Coral Reefs
https://doi.org/10.1007/s00338-019-01850-4

NOTE

In situ and remotely sensed temperature comparisons on a Central Pacific atoll

Danielle C. Claar[1,2,3] · Kim M. Cobb[4] · Julia K. Baum[3]

Received: 28 March 2019 / Accepted: 14 August 2019

Abstract Climate-induced warming events increasingly threaten coral reefs, heightening the need for accurate quantification of baseline temperatures and thermal stress in these ecosystems. To assess the strengths and weaknesses of NOAA satellite sea surface temperature and in situ measurements, we compared 5 yr of these data on Kiritimati atoll, in the central equatorial Pacific. We find that (1) satellite measurements were similar to in situ measurements (~ 10 m depth), albeit slightly warmer, with measurements converging once above Kiritimati's maximum monthly mean; (2) in situ loggers detected subsurface cooling events missed by satellites; (3) thermal baselines and anomalies were consistent around the island; and (4) in situ degree heating week (DHW) calculations were most comparable to NOAA DHWs when calculated using NOAA's climatology. These results suggest that NOAA's satellite products accurately reflect conditions on central Pacific reefs, but that in situ measurements can identify localized events, such as subsurface upwelling, that may be ecologically relevant for corals.

Keywords NOAA CoralTemp · Kiritimati · Kiribati · Sea surface temperature (SST) · Degree heating weeks · Thermal anomalies

Topic Editor Morgan Pratchett

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00338-019-01850-4) contains supplementary material, which is available to authorized users.

✉ Danielle C. Claar
danielle.claar@gmail.com

[1] School of Aquatic and Fisheries Sciences, University of Washington, Seattle, WA, USA

[2] Cooperative Programs for the Advancement of Earth System Science (CPAESS), University Corporation for Atmospheric Research (UCAR), Boulder, CO, USA

[3] Department of Biology, University of Victoria, Victoria, BC, Canada

[4] School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA

Introduction

With climate change-amplified pulse heat stress events threatening the persistence of many of the world's coral reefs (Hoegh-Guldberg et al. 2007; Hughes et al. 2018), the need for accurate quantification of temperatures on these ecosystems is more critical than ever. Temperature loggers deployed at depth on reefs have the potential to most accurately record the thermal conditions corals are experiencing, but these instruments vary widely in quality, and their use can be limited by expense, accessibility, and instrument loss. Satellite-derived sea surface temperature (SST) products (e.g., NOAA Coral Reef Watch 2018; Liu et al. 2012), which measure temperature at the ocean's skin (top ~ 0.1 mm), have provided consistent global SST coverage on coral reefs since the early 1980s. Although satellite SST products, such as those used by NOAA Coral Reef Watch, are "sea-truthed" and corrected using moored buoy (~ 20 cm depth) temperatures (Gleeson and Strong 1995; Strong et al. 2011), measurement depth is their major inherent limitation for the evaluation of thermal stress on reefs. This is because skin temperature is more variable than temperature at depth, and can be influenced by wind speed (Donlon et al. 2002) as well as diurnal temperature fluctuations (Gentemann and Minnett 2008). Satellites also may not detect localized events such as subsurface upwelling, which can significantly influence warming trajectories on individual reefs (Sheppard 2009; Karnauskas and Cohen 2012). Therefore, by combining consistent, broad spatial-scale SST with localized measurements, the integration of satellite SST and in situ measurements can provide a more accurate view of thermal stress affecting coral reefs.

Previous studies that have compared satellite SST products with in situ measurements found high correlations and good agreement between methods for coral reefs (Montgomery and Strong 1994; Aronson et al. 2002; Hendee et al. 2002), and those in temperate locations have found mean daily temperature differences ranging from − 0.62 °C to + 1.39 between data sources (Wellington et al. 2001; Stobart et al. 2016). Satellite SST products have also been validated against coral bleaching records, with good results (McClanahan et al. 2007). For example, a comparison of satellite SST and several in situ temperature measurements in Okinawa found agreement in determining the onset, development, and dissipation of a warming event (Strong et al. 2002).

Despite the central Pacific Ocean's importance as one of the main regions of El Niño warming, in situ temperature records of nearshore reefs in this area are scarce (but see Hoeke et al. 2009). Two islands in this region, Kiritimati (01°52′N, 157°24′W) and Jarvis (0°22′S, 159°59′W), were the hardest hit locations globally during the 2015–2016 El Niño, with both experiencing unprecedented heat stress and exceeding 25–30+ DHWs (Brainard et al. 2018). Here, we compare overall temperatures and degree heating weeks (DHWs) between NOAA's CRW satellite SST measurements and high-resolution temperature logger data from Kiritimati's reefs, over a 5-yr period.

Materials and methods

Study location

Kiritimati (Christmas Island, Republic of Kiribati) experiences limited intra-annual (seasonal) but significant interannual sea surface temperature variability (from El Niño events). The eastern and northeastern sides of Kiritimati are consistently influenced by the trade winds, while the atoll's western (leeward) side is subject to upwelling and lagoon outflow. Due to its local human disturbance gradient (Watson et al. 2016), and position in the center of the Niño-3.4 region, Kiritimati has been the focus of a monitoring program since 2007 (Walsh 2011; Claar and Baum 2019) as well as extensive coral paleoclimate and paleo-ENSO studies (Cobb et al. 2003, 2013; Grothe et al. 2016).

Data

We deployed SBE-56 temperature loggers (Sea-Bird Electronics Inc.; ± 0.002 °C) at 17 sites within six geographic regions on Kiritimati from 2011 to 2016 (Fig. 1). Sites within regions have similar oceanographic conditions, and a centrally located 5-km satellite pixel was chosen within each region. Loggers were deployed at multiple sites per region over time (Fig. 1a, Table S1). All loggers were deployed at ∼ 10 m depth on the forereef (range 8–12 m; Table S1). In situ data were manually quality controlled to remove measurements from deployment/retrieval dates, and data were plotted to ensure that sensors were measuring temperature consistently at depth. Data were standardized by minute then hourly and finally daily increments for comparison with the satellite product. Daily in situ data were calculated with: (1) all temperature data from each 24-h day and (2) only nighttime temperatures (20:00:00 to 05:00:00, GMT + 14).

Satellite SST and DHW data were obtained from the NOAA Coral Reef Watch (CRW) experimental daily global 5-km satellite product, CoralTemp version 1.0 and the NOAA CRW Daily Global 5-km Satellite Coral Bleaching Heat Stress Degree Heating Week version 3.1, respectively (NOAA CRW 2013; Maturi et al. 2017). The CoralTemp product provides a gap-free (1985–present) SST product using nighttime-only temperature at a depth of 20 cm (Skirving et al. 2018). This product is derived from three datasets: the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) Reanalysis (Jan 1985–Nov 2002), the NOAA/NESDIS Blended Reanalysis (Nov 2002–Oct 2016), and the NOAA/NESDIS Blended near-real-time product (Oct 2016–present) (Maturi et al. 2017; Skirving et al. 2018). SST and DHW values were extracted for each region on Kiritimati for January 2011–December 2016 (Fig. 1). Since these products contain curated daily data, no additional processing was necessary for comparison with in situ data.

Analyses

To compare temperatures, we calculated the mean offset between satellite and in situ temperature for each region as: mean((satellite temperature (°C)) − (in situ temperature (°C))), using (1) all available dates, and (2) all available dates, excluding El Niño warming. Mean offset is used to identify consistent differences between datasets; here, positive values indicate satellite measurements are consistently warmer than in situ temperature. We then calculated correlations between the datasets using ccf (R package stat) and visualized them with corrplot.mixed (Wei and Simko 2017).

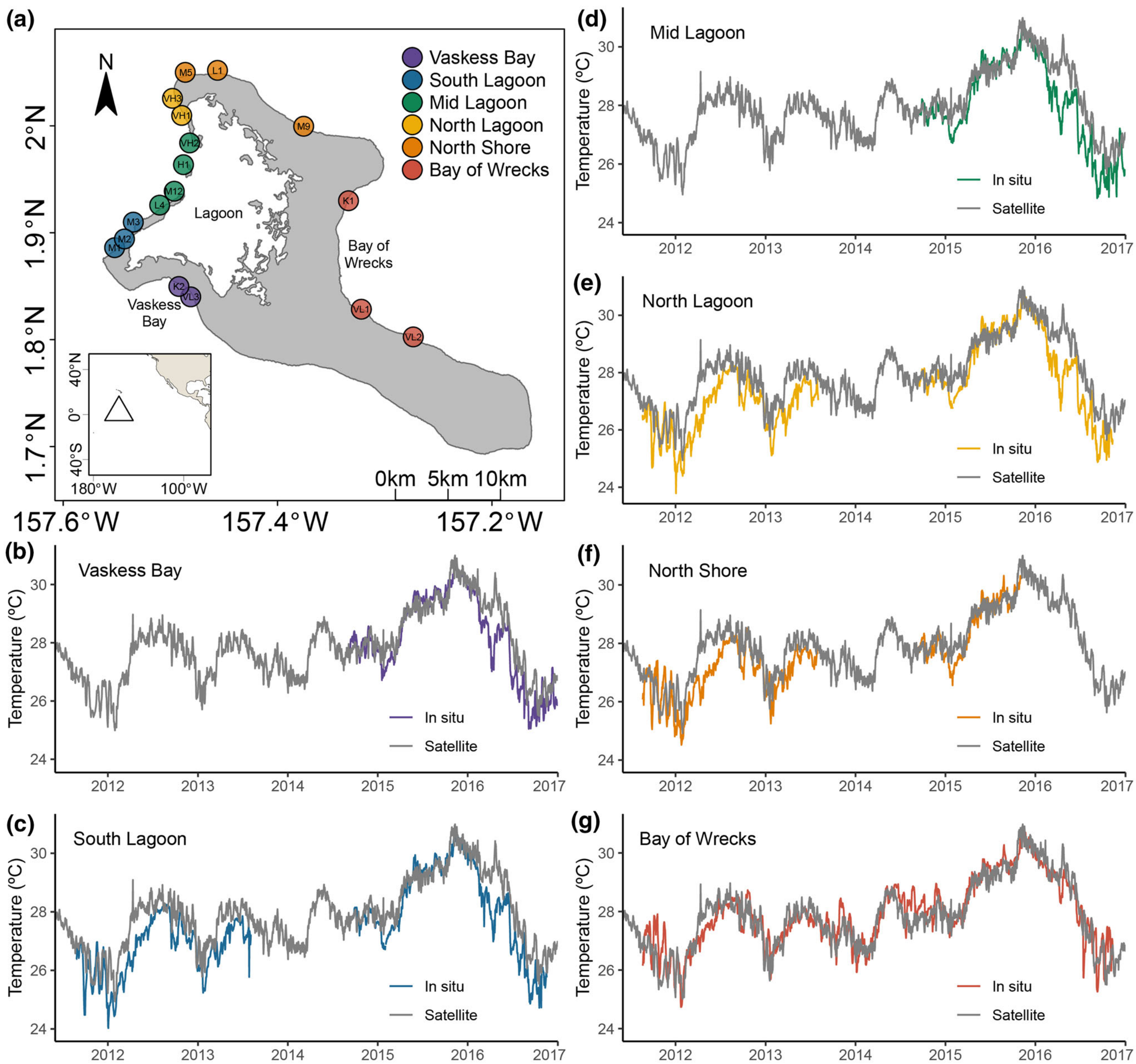

Fig. 1 Comparison of satellite and in situ temperature measurements at six regions around Kiritimati. Satellite data are continuous throughout the time series, and in situ data are plotted as available (and averaged when more than one logger was available within the region)

To compare DHW values between the satellite and in situ datasets, we calculated in situ DHW values for each region following NOAA's DHW calculations (Liu et al. 2017), based on three different maximum monthly mean (MMM) climatology options: (1) using the baseline NOAA MMM (ftp://star.nesdis.noaa.gov/pub/sod/mecb/crw/data/5km/v3.1/climatology/nc/ct5km_climatology_v3.1.nc), extracted directly from the NOAA climatology; (2) baseline NOAA MMM minus the mean offset calculated with all available data; and (3) baseline NOAA MMM minus the mean offset, excluding El Niño warming. NOAA's DHW values are calculated by first summing half-weekly hot spots (temperatures greater than the MMM) that are greater than 1 °C, over a 12-week rolling window. This value is divided by two to obtain DHWs, which are measured in °C-weeks.

All analyses were conducted in R (R Development Core Team 2008). Code for data extraction, visualization, and analyses is available at https://github.com/daniclaar/KI_temperature_insitu_NOAA.

Results and discussion

Satellite and in situ temperature data on Kiritimati were generally consistent over time in each of the six regions, with a few notable deviations (Fig. 1). The Bay of Wrecks region exhibited the most consistent temperatures between satellite and in situ measurements (Fig. 1, Tables 1, S2), likely due to thorough surface mixing associated with the predominant trade wind and swell direction. Two notable subsurface cooling events occurred on Kiritimati's leeward side, at the beginning of 2012 and 2016, that caused significant deviations between satellite (warmer) and in situ (cooler) measurements (Fig. 1). The first was driven by a La Niña that persisted through February of 2012, while the second event was likely due to upwelling as the Equatorial Undercurrent (EUC) resumed normal speeds as the 2015–2016 El Niño relaxed. The latter is supported by the lack of this signature in the east-facing Bay of Wrecks.

Satellite temperatures demonstrated a positive offset compared to in situ measurements in most regions (Table 1, Fig. 2), although the magnitude of the offset varied across temperatures (Fig. 2). This is in contrast to a study in Belize that found a cool bias in SST (MODIS Aqua and Terra) compared to in situ measurements (Castillo and Lima 2010). This difference may have been due to different logger depths [3–5 m in (Castillo and Lima 2010) vs. ~ 10 m in this study], different satellite data platforms, or it may be because local oceanographic/geographic effects (loggers from (Castillo and Lima 2010) were deployed on an inner lagoon reef and a barrier reef, compared to exclusively the fore reef in this study). Satellite measurements at lower temperatures (e.g., 24–27 °C) tended to be positively biased compared to in situ measurements, while those at higher temperatures (e.g., 29–30 °C) tended to cluster more centrally around the in situ measurements (Fig. 2). These higher temperatures are above Kiritimati's MMM and occurred primarily during the 2015–2016 El Niño event. This result aligns with a study in the Galapagos that found a smaller difference between AVHRR nighttime satellite data and in situ measurements during ENSO warming compared to baseline conditions (Wellington et al. 2001).

There was a high level of correlation between satellite and in situ temperatures, and among regions ($r > 0.89$; Figs. 2, S1). This is consistent with a previous study in Belize that found high correlations ($r > 0.85$) between daily averages of satellite-derived SST and in situ temperature at two sites from 1995 to 2001 (Aronson et al. 2002). Extremely high correlation values between satellite measurements across regions ($r > 0.995$; Fig. S1) could be due to physical autocorrelation (i.e., temperatures are similar among these sites) or artifacts from satellite optimal interpolation (i.e., interpolating values for missing satellite data such as cloudy days), but the fact that in situ measurements were also highly correlated among regions ($r > 0.95$; Fig. S1) suggests that water temperatures are remarkably stable around Kiritimati, despite varying oceanographic conditions across regions.

DHW values measured from NOAA CRW around the atoll during the 2015–2016 El Niño event were within 4% of one another (Table S3) and were consistently slightly lower than our calculated in situ DHW values (Figs. 3, S2). Surprisingly, utilization of the baseline NOAA MMM provided the closest approximation to the NOAA CRW DHW product during this El Niño event on Kiritimati. We had expected that, due to satellite data's positive offset, applying NOAA MMM climatology to in situ data would result in an underestimation of DHW. However, because satellite and in situ temperature measurements were more consistent during El Niño than during non-warming conditions, the DHW values during warming from these two sources end up being very similar. The addition of positive offsets to the NOAA CRW MMM climatology produced DHW values that were considerably higher (Fig. 3). Although it is possible that these latter DHWs calculated more accurately reflect the thermal stress experienced by corals on Kiritimati, because our in situ data do not extend long enough to calculate in situ MMM from them, we are

Table 1 Mean offset and mean monthly maximum (MMM) climatology for each Kiritimati region; including all available data, and excluding measurements during El Niño warming

Region	Mean offset		MMM		
	All data (°C)	Not including El Niño (°C)	NOAA	NOAA − offset (all data)	NOAA − offset (no El Niño)
Vaskess Bay	0.32	0.37	27.97	27.65	27.60
South lagoon	0.54	0.61	28.01	27.47	27.40
Mid lagoon	0.49	0.58	28.02	27.53	27.44
North lagoon	0.59	0.66	28.02	27.43	27.36
North shore	0.36	0.44	28.02	27.66	27.58
Bay of Wrecks	− 0.04	− 0.07	27.96	28.00	28.03

MMM from NOAA climatology, NOAA climatology minus mean offset (all data), NOAA climatology minus mean offset excluding El Niño

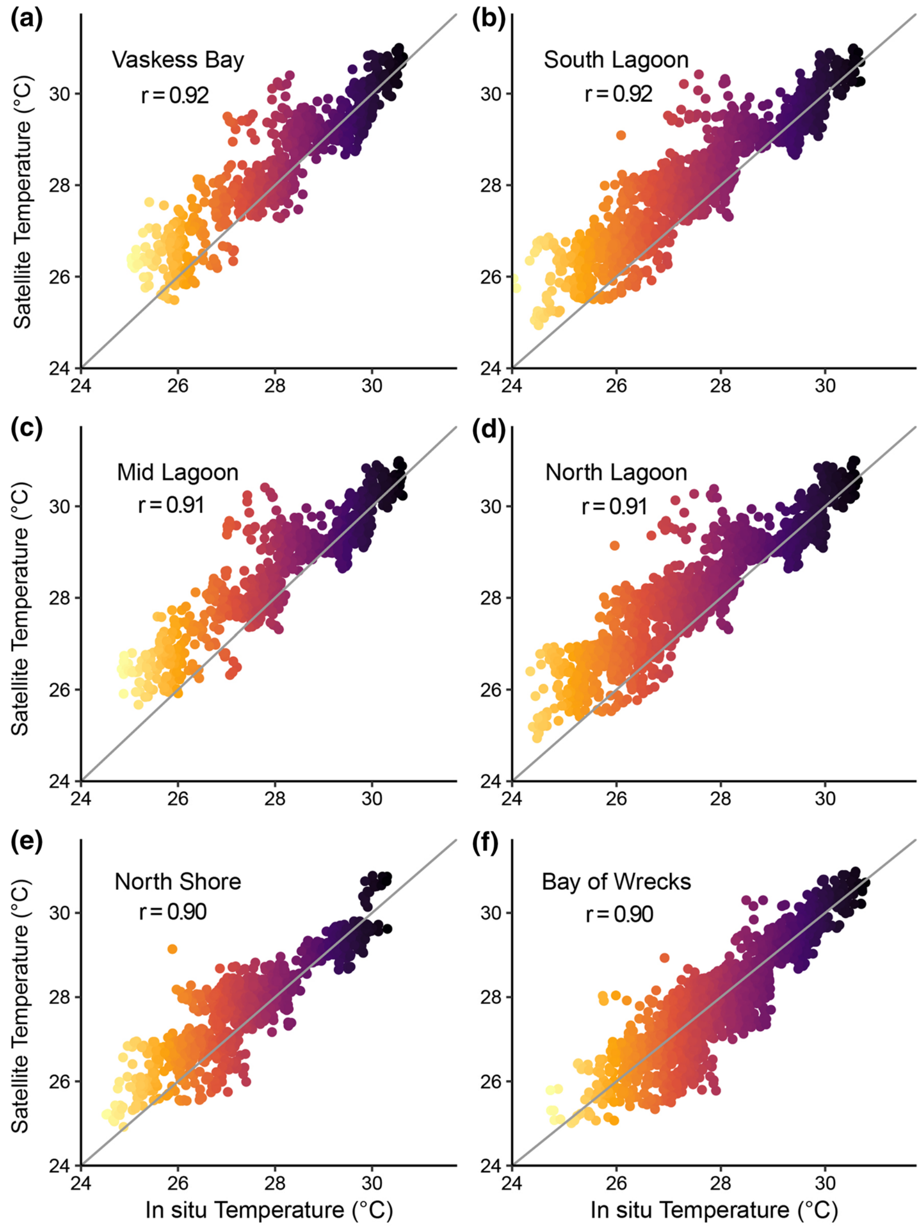

Fig. 2 Scatterplot of daily in situ versus satellite temperatures showing offset. Each point represents 1 d, and color is scaled from low (light yellow) to high (dark purple) in situ temperature. The gray line represents the 1:1 line of satellite to in situ temperature

unable to test whether this is the case for Kiritimati reefs. In this case, it seems sensible to utilize the baseline NOAA MMM for in situ thermal stress calculations, because it produces a thermal stress product that is directly comparable with NOAA's widespread and globally utilized DHW product. We expect that the effect of including/excluding offsets to "correct" in situ MMM could vary significantly in other local thermal regimes (e.g., those with seasonal variability) and suggest that additional research is needed to determine whether using the baseline NOAA MMM for in situ calculations is advisable for other regions of the world. We note that in particular, NOAA MMM methodology can be limited in equatorial regions due to weak intra-annual temperature variability, emphasizing the need to validate these conclusions in different oceanic regions.

An additional consideration when using in situ data for thermal stress calculations (such as DHW) is whether to include all data or nighttime-only measurements. NOAA's satellite product utilizes nighttime-only measurements in order to account for diel warming of the surface ocean, which can be extreme (e.g., greater than a few °C), and potential fine-scale stratification of the "skin" (i.e., the top few millimeters of the sea surface visible to satellite measurements). Exclusion of daytime data from in situ datasets is, however, likely unnecessary since the magnitude of diel warming at depth (e.g., reefs > 5–10 m depth) is typically much smaller and loggers by default measure

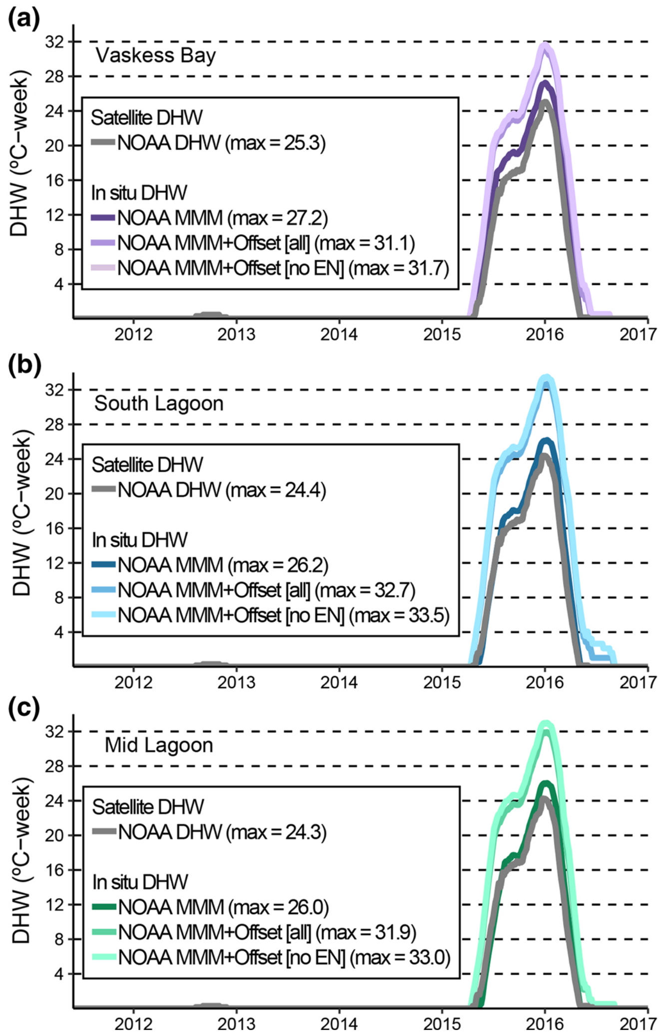

Fig. 3 Degree heating weeks (DHW) calculated with maximum monthly mean (MMM) values from Table 1 (colored lines) and DHW extracted directly from NOAA CRW's DHW product (gray line)

the temperatures that corals are actually experiencing during both day and night. For Kiritimati, we found only miniscule differences (mean offset = 0.0005 °C; Table S4) between daily mean temperatures that had been calculated with daytime + nighttime versus nighttime-only measurements (Fig. S3).

In conclusion, we found general consistency between satellite and in situ measurements on Kiritimati, with the exception of a slight warm bias in satellite measurements that occurred primarily outside of the 2015–2016 El Niño. Overall, NOAA's 5-km CoralTemp product accurately represented conditions experienced throughout the 2015–2016 El Niño event on these Central Pacific corals. However, the presence of in situ loggers allowed us to detect fine-scale cooling events, which may have ecological significance for coral recovery after warming. We therefore recommend that when possible, a combination of in situ and satellite measurements be used to enable researchers to leverage the consistency of satellite data with the fine-scale local accuracy of measurements on the reef.

Acknowledgements Thanks to the Kiritimati Field Team, especially K. Tietjen, for assistance in deploying and retrieving loggers, and to the NOAA CRW team for developing the satellite products used in these analyses. Thanks to J Schanze for discussion on an earlier version of the manuscript. DCC acknowledges funding from an NSERC Vanier Canada Graduate Scholarship, AAUS, a National Geographic Young Explorers Grant, the University of Victoria (UVic), the Women Divers Hall of Fame, and Divers Alert Network. This comparison was made possible by a Sea-Bird Electronics equipment grant to DCC. DCC and JKB acknowledge funding from UVic and UVic's Centre for Asia–Pacific Initiatives. JKB acknowledges support from the Schmidt Ocean Institute, the David and Lucile Packard Foundation, the Rufford Maurice Laing Foundation, an NSERC Discovery Grant and E.W.R. Steacie Fellowship, the Canadian Foundation for Innovation, and a Pew Fellowship in Marine Conservation. KMC acknowledges support from NSF award 1446343.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Aronson R, Precht WF, Toscano M, Koltes K (2002) The 1998 bleaching event and its aftermath on a coral reef in Belize. Marine Biology 141:435–447

Brainard RE, Oliver T, McPhaden MJ, Cohen A, Venegas R, Heenan A, Vargas-Ángel B, Rotjan R, Mangubhai S, Flint E, Hunter SA (2018) Ecological Impacts of the 2015/16 El Niño in the Central Equatorial Pacific. Bulletin of the American Meteorological Society 99:S21–S26

Castillo KD, Lima FP (2010) Comparison of in situ and satellite-derived (MODIS-Aqua/Terra) methods for assessing temperatures on coral reefs. Limnology and Oceanography: Methods

Claar DC, Baum JK (2019) Timing matters: survey timing during extended heat stress can influence perceptions of coral susceptibility to bleaching. Coral Reefs 38:559–565

Cobb KM, Charles CD, Cheng H, Edwards RL (2003) El Niño Southern Oscillation and tropical Pacific climate during the last millennium. Nature 424:271–276

Cobb KM, Westphal N, Sayani HR, Watson JT, Di Lorenzo E, Cheng H, Edwards RL, Charles CD (2013) Highly variable El Niño Southern Oscillation throughout the Holocene. Science 339:67–70

Donlon CJ, Minnett PJ, Gentemann C, Nightingale TJ, Barton IJ, Ward B, Murray MJ (2002) Toward improved validation of satellite sea surface skin temperature measurements for climate research. Journal of Climate 15:353–369

Gentemann CL, Minnett PJ (2008) Radiometric measurements of ocean surface thermal variability. Journal of Geophysical Research: Oceans 113

Gleeson MW, Strong AE (1995) Applying MCSST to coral reef bleaching. Advances in Space Research 16:151–154

Grothe PR, Cobb KM, Bush SL, Cheng H, Santos GM, Southon JR, Lawrence Edwards R, Deocampo DM, Sayani HR (2016) A comparison of U/Th and rapid screen ^{14}C dates from Line Islands fossil corals. Geochem Geophys Geosyst 17:833–845

Hendee J, Liu G, Strong A, Sapper J, Sasko D, Dahlgren C (2002) Near real-time validation of satellite sea surface temperature products at Rainbow Gardens Reef, Lee Stocking Island, Bahamas

Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell D, Sale PF, Edwards AJ, Caldeira K, Knowlton NN, Eakin CM, Iglesias-Prieto R, Muthiga NA, Bradbury RH, Dubi A, Hatziolos ME (2007) Coral reefs under rapid climate change and ocean acidification. Science 318:1737–1742

Hoeke R, Gove J, Smith E, Fisher-Pool P, Lammers M, Merritt D, Vetter O, Young C, Wong K, Brainard R (2009) Coral reef ecosystem integrated observing system: In-situ oceanographic observations at the US Pacific islands and atolls. Journal of Operational Oceanography 2:3–14

Hughes TP, Anderson KD, Connolly SR, Heron SF, Kerry JT, Lough JM, Baird AH, Baum JK, Berumen ML, Bridge TC, Claar DC, Eakin CM, Gilmour JP, Graham NAJ, Harrison H, Hobbs J-PA, Hoey AS, Hoogenboom M, Lowe RJ, McCulloch MT, Pandolfi JM, Pratchett M, Schoepf V, Torda G, Wilson SK (2018) Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science 359:80–83

Karnauskas KB, Cohen AL (2012) Equatorial refugee amid tropical warming. Nat Clim Change 2:530–534

Liu G, Eakin CM, Rauenzahn JL, Christensen TRL, Scott F, Li J, Skirving W, Strong AE, Burgess T (2012) NOAA Coral Reef Watch's Decision Support System for Coral Reef Management. 1997

Liu G, Skirving WJ, Geiger EF, De La Cour JL, Marsh BL, Heron SF, Tirak KV, Strong AE, Eakin CM (2017) NOAA Coral Reef Watch's 5 km Satellite Coral Bleaching Heat Stress Monitoring Product Suite Version 3 and Four-Month Outlook Version 4. Reef Encounter 32:39–45

Maturi E, Harris A, Mittaz J, Sapper J, Wick G, Zhu X, Dash P, Koner P (2017) A new high-resolution sea surface temperature blended analysis. Bull Am Meteorol Soc, 1015–1026

McClanahan TR, Ateweberhan M, Ruiz Sebastián C, Graham NAJ, Wilson SK, Bruggemann JH, Guillaume MMM (2007) Predictability of coral bleaching from synoptic satellite and in situ temperature observations. Coral Reefs 26:695–701

Montgomery RS, Strong AE (1994) Coral bleaching threatens oceans, life. Eos, Transactions American Geophysical Union 75:145–147

NOAA Coral Reef Watch (2018) CoralTemp version 3.1

NOAA CRW (2013) NOAA Coral Reef Watch Daily Global 5-km Satellite Coral Bleaching Degree Heating Week Product

R Development Core Team (2008) R: A language and environment for statistical computing

Sheppard C (2009) Large temperature plunges recorded by data loggers at different depths on an Indian Ocean atoll: Comparison with satellite data and relevance to coral refuges. Coral Reefs 28:399–403

Skirving WJ., Marsh BL, Liu G, De La Cour JL., Harris A, Heron SF., Geiger EF., Maturi E, Eakin CM (2018) NOAA Coral Reef Watch (CRW) CoralTemp: 5 km Gap-free Analyzed Blended Sea Surface Temperature Product for the Global Ocean

Stobart B, Mayfield S, Mundy C, Hobday AJ, Hartog JR (2016) Comparison of in situ and satellite sea surface-temperature data from South Australia and Tasmania: How reliable are satellite data as a proxy for coastal temperatures in temperate southern Australia? Mar Freshw Res 67:612–625

Strong AE, Kimura T, Yamano H, Tsuchiya M, Kakuma SI, van Woesik R (2002) Detecting and monitoring 2001 coral reef bleaching events in Ryukyu Islands, Japan using satellite bleaching HotSpot remote sensing technique. IEEE Int Geosci Remote Sens Symp 1:237–239

Strong AE, Liub G, Skirving W, Eakin CM (2011) NOAA's coral reef watch program from satellite observations. Annals of GIS 17:83–92

Walsh SM (2011) Ecosystem-scale effects of nutrients and fishing on coral reefs. Journal of Marine Biology 2011:1–13

Watson MS, Claar DC, Baum JK (2016) Subsistence in isolation: fishing dependence and perceptions of change on Kiritimati, the world's largest atoll. Ocean and Coastal Management 123:1–8

Wei T, Simko V (2017) R package "corrplot": visualization of a correlation matrix

Wellington GM, Glynn PW, Strong AE, Navarrete SA, Wieters E, Hubbard D (2001) Crisis on coral reefs linked to climate change. Eos, Transactions American Geophysical Union 82:1–5