In Situ Temperature Time Series Across U.S. Pacific Coral Reefs

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Executive Summary

Subsurface temperature loggers (STRs) have been deployed in coral reefs at varying depths (5 m, 15 m, 25 m) across the U.S. Pacific Islands as part of NOAA's National Coral Reef Monitoring Program (NCRMP). Specifically, continuous temperature time series have been collected from 2011–2018 across the islands of American Samoa, the Commonwealth of the Northern Marianas (CNMI), the Pacific remote island areas, the main Hawaiian Islands (MHI), and the Northwestern Hawaiian Islands (NWHI). The primary goal of this study was to compare temperature time series and thermal stress heat metrics across regions, islands, years, and depths. Initially, the success rate of STR deployment was examined since loggers can contain gaps in data due to battery failure or instrument loss from storms, waves, or accidentally being taken by humans on populated islands. Once continuous time series sites were identified, a series of analyses compared temperature trends and other heat stress metrics across the Pacific-wide basin.

Coral reefs across the U.S. Pacific Islands are experiencing heat stress through overall increasing trends in rising temperature, normalized exposure to extreme heat events, and regular occurrence of acute short-term heat stress. However, no increased heating rates through time were observed, except in the NWHI. Despite this general trend in increased heat stress across the Pacific-wide basin, the high-frequency in situ temperature data highlight nuanced differences between regions, islands, and years on temperature exposure for coral reefs. For example, temperature patterns behave similarly across most islands so when subsurface waters heat up in American Samoa, they heat up in all locations and at depth. CNMI covers a wide latitudinal range, and thus there is a geographical difference in temperature exposure between the northern and southern islands. The PRIAs experience temperature differently across the islands with Howland and Baker exposed to more heat stress compared to the other islands. Meanwhile, the Hawaiian Archipelago experiences temperature differences primarily between the MHI and the NMHI.

Introduction

Coral reefs are one of the most biologically diverse environments, providing ecosystem services like coastline protection from waves, sustaining fisheries for human consumption, and stimulating economies through tourism (Harris et al., 2018; Lin et al., 2023; Moberg & Folke, 1999; Reguero et al., 2018). These vital ecosystems thrive in a narrow tolerance of environmental conditions and are threatened by major changes in living conditions (Kleypas et al., 1999). Local stressors like sedimentation or nutrient pollution threaten reefs (Kleypas et al., 1999), as do global stressors like ocean acidification and warming (Hoegh-Guldberg et al., 2007; Pandolfi et al., 2011). Ocean acidification impacts coral reefs more gradually compared to heat stress events that can happen within a short period of time and have lasting impacts on reef health (Hoegh-Guldberg et al., 2007; Pandolfi et al., 2011). Rising ocean temperatures due to anthropogenic climate change likely pose the greatest threat to coral reefs due to the immediate physiological responses by corals.

High temperatures in coral reefs cause coral to lose their symbiotic zooxanthellae and they appear white from their exposed skeleton in a process known as coral bleaching (Brown, 1997). Bleaching occurs on a scale from slight paling to severe, where severe bleaching generally leads to starvation and mortality (McClanahan, 2004). Widespread bleaching was first witnessed in 1982–1983 during an extremely strong El Niño (Glynn, 1984). However, the first global-scale coral bleaching event was observed in 1998 (Goreau et al., 2000). A decade of respite was followed by the next global-scale bleaching event in 2010 (Heron et al., 2016), although the impacts of these events were not well documented. The third recorded global-scale bleaching event was unprecedented in that it lasted 3 full years from 2014–2017 and coincided with high coral mortality and rapid deterioration of reef structure (Eakin et al., 2019).

Over time, scientists have developed methods to study temperature time series and assess heat stress using various metrics. These heat metrics are particularly useful in understanding coral bleaching by linking them to ecological observations. Heating metrics are calculated from temperature time series and used as predictor variables of bleaching severity. The most commonly used heat metric linked to coral bleaching is degree heating week (DHW), which measures the accumulated heat stress that exceeds a bleaching threshold (maximum monthly mean temperature +1 °C (Liu et al., 2018). NOAA’s Coral Reef Watch program uses blended sea surface temperatures (SST) satellite data to calculate heat metrics like DHW, SST anomalies, stress frequency, and SST variability (Liu et al., 2017). This suite of heat metrics is highly adept for predicting global-scale impacts to reefs. However, these metrics are limited by using night-time, blended satellite-derived SST, which captures temperature only at the surface skin (< 1 millimeter depth) and can thus differ significantly from subsurface temperatures at depths where corals exist. Satellite-derived SST data are further limited in temporal frequency and do not account for daily variability.

To better reflect the actual subsurface temperature conditions experienced by corals on-site, we calculated heat metrics using in situ temperature time series data collected directly from coral reefs in various Pacific Island regions. These regions include American Samoa (AMSM), the Pacific Remote Islands Areas (PRIA), the Commonwealth of the Northern Mariana Islands (CNMI), the main Hawaiian Islands (MHI), and the Northwestern Hawaiian Islands (NWHI). In situ temperature loggers have the advantage of capturing vertical water column structure (i.e., deployed on the benthos at different depths). They also detect high-frequency temperature changes, such as acute heat stress events, which might only last a few hours.

In this study, we undertook a comprehensive analysis of long-term in situ temperature data from 2011–2018, focusing on different regions, islands, and depths. The temperature time series were decomposed to identify overall trends. We specifically calculated additional heat metrics for acute (short-term) and cumulative (long-term) stress, heating rates, and daily variability during the global bleaching event of 2014–2017. This period, marked by successive high temperatures as noted by Eakin et al. (2019), provided a critical context for comparing how various Pacific regions experienced temperature changes during this time.

Objectives of this report:

- Identify the number of sites with a continuous temperature time series data set.
- Assess the success rate of deploying and retrieving temperature loggers (STRs) by comparing sites with continuous time series to those with active fixed-sites, ensuring no gaps in the data.
- Evaluate the spatial and vertical coverage of long-term in situ temperature data by comparing the number of continuous time series sites across regions, islands, and depths.
- Compare the number of complete transects (deep, mid, shallow) that have a long-term temperature time series.
- Examine temperature time series patterns by region and island to determine if islands within the same region experience similar heat stress over the years.
- Analyze temperature time series across different depths (shallow at 5 m, mid at 15 m, and deep at 25 m) for select islands in each region to understand varying temperature stresses.
- Apply detrended time series analysis to extract trends and compare these trends across each island in each region.
- Compare the number of acute and cumulative heat stress events in each region and island during the global bleaching years (2014–2017).
- Assess temperature variability in each region and island during the global bleaching years.
- Compare heating rates in each region and island during the same period.

Methods

Temperature logger deployment

In situ temperature time series data are collected using subsurface temperature recorders (STRs) as part of NOAA's National Coral Reef monitoring Program (NCRMP). High accuracy temperature loggers, made by Sea-Bird Electronics (SBE-56 Temperature Sensor), are deployed at fixed sites for depths of either 5, 15, or 25 m (Figure 1). STRs are deployed in water at 1m depth at some additional sites which are rare but considered valuable since shallow depths experience higher temperature conditions. Furthermore, STRs are deployed at fixed sites in the cardinal directions of each island (N, E, S, W). The deep, mid, and shallow deployed in each cardinal transect make up one transect. For example, the deep, mid, and shallow STR deployed in the north side of Tutuila, American Samoa is considered the TUT-N transect.

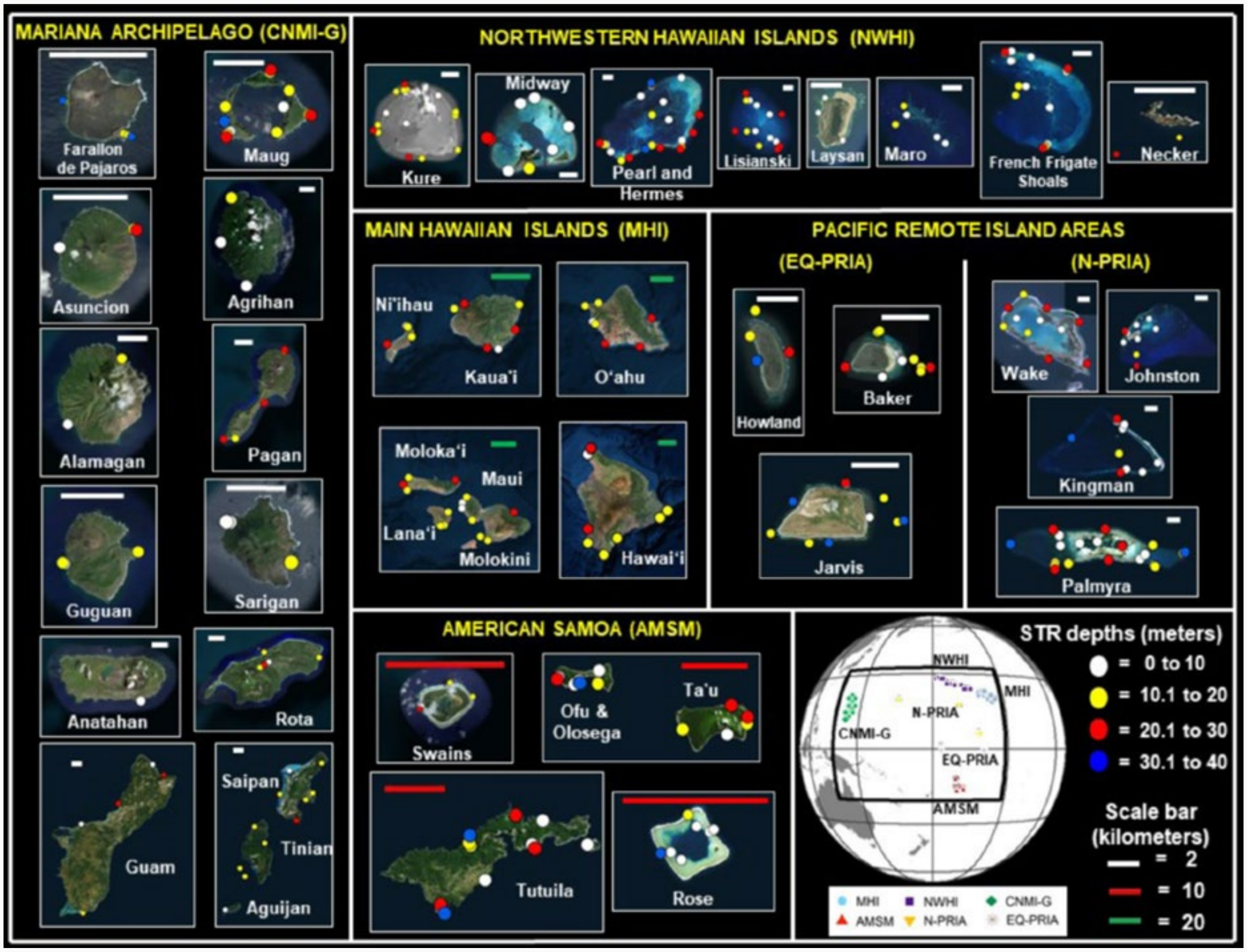

Figure 1. Map of islands and regions with deployment of subsurface temperature recorders (STRs) under the National Coral Reef Monitoring Program (NCRMP) , as documented by Venegas et al. (2019).

Not all sites where subsurface temperature loggers were deployed have continuous time series of data. Sometimes STRs do not get deployed in the same location as previous deployments. STRs were deployed for periods of 3–5 years between 2011 and 2018. When an STR is recovered, a new STR is deployed in the same location to maintain a continuous time series record for that specific site. STRs are programmed to collect data at intervals ranging from every 1 to 20 minutes. However, for the purpose of this study, the data are averaged hourly. STR data span the Pacific NCRMP regions for the following domains: main Hawaiian Islands (MHI), Northwestern Hawaiian Islands (NWHI), the Marianas (CMNI), American Samoa (AMSM), and the Pacific Remote Islands Areas (PRIAs).

Temperature time series data can have gaps at certain sites for a variety of reasons. Battery failure or instrument failure can lead to large gaps in data. Additionally, STRs may get lost between deployment and retrieval due to storms. Sometimes they are difficult to find due to overgrowth from macroalgae, turf, crustose coralline algae, and coral. Also, ocean conditions (e.g., large waves or strong currents) dictate whether or not an STR can be recovered. Regardless of the reason, sites with large gaps (more than a few days) in the data were excluded from this study. The number of sites with continuous time series data was identified for each region, island, and depth.

Time series analysis

Temperature time series analysis was conducted via detrended fluctuation analysis (DFA). DFAs were applied to temperature time series to decompose for trends, seasonality (daily, annual), and residual components (i.e., noise in the time series model). All DFAs were conducted in the R programming environment (version 4.0.3; R Core Team, 2020) using the 'mstl' function in the R package 'forecast' (version 8.21.1; Hyndman et al., 2024) . Since temperature data were recorded hourly, the seasonality variables set in each model were defined as 24 for daily periodicity and 8,766 corresponding to annual periodicity. The detrended components of the time series allow for the overall trend to be observed. The remaining trend line is nonlinear; therefore, the time series of the nonlinear trend line visually reveal years that were warmer than the previous years. Ultimately, the temperature trends were systematically compared between regions and islands.

Heat metrics

A series of heating metrics was calculated during the global bleaching event (2014–2017) to assess how different types of heat stress might have impacted the coral reefs in each region.

Cumulative thermal stress

Cumulative heat stress refers to long-term exposure of heat stress events for corals lasting on the order of multiple days or weeks. Traditionally, degree heating weeks (DHW) gets used as the primary heating metric to calculate cumulative heat stress. The threshold used for DHW is the maximum monthly mean plus one degree Celsius (MMM+1). However, this threshold does not consider historical patterns. Alternative methods for defining a bleaching threshold and identifying extreme marine heat waves include quantifying the frequency and duration that in situ temperature rises above the historical threshold (90th percentile) for temperature (Hobday et al., 2016; Tanaka & Van Houtan, 2022). The latter method was applied for this analysis. More specifically, historical (1985–2010) sea surface temperature data were sourced from NOAA's Coral Reef Watch (CRW) blended-SST satellite data (Liu et al., 2014). Historical temperature was derived for each island using every CRW SST grid located within a 1°×1° area surrounding the island. An extreme temperature event was identified as any instance where the STR logger measurements exceeded the 90th percentile of the historical temperature between 1985 and 2010. Both the frequency of these events and the number of days the STR temperature remained above this threshold were quantified and analyzed.

Acute thermal stress

A key advantage of in situ loggers compared to external gridded SST data lies in their ability to record at high-frequency sampling rates. In situ loggers can detect short-term heat stress events that occur on the order of hours that remote sensing data otherwise overlook. Here, we quantified the annual frequency of these short-term heat stress events characterized by temporary temperature spikes that persist for only a few hours.

Heating rates

The rate at which temperature warmed ($^{\circ}C\ hr^{-1}$) each year was calculated. This was evaluated by assessing the slope in temperature change from the coolest to the warmest time of year. The objective was to determine if heating rates varied by year, island, or region.

Generalized linear models (GLMs) with a Gaussian distribution and identity link function were used to determine the significant difference in heat metrics between regions, islands, and global bleaching years (2014–2017).

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Results

Successful deployments of continuous time series at fixed sites across regions (2011–2018)

Table 1 compares the number of active sites with STRs in each region to the number of sites that successfully have a continuous time series (i.e., temperature data from one deployment is able to be merged with minimal gaps with temperature data from a following deployment time at the same exact location).

Table 1. Number of sites with continuous temperature time series

Region	Number of sites with continuous time series	Number of active sites
AMSM	27	78
PRIA	49	97
CNMI	21	101
MHI	27	42
NWHI	31	41

The MHI and NWHI have the highest success rate of maintaining a long-term time series (MHI: 64%; NWHI: 76%). AMSM and the PRIAs rank in the middle for keeping a long-term continuous data set (AMSM: 35%; PRIA 51%). CNMI had the lowest success rate of having a long-term continuous time series (21%). During the 2014–2017 period, most STRs across the CNMI failed within a year due to battery issues. This resulted in only 21 out of 101 CNMI sites having complete long-term data. Many sites experienced gaps of 1–2 years in their data series and were not included in long-term analyses.

Number of sites that have continuous time series by region, island, and depth

Subsurface temperature recorders (STRs) are deployed at fixed sites with depths of 5 m, 15 m, and 25 m. STRs are deployed in water at 1 m depth at some additional sites which are rare but considered valuable since shallow depths experience higher temperature conditions. Continuous temperature time series are found at some islands and depths more than other locations (Table 2).

Table 2. Number of continuous temperature time series by island and depth.

Region	Island	Populated / Unpopulated Islands	1m	5m	15m	25m	All Depths
American Samoa (AMSM)	Ofu (OFU)	populated	1	0	1	2	4
	Rose (ROS)	unpopulated	0	1	2	2	5
	Swains (SWA)	unpopulated	1	1	2	1	5
	Ta'u (TAU)	populated	0	1	2	2	5
	Tutuila (TUT)	populated	0	1	4	3	8
Pacific Remote Island Areas (PRIA)	Baker (BAK)	unpopulated	0	1	3	3	7
	Howland (HOW)	unpopulated	0	2	2	1	5
	Jarvis (JAR)	unpopulated	0	2	3	3	8
	Johnston (JOH)	unpopulated	0	0	0	0	0
	Kingman (KIN)	unpopulated	0	4	4	3	11
	Palmyra (PAL)	unpopulated	2	4	4	4	14
	Wake (WAK)	unpopulated	0	0	2	2	4
Guam and Commonwealth of the Commonwealth of the Northern Marianas Islands (CNMI)	Agrihan (AGR)	populated	0	0	0	0	0
	Aguijan (AGU)	unpopulated	0	1	0	0	1
	Alamagen (ALA)	populated	0	0	1	0	1

Region	Island	Populated / Unpopulated Islands	1m	5m	15m	25m	All Depths
	Anatahan (ANA)	unpopulated	0	0	0	0	0
	Asuncion (ASC)	unpopulated	0	1	1	0	2
	Farallon de Pajaros (FDP)	unpopulated	0	0	1	0	1
	Guam (GUA)	populated	0	1	1	0	2
	Guguan (GUG)	unpopulated	0	0	0	0	0
	Maug (MAU)	unpopulated	1	1	2	0	4
	Pagan (PAG)	unpopulated	1	0	2	0	3
	Rota (ROT)	populated	0	0	0	0	0
	Saipan (SAI)	populated	0	0	2	0	2
	Sarigan (SAR)	unpopulated	0	0	1	0	1
	Supply Reef (SUP)	unpopulated	0	0	0	1	1
	Tinian (TIN)	populated	0	0	2	0	2
	Zealandia Bank (ZEA)	unpopulated	0	0	0	1	1
Main Hawaiian Islands (MHI)	Hawaiʻi (HAW)	populated	0	1	1	2	4

Region	Island	Populated / Unpopulated Islands	1m	5m	15m	25m	All Depths
	Kauaʻi (KAU)	populated	0	1	2	3	6
	Laānaʻi (LAN)	populated	0	1	1	0	2
	Maui (MAI)	populated	0	2	1	1	4
	Molokaʻi (MOL)	populated	0	1	2	2	5
	Ni'ihau (NII)	populated	0	0	0	1	1
	Oʻahu (OAH)	populated	0	2	1	2	5
Northwestern Hawaiian Islands (NWHI)	French frigate shoals (FFS)	unpopulated	0	2	1	1	4
	Kure atoll (KUR)	unpopulated	1	1	3	2	7
	Lisianski (LIS)	unpopulated	0	3	3	3	9
	Pearl and Hermes (PHR)	unpopulated	1	3	3	4	11

For most regions (AMSM, PRIA, CNMI, MHI), shallow sites (5 m) have fewer continuous temperature time series compared to mid (15 m) and deep (25 m) sites. The PRIAs have fair spatial coverage of continuous time series across islands and depths, with the exception of Johnson Island which had zero continuous time series despite having 11 active STR sites because NCRMP has not visited Johnson Island since 2015. Conversely, the CNMI region had the least number of sites with continuous temperature time series across all islands and depths. Some islands do not have any continuous time series (e.g., Agrihan, Anatahan, Guguan, Rota).

Across all regions, finding a continuous temperature time series for a complete NCRMP transect, which includes shallow, mid, and deep sites within the same transect, is uncommon. The STRs are strategically deployed at various depths in each cardinal direction around an island to comprehensively monitor temperature variations. However, achieving continuous temperature records across all these sites simultaneously is rare.

The data set's notable strength lies in its extensive temporal range, spanning from 2011 to 2018, and its broad spatial coverage across the Pacific. This extensive duration and wide geographical spread provide a valuable foundation for understanding regional temperature trends and anomalies over a significant period. However, a notable limitation of this data set is the scarcity of sites that offer long-term continuous data at each island and across various depths. This limitation constrains the potential for detailed within-island temperature comparisons, as the low number of sites with comprehensive long-term data limits the ability to conduct thorough analyses of temperature variations at specific islands.

Number of sites that have complete a complete transect (deep, mid, shallow) by region

Overall, there are only a few complete transects collected per region (Table 3). CNMI had zero transects with continuous temperature data. Many islands had no complete transects, some islands had at least one complete transect, a few islands had two complete transects; no island had a complete transect in all cardinal directions (N, E, S, W). Pearl and Hermes had the best spatial coverage (N, S, W) for complete transects.

Table 3. Number of continuous temperature time series that have a complete transect (deep, mid, shallow) by region.

Region	Transect No.	Transects
AMSA	4	ROS-SW, SWA-W, TAU-E, TUT-NE
PRIA	7	BAK-E, HOW-E, JAR-E, JAR-W, KIN-N,KIN-S, PAL-N
CNMI	0	n/a
MHI	3	KAU-S, MOL-N, OAH-E
NWHI	6	KUR-N, LIS-S, LIS-W, PHR-N, PHR-S, PHR-W

Temperature time series by region and island

Sites at the same depth (15 m) were analyzed and compared across islands within each region (Figure 2). At 15 m depth, certain islands (Ofu, Alamagen, Asuncion, Farallon de Pajaros, Guam, Sarigan, Hawai'i, Laāna'i, Maui, O'ahu, French Frigate Shoals) were represented by just one continuous temperature time series. The maximum number of sites with continuous time series at this depth is four at Tutuila and Palmyra. The following figure shows one temperature time series that was selected by choosing the longest running time series with the least amount of data gaps and (when possible) belonged to a complete transect. In some instances, only one time series was available. For visualization purposes, we show temperature time series per island to highlight general trends in temperature.

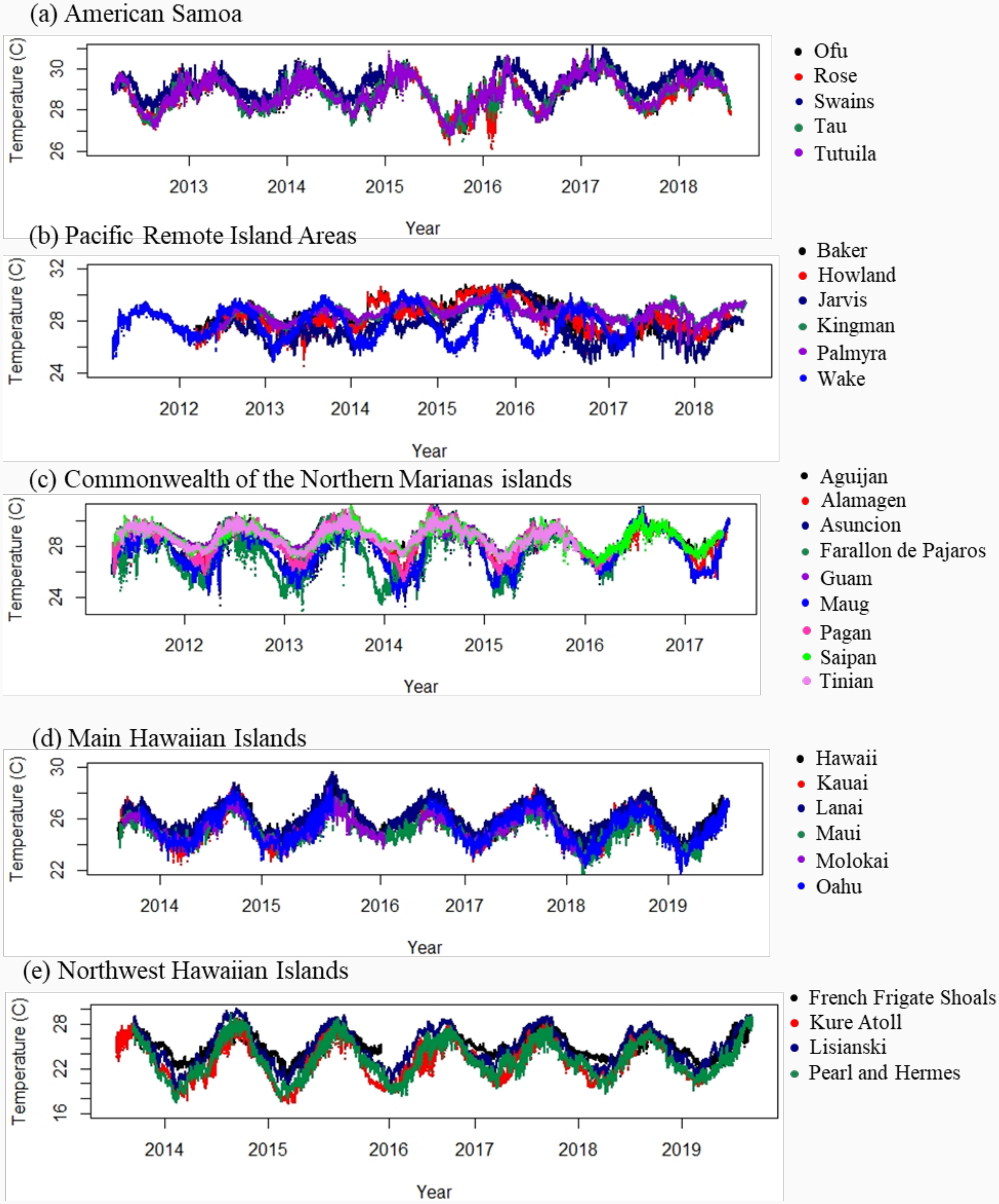

Figure 2. Temperature time series for AMSA, PRIAs, CNMI, MHI, and NWHI. One STR is represented per island selected from the mid depth (15 m).

Patterns in temperature data were very similar across islands in AMSA (especially Ofu, Rose, Tau, and Tutuila). Swains temperature pattern was elevated compared to the other islands, especially in 2016. Furthermore, the annual temperature range for the Swains was less compared to the other islands. Rose experienced a cooling period in 2016 that the other islands do not.

Patterns in temperature time series differed between islands in the PRIAs, although there were similarities for islands that were close to each other. Baker and Howland had a similar temperature pattern, as did Jarvis and Kingman. Palmyra and Wake had isolated patterns from the other islands. Palmyra experienced the lowest range in temperature variability. Temperature at Wake had a delay in warming compared to the other islands. Temperature at Wake increased rapidly and only remained elevated during summer for a short period of time. Temperature patterns at Wake remained consistent from year to year. Temperature patterns were variable for each year at Baker, Howland, Jarvis, and Kingman.

There was a distinct difference in temperature patterns in the northern islands (list from north to south: Farallon de Pajaros, Maug, Asuncion) and the southern islands (Pagan, Alamagan, Saipan, Tinian, Aguijan) of CNMI. The northern islands of CNMI experienced the largest annual range in temperature. Farallon de Pajaros (the northernmost island) warms earlier than all other islands, even nearby Maug. The northern and southern islands all experienced extreme heat temperatures, especially in 2014, 2015, and 2017.

Patterns in temperature data in the MHI were very similar across islands. Although the difference was slight, Laānaʻi experienced the warmest temperatures. For the NWHI, French Frigate shoals and Lisianski experienced warmer temperatures for all years compared to Kure Atoll and Pearl and Hermes.

Temperature time series were also plotted by depth for complete transects (deep, mid, shallow). Time series plots are presented for each region and islands that have available data in the Appendix (Figure A1). Deep reefs at some islands (e.g., Kingman and Palmyra in 2016) experienced cooling events that shallow reefs did not experience. However, certain areas, like Baker and Howland islands, did not experience a strong thermocline in water less than 25 m and the shallow, mid, and deep reefs are exposed to similar temperature values (e.g., Baker and Howland).

Temperature trends by region and island

Temperature time series were decomposed, and the trend was extracted and compared among islands of the same region (Figure 3).

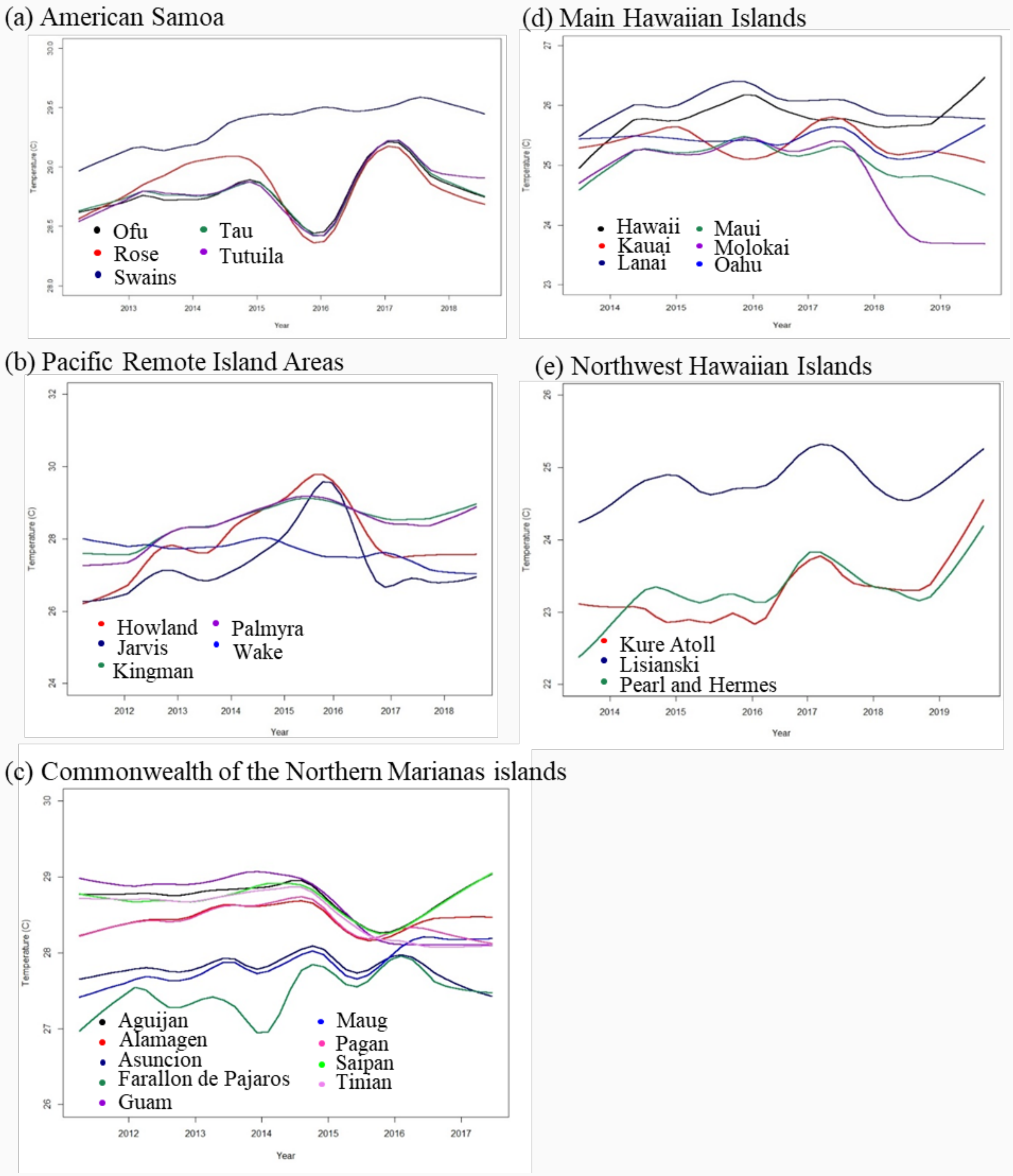

Figure 3. Temperature trends per region and island. Trend lines are decomposed from temperature time series through detrended time series analysis (DFA).

For AMSA, temperature trends were consistent across all islands except the Swains. , The trend in temperature increased from 2012–2015 at Ofu, Rose, Tau, and Tutuila, decreased in 2016, and increased once again in 2017. Only Swains experienced an increase in temperatures; it did not experience a reprieve in 2016 like the other islands of American Samoa.

For the PRIAs, Howland and Jarvis experienced an increase in temperature trend with peaks in 2013 and 2016, followed by a decrease in 2017 and 2018. Kingman and Palmyra also experienced a steady increase in temperature between 2013–2016, although the increase in the trend was less extreme compared to Howland and Jarvis. Interestingly, Wake did not experience a steady increase in temperature trend. Temperature remained mostly steady across the years. Baker Island was excluded from the trend analysis due to major gaps in the time series resulting in erroneous trends

For CNMI, the northern islands (from north to south: Farallon de Pajaros, Maug, Asuncion) and the southern islands (Pagan, Alamagan, Saipan,Tinian, Aguijan) experienced. different patterns in temperature trends. The southern islands showed elevated temperatures which increased steadily from 2012–2015. The upward trend was minimal and was followed by a decline midyear 2015. The temperature trend increased in the northern islands although it varied throughout the year. There was no prominent decline in temperature trend in mid-2015.

For MHI, temperature trends were similar for Kaua'i, Lana'i, and O'ahu. They were also similar for Moloka'i and Maui. Kaua'i temperature trends reduced in 2016 whereas they increased at the other islands. Meanwhile, in the NWHI, patterns in temperature trends were similar between islands, even though the temperatures were slightly warmer in Lisianski.

Heat metrics: Cumulative and acute stress, heating rates, and temperature variability (2014–2017)

Heat metrics for cumulative heat stress, acute heat stress, heating rates, and temperature variability were compared between years (2014–2017), islands, and regions.

Cumulative thermal stress. Both the frequency and duration of cumulative heat stress events where temperatures rose above the 90th percentile of the annual historical mean by island were evaluated for differences across region, island, years, and depth zones.

The frequency of cumulative thermal stress events significantly differed between region ($F_{(4,468)}$ = 42.6, $p < 0.001$) and year ($F_{(3,468)}$ = 28.4, $p < 0.001$) but not depth ($F_{(2,468)}$ = 0.4, $p = 0.67$). When reefs experienced long-term heat stress they experienced the same number of heat events whether they were in the shallow, mid, or deep zones. When each region was evaluated separately, the number of long-term events did not differ significantly by island for American Samoa ($F_{(3,75)}$ = 26.8, $p = 0.67$), CNMI ($F_{(9,29)}$ = 1.4, $p = 0.24$), MHI ($F_{(6,77)}$ = 1.7, $p = 0.13$), or NWHI ($F_{(3,90)}$ = 0.4, p =

0.75), but it did for the PRIAs ($F_{(5,151)} = 7.4$, $p < 0.001$). Baker and Howland experienced more cumulative heat events compared to the other islands. The number of cumulative heat stress events varied by year for American Samoa ($F_{(3,468)} = 28.4$, $p < 0.001$), the PRIAs ($F_{(3,151)} = 44.7$, $p < 0.001$), CNMI ($F_{(2,29)} = 11.8$, $p < 0.001$), MHI ($F_{(3,77)} = 14.5$, $p < 0.001$), but not for NWHI ($F_{(3,90)} = 2.2$, $p = 0.09$). American Samoa experienced the greatest cumulative stress in 2015 and 2017, the PRIAs had the most in 2015, CNMI had the most in 2015, and MHI had the most in 2017.

For all regions combined, the length of time (measured in weeks) of cumulative thermal stress events significantly differed between regions ($F_{(4,477)} = 18.7$, $p < 0.001$), year ($F_{(4,477)} = 39.4$, $p < 0.001$), and depth zones ($F_{(4,477)} = 12.2$, $p < 0.001$). Long-term heat stress events last longer in the shallow reefs for the PRIA ($F_{(2,149)} = 5.7$, $p<0.001$), MHI ($F_{(2,84)} = 9.3$, $p<0.001$), and NWHI ($F_{(2,95)} = 5.6$, $p < 0.001$), but depth did not differ for AMSM ($F_{(2,74)} = 1.1$, $p = 0.34$) or CNMI ($F_{(2,29)} = 1.5$, $p = 0.22$). The length of time above the 90th percentile for historical temperature did not differ by island for the PRIA ($F_{(5,149)} = 1.6$, $p = 0.17$), but it did for all other regions: AMSM ($F_{(4,74)} = 11.3$, $p < 0.001$), CNMI ($F_{(9,29)} = 2.3$, $p < 0.05$), MHI ($F_{(6,84)} = 8.8$, $p < 0.001$), and NWHI ($F_{(3,95)} = 24.4$, $p < 0.001$). Baker and Howland spent more time above the historical threshold compared to the other islands in the PRIAs. Furthermore, time above the threshold varied by year for all regions (Figure 4).

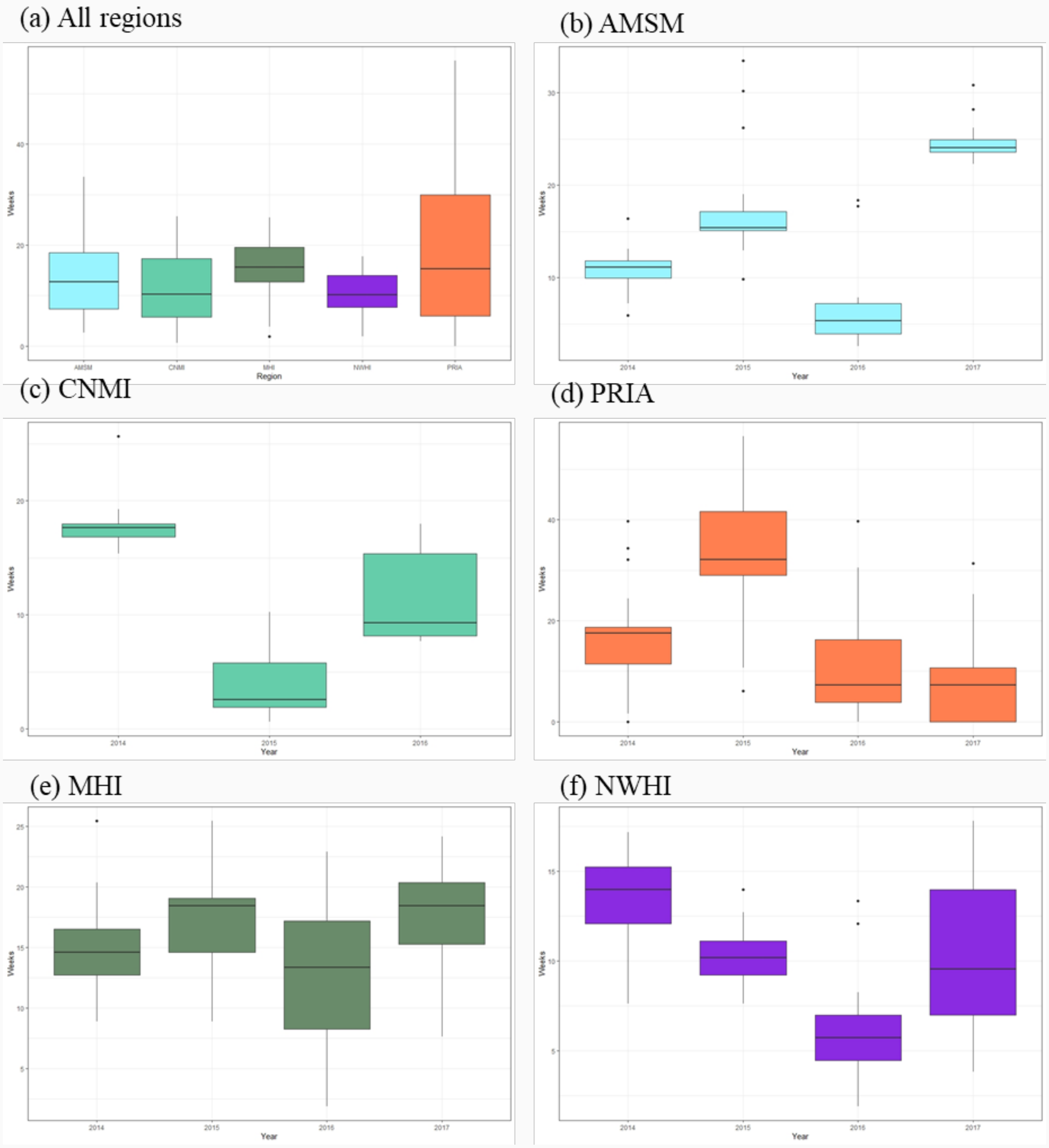

Figure 4. Cumulative heat stress. Length of time (weeks) temperature rose above the 90th percentile of the historical temperature mean (1985–2010).

Acute thermal stress. The number of acute (short-term) heat stress events significantly differed between regions ($F_{(4,468)} = 71.3$, $p < 0.001$), and years ($F_{(4,468)} = 9.1$, $p < 0.001$; Figure 5). The frequency of heat stress events varied by depth for AMSM ($F_{(2,79)} = 12.6$, $p < 0.001$) and NWHI ($F_{(2,89)} = 11.6$, $p < 0.001$), but not for the PRIAS ($F_{(2,29)} = 0.02$, $p = 0.90$), CNMI ($F_{(2,141)} = 0.6$, $p = 0.57$), or MHI ($F_{(2,82)} = 1.1$, $p = 0.35$). More acute heat stress events occurred in the shallow sites compared to the mid and deep sites, although the number of acute stress events that occurred in the mid and deep sites was similar. CNMI had the highest number of acute stress events despite having no temperature data in 2017, while AMSM experienced the lowest number of acute heat stress events. The number of acute stress events did not differ across islands for AMSM ($F_{(4,79)}$ = 1.1, p = 0.38) or CNMI ($F_{(4,79)}$ = 1.1, p = 0.38), but it did differ for the PRIAs ($F_{(5,141)}$ = 13.6, p < 0.001), MHI ($F_{(6,82)}$ = 3.3, p < 0.001), and NWHI ($F_{(3,89)}$ = 13.0, p < 0.001). Jarvis and Wake had the lowest observed acute heat stress events (< 2 events per year) in the PRIAs, while Kingman and Palmyra experienced the highest number of acute stress events (> 2 events per year). Kure and Lisianski experienced more acute heat stress events in the NWHI than French Frigate Shoals and Pearl and Hermes. Niʻihau experienced fewer acute heat stress events in the MHI than Laānaʻi, Maui, Molokaʻi, and Oʻahu.

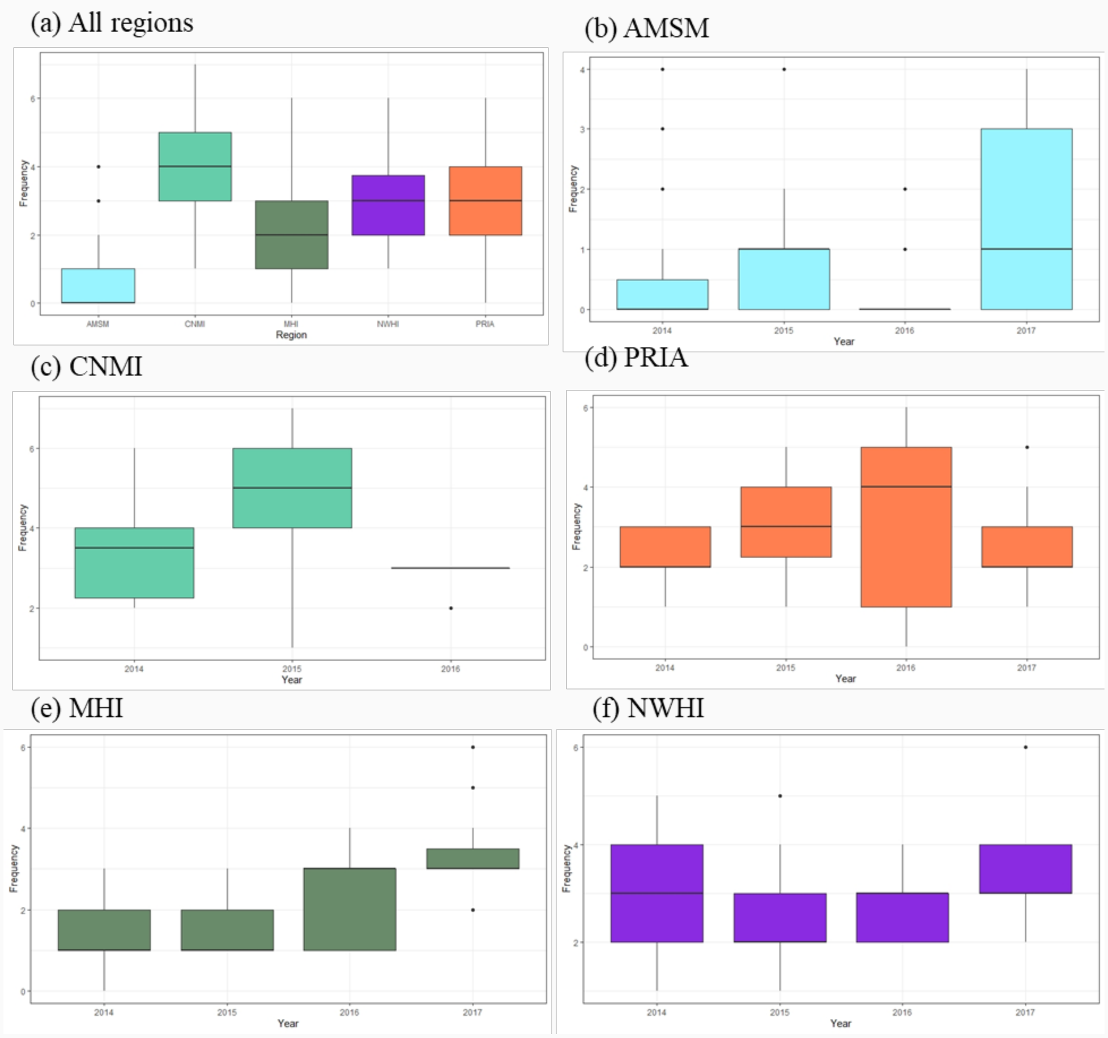

Figure 5. Frequency of acute heat stress events across regions and years

Heating Rates. For all regions, islands, and sites combined, heating rates were significantly different by region ($F_{(4,454)}$ = 207.2, p < 0.001) but not by year ($F_{(4,454)}$ = 1.6, p = 0.20) or depth ($F_{(4,454)}$ = 0.3, p = 0.73; [Figure 6]). The NWHI had the highest heating rates with a mean (±SE) of 0.06±0.003 °C day^{-1}. Meanwhile, the two regions closest to the equator, the PRIAs and AMSM, had the lowest heating rates at 0.009±0.0008 °C day^{-1} and 0.01±0.0004 °C day^{-1}. Evaluating differences in heating rates between each region reveals that heating rates significantly vary by island for all regions: AMSM ($F_{(4,74)}$ = 4.2, p < 0.001), PRIAs ($F_{(4,74)}$ = 4.2, p < 0.001), CNMI ($F_{(9,29)}$ = 16.6, p < 0.001), MHI ($F_{(6,78)}$ = 3.9, p < 0.05), and NWHI ($F_{(3,91)}$ = 12.9, p < 0.001). Even though heating rates did not vary by year for all regions combined, when each region was evaluate separately, all except AMSM experienced different heating rates by year: PRIAs ($F_{(5,136)}$ = 84.5, p < 0.001), CNMI ($F_{(9,29)}$ = 31.3, p < 0.001), MHI ($F_{(3,78)}$ = 26.1, p < 0.05), and NWHI ($F_{(3,91)}$ = 18.5, p < 0.001). Heating rates only increased by year for NWHI. Heating rates decreased with increasing year for CNMI and the PRIAs. No regions experienced different heat rates with depth; therefore, all depths for all regions and islands experienced increasing temperatures at the same rate of change.

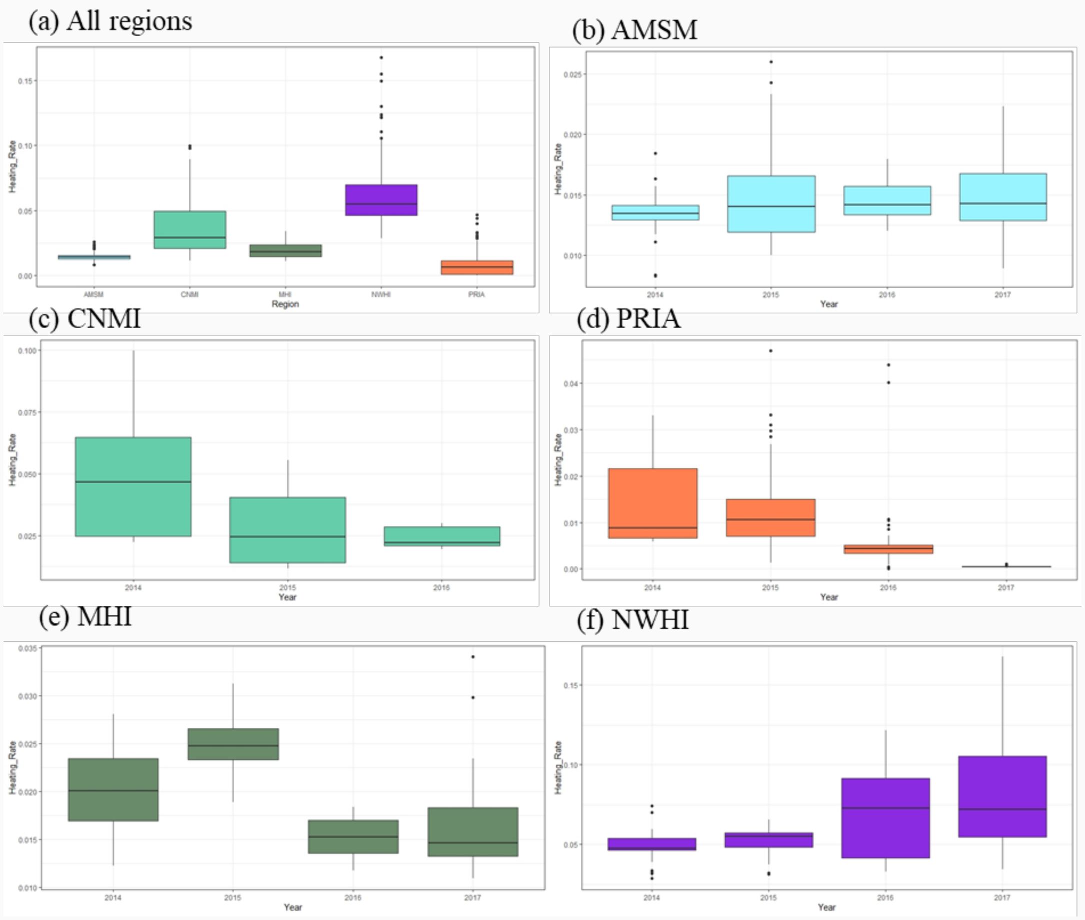

Figure 6. Heating rates (°C day-1) during the warming period by region and year.

Discussion

Coral reefs across the U.S. Pacific Islands are experiencing heat stress through overall increasing trends in rising temperature, increasing heating rates, normalized exposure to extreme heat events, and regular occurrence of acute short-term heat stress. Despite this general trend in increased heat stress across the Pacific-wide basin, the high-frequency in situ temperature data shares nuanced differences between regions, islands, and years on temperature exposure for coral reefs. For example, when subsurface waters warm in American Samoa, temperature patterns behave similarly across most islands and depths. Meanwhile, CNMI covers a wide latitudinal range, and thus there is a geographically difference in temperature exposure between the northern and southern islands. The PRIAs also experience temperature differently across the islands. Meanwhile, the Hawaiian archipelago experiences differences primarily between the main and northwestern Hawaiian Islands.

Temperature patterns observed from in this study confirm global investigations on increasing temperature trends (Johnson & Lyman, 2020) and also provide nuanced views into which areas found reprieve from rising temperatures during specific years. For example, ocean temperatures have hit record levels in the last decade which induced a global bleaching event from 2014–2017 (Eakin et al., 2019). Temperature trends across coastal sites in the Pacific confirm an overall increase, but also highlight years where temperature actually decreased compared to previous years. For example, temperatures in American Samoa decreased in 2016, a year when most islands in the PRIAs were experiencing their hottest year ever (Figure 4). Another example of geographical differences in trends is evident in the CNMI, where the southern islands are warmer than the northern islands and yet the trend increases at a slower rate compared to the northern islands.

In situ temperature loggers reveal that extreme heat events have become a common occurrence for most Pacific Island reefs. An extreme heat event in which the temperature was higher than the 90th percentile of the historical annual temperature was experienced across all regions and islands throughout the period of 2014–2017. There were differences in the number of extreme heat events experienced and the duration of the event, but all reefs observed experienced some measure of an extreme heat event during the that time. Therefore, this study confirms that the ocean is experiencing a recent normalization of marine heat extremes (Tanaka & Van Houtan, 2022).

For most of the reefs, depth was only marginally a refugia. The deeper reefs experienced fewer acute stress events, but if the shallow reefs experienced an extreme heat event, then the deeper reefs generally also experienced the same event though to a lesser degree overall. For reefs like Baker, Howland, and Jarvis located in the PRIAs, there was no strong vertical gradient in temperature with the three depth zones (shallow, mid, and deep). Instead, reefs in the deep (25 m) water experienced almost the same temperature as reefs in mid (15 m) and shallow sites (5 km). This is true for the eastern transect of these islands. The western sides of Baker, Howland, and Jarvis likely have upwelling, but there are no complete transects there to evaluate depth variation. The deeper reefs at Kingman and Palmyra occasionally experienced pulses of cool water, especially in 2016, that the shallow reefs did not experience. The transects for Kingman and Palmyra are both from the northern side of the islands where an upwelling signal is occasionally observed. In the face of climate change, depths are unlikely to provide long-term thermal refugia (Venegas et al., 2019), although pulses of cooler water from upwelling and internal tides may buffer some reefs from global warming (Bachman et al., 2022; Storlazzi et al., 2020).

Temperature on coral reefs is highly variable due to seasonal and daily cycles as well as short-term acute stress events (McClanahan & Azali, 2021). Furthermore, both long-term and short-term stress events are increasing in magnitude and frequency as climate change intensifies (Frölicher et al., 2018; Lough et al., 2018). Acute stress events have been linked to both increasing temperature variability tolerance of some corals, while reducing thermal performance of other corals (Klepac & Barshis 2022; Marzonie et al., 2023). The number of acute heat stress events at the Pacific Island sites increased in the same years there were long-term heat stress events. It is possible the short-term stress events added to the negative impacts of the long-term heat stress events and may have had negative impacts on corals. Matching the frequency of acute events to coral bleaching surveys would help determine if corals increased or decreased their thermal tolerance during heat events.

This study covered such a massive area and was restricted by limited spatial resolution of continuous temperature loggers around the islands. Information can be derived at the region or island scale, although sometimes obtaining temperature data at the even the island level can be difficult. For example, in populated islands, temperature loggers can be spotted by locals and removed from the reef. Also, large swell conditions during recovery may make it difficult to access the location to retrieve the STR. Meanwhile, the unpopulated islands and regions (PRIA and NWHI) have the highest numbers of sites with continuous temperature data despite not always having many temperature loggers deployed around each island. Benthic cover and coral bleaching responses are often variable within a small spatial area and differ by depth and around different sides of an island (Penin et al., 2007). The low spatial resolution of in situ loggers per island in this study means interpretation of ecological responses should be completed at the region or island scale, instead of examining variability of temperature within one island.

Future directions of this study could be to co-locate temperature time series data with coral bleaching survey data. Benthic surveys are conducted at the same fixed sites where the temperature loggers are re-deployed every 3–5 years as part of NCRMP surveys. Ecological data collected on benthic cover and coral demography can be examined at 3-year intervals to determine any ecological shifts that might be attributable to heat metrics even though bleaching is not measured directly during the time of the bleaching event.

Fine-scale spatial resolution of temperature around an island can be derived from ocean circulation models. An example of such a model is the Regional Ocean Modelling System (ROMS), which can provide temperature estimates at depth (Moore et al., 2011). The same temperature loggers deployed in this study were used to successfully validate ROMS in the main Hawaiian Islands and accurately predicted the 2014 and 2015 bleaching events around Hawaiʻi (Perelman et al., 2024). The in situ temperature loggers can be used to validate more fine-resolution ocean circulation models across the different Pacific regions. In situ temperature data coupled with fine-scaled ocean-modeled temperature data can be linked with benthic surveys collected around each island as part of NCRMP.

Even though NCRMP benthic surveys did not record bleaching occurrences during the 2014–2017 global bleaching event, they did capture the aftermath at certain locations. For example, hard coral cover at Jarvis Island declined from pre-bleaching cover of 18.7% in April 2015 to post-bleaching cover of 0.4% in May 2016 (Vargas-Ángel et al., 2019). By 2018, recovery was detectable as juvenile densities increased along with some stress-tolerant corals (Huntington et al., 2022). Overall, the 2014–2017 global bleaching event was unprecedented in successive record-breaking hot years which led to widespread bleaching and coral mortality (Eakin et al., 2019). Coral bleaching events are expected to continue with global climate change, and conservation efforts should be implemented to mitigate against future extreme heat events.

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Appendix

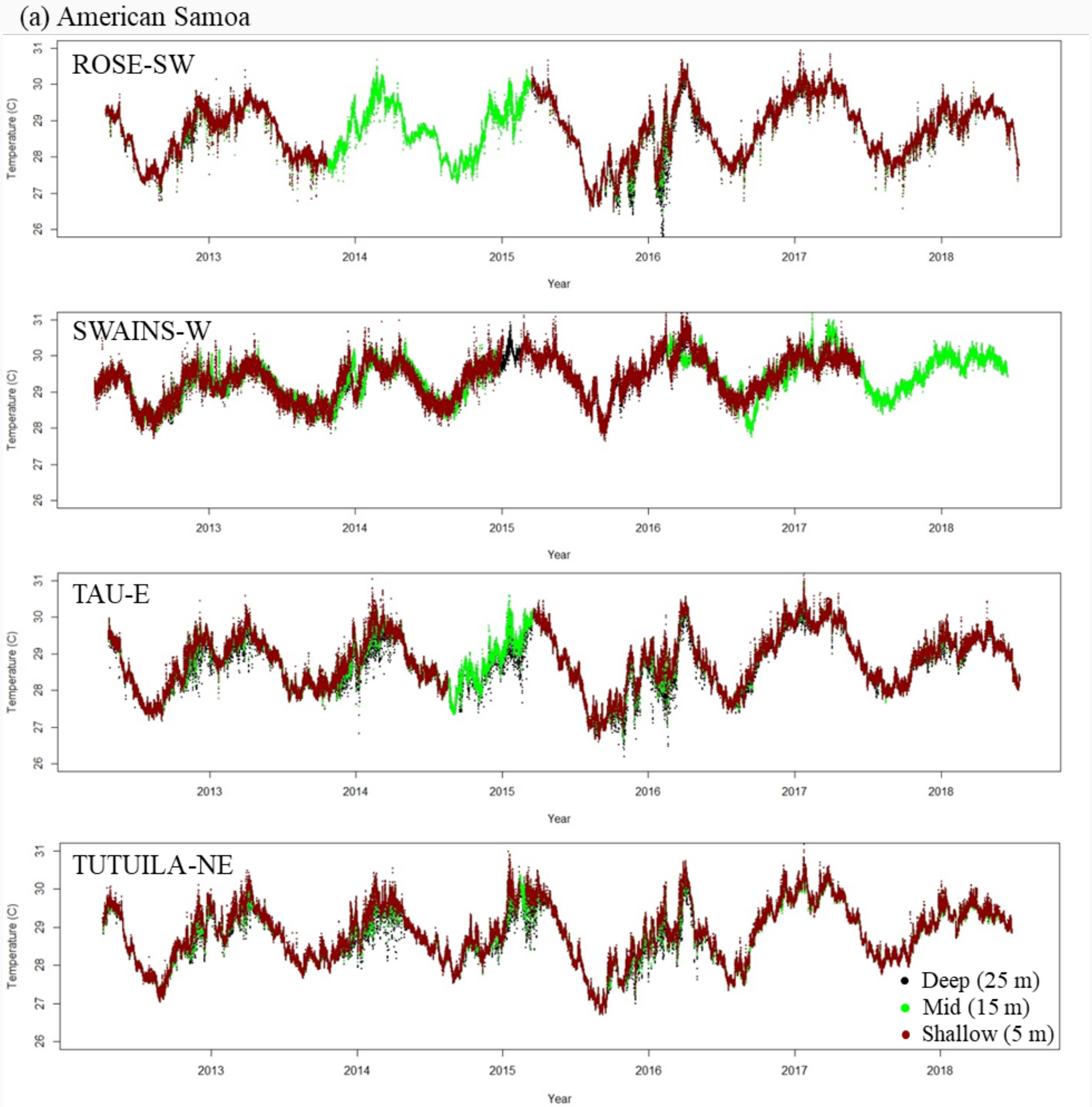

Figure A 1. Depth comparisons of temperature time series for complete transects (deep, mid, shallow). Transects are presented for islands in AMSM.

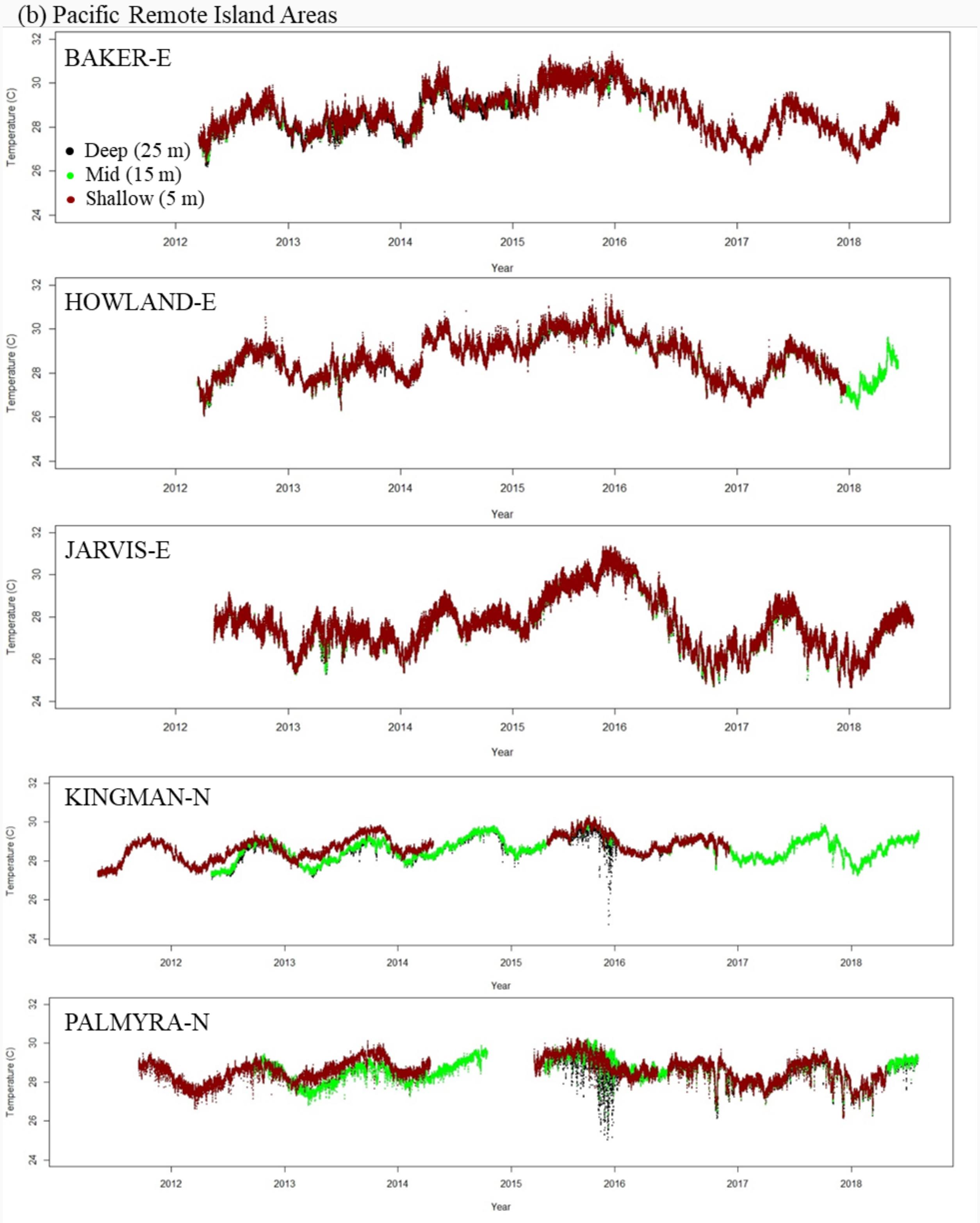

Figure A 2. Depth comparisons of temperature time series for complete transects (deep, mid, shallow). Transects are presented for islands in PRIAs.

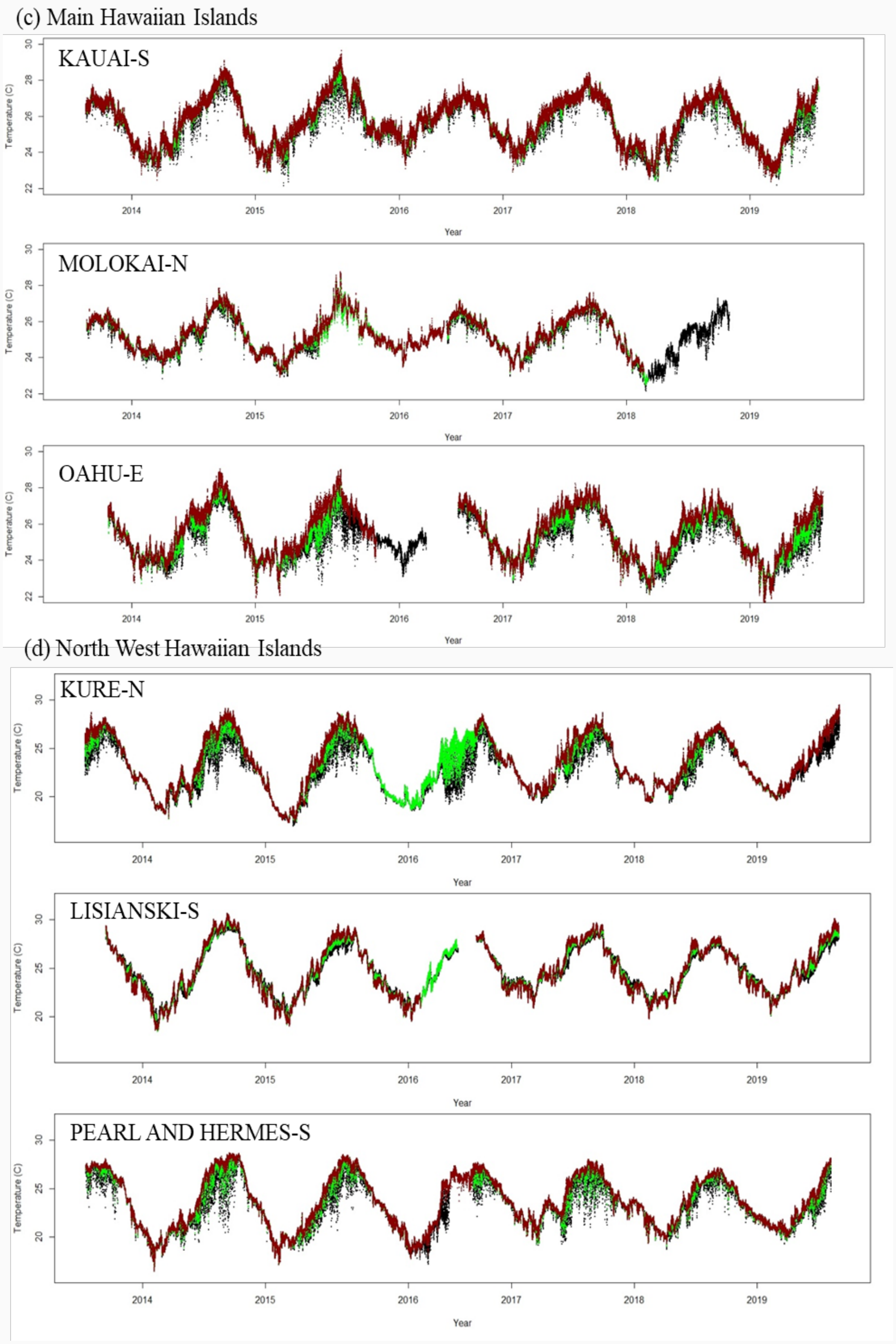

Figure A 3. Depth comparisons of temperature time series for complete transects (deep, mid, shallow). Transects are presented for islands in the MHI.