

Prepared in cooperation with the National Park Service

# Nearshore Water Quality and Coral Health Indicators Along the West Coast of the Island of Hawai'i, 2010–2014



Open-File Report 2020–1128

**Cover.** Photographs taken by Eric Grossman of partial bleaching of *Montipora capitata* (whole cover) and *Porites lobata* growth anomaly (center photograph).

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By Eric E. Grossman, Lisa Marrack, and Nathan R. vanArendonk

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**U.S. Geological Survey**

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## Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$$

## Supplemental Information

Ocean water salt concentrations are given in practical salinity units (PSU).

## Abbreviations

ANOVA	analysis of variance
CTD	conductivity temperature depth
cm	centimeter
°C	degree Celsius
ft	foot
GPS	Global Positioning System
km	kilometer
m	meter
NCRI	National Coral Reef Initiative
NPS	National Park Service
PSU	practical salinity unit
PVC	polyvinyl chloride
USGS	U.S. Geological Survey



# Nearshore Water Quality and Coral Health Indicators Along the West Coast of the Island of Hawai‘i, 2010–2014

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## Abstract

Coral reefs worldwide are experiencing rapid degradation in response to climate and land-use change, namely effects of warming sea-surface temperatures, contaminant runoff, and overfishing. Extensive coral bleaching caused by the steady rise of sea-surface temperatures is projected to increase, but our understanding and ability to predict where corals may be most resilient to this effect is limited owing to a lack of knowledge of nearshore habitat conditions and the role of compromised coral health in preconditioning bleaching vulnerability. On high islands and most atolls, fresh to brackish groundwater discharges to the coast through the beach face and seafloor, where it mixes with marine waters and commonly creates cool estuarine nearshore waters that are important to wildlife and ecosystem services that benefit people.

Here, we summarize results of a study to evaluate the ecosystem services and effects of groundwater on coral reef health and the potential role of groundwater to maintain cold-water refugia that can buffer corals from thermal stress during temperature maxima. Across 75 kilometers of the west coastline of the Island of Hawai‘i, paired time-series and discrete measurements of water quality, coral-community and colony size structures, and coral health indicators, including bleaching, at 33 stations grouped into 12 study areas were made from July 2010 to December 2013. The results show that nearshore water temperatures are depressed by groundwater across extensive areas of the nearshore. Persistent cold-water refugia ranging from 1 to 5 degrees Celsius below surrounding marine temperatures are shown to be associated with identified groundwater inputs. Significant correlations were found between metrics of coral health and water temperature. Because areas of temperature refugia were notable along the west coast of the Island of Hawai‘i and are identified by ecologists as increasingly important to valued wildlife, improved understanding of groundwater flux to the long-term resilience of coral reefs is likely important. In particular, evaluating the extent that the magnitude and timing of groundwater discharge across the nearshore mitigate thermal bleaching stress may help inform the fate of coral reefs projected to experience rising sea-surface temperatures worldwide.

## Introduction

### Coral Health and Bleaching

Coral reefs are one of the most productive and biologically diverse ecosystems on earth (Connell, 1978). In addition, coral reefs provide essential habitat for economically important fishery species, coastal protection from large waves, and a range of other aesthetic and cultural benefits (Moberg and Folke, 1999; Wilkinson, 2008). As part of one of the most isolated archipelagos in the world, the largest Hawaiian Island—the Island of Hawai‘i, hereinafter referred to as Hawai‘i—possesses some of the highest marine endemism recorded anywhere on Earth (Jokiel, 1987; Kay and Palumbi, 1987; Randall, 1998; Kane and others, 2014). The economic value of Hawai‘i’s coral reefs was estimated at \$10 billion with direct economic benefits of \$360 million per year in 2002 (Brander and van Beukering, 2013).

Despite their biologic and economic value, coral reefs have experienced high losses of live coral cover from anthropogenic stressors during the past 50 years (Bruckner and others, 2005; Wilkinson, 2008). Declines in coral abundance are associated with local-scale anthropogenic disturbances, disease, and bleaching—the process of corals expelling symbiotic algae from their tissue. Direct anthropogenic factors leading to coral reef decline include sedimentation, overfishing, introduced species, and contaminant runoff (Wilkinson and Hodgson, 1999; Bruckner and others, 2005; Wilkinson, 2008). These direct impacts have led to extensive loss of coral reefs throughout the main Hawaiian Islands, impacting fisheries and ecosystem services important to the economy of Hawai‘i and culture of Native Hawaiians (Freidlander and others, 2008).

Coral diseases are another major factor responsible for coral declines, especially in the Caribbean Sea (Harvell and others, 2007; Rogers and Miller, 2013). Although diseases naturally occur in most reef habitats, including remote offshore reefs as well as those near human population centers, evidence indicates coral disease is increasing in occurrence worldwide (Bruckner, 2009) and coral disease severity is linked to contamination from land-based sources, such as elevated

nutrients (Bruno and others, 2003; Voss and Richardson, 2006; Becker and others, 2013; Thurber and others, 2014), heat stress (Bruno and others, 2007), and overfishing of organisms that can control macroalgae and pest species like corallivores (Raymundo and others, 2009; Zaneveld and others, 2016). An improved understanding of disease dynamics and causal links can help inform management actions focused on conserving valuable reef ecosystems.

In the Indo-Pacific region, baseline data on disease occurrence are less established than in other oceanic regions; however, disease outbreaks have recently been documented (Bruckner, 2009). Baseline coral disease surveys were initiated at 78 sites on 6 different islands within the main Hawaiian Islands in 2004 to 2005 and 8 diseases were documented (Aeby and others, 2011). Corals of the genera *Porites* and *Montipora* had the highest disease prevalence. Signs of coral disease were widespread, occurring at 87.2 percent of the main Hawaiian Island sites surveyed, and the frequency of occurrence varied between diseases. A high occurrence of *Porites* growth anomalies within the main Hawaiian Islands suggest that *Porites* growth anomalies are related, directly or indirectly, to some environmental cofactor associated with increased human population sizes (Aeby and others, 2011; Couch and others, 2014).

Ocean warming has broad effects on coral reef ecosystems (Hoegh-Guldberg and Bruno, 2010). Large-scale anomalously high sea-surface temperatures can cause mass coral bleaching events as stressed corals release their symbiotic zooxanthellae (Marshall and Schuttenberg, 2006). If corals are close to their maximum thermal limits, only a 1–2 degree Celsius (°C) increase may trigger mass bleaching events (Marshall and Schuttenberg, 2006). If temperatures remain high, widespread coral die-offs may occur. Since 1998, coral bleaching has become a common phenomenon around the world, with severe bleaching occurring in every region (Marshall and Schuttenberg, 2006).

Around Hawai‘i, ocean waters show a trend of increasing temperature during the past several decades that are consistent with observations in other coral reef areas of the world (Coles and Brown, 2003; Jokiel and Brown, 2004). Average annual sea-surface temperatures around Hawai‘i have increased 0.8 °C since 1956, and rising water temperatures are expected to increase the frequency and severity of bleaching events (Jokiel and Coles, 1990; Friedlander and others, 2008). When this study was initiated in 2010, there had been only three documented large-scale bleaching events within the Hawaiian archipelago (Friedlander and others, 2008). In 2016 and 2019, two additional bleaching events occurred that led to extensive coral mortality (Rosinski and Walsh, 2016). Corals may recover from bleaching events (Jokiel and Brown, 2004), but in some regions massive coral die-offs have occurred after bleaching events (Glynn, 1984; Marshall and Schuttenberg, 2006). Although corals face numerous stressors, there is evidence that coral reefs have some resilience to change and disturbance

(Hughes and others, 2010). There is a great need for scientific, policy, and management approaches to support reef resiliency in the face of growing population and climate change.

## Submarine Groundwater Discharge

Recent studies show that submarine groundwater discharge along west Hawai‘i, like other areas, including Maui and Moloka‘i and most high islands and atolls, creates persistent and extensive nearshore plumes that are colder and fresher than surrounding seawater (Johnson and others, 2008; Grossman and others, 2010; Knee and others, 2010). Fluxes of submarine groundwater discharge into the coastal zone vary spatially and temporally in response to variations in recharge across watersheds and flow that can be affected by geology, slope, and complex structures like fractures, fissures, lava tubes, and porosity of rocks. Modeling shows that pumping all permitted wells will have the potential effect of decreasing the discharge of groundwater by about 50 percent and lowering the groundwater table 1–2 feet (ft) in and around Kaloko-Honokōhau National Historical Park since the mid-1970s (Oki and others, 1999). Extraction of groundwater to accommodate projected growth in population and tourism is expected to be exacerbated by climate change, which may already have induced a statewide decline in baseflow over the past several decades (Oki, 2004). Recent studies show that groundwater in Hawai‘i varies widely in composition of nutrients owing to natural sources and land-use activities, whereas contaminants are most commonly associated with urban, industrial, agricultural, and wastewater disposal activities (Johnson and others, 2008; Street and others, 2008; Knee and others, 2010; Hunt 2014). Recent studies have shown positive correlations between growth anomalies on *Porites* and phosphorous concentrations in the absence of thermal stress (McClanahan and others, 2009), and elevated phosphorous concentrations have been observed in groundwater discharging to the area likely related to industrial and septic leachate sources (Hunt, 2014). Increased population and urban development are projected to add nutrients, contaminants, and pathogens to groundwater, compromising its quality for ecosystem services and utility to people and communities.

## Project Objectives

In response to growing concerns of rising sea-surface temperatures, coral bleaching, reef degradation, unmanaged groundwater extraction and contamination, and projections of increased drought, the National Park Service (NPS) and partner agencies initiated research and communications addressing the link between coral reef health to water availability and quality on Hawai‘i to inform development of sustainable groundwater management policies. In coordination with the NPS Water Resources Division and Hawai‘i Division of Aquatic Resources, scientists from the U.S. Geological Survey (USGS)

Pacific Coastal and Marine Science Center conducted a multi-year study beginning in 2010 to examine nearshore habitat conditions, the influence of groundwater on coral reef habitats, and coral health along west Hawai'i. The goals of this work are to provide managers with quantitative baseline information to characterize the current condition of nearshore coral reef ecosystems, evaluate the influence of groundwater on coral health, including the potential for colder groundwater to buffer temperature stress and coral bleaching, and detect changes owing to expected land use and climate change.

Time-series and discrete measurements of sea-surface temperatures, salinity, coral-community and colony size structure, and coral health indicators along gradients of exposure to submarine groundwater discharge and land use across west Hawai'i were gathered between 2010 and 2014. These data were analyzed to evaluate trends between coral health and water quality and the extent of potential cold-water refugia that might benefit coral resilience. Previous research has documented the flux of submarine groundwater discharge, its composition entering the coast (Grossman and others, 2010; Knee and others 2010), and its potential importance to valued estuarine fish, bird, invertebrate, and plant species; some of the estuarine species are threatened or endangered. Improving our understanding of how groundwater hydrology shapes the structure and function of nearshore estuarine habitats has been identified as key information needed to help resource managers plan for resilience in a future of climate change. A central hypothesis guiding our research is that submarine groundwater discharge, where uncontaminated by land-use activities, may be important in buffering corals from bleaching stress during periods of high sea-surface temperatures because it is generally colder than surrounding seawater. If corals exhibited less bleaching or impaired coral health in such thermal refugia, it would signify that the magnitude of groundwater flux to the coast is important to coral reef resilience and the increasing threat of bleaching stress with rising sea-surface temperatures.

## Methodology

### Study Design

Paired measurements of water quality and coral health were made between June 2010 and December 2013 at 31 reef sites along 75 kilometers (km) of the west Hawai'i shoreline; additional water quality data were collected in two groundwater-fed anchialine pools (fig. 1B). This region of Hawai'i is arid and devoid of surface water runoff except during intense rainfall. Nearly all runoff occurs in the form of submarine groundwater discharge and, in some areas, submarine groundwater discharge flows out to sea with discharge comparable to small-to-moderate rivers (Grossman and others, 2010). West Hawai'i is a microtidal region and, although protected from the prevailing trade winds, it is exposed to periodic moderate to high wave energy associated with long-period ocean

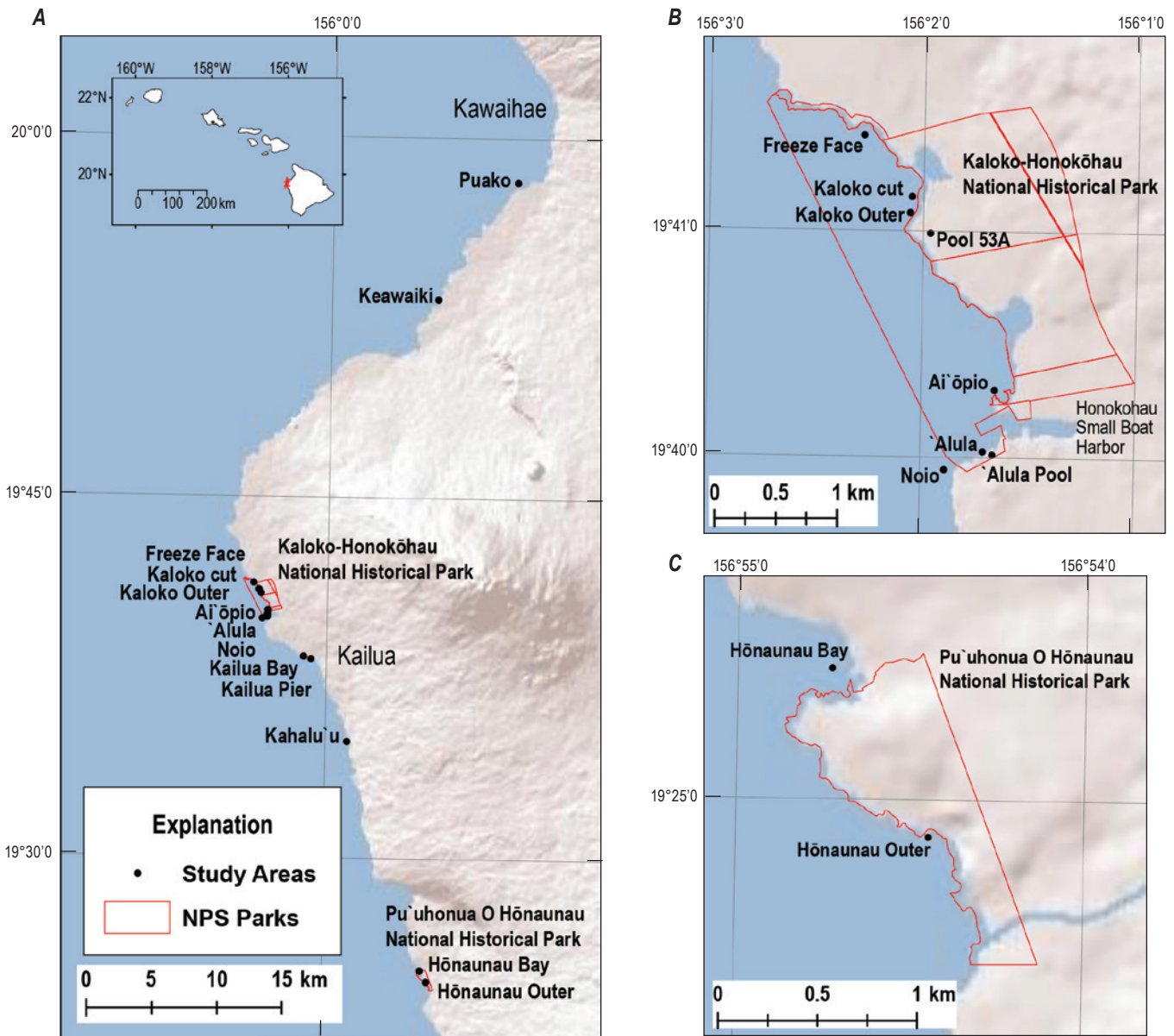
swell from the southern hemisphere and north Pacific Ocean. Although no robust studies of the age of coral reefs have been conducted in west Hawai'i, it is assumed that most coral reefs in the nearshore are generally thin veneers of late Holocene age since they formed on young (less than 10,000 years old) volcanic substrate, except in protected embayments where they may be several to tens of meters thick. West Hawai'i is largely undeveloped, except in the vicinity of Kailua and several resort areas where urban land uses may contribute to runoff of contaminants and nutrients in excess of what naturally occurs in groundwater.

Study sites were placed in shallow reef settings generally between 1 and 10 meters (m) depth to complement efforts concentrated in deeper reef zones ranging from 10 to 25 m (Couch and others, 2014). Study sites were selected around 11 principal study areas that are conceptually known or assessed to have distinct differences in groundwater inputs and influence. In each study area, multiple water temperature and (or) conductivity-temperature-depth (CTD) sensors were deployed to gather continuous time-series data and a set of three replicate transects were established to map coral community and colony size structure and health indicators (figs. 2, 3). Additional time-series data were collected in two groundwater-fed anchialine pools to characterize properties of groundwater entering the coastal zone. Discrete measurements of water quality were also measured via surface tows and CTD casts.

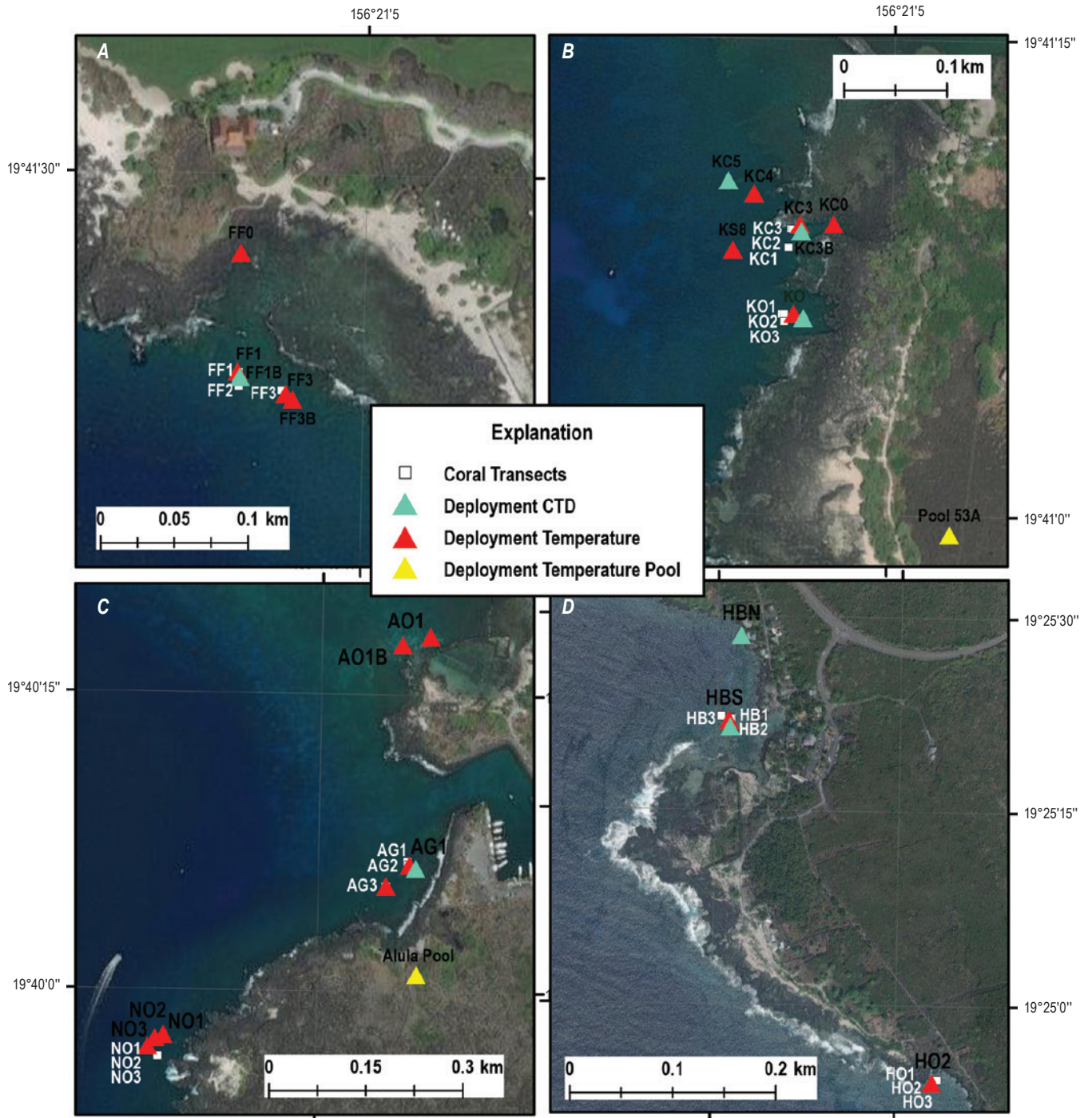
The study was initiated during the forecasted 2010 El Niño event, expecting to capture notable relations between water temperature, coral bleaching, and (or) coral health indicators. The El Niño climate phenomenon in Hawai'i commonly creates conditions of reduced trade winds, cloud cover, and high sea-surface temperatures that can lead to enhanced coral bleaching. The 2010 El Niño was mild and only moderate summer peak temperatures were captured in the study. The temperatures monitored in our study are suspected to have been significantly less than in the summer of 2015, which caused extensive bleaching and massive coral mortality.

Study sites were selected to have live coral cover in shallow reefs between 2 and 7 m (8–15 ft) depth (table 1). Sites were also chosen to represent areas within and outside of known submarine groundwater plumes (Johnson and others, 2008; Knee and others, 2008; Grossman and others, 2010) and where coastal circulation processes and their influence on the movement of submarine groundwater discharge plumes are well understood (Storlazzi and others, 2005; Presto and others, 2007; Grossman and others, 2010). The sites also represent a variety of potential land-use effects that may have a strong influence on groundwater quality. At each site, three 10-m transects were monitored. Cable ties were fixed to nonliving coral or volcanic substrate at the start and end of each transect and Global Positioning System (GPS) locations and detailed photographs of transect features were gathered to locate transects during repeat observations. Water-property sensors were mounted at the central coral mapping transect and around each study area to characterize variability (figs. 2, 3).

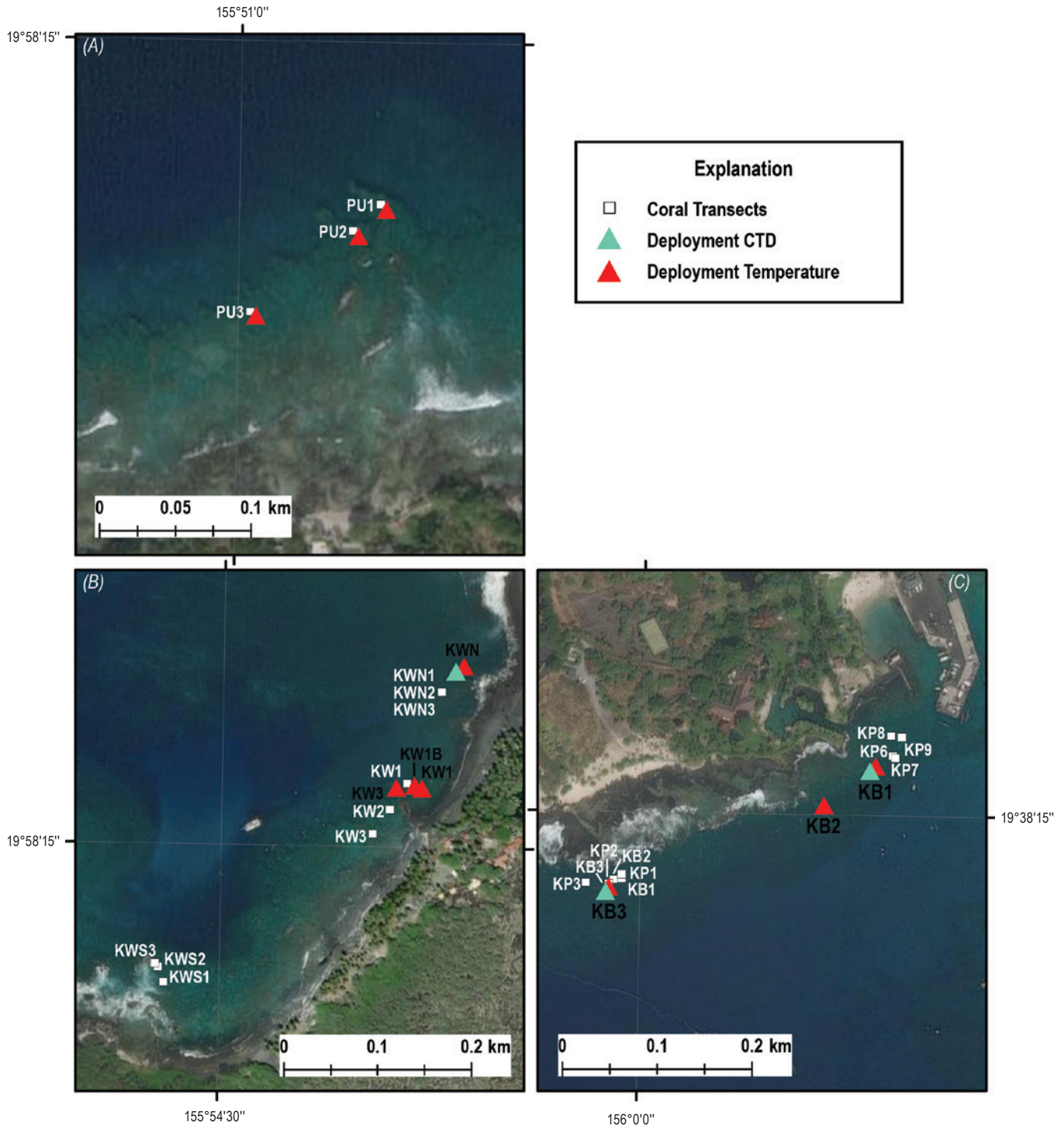
4 Nearshore Water Quality and Coral Health Indicators Along the West Coast of the Island of Hawai'i, 2010–2014



**Figure 1.** Map showing study areas (A) and the Kaloko-Honokōhau (B) and Pu'uhonua O Hōnaunau (C) National Historical Parks along the west coast of the Island of Hawai'i. km, kilometer; NPS, National Park Service.



**Figure 2.** Annotated photographs showing coral transect and sensor deployment locations within Kaloko-Honokōhau National Historical Park at Freeze Face cave (A), Kaloko bay and cut (B), and 'Ai'ōpio Fishpond, 'Alula Beach, and Noio Point study areas (C), and at Pu'u'honua O Hōnaunau National Historical Park (D). CTD, conductivity, temperature, and depth. km, kilometer. Site abbreviations correspond to those listed in table 1. Base map from Esri World Imagery and its licensors © 2014.



**Figure 3.** Annotated photographs showing coral transect and sensor deployment locations at the Puakō Point (A), Keawaiki (B), and Kailua Bay (C) study areas. CTD, conductivity, temperature, and depth. Site abbreviations correspond to those listed in table 1. Base map from Esri World Imagery and its licensors © 2014.



**Table 1.** Coral mapping transect location information.

[m, meter; ft, feet]

Site	Transect	Date	Start depth (m)	Start depth (ft)	Bearing (degrees)	Latitude	Longitude
Puakō Bay	PU1	6/20/2010	3	10	270	19.96987	-155.849
	PU2	6/20/2010	3	10	240	19.96971	-155.849
	PU3	6/20/2010	3	10	270	19.96922	-155.85
Keawaiki mid	KW1	6/24/2010	2.1	7	210	19.88808	-155.906
	KW2	6/24/2010	1.8	6	270	19.88786	-155.907
	KW3	6/24/2010	1.8	6	0	19.88762	-155.907
Keawaiki north	KWN1	11/7/2011	2.1	7	60	19.889	-155.906
	KWN2	11/7/2011	2.1	7	210	19.889	-155.906
	KWN3	11/7/2011	2.1	7	230	19.889	-155.906
Keawaiki south	KWS1	11/8/2011	2.7	9	0	19.88616	-155.909
	KWS2	11/8/2011	2.4	8	70	19.88631	-155.909
	KWS3	11/8/2011	2.1	7	10	19.88634	-155.909
Freeze Face	FF1	6/19/2010	3	10	330	19.69045	-156.038
	FF2	6/19/2010	2.7	9	120	19.69036	-156.038
	FF3	6/23/2010	2.1	7	50	19.69034	-156.038
Kaloko cut	KC1	6/23/2010	5	16.5	240	19.68567	-156.034
	KC2	6/23/2010	5	16.5	240	19.68585	-156.034
	KC3	6/23/2010	4.6	15	240	19.68585	-156.034
Kaloko outer	KO1	6/23/2010	4.9	16	320	19.68509	-156.034
	KO2	6/23/2010	4	13	60	19.68509	-156.034
	KO3	6/23/2010	4.6	15	100	19.68502	-156.034
'Alula Beach	AG1	6/22/2010	3	10	260	19.6685	-156.028
	AG2	6/22/2010	2.7	9	190	19.66845	-156.028
	AG3	6/22/2010	3.4	11	60	19.66815	-156.028
Noio Point	NO1	6/21/2010	5.8	19	10	19.66576	-156.031
	NO2	6/21/2010	6.7	22	30	19.66576	-156.031
	NO3	6/21/2010	5.8	19	240	19.66576	-156.031
Kailua Bay	KP1	6/26/2010	4.9	16	240	19.6369	-156
	KP2	6/19/2010	4.6	15	260	19.63678	-156
	KP3	6/19/2010	4.6	15	260	19.63682	-156.001
Kailua Pier	KP6	6/19/2010	2.7	9	290	19.63807	-155.997
	KP7	6/19/2010	2.7	9	265	19.63807	-155.997
	KP8	11/9/2011	3	10	235	19.63826	-155.997
	KP9	6/19/2010	3	10	210	19.63825	-155.997
Kailua Bay	KB1	11/9/2011	5.5	18	240	19.63686	-156
	KB2	11/9/2011	4	13	270	19.63685	-156
	KB3	11/5/2011	6.1	20	230	19.63681	-156

**Table 1.** Coral mapping transect location information.—Continued

Site	Transect	Date	Start depth (m)	Start depth (ft)	Bearing (degrees)	Latitude	Longitude
Hōnaunau Bay	HB1	10/7/2011	2.7	9	310	19.4228	–155.912
	HB2	10/7/2011	3	10	270	19.42278	–155.912
	HB3	10/8/2011	3	10	30	19.42284	–155.912
Hōnaunau outer	HO1	10/9/2011	2.7	9	60	19.41503	–155.908
	HO2	10/9/2011	3	10	120	19.41493	–155.908
	HO3	10/9/2011	2.7	9	230	19.41509	–155.907

## Mapping of Coral Community Structure and Health Indices

At each transect, scuba divers documented benthic cover and condition using photoquadrats and swath transects (table 2). In June and October 2010, nine sites were sampled. In October to November of 2011, seven of the initial sites and an additional four sites were assessed for fine-scale community structure and disease prevalence. During each site visit, divers also swam throughout the study area for evidence of widespread bleaching.

### Photoquadrats

Coral community condition was recorded at each 10-m transect during two or three time periods (June 2010, October 2010, or November 2011) using benthic survey protocols developed by the NPS at Kaloko-Honokōhau National Historical Park (Marrack and others, 2014; Weijerman and others, 2014) and modeled after USGS and NPS coral reef survey protocols (Rogers and Miller, 2001; Brown and others,

2006). Each 10-m transect was photographed along a transect tape using an underwater digital camera (Canon Powershot G11) set 0.6 m from the bottom. Photographs were taken at every 0.5-m interval along the transect tape starting at 0 m. Both sides of each transect were photographed using the wide angle setting with white balance adjusted underwater, providing a digital image of the condition of the benthic habitat at the time of data collection. The photographs provide an archive of coral community condition at the time of the study and provide digital photoquadrats for further analysis.

At the time photographs were collected, divers also collected data on coral bleaching prevalence for a 1×10-m swath centered along the transect tape. Holding a 1-m polyvinyl chloride (PVC) rod perpendicular to the transect, divers swam down the transect tape recording the total number of coral colonies present and where bleaching was observed, the species of coral, surface area of bleaching (length × maximum perpendicular width of bleached area), and severity of bleaching (partial or total) were recorded. These observations took between 10 and 15 minutes depending on the number of colonies present.

**Table 2.** Summary of coral health data collection methods, dates, and number of sites.

[m, meter]

Data type	Method	Date collected	Number of sites	Transects per site
Benthic cover (percentage of live coral, coral species, and other bottom types)	2×10 m photograph transects	June 2010	9	3
		Oct. 2010	8	3
		Oct. 2011	11	3
		June 2010	9	3
Coral bleaching prevalence	1×10 m swath	Oct. 2010	8	3
		Oct. 2011	11	3
Coral size and species prevalence	2×10 m swath	Oct. 2011	11	3
Disease prevalence by coral size and species	2×10 m swath	Oct. 2011	11	3

## Mapping of Fine-Scale Community Structure and Disease Surveys

In October and November of 2011, coral health indicators (table 3) were surveyed at 11 of the 12 sites, in 33 transects, using methods described by Walsh and others (2013) and Couch and others (2014). The surveys were designed to collect detailed information on population size structure for each species of coral observed, disease prevalence, lesion density, and bleaching. Because Hawaiian reefs are *Porites*-dominated and partial mortality is common, a colony was defined as all tissue fragments on the original parent skeleton. Colony color, morphology, and inflamed pink colony margins were also used to distinguish colonies.

To estimate the population size structure of scleractinian corals, divers identified the species and maximum diameter of colonies within a 2-m swath along the 10-m transect. Two divers, one on each side of the transect, made observations in 1-m increments until the entire transect was documented, then data was pooled. Surveys usually took 60–90 minutes for both divers. Colonies are assigned to the following size classes: 0–5 centimeters (cm), 6–10 cm, 11–20 cm, 21–40 cm, 41–80 cm, 81–160 cm, and greater than 161 cm.

To determine size-specific disease susceptibilities, the health state of each colony was recorded, including the presence or absence of growth anomalies, *Montipora* white syndrome, tissue loss syndrome, *Pocillopora* senescence, multifocal tissue loss, hypermycosis, algal overgrowth, bleaching, and predation after Couch and others (2014). The prevalence—number of individuals with a condition divided by the total number of colonies along a transect—of each condition was calculated across all species and within each species.

**Table 3.** Coral health indicator descriptions.

Lesion code	Description
GA	Growth anomaly
TLS	Tissue loss syndrome
SN	Snail grazing ( <i>Drupella</i> and <i>Coralliophila</i> )
COTS	Crown-of-thorns predation
PS	<i>Pocillopora</i> senescence
HYP	Hypermycosis
BL	Bleaching
ALOG	Algal and cyanobacterial overgrowth
CIL	Ciliates
MWS	<i>Montipora</i> white syndrome
MFTL	Multifocal tissue loss

We also estimated disease severity by counting the total number of lesions and lesion(s) size range on each colony surface. The data and additional information about the data are available in a data release (Grossman and others, 2019).

## Water Quality

Continuous and discrete measurements of nearshore water quality were made to gather quantitative data describing the variability of water temperature and salinity over a variety of spatial and temporal scales affecting coral reef habitats. Data were also collected in several anchialine pools close to the shoreline to characterize groundwater quality entering the coastal ocean and to complement a concurrent monitoring study of groundwater quality (Tillman and others, 2014a) that characterize the temperature, chemistry, and contribution of inland impounded groundwater to the coastal unconfined groundwater system that discharges to the nearshore coastal environment (Tillman and others, 2014b). Measurements were made through continuous time-series deployments, surface tows, and CTD casts.

## Continuous Monitoring

At each coral reef study area, multiple temperature loggers were placed on nonliving substrate at the beginning or end of coral reef mapping transects. Additionally, at least one CTD was deployed at each study area to characterize variability in salinity associated with groundwater inputs and local circulation as well as water level affected by tides and storm surge. All loggers were synched in time and recorded data principally at intervals of 10 minutes, although a few individual deployments were sampled at 20 minutes to maximize record length and minimize instrument recovery and redeployment effort. Each study area had replicates provided by multiple sensors to quantify variability and back up data. Additional information about the data collection and access to the data are available in Grossman and Marrack (2019).

## Discrete Samples

Discrete measurements of water quality were made across the study sites through surface tows and depth-profiling CTD casts. A multiparameter water quality sonde was used behind small boats or kayaks to record water temperature, salinity, pH, and dissolved oxygen in the upper 0.5 to 1.0 m of the surface. Tows were generally conducted along predefined transects both along and across the shore and helped determine the extent of groundwater plumes. CTD casts were made using a small skiff or kayak to characterize the extent and thickness of groundwater-fed plumes across each study area and general variability with depth. CTD casts were made at specific points and along surface tow transects. Both approaches were generally applied

over the course of 1–2 hours to capture conditions associated with specific periods of the tidal regime, diurnal heating cycle, weather events (during or following wind and [or] rain events), and to understand the effects of waves on mixing. Additional information about the data collection and access to the data are available in Grossman and Marrack (2019).

## Data Processing

### Coral Cover, Community Structure, and Health Indices

Photoquadrats were analyzed for percentages of live coral cover, live coral cover by species, bleached coral, algae cover, and other substrate details in the lab. Using the National Coral Reef Initiative (NCRI) software CPCe, a unique plot of 45 computer generated random points were placed over each digital photograph image. One analyst identified the coral species or other benthic type—bare rock, sand, turf algae, macroalgae, coralline crust—located under each point (Grossman and others, 2019). To reduce duplication along photoquadrat edges, every other photoquadrat from one side of each transect, for a total of 10 quadrats per transect, were analyzed. Prior analysis shows that this level of sampling effort is sufficient to capture total coral cover with low standard error (Marrack and others, 2009). Photoquadrat data were compared between time periods to examine change in total coral cover and benthic structure over time.

Coral health metrics were summarized for 11 study sites (Keawaiki mid, Keawaiki north, Keawaiki south, Freeze Face cave, Kaloko cut, Kaloko outer, ‘Alula Beach, Kailua Bay 1 and 3, Hōnaunau Bay, and Hōnaunau outer), integrating results from the three replicate transects. The coral health indicators are compared to water quality data and reported below at each water quality (sensor) site (locations shown in figs. 2 and 3). Metrics include the count of coral colonies, unique species affected, and health indicators observed at each site. The total, mean, and standard deviation of counts of colonies affected and counts of indicators on specific genera and species were enumerated. In addition, statistics of the counts of individual health indicators (for example, growth anomaly, algal and cyanobacterial overgrowth, snail grazing, and ciliates) on each species were summarized. Repeated analysis of variance (ANOVA) measurements were used to determine if significant changes in coral bleaching occurred over the sampling periods at each location. Data were transformed as needed to fulfill requirements of normal distribution and homogenous variance.

### Water Quality

Processing of water quality data consisted of merging in-water values with position information collected by GPS to flag and remove outliers associated with sensor fouling. Generally, data coverage was near complete for sensors retrieved,

although a few deployed for continuous measurements were lost or damaged during the 2011 Tohoku tsunami. In a few isolated cases, outliers in the 10-minute time-series and 10-second tow data that reflected individual instances of sensor fouling or, for tows, experienced sudden jumps above the surface because of waves that returned to normal continuous values were interpolated based on averaging either side of the outlier.

Similarly, GPS data periodically recorded one spurious point that was then averaged assuming continuous motion at the average speed of transit during the outlier. More information on data processing are available in Grossman and Marrack (2019).

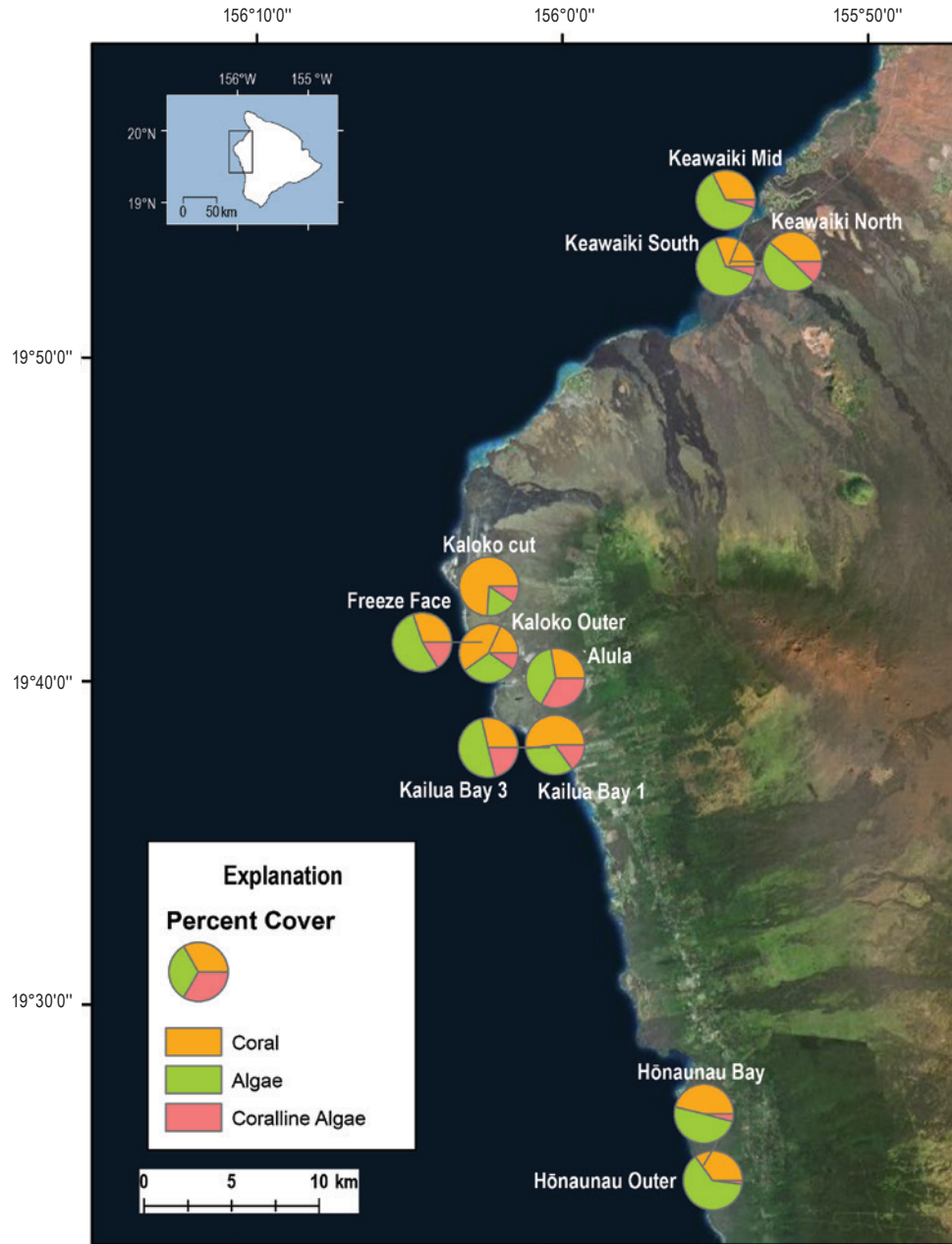
Water quality metrics were derived for each station and 11 study areas from the continuous temperature and salinity time series, surface tows, and CTD casts for comparison with the coral health metrics. Principal water quality metrics evaluated in this report focus on characteristics of nearshore water during the summer months of 2010 through 2012, spanning July 15 to October 15 when heat stress is typically highest in Hawai‘i, although other stressor and time periods may also be important. Mean, maximum, and minimum temperatures over the summer period along with the frequency and duration in hours of temperatures above 27, 27.5, 28, and 28.5 °C were calculated. In addition, a slightly lower threshold of 26.75 °C was also examined. The magnitude and frequency of deviation from the mean and maximum temperature across each area and across the entire study domain was calculated at each time step for overlapping measured values, then summarized for the entire summer period. The frequency of deviation of at least 0.5 °C below the 27 °C threshold was also calculated for each site.

## Results and Discussion

### Coral Community Structure

Analysis of photoquadrats showed that benthic habitat varied among sites from 12 to 82 percent total coral cover. Coral cover was relatively consistent between transects within each site, except in the case of the area adjacent to the Kailua Pier (KB1 sensor site) where coral cover along transects varied from 33 to 81 percent (fig. 4). Turf algae and coralline algae were the other dominant benthic components detected by photoquadrats. Other macroalga species were rarely observed.

Transects varied in scleractinian coral species richness from 5 to 13 species, with a mean of 8.6 species. As expected for shallow Hawaiian coral reefs, detailed community structure surveys showed the dominant corals at all sites were *Porites lobata* and *Pocillopora meandrina* (fig. 5). On average, *P. lobata* colonies made up 63 percent of all colonies per transect, whereas *P. meandrina* made up 20 percent of the total colonies per transect. The inner area of Kailua Bay near the pier (KB1) and Keawaiki were the only sites where *P. lobata* composed less than 50 percent of all coral colonies.



**Figure 4.** Map of the west coast of the Island of Hawai'i showing benthic cover by percent.

*Montipora* species and *Pavona varians* colonies were found at all sites with low abundance. The sites with the greatest species richness counts were 'Alula Beach (13 species), followed by Kailua Bay 1 (12 species) and Keawaiki (12 species). Detailed disease surveys were better at detecting the less common coral species than the photoquadrats because observers were able to find small cryptic colonies that were not apparent in photographs. Site abbreviations correspond to those listed in table 1.

Coral size structure varied among sites, but at all locations the dominant size of colonies was below 40 cm in diameter (fig. 6). The outer Kailua Bay site (KB3) had the highest proportion of coral colonies under 5 cm, with an average of 31 percent per transect. Kaloko cut, Kaloko outer, and Hōnaunau Bay had the lowest proportion of colonies under 5 cm (10–11 percent per transect). Colonies larger than 160 cm were unusual on transects but were most common at Hōnaunau Bay (4 percent of colonies) and Kailua Bay 1 (1 percent of colonies).

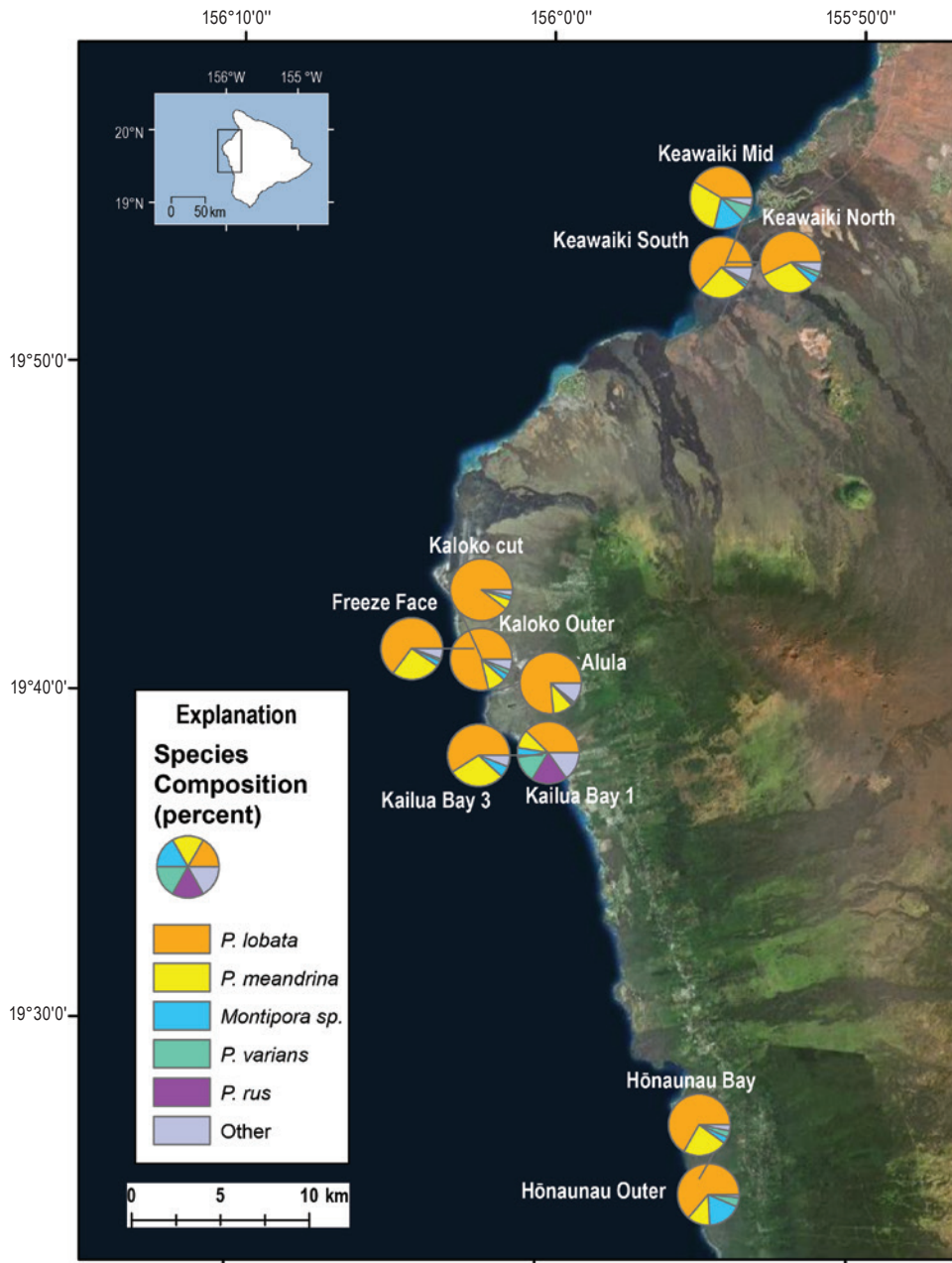


Figure 5. Map of the west coast of the Island of Hawai'i showing coral community composition by percent.

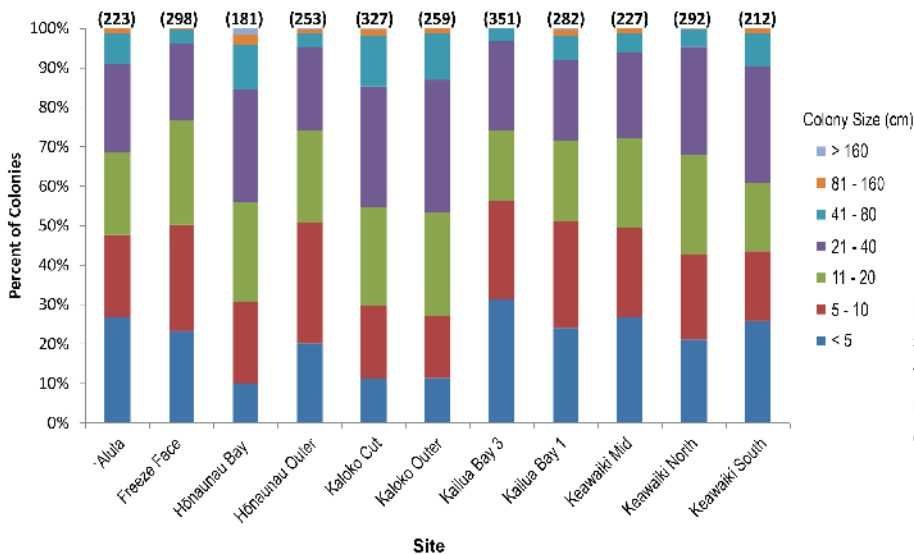
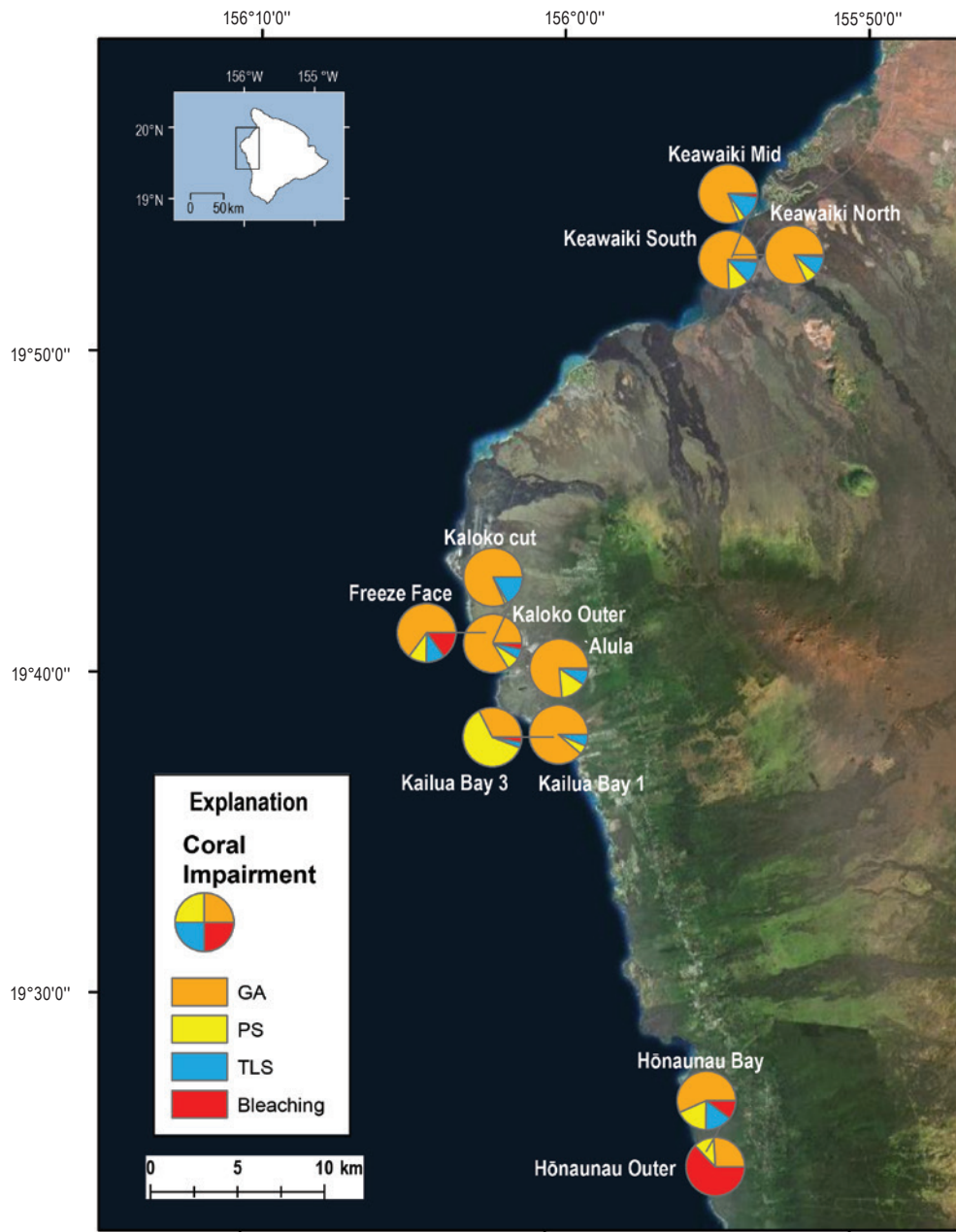


Figure 6. Plot of frequency of coral colony size structure in study areas with average total number of colonies within a transect noted above each column in parentheses. cm, centimeter

### Coral Community Health

The most prevalent coral health indicators observed were growth anomalies, *Pocillopora* senescence, and tissue loss syndrome, which were present at all sites (fig. 7). The prevalence of disease and other conditions varied among sites with the lowest prevalence at Freeze Face cave and the outer areas of Kailua Bay (Kailua Bay 3). Multifocal tissue loss

and *Montipora* white syndrome were not seen at any of the sites. Hypermucositis was not common and was only observed on 13 *Pavona varians* colonies in Hōnaunau sites. Only five coral colonies from all transects showed evidence of crown of thorns predation, and these were at Freeze Face cave, Kailua Pier, Kailua outer, and Hōnaunau Bay. During June 2010, crown of thorns predation was evident at Noio Point as well. More prevalent conditions are discussed individually below.



**Figure 7.** Map of the west coast of the Island of Hawai'i showing percent distribution of the three most prominent coral health indicators (growth anomaly, *Pocillopora* senescence, and tissue loss syndrome) and coral bleaching observed across the study area.

Growth Anomalies

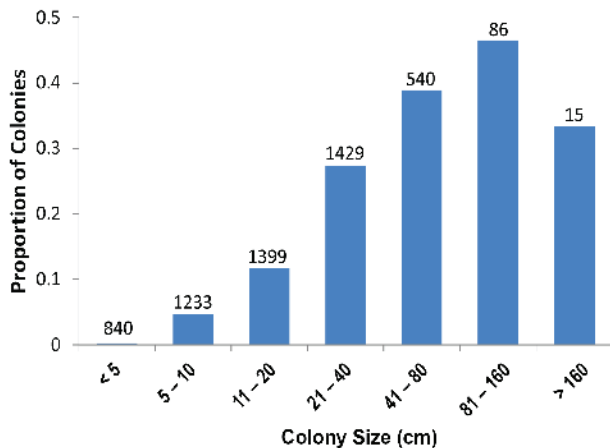
During detailed community surveys, growth anomalies were the most common type of coral disease recorded (table 4). Across all 33 transects, a total of 868 colonies were recorded with growth anomaly lesions. Of colonies with growth anomaly lesions, 99 percent were *P. lobata*. Other species observed with growth anomalies were *P. meandrina*, *Porites rus*, and *Montipora patula*. Kaloko cut and Kaloko outer, Keawaiki and Keawaiki north, and the Kailua Pier area (Kailua Bay 1) had the highest prevalence of growth anomaly

lesions (transect averages 22.7 to 31.3 percent of *P. lobata* colonies). Freeze Face cave, Hōnaunau outer, and Kailua Bay 3 had the lowest prevalence of growth anomalies (transect averages 2.1 to 5.4 percent of *P. lobata* colonies). The number of growth anomalies on an individual colony increased with colony size. When *P. lobata* colonies were examined across all 33 transects, the greatest prevalence was in the 81- to 160-cm-size category, in which 47 percent of *P. lobata* colonies had growth anomalies (fig. 8). The lowest prevalence was in the under-5-cm category, in which 2 out of 840 *P. lobata* colonies had growth anomaly lesions.

**Table 4.** Prevalence of health conditions for coral colonies along 2×10-meter transects.

[Values outside of parentheses represent percentages of colonies with a condition based on average of each site. Values within parentheses are the percentage of total colonies with the condition across the west coast of the Island of Hawai'i. *Pocillopora* senescence only occurs on *P. meandrina*, so percentage data are calculated from total colonies as well as total *P. meandrina* colonies. Growth anomalies occurred primarily on *Porites lobata*, so are calculated as a percentage of total colonies as well as total *P. lobata*. %, percent].

Site	Bleaching (% of total)	Growth anomaly (% of total)	Growth anomaly of <i>Porites lobata</i> (% of <i>P. lobata</i> )	<i>Pocillopora</i> senescence (% of total)	<i>Pocillopora</i> senescence of <i>P. meandrina</i> (% of <i>P. meandrina</i> )	Tissue loss syndrome (% of total)
‘Alula Beach	0.3 (0.2)	21.7 (10.2)	13.8	4.0 (1.8)	19.5	2.3 (1.05)
Freeze Face	1.0 (0.3)	4.3 (1.5)	2.3	0.7 (0.2)	1	0.7 (0.2)
Hōnaunau Bay	2.3 (1.3)	12.7 (6.9)	10.2	4.0 (2.2)	9	3.3 (1.9)
Hōnaunau outer	14.7 (4.1)	6.0 (3.1)	5.4	2.7 (1.1)	9.1	0.0 (0.0)
Kaloko cut	0.7 (0.2)	65.3 (20.2)	22.7	1.3 (0.4)	8.1	13.3 (4.1)
Kaloko outer	2.3 (1.0)	57.0 (22.1)	28.3	5.0 (1.9)	18.3	3.7 (1.4)
Kailua Bay 3	0.3 (0.1)	3.7 (1.0)	2.1	7.0 (2.0)	7.1	0.3 (0.1)
Kailua Bay 1	0.0 (0.0)	23.3 (8.7)	22.7	1.3 (0.5)	3.5	1.7 (0.6)
Keawaiki mid	0.7 (0.3)	28.3 (12.6)	31.3	1.3 (0.6)	2	4.7 (2.1)
Keawaiki north	0.7 (0.3)	42.3 (14.3)	25.7	3.3 (1.1)	3.8	5.3 (1.8)
Keawaiki south	0.3 (0.2)	24.7 (12.0)	18.7	3.7 (1.7)	5.6	4.0 (1.9)



**Figure 8.** Plot of the proportion of *Porites lobata* colonies with growth anomalies observed by size category across all sites and transects. The total number of *P. lobata* colonies counted within a size category across the entire study area in parentheses above bar.



### Pocillopora Senescence

*Pocillopora* senescence was observed at all sites, affecting 1 to 19 percent of total *P. meandrina* colonies per transect (table 4). Prevalence increased with colony size. When *P. meandrina* colonies were examined across all 33 transects, the greatest prevalence was in the largest observed size category (41–80 cm), in which 18 percent of *P. meandrina* colonies were in some stage of senescence (fig. 9). *Pocillopora* senescence prevalence did not show a relation with the percentage of cover of *P. meandrina*.

### Tissue Loss Syndrome

Across all sites, a total of 118 colonies were observed with tissue loss syndrome and 97 percent of these occurred on *P. lobata* (table 4). Tissue loss syndrome prevalence ranged

from 0 to 4 percent of all colonies per transect. The highest prevalence was at Kaloko cut, where the average number of colonies per transect with tissue loss syndrome was 13.

### Bleaching

During disease surveys in 2011 across all 11 sites, partial bleaching was observed on 18 out of 33 transects (55 percent), but 16 of these transects had 4 or fewer colonies with bleaching lesions (fig. 10, table 4). Partial bleaching was observed on 72 colonies, including *P. meandrina*, *P. lobata*, *M. capitata*, *M. patula*, *P. nei*, and *M. flabellata* colonies. During these surveys, 64 percent of all bleached colonies occurred at two transects near Hōnaunau—7 colonies at site HBS1 and 39 colonies at site HO2. Bleaching at Hōnaunau sites was primarily on *M. capitata* colonies from 5–40 cm in diameter. Average bleaching prevalence was 0 to 1.3 percent of total coral colonies per

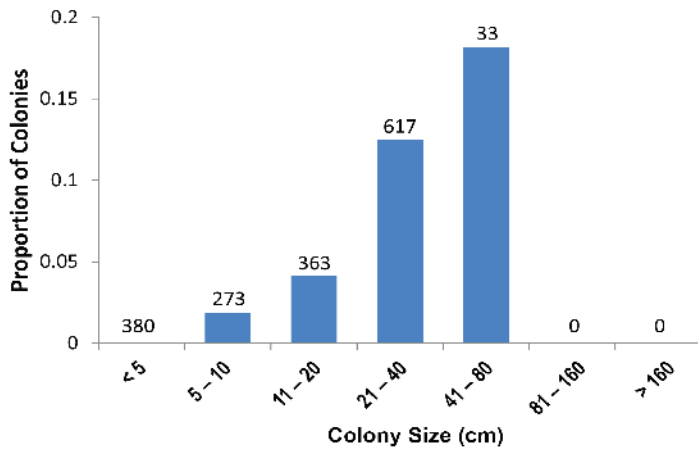


Figure 9. Plot of the proportion of *Pocillopora meandrina* colonies with *Pocillopora* senescence observed by size category across all sites and transects (total number listed above each column).

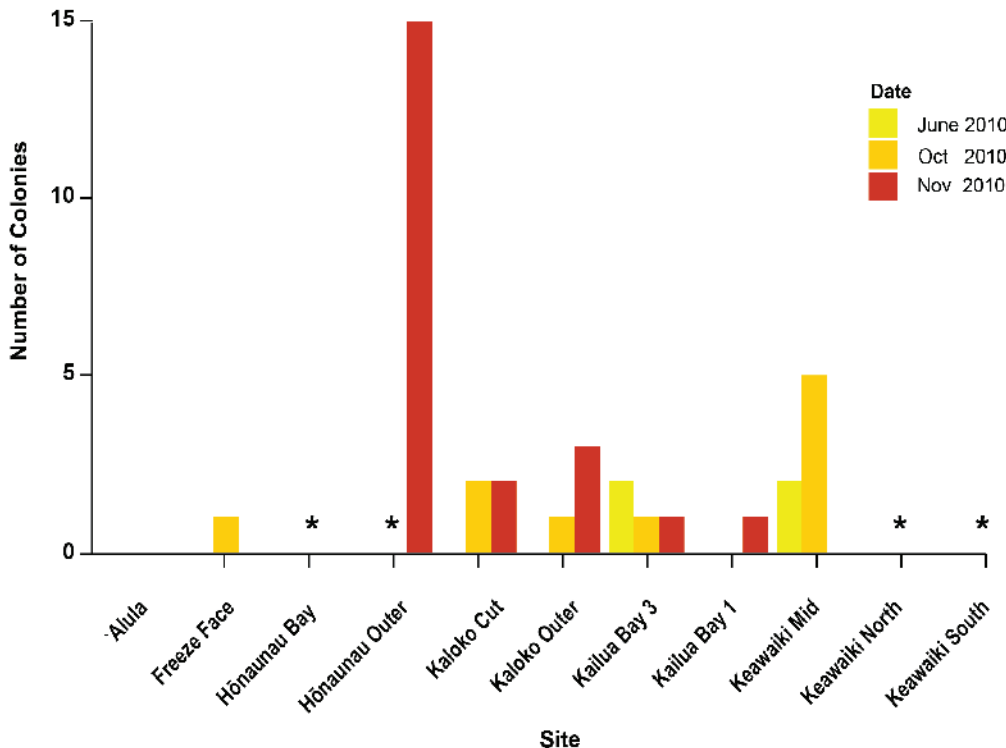


Figure 10. Plot of the total number of bleached colonies per site observed in June 2010, October 2010, and November 2011. Sites with an asterisk on the x-axis are sites that were only visited in November 2010.

2×10-m transects at all sites except at Hōnaunau outer, where 4.1 percent of colonies per transect were bleached.

For the observations made in June 2010, October 2010, and November 2011 using the rapid 1×10-m swath transects, there were minor amounts of bleaching. In 2010, there was no bleaching observed at 'Alula Beach, Noio Point, and Puakō Bay. The greatest occurrence was at Keawaiki on five colonies of *M. capitata*. However, visual scans of the surrounding reef showed that bleaching was not widespread. In 2011, the rapid swath transects confirmed observations made during detailed disease surveys. Bleaching was minor or absent at all sites except Hōnaunau, where 15 colonies of *M. capitata* were recorded with partial bleaching. Visual scans of areas around the transects showed that there was no widespread bleaching event at any site during 2010, 2011, or 2012 visits.

## Water Quality and Habitat

### Surface Patterns in Water Temperature and Salinity from Tows

Surface water temperature, salinity, pH, and dissolved oxygen were collected along 170 linear kilometers of the west Hawai'i nearshore at 11 study areas over four seasons including October 2010, March 2011, July 2011, and December 2013. Repeat surveys of water quality on shore-parallel and across-shore transects revealed the extent and persistence that lower temperature and salinity estuarine waters associated with groundwater seeps maintain cold-water refugia, defined as areas that are colder than the regional average and (or) nearby areas. Spatial gradients in temperature and salinity were used to characterize how groundwater plumes extend across the reef and nearshore and how these plumes can depress marine temperatures and salinities.

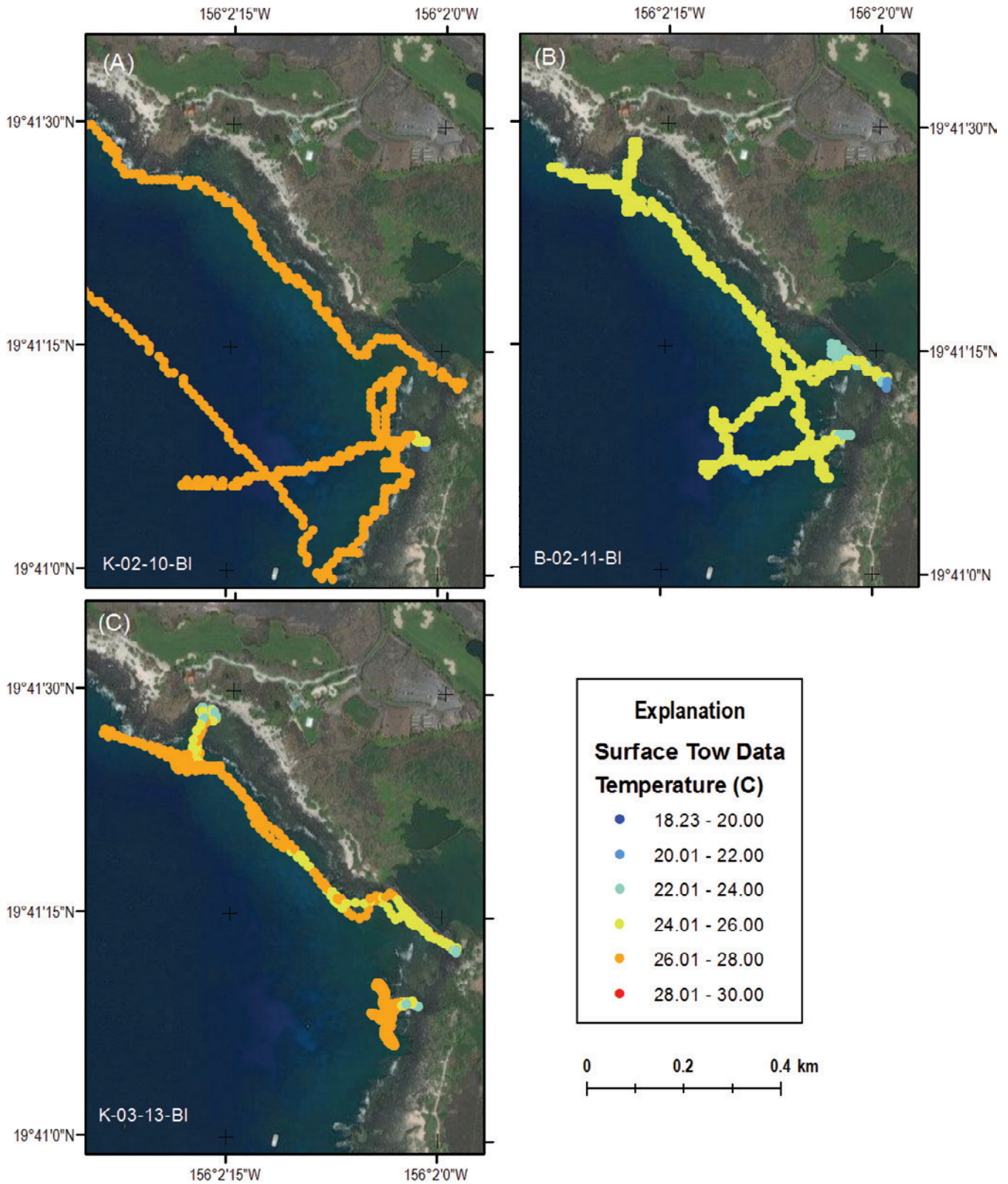
Repeat surveys across Kaloko bay in October 2010, March 2011, and December 2013 showed prominent inputs of water colder and of lower salinity than marine water offshore near the Kaloko Fishpond and known groundwater seeps of Kaloko cut (fig. 11). Temperatures on average were 1–2 °C colder nearshore in all seasons and colder in March 2011 than October 2010 and December 2013. The zone that marine water temperature was depressed by groundwater was larger in March 2011 and December 2013 than October 2011. Surface water salinities in Kaloko bay were higher and more uniform in October 2010 and March 2011 (greater than 33 practical salinity units [PSU]), than in December 2013 (27–33 PSU) (fig. 12). Salinity along shore was 2–4 PSU lower in December 2013 than the other seasons. In December 2013, prominent

low salinity groundwater seeps were also observed emanating from Kaloko Fishpond, Kaloko cut, and the Freeze Face area. The water temperature associated with the Freeze Face groundwater seep was about 1–2 °C warmer than the seep at Kaloko cut.

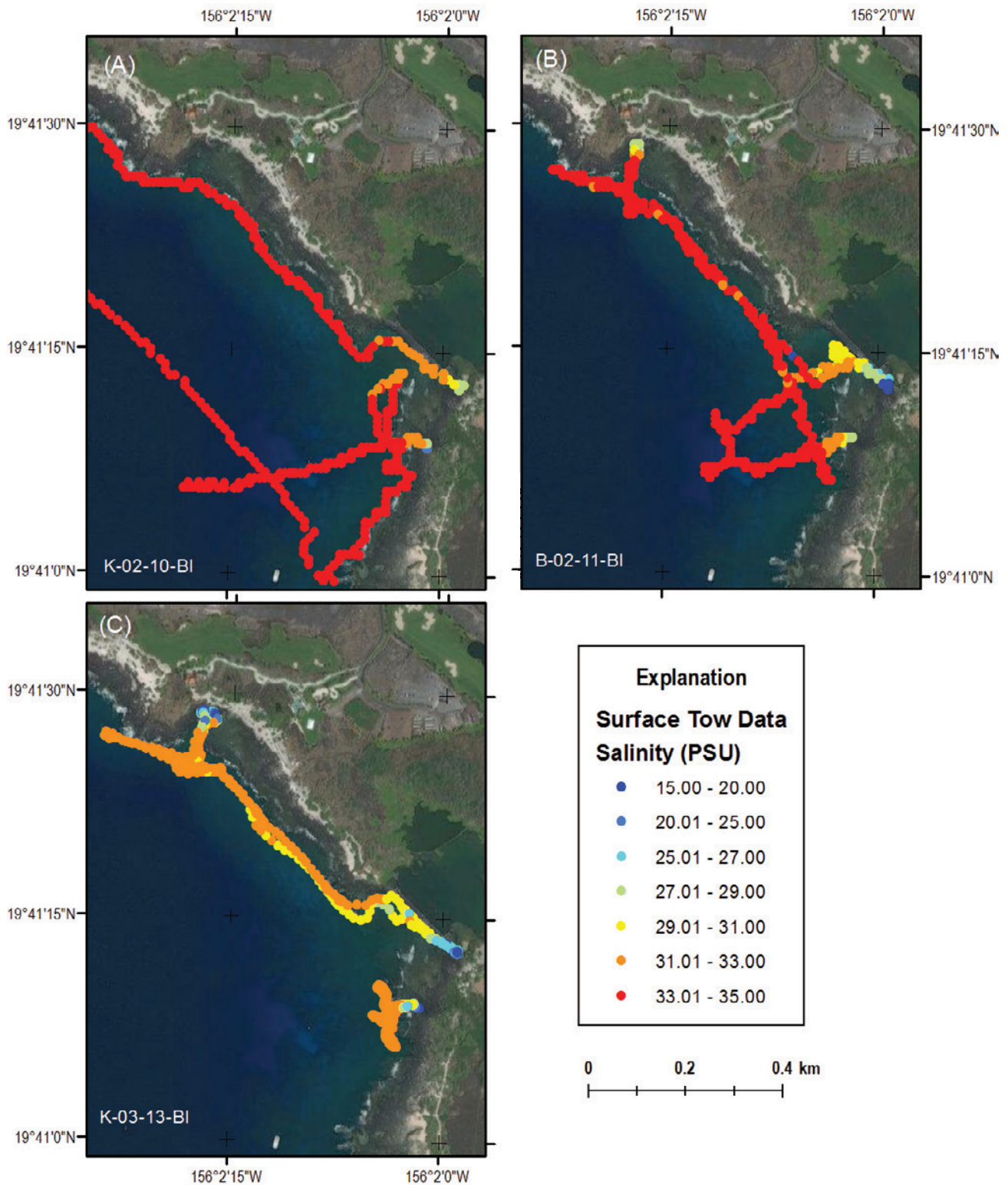
Repeat surveys in southern Kaloko-Honokōhau National Historical Park in and offshore of the 'Ai'ōpio Fishpond, Honokōhau Small Boat Harbor, and 'Alula also show persistent input of cold, low salinity water that creates a large estuarine plume of water extending 1–2 km offshore. In some places, temperatures just offshore the harbor were observed to be 1–2 °C lower than offshore marine waters (fig. 13) and in each season these depressed temperatures were associated with salinities ranging from 1 to 3 PSU lower than offshore marine values (fig. 14). In fact, during this study and prior research (Grossman and others, 2010), full marine salinities at the surface were rarely observed, indicating that estuarine waters extended out to and beyond the 1–2 km distances surveyed offshore of the coastline. Importantly, the estuarine conditions observed depress marine temperatures and salinities between 1–2 °C and 1–15 PSU, respectively, across expansive areas of the reef that corals and other important marine life depend on.

Repeat surveys across Hōnaunau Bay and Pu'uhonua O Hōnaunau National Historical Park similarly showed extensive estuarine plumes of surface water over each season surveyed. Temperatures (fig. 15) and salinities (fig. 16) were as much as 2 °C and 10–15 PSU, respectively, lower than marine values. Generally, temperatures were more uniform across Hōnaunau Bay than the Kaloko area, likely a result of more energetic mixing by waves and winds. Cross-shore gradients in temperature and salinity appear persistent over time, in agreement with past findings (Johnson and others, 2008).

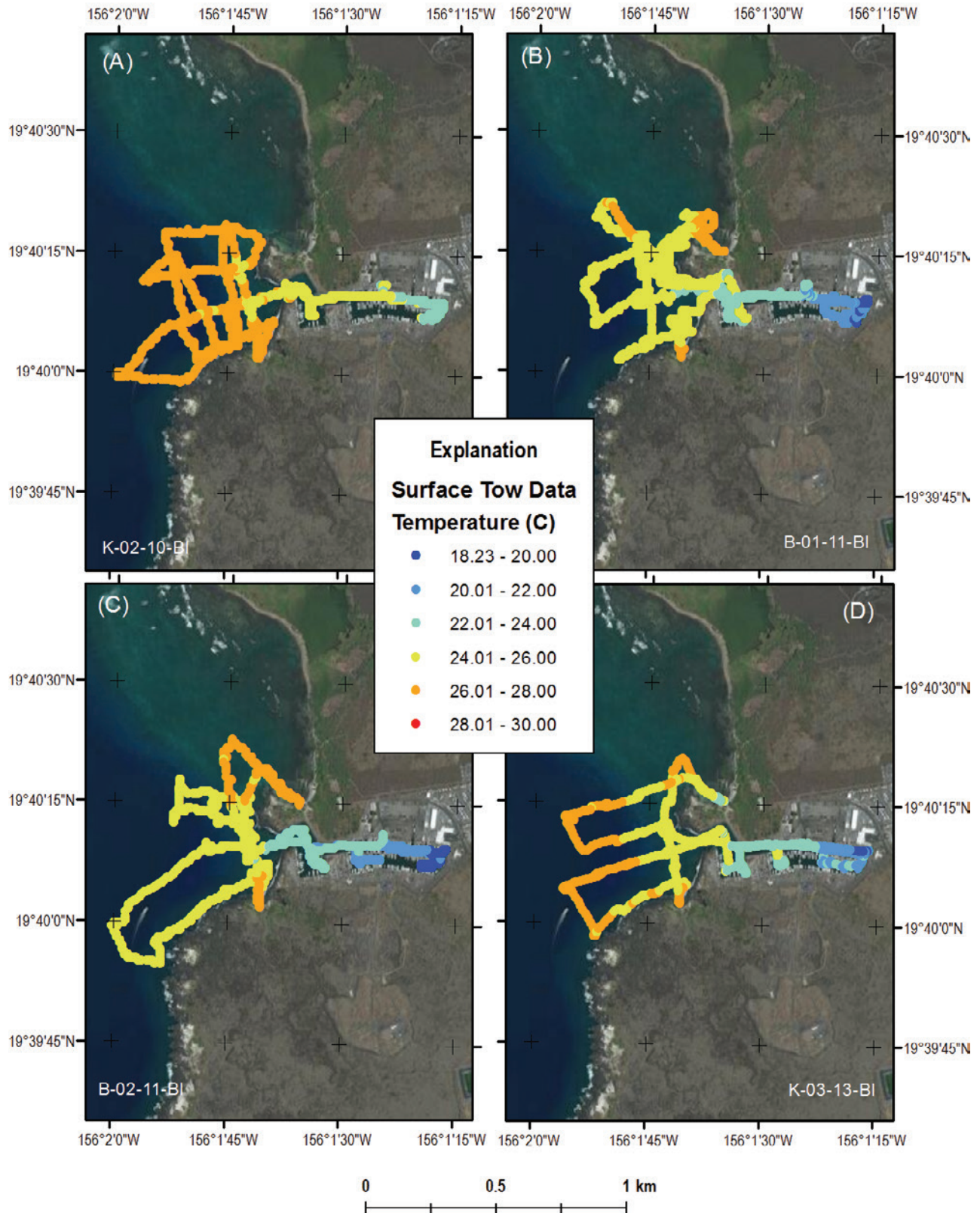
In addition to NPS sites, we surveyed sites at Keawaiki and Kailua Bay, which vary in groundwater influence, urbanization, and coastal circulation processes that mix waters. At Keawaiki, a location selected for its potential high groundwater input, isolation from urban influences, and moderate to low circulation, relatively uniform temperatures were found across the surface waters, despite strong gradients in salinity (appendix 1). At Keawaiki, low salinity waters were common entering the nearshore along the boundary between older Holocene (about 10,000 years old) and recent (less than 5,000 years old) lava flows. Water temperatures were generally colder in the north half of the bay than in the south and correlated with lower salinities. Kailua Bay showed lower temperature and salinity surface waters during all seasons close to shore along the innermost part of the bay and at what is locally known as King Kamehameha beach.



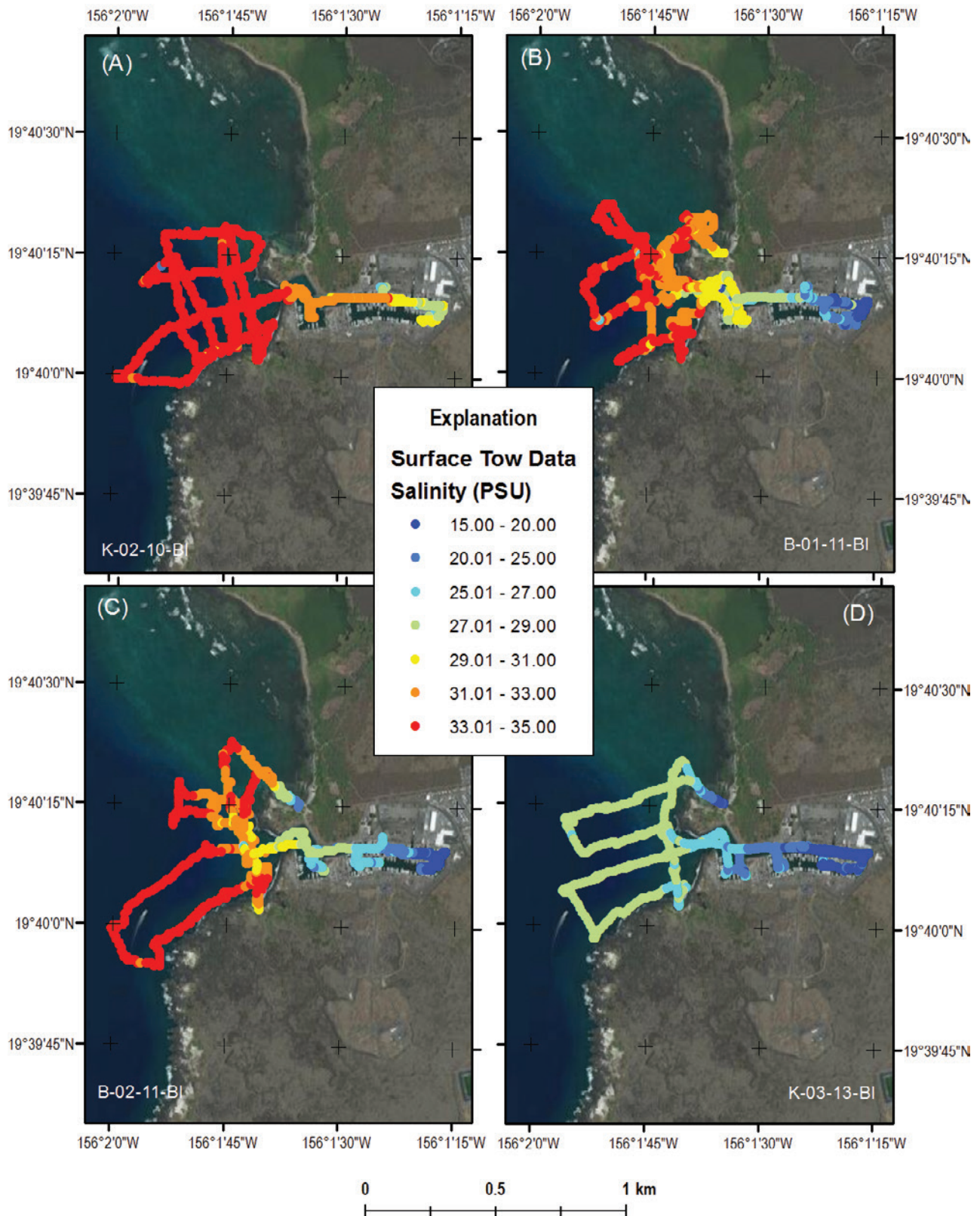
**Figure 11.** Map of surface water temperature (in degrees Celsius) from tows during October 2010 (A), March 2011 (B), and December 2013 (C) showing persistent cold-water inputs near groundwater seeps alongshore of Kaloko bay (location in fig. 1A, B).



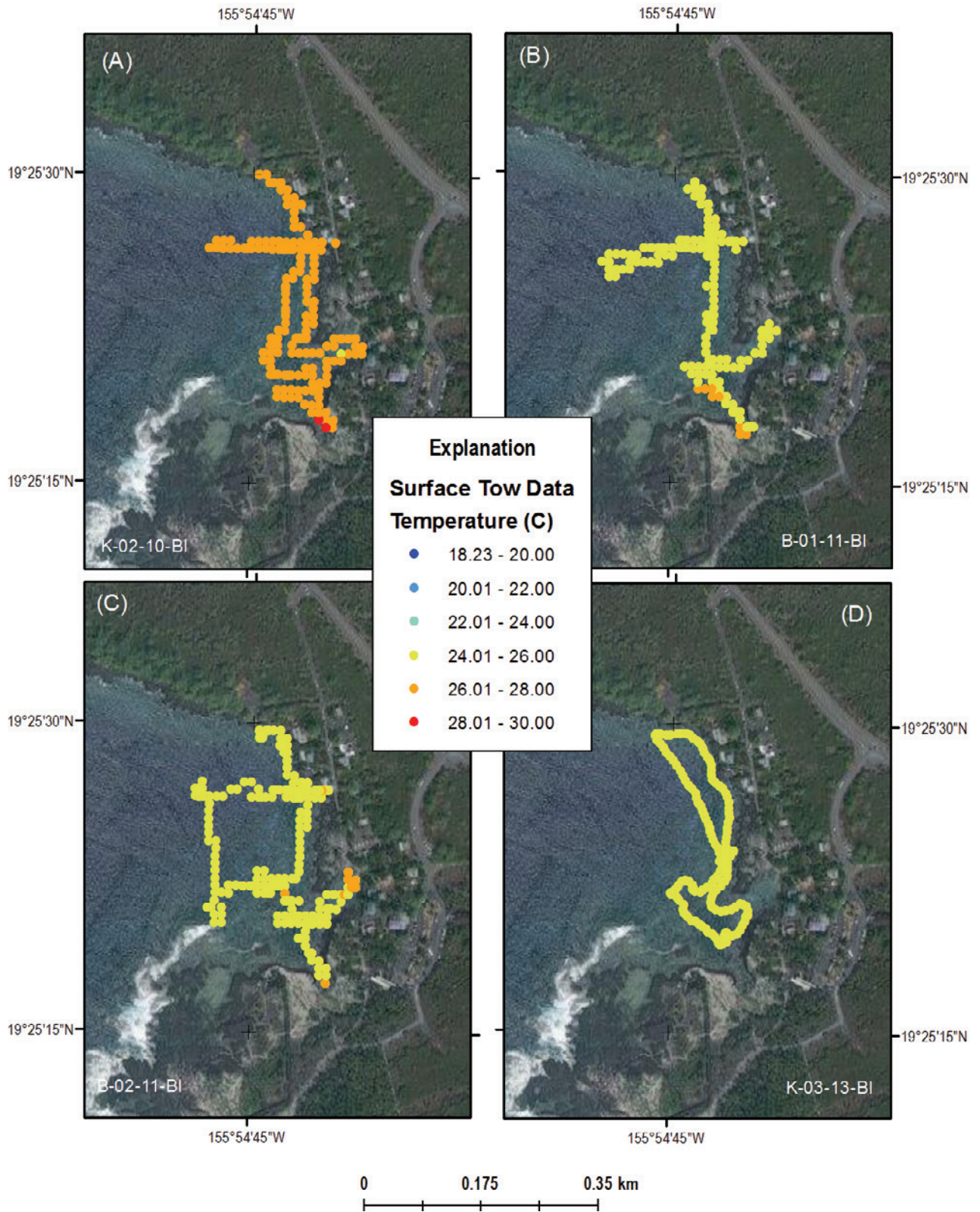
**Figure 12.** Map of surface water salinity from tows during October 2010 (A), March 2011 (B), and December 2013 (C) showing persistent low salinity inputs near groundwater seeps alongshore of Kaloko bay. PSU, practical salinity units (location in fig. 1A, B).



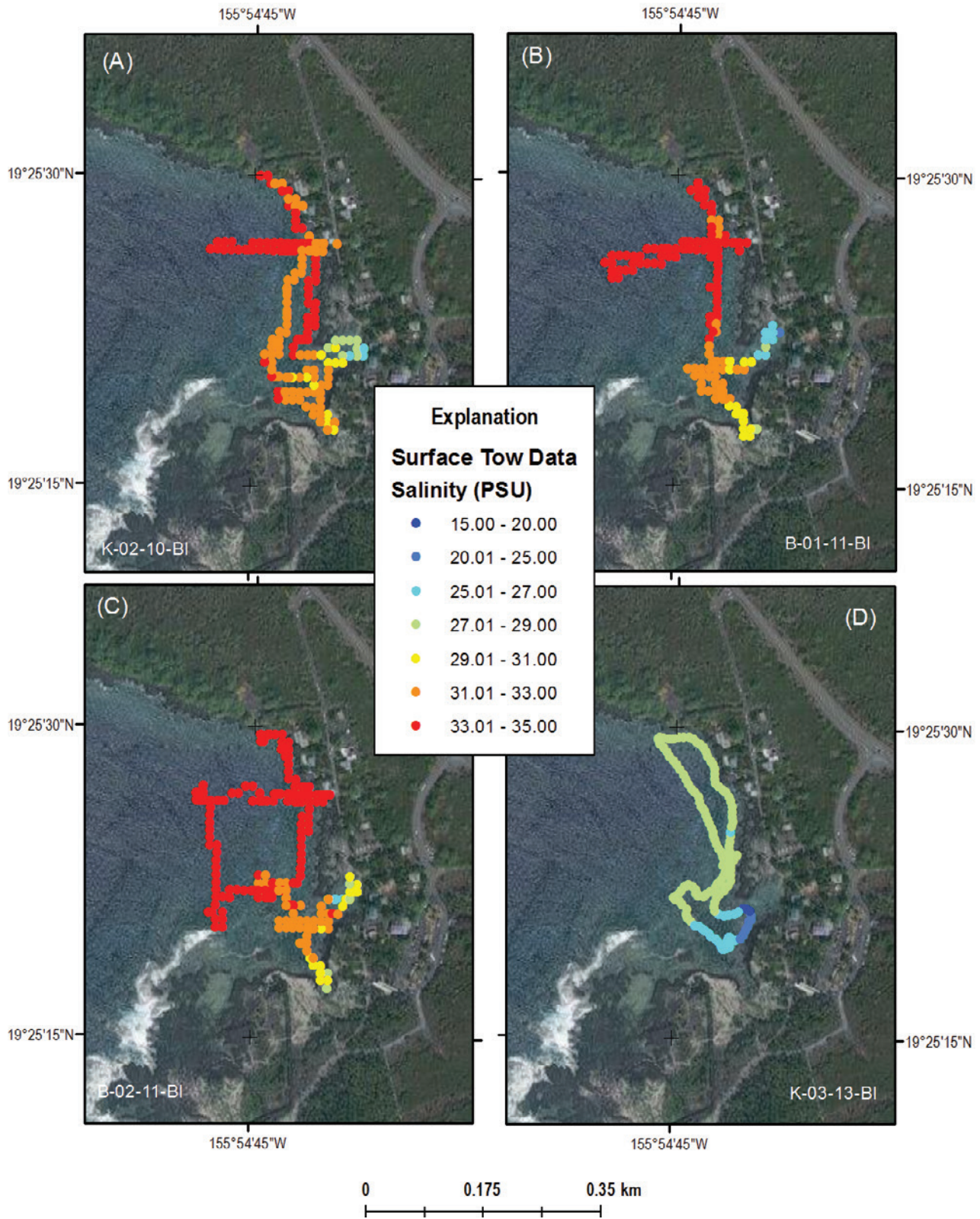
**Figure 13.** Map of surface water temperature (in degrees Celsius) from tows during October 2010 (A), March 2011 (B), July 2011 (C), and December 2013 (D) showing persistent cold-water inputs offshore of ‘Alula Beach and Honokōhau Small Boat Harbor (location in fig. 1B). Base map from Esri World Imagery and its licensors © 2014.



**Figure 14.** Map of surface water salinity (in practical salinity units [PSU]) from tows during October 2010 (A), March 2011 (B), July 2011 (C), and December 2013 (D) showing persistent low salinity inputs offshore of 'Alula Beach and Honokōhau Small Boat Harbor (location in fig. 1B). Base map from Esri World Imagery and its licensors © 2014.



**Figure 15.** Map of surface water temperature (in degrees Celsius) from tows during October 2010 (A), March 2011 (B), July 2011 (C), and December 2013 (D) showing persistent cold-water inputs alongshore of Hōnaunau Bay (location in fig. 1C). Base map from Esri World Imagery and its licensors © 2014.



**Figure 16.** Map of surface water salinity (in practical salinity units [PSU]) from tows during October 2010 (A), March 2011 (B), July 2011 (C), and December 2013 (D) showing persistent low salinity inputs alongshore of Hōnaunau Bay (location in fig. 1C). Base map from Esri World Imagery and its licensors © 2014.

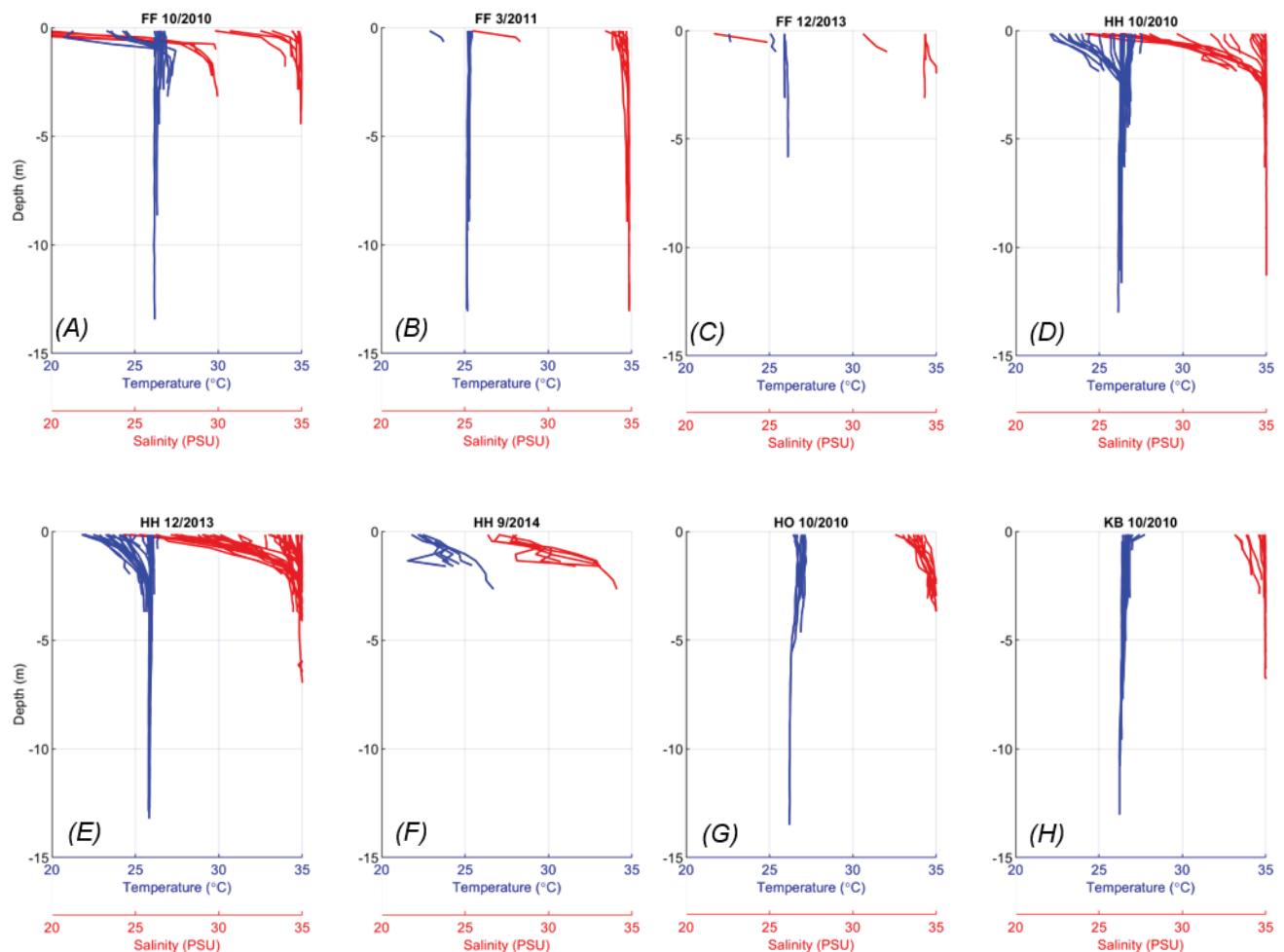


## Depth Variability in Temperature and Salinity from CTD Casts

Two hundred and ninety-three CTD casts were collected over four seasons (Grossman and Marrack, 2019). Casts made on across- and along-shore transects show a general bimodal distribution of temperature and salinity relations to depth with significantly more variability nearshore (shallow casts) and near uniform characteristics in offshore waters (deep casts) (fig. 17). Cast data show similar patterns of 1- to 3-m-thick surface layers of lower temperature and salinity waters nearshore as observed in previous studies (Grossman and others, 2010). The cast data help characterize the vertical structure and variability of temperature and salinity as well as the extent

that marine water is influenced by groundwater inputs and nearshore processes at depth. These data also help to characterize the relative differences in seasonal patterns of nearshore water quality across west Hawai'i and locations of cold-water refugia. Although not explicitly tested in this report, these data are an important baseline for tracking nearshore habitat response to projected warming with climate change, marine intrusion with sea level rise, statewide drought, and land use activities that affect groundwater runoff.

CTD cast data from within Kaloko-Honokōhau National Historical Park show the extent that plumes of colder and fresher waters alongshore influence conditions during peak late summer to early fall high sea-surface temperatures. The plumes also observed in tows ranged from 1 to 3 m thick



**Figure 17 (pages 24–25).** Plots of conductivity temperature depth casts by site and month surveyed (season) showing 1- to 3-meter-thick surface layers of lower temperature and salinity in practical salinity units (PSU) waters and more variability close to shore (for example, 200–500 meters of the shoreline, shallow casts) than more uniform properties offshore (deeper casts) at Freeze Face (A–C), 'Alula Beach, and Kaloko-Honokōhau Small Boat Harbor (D–F), Hōnaunau Bay (G), Kailua Bay (H–J), Kaloko cut (K, L), Kahalu'u (M, N), and Keawaiiki (O–Q).

alongshore of Freeze Face, Kaloko cut and Kaloko bay, and Honokōhau Small Boat Harbor between ‘Ai‘ōpio Fishpond and ‘Alula Beach (fig. 17). The relative difference in surface temperatures and salinities were larger during warm summer and fall periods than winter and spring. An approximately 1–2 °C change was observed in temperatures at depth between

peak warm conditions of summer compared to winter and spring (fig. 17), consistent with time-series measurements.

CTD data help characterize relative differences in seasonal water column properties across west Hawai'i. For example, during peak warm conditions of October 2010 surface temperatures, defined as the mean of the top 0.5-m surface layer

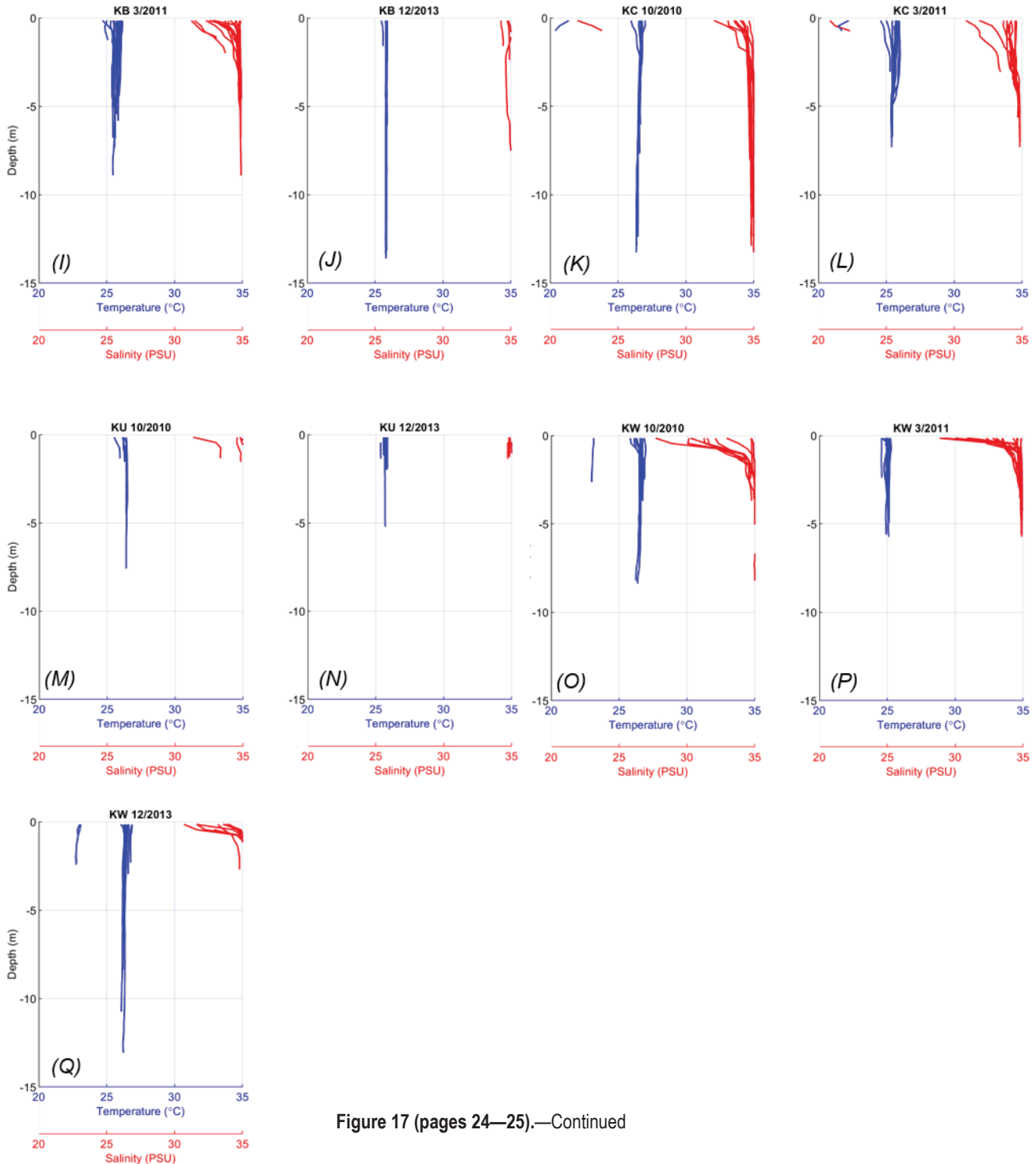
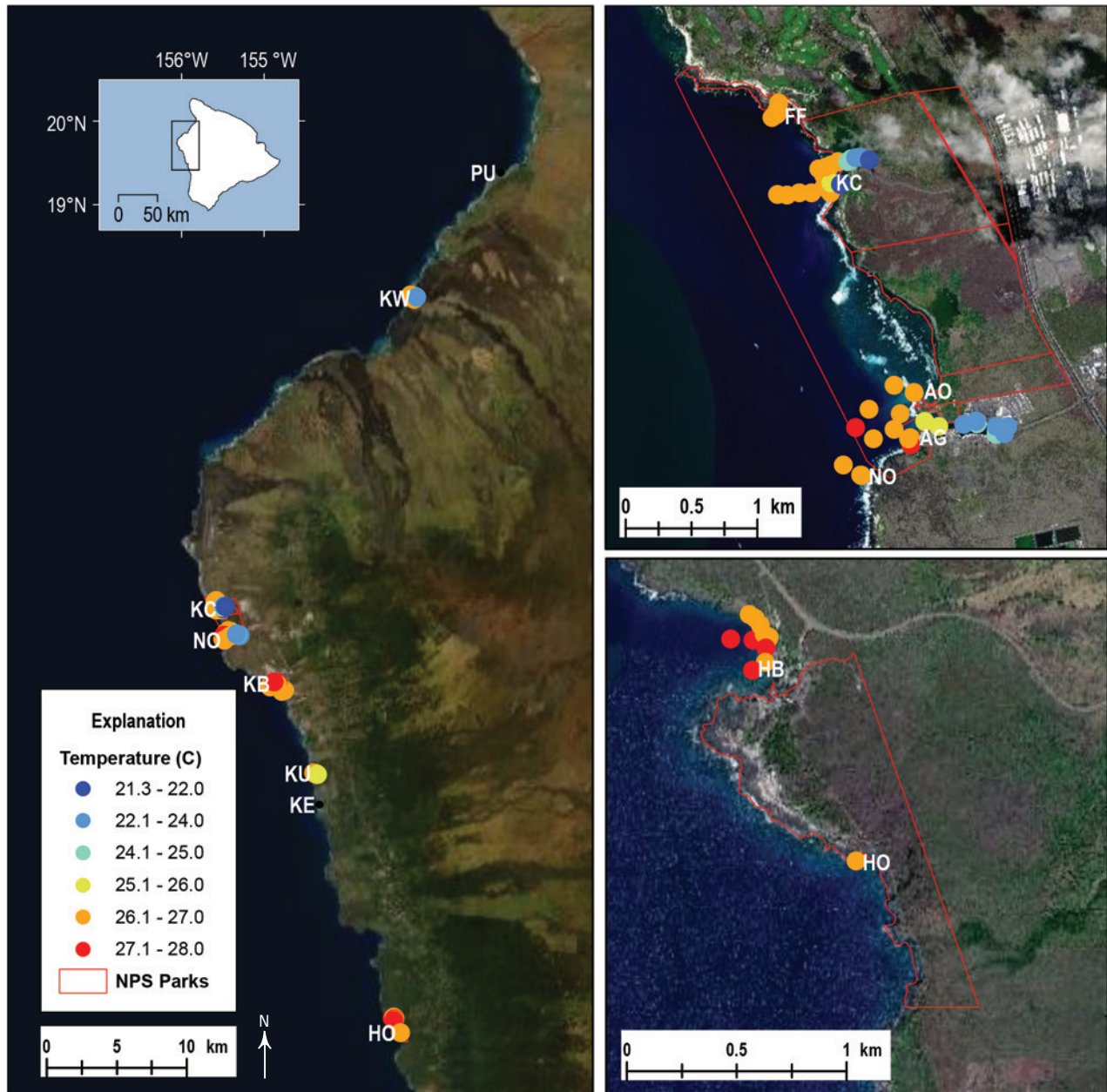


Figure 17 (pages 24–25).—Continued

from individual CTD casts, reveal similar patterns as the surface tows with temperatures nearshore that are 1–4 °C cooler than offshore (fig. 18). Bottom temperatures, defined as the mean of the deepest 0.5-m layer measured in each cast, show a similar pattern of cooler water nearshore in known areas of groundwater inputs (for example, Keawaiki mid, Freeze Face, and Kaloko cut) with a smaller range generally less than 2 °C relative to offshore waters (fig. 19).

### Temporal Patterns in Bottom Water Temperature and Salinity from Time-Series Deployments

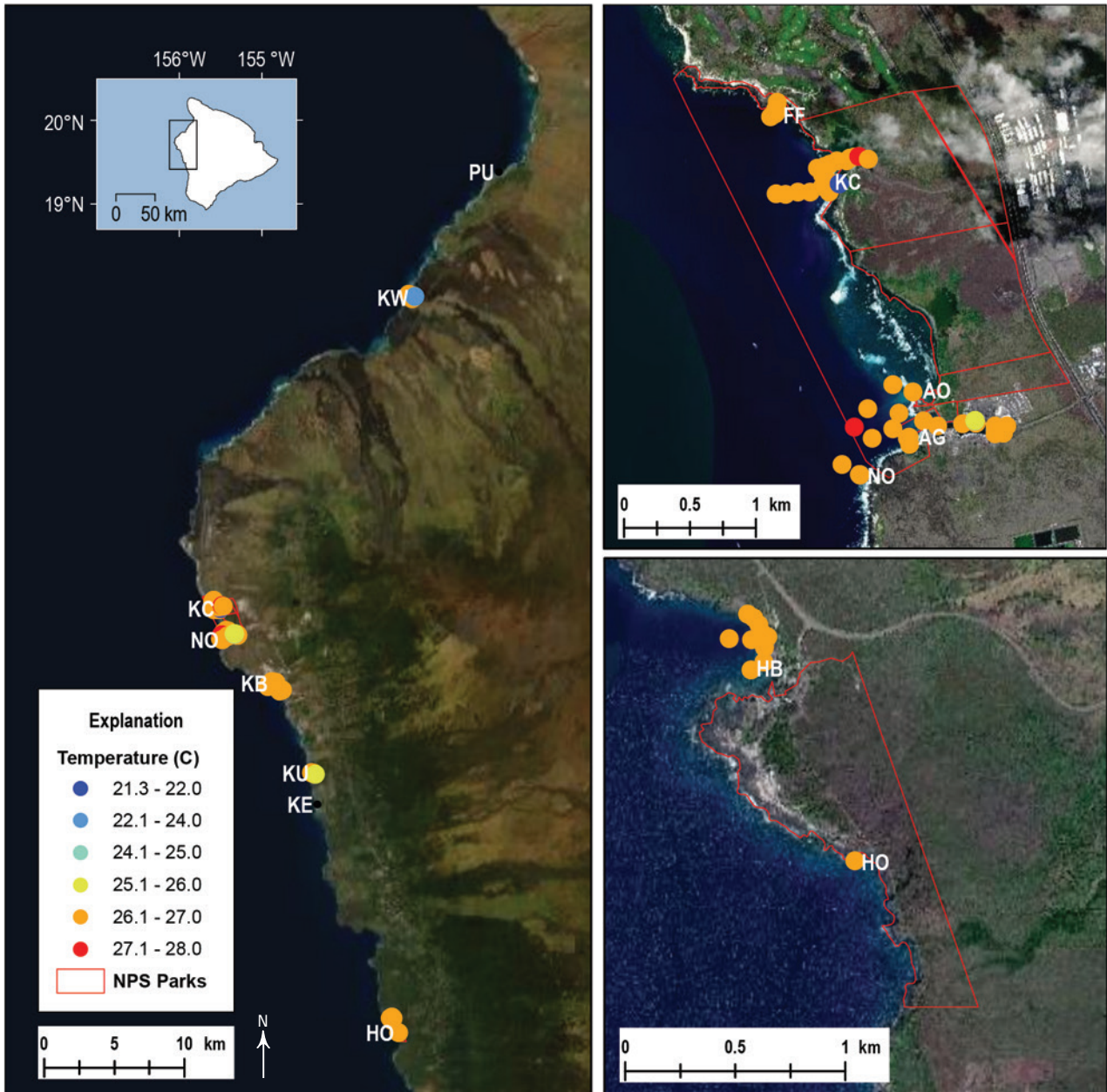
More than 2 million continuous measurements of water temperature and salinity were gathered from the 33 stations within the 12 study areas between June 2010 and December 2014. Time-series characteristics are described in this section for select sites to compare variability within the national parks



**Figure 18.** Plots of surface temperature from individual conductivity temperature depth casts during October 2010 showing relative differences and significantly colder waters nearshore along the west coast of the Island of Hawai'i (A), Kaloko-Honokōhau National Historical Park (B), and Pu'uhonua O Hōnaunau National Historical Park (C). Site abbreviations correspond to those listed in table 1. Base map from Esri World Imagery and its licensors © 2014.

and across areas of west Hawai'i and with respect to coral health. These data help show the spatial and temporal influence of groundwater inputs and persistence seasonally and annually that create cold-water refugia. They also help characterize nearshore water quality response to factors controlling its delivery to the coast (for example, precipitation, groundwater quantity, quality, and flux) as well as its mixing within the nearshore (for example, by winds, waves, and circulation).

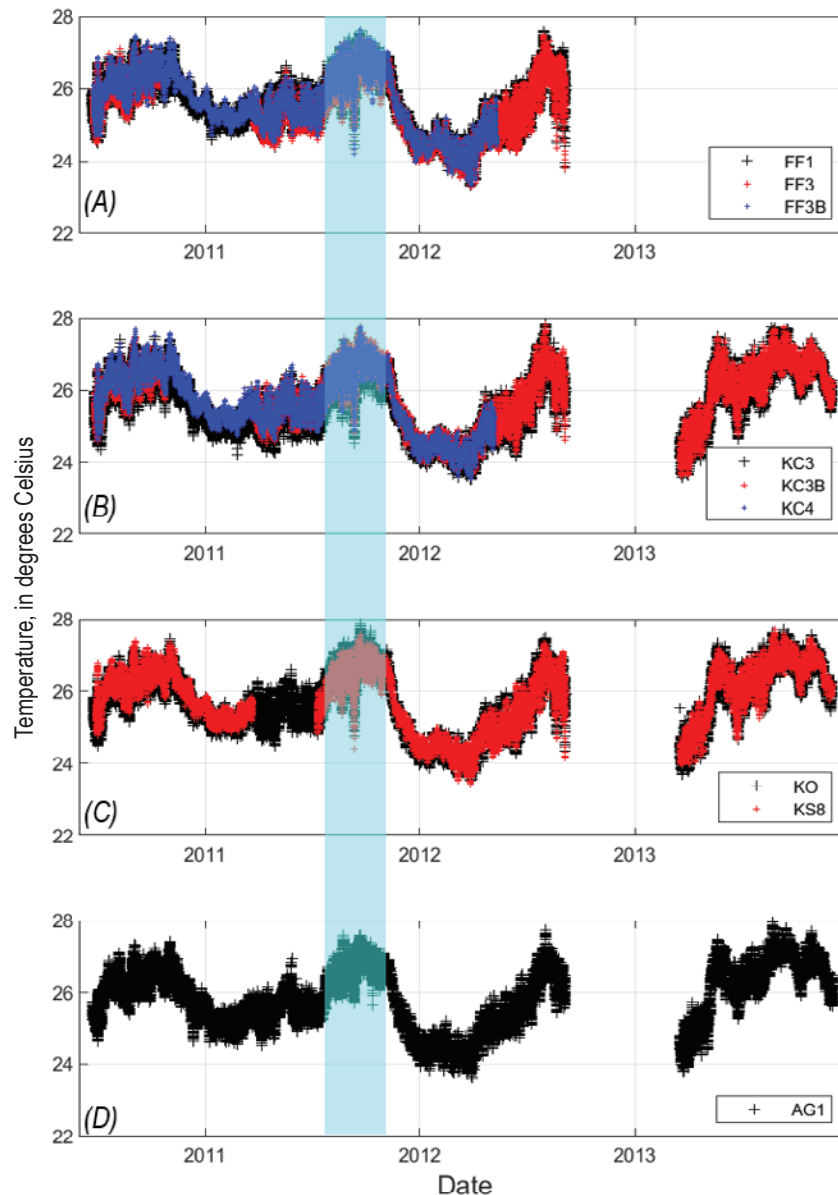
Continuous time-series data of water temperature across Kaloko-Honokōhau National Historical Park reveals a patchwork of variability across our study sites reflecting proximity and different (1) inputs of fresher and colder groundwater, (2) depths and locations within the complex nearshore reef architecture, and (3) patterns of water circulation interacting with the reef morphology (fig. 20). Summer peak temperatures were recorded over the 4 years of the study and ranged from



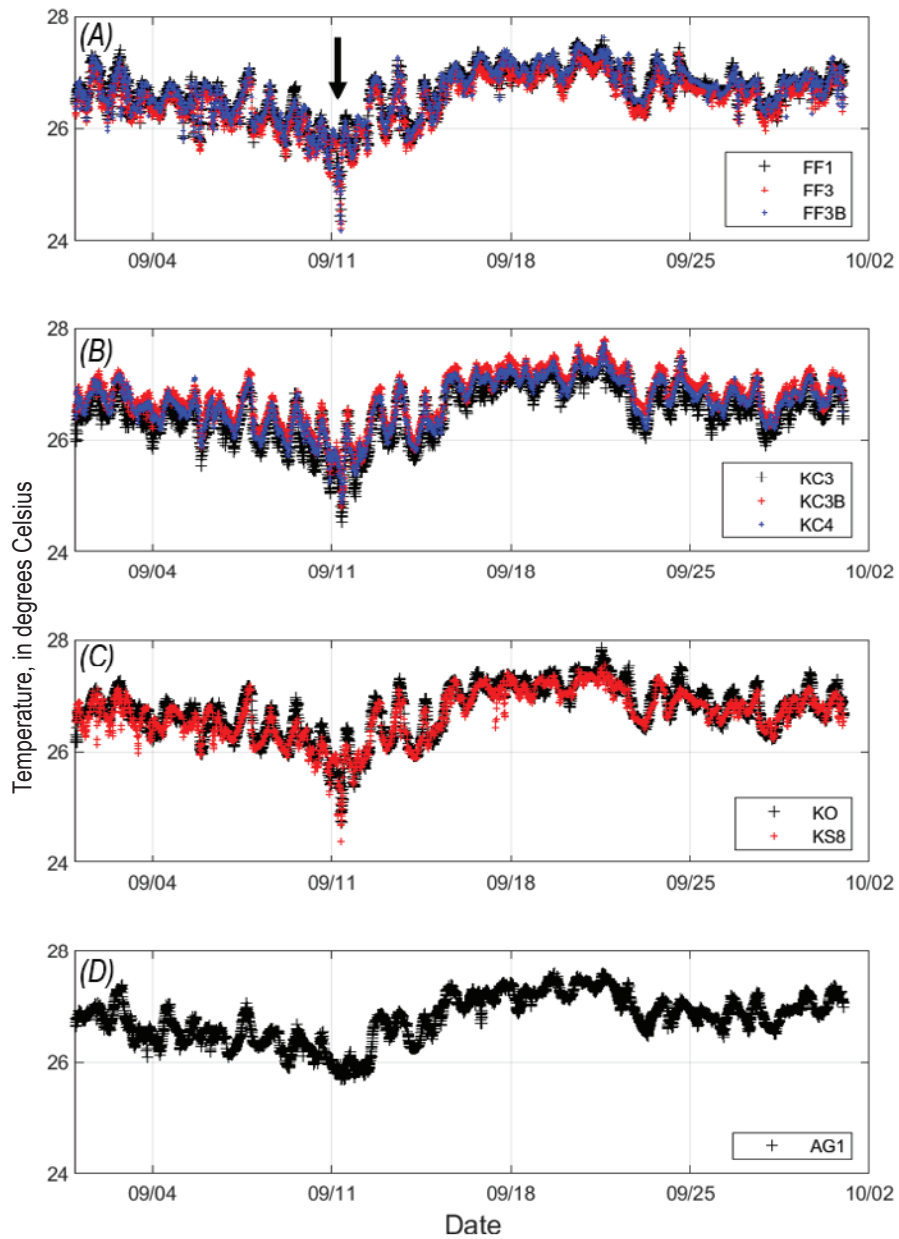
**Figure 19.** Plots of bottom temperature of individual conductivity temperature depth casts during October 2010 showing relative differences and significantly colder waters nearshore along the west coast of the Island of Hawai'i (A), Kaloko-Honokōhau National Historical Park (B), and Pu'uhonua O Hōnaunau National Historical Park (C). Site abbreviations correspond to those listed in table 1. Base map from Esri World Imagery and its licensors © 2014.

27 to 28 °C, with the warmest conditions observed in 2011 and 2012. Details of summer 2011 (shaded box of fig. 20) are shown in figure 21. Temperatures varied by 1–2 °C between sites at diurnal and semidiurnal timescales. A marked decrease in temperature of about 2 °C was observed across most of the park sites and about 0.5 °C offshore of ‘Alula Beach (AG1) (fig. 21). This cooling event followed three relatively high precipitation events that occurred at the low elevations of the

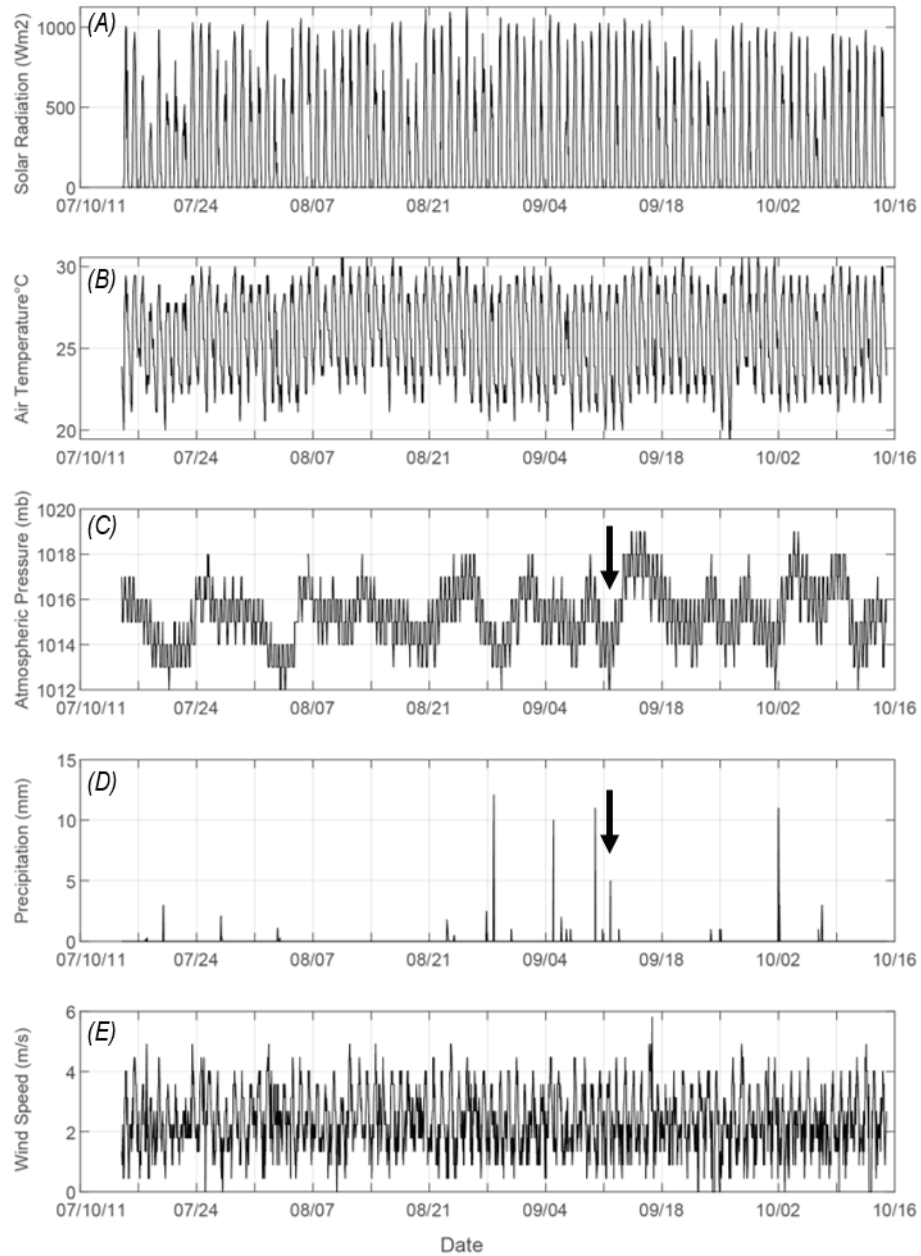
park between August 28 and September 11, 2011 (fig. 22). The extent that these local, low-elevation rainfall events caused increased submarine groundwater discharge and the associated cooling is uncertain. Understanding the source, magnitude, and phasing of groundwater recharge to the coast continues to be an identified information need. Similar patchy inter-site and temporal temperature variability was observed at all other study sites (Grossman and Marrack, 2019).



**Figure 20.** Time series plot of water temperature from sites in Kaloko-Honokōhau National Historical Park showing variability ranging from 0.5 to 1.0 degree Celsius (°C) between sites and areas of Freeze Face cave (A), the Kaloko cut (B), outer Kaloko bay (C), and ‘Alula Beach (D). Highlighted period of summer 2011 shown in figure 21.



**Figure 21.** Time series plot of the summer 2011 peak water temperature from sites Freeze Face (A), Kaloko cut (B), outer Kaloko bay (C), and 'Alula Beach in Kaloko-Honokōhau National Historical Park (D) showing inter-site and diurnal and semi-diurnal variability ranging from 0.5 to 1.0 degree Celsius (°C), and a notable cooling event across all sites on September 11–12 (black arrow).

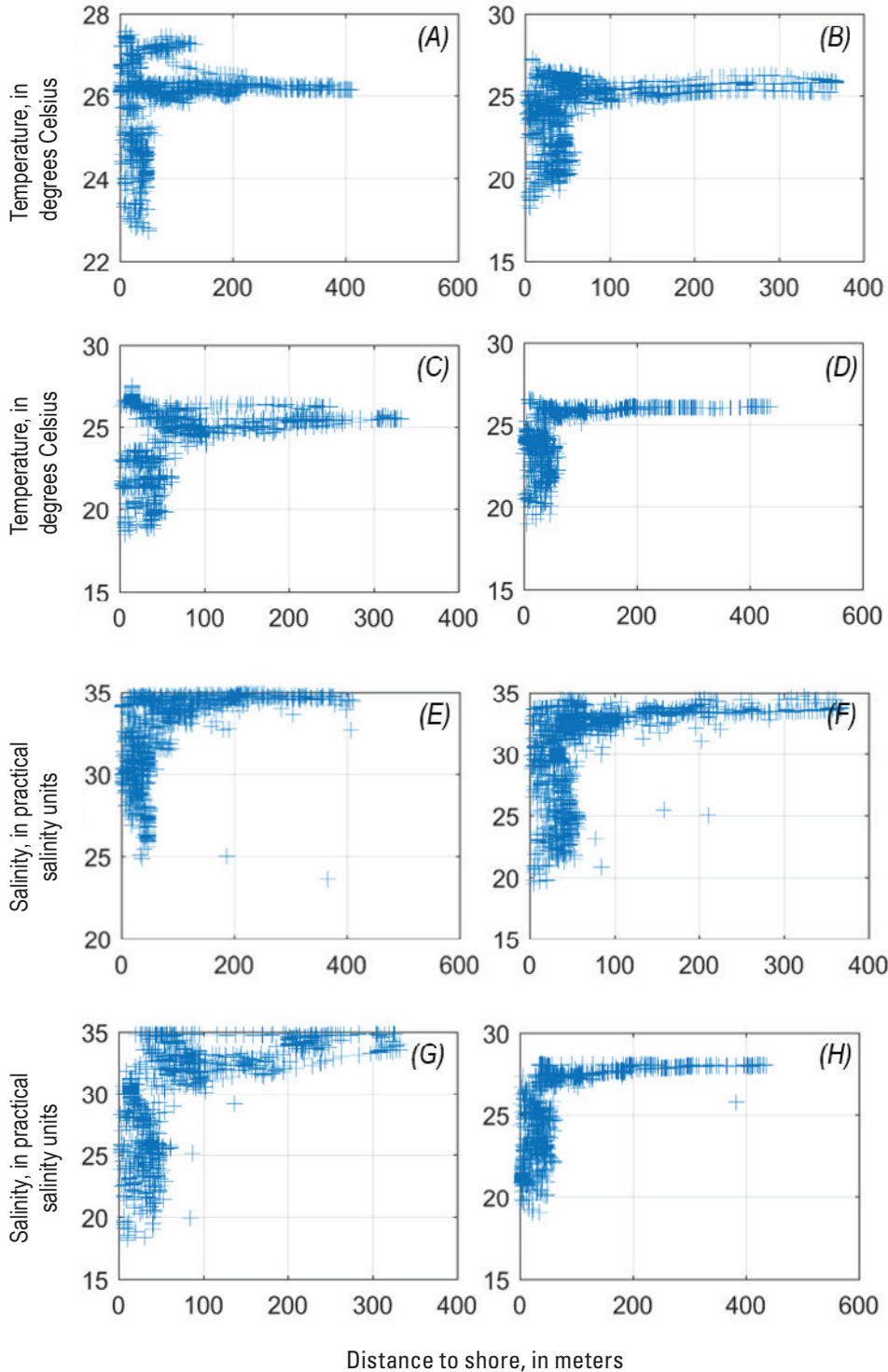


**Figure 22.** Plot of solar insolation, in watts per square meter (A), air temperature, in degrees Celsius (B), atmospheric pressure, in megabytes (C), precipitation, millimeters (D), and wind speed, meter per second, (E) from the Western Regional Climate Center Remote Automated Weather Stations (RAWS) site at Kaloko-Honokōhau National Historical Park (Station hiHKAL) during summer 2011, and timing of the cold temperature excursion in figure 21 following three relatively large precipitation events between August 28 and September 11 (arrow).

### Temperature and Salinity Relations

Results from surface tows, CTD casts, and the time-series deployments of this study corroborate patterns of lower temperature and salinity estuarine surface waters alongshore observed in the past using diverse approaches, including thermal infrared remote sensing (Johnson and others, 2008),

in situ oceanographic measurements casts (Grossman and others, 2010), and radiochemistry (Knee and others, 2008; Knee and others, 2010; Street and others, 2008). Surface tow data stratified by each season surveyed were used to characterize temperature and salinity variability in surface waters with distance across the nearshore (fig. 23) and to define the temperature and salinity characteristics of seawater



**Figure 23.** Plots of surface water temperature in October 2010 (A), March 2011 (B), July 2011 (C), and December 2013 (D) and salinity in October 2010 (E), March 2011 (F), July 2011 (G), and December 2013 (H) with distance to shore from tows offshore of ‘Alula Beach and the Kaloko-Honokōhau Small Boat Harbor showing high variability nearshore and extent of estuarine influence (spatial variations of 1–2 degrees Celsius [°C]) hundreds of meters offshore.

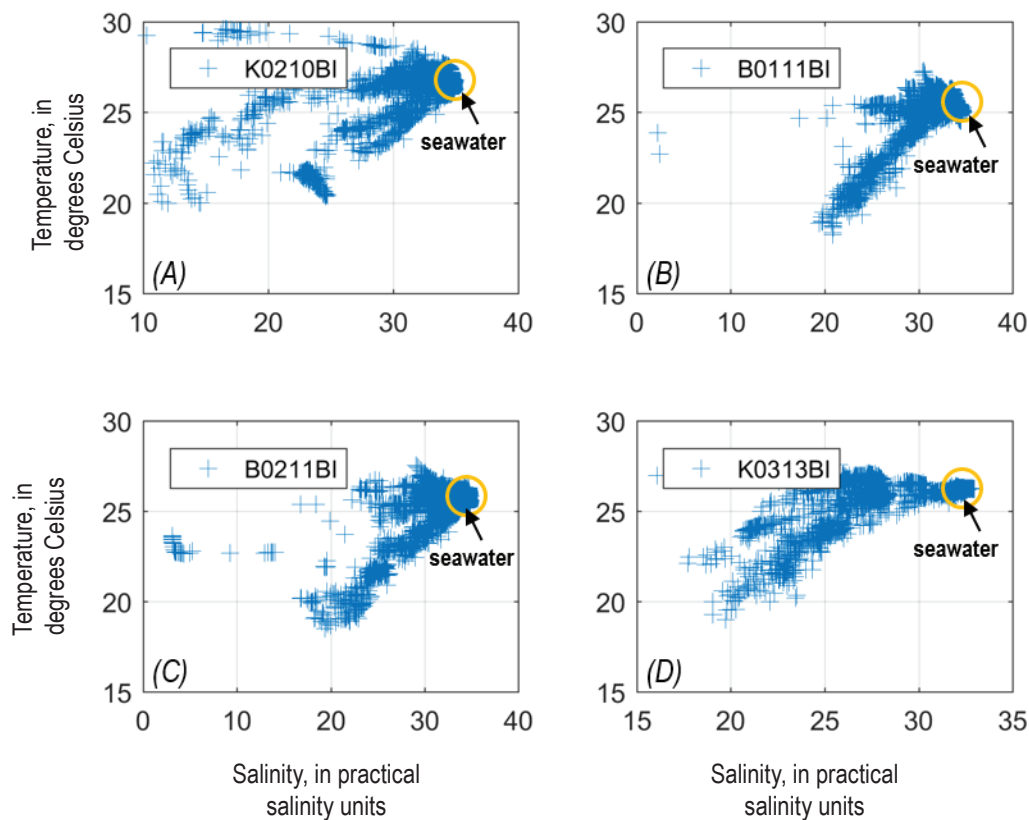


offshore (fig. 24). Similar relations were observed with CTD cast data from offshore deeper settings (fig. 25) and time-series deployments on the seafloor (fig. 26).

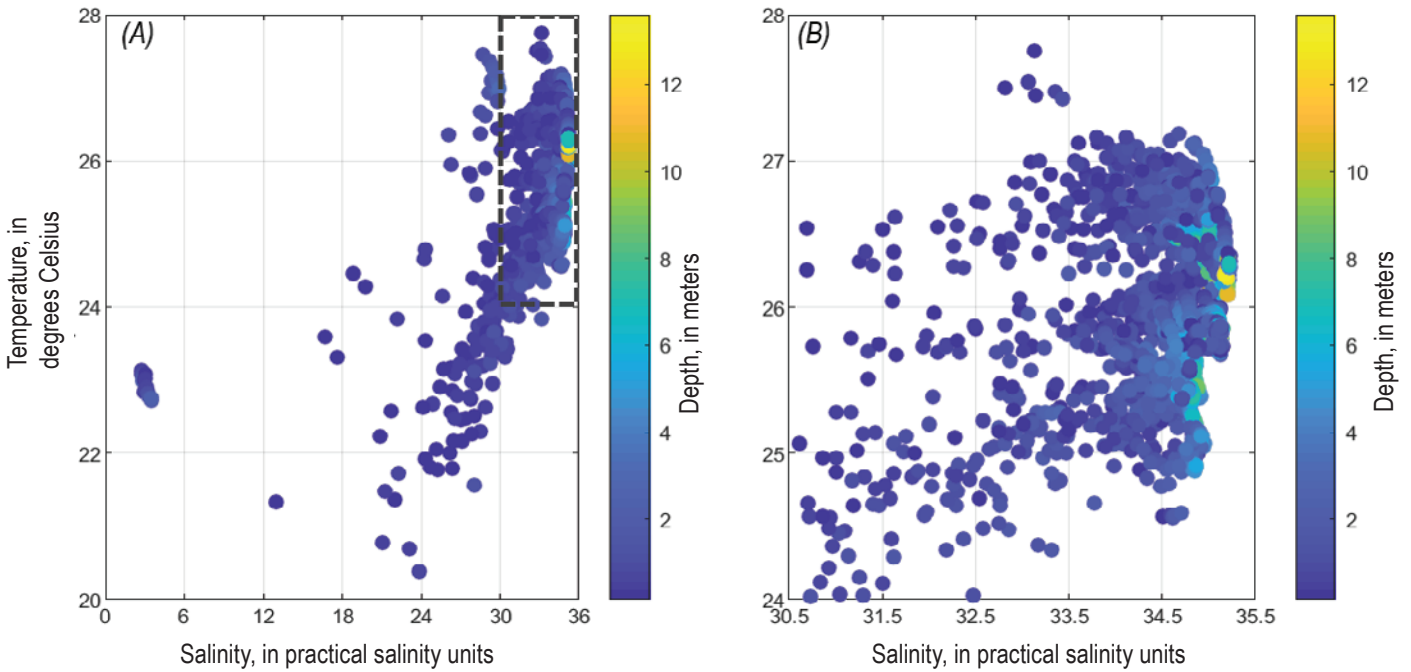
### Tidal Influence on Bottom Water Temperature and Salinity

All sites studied reveal some influence of tides on temperature and salinity where available. Concurrent measurements of water level, temperature, and salinity with a fixed CTD sensor at site Kaloko outer, the deepest site assessed in Kaloko bay, showed fluctuations in temperature of 0.50–0.75 °C and salinity of 2–3 PSU in response to the semi- and diurnal tides (fig. 26). Marked decreases in temperature and salinity occur during both daily ebb-tide events with the lowest temperatures and salinities occurring at, during, and commonly for 1–3

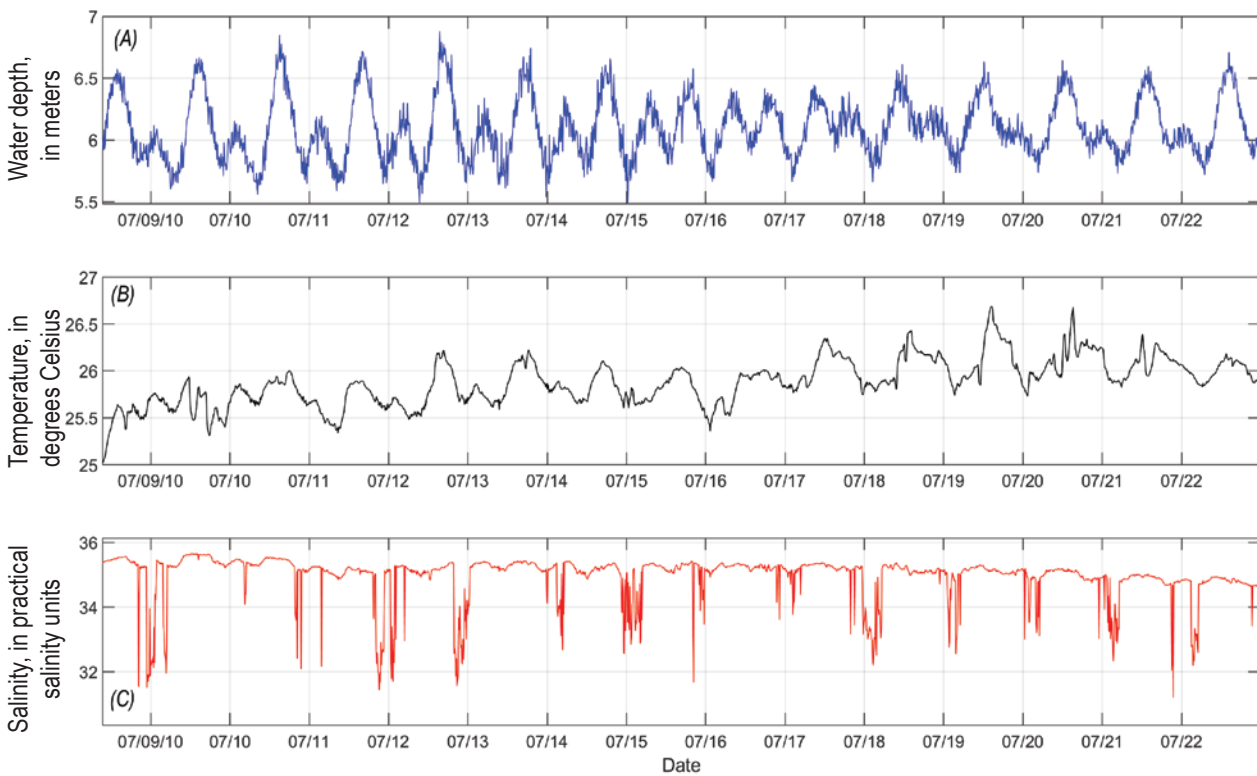
hours following the lowest tide. Although the daily temperature changes are also in phase with daily heating and cooling by the sun, the regular 1–2 PSU decreases in salinity are strongly associated with the ebb and low tides. These decreases in salinity are consistent with and thought to be associated with colder and fresher groundwater discharging through the beach face and seafloor. This depression in temperature and salinity is caused by the process of tidal pumping when the lower sea surface at low tides enables stronger terrestrial runoff. These regular, tidally forced reductions in temperature and salinity at the Kaloko outer site and most sites last on average 2–4 hours and as long as 6–8 hours, such as those observed on July 12, 15, and 18 in 2010 (fig. 26). These decreases in temperature and salinity create conditions of thermal refugia relative to areas without groundwater influence and may be important to the overall sensitivity and tolerance to heat stress among corals.



**Figure 24.** Plots of surface water temperature and salinity relations from tows during October 2010 (A), March 2011 (B), July 2011 (C), and December 2013 (D) showing the characteristics of seawater temperature (about 26–27 degrees Celsius [°C]) and salinity (34–35 practical salinity units [PSU]) relative to much lower values nearshore associated with colder and fresher groundwater entering the nearshore.



**Figure 25.** Scatter plot of temperature and salinity relations from conductivity temperature depth casts (A) and details of the marine water endmember shown in the inset (dashed) box characterized by temperatures of 26–28 degrees Celsius (°C) and salinities of 34.5–35.5 practical salinity units (B).



**Figure 26.** Time series plot of water level (A), temperature (B), and salinity (C) from the Kaloko outer site, the deepest site at –5 meters (–24 feet) in Kaloko bay, showing fluctuations in temperature of 0.50 to 0.75 degrees Celsius (°C) and salinity of 2–3 practical salinity units (PSU) at semi- and diurnal time-scales associated with tidal oscillations.

## Relations Between Coral Health Indicators and Water Quality Along West Hawai‘i

Surface tows, CTD casts, and continuous time-series measurements show the variability patterns of influence of colder, low salinity groundwater across the 33 stations and 11 principal study areas of west Hawai‘i. We hypothesized that these variations in water temperature and salinity influence coral bleaching and health and perhaps coral community and size structure as well. The first hypothesis we hoped to test was that colder, uncompromised groundwater quality mitigates coral bleaching by buffering high sea-surface temperatures. A second hypothesis we sought to test was that coral health indicators relate to water temperatures and the influence of groundwater, with positive relations where groundwater quality does not stress corals and potentially negative relations where urban and (or) natural contaminants stress corals.

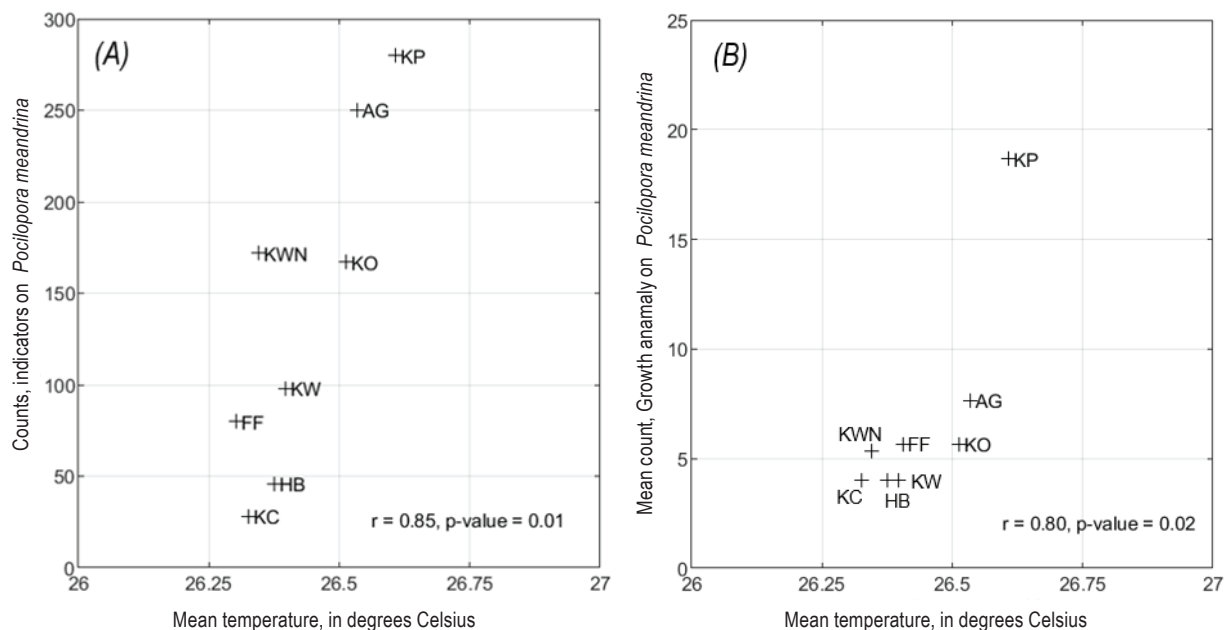
### Water Quality and Coral Bleaching

Although two high sea-surface temperature events associated with El Niño conditions were forecasted during the study for 2010 and 2013, they didn’t occur. Sea-surface temperatures in tows, casts, and time-series gathered for the study between 2010 and 2013 ranged between 19 and 28 °C with each summer showing slight increases and more frequent high temperatures. Despite time-series observations of temperatures ranging from 27 to 28 °C during the 2011 summer that are generally considered low to moderately stressful for Hawaiian corals (Jokiel and Coles, 1990; Jokiel, 2004), we did observe bleaching at a number of sites, although most were characterized as partial and likely did not lead to mortality. The shallower sites studied in this report

also exhibited significantly higher and more frequent high temperatures than deeper sites (Couch and others, 2014). The extent that temperatures in the range of 27 to 28 °C explain the bleaching observed is uncertain, as many coral health indicators also showed a positive correlation to temperature. The temperatures and bleaching observed in this study were lower relative to qualitative accounts of the 2014 and 2015 summer bleaching events that led to widespread mortality across west Hawai‘i and the main Hawaiian Islands (Rosinski and Walsh, 2016). The opportunity to test the hypothesis of the ecosystem service of cold-water refugia to buffer thermal bleaching may exist in monitoring the recovery from the 2015 summer bleaching event. Such research may also help explain the extent that compromised coral health influences coral response and recovery from extreme thermal stress events like summer 2015.

### Water Quality and Coral Health Indicators

Relations between mean temperature, maximum and minimum temperature, frequency of temperature threshold exceedances, duration of high temperatures, and mean temperature of select thresholds in duration (for example, 10th and 70th percentile in frequency) all have significant correlations with the coral health indicators studied. Mean area temperatures in the summers of 2010 and 2011 correlated significantly with different coral health indicators derived from observations in 2011. Although coral bleaching was limited to partial bleaching in a few areas, mean temperature from July 15 to October 15, 2011, show positive correlations with total counts of health indicators affecting mainly the species *Pocillopora meandrina* (fig. 27A). Mean temperature correlated significantly with the total and mean count of growth anomalies



**Figure 27 (pages 34–35).** Plots of the relation in 2011 between mean temperature and counts of health indicators on *Pocillopora meandrina* (A), mean counts of growth anomalies on *P. meandrina* (B), maximum temperature and count of indicator types (C), and percent of time that temperature exceeded 27 degrees Celsius (°C) and mean area count of indicators on *P. meandrina* (D). Health indicator abbreviations correspond to those listed in table 3.

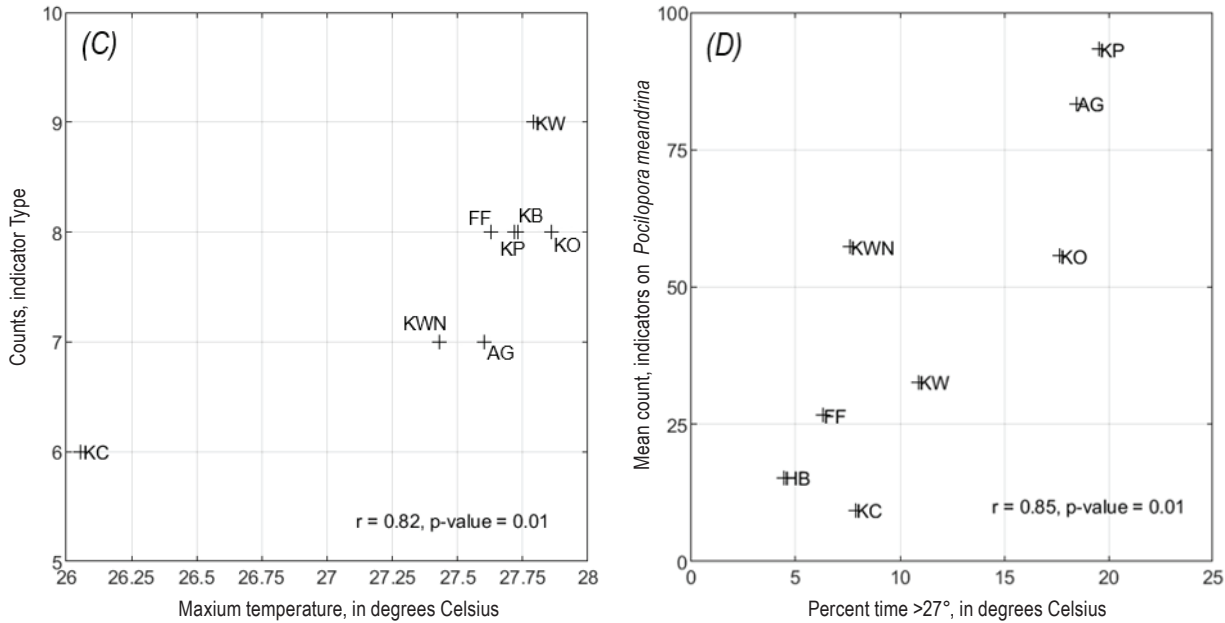


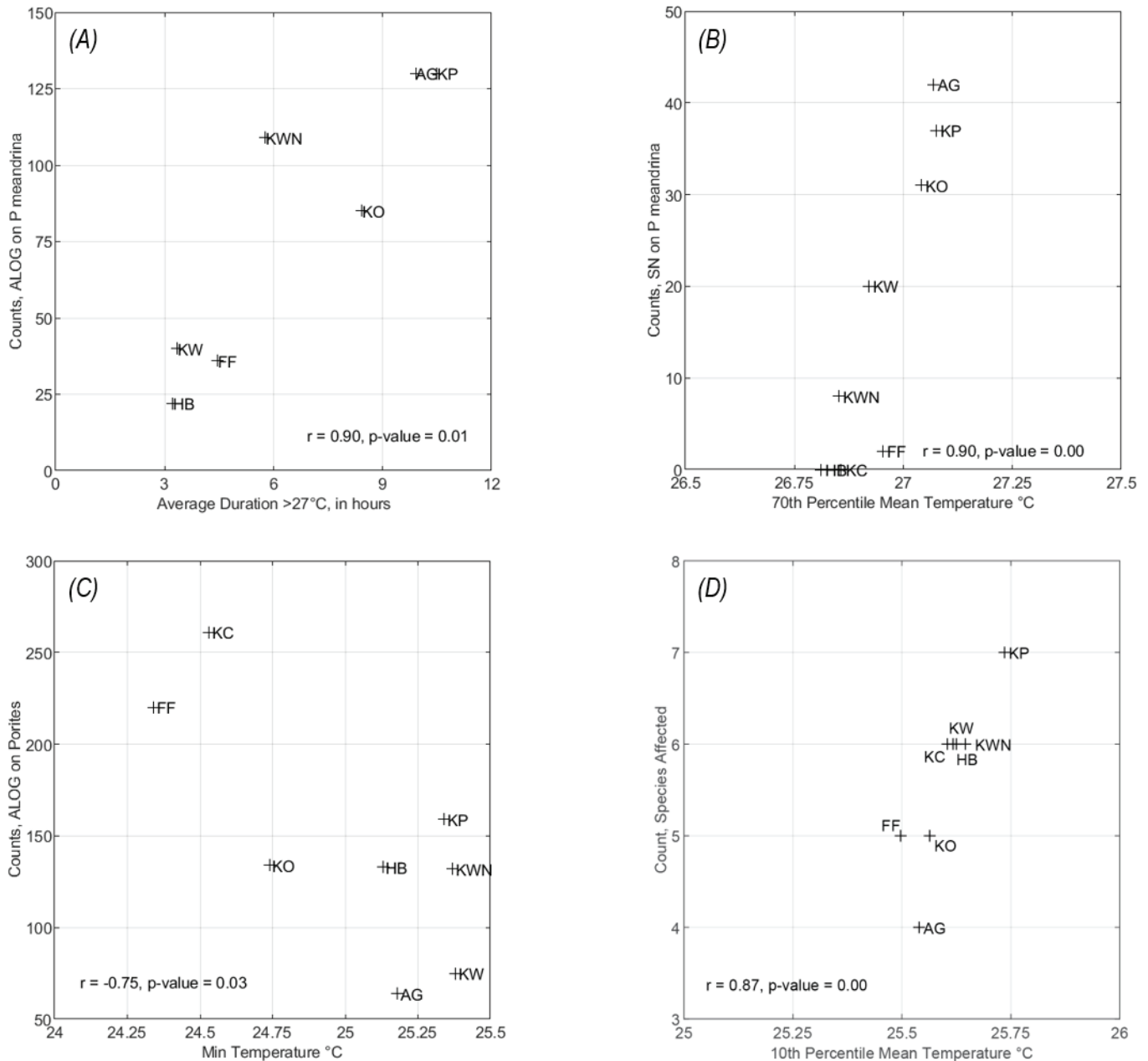
Figure 27 (pages 34–35).—Continued

on *Pocillopora meandrina* (fig. 27B), as well as other health indicators including ciliates and snail grazing, indicating that temperature affects a range of derivative stressors to coral (for example, grazing pressure). Maximum temperature showed correlations with a range of indicators and the number of health indicators found at sites (fig. 27C).

Maximum temperatures measured in this study just reached levels observed in the past to cause bleaching, 27–28 °C (Jokiel and others, 2004; Jokiel and Coles, 1990), yet partial and, in some locations, relatively abundant bleaching was observed in 2010 and 2011 at our sites. We investigated correlations between coral health and a range of additional thresholds that may contribute to compromised health before temperature stress influences bleaching, including the frequency of temperatures above 27 °C, duration of excursions above 27 °C, counts of 26.75 °C and the mean of the highest 10 percent and 30 percent of summer temperatures. The percentage of time that summer temperatures exceeded 27 °C was correlated to various health metrics, including the mean count of indicators on *P. meandrina* across each area (fig. 28D). The average duration of events above 27 °C was also correlated with the total and mean counts of indicator types on *P. meandrina* (fig. 28A). Assessing slightly lower thresholds in temperature, the 70th percentile mean temperature, defined as the mean of the top 30 percent of ranked high temperatures, which ranged from 26.6 to 27.2 °C, was also correlated to counts of many indicators on *P. meandrina*, including snail grazing (fig. 28B). These relations reflect the number of *P. meandrina* colonies affected, but also potentially important influences of thresholds to the range in specific health indicators studied below temperatures of concern to thermal bleaching stress.

Minimum temperature and exposure to lower temperatures show notable negative correlations to coral health indicators among *Porites* colonies, including algal and cyanobacterial overgrowth on *Porites compressa*, *P. lobata*, *P. lutea*, and *P. rus* (fig. 28C). This may indicate other important stressors at play associated with site location, including contaminants associated with urban land use or transported by colder groundwater or nearshore circulation patterns. The extent to which natural contaminants in the form of dissolved and particulate minerals and trace metals from the region's geologic framework influence coral health is unknown but may be important. Lastly, the 10th percentile mean temperature, defined as the mean temperature of the lowest 10 percent of ranked low temperatures, showed a positive correlation to the number of coral species affected by health indicators in each area (fig. 28D). In other words, coral species susceptibility to health anomalies were lower where temperatures were persistently cooler, a potentially important benefit of colder temperature refugia.

The narrow temperature range of relations with health indicators observed is notable and potentially important in that they may indicate corals in our study area are close to their stress tolerance of high temperatures. Slight increases in temperature predict large increases in the number of health indicators across most species and indicator types and are a concern under projected increases in sea-surface temperatures in the State of Hawai'i that contribute to both thermal bleaching stress and compromised health indicators like those found here. Observations of about 70–100 percent mortality associated with coral bleaching in 2015 (Rosinksi and Walsh, 2016) attest to these corals existing relatively



**Figure 28.** Plots of the relation in 2011 between average duration of events exceeding 27 degrees Celsius (°C) and counts of algal and cyanobacterial overgrowth on *Pocillopora meandrina* (A), 70th percentile mean temperature and counts of snail grazing on *P. meandrina* (B), minimum temperature and counts of algal and cyanobacterial overgrowth on *Porites* colonies (C), and the 10th percentile mean temperature relative to counts of species affected (D). Health indicator abbreviations correspond to those listed in table 3.

close to their stress tolerance. Cold-water refugia therefore may be important for coral resilience. The extent of cold-water refugia during the 2015 bleaching event and its capacity to buffer high temperatures remains uncertain since it was not rigorously monitored. Recent studies suggest the flux of groundwater to the coastal ocean has decreased owing in part to more persistent statewide drought and lower baseflow as well as potential extraction for urban uses (Oki, 2004). It

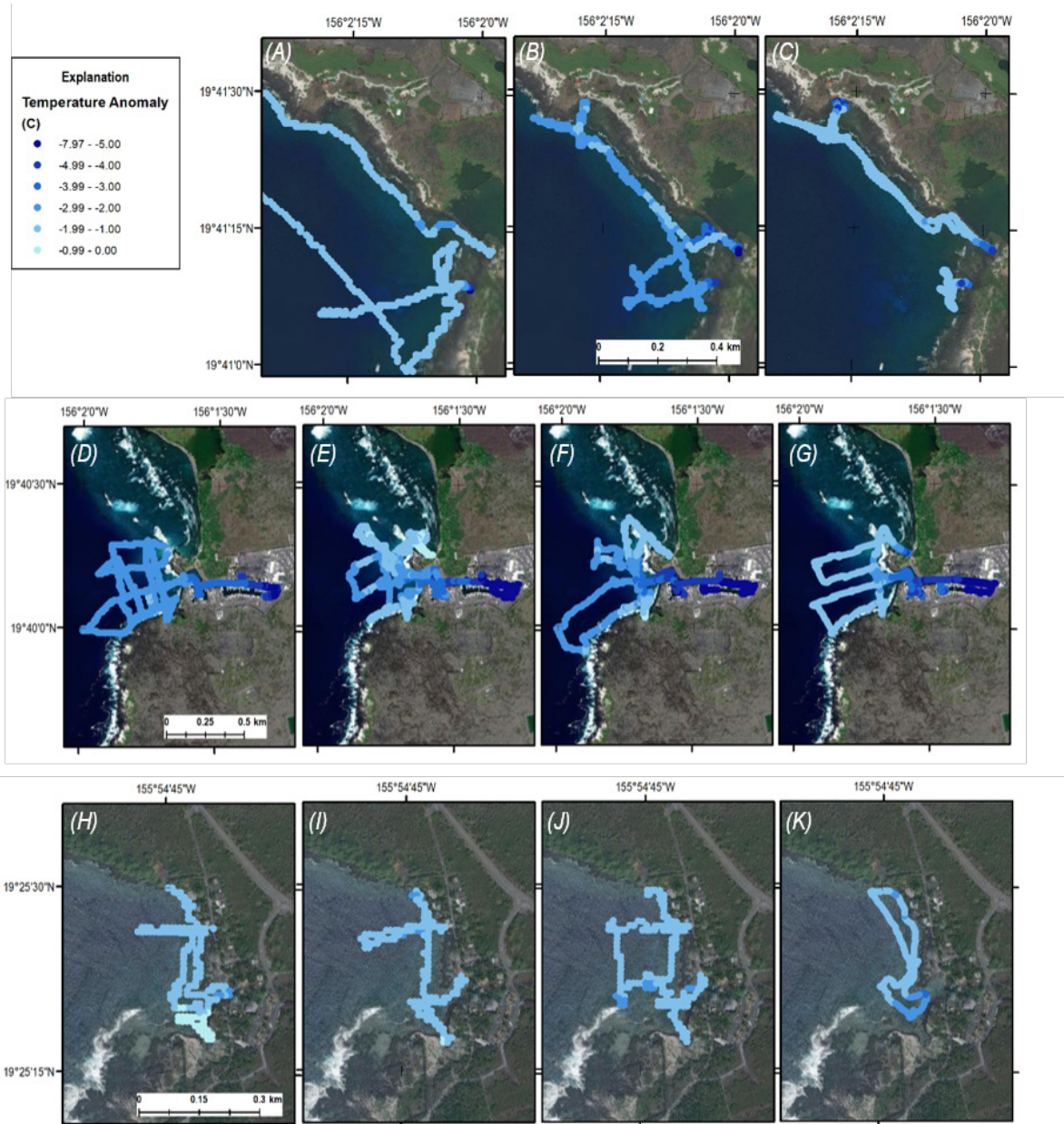
remains uncertain how groundwater discharge to coasts has changed and affected coral health and bleaching. This study indicates that maintaining groundwater flux has the capacity to buffer high sea-surface temperatures across modest areas of the nearshore, a principal stressor to coral health. Protection of groundwater resources from contamination associated with land use can also potentially reduce stress that may be compromising coral health.

## Regional Patterns of Estuarine Influence and Cold-Water Refugia Along West Hawai'i

### Extent of Marine Water Temperature and Salinity Depression by Groundwater

The spatial and temporal extent that groundwater influences the nearshore and depresses marine water temperatures and salinity to create cooler estuarine conditions was examined by calculating the difference in water temperature

and salinity along survey transects from the marine values observed offshore during each survey (fig. 24). The magnitude that representative marine values of temperature and salinity were depressed by groundwater increased markedly toward the shore. In Kaloko-Honokōhau National Historical Park, temperatures across the reef ranged from 2 to 4 °C below marine temperatures observed offshore and were 5–7 °C lower than typical seawater near groundwater seeps (fig. 29A–G). A large area of estuarine conditions extended from ‘Ai‘ōpio to offshore of ‘Alula Beach and the Kaloko-Honokōhau Small Boat Harbor and was persistent in all years.



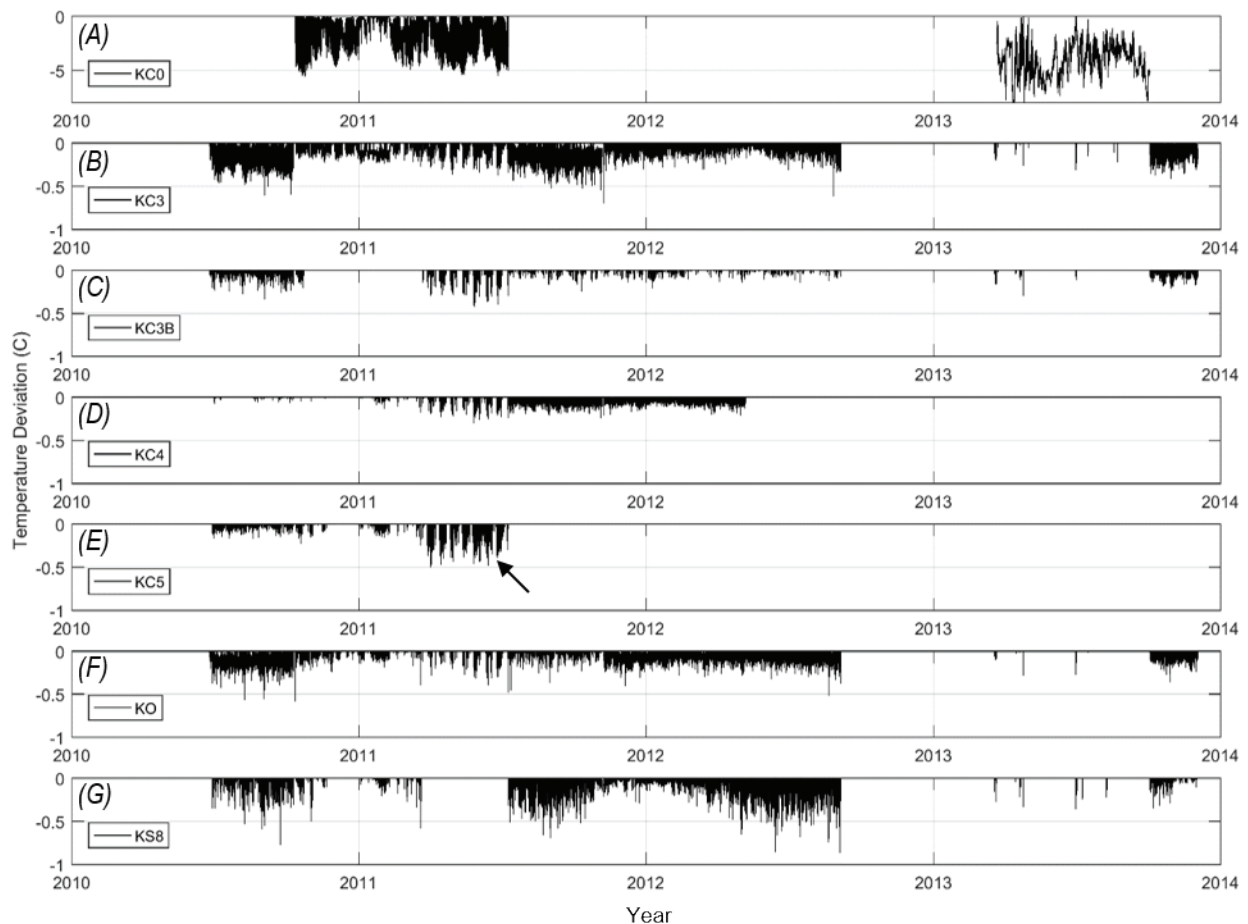
**Figure 29.** Maps showing the magnitude that water temperature was depressed below the maximum marine value observed in each season across Kaloko bay in northern Kaloko-Honokōhau National Historical Park in October 2010 (A), March 2011 (B), and December 2013 (C), southern Kaloko-Honokōhau National Historical Park in October 2010 (D), March 2011 (E), July 2011 (F), and December 2013 (G), and Pu'uhonua O Hōnaunau National Historical Park in October 2010 (H), March 2011 (I), July 2011 (J), and December 2013 (K) from surface tows. PSU, practical salinity unit. Base map from Esri World Imagery and its licensors © 2014.

Similar patterns were observed in Pu‘uhonua O Hōnaunau National Historical Park (fig. 29H–K) and other sites along west Hawai‘i (appendix 2).

### Extent and Frequency of Marine Water Temperature and Salinity Depression at Depth

The magnitude and frequency of local temperature deviations was calculated by taking the difference of the mean and maximum temperature observed within each individual study area and across the entire study area from the temperatures measured at each site (figs. 2, 3). Time-series temperature deviations (for example, from the Kaloko bay area of Kaloko-Honokōhau National Historical Park) showed that most stations have frequent negative temperature anomalies ranging from 1 to 5 °C from the area mean (fig. 30) and greater difference relative to area maximum temperatures important to bleaching stress. These data also showed inter-site variability and the important influence of transport processes that influence cold-water refugia related to groundwater. For

example, sites like Kaloko cut 5 that are farther offshore and from groundwater inputs than sites like Kaloko cut 3B and Kaloko cut 4 show comparable lower temperatures during late 2011 (fig. 30, arrow). Unlike deeper sites nearby, for example, Kaloko outer and Kaloko cut outer (KS8) that are more commonly affected by vertical temperature gradients and generally cooler water, sites like Kaloko cut 5 reveal unique and patchy cold-water associated with groundwater that may serve as cold-water refugia and are important to coral resilience. Similar magnitudes of temperature anomalies were observed in each area. Summing the frequency of deviations at each site reveals that most sites experience temperature depression below the area and entire coast mean and maximum ranging from 25 to 90 percent of the time. These mean and maximum anomalies below the area and coastwide are in part related to colder water at depth but mostly associated with inputs of colder, lower salinity groundwater. This is substantiated by vertical temperature gradients observed in CTD casts that generally show less than 1–2 °C change over the entire depth surveyed in offshore marine waters (fig. 17).



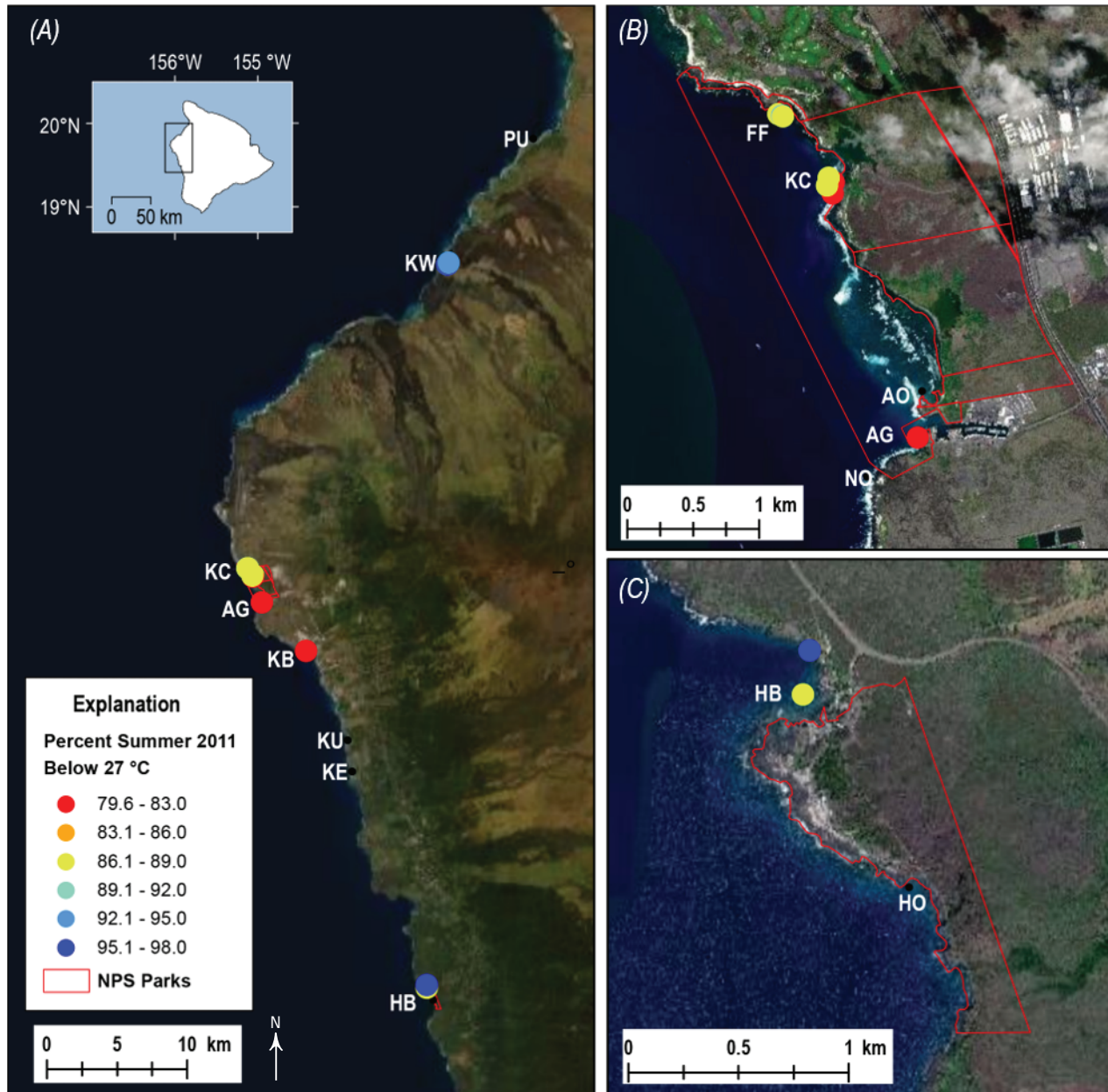
**Figure 30.** Time series plot of deviations in water temperature (in degrees Celsius [°C]) from the mean temperature across all deployment sites in Kaloko bay showing the prevalence and extent of temperature depression at all depths, with complex patchy influence of groundwater and varying distance from groundwater inputs and broad spatial patterns of cooling across most sites (black arrow).

### Cold-Water Refugia Along West Hawai'i

The temporal variability in temperature between sites over the study period help characterize the prevalence of temperatures stressful to or that correlate with coral health and reveal areas that may provide refugia from stressful temperatures. Analyses of the deviations in site and area temperatures below thresholds of concern and the simple mean across all sites was calculated and mapped in terms of frequency or percentage of occurrence. The percentage of time that temperatures at each site were below 27 °C during summer 2011 ranged from 80 to 98 percent. These results indicate

that sites like Freeze Face and Kaloko cut were cooler and more frequently cooler than Kaloko outer and 'Alula Beach within Kaloko-Honokōhau National Historical Park and in and around Pu'uhonua O Hōnaunau National Historical Park; Hōnaunau Bay north was cooler than Hōnaunau Bay south (fig. 31). Within the context of the entire west Hawai'i shoreline, Keawaiki mid, Freeze Face, Kaloko cut, and Hōnaunau Bay north were on average 10–15 percent more frequently below the 27 °C threshold than other sites studied.

A similar pattern is indicated by the percentage of time during summer 2011 that individual sites were at least 0.5 °C below the mean temperature of all sites, which ranged from



**Figure 31.** Map showing the percent of temperatures during summer 2011 (July 15 to October 15) that were below the 27 degrees Celsius (°C) bleaching threshold and spatial distribution of cold-water refugia across the study area (A), within Kaloko-Honokōhau National Historical Park (B), and Pu'uhonua O Hōnaunau National Historical Park (C). Site abbreviations correspond to those listed in table 1. Base map from Esri World Imagery and its licensors © 2014.

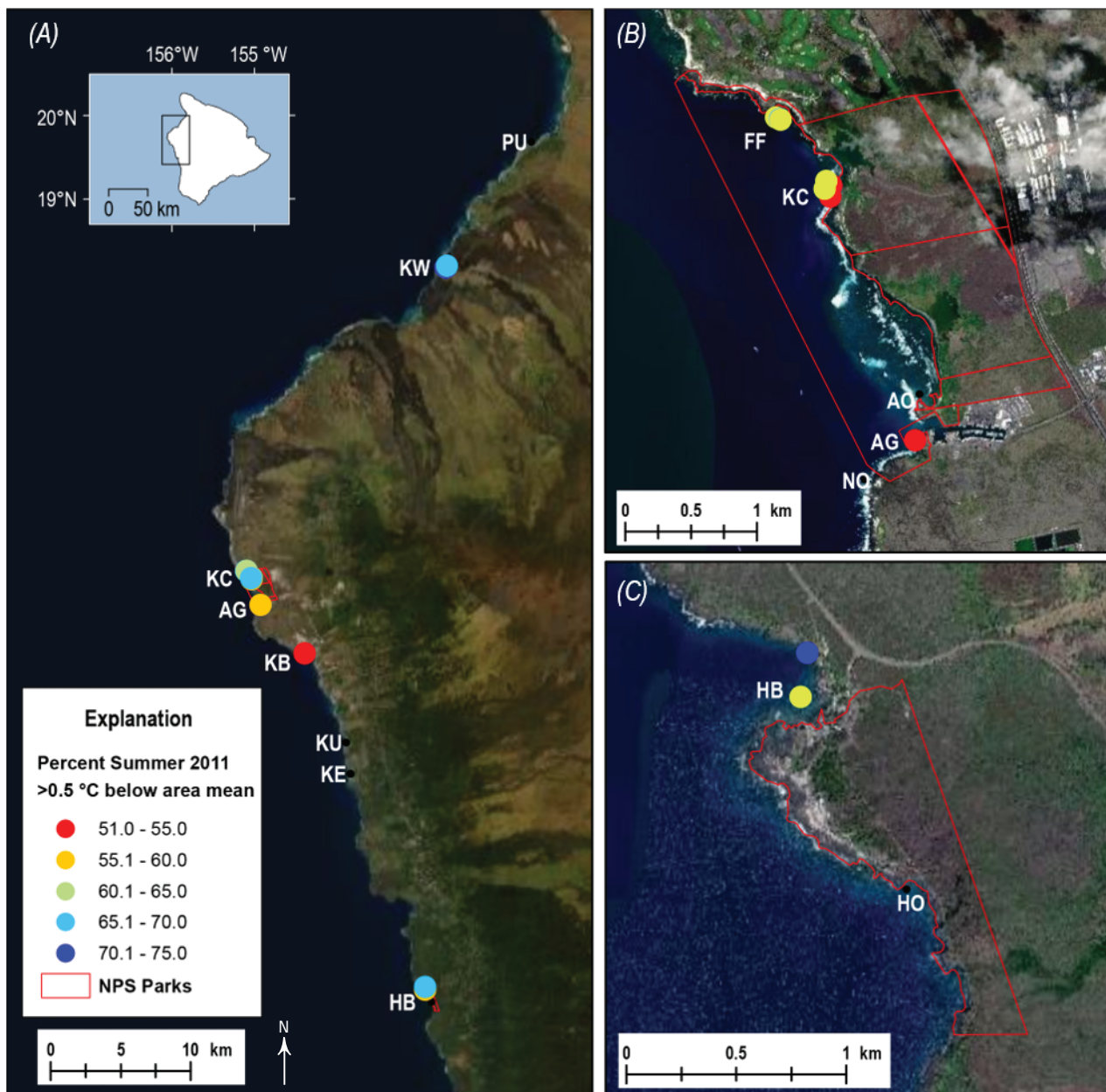


about 50 to 75 percent (fig. 32). More persistent colder sites like Keawaiki mid, Freeze Face, Kaloko cut, and Hōnaunau Bay north show lower water temperatures 10–15 percent more commonly than other sites studied, like Kaloko outer, ‘Alula Beach, Noio Point, Kailua Bay, and Hōnaunau outer. Similar patterns were found during the summers of 2010, 2012, and 2013. These persistent patterns of thermal refugia may benefit corals in mitigating bleaching and (or) adverse coral health impacts where water quality is not compromised, although the extent of benefits may depend on the extremity of thermal stress when it occurs and compounding effects of land-use activities to water quality and quantity. For example,

the capacity of these sites to provide refugia may have been exceeded by the extreme warm sea-surface temperatures of the 2015 coral bleaching event but potentially can buffer impacts associated with more, and increasingly frequent, less extreme events.

## Summary

Paired measurements of water quality and coral health indicators, including coral bleaching, made across west Hawai‘i and gradients in exposure to groundwater discharge to the coast and urban influences were made from July 2010



**Figure 32.** Map showing the percent of temperatures during summer 2011 (July 15 to October 15) that were below the mean temperature (in degrees Celsius [°C]) of all sites and the spatial distribution of cold-water refugia across the study area (A), within Kaloko-Honokōhau National Historical Park (B), and Pu‘uhonua O Hōnaunau National Historical Park (C). Site abbreviations correspond to those listed in table 1. km, kilometer. Base map from Esri World Imagery and its licensors © 2014.

through December 2014. Continuous time-series and discrete measurements of water temperature and salinity from 33 sites showed a complex patchwork of variability in habitat conditions that affect coral reef structure and identify areas of cold-water refugia. The extent, frequency, and timing of temperature and salinity variations are correlated with daily, tidal, and seasonal processes that affect nearshore water quality. Metrics related to temperature thresholds considered to affect coral bleaching were derived and used to examine correlations with coral health.

Water temperature was positively correlated to several coral health indicators, particularly those found on *Pocillopora meandrina*, and also the number of health indicators and species affected by adverse health indicators at each site, indicating that colder sites have less compromised coral health and that areas of cold-water refugia fed by groundwater may protect coral health. Several sites showed a negative correlation with higher counts of disease, including growth anomalies on *Porites lobata*, where waters were generally colder. The extent that these health anomalies are related to cold groundwater is confounded by known or suspected impacts of contaminant runoff associated with nearby industry and urban land uses.

This research complements the few comprehensive studies that exist to evaluate the potential benefits and adverse impacts of groundwater discharge to coral health. Groundwater entering the coast of Hawai'i, most high islands, and many atolls away from geothermal sources is colder and has the capacity to depress surrounding marine water temperatures, particularly during periods of high sea-surface temperature that cause stress and bleaching. However, poor groundwater quality compromised by human land-use activities that add contaminants and reduce groundwater flux to the coast may adversely impact coral reef health. This study indicates that improved understanding of the role of groundwater flux to reducing thermal bleaching stress associated with rising sea-surface temperatures and affecting many emerging coral health indicators is important to assessing the fate of coral reefs. In addition to its importance to many estuarine plants and wildlife, adequate submarine groundwater discharge and associated estuarine conditions are likely to be one of the few tangible opportunities to reduce coral vulnerability to global stressors and enhance local to regional coral reef resilience.

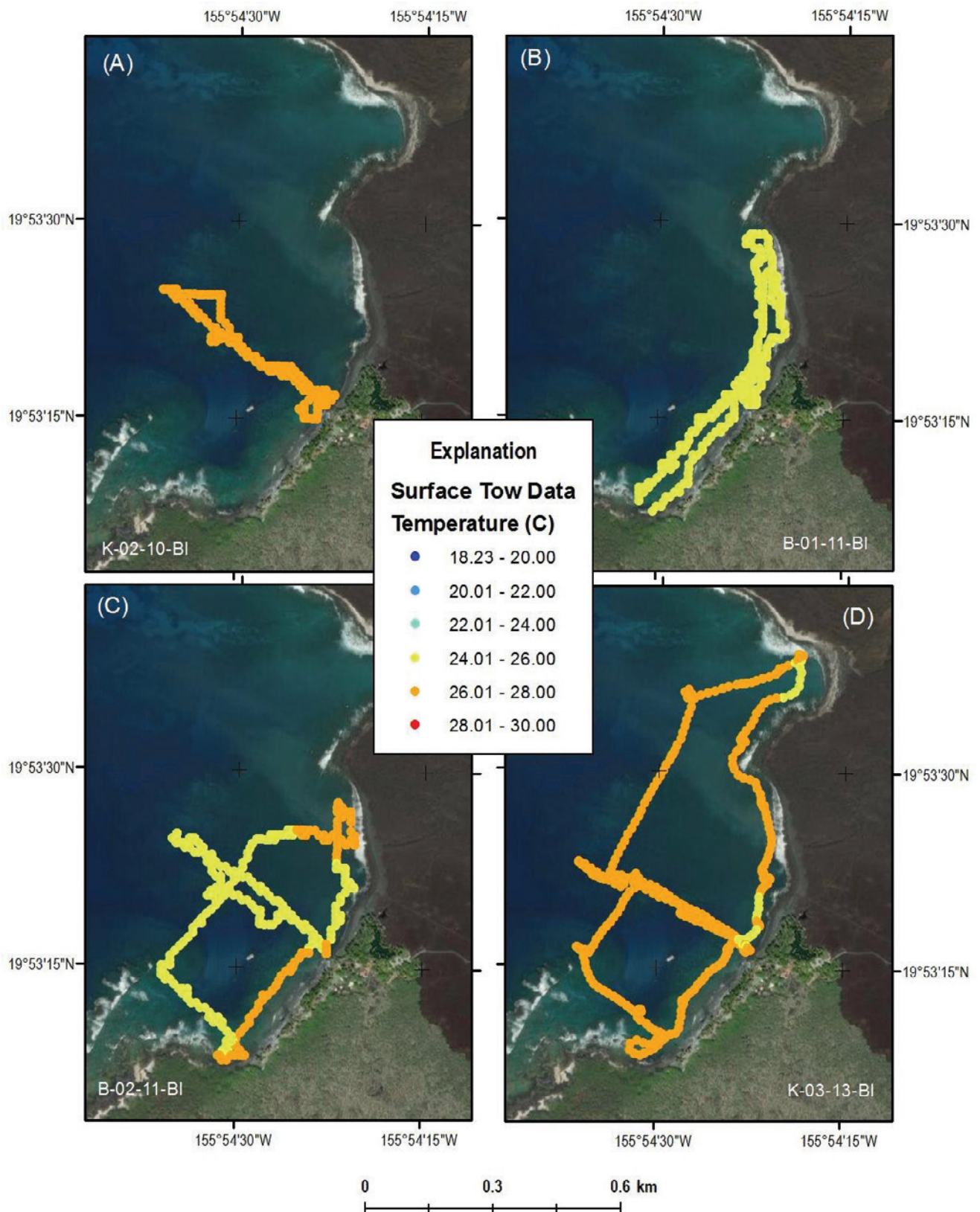
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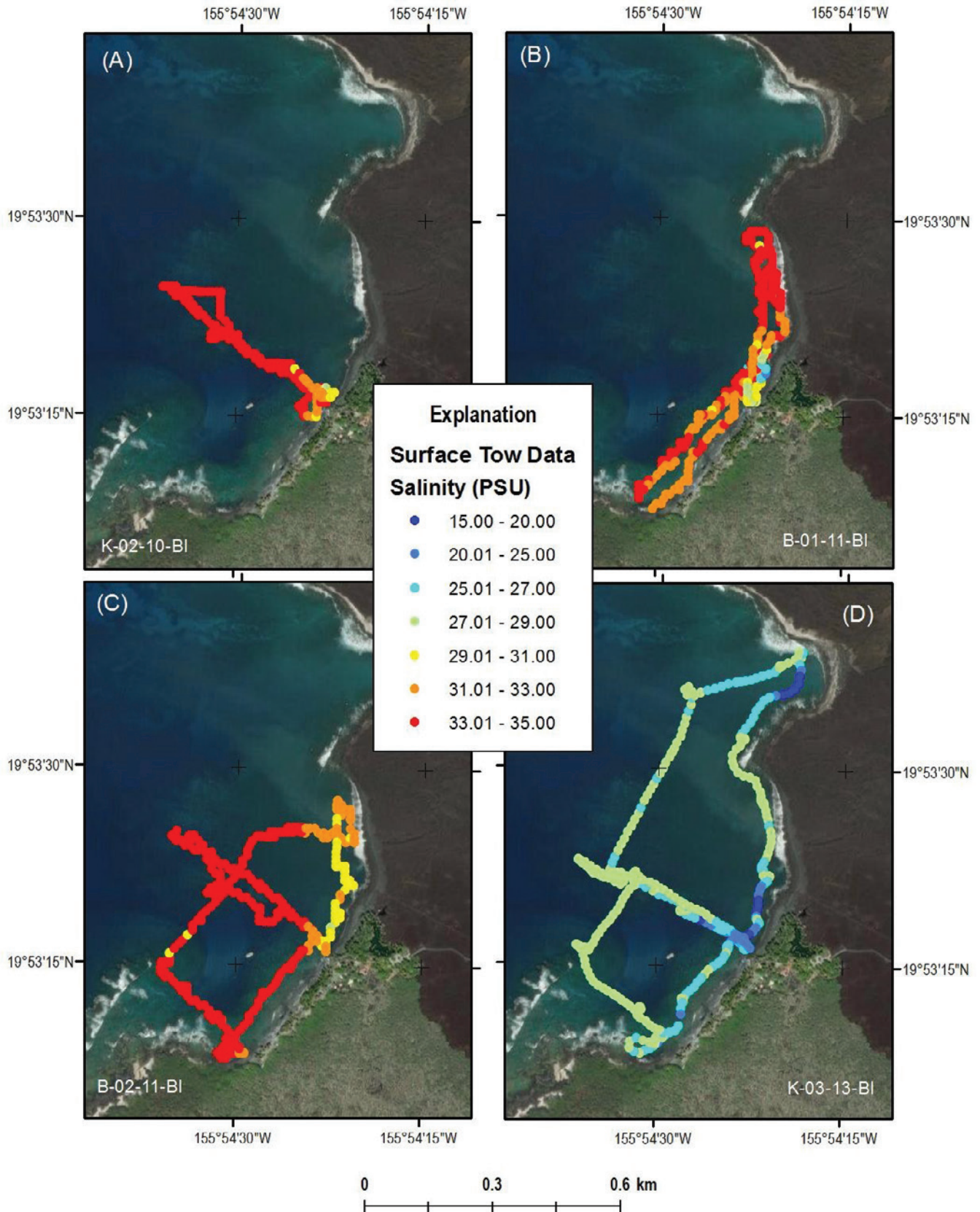
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## Appendix 1. Temperature and Salinity Data from Surface Tows for Additional West Hawai'i Study Sites

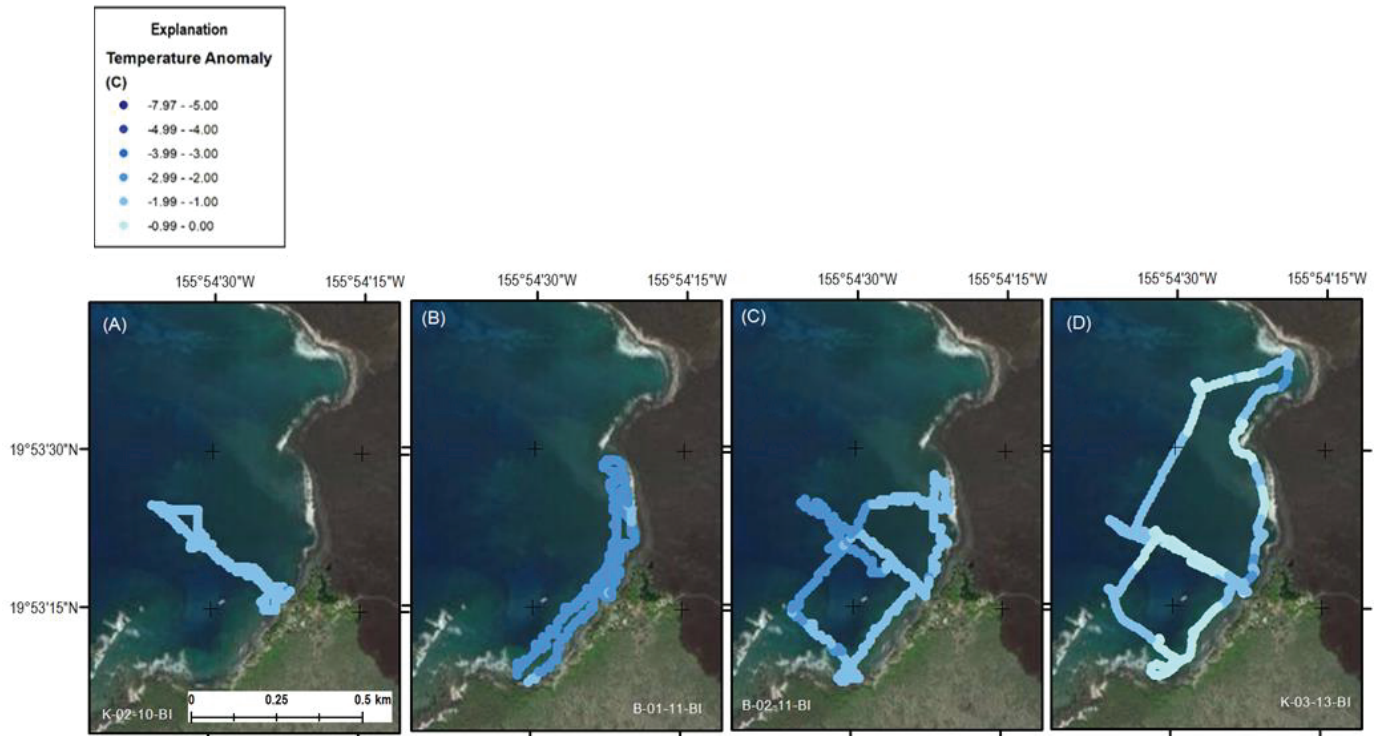


**Figure 1.1.** Map of surface water temperature, in degrees Celsius (C), from tows during October 2010 (A), March 2011 (B), July 2011 (C) and December 2013 (D) showing persistent cold-water inputs alongshore of Keawaiki (location in fig. 1A).



**Figure 1.2.** Map of surface water salinity, in practical salinity unit (PSU), from tows during October 2010 (A), March 2011 (B), July 2011 (C), and December 2013 (D) showing persistent low salinity inputs alongshore of Keawaiki (location in fig. 1A).

## Appendix 2. Temperature Anomalies across Additional West Hawai'i Study Sites



**Figure 2.1.** Maps showing the magnitude that temperature, in degrees Celsius (C),e was depressed below the maximum marine value observed in October 2010 (A), March 2011 (B), July 2011 (C), and December 2013 (D) across the Keawaiki study area (location in fig. 1A).

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