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REPORT

Rapid fluctuations in flow and water-column properties in Asan Bay, Guam: implications for selective resilience of coral reefs in warming seas

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Abstract Hydrodynamics and water-column properties were investigated off west-central Guam from July 2007 through January 2008. Rapid fluctuations, on time scales of 10s of min, in currents, temperature, salinity, and acoustic backscatter were observed to occur on sub-diurnal frequencies along more than 2 km of the fore reef but not at the reef crest. During periods characterized by higher sea-surface temperatures (SSTs), weaker wind forcing, smaller ocean surface waves, and greater thermal stratification, rapid decreases in temperature and concurrent rapid increases in salinity and acoustic backscatter coincided with onshore-directed near-bed currents and offshore-directed near-surface currents. During the study, these cool-water events, on average, lasted 2.3 h and decreased the water temperature 0.57 °C, increased the salinity 0.25 PSU, and were two orders of magnitude more prevalent during the summer season than the winter. During the summer season when the average satellite-derived SST anomaly was +0.63 °C, these cooling events, on average, lowered the temperature 1.14 °C along the fore reef but only 0.11 °C along the reef crest. The rapid shifts appear to be the result of internal tidal bores pumping cooler, more saline, higher-backscatter oceanic water from depths >50 m over cross-shore distances of 100 s of m into the warmer, less saline waters at depths of 20 m and shallower. Such internal bores appear to have the potential to buffer shallow coral reefs from predicted increases in SSTs by bringing cool, offshore water to shallow coral environments. These cooling internal bores may also provide additional benefits to offset stress such as supplying food to thermally stressed corals, reducing stress due to ultraviolet radiation and/or low salinity, and delivering coral larvae from deeper reefs not impacted by surface thermal stress. Thus, the presence of internal bores might be an important factor locally in the resilience of select coral reefs facing increased thermal stress.

Keywords Bores · Internal · Temperature · Salinity · Backscatter · Refugia

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Introduction

The mass bleaching events of 1997–1998 (Strong et al. 1998; Wilkinson 1998; Jiménez et al. 2001) and 2010 (Krishnan et al. 2011; Guest et al. 2012), as well as many other localized events, have shown the impact of elevated water temperatures on shallow hermatypic coral reefs. As carbon emissions continue to rise (e.g., Intergovernmental Panel on Climate Change 2007), it is widely accepted that global atmospheric and oceanic sea-surface temperature (SSTs) will continue to rise and adversely impact many shallow-water coral reefs (Hoegh-Guldberg 1999; Pandolfi et al. 2011). A number of recent studies have shown that historical temperature variability can affect corals' response to heat stress (McClanahan and Maina 2003; Ateweberhan and McClanahan 2010; Donner 2011; Carilli et al. 2012), in that those reefs that undergo greater temperature variability may be more resistant to thermal stress. This possibility, along with observations that coral in upwelling zones have sometimes fared better during larger-scale bleaching events (Jiménez et al. 2001; Riegl 2003), has led to the suggestion that upwelling zones may be refuges for corals in times of thermal stress (Riegl and Piller 2003; West and Salm 2003). The suitability of upwelling zones as refugia, however, has been debated based on observations that upwelling zones are often characterized by waters with reduced aragonite saturation states that can negatively affect corals (Feely et al. 2008; Manzello et al. 2008), and that the upwelling of cold, deep waters does not always occur concurrently with thermally induced stress (Chollett et al. 2010).

While upwelling typically occurs on the scale of days (e.g., Leichter et al. 1996; Storlazzi et al. 2003), episodic nonlinear internal waves ("bores") can be an important source of high-frequency (order ~min–h) upwelling that advects deeper, cooler waters up into shallow-water environments. These features, which are generated by breaking internal waves at the leading edge of the internal tide, have been shown to occur over coral reefs worldwide (Wolanski and Pickard 1983; Novozhilov et al. 1992; Wolanski and Delesalle 1995; Leichter et al. 1996, 2005; Wolanski and Deleersnijder 1998; Storlazzi and Jaffe 2008; Sheppard 2009; Roder et al. 2011; Sevadjian et al. 2012; Wall et al. 2012), but their occurrence is difficult to predict and is poorly correlated with the surface tide (Nash et al. 2012). Although the deep internal tide and internal waves occur throughout the year, the propagation of internal waves into shallow-water depths generally only occurs during periods of high stratification (e.g., Storlazzi et al. 2003). Most of these previous observations of internal waves and bores in coral reef environments, however, were either focused on hydrodynamics of such events only over a duration of days and thus do not account for their seasonal variability or contribution to annual dynamics, or simply long-term measurement of fluctuations in water-column properties (e.g., temperature) without concurrent measurements of the physical processes driving those variations.

In this paper, we present long, in situ records of hydrodynamics and the resulting variations in water-column properties over a Pacific island fringing reef that were collected as part of an effort understanding land-based sediment impacts to coral reefs off western Guam (Storlazzi et al. 2009). Our goal here is to utilize these data to quantify the spatial and temporal structure of internal bores, identify their seasonal variability, and infer the role the bores may play in offsetting thermally induced stress to coral communities.

Study area

Guam is located in the northwestern Pacific Ocean at approximately 13°N and 144°E, and has an area of 541 km^2; it is the southernmost island in the Mariana Islands and the largest island in Micronesia. The northern part of the island is a forested coralline limestone plateau rising more than 260 m above sea level, while the south is primarily highly erodible volcanic terrain with peaks up to 406 m in elevation that are covered in forest and grassland. Coral reefs surround most of the island, except where rivers discharge into bays. The average annual rainfall in Guam is 2,260 mm (Lander and Guard 2003); the wet season runs from July through November (~70 % rainfall), with the remaining months constituting the dry season (~30 % rainfall). The highest occurrence of typhoons is in October and November.

US Army Corps of Engineers Wave Information Studies wind and wave hindcast data for west-central Guam (Coastal Hydraulic Laboratory 2008) for the period from 1981 to 2004 show the dominance of the northeast trade winds on the general wind and wave climate for the area. Winds are predominantly out of the east–northeast at speeds of approximately 12 m s^{-1}; similarly, waves are primarily out of the east–northeast and have mean heights on the order of 2 m. The west-central coast of Guam is in the lee of the dominant trade wind forcing and thus is generally exposed to slower wind speeds and smaller wave heights. While the mean wind and wave climate is dominated by the northeast trade winds, the influence of typhoons passing close to Guam is evident in the directional distribution of high-speed winds and large waves. Although the frequency of occurrence of typhoon-driven winds and waves is low, their directions are more uniformly distributed than the mean wind and wave directions that are dominated by the trade winds, with the fastest wind speeds and largest waves coming out of the south and southwest. The mean daily tidal range is approximately 0.71 m, while the minimum and maximum daily tidal ranges are 0.16 and 1.10 m, during neap and spring tides, respectively (Storlazzi et al. 2009). The National Oceanic and Atmospheric Administration's Coral Reef Watch (2000a) gives an annual SST range from 27 to 31 °C over the period from 2001 to 2012, with the monthly mean climatology ranging from 27.5 to 29.5 °C.

The data presented here are from Asan Bay (13.46–13.50°N and 144.70–144.73°E) in west-central Guam, which is characterized by a continuous shallow (<1 m) reef flat that extends just under 2.5 km alongshore, ranges in width from 60 m to 250 m, and has a steeply (~20°–35°) sloping fore reef. The fore reef transitions at a depth of 30–40 m to a similarly sloping insular shelf that descends past 200 m <1 km from shore. The shallow (depths <30 m) sea floor off west-central Guam is predominantly a coral pavement with limited aggregate reef (NOAA's National Center for Coastal Ocean Science 2005). The reef flats and reef crest are covered with macroalgae, 10–50 and 50–90 %, respectively. The fore reef is covered by a mix of live coral and turf algae, which vary in coverage from 10 to 90 %, with an average hard coral cover of 27 % (National Park Service 2009). The highest coral coverage is between the 5- and 30-m isobaths.

Methods

In 2007, US Geological Survey and US National Park Service researchers conducted a study to determine coastal circulation patterns and sediment fluxes in War-in-the-Pacific National Historical Park's Asan Unit along west-central Guam. Detailed study methods are reported by Storlazzi et al. (2009), but will be briefly summarized here. From July 2007 through January 2008, flow and water-column properties were investigated using a suite of oceanographic and meteorologic instrument packages deployed along the Asan coast and on the insular shelf in water depths <20 m. Five bottom-mounted instrument packages were deployed over a distance of more than 2 km along the 20-m isobath on the fore reef and two at depth of 2 m on the reef crest; three moorings were deployed adjacent to the bottom-mounted instrument packages along the 20-m isobath on the fore reef. The instruments were recovered half way through the experiment in late October 2007 to download, as well as clean the instruments and replace the batteries. The oceanographic instrument packages included temperature and salinity sensors that logged every 5 min near the seabed. The moorings provided near-surface (depth ~2 m) measurements of temperature and salinity every 5 min. Stratification was computed as the differences between the near-surface and near-bed temperature and salinity data from the sensors on the bottom-mounted instrument packages and moorings. Both of the salinity sensors deployed along the 2-m isobath were plugged with sediment during a large wave event during the winter and thus those salinity data were not available for analyses.

The seabed instrument packages also contained 614-kHz upward-looking acoustic Doppler current profilers (ADCPs), which measured current speed, current direction, and acoustic backscatter at 0.5-m intervals throughout the water column every 10 min and directional wave information every 2 h. Maximum scattering of the 614-kHz ADCPs acoustic signal, which is recorded as acoustic backscatter, occurs with particles that have a diameter on the order of 1.0–1.5 mm (Storlazzi et al. 2006). A weather station with an anemometer, temperature sensor, and rain gauge was placed on top of a building along the shoreline at the midpoint of the bay to provide unobstructed local meteorologic data and recorded a 25-min average of each parameter every 30 min.

To provide more detailed information on water-column structure, a shipboard water-column profiler was used at multiple locations along the west-central Guam coast to collect vertical profiles of water temperature, salinity, and chlorophyll at the beginning and end of the instrument deployments. The vertical casts collected data at 4 Hz from just below the surface to the seabed or to a maximum depth of 30 m; these data were subsequently averaged to 1.0-m vertical bins.

When concurrent data were available across instrument records from multiple sensors along the same isobath, the data were averaged together along isobath such that all of the concurrent data from the sites stretching more than 2 km along the 20-m isobath were averaged together and those data from the reef crest on the 2-m isobath were averaged. This averaging was done to show the influence of physical forcing and water-column response over a greater area; such averaging also helped to filter out minor, site-specific changes in temperature, salinity, and acoustic backscatter that vary over longer time scales due to a number of physical processes (e.g., river floods and submarine groundwater discharge). In order to accurately compare the frequency of occurrence of oceanographic phenomena between the different seasons, the sample sizes (durations) taken from the two seasons were constrained to 52 d, as the length-of-time data were recorded during the shorter (trade wind) of the two seasons.

Results

Meteorologic and oceanographic forcing

The 7-month study period encompassed both the warmer, wetter rainy season and the cooler, drier trade-wind season. The wet season was characterized by winds that were variable in strength and direction, higher and more variable air temperatures, more frequent and higher rainfall, and smaller waves (Fig. 1). The transition from the warmer wetter season to the cooler drier season occurred around 2007 year day (YD) 335 (1 December 2007). The cooler, drier trade-wind season was characterized by consistent, strong winds from the northeast, lower air temperatures with smaller daily fluctuations, lower and less frequent rainfall, and larger waves. The trade-wind period was also characterized by higher near-surface current velocities, driven by the trade winds.

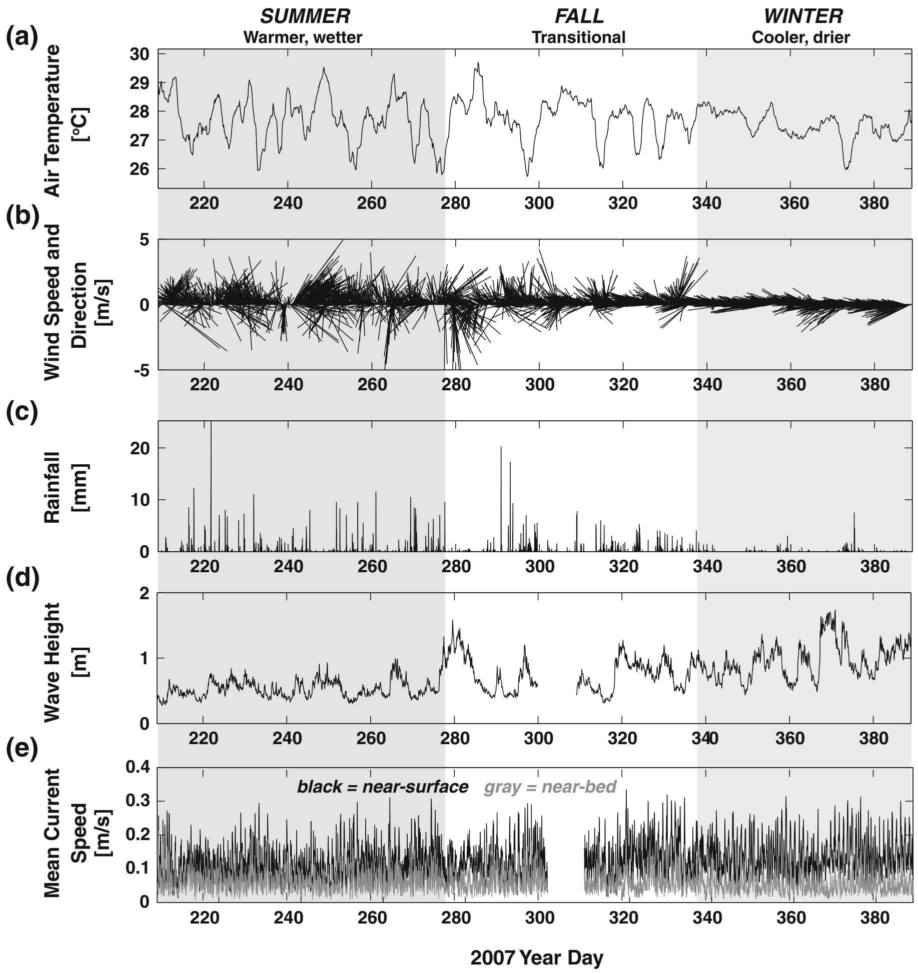

Fig. 1 Meteorologic and oceanographic forcing during the study. **a** Daily-running mean of air temperature. **b** Wind speed and direction every half hour. **c** Rainfall every half hour. **d** Mean wave height every 2 h along the 20-m isobath. **e** Mean near-surface (*black*) and near-bed (*gray*) current speeds along the 20-m isobath. The non-trade-wind season (summer and fall) was characterized by more variable air temperatures, wind speeds, and wind directions and higher rainfall, smaller wave heights, and slower surface currents than during the winter

Temporal patterns in flow and water-column properties

The water at the shallow sites typically warmed 1–2 °C daily due to insolation (Fig. 2). The temperature changes at the deep sites, however, were predominantly semi-diurnal in nature, with frequent, rapid decreases of 0.5–2 °C over periods of 10s of min. The long-term trends in water temperature exhibit a seasonal cooling at both the deep and shallow sites and less variation during the cooler trade-wind season. The standard deviation of the daily running average in temperature changed from 0.54 °C during the wet season (prior to 2007 YD 335) to 0.21 °C during the dry trade-wind season. Salinity values at the deep sites (Fig. 2) were higher than those at the shallow sites due to the influence of saltier oceanic water, although salinity at the deep sites decreased during times of heavy rainfall (e.g., 2007 YD 285–300). Over the course of the entire experiment, salinity and temperature at the deep sites had a significant inverse relationship ($r^2 = 0.928$, $n = 27{,}217$, $p < 0.00001$), but this relationship did not hold for the shallow sites ($r^2 = 0.006$, $n = 27{,}217$, $p > 0.05$).

Temperature and salinity at the deep sites changed by as much as 2.0 °C and 0.8 PSU, respectively, during a 3-h period and then, subsequently, returned to pre-event levels (Fig. 3). The greatest changes in temperature and salinity along the 2 km of fore reef occurred during large changes in tidal height, generally when the tide fell from the higher high to the lower low. This pattern of decrease in temperature and increase in salinity at the deep sites was not observed at the shallow sites, where the salinity generally remained constant, except for variations caused by the presence of fresh water or daily heating due to insolation. Although temperature variability was expected to be greatest at the surface due to insolation-driven heating and cooling cycles and decrease with depth (e.g., Storlazzi et al. 2003, 2009), at this site the overall variability in temperature along the 20-m isobath was slightly greater (2.89 °C) than along the 2-m isobath (2.21 °C).

The decreases in temperature and simultaneous increases in salinity along the 2 km of fore reef occurred during times of strong vertical stratification and vertical shear in the cross-shore current velocities (Fig. 4). The periods when near-bed

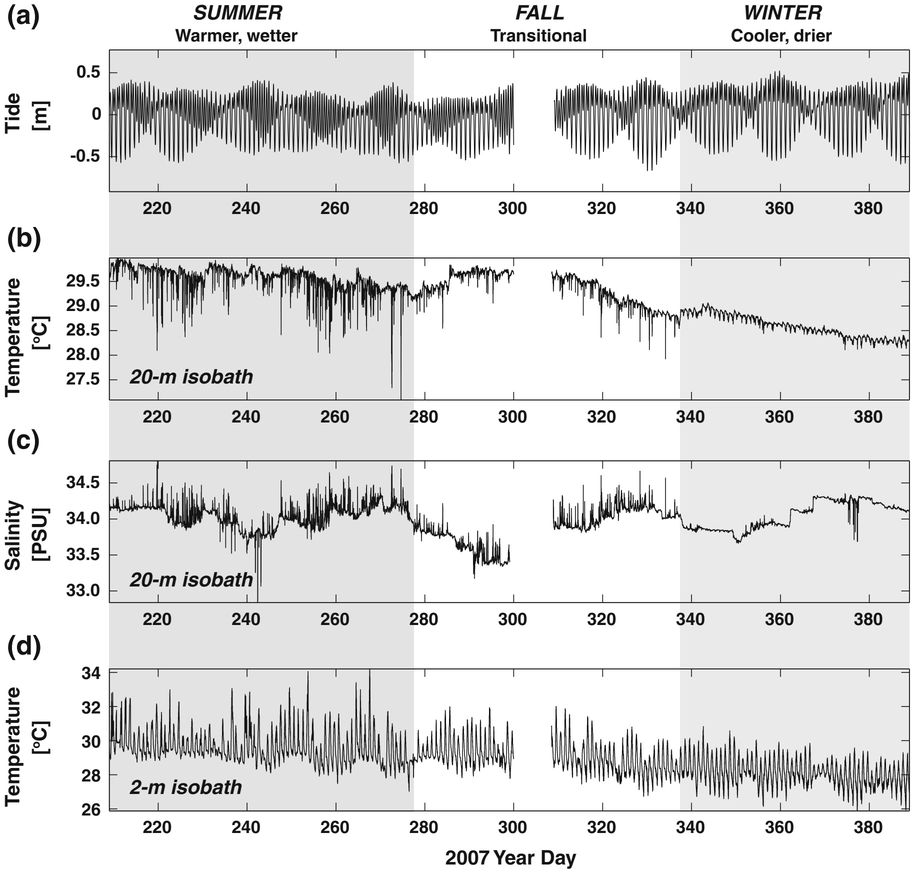

Fig. 2 Tidal variation and water-column properties during the study period. **a** Water depth. **b** Near-bed temperature along the 20-m isobath. **c** Near-bed salinity along the 20-m isobath. **d** Temperature along the 2-m isobath. The temperature data from the deep fore reef sites show rapid, significant temperature drops up to 2007 year day 337, after which the temperature fluctuations became less pronounced. The increases in salinity at the fore reef sites mirrored the temperature data from the deep sites up to 2007 year day 337, after which the salinity data were less variable. The temperature data at the shallow reef crest sites show fluctuations due to the tides and daily and seasonal insolation changes

water temperature rapidly decreased as salinity increased were characterized by offshore-directed near-surface currents and onshore near-bed currents at speeds >0.10 m s^{-1}, resulting in vertical velocity shear in the water column. The occurrence of these sheared cross-shore currents were not correlated with the wind speed or direction. Near-bed water temperature over the entire experiment was inversely correlated to near-bed onshore current velocities ($r^2 = 0.242$, $n = 27{,}217$, $p < 0.00001$) and salinity was positively correlated to near-bed onshore current velocities ($r^2 = 0.243$, $n = 27{,}217$, $p < 0.00001$) during the periods when water temperatures rapidly decreased and salinity increased (Fig. 5). Although the cool, more saline water delivered by internal bores generally mixed in with the warmer, less saline ambient reefal waters over the course of a few hours, the particulate matter causing the elevated backscatter persisted longer until it settled out of the water column. Because of this, acoustic backscatter over the entire experiment was also positively correlated to near-bed onshore current velocities ($r^2 = 0.161$, $n = 27{,}217$, $p < 0.00001$); the correlation, however, was not as robust because of the time it took the particulates to settle and because variations in acoustic backscatter were sometime dominated by large waves events that resuspended seabed sediment. These variations in near-bed water-column properties (temperature, salinity, and acoustic backscatter) lagged the near-bed onshore current velocities, on average, by 50 min. These rapid transition periods were also characterized by high thermal stratification; over the entire record at the 20-m sites on the fore reef, near-bed water temperature was inversely correlated to thermal stratification ($r^2 = 0.638$, $n = 27{,}217$, $p < 0.00001$) and salinity was positively correlated to thermal stratification ($r^2 = 0.642, n = 27{,}217, p < 0.00001$).

Although the tides are of mixed, semi-diurnal nature, the variations in near-surface currents, temperatures, and salinities were dominated more by diurnal (order ~24 h) variations (Fig. 6). Near the bed, however, the currents and water-column properties were dominated by semi-diurnal (order ~12 h) motions and had a greater proportion of energy at greater-than-tidal frequencies (periods <12 h), suggesting a greater influence of high-frequency currents on the resulting water-column properties.

In general, the near-bed cross-shore tidal currents were slow, generally <0.05 m s^{-1}, whereas flows associated with the observed high-frequency fluctuations in currents and water-column properties often exceeded 0.10 m s^{-1}. The onshore-directed near-bed currents generally sustained speeds of 0.10 m s^{-1} for at least an hour. The magnitude of these stronger near-bed onshore currents, coupled with the 50-min lag between their initiation and the observed

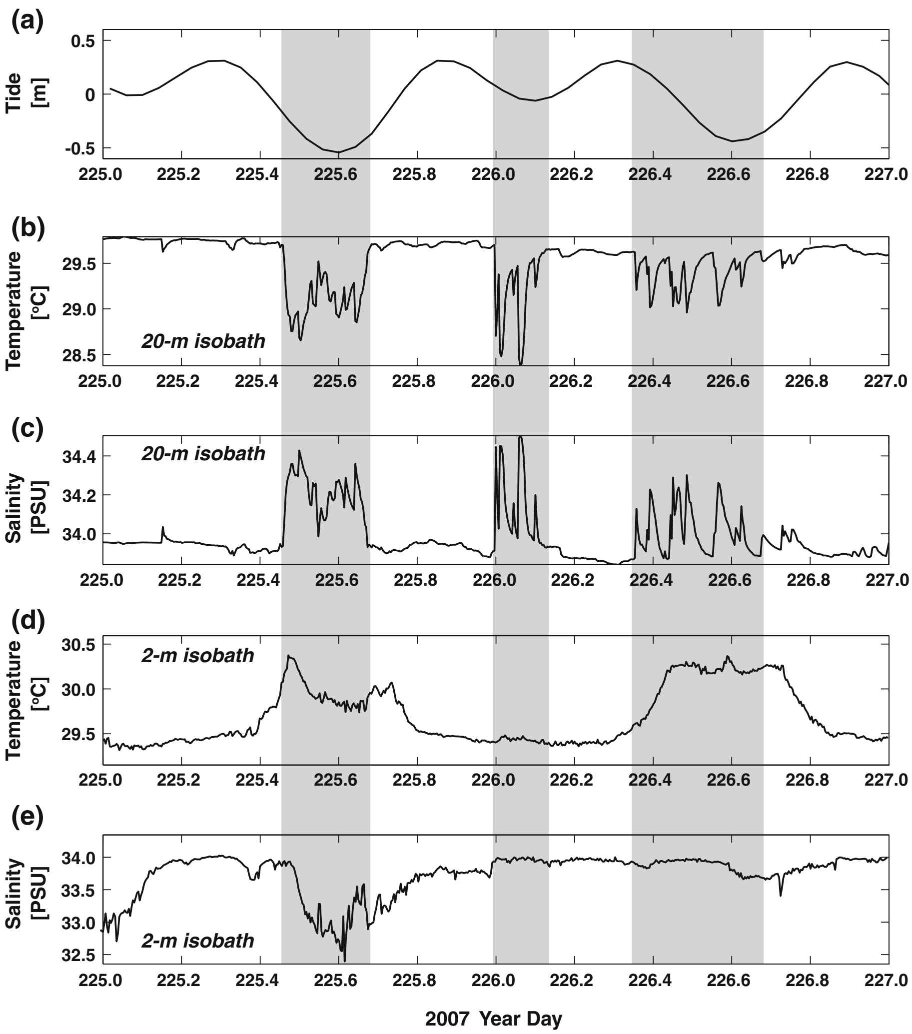

Fig. 3 Tidal variation and water-column properties during three cool-water events, denoted by gray shading. **a** Tide. **b** Near-bed temperature along the fore reef at the 20-m isobath. **c** Near-bed salinity along fore reef. **d** Near-bed temperature along the reef crest at the 2-m isobath. **e** Near-bed salinity along the reef crest. The data from the deeper fore reef sites that covered a 2-km along-shore extent showed concurrent decreases in temperature and increases in salinity; the data from the shallow reef crest sites did not exhibit these same patterns. The shallow-water temperatures along the reef crest increased daily with solar heating and cooled at night; the salinity data along the reef crest were relatively constant over the 2-d period except due to fresh water inputs during the falling tides

decreases in temperature and increases in salinity and acoustic backscatter, suggests that the near-bed currents advected this cooler, more saline, higher-backscatter water to the fore reef on the 20-m isobath from as far as 300 m farther offshore. These calculations match data from the water-column profiler (Fig. 7) that showed cooler, more saline, and higher chlorophyll waters at greater depths approximately 450 m offshore of the 20-m isobath during the instrument turn-around period in late October 2007; water-column profiles taken close to the fore reef on the 20-m isobath show that chlorophyll along the 20-m isobath was lower than that measured offshore at depth.

In order to understand the relative contribution of these high-frequency fluctuations in currents and water-column properties to potential cooling of coral reef waters, the cumulative cooling along the 2 km of reef during each event was examined for the wet rainy season and the drier trade-wind season. The cumulative cooling during each event was determined by first calculating the daily-running mean of the 5-min, near-bed temperature data from along the 20- and 2-m isobaths. Then, cooling anomalies were calculated by subtracting the running mean from the 5-min temperature data. A cooling event was defined as a set of at least 3 sequential cool anomalies (equivalent to $\sim$15 min in duration) of at least 0.25 °C. The cumulative cooling over an event was computed as the cumulative product of the anomaly values with the time intervals, giving a resulting unit of $°\mathrm{Ch}^{-1}$. These analyses were applied to two 52-d periods during the non-trade-wind (2007 YD 225–277) and trade-wind (2007 YD 337–389) seasons (Figs. 1, 2) to compute the relative frequency and magnitude of the cool-water events between the two seasons. On the fore reef along the 20-m isobath, the cooling events, on average, lasted 2.3 h, decreased the water temperature 0.57 °C, increased the salinity 0.25 PSU, and were two orders of magnitude more prevalent ($\sim$2.01 d^{-1}) during the summer season than during the winter ($\sim$0.02 d^{-1}; Table 1). The summer was characterized by higher SSTs, weaker (to nonexistent) trade wind forcing, and smaller ocean surface waves than during the winter. Overall, in

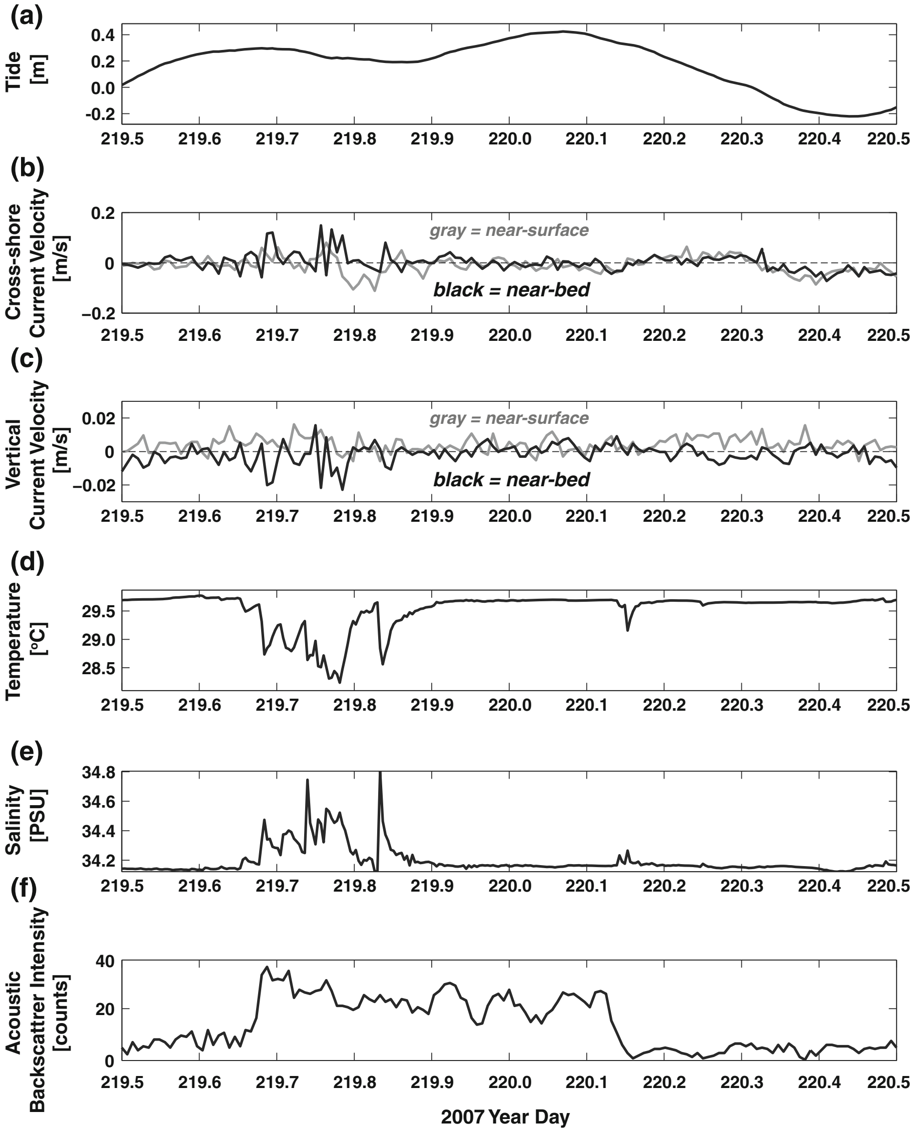

Fig. 4 Hydrodynamics and water-column properties along the 20-m isobath during a cool-water internal bore event. **a** Tide. **b** Cross-shore current velocity, with near-surface flow in *gray* and near-bed flow in *black*. **c** Vertical current velocity, with near-surface flow in *gray* and near-bed flow in *black*. **d** Near-bed temperature. **e** Near-bed salinity. **f** Near-bed acoustic backscatter intensity. The 1-d period shows an internal bore pumping colder, more saline, higher-backscatter water into the area at cross-shore velocities >0.16 m s^{-1}. Although the cool, more saline water delivered by the bore mixed in with the warmer, less saline ambient reefal waters over the course of a few hours, the particulate matter causing the elevated backscatter persisted almost twice as long until it settled out when the near-bed currents were oriented toward the seabed

summer, these cooling events had average cumulative cooling effects of 2.8 °C-h along the 2 km of fore reef and occurred 18.6 % of the time; in winter, the average was 1.5 °C h^{-1}, and the events occurred 0.3 % of the time. Occasionally, cooling at the reef crest (along the 2-m isobaths) was observed concurrently with the events recorded along fore reef (along the 20-m isobaths); however, none of the reef crest cooling patterns were of sufficient magnitude and duration to meet the criteria used here to define a cooling event.

Comparison to satellite sea-surface temperatures

NOAA's Coral Reef Watch (2000a) generates twice-weekly SST data from satellites around the world. These relatively temporally sparse data (as compared to the in situ measurements described here) are often used to identify areas that are experiencing anomalously high surface-water heating and, therefore, are potentially at risk for coral bleaching. The SST anomaly data are produced by subtracting the long-term mean SST for that location and time of year from the current value. Similarly, the Coral Bleaching HotSpot product (NOAA Coral Reef Watch 2000b) highlights regions where the SST is currently warmer than the highest climatological monthly mean SST for that location; a HotSpot value of 1.0 °C is defined a threshold for thermal stress that may lead to coral bleaching.

Because there are no Coral Reef Watch Program virtual stations in the location of this study, the two closest stations (Guam East and Santa Rosa Reef) were used for comparison to the in situ instrument data collected along the 2 km of reef in the study area. The two stations had very similar SSTs ($r^2 = 0.909$, $n = 72$, $p < 0.001$); the HotSpot anomalies,

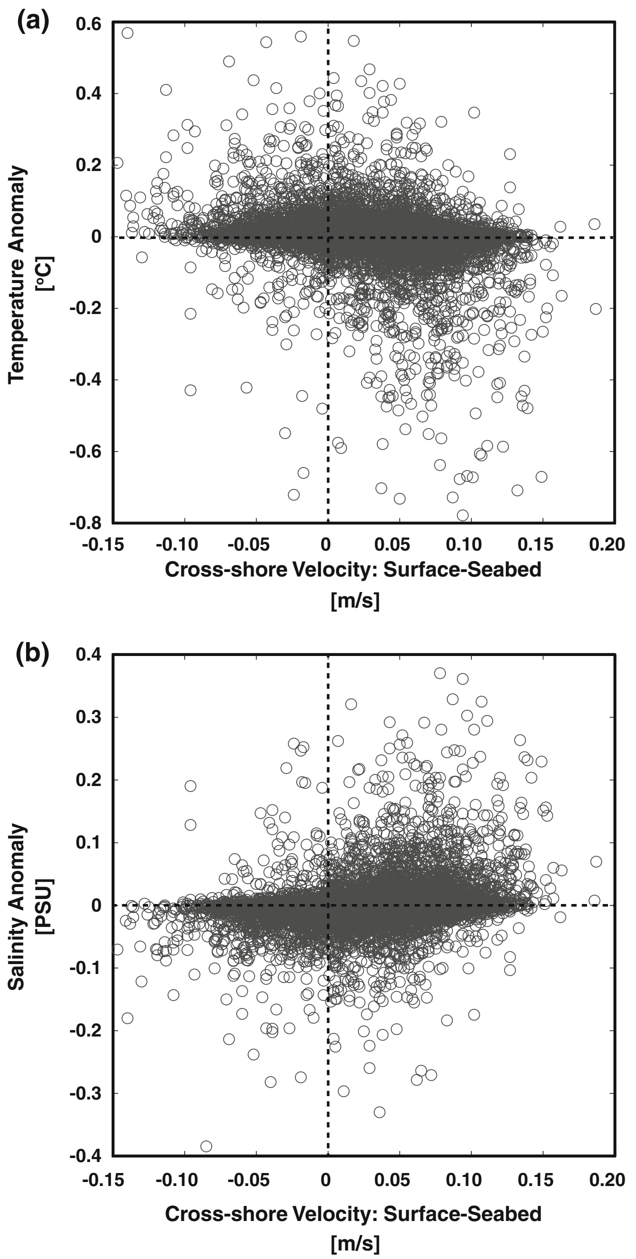

Fig. 5 Variations in water-column properties as a function of vertical velocity shear. **a** Near-bed temperature anomaly. **b** Near-bed salinity anomaly. Although there is scatter in the data due to the large number of samples taken over a range of seasons and other processes that also affect temperature and salinity, such as river floods and submarine groundwater discharge, the influence of near-bed onshore flow and offshore-directed surface flow driving negative temperature anomalies and positive salinity anomalies is evident

being based on the historical means, were slightly more variable ($r^2 = 0.677$, $n = 72$, $p < 0.001$) but also statistically correlated. The average satellite SST values and HotSpot anomalies showed that thermal stress was predicted to occur in surface waters during the warmer non-trade-wind season, the same season during which more prevalent and intense cooling events associated with high-frequency fluctuations in near-bed currents and water properties were observed (Fig. 8).

If we assume that SSTs are stable (can be linearly interpolated) between the twice-weekly satellite measurements, we can use those data to understand the relative impact of the cooling events. The study area was not subjected to degree-heating weeks (DHW) during the study period; thus, we cannot compute a relative measure of cooling using that metric. We can, however, determine the relative cooling imparted by the internal bore-driven cooling events compared to the elevated thermal stress as measured by the SST anomalies. During the warmer summer period, the cooling events reduced the water temperatures on the fore reef along the 20-m isobath on average 1.14 °C per twice-weekly measurement. The same calculations made using the in situ instruments along the reef crest on the 2-m isobath result in only a reduction of 0.11 °C per twice-weekly measurement. The average SST anomaly during this same time was +0.63 °C per twice-weekly measurement, suggesting that the internal bore-driven cooling events measured on the fore reef along the 20-m isobath more than offset the SST anomalies measured at the surface. At no time during the experiment were corals observed to bleach in the study area (National Park Service, personal communication).

Discussion

The multi-hour-long decreases in temperature and concurrent increases in salinity and acoustic backscatter during onshore-directed, near-bed flow on subtidal timescales were much more prevalent during the warmer, wetter non-trade-wind season when thermally induced bleaching is more probable, based on the Coral Reef Watch Program's SST anomalies and HotSpot values. The inverse temperature–salinity relationship, along with the high-frequency (greater than semi-diurnal tidal frequencies) decreases in temperature and increases in salinity that correlate with high-frequency near-bed onshore currents, is typically an indication of high-frequency internal waves following the head of the internal tidal bore (Leichter et al. 1996, 2005; Storlazzi et al. 2003). These features, which extended along more than 2 km of reef in this study, have been observed throughout the world's ocean (e.g., Jackson 2004) and specifically on coral reefs in the Pacific (Wolanski and Pickard 1983; Wolanski and Delesalle 1995; Storlazzi and Jaffe 2008; Sevadjian et al. 2012), Atlantic (Leichter et al. 1996, 2005), and Indian Oceans (Novozhilov et al. 1992; Wolanski and Deleersnijder 1998; Sheppard 2009; Roder et al. 2011; Wall et al. 2012).

The more frequent occurrence and greater intensity of the internal bores during the non-trade-wind summer

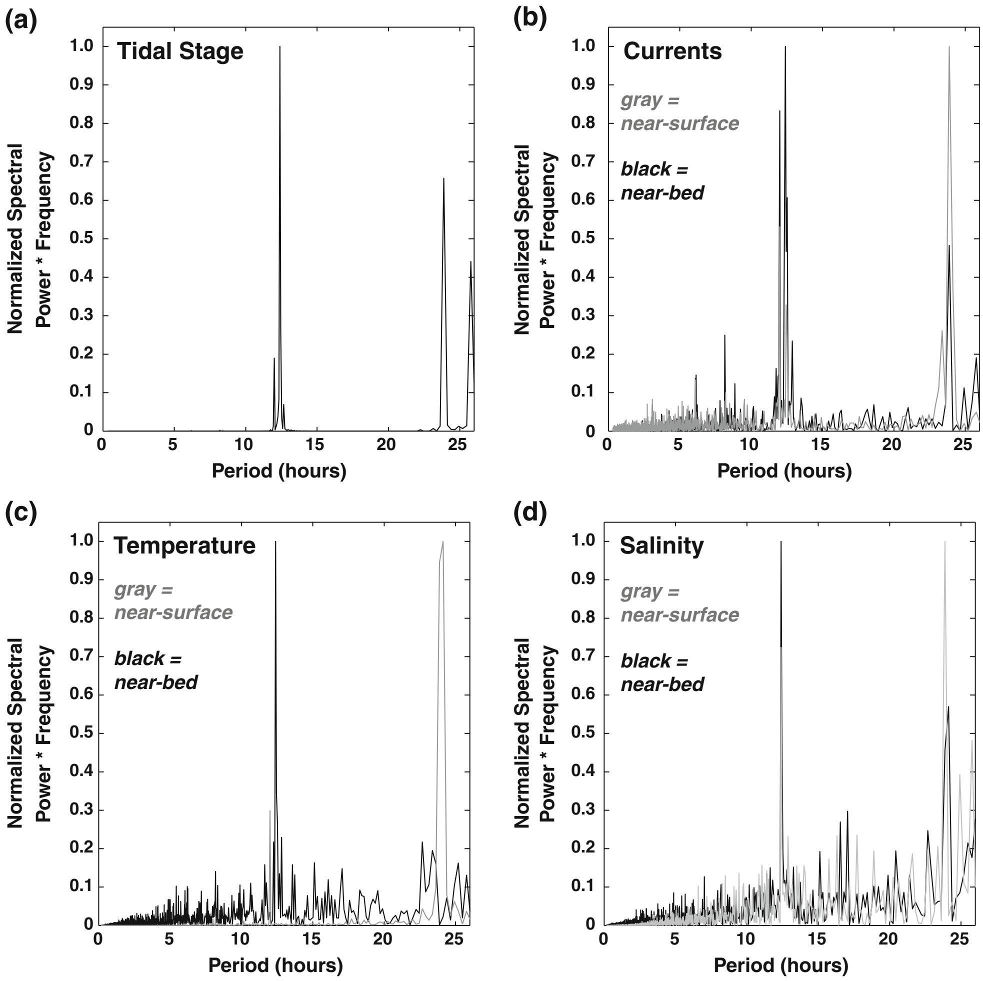

Fig. 6 Normalized variance-conserving power spectra of the forcing and water-column data from along the 20 m isobath. **a** Tide. **b** Cross-shore current velocity. **c** Temperature. **d** Salinity. For subplots **b–d**, near-surface data are *gray* and the near-bed data are *black*. Although the tides are of mixed, semi-diurnal nature, the near-surface currents, temperatures, and salinities are dominated more by diurnal (order ~24 h) variations. Near the bed, however, the currents and water-column properties are dominated by semi-diurnal (order ~12 h) motions and have a greater proportion of energy at sub semi-diurnal (<12 h) frequencies, suggesting a greater influence of high-frequency currents, likely related to internal waves, on the resulting water-column properties

season likely result from the higher thermal stratification caused by insolation-driven surface heating. The decreased frequency and intensity of internal bores during the drier, cooler trade-wind winter season are likely due to larger ocean surface waves mixing the water column, a process that decreases stratification to a point where it is insufficient to support internal motions. This seasonal relationship between the presence of internal bores during the summer when stratification is high due to insolation and low wave-induced mixing is similar to observations of internal bores on temperate bedrock reef systems at higher latitudes (e.g., Storlazzi et al. 2003). As evidenced from the data here and those presented by Leichter et al. (2005) and Sheppard (2009), the temperatures that corals experience at depth can fluctuate considerably on sub-diurnal time scales and these high-frequency temporal temperature fluctuations cannot be resolved by daily or weekly SST records.

These cooling events that were associated with internal bores may help buffer the reefs in this area from atmospheric-driven thermal stress, as also suggested by Leichter et al. (2005) and Sheppard (2009). At our study site, the cool internal bore features were most prevalent during the warmer, wetter non-trade-wind season when bleaching is more probable. Not only could the temporarily depressed water temperatures along the 2 km of reef during these events potentially buffer stress-inducing surface temperatures, these cooling events could also acclimate the corals on the fore reef below the insolation-driven surface layer (a depth of 5 m off western Guam, as shown in Fig. 7) to greater thermal variability (e.g., McClanahan and Maina

2003; Donner 2011; Carilli et al. 2012) and thus make them more resilient to short-term temperature increases compared to fore reefs that are not subjected to such phenomena. The pumping of colder, more saline deep ocean waters into warmer nearshore waters could provide thermal refuges for reefs and offset the effects of global warming (Riegl and Piller 2003; West and Salm 2003; Mumby et al. 2011). While the average temperature decreases observed along the 2 km of reef in our study area were not exceedingly large, much greater decreases in temperature that were likely related to similar internal wave forcing have been observed at other coral reef sites (e.g., Leichter et al. 2005; Sheppard 2009; Roder et al. 2011). Thus, there is potential for these cool internal bore events to provide substantial thermal buffering at other locations around the globe. Coles and Jokiel (1978) noted that low ocean salinity associated with run-off negatively affected corals that were thermally stressed. Because the cool-water bores also resulted in the increased salinity of the shallow waters, these features may also increase resilience to thermal stress in areas subjected to freshwater run-off or submarine groundwater discharge, which is common to many tropical high islands (e.g., Swarzenski et al. 2012).

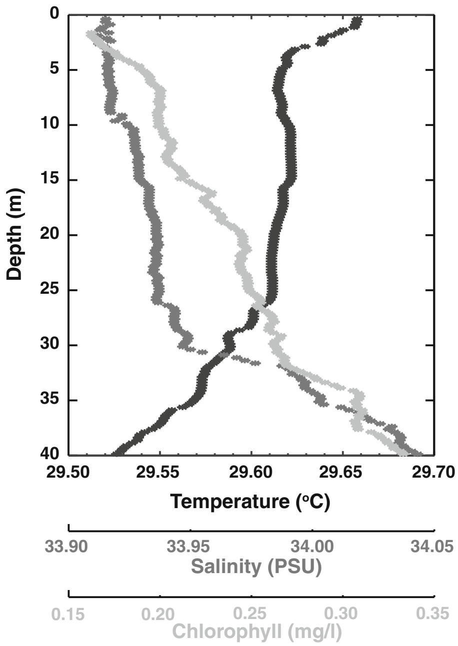

Fig. 7 Variations in temperature, salinity, and chlorophyll with depth from a water-column profiler cast taken approximately 450 m offshore of the 20-m isobath in late October 2007. Note the cooler, more saline, and higher chlorophyll waters at depth, with thermoclines approximately 3 and 30 m below the surface

These cool internal bores may also be pumping abiotic or biologic matter into these nearshore areas, and this material may further support coral reefs impacted by stress. We observed elevated acoustic backscatter during these internal bore events (Fig. 4), and a water-column profile taken offshore from the study site shows phytoplankton concentrations increasing with depth (Fig. 7). If the internal bores are pumping organic particulates, these likely include phytoplankton species that can be prey for the corals. Grottoli et al. (2006) and Houlbrèque and Ferrier-Pagès (2009) showed that increased heterotrophic feeding by corals has the potential to offset trophic stress associated with a paucity of symbionts, which often occurs due to external stressors (thermal stress, contaminants, etc.). Even the advection of inorganic particulates (sediment) into shallow coastal waters may provide a similar function by providing a food source to stressed corals, as described by Rosenfeld et al. (1999) and Anthony (2000). Furthermore, the particulate matter advected onshore over the coral reefs by the internal bores would also result in greater scattering of light; this might reduce the ultraviolet light stress on corals that acts synergistically with heat stress to cause bleaching (e.g., Fitt et al. 2001). Lastly, if such transport of deep, cooler waters to shallower nearshore waters occurs during periods of coral spawning, this cross-shelf transport may also bring coral larvae from deeper reefs to settle on shallower reefs (e.g., Bongaerts et al. 2010) that were impacted by thermal stress (e.g., Strong et al. 1998; Wilkinson 1998; Jiménez et al. 2001). Although internal bores, coral spawning, and thermal stress patterns all exhibit different temporal and spatial patterns across different coral reef environments, most corals in the Pacific Ocean and Caribbean Sea chains spawn during the summer months (e.g., Richmond and Hunter 1990) when the potential for thermal stress is the greatest and more internal bore activity occurs, as described here and the studies cited above. Combined, these beneficial effects provided by internal bores might explain why some fore reefs are more resistant to bleaching than others.

By providing cooler waters to shallow-water reefs, internal bores may have the potential to buffer shallow

Table 1 Number and maximum intensity of cooling anomalies by season

	0.25–0.50 °C	0.50–1.00 °C	1.00–1.50 °C	1.50–2.00 °C	>2.00 °C	Total
Warmer, wetter non-trade-wind season (2007 year day 225–277)	58	39	6	1	1	105
Cooler, drier trade-wind season (2007 year day 337–389)	1	0	0	0	0	1

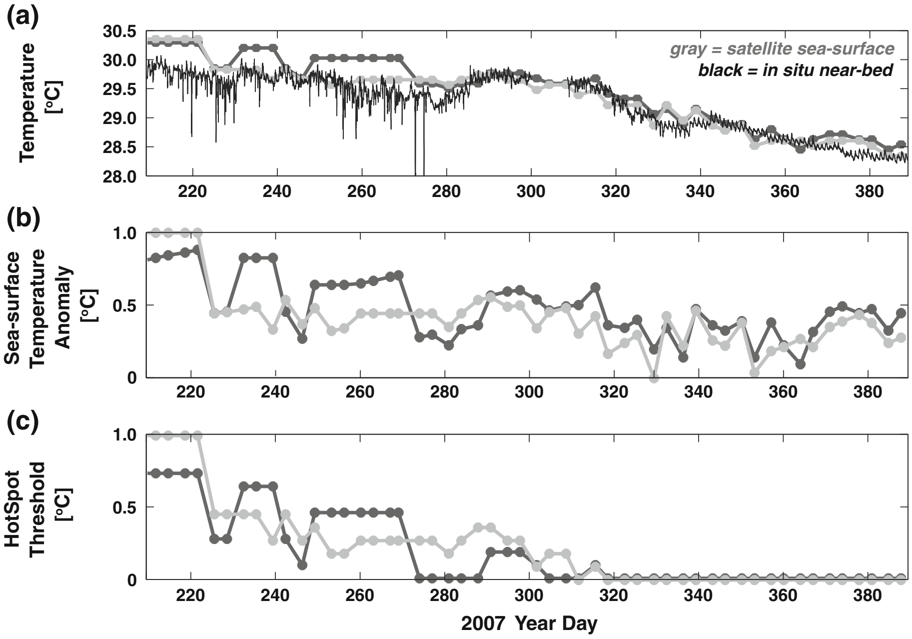

Fig. 8 Water temperatures, anomalies, and cumulative thermal stress for the study area from in situ and satellite sensors. **a** In situ 5-min averaged water temperatures along the 20-m isobath (*black*) and twice-weekly average satellite sea-surface temperatures (SST) from the adjacent Guam East and Santa Rosa Reef virtual stations (*gray*). **b** Average satellite-derived SST anomaly from the adjacent Guam East and Santa Rosa Reef virtual stations. **c** Average satellite-derived HotSpot value from the adjacent Guam East and Santa Rosa Reef virtual stations. Cool-water events driven by internal bores are more prevalent during the summer when remote-sensing products predict greater thermal stress

coral reefs from predicted increases in SSTs. If the water temperatures below the thermocline remain the same during future global warming, internal bores will still be able to pump deeper, cooler water up onto the shallower coral reefs. Because their occurrence is related to the thermal stratification of the water column, even if the sub-thermocline water temperatures increase the same amount as those at the surface under climate change, bores will still be able to supply cooler, deep water to the shallower portions of the reef than they would be subjected to above the thermocline. Considering the thermal effects, combined with the increases in salinity and the potential for contributing food and/or larvae to shallow-water reefs, there are many ways internal bores may provide benefits that offset stress to nearshore reef environments and thus might be an important factor for the selection of marine managed areas established for the purpose of coral reef protection. Because air- and space-borne SST measurements only provide information on the uppermost few millimeters of the water column, they cannot be used to identify the presence of internal bores or characterize their contribution to cooling coral fore reefs because of the varied nature of the internal tide and water-column structure that allows internal bores to propagate into shallow water. In situ measurements of physical forcing and water-column response are therefore necessary to determine the presence of such events and evaluate their contribution to providing present-day and future refugia for coral reefs.

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