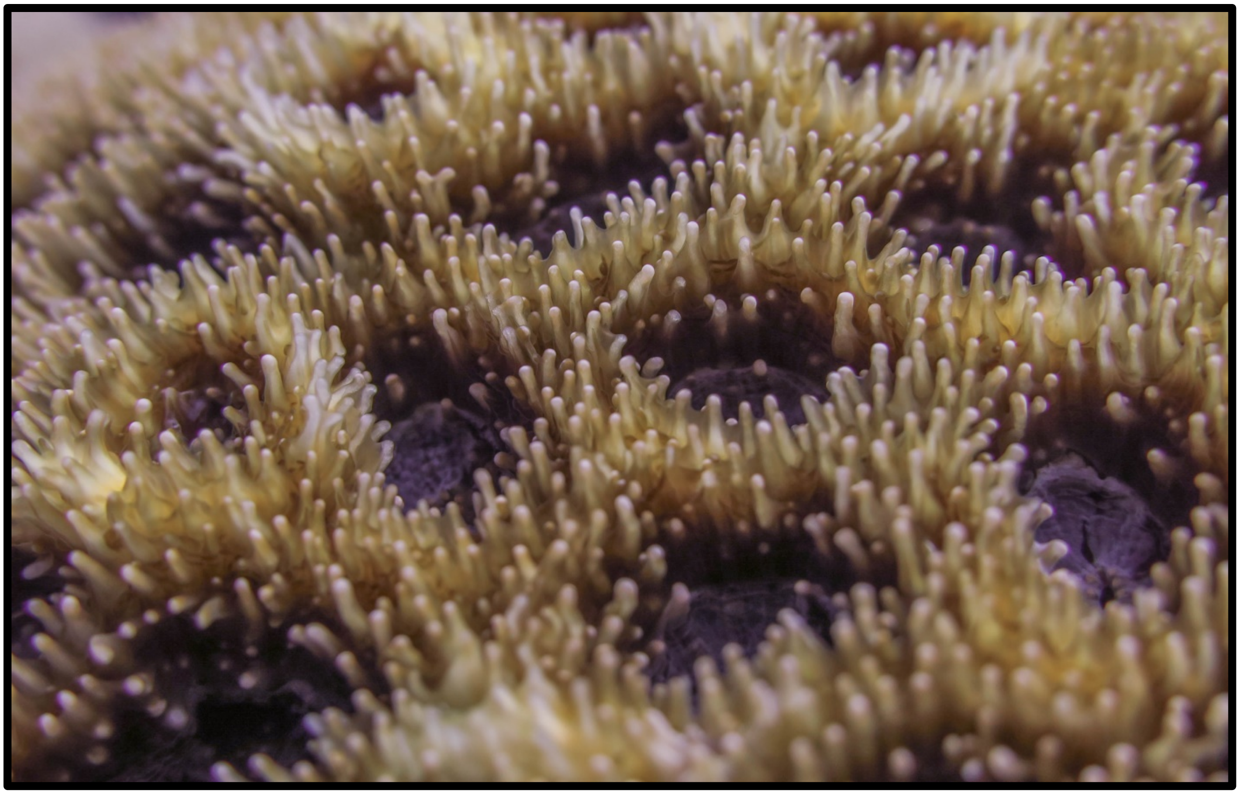
**Figure 40. Density of conspicuous, ecologically- or economically-important macroinvertebrates (urchins, giant clams, sea cucumbers, and crown-of-thorns sea stars) observed per segment from benthic towed-diver surveys (TDS) conducted throughout all depth strata (>0–30 m) around Wake Atoll from 2005 through 2017. Sea cucumber observations were discontinued from TDS in 2014.**

Urchins were observed around Wake Atoll on TDS during all survey years. Their spatial distribution around the atoll was patchy and mainly concentrated in the South, East, and North georegions. The highest densities of urchins per segment (11 individuals per 100 $m^2$) peaked in 2009 in the North georegion.

Giant clams—currently under status review (Federal Register 2017)—were also observed to be widely distributed around Wake Atoll during each of the survey years from 2005 through 2017. The highest densities of giant clams were sighted in the North and Northwest georegions where, in 2009, towed-divers recorded densities as high as 5 individuals per 100 $m^2$.

Sea cucumbers were recorded around Wake Atoll during each of the survey years from 2005 through 2014. Sea cucumbers were generally broadly distributed around the atoll, with highest densities in the South georegion and lowest densities observed in the Northwest georegion. Individual segment densities peaked at 63 individuals per 100 $m^2$, during the 2009 surveys with the majority of individuals found within the South georegion.

Crown-of-thorns sea star sightings around Wake Atoll have been extremely rare, with only a single individual recorded in 2005 (Figure 40) and none recorded in 2007, 2009, 2011, 2014, or 2017.



*Microscopic view of intricate patterns of* Acanthastrea brevis *at Wake Atoll.*
*Photo: Tate Wester, NOAA Fisheries.*

# *Microbiota*

## 5.5 Microbiota

*A scene of NOAA divers diving down to a survey site of Wake Atoll.*
*Photo: Noah Pomeroy, NOAA Fisheries*

The reef microbiota facilitates the cycling of essential nutrients by breaking down organic materials released by photosynthetic picoplankton (e.g., cyanobacteria) and benthic macroorganisms (corals and macroalgae). Habitats dominated by reef-building organisms (i.e., stony corals and calcified algae), such as Wake Atoll, illustrate a functional role that suppresses the energetic losses through microbial catabolism and promotes trophic transfer of energetic resources, carbon and inorganic nutrients, into metazoan food webs. This function is observed through the low microbial standing stocks in the water column and high turnover rates of microbial populations on reefs compared to the surrounding oceanic waters. Reef water samples were collected from all RAMP sites across the U.S. Pacific Islands region beginning in 2008, with the first PRIMNM samples measured in 2009 (i.e., Wake and Johnston Atolls) and 2010 (i.e., Jarvis, Howland, and Baker Islands, Palmyra Atoll, and Kingman Reef). The assessment and monitoring of the reef microbiota paired with data collected on benthic and pelagic macro-biota across the entire U.S. Pacific Islands region allow for characterization of coral reefs from a molecular to an ecosystem scale.

## Microbial Biomass on Reefs

Habitats dominated by reef building organisms (i.e., stony corals and calcified algae), such as Wake Atoll, illustrate a functional role that suppresses the flow of energy through the microbial pathways and promotes movement through particulate pathways channeling energy and nutrients towards metazoan food webs. Microbial biomass on Wake Atoll, similar to other remote atolls (e.g., Rose and Palmyra) is lower than on remote equatorial islands (e.g., Jarvis, Howland, and Baker) (Figure 41). Non-calcifying benthic organisms, like fleshy macro and turf algae (observed in higher abundances on human-impacted reef systems), release high amounts of bioavailable dissolved organic carbon (DOC) and select for larger, fast growing microbial communities that utilize these higher energetic organic resources to sustain their greater metabolic demands. Reef degradation towards algae-dominated states promotes greater cell biomasses and higher proportions of fast growing heterotrophic taxa (as observed on the main Hawaiian Islands), which exhibit up to an order of magnitude more microbial biomass in the overlying reef waters (i.e., Wake 2009 = 12 mg $m^{-3}$ and Oahu 2008 = 153 mg $m^{-3}$). The associated changes in microbial community structure and growth strategies when benthic community composition shifts from corals to algae shunts much more of the energy produced by the system towards decomposition pathways with enhanced respiration of organic compounds to carbon dioxide. This phenomenon is referred to as microbialization.

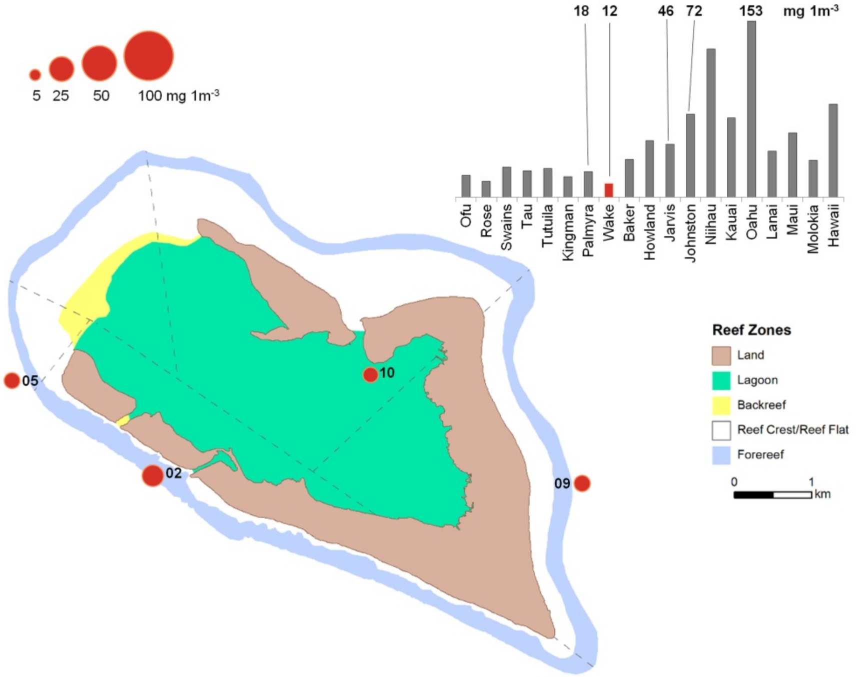
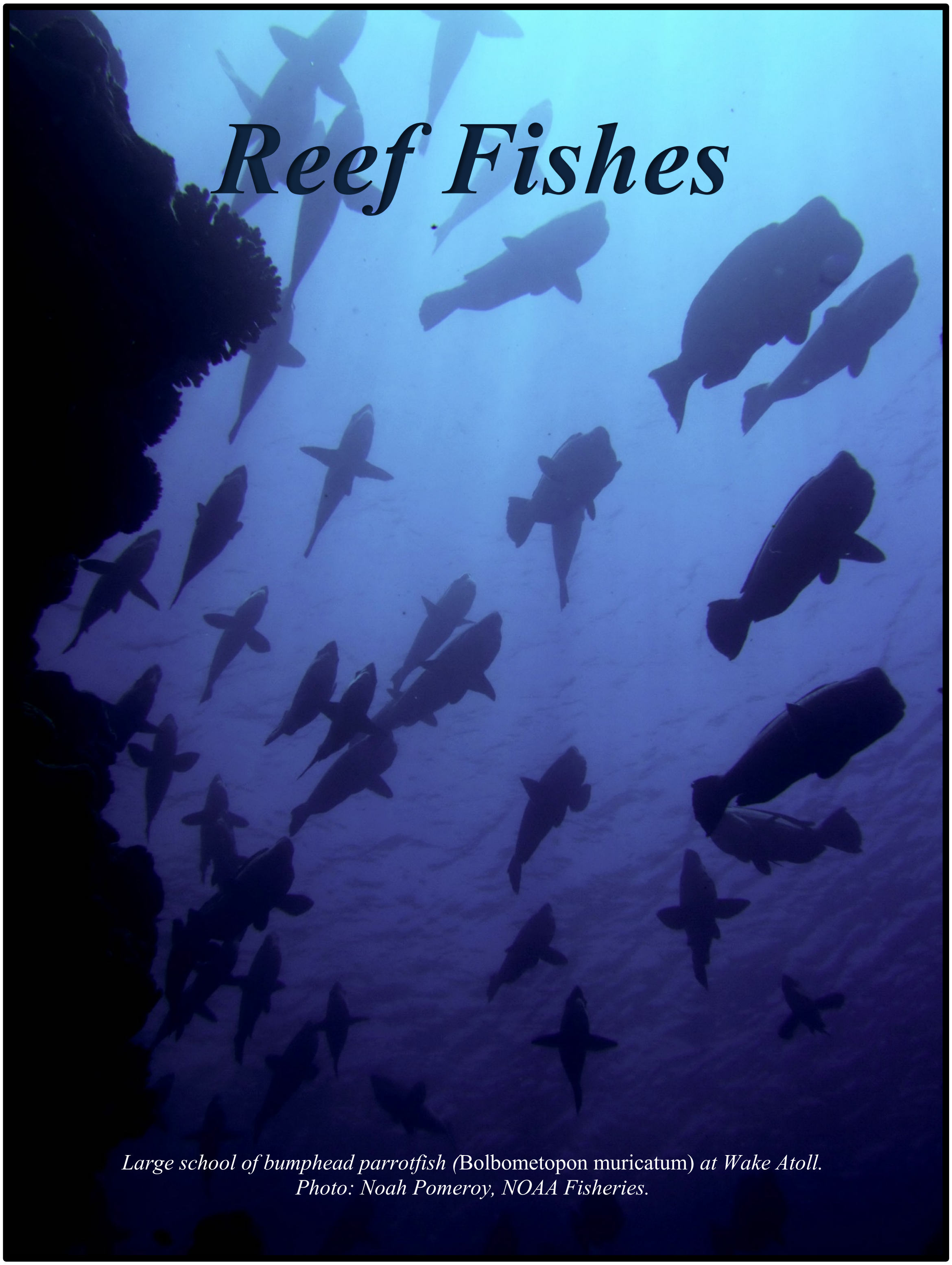


Figure 41. Microbial biomass collected on Wake Atoll in 2009 (n = 4). Cell volume is estimated based on measurements of cell length and width and cell abundances enumerated using epi-fluorescent microscopy. Biomass is reported as milligrams per cubic meter (mg $m^{-3}$). The data were published in (McDole et al. 2012).

# Reef Fishes



*Large school of bumphead parrotfish (*Bolbometopon muricatum) *at Wake Atoll.*
*Photo: Noah Pomeroy, NOAA Fisheries.*

## 5.6 Reef Fishes

*Large school of chubs at Wake Atoll.*
*Photo: Paula Ayotte, NOAA Fisheries.*

### Survey Effort and Site Information

Reef fishes were surveyed at Wake Atoll during each of the 6 survey years from 2005 through 2017 (Table 4). Reef fish surveys each year included a mix of comprehensive small-area surveys (belt-transect [BLT] or stationary point count [SPC]), and broad-scale (~2.2 km) towed-diver surveys (TDS) that focused on large-bodied fishes (>50 cm total length).

TDS have been conducted along forereefs primarily in depths between 10 and 20 m around the atoll perimeter in an approximately systematic fashion. BLT surveys, utilized between 2005 and 2009, were mostly conducted at haphazardly-located, mid-depth (~10–15 m) forereef sites, with the South, West, and Northwest georegions being more intensively surveyed than the more exposed North and East georegions (Figure 42). In 2009, Pacific RAMP initiated the transition from BLT surveys to the current SPC survey method and at the same time moved to a stratified-random sampling (StRS) survey design encompassing all hard-bottom habitats in less than 30 m water depths (Figure 42). Since that time, there have been concerted efforts to increase the number of survey sites per visit. Twenty-nine or more sites have been surveyed every visit since and including 2009, compared to 13 or fewer sites before 2009 (Table 4). One consequence of the shift in survey design is that SPC sites have been much more widely and evenly distributed around the atoll (Figure 42). BLT data gathered at the time of the transition to the stratified-random design in 2009 cannot be meaningfully compared with earlier BLT data gathered at fixed locations. Thus, the time series shown were primarily built from TDS from 2005 through 2017 for large fishes and from the SPC surveys conducted from 2009 through 2017 for all reef fishes combined.

No reef fish surveys have been conducted in the lagoon or backreef habitats at Wake Atoll as part of the Pacific RAMP (Figure 42). Due to the limited amount of survey time available at Wake Atoll each year, surveys focused on forereef habitats (i.e., the outer-reef and shelf areas that are most suitable for large-scale comparison among all islands and regions surveyed).

**Table 4. Reef fish survey effort at Wake Atoll. Data are number of surveys by year and method. Towed-diver surveys (TDS) are ~2 km long by 10 m wide transects (~20,000 m$^2$), typically in mid-depth forereef habitats in which divers counted only fishes >50 cm total length (TL). In contrast, during belt-transect (BLT) and stationary point count (SPC) surveys, divers attempted to count all fishes within small areas of reef (~350 to 600 m$^2$).**

| | All Fishes | | Large Fish (>50 cm TL) |
|---|---|---|---|
| **Year** | **BLT** | **SPC** | **TDS** |
| 2005 | 13 | – | 14 |
| 2007 | 12 | – | 16 |
| 2009 | 13 | 29 | 12 |
| 2011 | – | 30 | 14 |
| 2014 | – | 45 | 10 |
| 2017 | – | 53 | 9 |

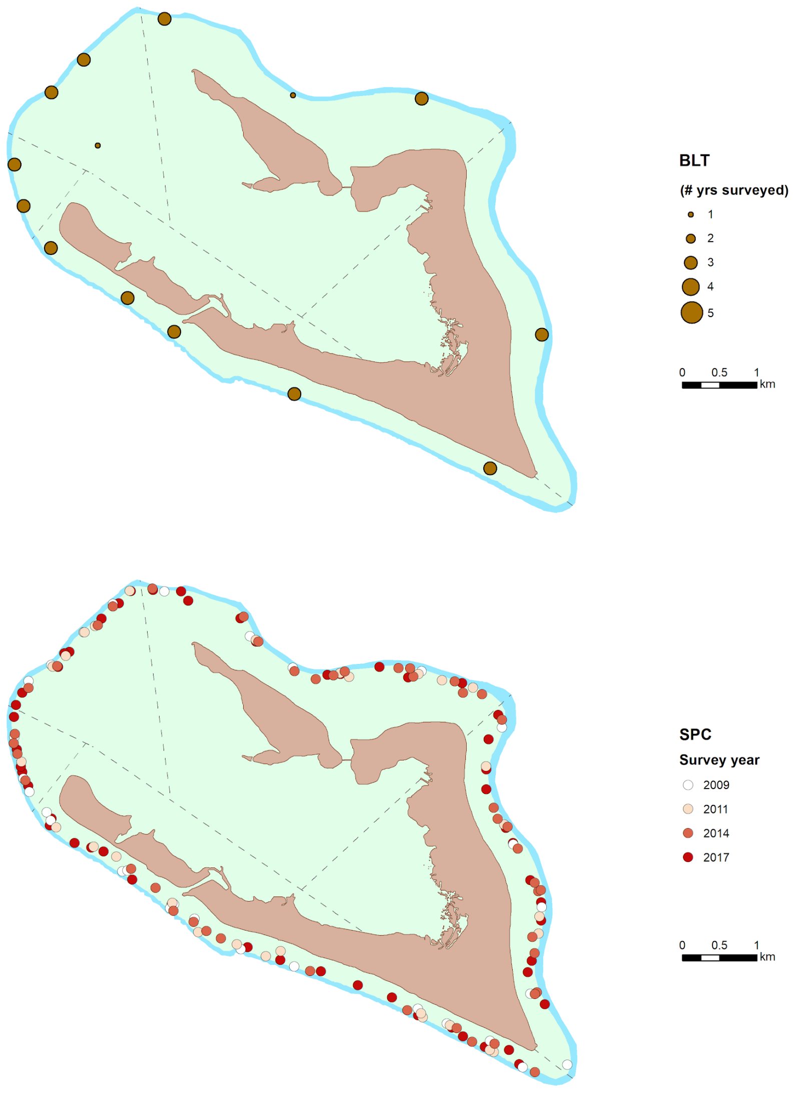


**Figure 42. Location of belt-transect (BLT) and stationary point count (SPC) sites at Wake Atoll. SPC sites were not revisited, but the year of survey is distinguished by color. BLT survey sites were generally revisited during multiple survey years. For those sites, the total number of times each was surveyed is indicated by the size of the bubble.**

## Distribution of Reef Fish Biomass and Abundance

Reef fish biomass was generally evenly distributed around Wake; however, biomass of most consumer groups tended to be higher in the West georegion (Figure 43). Particularly notable was the very high biomass of secondary consumers there—largely due to frequent observations of the corallivorous bumphead parrotfishes (*Bolbometopon muricatum*).

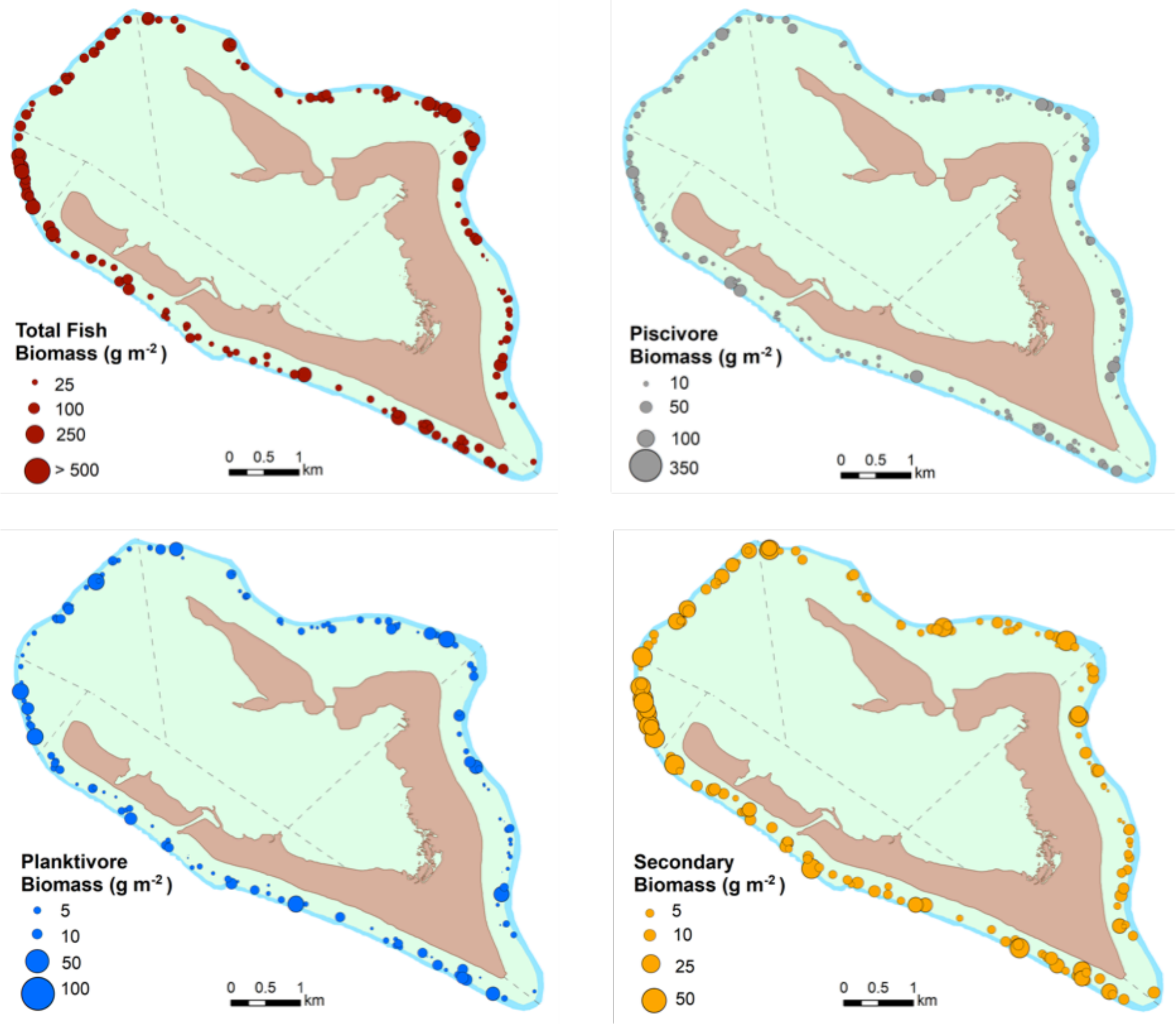


**Figure 43. Biomass maps of Total Fish, Planktivore, Piscivore and Secondary Consumer Groups from stationary point count surveys around Wake Atoll over the period 2009 through 2017. Secondary consumers include corallivores, omnivores, and invertivores, including many abundant and generally small-bodied species, as well as the bumphead parrotfish, *Bolbometopon muricatum*.**

As with several other groups, herbivorous fish biomass was relatively evenly distributed, although tended to be lower in the South georegion (Figure 44). As noted above, the bumphead parrotfish is classified as a corallivore and therefore not included in this group. Other frequently encountered parrotfish species include the tan-faced parrotfish (*Chlorurus frontalis*), the bullethead parrotfish (*C. spilurus*), and Forsten's parrotfish (*Scarus forsteni*).

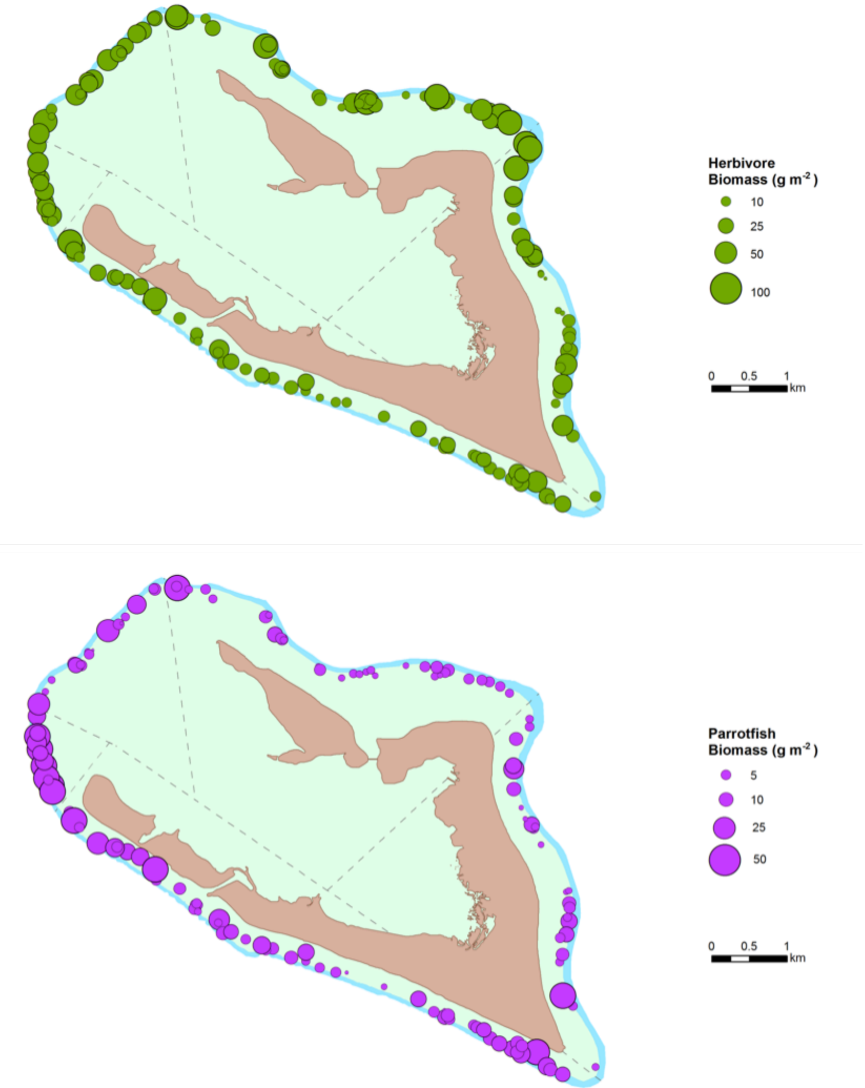


**Figure 44. Total herbivorous fish and parrotfish biomass from stationary point count surveys around Wake Atoll over the period from 2009 through 2017.**

Most sharks observed during surveys at Wake Atoll were gray reef sharks (*Carcharhinus amblyrhynchos*). Divers have also occasionally recorded whitetip reef sharks (*Triaenodon obesus*—a total of three observations during TDS), as well as a single observation of a blacktip reef shark (*Carcharhinus melanopterus*—recorded in 2014 during an SPC survey). Many of the shark observations were concentrated around a few areas—particularly the northwestern and eastern ends of the atoll, as well as a cluster around the boundary between North and East georegions (Figure 45).

More generally, large piscivores were not common around Wake Atoll during any of the 6 survey years, with biomass of this group being largely made up from occasional encounters with schools of bigeye jacks (*Caranx sexfasciatus*), more frequent observations of the bluefin trevally (*Caranx melampygus)*, as well as the most common grouper—the peacock hind (*Cephalopholis argus*).

Observations of humphead wrasses (*Cheilinus undulatus*) during TDS have been widely distributed around Wake Atoll, with no clear differences in encounter rates among georegions (Figure 45). Over the entire time period, humphead wrasses were observed on nearly 20% of all TDS segments. As noted above, bumphead parrotfishes (*Bolbometopon muricatum*) have also often been observed at Wake Atoll, sometimes in large groups. Encounters with this species have been particularly common in the West georegion (Figure 45), which appears to be their main breeding aggregation site (Muñoz et al. 2014).

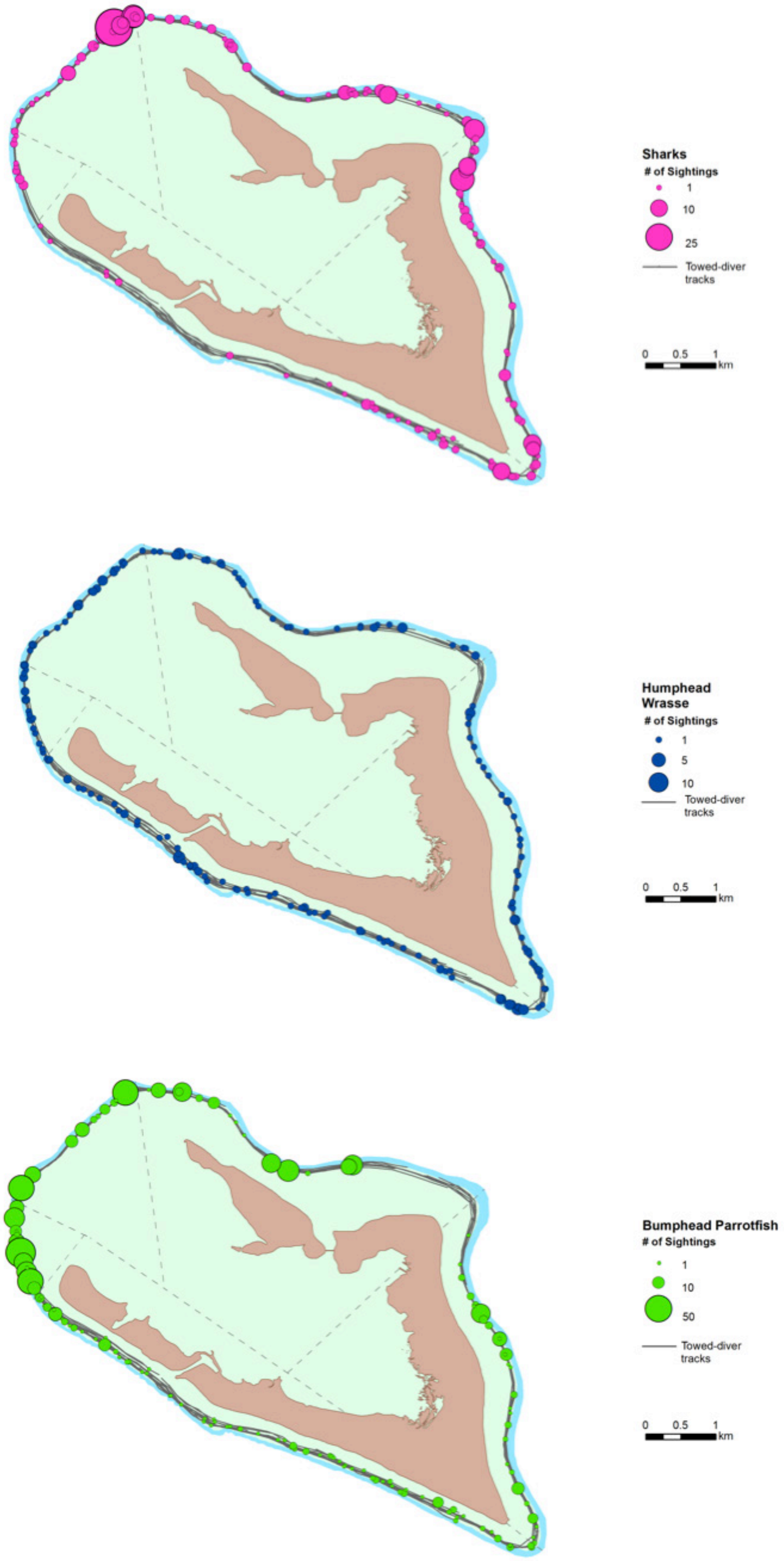


**Figure 45. Towed-diver sightings of sharks, humphead wrasse, and bumphead parrotfish from 2005 to 2017 around Wake Atoll.**

## Distribution of Other Species of Interest

During the entire survey period from 2005 through 2017, there was only one recording of a manta ray (*Mobula* sp.), which was observed during a TDS in 2014, toward the southeastern end of the South georegion (Figure 46). It is important to recognize that divers cannot readily and reliably distinguish between *Mobula birostris*, the giant Manta, which is ESA listed, and the reef manta, *Mobula alfredi*, that is not.

Over the 6 survey years, sea turtles were observed once in approximately every three TDS (each survey being approximately 2 or more km in linear distance). All observations made to species have been recorded as green turtles (*Chelonia mydas*), which are ESA listed. Sea turtles have been observed in each of the georegions, though encounters appeared to be somewhat concentrated along the West and South georegions (Figure 46).

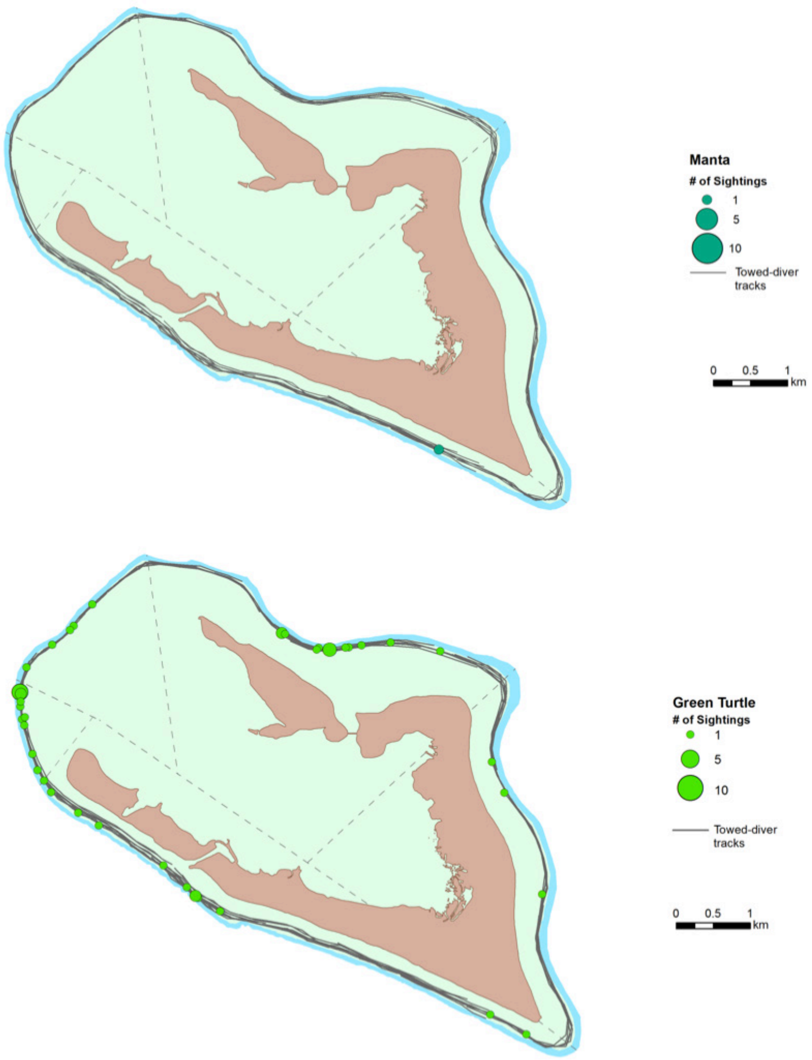


**Figure 46. Towed-diver sightings of manta rays and sea turtles at Wake Atoll during the period from 2005 through 2017. Green turtle sightings shown above include observations recorded as (unspecified) sea turtle, as all sea turtles identified to species level at Wake were green sea turtles.**

## Reef Fish Time Series

Time series of biomass of reef fishes, incorporating data from both BLT and SPC surveys, are shown in Figure 47. As is evident from the size of the confidence intervals in early years, there was insufficient sampling effort during the 2005 and 2007 survey periods to identify clear patterns—but there are no clear indications of significant changes in that earlier time period (Figure 47). Based on the increased effort with the stratified-random survey design, confidence intervals for the SPC data collected from 2009 through 2017 are much reduced and show that reef fish biomass was relatively stable over that time period (Figure 47).

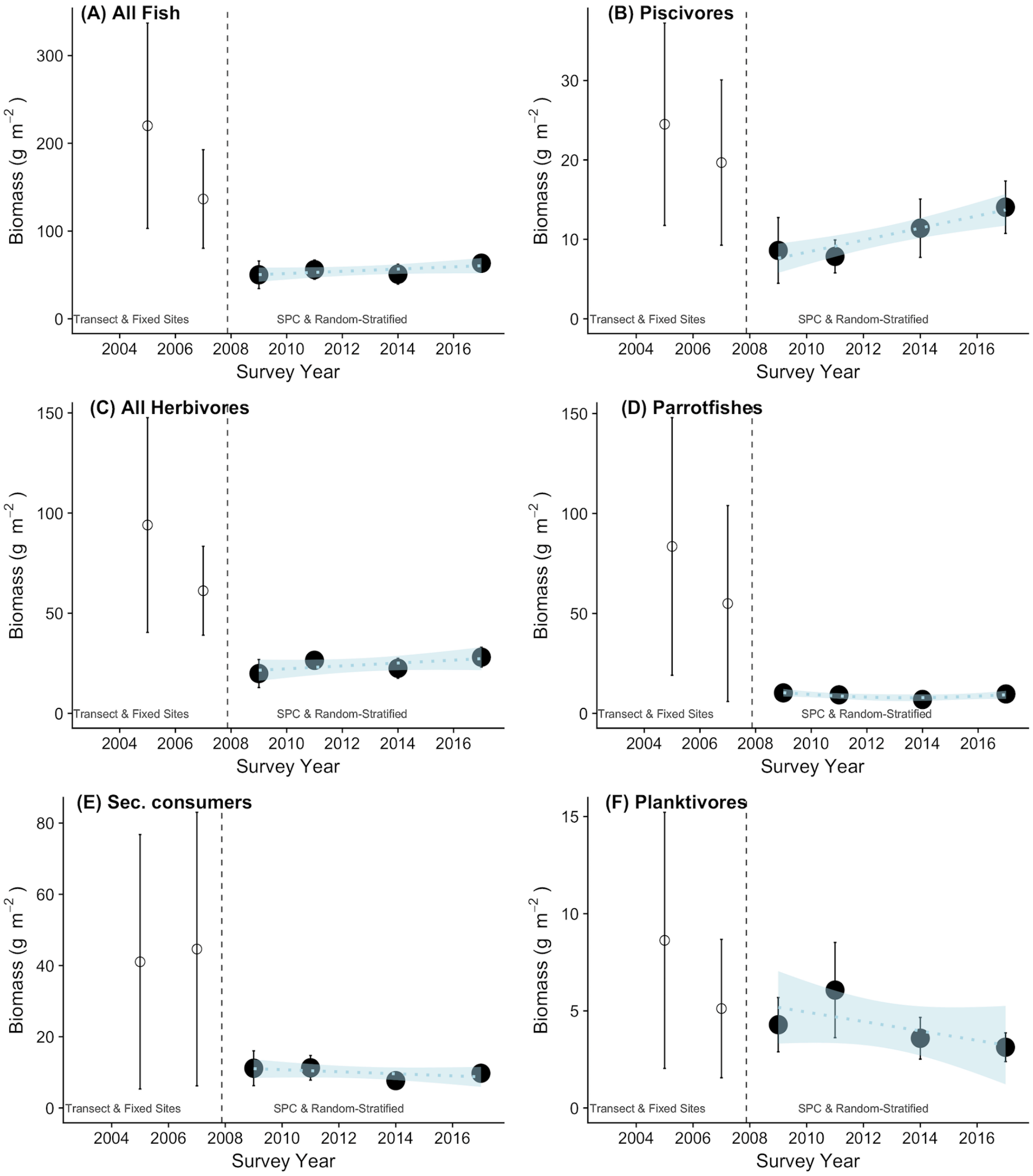


**Figure 47. Time series of reef fish biomass at Wake Atoll. Data are shown for belt-transect surveys conducted at a limited number of mid-depth forereef sites in 2005 and 2007, and stationary point count surveys (SPC) conducted at randomly located sites encompassing all hard-bottom forereef in water depths ≤30 m from 2009 through 2017. Gray circles represent mean values, and error bars represent 95% confidence intervals per time period. The light blue dotted trend lines and confidence intervals were derived from generalized additive models of biomass against survey year. Biomass values from the different periods cannot be directly compared due to differences in methods and survey locations.**

Based on TDS data from 2005 through 2017, there were no clear trends in overall reef shark abundance at Wake. The majority of jacks observed during TDS were the bigeye trevally (*Caranx sexfasciatus*), which is a schooling species that can at times be seen in very large numbers and is always highly variable in survey counts. In 2004, there were two observations in the South georegion of aggregations estimated to be between 800 and 900 individuals. As those observations were within a few days and less than 2 km apart, it is likely that those observations were of the same school. Since that time, there have been no recorded observations of any schools larger than 50 individuals, but given the extreme patchiness of this species' distribution, it is not clear whether that represents an ecologically meaningful change. With the exception of 2004, the abundance of jacks has been relatively consistent across years (Figure 48).

Counts of humphead wrasse during TDS transects were notably low in 2014 and 2017. In fact, none were recorded "on-transect" (i.e., within the 10 m wide belt that divers primarily survey) during the 9 TDS conducted in 2017 (Figure 48). Divers continued to record "off-transect" presence (i.e., they were seen in the general vicinity of the TDS in all years), but those encounters became less common. Prior to 2011, divers recorded humphead wrasse during 80–90% of TDS, but during 2014 and 2017 surveys, they were only recorded during 55% of TDS (11 of the 20 surveys). Therefore, although this species is still commonly seen around Wake, it will be important to continue to monitor their status to determine whether lower counts and encounter rates persist.

Counts of bumphead parrotfishes were also somewhat lower in 2014 and 2017 than in previous years (Figure 48). However, the high variability in counts among years, driven in part by lunar phase and the fact that they tend to be unevenly distributed spatially, indicates that high-variability and occasional low counts were not necessarily indicative of an ecologically-significant population decline. It is inherently challenging to gather robust survey data on the abundance of this species from general purpose surveys, such as the SPC and TDS. Notably, SPC divers reported regularly seeing bumphead parrotfish in the vicinity of dive sites during the 2017 surveys, including several cases in which small schools of bumphead parrotfishes were observed.

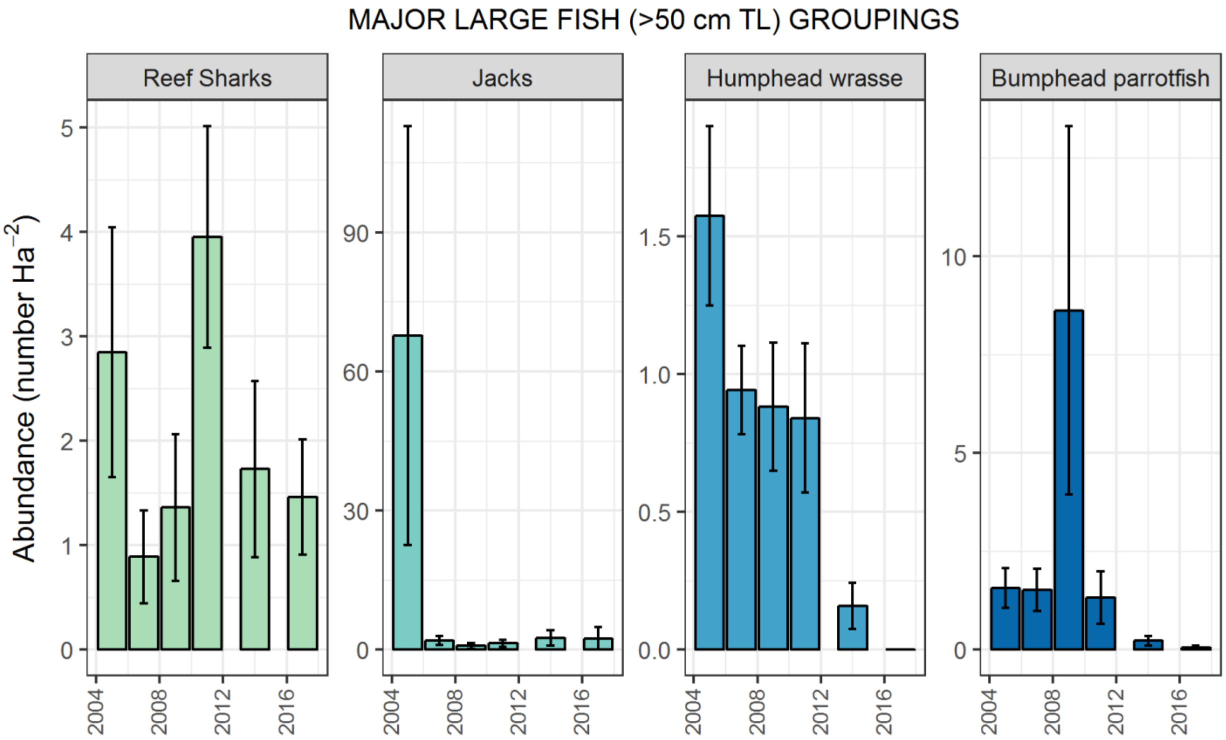


**Figure 48. Bar plots by year for reef sharks, jacks, humphead wrasse, and bumphead parrotfish at Wake Atoll from towed-diver survey (TDS) data over the period 2005 through 2017. In order to increase consistency among years, trends were derived only from TDS >500 m in length, which were conducted in forereef habitats between 10 and 20 m deep.**

## Species Lists, Encounter Rates and Diversity

Mean species richness of reef fishes around Wake was typically lower than at other islands of the PRIMNM, except for Johnston Atoll which is also located in oligotrophic waters, reflecting biogeographic differences in diversity. Over the period for which we have comparable data, 2009 through 2017, there was a slight tendency for mean richness and evenness of reef fishes to increase at Wake (Figure 49).

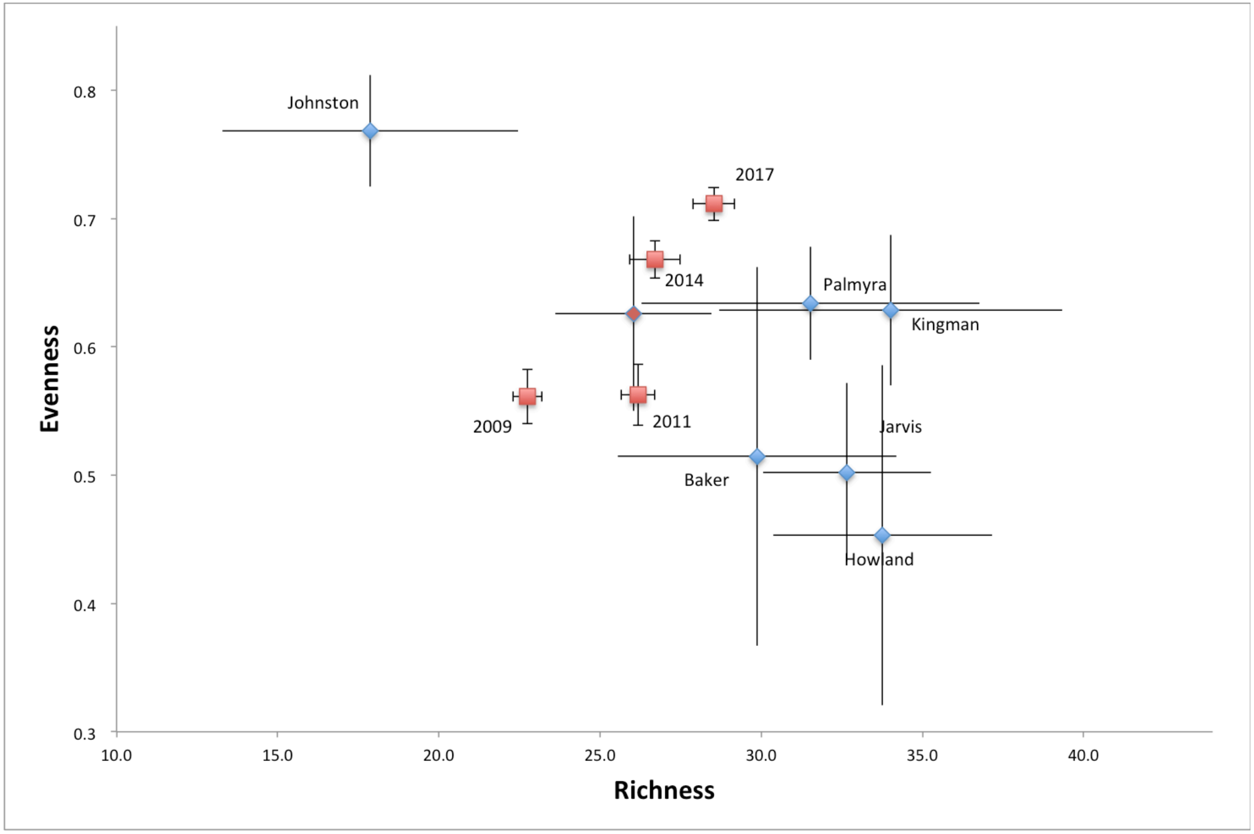


**Figure 49. Richness vs evenness of reef fish diversity at Wake Atoll. Red squares are species richness (the number of species encountered per survey) and evenness (how equally distributed the total fish abundance was among species) values (± SE) at Wake Atoll by year. Blue circles represent mean (± SD) of richness and evenness values for other islands in the Pacific Remove Islands Marine National Monument across all years. The single red dot represents the mean values of richness and evenness at Wake across all years. For consistency among locations, only data from forereef areas are included.**

As noted above, the green sea turtle (*Chelonia mydas*) are ESA listed, as are the giant Manta (*Mobula birostris*). Although divers have observed a species of manta ray at Wake, it is not possible for divers to reliably distinguish between the giant manta and the reef manta (*Mobula alfredi*) during most visual surveys. In addition, eight species of fish recorded during surveys at Wake Atoll are listed as endangered, vulnerable, or near threatened by the International Union for Conservation of Nature (IUCN) Red List, and five of those were regularly encountered by survey divers. Wake is clearly an important location for at least two of those: the humphead wrasse (*Cheilinus undulatus*) and the bumphead parrotfish (*Bolbometopon muricatum*), both of which have been regularly observed around Wake. In fact, densities of the bumphead parrotfish at Wake have been much higher than any other island or atoll surveyed by the Pacific RAMP. Other listed species regularly encountered at Wake include: the gray reef shark, *Carcharhinus amblyrhynchos*, the eagle ray, *Aetobatus narinari*, and the camouflage grouper, *Epinephelus polyphekadion*, all of which were recorded at approximately 10–20% of SPC sites surveyed in recent years. The three other IUCN-listed species observed were rarely encountered: the blacktip reef shark, *Carcharhinus melanopterus*, manta rays, *Mobula* sp. (both species of manta are IUCN listed), and the chevron butterflyfish, *Chaetodon trifascialis*. The chevron butterflyfishes are very closely associated with table *Acropora* corals and hence are highly unlikely to be encountered except where those corals are present. A complete list of fish species observed each year is given in Appendix B of “Chapter 9: Pacific Remote Islands Marine National Monument in the Pacific-wide Context.”

# Marine Debris

*Shipwreck at Wake Atoll.*
*Photo: Rebecca Weible, NOAA Fisheries.*

## 5.7 Marine Debris

Marine debris was noted sporadically at Wake Atoll during TDS conducted between 2007 and 2011 (Figure 50). A total of 73 observations of marine debris of various forms were recorded during benthic TDS. As debris is not always recorded during surveys and because surveys do not completely cover all reef areas, these observations do not constitute all debris around Wake Atoll. It is also important to realize that several observations in consecutive years are in some cases likely to be the same debris. Nets made up the majority of the debris sightings in 2007, line dominated in 2009, and a variety of debris types were sighted in 2011.

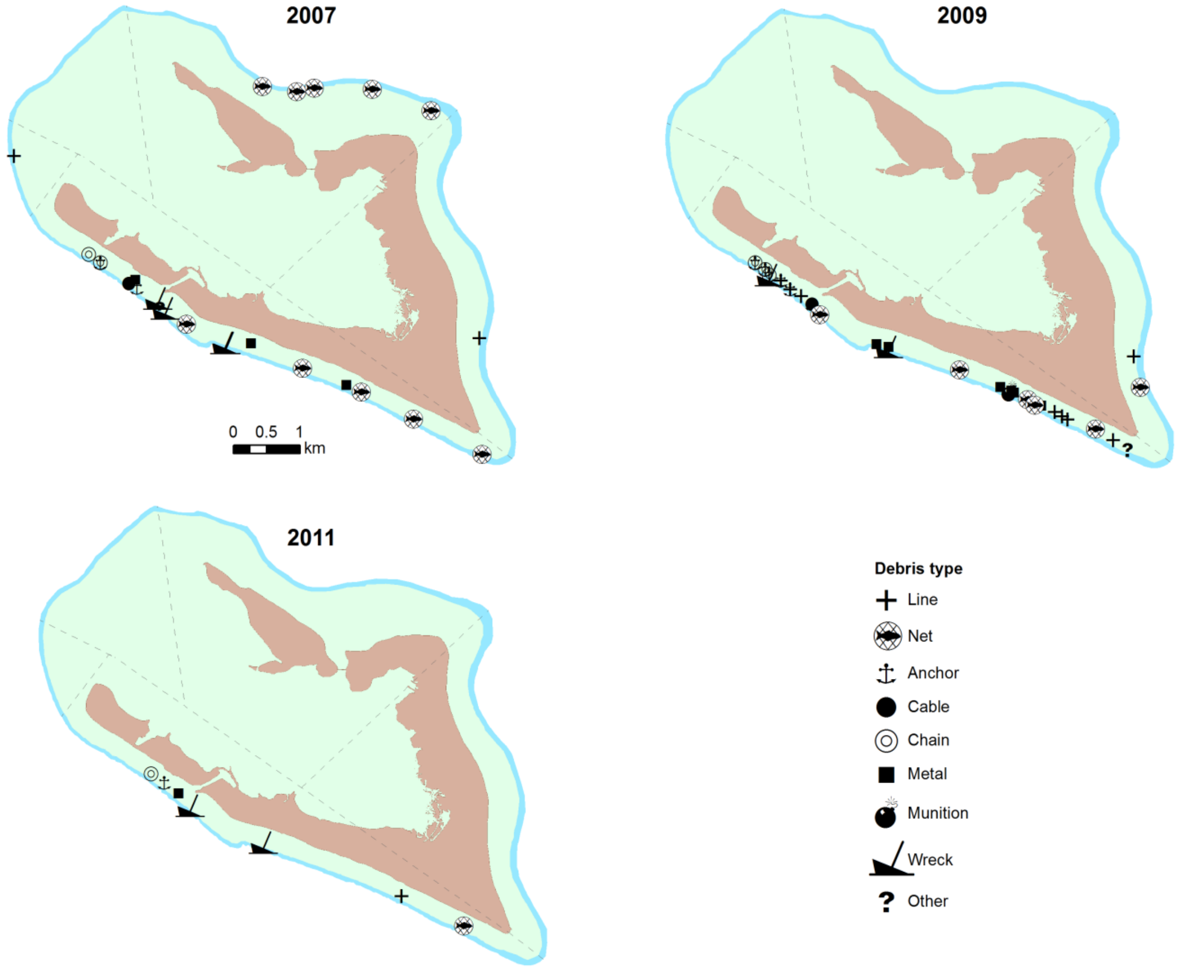


**Figure 50. Marine debris sightings. Line, net, anchors, chain, metal, wrecks, and miscellaneous debris found around Wake Atoll from 2007 to 2011.**

*A healthy coral reefscape at Wake Atoll.*
*Photo: Tate Wester, NOAA Fisheries.*

# *Ecosystem Integration*

## 5.8 Ecosystem Integration

*Photos left to right at Wake Atoll: Aerial view of Wilkes Island, Wake Atoll. Photo: Capt. Anastasia Schmidt, Joint Base Elmendorf-Richardson; human impacted reef outside small boat harbor, followed by unimpacted forereef in West georegion, Photos: Bernardo Vargas-Angel, NOAA Fisheries; free-diver deploys oceanographic instrument, and a school of bumphead parrotfishes* (Bolbometopon muricatum) *swim together at Wake Island, Photos: NOAA Fisheries.*

### Oceanic Drivers of Benthic and Fish Populations

Due to its location far north of the equator in the western Pacific Ocean, Wake Atoll is largely removed from the extreme ENSO-related interannual variability in ocean conditions observed in the more equatorial islands of the PRIMNM. As a result, thermal anomalies and enrichment of nutrients in surface waters typically linked with El Niño events were somewhat muted (when discernible) at Wake. On the other hand, this more northerly location does place Wake in the path of tropical cyclones; such disturbances can cause fragmentation and damage to corals, and leave altered reefs in their wake. Indeed, although the forereef was disease-free and supported a diverse community of microbes, the benthic community at Wake was dominated by non-calcified organisms, namely turf algae and fleshy macroalgae (~60% of the observed benthic cover), and notably low abundances of CCA compared to the other islands of the PRIMNM. The extent to which hurricanes have influenced and shaped Wake's benthic community through time remains unclear; low occurrence of calcified organisms could also be related to the predominantly oligotrophic waters surrounding Wake, direct and indirect impacts of historical human activity, and/or the observed carbonate accretion rates, which were much lower than expected given the high aragonite saturation states measured at Wake.

Nonetheless, hard corals that were present at Wake Atoll appeared capable of recovering from acute disturbances, as suggested by surveys conducted following Typhoon Ioke that passed directly over Wake Atoll in August 2006 as a category 5 system; however, recovery has not been uniform across all georegions (see below for further detail). The forereef at Wake has also been exposed to periods of thermal anomalies, most notably during thermal events in 2008 and 2011, but subsurface measurements of water temperature revealed these reefs have yet to experience extensive thermal stress that would be associated with major bleaching events. Indeed, across survey years, the composition of benthic assemblages have remained relatively constant at Wake.

Given the characteristically low oceanic productivity at Wake Atoll, it was perhaps unsurprising the biomass of planktivorous and piscivorous fishes were consistently low through time. An exception to this trend was a slight increase in productivity in 2010, after which there was some indication of an increase in planktivore biomass in 2011. Only one sighting of a manta ray

(*Mobula* sp.), the largest of the planktivores sighted across the PRIMNM, was reported over the extent of survey effort from 2005 through 2017, which may have been an individual of the ESA-listed *M. birostris*. The isolation and low oceanic productivity of Wake may have been limiting for planktonic larval dispersal, development, and settlement of the crown-of-thorns sea star (Fabricius et al. 2010), which was sighted only once in 2005 and has remained absent during all other survey years.

Lastly, tracking patterns in abundance of the humphead wrasse (*Cheilinus undulatus*) through time remains a priority at Wake Atoll given that this location typically maintains the highest densities of this endangered fish species (Zgliczynski et al. 2013).

## Spatial Variation within the Atoll

Prominent swell from the northern and eastern directions results in a major distinction among georegions between wave-exposed (Northwest, North, and East georegions) and more protected environments (West and South georegions) at Wake Atoll. Some key macroinvertebrates appeared to be spatially distributed according to this variance in wave exposure. For example, giant clams were consistently recorded throughout the wave-exposed areas of forereef in the Northwest and North georegions, whereas sea cucumbers tended to be sighted along the wave-protected forereef of the South georegion with only moderate numbers of sightings in the neighboring West and East georegions. Sightings of the ESA-listed green sea turtle (*Chelonia mydas*) also appeared to be somewhat concentrated along the protected West and South georegions.

Benthic communities in the South and East georegions were typically characterized by declining coral cover and reef conditions typically considered less healthy, consisting of a combination of low coral and high algal cover. In contrast, the remaining georegions sustained relatively greater abundances of CCA, encrusting macroalgae, and hard corals, as well as lower cover of turf algae. Further, these reefs tended to exhibit localized increases in coral cover over the course of the Pacific RAMP surveys, with a statistically significant increase evident in the North georegion in the years following Typhoon Ioke (2007–2017). The apparent differences in benthic communities among georegions could be artifacts of historical human impacts on Wake Atoll from decades of human use for military-related purposes, particularly along areas of forereef adjacent to the airport runway and boat harbor in the South and East georegions. Measured accretion rates were also noticeably higher in georegions that also tended to have higher abundances of calcifying organisms. Patterns in herbivorous fish biomass also appeared to correspond somewhat with patterns in benthic cover. Importantly, these potential underlying drivers discussed may not be mutually exclusive in structuring the forereef communities of Wake, yet the relative influence of these factors remains unknown.

Encounter rates with reef sharks were notably highest near promontories of Wake Atoll, which was not surprising given that most of these sightings were of gray reef sharks (*Carcharhinus amblyrhynchos*) that are known to be associated with high-current habitats near deeper water (Richards et al. 2012). During some survey periods, large numbers of bumphead parrotfishes were observed in a concentrated area mostly in the West georegion. This pattern was likely related to spawning activity that regularly occurs at certain points in the lunar cycle (Muñoz et al. 2014). It remains unclear why that specific area is an important breeding site, but it is the only such area that has been identified from the Pacific RAMP surveys and researchers studying the spawning patterns of this species at Wake (Muñoz et al. 2014).

## 5.9 References

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