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Comment on "Equatorial Pacific coral geochemical records show recent weakening of the Walker circulation" by J. Carilli et al.

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Carilli et al. [2014] present new geochemical proxy records of sea surface temperature (SST) and salinity spanning 1959–2010 from coral cores collected from Butaritari Atoll, Gilbert Islands, Republic of Kiribati (3.07°N, 172.75°E). The continuous measurement of SST by in situ and satellite platforms generally began in the early 1980s (e.g., the Tropical Atmosphere-Ocean array of moorings [*McPhaden et al.*, 1998] and the Advanced Very High Resolution Radiometer infrared satellite [*Reynolds et al.*, 2002]), and instrumental reconstructions extending back to the midnineteenth century [e.g., *Smith et al.*, 2008] rely on sparse observational sampling both in space in time. The *Carilli et al.*'s [2014] records thus represent a potentially valuable addition to estimates of past climate variability in the important western tropical Pacific region, confirming the dominant role of El Niño–Southern Oscillation (ENSO). However, the conclusion that the Walker circulation has exhibited a long-term weakening trend over the last several decades is based on an interpretation of the proxy record that does not consider well-documented natural interdecadal variability and is based on trends in a proxy record that are opposite from trends in the observational record over the overlapping portion of the satellite era. In addition, *Carilli et al.* [2014] misinterpret the relationship between their proxy record of SST and trends in ocean circulation due to incorrect assumptions about the physical oceanographic context of Butaritari. These two issues are addressed below.

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

There are justifiable alternatives to interpreting the Butaritari Sr/Ca-based proxy SST record (Figures 3b and 8b of *Carilli et al.* [2014]) as a long-term trend. The "small but significant increase in SST (0.39°C) from 1959 to 2010" is entirely consistent with the well-documented Pacific climate shift of 1976/1977 [*Trenberth*, 1990; *Miller et al.*, 1994; *Guilderson and Schrag*, 1999], often ascribed to the Pacific (inter) Decadal Oscillation (PDO) [*Mantua et al.*, 1997]. The Butaritari Sr/Ca_{SST} time series is reproduced here in Figure 1 to reveal that the trend can be fully explained by a single jump (by more than 2.5°C) that occurred over the course of just 6 months in 1976. Rather than a long-term warming trend, the two individual periods before and after 1976 show statistically significant cooling trends (-0.52 ± 0.22°C/decade and -0.18 ± 0.09°C/decade, respectively, where error bars represent 95% confidence bounds) that are even larger in magnitude and more robust than the warming trend computed over the full period (0.11 ± 0.05°C/decade). Despite these robust cooling trends, the difference in mean SST (postshift minus preshift) is 0.7°C, which is why a trend line drawn through these data will have a positive slope. For these reasons, we find a more apt characterization of the Butaritari Sr/Ca_{SST} record to be an abrupt warming superimposed upon a long-term cooling trend, which is inconsistent with a long-term weakening of the Walker circulation.

A difference of linear trends in proxy SST records at the Gilbert Islands and the Line Islands (to the east) is presented as evidence of a long-term weakening trend in the zonal SST gradient and thus Walker circulation. However, those additional sites also appear to be influenced by the 1976/1977 interdecadal shift (Figure 8b of *Carilli et al.* [2014]), so the difference in trends computed over this period between the Gilbert and Line Islands may be indicative of differences in the local amplitude of the SST response to a single pan-Pacific event, rather than of differences in real long-term linear trends. Indeed, the SST spatial loading pattern associated with the PDO is such that a higher-amplitude response is expected at the longitude of the Line Islands than at the Gilbert Islands [*Mantua et al.*, 1997; *Deser et al.*, 2010].

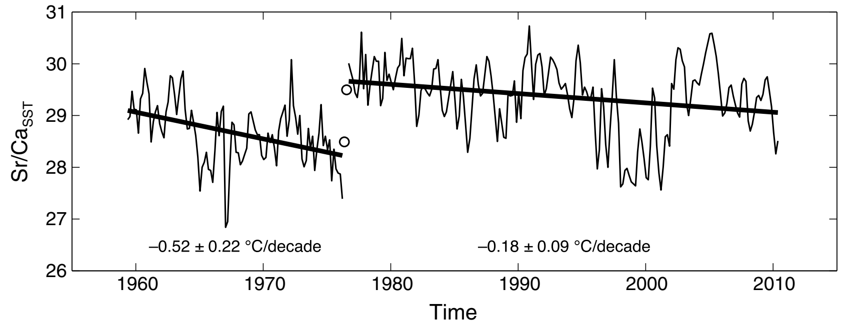

Figure 1. Time series of Butaritari Sr/Ca-based proxy SST (Sr/Ca$_{SST}$) from *Carilli et al.* [2014], downloaded from the NOAA National Climatic Data Center (NCDC) Paleoclimate Archive (ftp.ncdc.noaa.gov/pub/data/paleo/contributions_by_author/carilli2014/carilli2014-but3.txt; retrieved November 16, 2014). The complete time series spans May 1959 through May 2010 at a temporal resolution of 2 months. The two segments are May 1959 through March 1976 and September 1976 through May 2010. The linear trends (means) computed over the two segments are −0.52 ± 0.22°C/decade (28.66°C) and −0.18 ± 0.09°C/decade (29.36°C). The linear trend over the full period is 0.11 ± 0.05°C/decade. The two data points not included in either period (centered on May and July 1976) are plotted as open circles.

Further, it is not inherently clear that the Line Islands are far enough east of the Gilberts to characterize the Walker circulation vis-à-vis the basin-scale zonal SST gradient. The Gilbert Islands chain crosses the equator at 174°E (although they are incorrectly marked east of the date line in Figure 1 of *Carilli et al.* [2014]). At ~157°W, the Line Islands are ~29° longitude east of the Gilbert Islands, which is equivalent to 24% (31%) of the distance (decrease in climatological SST) between the center of the warm pool (~150°E) and the heart of the cold tongue near the Galapagos (90°W) [*Reynolds et al.*, 2002]. In general, the closer two sites lie along a broad spatial gradient, the smaller the signal-to-noise ratio to be expected. As *Carilli et al.* [2014] do not show explicitly that the SST difference between the Gilbert and Line Islands is a sufficient representation of the basin-scale SST gradient or Walker circulation, there is a possibility that SST gradients at this spatial scale simply represent local or regional scale variability rather than a physically meaningful proxy for the state of the coupled ocean-atmosphere system.

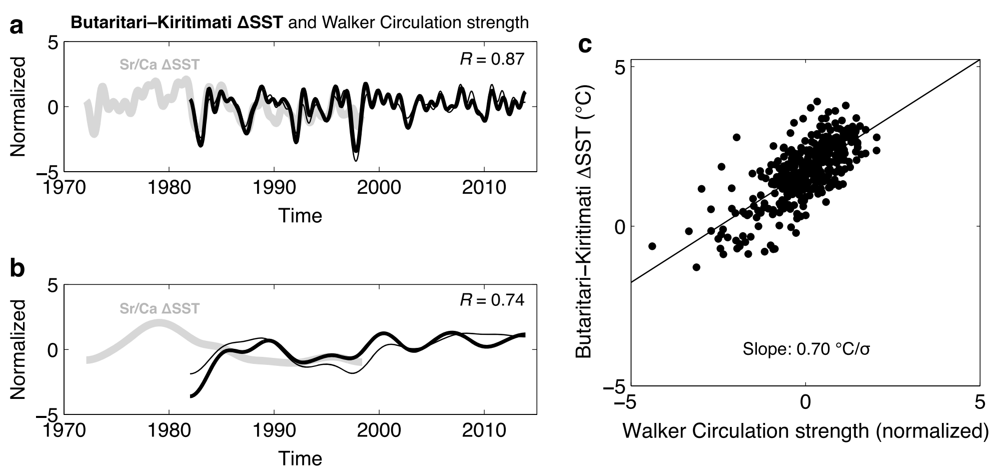

Figure 2. (a) Observed monthly SST difference (ΔSST) between Butaritari (Gilbert Islands) and Kiritimati (Line Islands) (heavy black line) [*Reynolds et al.*, 2002], proxy-based ΔSST (heavy gray line) [*Carilli et al.*, 2014; *Nurhati et al.*, 2009], and observed monthly Walker circulation strength based on the 10 m zonal wind ($u_{10\ m}$) zonally averaged across the equatorial Pacific (160°E–90°W) (thin black line) [*Kanamitsu et al.*, 2002] with a 12 month low-pass filter. (b) Same as in Figure 2a but with a 7 year low-pass filter. (c) Scatterplot relating the unfiltered monthly time series of ΔSST and Walker circulation strength, where the *x* axis has units standard deviation of Walker circulation change and the *y* axis has units °C. Quantitatively, similar results are found defining the Walker circulation strength based on gradients of sea level pressure and 500 mb vertical pressure velocity ($\omega_{500\ mb}$) across the equatorial Pacific (not shown). Kiritimati Sr/Ca$_{SST}$ [*Nurhati et al.*, 2009] downloaded from the NOAA National Climatic Data Center (NCDC) Paleoclimate Archive (ftp.ncdc.noaa.gov/pub/data/paleo/coral/east_pacific/line-islands2009.txt; retrieved March 18, 2015).

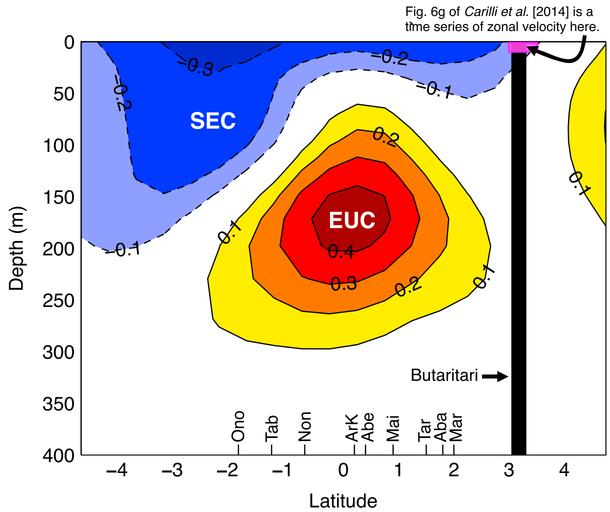

Figure 3. Latitude-depth section of the time-mean (1958–2007) zonal ocean velocity at the longitude of Butaritari (172.75°E) from SODA version 2.0.2–4 [*Carton and Giese*, 2008]. Zonal velocity is contoured every 0.1 m/s, with the zero contour omitted. The eastward flowing EUC and westward flowing SEC are labeled. The location and latitudinal extent of Butaritari Atoll (3.05–3.3°N at the surface; the coral core analyzed in *Carilli et al.* [2014] is from 3.07°N) is also indicated (black rectangle), along with the locations of nine other major islands in the Gilberts chain (Onotoa, Tabiteuea, Nonouti, Aranuka/Kuria, Abemama, Maiana, Tarawa, Abaiang, and Marakei). The magenta rectangle represents the SODA grid cell from which the time series in Figure 6g of *Carilli et al.* [2014] was extracted (3.25°N, 172.25°E) and reproduced in Figure 4a.

Fortunately, such an analysis of observed SST [*Reynolds et al.*, 2002] and atmospheric circulation [*Kanamitsu et al.*, 2002] reveals that the difference in SST between the Gilbert and Line Islands (ΔSST) does serve as a faithful proxy for the strength of the Walker circulation (Figures 2a and 2b), but the slope of this dependence makes the magnitude of Walker circulation trend suggested by *Carilli et al.* [2014] quite worrisome.

Based on linear least squares regression, we should expect a 0.70°C change in Butaritari-Kiritimati ΔSST for a 1 standard deviation (σ) change in the strength of the Walker circulation (Figure 2c). The Butaritari-Kiritimati proxy ΔSST trend presented by *Carilli et al.* [2014] of −1.28°C per 26 years suggests a nearly 2σ weakening of the Walker circulation—roughly equivalent to the breakdown of the Walker circulation at the height of the 1982–1983 El Niño event. Interpreting this as a long-term trend implies that the Walker circulation is weakening at a rate of 7σ per century, bearing in mind that σ here includes ENSO variability. Using observed regression slopes and proxy ΔSST trends for Butaritari-Tabuaeran and Butaritari-Palmyra yields Walker circulation trends of –9σ and –15σ per century, respectively. Such long-term trends are probably unrealistic.

Finally, for the period of 1982–2013, over which we have very high confidence in SST observations, the sign of the trend in the observed Butaritari-Kiritimati ΔSST (and thus Walker circulation strength) is opposite from that suggested by *Carilli et al.* [2014]. For the exactly overlapping period of high-quality satellite and in situ observations [*Reynolds et al.*, 2002] and proxy-based ΔSST (1982 through 1997), the observed trend is +0.03°C/decade, while the proxy-based trend is −0.19°C/decade. Since the proxy-based ΔSST record fails to capture even the sign of the observed trend over a period during which we have the highest confidence in the observational record, caution should be used when using Sr/Ca-based proxies to interpret trends in earlier periods.

2. The Physical Oceanographic Context of Butaritari Atoll

Due to incorrect assumptions about the physical oceanographic context of Butaritari, *Carilli et al.* [2014] also misinterpret their proxy record of SST and its relation to trends in ocean circulation. *Carilli et al.* [2014] state "*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 (from the Simple Ocean Data Assimilation or SODA [*Carton and Giese*, 2008]). 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, or the coral may not be deep enough to detect EUC changes (the coral is at 5 m water depth)." There are four critical issues with this argument that make *Carilli et al.* [2014] unable to draw inferences about past changes in the EUC, including their connection to coral geochemistry or SST.

1. Butaritari Atoll does not lie in the path of the EUC. The Gilbert Islands are composed of 16 low-lying atolls and reef-top islands straddling the equator near 174°E. The EUC is dynamically constrained to the equator by the Coriolis force, thus understanding that its meridional width scale is essential in this case.

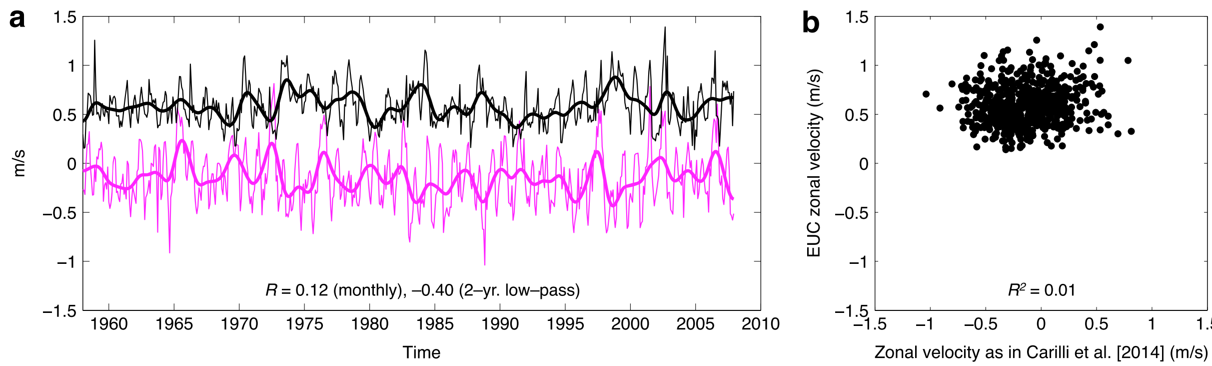

Figure 4. (a) Time series of surface zonal velocity at 3.25°N, 172.25°E as in Figure 6g of *Carilli et al*. [2014] (magenta) and a measure of the EUC velocity at the same longitude (maximum zonal velocity within 1°S–1°N, 0–400 m; black). The thin lines are standard SODA monthly means, and the heavy lines are smoothed with a 2 year low-pass filter. (b) Scatterplot relating the monthly time series shown in Figure 4a. Linear least squares correlation coefficients (*R*) and their squares are noted in each panel.

The time-mean EUC at this longitude spans roughly 2°S–2°N, as do the majority of the Gilbert Islands (Figure 3). At a latitude of 3.07°N, Butaritari is not only a geographic outlier but is in a distinctly different ocean circulation regime than the other islands. That Butaritari does not lie in the path of the EUC is also clearly evident in high-resolution satellite maps of SST and chlorophyll [*Karnauskas and Cohen*, 2012]. Butaritari appears as the one island in the chain without a cold, high-chlorophyll pool on its west side, a clear indication that 3.07°N is too far from the equator to experience the topographic upwelling associated with EUC-island interaction.

2. *Carilli et al.* [2014] compare their coral records to zonal velocities at the surface, while the EUC is a subsurface current (centered around 175 m depth at the longitude of Butaritari; Figure 3). Therefore, even if the EUC were wide enough to encompass Butaritari, the surface velocity would not be a measure of its strength. The zonal velocity time series in Figure 6g of *Carilli et al.* [2014] is reproduced in Figure 4a, along with an appropriate metric of EUC strength (the maximum zonal velocity within the domain 1°S–1°N latitude, 0–400 m depth). That the correlation between these monthly time series is effectively zero ($R^2 = 0.01$; Figure 4b) confirms that the surface zonal velocity metric used by *Carilli et al.* [2014] does not reflect EUC variability. In fact, cross-spectral and coherence analysis (not shown) indicates that the closest correspondence between these two metrics exists at the 2 year period and is inverse; the linear trends are also of the opposite sign.
3. The above issues notwithstanding, one should not expect EUC variability to be well correlated with SST on one side of an equatorial island in isolation. We know that the EUC upwells on the west sides of islands within ~2° latitude of the equator [*Gove et al*., 2006], so large-scale SST variability that influences both sides strongly and equally (such as that driven by the dynamics of the annual cycle or ENSO [*Picaut et al*., 2001]) must be controlled for. This was achieved in *Karnauskas and Cohen* [2012] by considering the cross-island SST difference (i.e., SST on the west side of an island minus SST on the east side). In the global warming scenario, although the SST trend on the west side of an equatorial island will be positive if the radiatively forced warming term is stronger than the cooling term driven by a strengthening EUC, it will be mitigated relative to the east side where the EUC does not influence the surface. Knowledge of SST on both sides of an island is key to capturing the influence of the EUC.
4. A temporal correlation between *A* and *B* is not a test for a linear trend in *B* unless the sole source of variability in *A* is a linear trend. Even if Butaritari was in the path of the EUC, and even if the zonal velocity time series used in *Carilli et al*. [2014] represented the EUC, a strong correlation (of any sign) between Butaritari SST and the EUC would not be an indicator of a long-term trend in EUC strength. It would be an indicator of a correlation between temporal fluctuations in SST (of ambiguous spatial scale) and EUC strength. Assuming Sr/Ca is a faithful proxy for SST, and SST in this case is assumed to be physically related to EUC strength, then a logical way to infer a trend in EUC strength would be to test for a trend in Sr/Ca_{SST}. Instead, *Carilli et al*. [2014] interpret the lack of temporal correlation between Sr/Ca_{SST} and EUC strength as a lack of long-term trend in EUC strength. Moreover, *Carilli et al*. [2014] detrended the Sr/Ca_{SST} record prior to computing the correlation with zonal velocity, rendering the test inapplicable to long-term trends by construction. Appropriate tests for a long-term trend in EUC strength would be to evaluate the

long-term trend in an estimate of EUC velocity or transport (as in *Drenkard and Karnauskas* [2014]), to evaluate the long-term trend in the cross-island SST gradient (not SST on one side in isolation), or to evaluate the long-term trend in the cross-island Sr/Ca$_{SST}$ gradient. The latter test would presumably be very challenging due to the additional requirements that (i) one have cores from both sides of the island, (ii) a single calibration can confidently be applied to both cores, and (iii) statistical stationarity can be assumed in both records.

In summary, while the *Carilli et al.* [2014] record may serve as valuable confirmation of existing instrumental estimates of certain features of the climate record over the past half century such as the 1976/1977 shift and major ENSO events, their presentation as evidence of a long-term slowdown of the Walker circulation is in fact the opposite of what the data show when taking into consideration previously documented natural, interdecadal variability, and opposite of what well-constrained observations indicate has taken place over the satellite era. Also, at 3.07°N, Butaritari does not lie within the EUC, so coral records from that atoll cannot inform us of this key aspect of tropical ocean circulation. Moreover, a recent study using the extended SODA ocean velocity data set revealed a robust strengthening of the EUC over the historical period of 1871–2008 [*Drenkard and Karnauskas*, 2014], which is significant in the vicinity of the Gilbert Islands. By the best available in situ measurements and historical estimates, the EUC has indeed been strengthening at a rate comparable to that predicted for the future in the latest fully coupled climate model simulations. It remains quite reasonable to expect important consequences thereof for near-shore temperatures, seawater chemistry including nutrients, coral geochemistry, and the overall marine ecosystem response to climate change.

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