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Predicting extreme tide events to inform shallow reef community restoration and management in Guam

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Predicting extreme tide events to inform shallow reef community restoration and management in Guam

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Executive Summary

Predicting extreme tide events to inform shallow reef community restoration and management in Guam

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Introduction – This study builds on previous research and management efforts to develop a comprehensive region-wide management and restoration approach for sensitive and critical fish habitat on shallow reef flats. These habitats have precipitously declined over recent years from annual coral mass mortality events. Ocean warming-induced bleaching and ENSO-related extreme low-stand tidal events (particularly in 2015) have decimated staghorn *Acropora* and caused significant mortality in other dominant genera and species, including the ESA-listed species *A. globiceps*. A management plan for remaining populations involves investigating the environmental attributes contributing to survival at sites with remaining populations, analyzing biotic factors contributing to resilience and recovery, and restoration using ocean nursery culture and reestablishment. To support these initiatives, this project has applied a novel approach to a high-tide flooding model, using existing data from the Guam Apra Harbor station tide gauge to develop a spatially explicit model to predict the frequency of low-stand events. These data were calibrated to ground-truthed tidal measurements from 18 sites around Guam that have seen significant recent coral mortality from extreme low tide events or were strategically selected to give geographic representation around the island. Assessment surveys at these sites were undertaken to evaluate mortality, providing an additional longitudinal reference point for the sites that were already within monitoring programs. This information will help guide the selection of restoration sites, and identify both sites at future risk and those with greater refuge from low-stand events that could benefit from increased management. We also see a future application of the results of this study in forecasting of such events in Guam, CNMI, and American Samoa that have also experienced recent mass mortality.

Objectives

Objective 1. Reassessing extent and condition of the important fish habitat-forming staghorn *Acropora* populations around Guam.

Objective 2. Quantifying local tide levels at staghorn sites around Guam, adding additional sites to achieve greater geographic representation, and cross-calibrating the Apra Harbor station tide gauge measurements with these spatially-explicit measurements.

Objective 3. Constructing a predictive model for historical extreme tide excursion impacts at the staghorn sites around Guam.

Results – *Objective 1*. All reassessed sites showed reductions in staghorn coral cover by 29-100% from pre-2013 estimates. However, many sites had evidence of recovery through colonization on dead skeleton (tissue re-sheeting), both by staghorn *Acropora* and other coral taxa. The notable loss of taxonomic diversity among staghorn *Acropora* species across the sites suggests risk of extirpation of some species.

Objective 2. Local tide levels were measured through field-deployment of depth loggers at 18 sites around Guam. Values were regressed against Apra Harbor tide gauge measurements, showing a moderate to very high degree of correlation that enabled cross-referencing of the long-term gauge with localized conditions. At low-water, depth data from several sites diverged from the expected relationship with the tide gauge during periods of lower tides, which is proposed to be due to restricted flow in areas of high reef complexity.

Objective 3. Using the identified relationships between the tide gauge and each logger site, a predictive model of past low-water events was established for the 22-year period, 1996-2017. Low-water events occurred less often in the latter half of the period (4% of the time) than the former (5%), likely due in part to recorded sea level rise. However, the latter period had a 15% greater proportion of those events occurring in early afternoon times – when solar irradiance is typically highest and thus causes the greatest ecological impact – than across the full day; in contrast, the proportion of events in the afternoon during the earlier period was slightly less than the full-day proportion. The notable exception was 2015 in which an average of 35% of low-water events occurred in early afternoons. Vulnerability to subaerial exposure was assessed as high for two sites and low for nine of the 18 sites (Figure ES1).

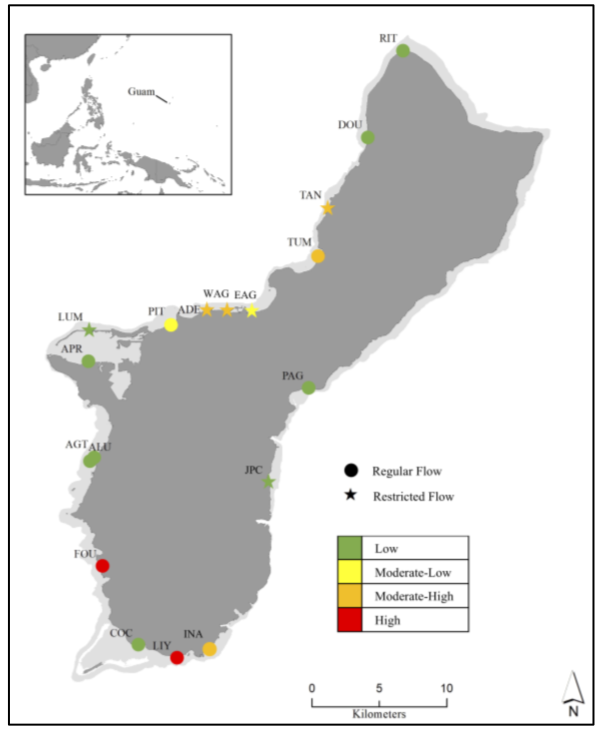

Figure ES1. Predicted vulnerability to subaerial exposure for 18 sites around Guam.

<u>Next Steps</u> – While global sea level rise will generally increase local sea level, ENSO variability is predicted to increase low-stand events in Guam by as much as 100% over historical frequencies. The analysis presented here is useful for coral restoration design in Guam to inform optimal depths and desired reef complexity for transplantation activities. This study has demonstrated a method that can be applied to other Pacific reef regions affected by extreme low-stand tide events, including American Samoa and CNMI (notably Saipan), which have experienced similar significant recent coral loss.

<u>Site summaries</u> – This report concludes with one-page summaries for each survey site that present: the site name, code, and assessed vulnerability; location and benthic habitat map; reef photograph and brief description; depth time-series and comparison of site and Apra Harbor tide gauge depths; description of factors affecting subaerial exposure; and a supporting data table.

<u>Acknowledgments</u> – Financial support for this applied research was provided by a grant from the NOAA Coral Reef Conservation Program to Raymundo and Burdick. Resources were also provided in support of the fieldwork and project staff from the University of Guam Marine Laboratory. The contents of this report are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of NOAA or the U.S. Government.

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Introduction

Guam's shallow back reef and reef flat environments provide important fish habitats critical to the island's ecology and economy. They have become increasingly important to coral reef health and island sustainability in recent years, principally due to the continued decline of deeper fore reef communities from repeated Crown-of-Thorns starfish outbreaks and the growing importance of tourism to the island's economy (Birkeland and Lucas 1990; van Beukering et al. 2007; Burdick et al. 2008). However, shallow reef communities have precipitously declined in recent years due to annual mass mortality events. A combination of ocean warming-induced bleaching and ENSO-related extreme low-stand tide events caused significant mortality in species of staghorn *Acropora* and other dominant coral genera (*Porites*, *Pocillopora*, and *Pavona)* associated with staghorn habitats. 2013 brought the most extensive regional mass bleaching event ever recorded occurred, affecting 85% of species in Guam and the Commonwealth of the Northern Mariana Islands (CNMI; Reynolds et al. 2014; L. Johnston, pers. comm.). This was followed by another bleaching event beginning six months later, principally affecting shallow staghorn populations. ENSO-related extreme low-stand tide events occurred in 2015, extending through the year and causing shallow reef communities to be subaerially exposed for several afternoon hours on successive days each month (see Figure 1). These combined events resulted in the loss of 53% of staghorn populations over this three-year period (Raymundo et al. 2017). These events were immediately followed by two consecutive years of heat stress and associated bleaching.

Climate change is creating a new environmental paradigm wherein sessile benthic communities must either adjust (acclimate and adapt) to new regimes of sea surface temperature, seasonality, and extreme event frequency, duration and severity, or become extirpated or extinct. How species and populations respond to these events, their genetically-based ability to acclimate and adapt, and the role of local environmental variability in their acclimatization are topics of current local and global research focus. Such information is critical to the formulation of adaptive management and restoration strategies.

Figure 1. Exposed *Acropora* cf. *pulchra* on Guam, during an extreme low tide event in 2015. Photo: V. Lapacek

This project has provided managers and community members with a better understanding of extreme tide excursions including spatially-explicit information for specific reef flat communities around Guam. The model employed is adapted from one used to predict high-tide (or nuisance) events (Sweet and Park 2014), using similar principles for extreme low tide excursions that negatively impact shallow water coral communities. Based on this analysis, the methodology has been demonstrated as applicable to other sites in the Pacific region, such as American Samoa and the Saipan Lagoon in CNMI (which includes the Mañagaha Marine Conservation Area), both of which have experienced similar significant recent coral loss.

Study Objectives

Objective 1. Reassessing mortality and recovery (i.e., current extent and condition) of the important fish habitat-forming staghorn *Acropora* populations around Guam.

Objective 2. Quantifying local tide levels at staghorn and other shallow reef sites around Guam, and cross-calibrating the Apra Harbor station tidal measurements with these spatially-explicit measurements.

Objective 3. Constructing a predictive model for historical extreme tide excursion impacts at the staghorn sites around Guam.

Methods

Field sites were selected at shallow staghorn *Acropora* populations previously surveyed in 2015, many of which had shown severe impact (Raymundo et al. 2017). Additional non-*Acropora* sites were selected from those previously surveyed during other projects (Raymundo et al. 2018), to provide more complete geographic representation around Guam. Specific note was taken where remnant scarring of corals was present from subaerial exposure in 2015. Loggers were installed at sites to monitor tidal variation, typically over five weeks to encompass a lunar month, for comparison with the long-term tide gauge located in Apra Harbor. While unlikely to include low-stand events, this procedure will identify the relationship for the majority of conditions including spring low tides. By establishing relationships between the tide gauge and each logger, predictions of past likelihood of subaerial exposure were determined from the historical tide gauge data (since 1996) using critical depth thresholds determined for each site. Detailed methods for each study objective are described below.

Objective 1. Reassessing mortality and recovery of staghorn populations

A total of 21 populations of staghorn *Acropora* were originally surveyed in 2015, in response to anecdotal reports of significant bleaching mortality from two sea surface warming events in July-October 2013 and May-June 2014. Extreme low tides were first observed in late-2014 and extended through 2016. Those first surveys were intended to be rapid, semi-quantitative assessments of mortality based on accumulated data collected by D. Burdick on georeferenced spatial extent; results were summarized in Raymundo et al. (2017). From our 2015 data, we estimated a total reduction in staghorn populations of 53 ± 10% (from pre-2013 levels).

To update knowledge of condition and extent of remaining populations, assuming some recovery (and possible additional mortality) had occurred, previously surveyed populations were revisited as the first objective of this project. Multiple 0.25 m^2 quadrats, spaced 2 m apart, were assessed along transects bisecting staghorn thickets, with the number of transects determined by the size of the thicket. Thickets 20 m in diameter and smaller were assessed via two transects perpendicular to each other; with the longer transect laid along the maximum diameter axis. Larger thickets were assessed along four transects, with two parallel transects laid along the maximum diameter and two laid perpendicular to maximum. Within each quadrat, 16 points were assessed for species identification; live vs. dead coral; presence of disease, bleaching, and predation; and disintegration of dead skeleton to rubble (as a subset of dead coral). Non-staghorn corals recruiting to dead skeleton were also noted but were not counted in the total number of live staghorn points. The percent of each of category of condition (live/dead) was then calculated per species and the percent of species contribution to the entire thicket was likewise calculated. The amount of dead skeleton weathered to rubble was a separate indication of the ability of the site to recover, as rubble substrates tend to persist, creating an altered community state (Raymundo et al. 2007).

We identified areas where communities have shown a positive recovery trajectory in contrast to those where populations had continued decline or showed no recovery. To do this, we compared historical coral cover based on georeferenced spatial cover calculations from 2005-2010 (Raymundo et al. 2017) and estimates from 2015. Both bleaching and predation are associated with increased susceptibility to disease (Miller et al. 2006; Palmer et al. 2010; Page and Willis 2007; Nugues and Bak 2009; Raymundo et al. 2017). As partial mortality from subaerial exposure also compromises the coral tissue, disease outbreaks may also follow low-water events.

Objective 2. Quantifying local tide levels

Logger sites at or near historically surveyed reefs were preferred but some had to be located elsewhere due to operational logistics (e.g., inappropriate for deployment, safety considerations), which resulted in some tide loggers deployed in water deeper than that of the surveys. Hobo® water level data loggers (U20L-01 model) were deployed at each site for a five-week period to obtain data over a complete lunar cycle. Loggers were programmed to record pressure (for conversion to depth) every six minutes to match the sampling frequency of the Apra Harbor tide gauge. Loggers were secured using zip ties through the logger mounting hole either on stakes adjacent to corals or to the base of coral stands, and were visited each week to check their positioning. As we had seven loggers, deployments of six were staggered through the project period, with the seventh logger reserved for cross-calibration. Loggers were also cross-calibrated between deployments (by immersion together for one day) to ensure consistency across the measurements.

Key thresholds for low-water exposure within local reef populations were determined by recording the depths of any remnant scars from previous subaerial exposure (i.e., in 2015), as well as the current height of the coral stand. Logger depths were compared with Apra tide gauge data to test for linear relationships, which enabled referencing of the key depth thresholds to the long-term (gauge) data. Notably, phase lags were identified and adjusted for, and periods of inclement weather (which influenced logger depths but not gauge depths, as the gauge design serves to insulate from weather events) were excluded from the linear regression calculation.

Conversion of logger pressure, *p*, to depth, *d*, was undertaken using a formula reported in Fofonoff and Millard (1983) and considered an industry standard (e.g., http://seabird.com/document/an69-conversion-pressure-depth):

$$d = \frac{-1.82 \times 10^{-15} p^4 + 2.279 \times 10^{-10} p^3 - 2.2512 \times 10^{-5} p^2 + 9.72659 p}{g},$$

where

$$g = 9.780318 * [1 + 5.2788 \times 10^{-3} x + 2.36 \times 10^{-5} x^2] + 1.092 \times 10^{-6} p; \text{ and}$$

$$x = \sin^2\left[\frac{\phi}{57.29578}\right],$$

for depth in meters, pressure in decibars, and latitude (ϕ) in degrees.

Objective 3. Predicting historical extreme tides

High-tide flooding is an established high-water corollary to the low-water events investigated here, and occurs when locally high tidal water results in localized impacts (Sweet et al. 2014). We used the Apra Harbor tide gauge data for the period 1996-2017 and applied techniques similar to those used for high-tide flooding events to examine low-water events. Site-specific thresholds were related to the tide gauge data via the determined linear regressions. The historical record was used to determine past frequency of low-water events at sites around Guam to identify locations at the greatest potential risk to future tidal exposure.

Results

Objective 1. Reassessing mortality and recovery of staghorn populations

Dead coral cover ranged 29–100% across the 21 sites resurveyed (Figure 2), with pre-2013 areal extent estimates providing a basis for assessing the current condition and loss within these populations. While no quantitative assessments of percent cover were undertaken prior to the 2013-2017 bleaching and exposure events, snorkel observations made during the original mapping indicated all of these populations were healthy and dominated by living coral (Burdick, D. pers. obs.) As the survey methods were more quantitative in 2017 than for the rapid surveys undertaken in 2015, direct comparisons could not be made between the two censuses. Across all sites, mean percent dead coral was 60.2 ± 18.2% (SD). Two sites were devoid of living staghorn, reduced to dead skeleton or rubble piles; three showed >70% dead skeleton, while five populations showed >50% live cover (Table 1). Percent live staghorn coral in 2017 ranged from 0 to 71.2%, with a mean of 39.5 ± 18.5%. Approximately half of the sites contained little to no rubble; dead skeletons were predominantly intact, though weathered. At other sites, rubble constituted <16%, suggesting that dead skeleton will continue to provide substrate for new recruits at most sites.

The most extensive mortality occurred in Alutom Island (ALT), a large population of *A.* cf. *pulchra* (Table 1), where we observed no live staghorn in either late 2014 or in 2017. The cause of mortality at this site was not directly observed as it was not regularly monitored. It is located at the seaward margin of an extensive shallow reef flat, exposed to wave energy and thus well-flushed. As we noted that other sites with similar flushing did not experience extensive mortality during bleaching events, we concluded that the complete mortality experienced by this large reef-crest population was most likely to subaerial exposure. The 2014 survey noted no live coral but intact skeletons; the 2017 survey noted a large amount of rubble and algae (estimated at >50%) (Figure 3). Wave energy and bioerosion likely broke the intact skeletons down into rubble.

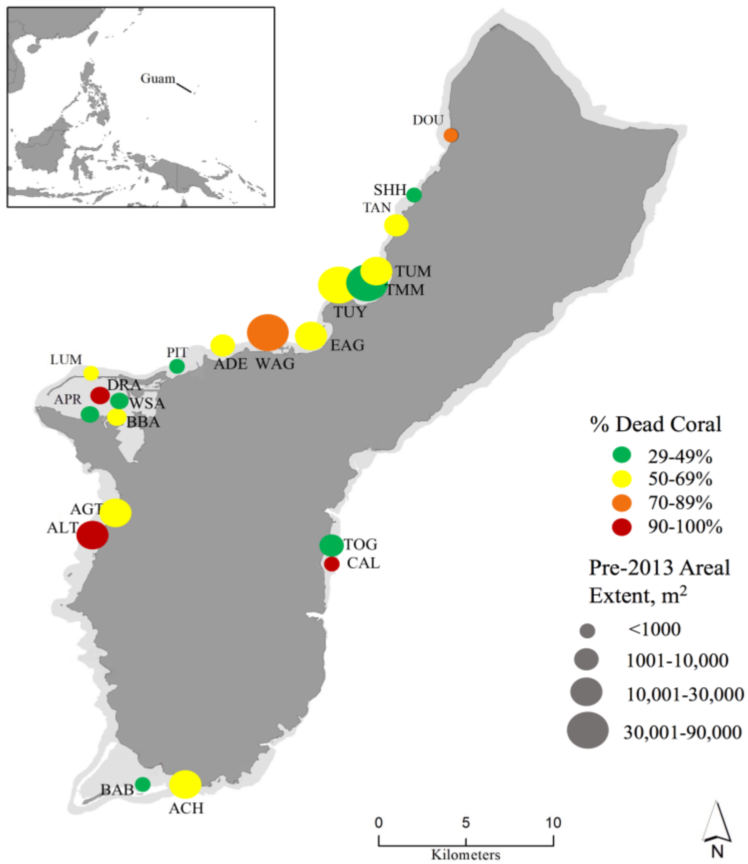

Figure 2. Location of Guam's staghorn *Acropora* populations resurveyed in 2017. Percent dead coral determined from replicate quadrats at each site and pre-2013 areal extent reported in Raymundo et al. (2017). Site Codes are listed in Table 1, for reference.

Figure 3. Dead staghorn at Alutom Island showing intact skeleton in 2014 and rubble and algae 2017, after mass mortality with no recovery. Photos by D. Burdick (2014) and L. Raymundo (2017).

Table 1. Results of the 2017 survey of the condition and species composition of all known staghorn *Acropora* populations in Guam.

Staghorn *Acropora* site	**Site codes**	***Acropora* species present**	**Pre-2013 areal extent, m²**	**2017 mean % live coral**	**2017 mean % rubble**
Double Reef	DOU	*A. austera, A. acuminata*	234	23.7 ± 30.9	0.7 ± 8.6
Sharks Hole	SHH	*A. austera, A. acuminata*	6,523	54.7 ± 22.6	0
Tanguisson	TAN	*A.* cf. *pulchra*		30.6 ± 35.0	1.1 ± 9.7
Tumon Outrigger	TUM	*A.* cf. *pulchra, A. acuminata*	19,939	33.4 ± 27.4	0.4 ± 3.7
Tumon Matapang	TMM	*A. cf. pulchra*	53,601	52.4 ± 25.1	15.1 ± 26.8
Tumon Ypao	TUY	*A.* cf. *pulchra, A. muricata*	77,883	36.2 ± 33.1	1.8 ± 11.0
East Agaña	EAG	*A.* cf. *pulchra*	27,952	47.2 ± 26.3	14.3 ± 33.1
West Agaña	WAG	*A.* cf. *pulchra*	64,372	28.8 ± 31.3	8.2 ± 25.5
Adelup	ADE	*A.* cf. *pulchra*	3,221	40.2 ± 36.2	0
Piti Bomb Holes	PIT	*A.* cf. *pulchra, A. muricata, A. teres*	485	58.9 ± 39.0	0
Luminao	LUM	*A* cf. *pulchra, A muricata*	890	40.9 ± 32.8	0
Big Blue, Apra	BBA	*A. muricata*	809	44.6 ± 34.3	0
Gabgab, Apra	APR	*A. austera*	391	71.2 ± 17.1	0
Western Shoals, Apra	WSA	*A. muricata, A. acuminata*	435	64.2 ± 26.4	0
Dogleg Reef, Apra	DRA	*A. virgata*	13	8.3 ± 9.5	0
Agat Cemetery	AGT	*A.* cf. *pulchra, A. muricata*	24,488	38.3 ± 27.5	1.5 ± 10.5
Alutom Island*	ALT	*A.* cf. *pulchra*	24,652	0	>50% est.
Babi Island, Cocos	BAB	*A.* cf. *pulchra*	250	71.2 ± 11.4	0
Achang	ACH	*A. aspera*	21,338	38.6 ± 36.6	0.2 ± 1.1
Togcha	TOG	*A.* cf. *pulchra*	5,035	64.0 ± 45.7	0
Calvo Beach*	CAL	*A.* cf. *pulchra*	75	0	>50% est.

**Quadrats were not undertaken at these sites in 2017 after systematic searches revealed no live cover. The amount of rubble was visually estimated to be greater than half of the size of the entire thicket.*

Signs of reef recovery in many sites were visible within extensive areas of dead skeleton as tissue resheeting (a probable "phoenix effect"; Roff et al. 2014; Figure 4A). In addition, coral juveniles from the genera *Porites, Pavona,* and *Pocillopora* were observed at several sites, recruiting to dead skeleton (Figure 4B). Larger thickets had healthy growth around their margins, with extensive dead patches in the middle, suggesting that water motion around the thicket fringes increased survival during warming and exposure events (Fifer et al., in review). A follow-up assessment of these sites using this method is planned for late-2020, which will allow a comparison of population conditions with those of the 2017 evaluation. This will quantify recovery vs. continued decline and identify populations showing greater resilience compared with those at risk.

Species composition suggests that there may be several species at risk of extirpation from Guam. *Acropora* cf. *pulchra* was the dominant species, comprising 83.4% of thickets in 14 of the 21 sites, while three other species (*A. acuminata, A. muricata,* and *A. austera*) were less common but found in more than one site. Three further species (*A. aspera, A. teres, A. virgata*) were limited to one site each, though small patches of *A. teres* were found at a second site after 2017 surveys (Table 2). The reduction in population size of these three species puts them at risk of local extinction. *A. vaughani* has not been observed since at least 2013 and may be extirpated (Raymundo et al. 2017).

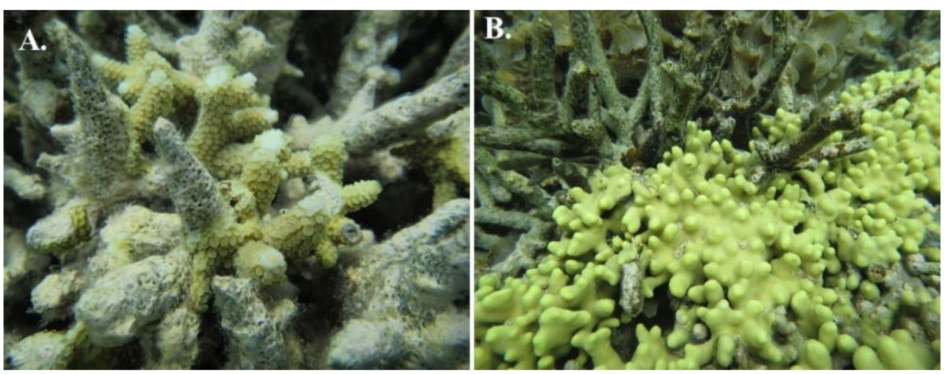

Figure 4. Reef recovery after mass mortality from bleaching and subaerial exposure. (A) staghorn tissue resheeting; (B) recruitment of non-staghorn species onto dead skeleton. Photos by: L. Raymundo.

Table 2. Staghorn *Acropora* species documented during 2017 surveys and their relative abundance.

Staghorn species	No. sites where present	Percent composition per site (± SD)
Acropora cf. *pulchra*	14	83.4 ± 21.3
Acropora muricata	6	26.6 ± 16.1
Acropora acuminata	4	43.6 ± 28.2
Acropora austera	3	33.4 ± 15.5
Acropora virgata	1	6
Acropora teres	1	9.8
Acropora aspera	1	96.7

Objective 2. Quantifying local tide levels

Loggers were deployed to the sites in groups, staggered throughout the project period (Figure 5; Table 3). However, three logger units were lost (presumably either removed, n=2, or lost in a storm, n=1) during deployments, which resulted in an extended period of fieldwork to ensure data collection at all sites. Where a logger was not recovered, an alternative logger was subsequently deployed (for a further five-week period) in a nearby location to reduce risk of additional instrument loss (Table 3). Observations of water depth, top-of-coral depth and evidence of scarring from past subaerial exposure were recorded at logger sites. Data were downloaded from loggers upon retrieval.

Tide gauge data for Apra Harbor (station ID 1630000) coinciding with the logger deployments were acquired from the NOAA Tides and Current web portal (https://tidesandcurrents.noaa.gov/waterlevels.html). Options selected were for six-minute resolution data using the mean lower low water (MLLW) datum and GMT (i.e., UTC) time zone.

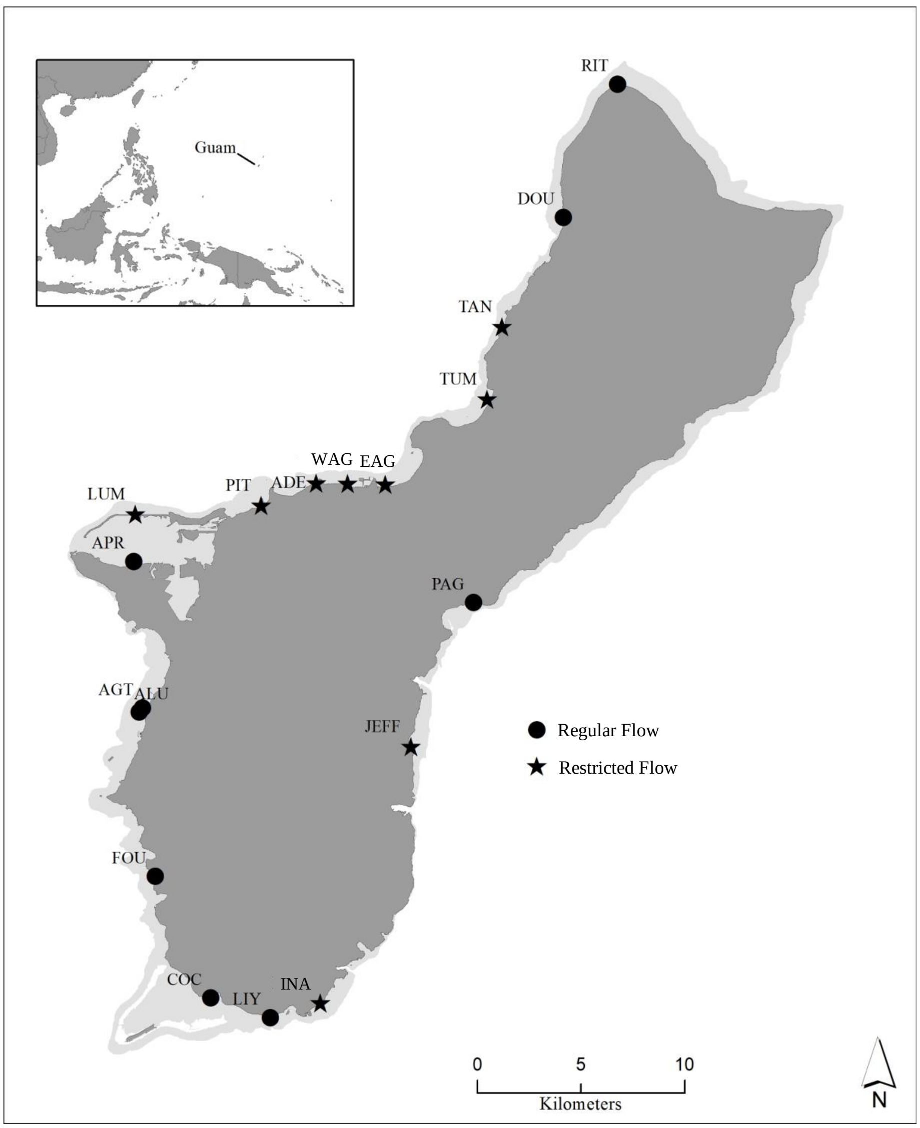

Figure 5. Depth logger deployment locations around Guam. Sites identified during analysis as having occurrences of low-water divergence are indicated with stars, associated with restricted flow due to high/moderate reef complexity.

Table 3. Depth logger deployment site names, codes, coordinates and deployment/recovery dates.

Site	Site code	Coordinates	Date deployed:	Date recovered:
Adelup	ADE	N 13°28'44.8", E 144°43'39.9"	Sep 21, 2018	Oct 16, 2018
Agat Marina++	AGT	N 13°22'48.56", E 144°39'04.21"	Mar 27, 2019	May 1, 2019
Alutom Island+	ALU	N13°22'41.9" E144°38'58.9"	May 24, 2018	Jun 29, 2018
Apra Harbor	APR	N 13°26.651', E 144°38.802'	Feb 7, 2019	Mar 15, 2019
Cocos Lagoon	COC	N 13°15'13.4", E 144°40'58.3"	Oct 31, 2018	Dec 5, 2018
Double Reef	DOU	N 13°35.773', E 144°50.214'	Feb 8, 2019	Mar 13, 2019
East Agaña	EAG	N13°28'44.1" E144°45'30.7"	Jul 24, 2018	Sep 4, 2018
Fouha Bay++	FOU	N 13°18'23.8", E 144°39'26.9"	Nov 1, 2018	Dec 5, 2018
Jeff's Pirate's Cove++	JPC	N 13°21.867', E 144°46.264'	Feb 6, 2019	Mar 14, 2019
Liyog++	LIY	N 13°14'43.5", E 144°42'33.9"	Oct 31, 2018	Dec 5, 2018
Luminao	LUM	N 13°27'53.8", E 144°38'50.0"	Sep 21, 2018	Oct 16, 2018
Inarajan++	INA	N 13°15'07.63", E 144°43'53.98"	Mar 27, 2019	May 1, 2019
Pago Bay++	PAG	N13°25'39.3" E144°47'54.1"	Apr 9, 2018	May 17, 2018
Piti Bomb Holes+	PIT	N 13°28'09.3", E 144°42'12.0"	Sep 21, 2018	Oct 16, 2018
Ritidian Point++	RIT	N13°39'16.7" E144°51'38.4"	Jul 16, 2018	Aug 30, 2018
Tanguisson	TAN	N 13°28'42.8", E 144°44'29.6"	Sep 21, 2018	Oct 16, 2018
Tumon Bay (Outrigger)	TUM	N13°30'59.6" E144°48'13.3"	Jul 24, 2018	Aug 30, 2018
West Agaña	WAG	N13°28'44.9" E144°44'30.1"	Jul 24, 2018	Sep 4, 2018

+Logger deployment not co-located with historical staghorn surveys
++Site added for geographical representation around Guam

The analysis steps involved:

- trimming of values to include only the time period that the logger was installed at the site;
- conversion of logger pressure records to depth, using the site-specific latitude;
- determining any phase difference between the logger and tide gauge depths using cross-correlation of the two datasets;
- identifying any periods of inclement weather by examining the residuals (i.e., logger minus tide gauge) and confirming against meteorological records; and
- linearly regressing the tide gauge and phase-corrected logger depths, excluding data from periods of inclement weather.

Scatterplots of logger depths against tide gauge depths revealed that, for several sites, there was a tide gauge depth threshold below which the linear relationship with logger values did not hold – the logger values plateaued at a minimum value (referred to here as “low-water divergence”). For these locations, data points for which the tide gauge depth was below the identified threshold were excluded and the linear regression repeated. An example of the analysis is provided for the Adelup site, at which two storm periods occurred during the deployment and for which low-water divergence was observed (ADE; Figure 6).

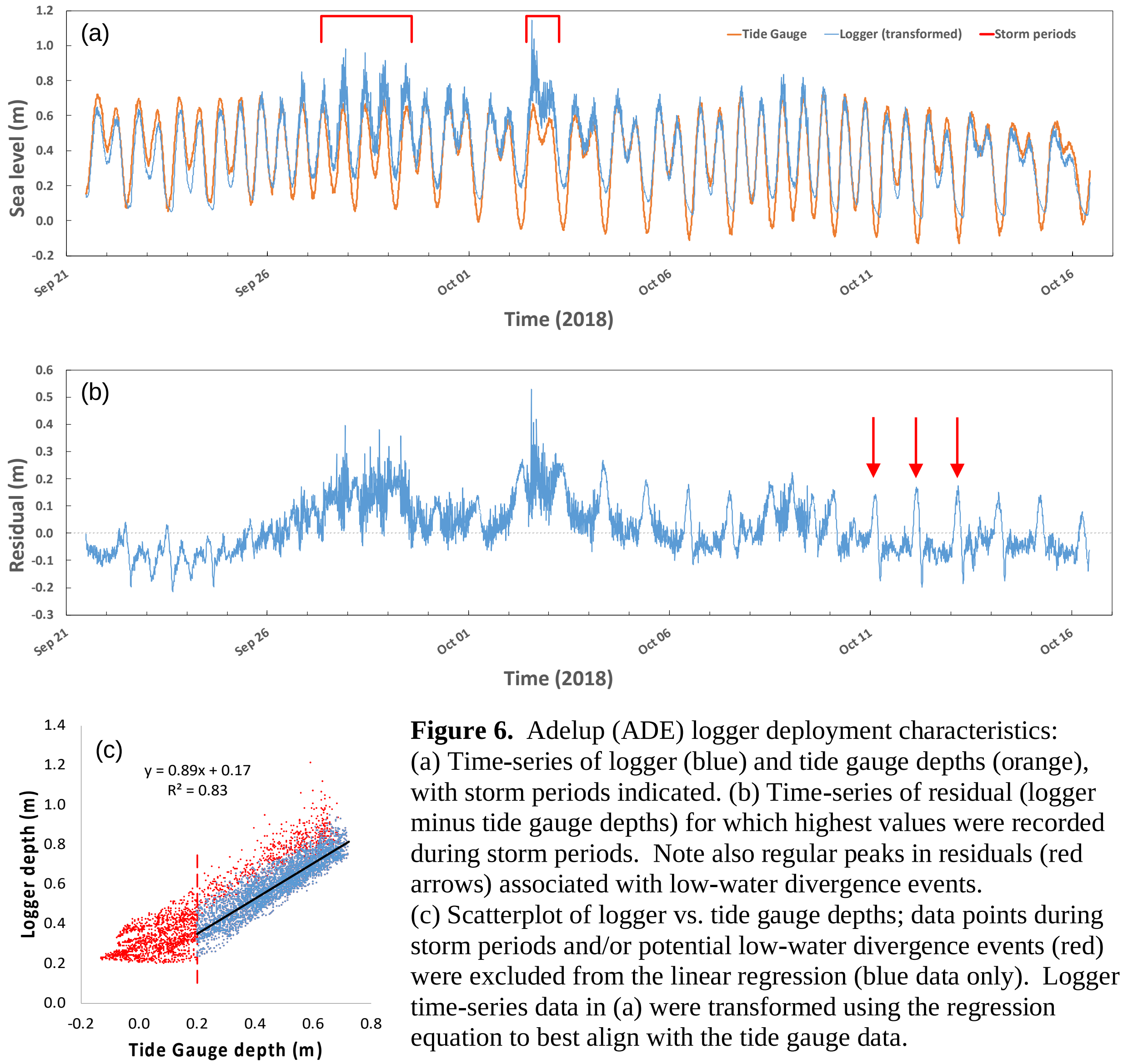

Figure 6. Adelup (ADE) logger deployment characteristics: (a) Time-series of logger (blue) and tide gauge depths (orange), with storm periods indicated. (b) Time-series of residual (logger minus tide gauge depths) for which highest values were recorded during storm periods. Note also regular peaks in residuals (red arrows) associated with low-water divergence events. (c) Scatterplot of logger vs. tide gauge depths; data points during storm periods and/or potential low-water divergence events (red) were excluded from the linear regression (blue data only). Logger time-series data in (a) were transformed using the regression equation to best align with the tide gauge data.

Variability between the logger and gauge was quantified by the standard error of estimate from the regression, which demonstrated spatial variation across the study sites (Table 4). The lowest variabilities were observed for sites closest to the Apra Harbor tide gauge (e.g., APR, AGT), with the highest values, unsurprisingly, for the sites on the east coast (i.e., JPC, PAG).

Low-water divergence events were characterized by transformed logger depths that deviated above the tide gauge depth when the latter was approaching the low tide mark. These events were observed at six study sites: ADE (Figure 6), EAG, JPC, LUM, TAN and WAG (Table 4; stars on Figure 5). With the exception of EAG, the reef complexity of the upper reef flat at these logger locations is high or moderate (Table 4), which appears to have restricted flow. Community complexity was categorized using expert assessments of the structure provided by the three-dimensional living (e.g., morphology and size of live corals) and non-living substrate in the area of the logger location. High complexity sites were characterized by a high density of large boulders, extensive branching thickets, and channels and crevices; moderate complexity sites had a moderate density of mid-sized branching colonies, small staghorn thickets and/or low-lying bommies or atolls (e.g., *Porites* spp., *Pavona decussata* flats), predominantly on sand or flat pavement substrate; and low complexity sites were typified by pavement, seagrass, and/or sand with low-relief, with small colonies of low density. Slowed outflow from a site during ebb tide would result in the observed low-water divergence. This maintenance of water level inside the reef complex may be beneficial to those corals during broad-scale low-stand periods. Further study is required to ascertain the cause of low-water divergence at EAG, and also why this was not observed at other high complexity sites.

Exposure to waves may also be of benefit during low-stand events because of wave setup and breaking. Wave exposure was categorized for each study site through analysis of the time-series and expert consultation to indicate potential for mitigation due to this factor (Table 4).

Table 4. Characteristics of Guam sites: geographical region, comparisons with Apra Harbor tide gauge, and observed wave exposure and reef complexity.

Site code	Region	Low-water divergence	Logger-Gauge variability (cm)	Wave exposure	Relative complexity
ADE	NW	Yes	5.6	High	Moderate
AGT	W	No	2.7	Low	Moderate
ALU	W	No	3.9	Low	Low
APR	W	No	2.4	High	High
COC	S	No	4.7	Low	Moderate
DOU	N	No	5.7	High	High
EAG	NW	Yes	7.0	Moderate	Low
FOU	SW	No	7.2	Moderate	Moderate
JPC	E	Yes	8.3	Moderate	High
LIY	S	No	4.8	Low	Moderate
LUM	W	Yes	8.2	High	High
INA	S	No	5.7	Moderate	Low
PAG	E	No	8.5	High	Low
PIT	NW	No	3.1	Low	Low*
RIT	N	No	7.0	High	Low
TAN	NW	Yes	4.7	Moderate	Moderate
TUM	NW	No	6.0	High	Moderate
WAG	NW	Yes	3.4	Low	Moderate

*Beyond the immediate vicinity of the logger deployment at PIT, which was in a seagrass bed that was exposed at low tide, the reef complexity is high.

Objective 3. Predicting historical extreme tides

Long-term sea level data from the Apra Harbor tide gauge reveal an increasing trend (i.e., rise) during the 22-year period studied (1996-2017) of around 2.2 mm/year (Figure 7). The data show that mean sea level dropped below 0.4 m during low-stand events in late-1997 (and presumably into 1998 though there are no tide gauge data from that time to support this), 2002-03, 2004-05 and 2014-16 (Figure 7). Each of these periods coincided with high values of the Ocean Niño Index (ONI, Figure 8), which is one indicator for El Niño events. High ONI values also occurred in 2006-07 and 2009-10, which coincided with smaller but apparent decreases in the mean sea level (Figure 7).

For each study site, the recorded top-of-coral depth was transformed using the calculated linear regressions to an effective threshold for the tide gauge data from the Apra Harbor station (Table 5). This long-term gauge record combined with the thresholds provides a method to consider historical occurrences of low-water events. Analysis of the 22 years of tide gauge data in two 11-year periods (1996-2006 and 2007-2017) revealed marked differences between the periods (Table 5, Figure 9). The measure of uncertainty in the linear regressions (standard error of estimate) was used to calculate the variability associated with predicted historical frequency of subaerial exposure (Figure 9, whiskers).

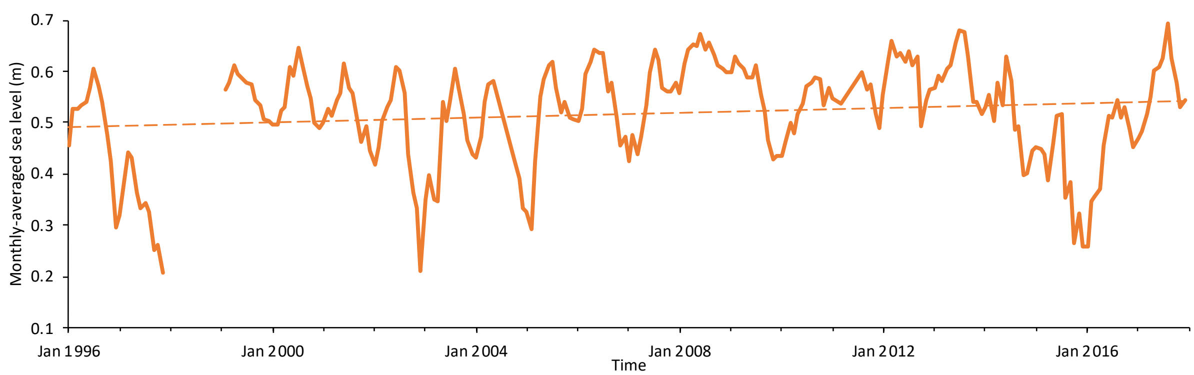

Figure 7. Monthly-averaged mean sea level data from the Apra tide gauge reveals an increasing trend of 2.3 mm/yr over the 22 year record and shows multiple periods of low-water excursion.

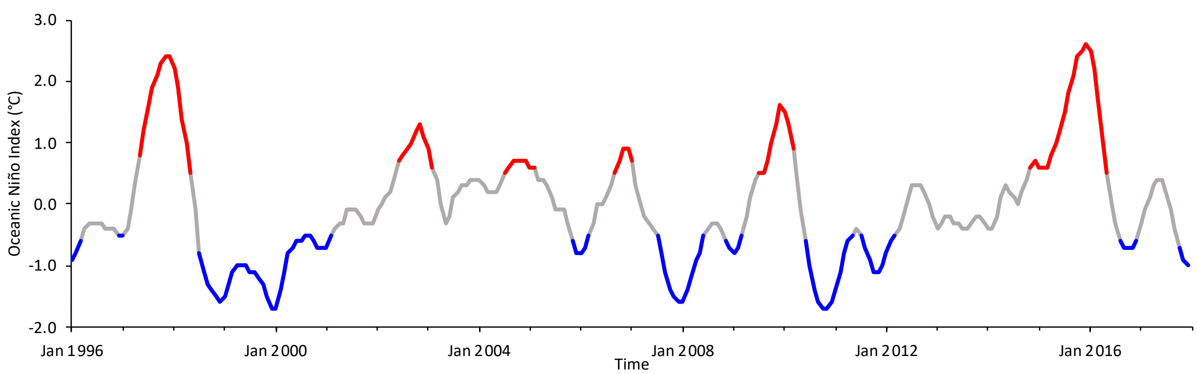

Figure 8. Oceanic Niño Index (ONI) for 1996-2017. High values (ONI ≥ 0.5°C, red) that persist for five monthly reported values (three-month averages) are considered an indicator of El Niño, and corresponding persistent low values (ONI ≤ -0.5°C, blue) of La Niña.

Low-water events occurred less often during the more-recent 11-year period (4% averaged across all sites) compared with the earlier period (5%). The reduction was by at least 20% across all sites, and by over 50% for half of the 18 studied locations. This is likely due in part to the increase in sea level observed during the record; however, it may also be related to the lack of El Niño events from early-2010 to late-2014 (as evidenced by the ONI index, Figure 8). One result of this period with few low-water events is that corals may have undergone more vertical growth, which would have provided more coral to be exposed in subsequent low-water events; however, there was no clear evidence to support this based on the local observations. Another explanation is that, due to a lack of low-water occurrence, corals may have lost capacity to acclimate to and survive through periods of subaerial exposure.

A second notable difference between the 11-year periods was in regard to timing of low-water events. Solar irradiance is typically highest in the early afternoon (12nn-4pm local time); low-water events during this period can therefore result in greater physiological (and ecological) impacts (Raymundo et al. 2017). In the 1996-2006 period, when averaged across all sites, the proportion of early-afternoon measurements that were low-water events was 2% less than the proportion observed across all hours of the day – a very similar proportion (though, notably, there were no tide gauge data during the strong El Niño of 1998; Figure 7). In contrast, during 2007-2017 (again averaged across all sites), the proportion of early-afternoon occurrences of low-water events was 15% greater than that across all hours of the day. This variation was likely related to the fewer number of low-water events in the latter period (potentially related to sea level rise), and the requirement of a greater (negative) anomaly to reach the low-stand threshold. Here we posit that such anomalies may occur only when the astronomical positions of the sun and moon are close to alignment, which may explain the greater incidence of low-water events in the early-afternoon. Further investigation of the timing of events is required. In 2015, the proportion of early-afternoon measurements that were low-water events rose to 35% when averaged across all sites (see details at exemplar sites below).

Predicted subaerial exposure at Jeff's Pirates Cove (JPC) was very infrequent in the earlier period and there were no predicted events within the most-recent period. This was consistent with anecdotal observations of the site from the past decades (Jeff Pleadwell, pers. comm.). This reef community is dominated by large massive colonies of *Porites* spp., which are known to be generally resilient to stress. As such, sensitivity of this site to exposure would be very low.

Four of the low vulnerability sites (ALU, COC, LUM and PAG) had observed scarring during the 2015 low-stand event, indicating subaerial exposure. For each of these four sites, the predicted low-stand afternoon occurrences in 2015 represented a high proportion of those events during the 2007-2017 period (68%, 50%, 48% and 100%, respectively). Notably, this was much higher than the proportion of afternoon events across the preceding four years (0%, 2%, 3% and 0%, respectively). The impact in 2015 at these sites may reflect a combined effect of high exposure after recent naivete to the conditions. The previously described mortality at the reef crest of the Alutom Island (ALU) site was not explained by observations; however, the predictive model here is based on a logger deployment that was inshore from the crest and in

Table 5. Vulnerability of Guam sites to subaerial exposure based on predicted impacts for 1996-2006 and 2007-2017.

Site code	Top-of-coral depth, referenced to tide gauge (m)	Predicted subaerial exposure 1996-2006 (%)	Predicted subaerial exposure 2007-2017 (%)
JPC	-0.430	0.01	0
APR	-0.326	0.1	0.005
DOU	-0.249	0.3	0.1
PAG	-0.227	0.4	0.1
RIT	-0.170	0.8	0.3
AGT	-0.146	1.0	0.4
ALU	-0.143	1.0	0.4
COC	-0.062	2.2	1.1
LUM	-0.052	2.4	1.2
PIT	0.033	4.8	3.0
EAG	0.049	5.4	3.5
TUM	0.110	8.1	5.6
ADE	0.116	8.5	5.9
INA	0.116	8.5	5.9
WAG	0.122	8.8	6.2
TAN	0.132	9.2	6.7
LIY	0.183	12.6	9.5
FOU	0.227	15.8	12.4

deeper water (due to operational logistics), suggesting that if any mortality near the logger was due to subaerial exposure then it was an unusual event with severe consequences.

Subaerial exposure in 2015 was also observed at two moderate-high vulnerability sites (TUM and TAN). At Pago Bay (PAG), there is very little coral on the reef flat due to past disturbances resulting in very low relief (Table 4), which suggests a high likelihood of exposure at low tide; however, this analysis indicated that tidal excursions below the identified threshold were infrequent.

There is anecdotal observational evidence supporting the high assessment for the two most-vulnerable sites. Subaerial exposure of coral ledges in Fouha Bay (FOU) has been observed during extreme low tide events, though quantitative surveys of impacts have not been conducted. Substantial mortality in Liyog Channel in 2016 (31.7%) was attributed to bleaching; the impacts on corals (mainly *Pocillopora* spp.) may have been exacerbated by low-water levels and unobserved subaerial exposure.

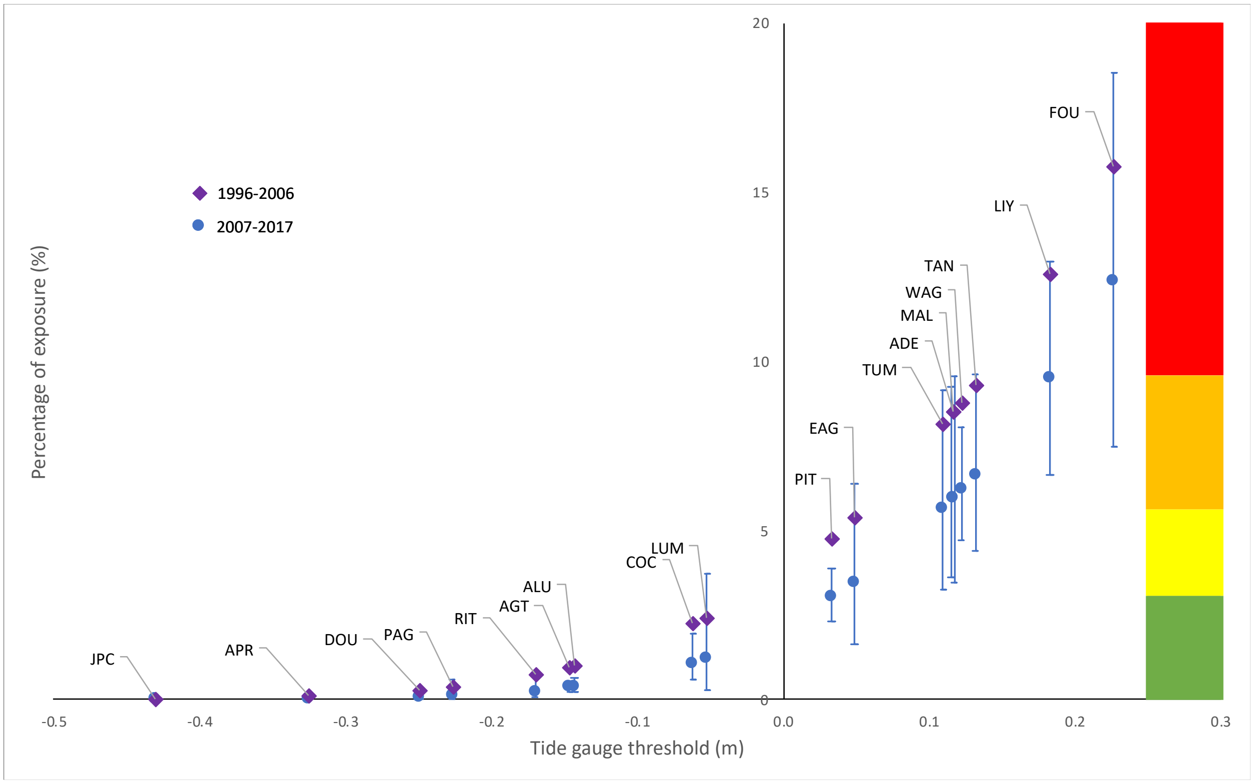

Figure 9. Frequency of subaerial exposure for depth threshold (transformed to tide gauge reference) for Guam sites during 1996-2006 (purple diamonds) and 2007-2017 (blue circles). Vulnerability of sites is color-coded at right. Whiskers indicate range of variability in exposure associated with the linear regression of deployed loggers with the tide gauge record, specifically using one standard error of estimate about the identified threshold depth.

Mapping the assessed vulnerability across the study sites reveals some key spatial patterns (Figure 10). Clusters of sites in the north and east had low vulnerability to subaerial exposure, as did a group of sites along the central west coast (Apra Harbor and nearby to the south). Sites near the populated areas along the northern section of the west coast had moderate-low to moderate-high vulnerability. The most vulnerable sites were located in the south and south-west. However, the reasons for these clusters is unclear and the observed patterns do not necessarily indicate all reefs in those regions would be similarly vulnerable (e.g., due to individual reef profile, circulation, wave exposure).

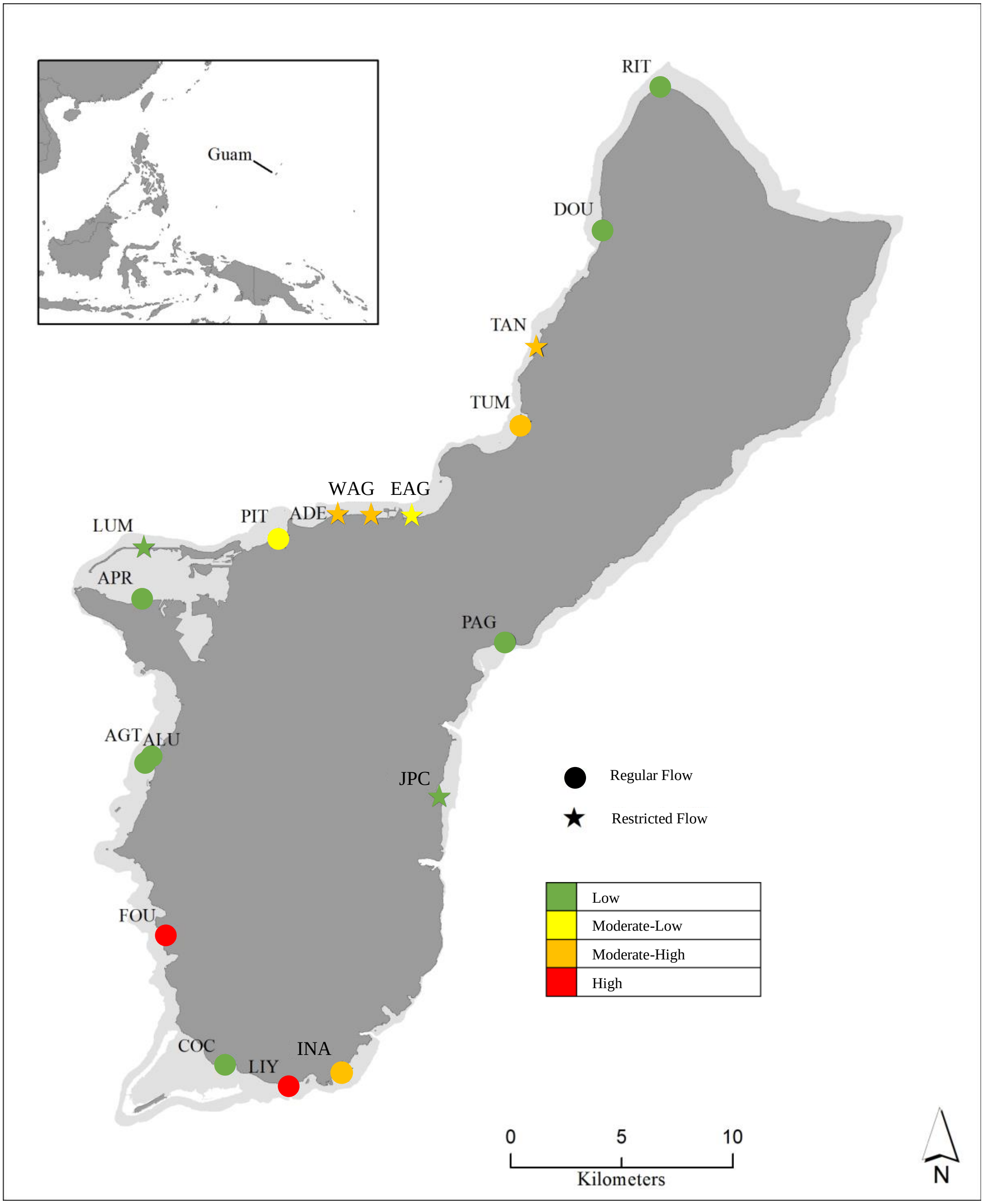

Figure 10. Assessed vulnerability for study sites around Guam.

Next Steps & Implications

Understanding the localized vulnerability to subaerial exposure is important for both natural and transplanted coral systems. This will be most relevant for natural systems in recognizing the compounding effects of multiple concurrent disturbances, as was observed in 2015 (Raymundo et al. 2017). While noting the historical and predicted increase in global sea level, variability during ENSO events (which may increase in their strength and frequency) has been predicted to increase low-stand events in Guam by as much as 100% over historical frequencies (Widlansky et al. 2015). Projections of climate impacts can now be informed by this additional potential disturbance to Pacific reefs. Low sea level is common on some western Pacific reefs during El Niño and on some eastern Pacific reefs during La Niña (Glynn et al. 2017).

The analysis presented here is useful for coral restoration design in Guam to inform optimal depths for transplantation activities. The effective depth thresholds determined here, referenced to the tide gauge, can indicate target depths for different levels of predicted subaerial exposure. For example, the threshold at Tumon Bay (TUM) is 11.0 cm below the tide gauge datum, while for Cocos Lagoon (COC) the threshold is 6.2 cm above the datum (a difference of ~17 cm). Active restoration of corals at TUM targeting a depth 20 cm below the current top-of-coral level would match the threshold at COC and therefore reduce the predicted exposure to that of COC (by ~4.5%, see Table 5). A further implication of this study for management may be to increase reef complexity at high-value sites (natural and/or restored) to promote retention of water, as observed in sites with low-water divergence. A key aspect of management response to the information in this report is in regard to specific restoration objectives. If restoration is intended to increase live coral cover and biodiversity for fish habitat, it would be important to restore corals below the depth threshold (if possible) so that they are unlikely to be damaged by subaerial exposure. However, if the objective is to build a protective barrier to reduce storm surge or entrap water (thereby protecting other corals), shallower restoration might be desired.

Additional research is required to consider the effects of recent naivete on impacts from subaerial exposure, akin to the proposition of ecological memory observed with respect to heat stress leading to coral bleaching (Hughes et al. 2018). With the predicted increase in low-stand events in Guam, despite overall rising sea levels, the role that coral naivete might play is uncertain.

This pilot study has indicated utility for examining similar effects in other Pacific regions that are affected by extreme low-stand tide events. These include reefs in American Samoa and Mañagaha Lagoon (Saipan, Commonwealth of the Northern Mariana Islands), which have experienced similar significant recent coral loss.

Outreach

The project began with a workshop in Guam that included engagement with the science and management community (Figure 11), as well as site familiarization visits that afforded opportunity to engage with additional community members. Near this project's conclusion, a second online community workshop was held to outline the results. Across both workshops over

50 people attended including coral reef and fisheries managers, scientists, academics, policy specialists and managers, staff from conservation organizations and public service non-profits, and students.

The results from the project have been compiled into one-page summaries for each site with the purpose of dissemination to and use by local stakeholders. These are provided, together with a legend (designed to appear on the reverse side of each for printed copies) in Appendix 1.

Figure 11. Presentation by Scott Heron during the July 2018 workshop.

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Appendix 1 - Site Summaries

Site summaries are provided on the following pages, preceded by a legend explaining the components of each page. For print copies of each summary, the legend is designed to appear on the reverse side. The summaries are presented here in alphabetical order of site names; sites are ordered by assessed vulnerability to subaerial exposure in Table 5. Information on each summary page includes:

- Site name and code
- Map of Guam with the site location identified
- Satellite photo and NOAA benthic habitat map of the site's immediate vicinity
- Photograph and brief description of the reef, including recent mortality
- Comparison of logger (site) and tide gauge (Apra Harbor) depths during the study
- Time-series of depth during instrument deployment
- Description of factors affecting subaerial exposure
- Supporting data table including region, divergence between logger and tide gauge at low water, variability between measured depths, wave exposure, and subaerial exposure frequency
- Assessed vulnerability to subaerial exposure (four-point categorical scale).