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Reply to comment by Karnauskas et al. on "Equatorial Pacific coral geochemical records show recent weakening of the Walker circulation"

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In our paper describing a new coral record from Butaritari, we hypothesized that comparing the temporal trends in our records to coral records from farther east in the equatorial Pacific may support the evidence for a weakening of a Walker circulation, documented elsewhere in the literature [*Power and Smith*, 2007; *Tokinaga et al.*, 2012]. Weakening of the Walker circulation is expected under global warming due to an imbalance in the rate of change in different aspects of the hydrological cycle [*Vecchi and Soden*, 2007].

We thank *Karnauskas et al.* [2015] for recognizing the value of our Butaritari coral climate reconstruction, and we appreciate their critique of our study. The *Karnauskas et al.* [2015] analyses strengthen our argument regarding the utility of interisland coral-proxy derived sea surface temperature (SST) gradients as a Walker circulation metric, but we disagree with their interpretation of decadal variability in our records. Here we provide additional analyses, which confirm that our reconstruction [*Carilli et al.*, 2014] shows a long-term weakening of the Walker circulation over 1972–1998. We also document that significant decadal variations in Walker circulation strength, and for particular choices of start and end years over which trends are calculated, are able to show slight Walker strengthening. Overall, we conclude that Walker circulation variations are more nuanced than either our original publication [*Carilli et al.*, 2014] or the subsequent *Karnauskas et al.* [2015] comment would suggest. *Karnauskas et al.* [2015] also provide a detailed analysis of Equatorial Undercurrent (EUC) activity near the Gilbert Islands and argue that the EUC does not strongly affect Butaritari. Our original publication did not claim to find significant EUC/Butaritari linkages, and we appreciate the diligence of *Karnauskas et al.* [2015] for ruling this out as a possibility.

Here we outline the details of our findings.

1. Trends in Proxy SST and Their Relation to the Walker Circulation

Karnauskas et al. [2015] present an alternative picture of the Butaritari Sr/Ca-SST record, whereby the record is split into two segments, each with a cooling trend, and offset by a shift at 1976/1977 (Figure 1a). However, we question such an interpretation of the Butaritari Sr/Ca SST record. The 1976/1977 shift is well documented for the tropical Pacific [*Mantua and Hare*, 2002; *Bond et al.*, 2003], and *Karnauskas et al.* [2015] point out that the Butaritari Sr/Ca-based SST (Sr/Ca$_{SST}$) records a 2.5°C shift occurring over 6 months within the 1976/1977 interval. We note, however, that the Butaritari Sr/Ca$_{SST}$ displays other intervals that could also be interpreted as abrupt shifts, for example, an abrupt shift also of ~2.5°C in 8 months in 1997, and the record could be divided accordingly (Figure 1b). Spectral analysis of the Butaritari Sr/Ca$_{SST}$ shows that the record contains significant decadal variability and significant correlations with the Pacific Decadal Oscillation at various time scales [*Carilli et al.*, 2014]. Therefore, it is unsurprising that the Butaritari coral records the 1976/1977 shift in the mean state of the Pacific, which is part of the longer-term decadal scale SST variability at Butaritari. That said, along with the decadal variation, the Sr/Ca SST record does contain a long-term trend component (Figure 1c). The length of the record necessarily makes the magnitude of the trend sensitive to the choice of endpoints, as demonstrated by *Karnauskas et al.* [2015] and in Figure 1, but we view this finding as another argument for the unique utility of coral records to provide longer observational periods for trend estimates.

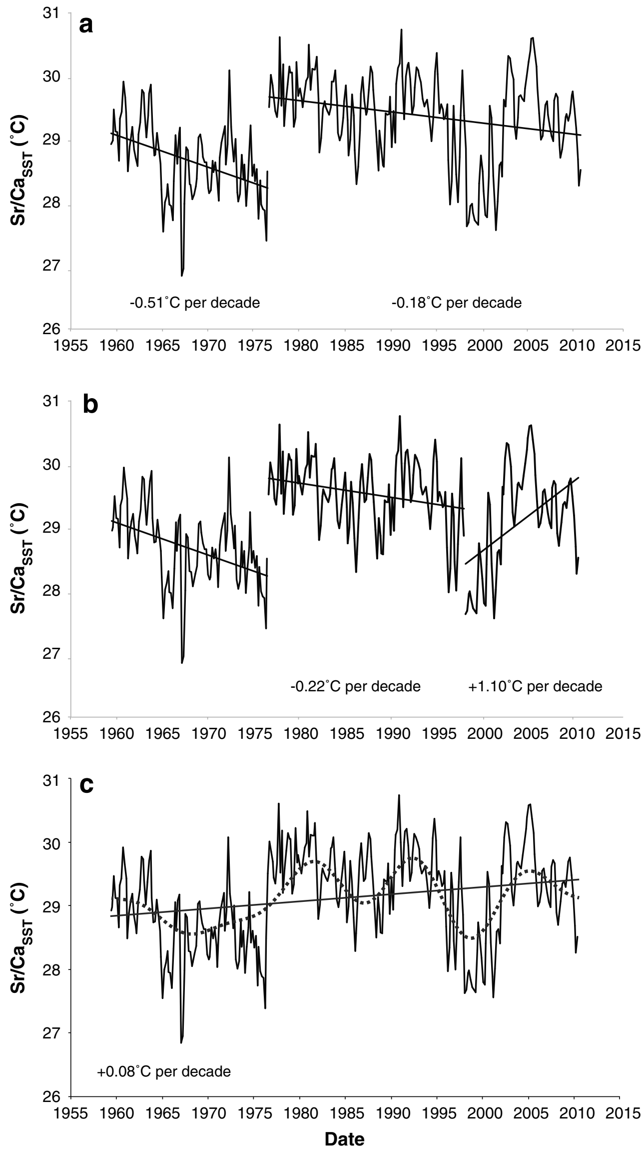

Figure 1. Butaritari Sr/Ca-based SST from 1959 to 2010 showing different ways to assess trends over the record. (a) The time periods before and after the abrupt shift in 1976 are differentiated and fit with linear regressions as presented by *Karnauskas et al.* [2015], (b) an additional section is differentiated at the abrupt SST shift in 1998, and (c) the overall trend is shown with a linear regression over the length of the record, and decadal variability is highlighted with an 8 year low-pass filter (dashed).

Karnauskas et al. [2015] also argue that cooling trends at Butaritari would not be consistent with Walker weakening. Absolute trends in SST at a single location cannot provide Walker circulation estimates, as it is the SST difference between reconstructions in the east and west equatorial Pacific that is important for determining the state of the Walker circulation [*Bjerknes*, 1969]. *Karnauskas et al.* [2015] acknowledge this later during their analysis of Gilbert/Line Island gradients.

Karnauskas et al. [2015] postulate that the Gilbert and Line Islands may be too close to each other to detect any east-west SST difference (Figure 2) and argue that any differences in linear trends between the island groups may reflect the difference in the local response to the 1976/1977 shift. However, they then provide an analysis of SST differences (ΔSST) between Butaritari and Kiritimati Atolls, using instrumental data sets, which confirms that ΔSST for these atolls is a “faithful proxy for the strength of the Walker circulation.” We extend this analysis and show that Butaritari-Tabuaeran and Butaritari-Palmyra ΔSSTs are also recorders of

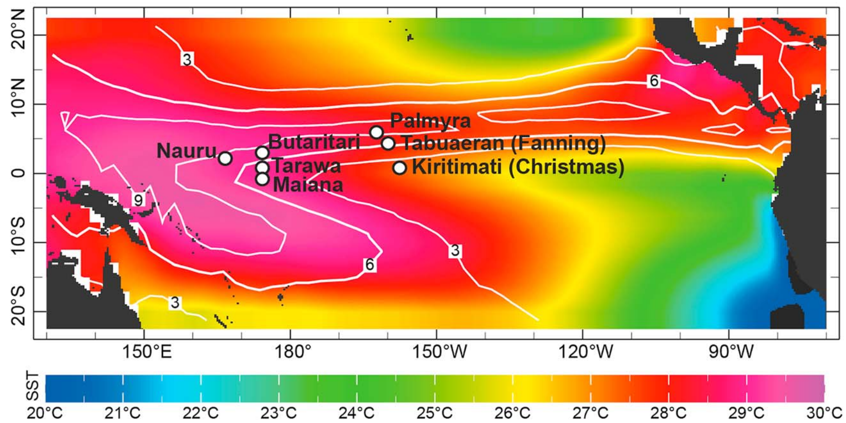

Figure 2. Location of the study area and distribution of equatorial Pacific rainfall and sea surface temperature (SST). Monthly Global Precipitation Climatology Project v2 combined satellite-gauge rainfall data (contours in mm/d [*Adler et al.*, 2003]) and extended reconstructed SST version 3b (ERSSTv3b) data for 1979–2010 (colors [*Smith et al.*, 2008]). Locations of islands with coral core records from Nauru, the Gilbert Islands (including Butaritari), and the Line Islands chains are indicated (white circles). Note that this version of the map should replace the published map (Figure 1 in *Carilli et al.* [2014]) due to an error in placement of the Gilbert Islands.

Walker circulation variability. In Figure 3, 12 month low-pass-filtered time series of zonal wind (National Centers for Environmental Prediction [*Kanamitsu et al.*, 2002]) and ΔSST are shown for all three island pairs, illustrating that correlations are significant regardless of the island pair used for ΔSST computation. Figure 4 then further confirms that ΔSST for different island pairs is highly robust. These analyses show that comparing ΔSST between the Gilbert and Line Islands provides useful estimates of Walker circulation strength; however, making quantitative statements including extrapolating to century scales based on decadal scale metrics requires a great deal of caution.

Karnauskas et al. [2015] also take issue with our choice of the 1972–1998 interval for trend computation. This interval was chosen to correspond with previous studies [*Nurhati et al.*, 2009] and to provide the maximum number of equatorial Pacific Sr/Ca-based SST reconstructions available for this period (Butaritari, Kiritimati, Tabuaeran, and Palmyra [*Carilli et al.*, 2014; *Nurhati et al.*, 2009, 2011]). *Karnauskas et al.* [2015] advocate that instead of using the "common period," we should instead investigate the post 1976/1977 interval, particularly 1982–2013—however, note that this argument is based on confidence in SST reconstructions (discussed by *Karnauskas et al.* [2015] in their Comment), which is not relevant when choosing time periods to compare in our coral-based study.

Karnauskas et al. [2015] also argue that because trends in Butaritari-Kiritimati ΔSST based on coral-proxy records do not match the trend from a satellite-based SST data product during the period of 1982–1998, the coral-proxy data sets should be questioned. The apparent disagreement between the SST data sets and the coral-proxy-based data described by *Karnauskas et al.* [2015] could be due to the resolution of the SST data product and the nature of their analysis, rather than a flaw in the proxy data. In a gridded global SST data set, the SST value from a grid cell containing a particular coral on the outer reef on an atoll can represent a mix of open ocean and lagoon waters and possibly both leeward and windward sides of the atolls (note that the resolution and specific grid cells used are not stated in *Karnauskas et al.* [2015]). This is a common problem in ground-truthing satellite-based SST data in the Pacific Islands. More careful analysis is necessary to verify whether the SST values in the gridded data set could be representative of the experience of the coral. Further, the magnitude, direction, and significance of trends during this time interval are sensitive to the particular temporal endpoints and the data products used (Table 1). Even if instrumental data sets are considered more rigorous than coral-based reconstructions over the more recent time period, paleoarchives are the only way to extend records into the past prior to robust instrumental records.

To further expand on the points raised by *Karnauskas et al.* [2015], we focused on longer records from two of the Line Islands: the Sr/Ca SST reconstruction from Tabuaeran Island because this record spans 1972–2005

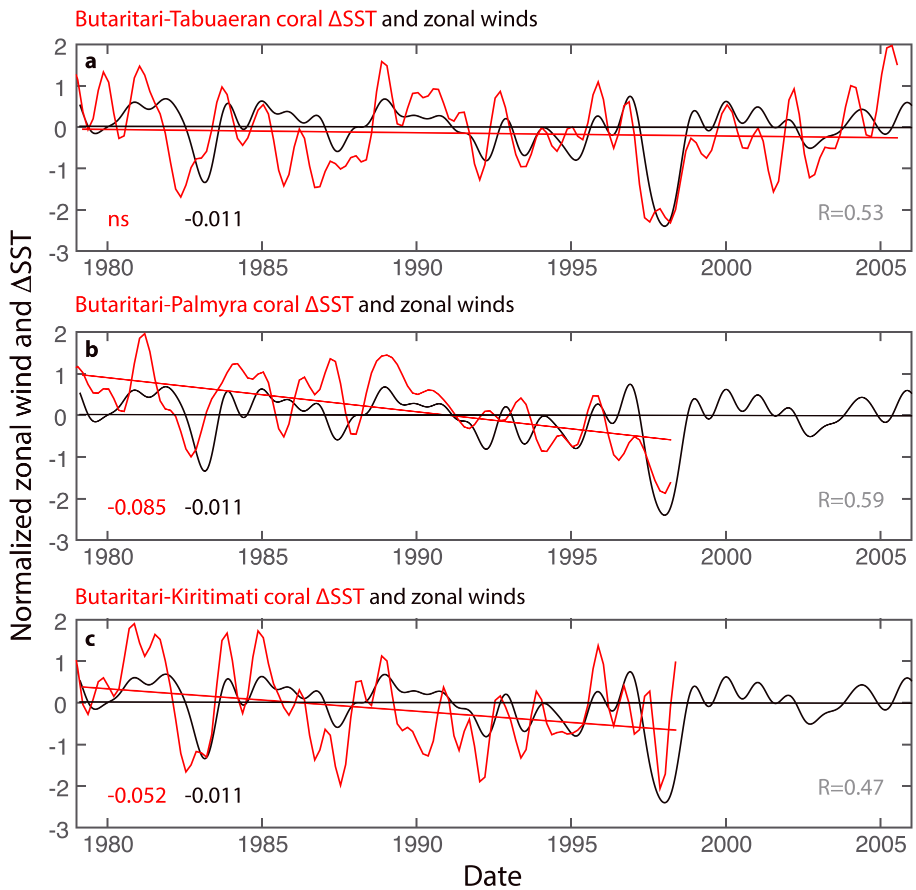

Figure 3. Twelve-month low-pass-filtered ΔSST from coral records from (a) Butaritari-Tabuaeran (red), (b) Butaritari-Palmyra (red), (c) Butaritari-Kiritimati (red), and (a–c) zonal winds averaged across 5°N–5°S and 160°E–90°W (black) from *Kanamitsu et al.* [2002]. Kendall-Thiel linear regressions (see details in *Carilli et al.* [2014]) through the data for the longest overlapping time periods available are also shown: 1979–1998 (Butaritari-Palmyra and Butaritari-Kiritimati) or 1979–2005 (Butaritari-Tabuaeran and zonal winds). Text on the plots indicates the correlation coefficients (*R* values on right) between the coral ΔSST and zonal wind (gray), as well as the slopes of the linear regressions (values on left) on the coral ΔSST (red), and zonal wind (black). Slopes of trends are significant unless reported as “ns” for not significant.

and allows us to investigate Butaritari-Tabuaeran ΔSST over the more recent period [*Cobb et al.*, 2013] and the Sr/Ca SST reconstruction from Palmyra Island because this record spans 1889–1998 and allows us to investigate Butaritari-Palmyra ΔSST over a longer period [*Nurhati et al.*, 2011]. The Tabuaeran Sr/Ca SST record spans 1972–2005 and affords us the opportunity to investigate a large part of the 1982–2013 interval, albeit based on only single reconstructions.

We calculated ΔSST between Butaritari and Tabuaeran for their full period of overlap, which encompasses much of the post 1976/1977 interval, as recommended by *Karnauskas et al.* [2015] Irrespective of the 1976/1977 shift, the difference between Butaritari and Tabuaeran SST decreases over time (Figures 5a and 6a), including for the post-1976 interval only (Figures 5b and 6b). The shortest portion of the record, 1982–2005, contains no significant trend (Figures 5c and 6c). The post-1982 interval includes the period from the 1990s into 2000s, where zonal winds (Walker circulation) are known to have strengthened [*Merrifield*, 2011; *England et al.*, 2014]. In contrast, the Butaritari-Palmyra ΔSST shows a slight positive trend over the longest portion of the record (1959–1998; Figures 5d and 6d) but decreases over time using the periods 1977–1998 (Figures 5e and 6e) and 1982–1998 (Figures 5f and 6f).

Our conclusion from this analysis is that there is considerable decadal change in the strength of the Walker circulation, and the magnitude and even the sign of temporal trends are dependent upon the time period chosen for study. Overall, the results we present here and the conclusions from our paper are consistent

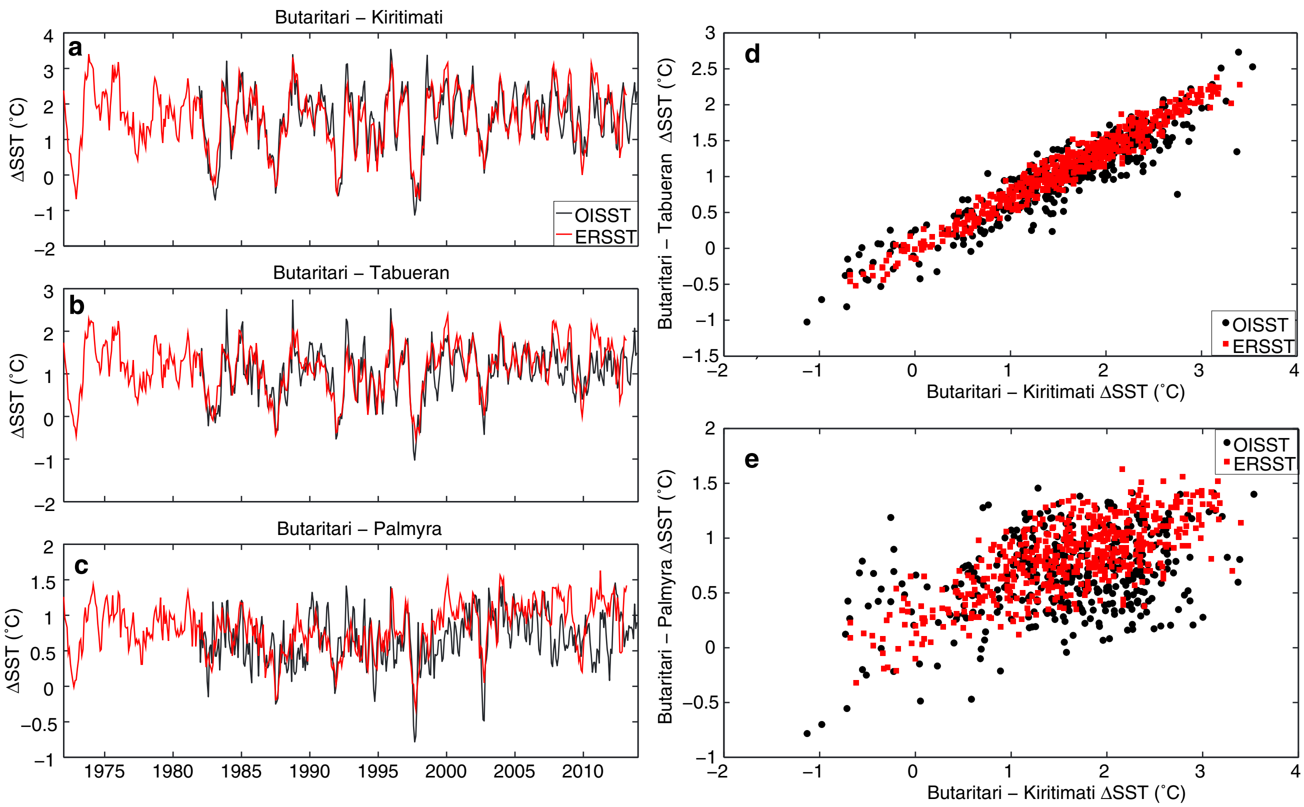

Figure 4. Correspondence between ΔSST calculated from optimum interpolation SST v2 (OISSTv2) and ERSSTv3b data products, for various combinations of islands. (a–c) The ΔSST time series for Butaritari-Kiritimati, Butaritari-Tabueran, and Butaritari-Palmyra. Scatterplots of ΔSST pairs are shown (d) for Butaritari-Tabueran versus Butaritari-Kiritimati and (e) for Butaritari-Palmyra versus Butaritari-Kiritimati.

with other studies that found evidence for weakening Walker circulation over the late twentieth century [*Vecchi et al.*, 2006; *Power and Smith*, 2007; *Deser et al.*, 2010; *Tokinaga et al.*, 2012]. We stand by the conclusions from our original analysis, which do not by any means negate the preponderance of evidence for Walker strengthening since the 1990s [*Merrifield*, 2011; *England et al.*, 2014].

Table 1. Temporal Trends in Butaritari-Kiritimati ΔSST From Different Data Sets Calculated Over Different Time Intervals Using Kendall-Thiel Fitting on Prewhitened Data (Described in *Carilli et al.* [2014])

Butaritari-Kiritimati ΔSST Data Set	Time Period	Trend (°C/decade)	Significant at 90%
OISSTv2	Jan 1982 to Dec 1997	+0.11	No
	June 1982 to Dec 1997	+0.15	No
	June 1982 to June 1997	+0.35	Yes
	Jan 1982 to June 1997	+0.30	Yes
ERSSTv3b	Jan 1982 to Dec 1997	−0.07	No
	June 1982 to Dec 1997	−0.09	No
	June 1982 to June 1997	+0.12	No
	Jan 1982 to June 1997	+0.12	No
HADSST	Jan 1982 to Dec 1997	−0.02	No
	June 1982 to Dec 1997	+0.03	No
	June 1982 to June 1997	+0.27	Yes
	Jan 1982 to June 1997	+0.17	No
Coral Sr/Ca_{SST}	Jan 1982 to Dec 1997	−0.20	Yes
	June 1982 to Dec 1997	−0.32	Yes
	June 1982 to June 1997	−0.15	No
	Jan 1982 to June 1997	−0.02	No

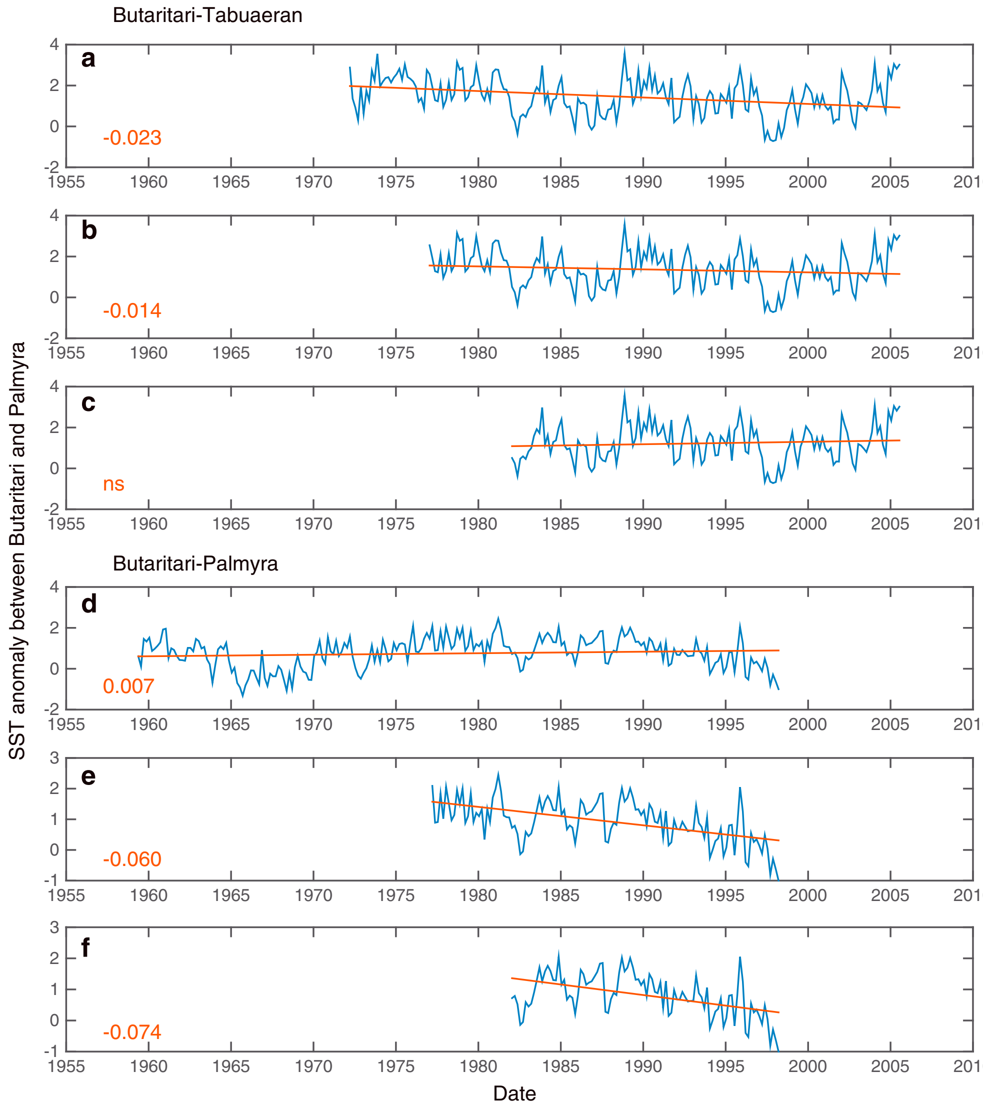

Figure 5. Coral Sr/Ca-based sea surface temperature (SST) difference between (a–c) Butaritari and Tabuaeran and (d–f) Butaritari and Palmyra over different time intervals (blue), with Kendall-Thiel linear regressions (see details in *Carilli et al.* [2014]) and slopes of trends (orange lines and text), using raw bimonthly data sets. Slopes of trends are significant unless reported as "ns" for not significant.

2. The Physical Oceanographic Context of Butaritari Atoll

The second issue that *Karnauskas et al.* [2015] raise has to do with whether our coral records from Butaritari could be used to make inferences about changes in the strength of the Equatorial Undercurrent (EUC). In our paper we state the following:

> "*Karnauskas and Cohen* [2012] found that under a warming climate, the Equatorial Undercurrent (EUC) should strengthen, providing a potential thermal refuge for corals in the Gilbert Islands, reducing the likelihood of coral bleaching. However, the Butaritari coral geochemical records do not show a strong correlation with current velocity (Figure 7). This could indicate that strengthening in the EUC has not occurred, at least at 3.2°N latitude, that the coral records are not strongly affected by current velocities (Figure 7), or the coral may not be deep enough to detect EUC changes (the coral is at 5 m water depth)."

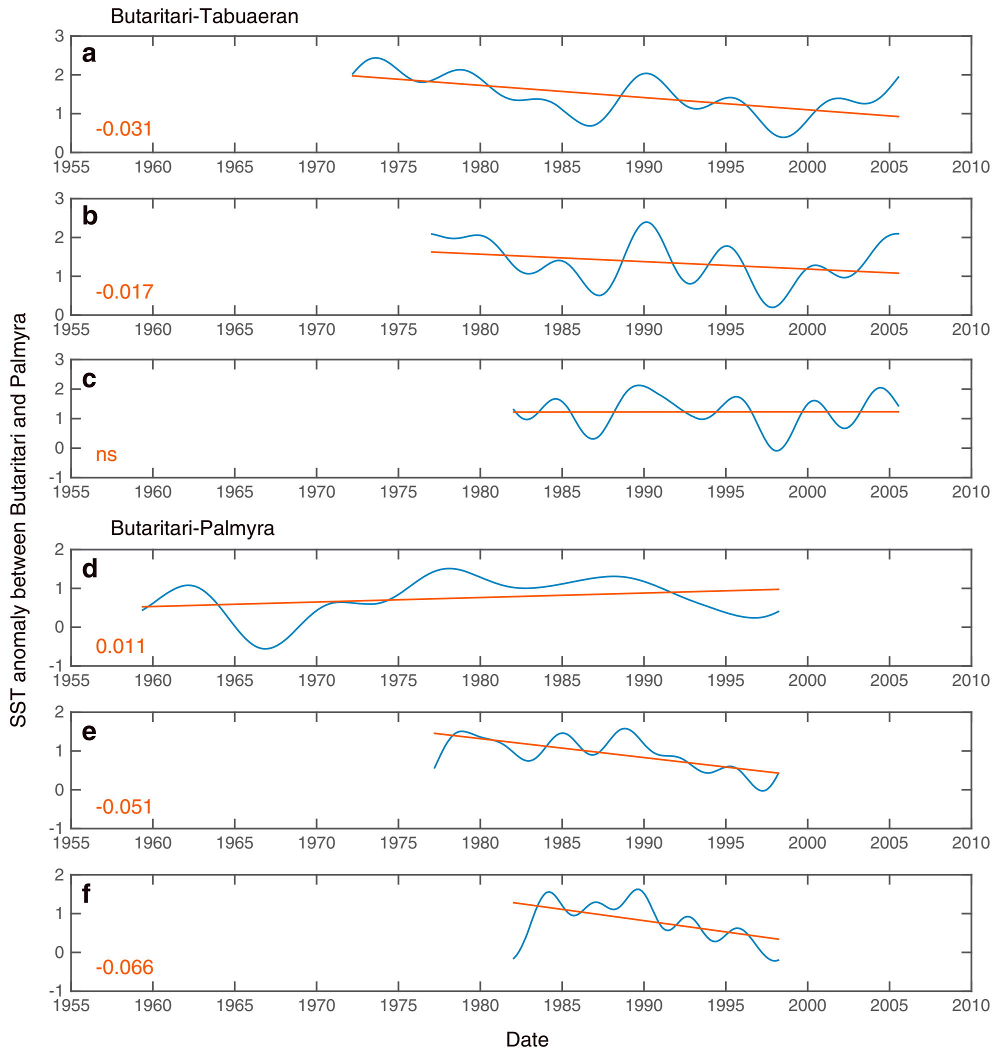

Figure 6. Coral Sr/Ca-based sea surface temperature (SST) difference between (a–c) Butaritari and Tabuaeran and (d–f) Butaritari and Palmyra over different time intervals (blue), with Kendall-Thiel linear regressions (see details in *Carilli et al.* [2014]) and slopes of trends (orange lines and text), and 8 year low-pass-filtered data sets. Slopes of trends are significant unless reported as "ns" for not significant.

We do not claim that the EUC explains our observed patterns—simply that we did not see the patterns that might be expected in our records, had the Butaritari coral been influenced by a strengthening EUC. The *Karnauskas et al.* [2015] analysis clarifies that the EUC is not a major influence at Butaritari, and we are grateful for their additional analyses. The short discussion (quoted in full above) on the EUC was simply invoked to discuss why our geochemical records do not appear strongly influenced by current strength, and to acknowledge the *Karnauskas and Cohen* [2012] work, which suggests important ecological consequences for corals in the Gilbert Islands. The section we include on the EUC (quoted above) is not a central part of our discussion. *Karnauskas et al.*'s [2015] thorough EUC discussion in their Comment provides support and context for their earlier analyses of patterns in equatorial Pacific oceanography but is not as clearly relevant to our publication.

Overall, the issue of Walker circulation strengthening or weakening is controversial and has implications for global climate. Our data set provides a useful perspective on the debate. We look forward to the publication of additional coral reconstructions from across the equatorial Pacific, in addition to our data set, to provide a longer-term perspective on decadal scale SST variability and changes to the Walker circulation.

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