

Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE

10.1029/2020GC009398

Key Points:

- Coral Mn/Ca captures westerly wind events (WWEs) at Kiritimati and Butaritari, albeit with a 1-year lag and key variations among sites
- Fidelity of the Mn/Ca proxy across sites demonstrates the potential to extend this proxy to additional islands, and even new environments
- WWE location, Mn reservoir, transport pathways, and coral biomineralization may impact the timing and amplitude of the Mn/Ca-wind signal

Supporting Information:

- Supporting Information S1

Correspondence to:

H. R. Sayani,
hsayani@gatech.edu

Citation:

Sayani, H. R., Thompson, D. M., Carilli, J. E., Marchitto, T. M., Chapman, A. U., & Cobb, K. M. (2021). Reproducibility of coral Mn/Ca-based wind reconstructions at Kiritimati Island and Butaritari Atoll. *Geochemistry, Geophysics, Geosystems*, 22, e2020GC009398. <https://doi.org/10.1029/2020GC009398>

Received 25 AUG 2020

Accepted 15 DEC 2020

Reproducibility of Coral Mn/Ca-Based Wind Reconstructions at Kiritimati Island and Butaritari Atoll

Hussein R. Sayani¹ , Diane M. Thompson² , Jessica E. Carilli³ , Thomas M. Marchitto⁴ , Alice U. Chapman² , and Kim M. Cobb¹ 

¹Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA, ²Department of Geosciences, University of Arizona, Tucson, AZ, USA, ³Energy and Environmental Sciences, Naval Information Warfare Center Pacific, San Diego, CA, USA, ⁴Department of Geological Sciences, University of Colorado, Boulder, CO, USA

Abstract Global surface temperatures during the twentieth century are characterized by multidecadal periods of accelerated or reduced warming, which are thought to be driven by Pacific decadal variability, specifically changes in trade-wind strength. However, the relationship between trade-wind strength and global surface warming remains poorly constrained due to the scarcity of instrumental wind observations. Previous work has shown that corals growing at Tarawa Atoll (1.3°N, 173°E) incorporate dissolved Mn flushed from lagoon sediments by El Niño-related westerly wind events (WWEs), providing records of both westerly wind variability and trade-wind strength (on decadal time scales). Here, we explore the utility of this novel coral Mn/Ca-wind proxy at two nearby islands that also feature west-facing lagoons. Short coral Mn/Ca records from Butaritari (3°N, 173°E) and Kiritimati (2°N, 157.5°W) track WWEs, albeit with some intercolony variability in the magnitude and timing of the signal. Variability in coral Mn/Ca signal intensity among records from Butaritari suggests that wind-driven mixing of the sediment Mn reservoir may be finite and/or localized. At Kiritimati, a coral growing outside the lagoon shows higher Mn/Ca concentrations during the 1997/1998 El Niño event, suggesting that nearshore sediments may be an overlooked dissolved Mn reservoir. Taken together, these results highlight a need for additional studies of Mn reservoir variability within and across atolls that hold promise for recording WWEs. These results also suggest that Mn/Ca records from multiple coral colonies and sites are needed to generate robust coral-based wind reconstructions, particularly from sites with unknown or complex Mn transport pathways.

1. Introduction

Internal climate variability in the tropical Pacific plays a profound role in regulating global temperatures via subsurface ocean heat storage and transport (e.g., Liu et al., 2016), yet decadal variability in Pacific trade-wind strength, a critical component of this system, remains poorly constrained. The early-2000s were marked by a pronounced decrease in the rate of global surface warming (Easterling & Wehner, 2009; England et al., 2014; Fyfe et al., 2016; Trenberth & Fasullo, 2013). Both observations and modeling studies attribute this reduction in surface warming to a strengthening of the Pacific Walker circulation (England et al., 2014; Kosaka & Xie, 2013; L'Heureux et al., 2013; Peyser et al., 2016), which increased upwelling of cooler deep waters in the eastern and central tropical Pacific and subduction of warm waters to the subsurface ocean in the western tropical Pacific (Meehl et al., 2011). The presence of similar multidecadal periods of either reduced or accelerated surface warming observed across the last century (e.g., Meehl et al., 2016; Yin et al., 2018) highlights the need to investigate the link between Pacific trade-wind strength and global surface temperatures. However, instrumental wind observations from the tropical Pacific are virtually nonexistent prior to 1970 (Figure 1), and as such, gridded wind data sets and reanalysis products largely disagree on the magnitude and sign of trade-wind variability over the twentieth century (Thompson et al., 2015; Wu & Xie, 2003).

Skeletal manganese-to-calcium (Mn/Ca) ratios in coral from Tarawa Atoll (1.3°N, 173°E) track westerly wind variability on interannual time scales (Shen et al., 1992; Thompson et al., 2015) and trade-wind strength on multidecadal time scales (Thompson et al., 2015). Across the tropical Pacific, coral Mn/Ca ratios have been linked to either riverine sediment flux (Inoue et al., 2014) or wind-driven sediment or sediment porewater resuspension (Carriquiry & Villaescusa, 2010; Delaney et al., 1993; Linn et al., 1990; Shen et al., 1992). Tarawa Atoll's hydrography is such that coral Mn/Ca ratios track westerly wind anomalies via

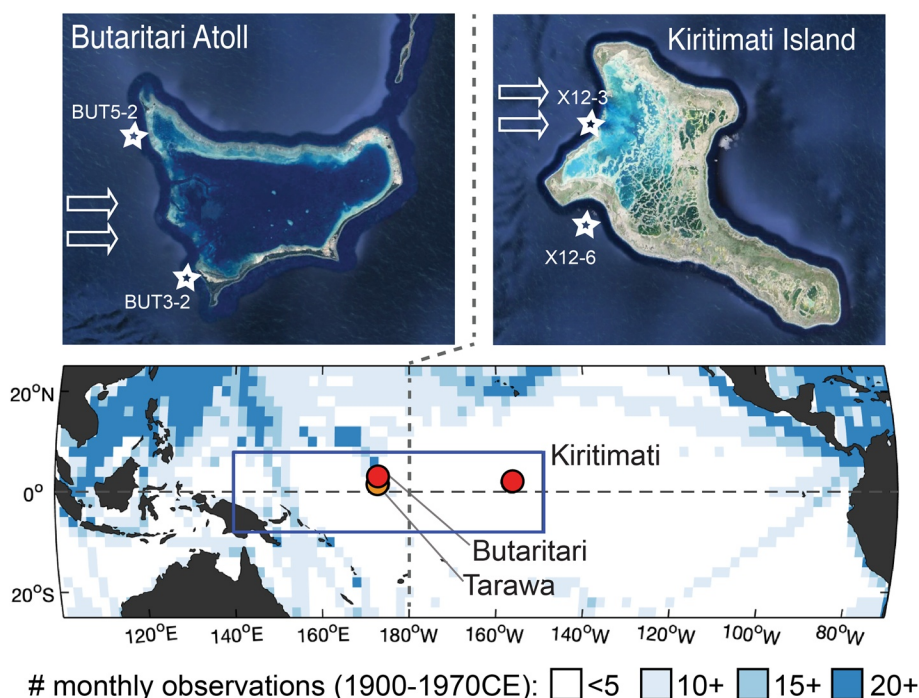


Figure 1. Satellite images (top) showing hydrography of Butaritari Atoll and Kiritimati Island, locations of coral cores used in this study (stars), and direction of westerly winds (white arrows). Map (bottom) shows the location of Tarawa (orange circle) and Butaritari and Kiritimati (red circles) in relation to the region of most active ENSO-related westerly wind events (blue box; Vecchi & Harrison, 2000). Blue shading (bottom) represents the average number of observations available per month in each $2^\circ \times 2^\circ$ ICOADS grid between 1900 and 1970CE (Freeman et al., 2017; Woodruff et al., 1987). ENSO, El Niño Southern Oscillation.

the latter mechanism, as the island sits far from most continental sources of Mn and features a west-facing lagoon that is sheltered from the easterly trade winds. As such, airborne particulate Mn^{4+} settles in the lagoon, where it is quickly buried in the sediments, reduced to Mn^{2+} , and accumulates within the sediment porewaters (Froelich et al., 1979). This porewater Mn^{2+} is periodically flushed into the overlying water column by westerly wind events (WWEs)—short-lived (6–15 days) wind gusts that occur in the equatorial Pacific before and during El Niño events (Eisenman et al., 2005; Harten, 1996; Vecchi & Harrison, 2000), which cause turbulence in the normally protected lagoon. The remobilized Mn^{2+} is then readily incorporated into coral skeletons during calcification, like many other divalent cations found in seawater with ionic radii comparable to that of Ca^{2+} (Gagnon et al., 2012).

As the frequency of WWEs is largely determined by the background state of the tropical Pacific (Vecchi & Harrison, 2000; Yu et al., 2003), long-term variability in Tarawa coral Mn/Ca is driven by changes in Pacific trade-wind strength (Thompson et al., 2015). For example, a ~90-year-long Mn/Ca-wind reconstruction from Tarawa supports a strong link between trade-wind strength, WWEs, and rates of global warming, with frequent WWEs and weakened trades during periods of accelerated warming, and vice versa (Thompson et al., 2015). In the absence of instrumental wind observations, coral Mn/Ca records can be used to constrain past trade-wind variability and improve our understanding of how tropical Pacific climate variability influences global temperature patterns. However, to date, the coral Mn/Ca proxy has not been used to reconstruct wind variability beyond Tarawa Atoll.

As the location, frequency, and duration of WWEs (Figure 1) vary across the tropical Pacific based on the type of El Niño event (e.g., Capotondi et al., 2015), robust paleo-wind reconstructions require coral Mn/Ca records from different sites around the Pacific. Here, we test the efficacy and reproducibility of the coral Mn/Ca-wind proxy using short coral Mn/Ca records from two new research sites in the western and central equatorial Pacific, Butaritari Atoll (3°N , 173°E) and Kiritimati Island (1.5°N , 157°W). Both research sites have strong climatological and hydrographic similarities to Tarawa Atoll (Figure 1); they contain

westward-facing lagoons and are located in a region where WWE activity is strongly associated with the El Niño Southern Oscillation (ENSO; Vecchi & Harrison, 2000).

We also leverage advances in instrumentation to improve the temporal resolution of these critical wind reconstructions. Previous coral Mn/Ca measurements from Tarawa were limited to seasonal resolution, as extremely large sample sizes were needed to overcome the very low (nanomolar) concentrations of Mn/Ca in coral skeletons and the relatively high detection limits afforded by graphite furnace atomic absorption spectrometry. Thus, in addition to reporting coral Mn/Ca from two new sites, we demonstrate that sector field inductively coupled plasma mass spectrometry (ICP-MS), which is routinely used to measure trace elements in microfossils (e.g., Marchitto, 2006; Rosenthal et al., 1999), can generate monthly to bimonthly resolution coral Mn/Ca records using significantly smaller sample sizes.

2. Methods

This study presents four new coral Mn/Ca and Sr/Ca records from *Porites* spp. corals collected from Butaritari and Kiritimati atolls that collectively span 1986–2012. Paired coral Sr/Ca measurements, which closely track sea surface temperature (SST; Smith et al., 1979), were primarily used here to constrain the age model for coral Mn/Ca. Cores BUT3-2 (3.073°N, 172.747°E) and BUT5-2 (3.044°N, 172.701°E) were collected from *Porites* spp. colonies growing at the southern-most and northern-most points along the entrance of Butaritari's large west-facing lagoon, respectively, in 2010 (Figure 1). Annual extension rates from both cores were presented in J. Carilli et al. (2012), while Sr/Ca and oxygen isotopes from BUT3-2 were presented as part of a broader reconstruction of tropical Pacific climate variability in J. E. Carilli et al. (2014). Core X12-3 (1.937°N, 157.497°W) was collected near the entrance of Kiritimati's west-facing lagoon in 2012, while core X12-6 (1.825°N, 157.505°W) was collected further away from the lagoon opening, on the southwest side of Kiritimati in 2012 (Figure 1). Both cores were sliced into 1-cm thick slabs, X-rayed to identify optimal sampling transects, and screened for diagenetic alteration using procedures outlined in Sayani et al. (2011) and Grothe et al. (2019). Coral oxygen isotope records and ENSO reconstructions from cores X12-3 and X12-6 were presented in Grothe et al. (2019).

Samples were prepared for geochemical analyses by drilling ~1 mg of coral powder, at 2 mm intervals along a transect parallel to the coral's primary growth axis using a manual bench press drill to obtain approximately bimonthly resolved records. Coral powders were then dissolved in ultrapure 2% HNO₃, and Mn/Ca and Sr/Ca ratios were measured using a ThermoFinnigan Element2 magnetic sector ICP-MS following procedures adapted from Marchitto (2006). Measurement of ⁵⁵Mn was moved from low resolution to medium resolution to avoid mass interferences from the polyatomic species ⁴⁰Ar¹⁵N and ⁴⁰Ar¹⁴N¹H, which become significant at nmol mol⁻¹ levels of Mn/Ca. To lower the Mn detection limit, the sample time (time spent dwelling on each discrete mass within the ⁵⁵Mn peak) was increased from 0.01 to 0.04 s, and coral samples were analyzed at either ~10 or 20 mM [Ca], a fivefold to tenfold increase over the foraminifer-based method of Marchitto (2006). Analytical precision for Mn/Ca was ±3% (±2 nmol mol⁻¹, 1σ) and for Sr/Ca it was ±0.6% (±0.042 nmol mol⁻¹, 1σ), based on routine analysis of a gravimetric liquid consistency standard.

Prior to the above high-resolution analyses, initial measurements of skeletal Mn concentrations used a VG Plasma Quad ExCell ICP-MS located at Boston University and very large coral samples (25–50 mg). Small aliquots of these samples were diluted and sent to the Georgia Institute of Technology, where skeletal Ca was measured using a Horiba Jobin Yvon Ultima Expert ICP-OES. These initial skeletal Mn measurements showed that the coral's tissue layer (top ~1–2 cm of each core) contained approximately 10 times more Mn than samples further down core (Figure S1). To remove the organic-bound Mn associated with the tissue layer, two methods were compared: (i) filtering dissolved samples through a 0.45-μm filter (Puradisc 25 Depth Polypropylene Syringe Filter) and (ii) an oxidative cleaning step modified after Boyle and Keigwin (1985) and Shen and Boyle (1988). For the oxidative cleaning, 250 μL of an oxidizing agent (equal parts 0.1 N NaOH and 30% H₂O₂) was added to each sample, which were then treated in a hot-water bath (~85°C) for 30 min, sonicating for a few seconds every 5 min. The samples were then rinsed with 18.2 MΩ water 5 times (heating for 5 min and sonicating on the third and fourth iterations).

Initial age models for the Kiritimati cores were obtained from Grothe et al. (2019), as we used the same sampling transects, while the initial age models for the Butaritari corals were obtained from J. E. Carilli

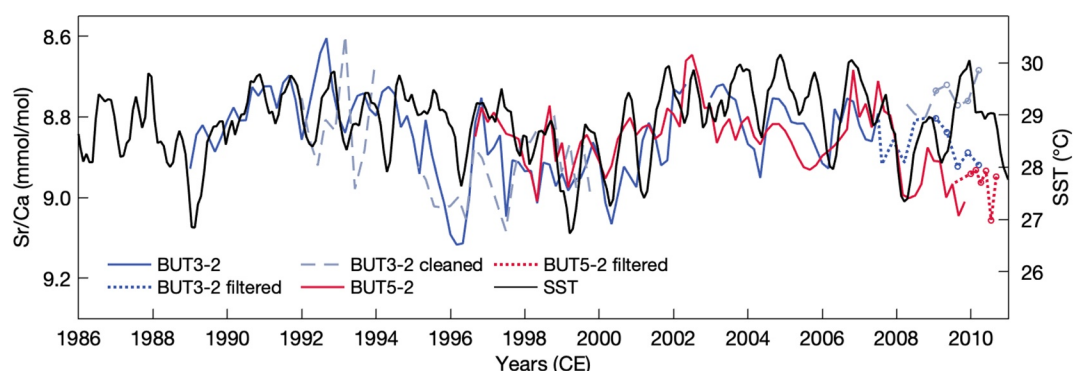


Figure 2. Coral Sr/Ca from filtered (dotted), oxidatively cleaned (dashed), and untreated (solid) samples from Butaritari cores BUT3-2 (blue) and BUT5-2 (red), compared to a 2-month running mean of sea surface temperature (SST; from OISST). Samples containing coral tissue are marked with open circles.

et al. (2014). We used paired Sr/Ca to verify these age models, as seasonal changes in coral Sr/Ca can be directly tied to instrumental SST. The ages assigned to a small subset of datapoints were shifted either forwards or backwards by 1–3 months to better match SST from the $1^\circ \times 1^\circ$ resolved OISSTv2 data set (Reynolds et al., 2007). These adjustments were made to account for slight differences in the location of manually drilled samples and/or differences in coral growth rates between previous studies and this study. As in situ wind observations are not available for our study period from either site, we compare coral Mn/Ca records to the $1^\circ \times 1^\circ$ zonal wind anomalies from the twentieth century Reanalysis 3 (Compo et al., 2011; hereafter referred to as “20CR”). As discussed in Sections 3.2 and 3.3, an ~ 1 year lag was applied to the age model of each coral Mn/Ca record to account for the time delay between westerly wind anomalies and incorporation of the Mn/Ca signal into the sampled corals.

3. Results

3.1. Coral Sr/Ca From Butaritari and Kiritimati

Untreated bimonthly coral Sr/Ca measurements from both Butaritari corals exhibit similar seasonal variability between 1996 and 2010 (Figure 2) and are significantly correlated with bimonthly OISST across their respective common intervals ($r = -0.44$, $p < 0.05$ for BUT3-2 from 1989 to 2007 and $r = -0.48$, $p < 0.05$ for BUT5-2 from 1997 to 2009). Similarly, bimonthly coral Sr/Ca from both Kiritimati cores are significantly correlated with OISST ($r = -0.61$, $p < 0.05$ for X12-3 from 1994 to 2010 and $r = -0.80$, $p < 0.05$ for X12-6 from 1997 to 2003) across their respective intervals of overlap (Figure 2). As coral Sr/Ca tracks SST variability at each site, we use the depth-age models developed for these records to determine the timing of coral Mn/Ca spikes measured in the same samples from each core.

3.2. Impact of Cleaning on Coral Mn/Ca and Sr/Ca

Preliminary measurements revealed that samples from the tissue layer of BUT3-2 contained almost an order of magnitude more Mn than samples collected downcore (Figure S1), suggesting that coral tissue contains far more Mn than the skeleton, and that Mn in organic matter from samples collected within and near the tissue layer could affect coral Mn/Ca reconstructions. We tested two different cleaning methods to remove coral tissue in samples drilled from the tops of each core: filtering and oxidative cleaning. Filtering removes undissolved organic matter, limiting the amount of tissue-bound Mn and Sr that is dissolved in the sample and subsequently analyzed. Coral Sr/Ca in filtered and uncleaned samples from the tissue layers of cores BUT3-2 (from 2009 onwards) and BUT5-2 (all filtered samples) are decoupled from SST and contain more Sr/Ca than expected (Figure 3). Filtered samples from the tissue layer (open circles, Figure 4) in cores BUT3-2 and BUT5-2 contain similar levels of Mn/Ca as downcore samples. In contrast, tissue layer samples from BUT3-2 that were oxidatively cleaned contain lower Sr/Ca on average than untreated samples from the same depth, display a severely dampened seasonal cycle, and do not strongly track SST ($r = -0.10$, $p > 0.05$; Figure 2). Coral Mn/Ca in these oxidatively cleaned samples contains substantially less Mn/Ca

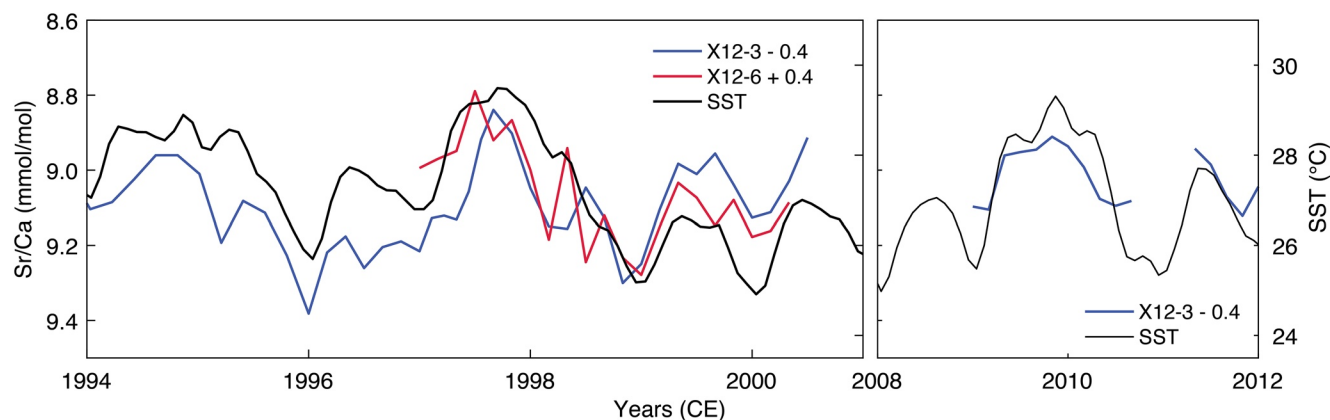


Figure 3. Bimonthly coral Sr/Ca from Kiritimati cores X12-3 (blue) and X12-6 (red) compared to monthly sea surface temperatures (SSTs; from OISST). The baselines of coral Sr/Ca data from X12-3 and X12-6 have been offset by -0.4 and +0.4 mmol/mol, respectively, for plotting purposes.

than both untreated and filtered samples but still shows some correspondence to zonal wind anomalies with a peak correlation with zonal wind anomalies occurring at a lag of -0.17 year.

3.3. Coral Mn/Ca From Butaritari

Coral Mn/Ca records from both Butaritari cores generally track ENSO-related westerly winds; however, the magnitude of coral Mn/Ca spikes during El Niño events varies considerably between cores (Figure 4). Coral Mn/Ca spikes in untreated samples from core BUT3-2 track 2-month smoothed zonal wind anomalies between 1987 and 2006 ($r = 0.3$, $p < 0.10$), albeit at a lag of -1.2 years (i.e., Mn/Ca lags zonal wind anomalies by 1.2 years; Figure S2). While this lag is much larger than that observed between cleaned Mn/Ca samples

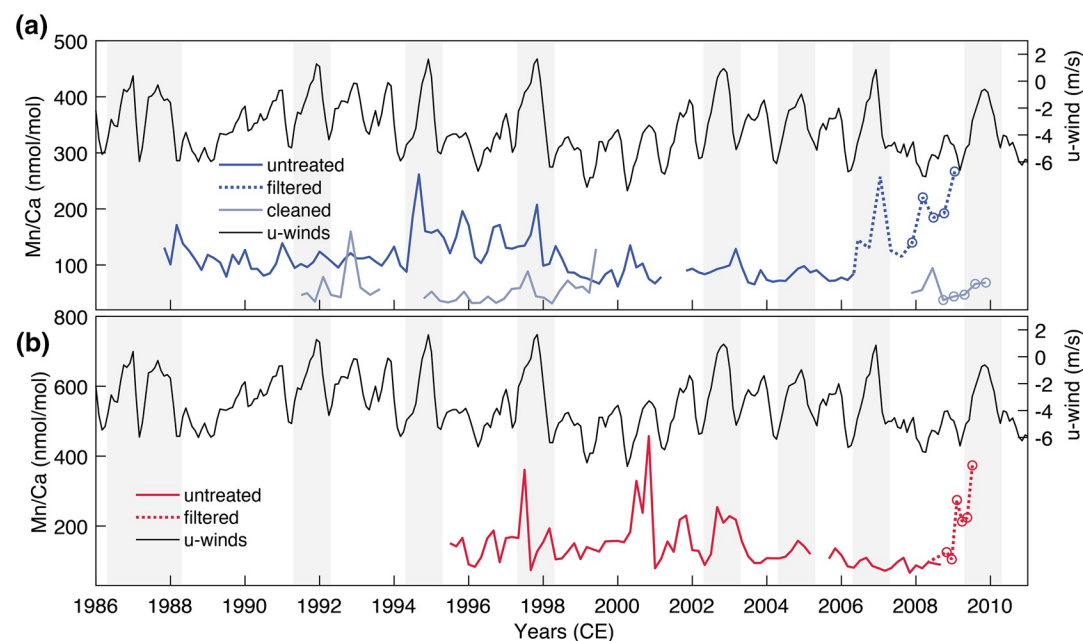


Figure 4. Bimonthly Mn/Ca from cores (a) BUT3-2 and (b) BUT5-2 compared to 2-month smoothed zonal wind from the Twentieth Century Reanalysis (black). A lag of -0.17 year is applied to cleaned Mn/Ca samples (light blue line), and a lag of -1.17 is applied to untreated (solid blue line) and filtered (dashed blue line) Mn/Ca samples from BUT3-2. A lag of -1.2 years is applied to both untreated (solid red) and filtered (dashed red) Mn/Ca measurements from BUT5-2. Filtered samples that contained coral tissue are marked with open circles. Gray shading shows El Niño Southern Oscillation (ENSO) events during which anomalous westerly winds drive increases in coral Mn/Ca.

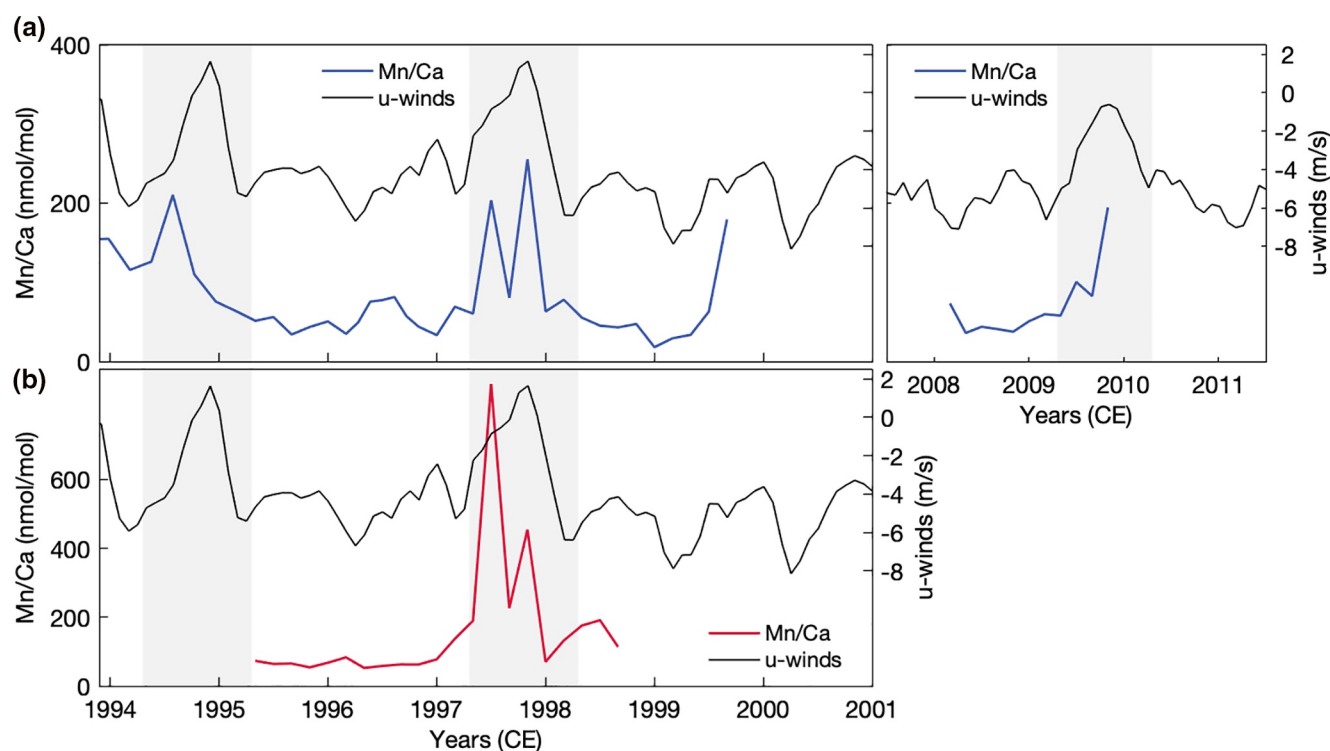


Figure 5. Bimonthly Mn/Ca from cores (a) X12-3 (blue) and (b) X12-6 (red) compared to 2-month smoothed zonal wind from the Twentieth Century Reanalysis (black). Lags of -1 year and -1.5 years are applied to Mn/Ca from X12-3 and X12-6, respectively. Gray shading shows El Niño Southern Oscillation (ENSO) events during which anomalous westerly winds drive increases in coral Mn/Ca.

and zonal wind anomalies, we note that we may not have enough samples to fully constrain the relationship between cleaned Mn/Ca and wind anomalies. The largest spikes in coral Mn/Ca from 1994 to 2011 coincide with westerly wind anomalies during El Niño events (Figure 4); however, there is little correspondence between BUT3-2 coral Mn/Ca and zonal wind anomalies prior to 1994. Moreover, while the timing of coral Mn/Ca spikes matches that of ENSO-related westerly winds, the magnitude of coral Mn/Ca spikes is not always correlated with the strength of the wind anomalies. In some cases, such as the 2004/2005 El Niño event, bimonthly coral Mn/Ca from BUT3-2 does not appear to capture ENSO-related westerly winds at all.

Bimonthly coral Mn/Ca from core BUT5-2, which was collected ~15 km away from core BUT3-2 at the northern end of Butaritari's lagoon entrance, similarly tracks zonal wind anomalies from 1995 to 2008 ($r = 0.2$, $p < 0.10$) at a lag of -1.2 years. The timing of coral Mn/Ca spikes is similar between cores BUT3-2 and BUT5-2, but the magnitude of these spikes varies considerably between cores. Intercolony Mn/Ca differences among the two Butaritari corals are apparent from 2001 to 2004, where core BUT5-2 Mn/Ca follows zonal winds more closely than core BUT3-2.

3.4. Coral Mn/Ca From Kiritimati

Coral Mn/Ca spikes in cores X12-3 and X12-6 largely coincide with ENSO-related westerly wind anomalies around Kiritimati Atoll (Figure 5). During the 1994–1999 and 2008–2010 time periods sampled, bimonthly coral Mn/Ca in X12-3 closely tracks bimonthly westerly wind anomalies ($r = 0.4$; $p < 0.10$), with a lag of -1 year (Figure 5a). Further, elevated coral Mn/Ca values in core X12-3 coincide with 20CR wind anomalies during the 1994/1995, 1997/1998, and 2009/2010 El Niño events. While 20CR shows a similar magnitude of westerly wind anomalies during the 1994/1995 and 1997/1998 El Niño events, ICOADS shows weaker anomalies at Kiritimati during the 1994/1995 event (Figure S3), which is consistent with our coral Mn/Ca measurements from core X12-3. Coral Mn/Ca from core X12-6 also tracks zonal wind anomalies ($r = 0.5$; $p < 0.10$; Figure 5b) from 1995 to 1998 with a lag of -1.5 years (Figure S2). Core X12-6 which is located on the south side of Kiritimati Island, relatively far from the lagoon entrance, yields much larger coral Mn/Ca

spikes than core X12-3, which is located near the lagoon entrance. Both Kiritimati cores show large coral Mn/Ca spikes during the 1997/1998 El Niño, however the short length of these records precludes a thorough assessment of intercolony reproducibility at this site.

4. Discussion

Coral Mn/Ca records from Butaritari and Kiritimati generally track westerly wind anomalies observed at each site, albeit with some discrepancies in the magnitude and to a lesser extent the timing of wind-driven Mn/Ca spikes recorded by each coral. These discrepancies in coral Mn/Ca, especially within corals from the same island, highlight a need for further research into the heterogeneity of and mechanisms governing Mn cycling through island environments and the incorporation of Mn in coral skeletons. Differences in coral Mn/Ca records between Kiritimati and Butaritari are expected given the spatial variability in ENSO and associated WVEs, highlighting the need to replicate coral Mn/Ca records across several sites in the western and central tropical Pacific to generate robust wind reconstructions that are representative of the broader Pacific pattern. Nevertheless, variability in coral Mn/Ca among corals from the same island reveals both challenges in interpreting coral Mn/Ca records and opportunities for broader application of this proxy as discussed below.

4.1. Incorporation of Mn/Ca in Coral Skeletons

Environmental, biological, and mineralogical constraints on the incorporation of trace elements in coral aragonite have become increasingly clear over the past few decades, particularly for more well-established coral proxies (most notably, Sr/Ca and U/Ca). Several studies have established temperature-dependent partitioning of trace elements between seawater and aragonite (e.g., Holcomb et al., 2009; Kinsman & Holland, 1969) and explored different mechanisms by which trace elements are transported to calcification sites within the coral (Cohen & McConnaughey, 2003; Gagnon et al., 2012; Marchitto et al., 2018; McCulloch et al., 2017). Considerable work has also been done to establish the reproducibility of coral proxies across different species and sites (e.g., Chave, 1954; Weber, 1973) and within the same species on a particular reef (e.g., DeLong et al., 2011; Felis et al., 2003; Fowell et al., 2016; Kuffner et al., 2017; Sayani et al., 2019). These studies greatly inform the interpretation of more mature coral proxies; however, such work has yet to be extended to the relatively new coral Mn/Ca proxy.

Several fundamental questions therefore remain regarding the mechanism(s) by which Mn is incorporated into coral aragonite. The original mechanism proposed by Shen et al. (1992) implies that Mn substitutes for Ca in the coral aragonite matrix. Yet, Mn adsorption or Mn-oxyhydroxide coatings are also significant contributors to Mn/Ca ratios in other marine carbonates (e.g., Boyle, 1983). Sample pretreatment is often used to remove organics and other Mn-rich contaminant phases prior to trace element measurements in some carbonates to isolate the ratio of elements that have truly substituted for Ca and have not been incorporated into the skeletal matrix by other means. Here, we employed two cleaning procedures to minimize the contribution of Mn from organic material in samples taken within the tissue layer (top 1–2 cm) of our Butaritari coral. To test the effectiveness of this cleaning, we also applied the same treatment to a set of samples taken downcore of the tissue layer that only contain small amounts of organic matter.

As Sr is known to be both lattice-bound and resistant to cleaning procedures that do not dissolve the sample (e.g., Barker et al., 2003; Holcomb et al., 2015; Watanabe et al., 2001), we can infer that Mn is lattice-bound if both Mn/Ca and Sr/Ca ratios are unaffected by cleaning procedures in the downcore samples (i.e., outside the tissue layer). However, the oxidative cleaning procedures used here impact both Sr/Ca and Mn/Ca measurements. While we do not observe a statistically significant difference in the mean Sr/Ca of cleaned and uncleaned samples below the tissue layer (8.90 ± 0.02 mmol/mol vs. 8.88 ± 0.02 mmol/mol, 1 σ , respectively), the cleaned Sr/Ca data are clearly decoupled from SST ($r = -0.03$, $p > 0.05$), suggesting some mass loss may have occurred. As such, it is unclear whether the significant reduction of Mn/Ca in cleaned samples results from the removal of non-lattice-bound Mn, leaching of lattice-bound Mn, and/or mass loss during the cleaning of coral powders. Even so, cleaned Mn/Ca data still track westerly wind anomalies, have a smaller lag, and have values that are more consistent with Thompson et al. (2015).

In contrast, filtered samples from BUT3-2 and BUT5-2 display Mn/Ca anomalies during the 2009/2010 El Niño that are on par with previous events in both records, and Sr/Ca from these cores track SSTs prior to peak El Niño warming. Elevated Sr/Ca in both filtered and uncleaned samples during peak warming may result from a slowdown in calcification, which elevates Sr in the coral calcifying fluid and skeletal Sr/Ca ratios (via Rayleigh fractionation) as observed at other sites during thermal stress (D'Olivo & McCulloch, 2017). Consistent with these results, density, extension, and calcification all displayed below-average departures during this event in BUT3-2 (J. Carilli et al., 2012). Similar declines in the fidelity of the Sr/Ca-SST relationship are also observed during the 1995/1996 and 2004 thermal stress events, coinciding with large departures in skeletal growth parameters in BUT3-2, with the 2004 event being the most anomalous on record (J. Carilli et al., 2012). Due to the challenges with deconvolving the potential impact of thermal stress and cleaning methods on skeletal geochemistry, additional work using tissue layer samples of cores collected during non-El Niño years is needed to (i) understand where and how Mn is stored in coral skeletons and (ii) explore optimal cleaning methods to produce more robust wind reconstructions (e.g., Shen et al., 1992; Thompson et al., 2015). The presence of Mn/Ca signals across all cleaning methods supports the fidelity of the Mn/Ca-wind proxy in capturing westerly wind anomalies, though resolving these questions will help constrain the timing and magnitude of Mn/Ca signals within and across events and among sites.

The need to better understand Mn partitioning and transport to coral calcification sites is further indicated by the 1–1.5 years lags between the timing of WWEs and coral Mn/Ca spikes in all four corals presented here. No lags were observed in previous studies measuring coral Mn/Ca at Tarawa (Shen et al., 1992; Thompson et al., 2015), possibly due to differences in sampling resolution and cleaning methodologies. The methodology used here requires just 1 mg of coral powder, which averages up to 2 months of growth across 1–2 corallites, whereas earlier work used ~70X more material, averaging several months' worth of skeletal growth across many corallites. The coarser sampling resolution and cleaning employed by previous studies may have masked any lags between WWE and coral Mn/Ca at Tarawa. While the exact mechanistic origins of these apparent lags in the Butaritari and Kiritimati Mn/Ca records are currently unknown, we postulate that they either result from the biomineralization processes by which Mn is incorporated into the coral skeleton or reflect the residence time and transport pathways of Mn in the water column following WWEs. Corals are thought to deposit their skeleton over time, with ~50% deposited initially and the remaining skeletal mass thickening over several months (Barnes et al., 1995; Gagan et al., 2012; Gagnon et al., 2012). Given the high concentrations of Mn present in the coral tissue layer, which often covers ~1 year of skeletal growth, it is possible that the incorporation of Mn into the coral skeleton occurs over the course of several months, whether during thickening, formation of tissue inclusions, or adsorption onto the skeleton following tissue decay. Such biosmoothing may be exacerbated during the El Niño-related warming that follows WWEs, given sufficient stress to impact calcification rates (D'Olivo et al., 2019). However, another possibility is that the morphology of Tarawa's lagoon is very different from that of either Kiritimati or Butaritari. Tarawa's lagoon is much deeper than the lagoon at Kiritimati, and larger and more open than the lagoons at both our research sites. As such, the strength of the winds required to remobilize Mn may be different at each site. The narrower lagoon outlets and complex bathymetry at Kiritimati and Butaritari may also influence the timing between the flushing of Mn-rich sediment porewaters and transport to corals growing at each site.

A final source of uncertainty in interpreting coral Mn/Ca records comes from the fact that WWEs typically precede El Niño-related warming—when many corals experience thermal stress and bleaching which adversely impact coral calcification rates (e.g., Leder et al., 1991). Previous studies have cataloged the impacts of thermal stress on carbon and oxygen isotopes (e.g., Weiner, 2003) and trace elemental proxies (D'Olivo & McCulloch, 2017; Felis et al., 2009; McCulloch et al., 2017), which are consistent with decoupling of Sr/Ca from SST observed in our Butaritari records across periods of reduced calcification (J. Carilli et al., 2012). As with other geochemical measures, coral Mn/Ca may also be impacted by thermal stress and associated effects on calcification rates, which may explain some of the differences we observed in the magnitude of Mn/Ca anomalies following WWEs at our sites, particularly as susceptibility to thermal stress and impact on calcification varies among *Porites* spp. colonies (Cantin & Lough, 2014) and across sites as a function of historical temperature variability (Thompson & van Woessik, 2009). More work is needed to understand (i) how, where, and on what time scales Mn uptake occurs in corals, (ii) how thermal stress, bleaching, and reduced growth rates might influence this uptake, and (iii) the dynamics of how Mn is stored, liberated, and transported around tropical atolls. Nonetheless, the reproducibility in the timing of coral Mn/Ca spikes in

records from both Butaritari and Kiritimati, taken together with previous work at Tarawa, strongly suggests that coral Mn/Ca variability at these sites is indeed tied to WWEs.

4.2. Hydrographic Controls on Coral Mn/Ca

Our results represent the first attempt at reproducing coral Mn/Ca both within and across islands, providing a unique opportunity to assess spatial and temporal variability in the Mn source reservoirs, and the processes by which the seawater Mn plume gets advected to the coral sites following WWEs. Beyond the initial set of Mn measurements in seawater and lagoon sediments by Shen et al. (1992) during ENSO-neutral conditions, little work has been done to investigate the hydrographic mechanisms controlling coral Mn/Ca, especially during an El Niño event. Coral Mn/Ca in core BUT3-2 closely tracks westerly wind anomalies from 1994 to 1998, but with decreasing amplitude across this period, with the lowest Mn/Ca spike observed during the 1997/1998 super El Niño (Figure 4). This reduction in coral Mn/Ca across back-to-back events suggests that the sediment porewater Mn reservoir may be finite until “recharged” (by Mn^{4+} dust flux and subsequent reduction); as such, the magnitude of coral Mn/Ca spikes is influenced by both El Niño event strength and the timing between successive events. The absence of large coral Mn/Ca spikes in BUT3-2 from 1999 to 2006, following the extremely strong 1997/1998 event, suggests that the porewater Mn reservoir may take several years to fully recharge. The depth of the lagoon, the size and depth of the sediment Mn reservoir, and ease by which this reservoir is remobilized into the water column during WWEs may also play an important role in the timing and pattern of Mn/Ca anomalies among atolls. Alternatively, the fact that core BUT3-2, collected from the southern end of the lagoon outlet, captures WWEs prior to 1998, while core BUT5-2, collected from the northern end of the lagoon outlet, captures WWEs after 1998, implies that wind-driven mixing may be highly localized. Taken together, our results from Butaritari suggest that the location of WWE-induced mixing, the spatial variability of sediment porewater Mn, and varying advection pathways have significant impacts on the magnitude of the coral Mn/Ca records. If this pattern is reproduced at other sites, the Mn/Ca proxy may be best utilized to assess the frequency and timing of WWEs prior to the instrumental record.

At Kiritimati Island, we measured coral Mn/Ca in two cores—X12-3 from a colony near the lagoon outlet and X12-6 from a colony relatively far from the lagoon outlet, in Vasquez Bay. Based on the mechanism proposed by Shen et al. (1992), which suggests that the lagoon is the primary source of seawater Mn during El Niño events, we expected to see a weaker Mn/Ca signal in core X12-6 which is further away from the lagoon entrance than core X12-3. However, core X12-6 shows a strong coral Mn/Ca spike during the 1997/1998 El Niño event, suggesting that Mn may also accumulate in nearshore sediments that are sheltered from the easterly trade winds (i.e., the western side of the island and within semiencllosed bays). If this is indeed the case, then the coral Mn/Ca-wind proxy may be applied more broadly across the tropical Pacific, even at sites lacking westerly facing lagoons, provided that at such sites (i) sediments can accumulate in areas protected from the trade winds and (ii) the sediments are shallow enough that WWE-induced mixing can resuspend Mn-rich porewaters from the first centimeters of the sediment layer. Alternatively, the residence time of the seawater Mn signal may dictate Mn/Ca magnitude. Residence time of Mn is likely lengthened within enclosed bays, relative to the narrow channels near the mouth of the lagoon (Valencia, 1977). Ongoing work will further investigate spatiotemporal variability in the sediment and porewater Mn reservoir at Kiritimati Atoll and long-term variations in seawater Mn concentration at this site.

A major challenge in validating coral Mn/Ca records arises from differences among the spatial and temporal scales of WWEs and the resulting seawater Mn plumes, the spatial resolution of gridded wind data, and the sampling resolution of coral Mn/Ca. In situ wind observations are not available from either research site during our study interval, requiring us to rely on gridded wind products that are better suited to investigating large-scale patterns. Instrumental observations from ICOADS (Woodruff et al., 1987) have limited coverage across our study period, and the available observations are not always consistent with the more continuous Twentieth Century Reanalysis data used here (Figure S3). For example, 20CR shows equally strong westerly wind anomalies at Kiritimati during the 1994/1995 and 1997/1998 El Niño, whereas both our coral Mn/Ca record and ICOADS show weaker westerly wind anomalies at Kiritimati during the 1994/1995 event. Similarly, the Kiritimati coral Mn/Ca records show two distinct WWE pulses around the 1997/1998 El Niño event that present in ICOADS but not in 20CR (Figure S3). The limited reproducibility

between Butaritari records, particularly in terms of their fidelity of capturing the 20CR zonal winds through time, may also stem from the fact that (i) our coral sampling resolution is much larger than the duration of WVEs (bimonthly vs. 1–2 weeks) and/or (ii) WVEs and subsequent wind-driven mixing and seawater residence time may be more localized (i.e., they occur across a much smaller area than the $1^\circ \times 1^\circ$ grid box over which 20CR winds are averaged), causing heterogeneity in coral Mn/Ca records from different sides of the island. Given the substantial uncertainties present in existing wind products, coral Mn/Ca records can provide much-needed independent constraints on past westerly wind variability on interannual time scales, and trade-wind strength on multidecadal time scales.

5. Conclusions

New Mn/Ca records from Kiritimati and Butaritari suggest that this novel wind proxy, developed at Tarawa, captures WVEs at other equatorial Pacific Atoll sites with western-opening lagoons. This study represents the first published attempt at expanding coral Mn/Ca-based wind reconstructions beyond Tarawa Atoll, and in doing so, reveals several sources of uncertainty and areas for future study, as is expected in the course of refining a new proxy. Our results highlight that corals at each site are responding to spatial variability in westerly wind anomalies and/or transport and residence time of the signal, and as such, multi-island reconstructions are essential for deriving robust reconstructions of past Pacific trade-wind variability. Future advances in the Mn/Ca proxy system and development of robust replicated records from individual islands may ultimately provide insights into spatiotemporal patterns in WVEs and their relationship to ENSO diversity. Finally, the presence of strong Mn/Ca signals associated with WVEs in a Kiritimati coral located far from the lagoon implies that shallow, nearshore sediments may be an overlooked and significant reservoir of dissolved Mn, which opens up the possibility of more broadly applying this proxy across the western and central tropical Pacific at islands without westerly facing lagoons.

Data Availability Statement

NOAA Optimum Interpolation Sea Surface Temperature and Twentieth Century Reanalysis data are provided by the NOAA/OAR/ESRL PSL, Boulder, CO, USA, from their web site (<https://psl.noaa.gov/>). New Mn/Ca and Sr/Ca data presented in this study are archived on the Paleoclimatology section of the NOAA National Centers for Environmental Information data repository (<https://www.ncdc.noaa.gov/paleo/study/31913>).

Acknowledgments

We would like to thank Thomas Ireland and Landry Bennett for their assistance with initial geochemical measurements conducted at Boston University and Georgia Institute of Technology, and John Morton for assistance with analyses conducted at University of Colorado – Boulder. Funding for this work was provided by the National Science Foundation (Award #1702130 to D.M.T. and J.E.C.).

References

- Barker, S., Greaves, M., & Elderfield, H. (2003). A study of cleaning procedures used for foraminiferal Mg/Ca paleothermometry. *Geochemistry, Geophysics, Geosystems*, 4(9), 8407. <https://doi.org/10.1029/2003GC000559>
- Barnes, D. J., Taylor, R. B., & Lough, J. M. (1995). On the inclusion of trace materials into massive coral skeletons. Part II: Distortions in skeletal records of annual climate cycles due to growth processes. *Journal of Experimental Marine Biology and Ecology*, 194(2), 251–275.
- Boyle, E. A. (1983). Manganese carbonate overgrowths on foraminifera tests. *Geochimica et Cosmochimica Acta*, 47(10), 1815–1819. [https://doi.org/10.1016/0016-7037\(83\)90029-7](https://doi.org/10.1016/0016-7037(83)90029-7)
- Boyle, E. A., & Keigwin, L. D. (1985). Comparison of Atlantic and Pacific paleochemical records for the last 215,000 years: Changes in deep ocean circulation and chemical inventories. *Earth and Planetary Science Letters*, 76(1–2), 135–150. [https://doi.org/10.1016/0012-821X\(85\)90154-2](https://doi.org/10.1016/0012-821X(85)90154-2)
- Cantin, N. E., & Lough, J. M. (2014). Surviving coral bleaching events: *Porites* growth anomalies on the great barrier reef. *PLoS One*, 9(2), e88720. <https://doi.org/10.1371/journal.pone.0088720>
- Capotondi, A., Wittenberg, A. T., Newman, M., Di Lorenzo, E., Yu, J.-Y., Braconnot, P., et al. (2015). Understanding ENSO diversity. *Bulletin of the American Meteorological Society*, 96(6), 921–938. <https://doi.org/10.1175/BAMS-D-13-00117.1>
- Carilli, J., Donner, S. D., & Hartmann, A. C. (2012). Historical temperature variability affects coral response to heat stress. *PLoS One*, 7(3), e34418. <https://doi.org/10.1371/journal.pone.0034418>
- Carilli, J. E., McGregor, H. V., Gaudry, J. J., Donner, S. D., Gagan, M. K., Stevenson, S., et al. (2014). Equatorial Pacific coral geochemical records show recent weakening of the Walker Circulation. *Paleoceanography*, 29, 1031–1045. <https://doi.org/10.1002/2014PA002683>
- Carriquiry, J. D., & Villaescusa, J. A. (2010). Coral Cd/Ca and Mn/Ca records of ENSO variability in the Gulf of California. *Climate of the Past*, 6(3), 401–410. <https://doi.org/10.5194/cp-6-401-2010>
- Chave, K. E. (1954). Aspects of the biogeochemistry of magnesium 1. Calcareous marine organisms. *The Journal of Geology*, 62(3), 266–283. <https://doi.org/10.1086/626162>
- Cohen, A. L., & McConnaughey, T. A. (2003). Geochemical perspectives on coral mineralization. *Reviews in Mineralogy and Geochemistry*, 54(1), 151–187. <https://doi.org/10.2113/0540151>
- Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., et al. (2011). The twentieth century reanalysis project. *Quarterly Journal of the Royal Meteorological Society*, 137(654), 1–28. <https://doi.org/10.1002/qj.776>

- Delaney, M. L., Linn, L. J., & Druffel, E. R. M. (1993). Seasonal cycles of manganese and cadmium in coral from the Galapagos Islands. *Geochimica et Cosmochimica Acta*, 57(2), 347–354. [https://doi.org/10.1016/0016-7037\(93\)90436-Z](https://doi.org/10.1016/0016-7037(93)90436-Z)
- DeLong, K. L., Flannery, J. A., Maupin, C. R., Poore, R. Z., & Quinn, T. M. (2011). A coral Sr/Ca calibration and replication study of two massive corals from the Gulf of Mexico. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 307(1–4), 117–128. <https://doi.org/10.1016/j.palaeo.2011.05.005>
- D'Olivo J. P., Georgiou, L., Falter, J., DeCarlo, T. M., Irigoien, X., Voolstra, C. R., et al. (2019). Long-term impacts of the 1997–1998 bleaching event on the growth and resilience of massive *Porites* corals from the Central Red Sea. *Geochemistry, Geophysics, Geosystems*, 20, 2936–2954. <https://doi.org/10.1029/2019GC008312>
- D'Olivo, J. P., & McCulloch, M. T. (2017). Response of coral calcification and calcifying fluid composition to thermally induced bleaching stress. *Scientific Reports*, 7(1), 929. <https://doi.org/10.1038/s41598-017-02306-x>
- Easterling, D. R., & Wehner, M. F. (2009). Is the climate warming or cooling? *Geophysical Research Letters*, 36, L08706. <https://doi.org/10.1029/2009GL037810>
- Eisenman, I., Yu, L., & Tziperman, E. (2005). Westerly wind bursts: ENSO's tail rather than the dog? *Journal of Climate*, 18(24), 5224–5238. <https://doi.org/10.1175/JCLI3588.1>
- England, M. H., McGregor, S., Spence, P., & Meehl, G. A. (2014). Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nature Climate Change*, 4(3), 222–227. <https://doi.org/10.1038/nclimate2106>
- Felis, T., Pätzold, J., & Loya, Y. (2003). Mean oxygen-isotope signatures in *Porites* spp. corals: Inter-colony variability and correction for extension-rate effects. *Coral Reefs*, 22(4), 328–336. <https://doi.org/10.1007/s00338-003-0324-3>
- Felis, T., Suzuki, A., Kuhnert, H., Dima, M., & Lohmann, G. (2009). Subtropical coral reveals abrupt early-twentieth-century freshening in the western North Pacific Ocean. *Geology*, 37(6), 527–530. <https://doi.org/10.1130/G25581A.1>
- Fowell, S. E., Sandford, K., Stewart, J. A., Castillo, K. D., Ries, J. B., & Foster, G. L. (2016). Intrareef variations in Li/Mg and Sr/Ca sea surface temperature proxies in the Caribbean reef-building coral *Siderastrea siderea*. *Paleoceanography*, 31, 1315–1329. <https://doi.org/10.1002/2016PA002968>
- Freeman, E., Woodruff, S. D., Worley, S. J., Lubker, S. J., Kent, E. C., Angel, W. E., et al. (2017). ICOADS Release 3.0: A major update to the historical marine climate record. *International Journal of Climatology*, 37(5), 2211–2232. <https://doi.org/10.1002/joc.4775>
- Froelich, P. N., Klinkhammer, G. P., & Bender, M. L. (1979). Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic: Suboxic diagenesis. *Geochimica et Cosmochimica Acta*, 43(7), 1075–1090. [https://doi.org/10.1016/0016-7037\(79\)90095-4](https://doi.org/10.1016/0016-7037(79)90095-4)
- Fyfe, J. C., Meehl, G. A., England, M. H., Mann, M. E., Santer, B. D., Flato, G. M., et al. (2016). Making sense of the early-2000s warming slowdown. *Nature Climate Change*, 6(3), 224–228.
- Gagan, M. K., Dunbar, G. B., & Suzuki, A. (2012). The effect of skeletal mass accumulation in *Porites* on coral Sr/Ca and $\delta^{18}\text{O}$ paleothermometry. *Paleoceanography*, 27, PA1203. <https://doi.org/10.1029/2011PA002215>
- Gagnon, A. C., Adkins, J. F., & Erez, J. (2012). Seawater transport during coral biomineralization. *Earth and Planetary Science Letters*, 329–330, 150–161. <https://doi.org/10.1016/j.epsl.2012.03.005>
- Grothe, P. R., Cobb, K. M., Liguori, G., Di Lorenzo, E., Capotondi, A., Lu, Y., et al. (2019). Enhanced El Niño–Southern Oscillation variability in recent decades. *Geophysical Research Letters*, 47, e2019GL083906. <https://doi.org/10.1029/2019GL083906>
- Hartten, L. M. (1996). Synoptic settings of westerly wind bursts. *Journal of Geophysical Research*, 101(D12), 16997–17019. <https://doi.org/10.1029/96JD00030>
- Holcomb, M., Cohen, A. L., Gabitov, R. I., & Hutter, J. L. (2009). Compositional and morphological features of aragonite precipitated experimentally from seawater and biogenically by corals. *Geochimica et Cosmochimica Acta*, 73(14), 4166–4179. <https://doi.org/10.1016/j.gca.2009.04.015>
- Holcomb, M., DeCarlo, T. M., Schoepf, V., Dissard, D., Tanaka, K., & McCulloch, M. (2015). Cleaning and pre-treatment procedures for biogenic and synthetic calcium carbonate powders for determination of elemental and boron isotopic compositions. *Chemical Geology*, 398, 11–21. <https://doi.org/10.1016/j.chemgeo.2015.01.019>
- Inoue, M., Ishikawa, D., Miyaji, T., Yamazaki, A., Suzuki, A., Yamano, H., et al. (2014). Evaluation of Mn and Fe in coral skeletons (*Porites* spp.) as proxies for sediment loading and reconstruction of 50 yrs of land use on Ishigaki Island, Japan. *Coral Reefs*, 33(2), 363–373. <https://doi.org/10.1007/s00338-014-1128-3>
- Kinsman, D. J. J., & Holland, H. D. (1969). The co-precipitation of cations with CaCO_3 —IV. The co-precipitation of Sr^{2+} with aragonite between 16° and 96°C. *Geochimica et Cosmochimica Acta*, 33(1), 1–17. [https://doi.org/10.1016/0016-7037\(69\)90089-1](https://doi.org/10.1016/0016-7037(69)90089-1)
- Kosaka, Y., & Xie, S.-P. (2013). Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature*, 501(7467), 403–407. <https://doi.org/10.1038/nature12534>
- Kuffner, I. B., Roberts, K. E., Flannery, J. A., Morrison, J. M., & Richey, J. N. (2017). Fidelity of the Sr/Ca proxy in recording ocean temperature in the western Atlantic coral *Siderastrea siderea*. *Geochemistry, Geophysics, Geosystems*, 18, 178–188. <https://doi.org/10.1002/2016GC006640>
- Leder, J. J., Szmant, A. M., & Swart, P. K. (1991). The effect of prolonged “bleaching” on skeletal banding and stable isotopic composition in *Montastrea annularis*. *Coral Reefs*, 10(1), 19–27. <https://doi.org/10.1007/BF00301902>
- L'Heureux, M. L., Lee, S., & Lyon, B. (2013). Recent multidecadal strengthening of the Walker circulation across the tropical Pacific. *Nature Climate Change*, 3, 571–576. <https://doi.org/10.1038/nclimate1840>
- Linn, L. J., Delaney, M. L., & Druffel, E. R. M. (1990). Trace metals in contemporary and seventeenth-century Galapagos coral: Records of seasonal and annual variations. *Geochimica et Cosmochimica Acta*, 54(2), 387–394. [https://doi.org/10.1016/0016-7037\(90\)90327-H](https://doi.org/10.1016/0016-7037(90)90327-H)
- Liu, W., Xie, S.-P., & Lu, J. (2016). Tracking ocean heat uptake during the surface warming hiatus. *Nature Communications*, 7, 10926. <https://doi.org/10.1038/ncomms10926>
- Marchitto, T. M. (2006). Precise multielemental ratios in small foraminiferal samples determined by sector field ICP-MS. *Geochemistry, Geophysics, Geosystems*, 7, Q05P13. <https://doi.org/10.1029/2005GC001018>
- Marchitto, T. M., Bryan, S. P., Doss, W., McCulloch, M. T., & Montagna, P. (2018). A simple biomineralization model to explain Li, Mg, and Sr incorporation into aragonitic foraminifera and corals. *Earth and Planetary Science Letters*, 481, 20–29. <https://doi.org/10.1016/j.epsl.2017.10.022>
- McCulloch, M. T., D'Olivo, J. P., Falter, J., Holcomb, M., & Trotter, J. A. (2017). Coral calcification in a changing World and the interactive dynamics of pH and DIC upregulation. *Nature Communications*, 8(1), 929–938. <https://doi.org/10.1038/ncomms15686>
- Meehl, G. A., Arblaster, J. M., Fasullo, J. T., & Hu, A. (2011). Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods. *Nature Climate Change*, 1(7), 360–364. <https://doi.org/10.1038/nclimate1229>
- Meehl, G. A., Hu, A., Santer, B. D., & Xie, S. P. (2016). Contribution of the Interdecadal Pacific Oscillation to twentieth-century global surface temperature trends. *Nature Climate Change*, 6(11), 1005–1008. <https://doi.org/10.1038/nclimate3107>

- Peyser, C. E., Yin, J., Landerer, F. W., & Cole, J. E. (2016). Pacific sea level rise patterns and global surface temperature variability. *Geophysical Research Letters*, 43, 8662–8669. <https://doi.org/10.1002/2016GL069401>
- Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., & Schlax, M. G. (2007). Daily high-resolution-blended analyses for sea surface temperature. *Journal of Climate*, 20(22), 5473–5496. <https://doi.org/10.1175/2007JCLI1824.1>
- Rosenthal, Y., Field, M. P., & Sherrell, R. M. (1999). Precise determination of element/calcium ratios in calcareous samples using sector field inductively coupled plasma mass spectrometry. *Analytical Chemistry*, 71(15), 3248–3253. <https://doi.org/10.1021/ac981410x>
- Sayani, H. R., Cobb, K. M., Cohen, A. L., Elliott, W. C., Nurhati, I. S., Dunbar, R. B., et al. (2011). Effects of diagenesis on paleoclimate reconstructions from modern and young fossil corals. *Geochimica et Cosmochimica Acta*, 75(21), 6361–6373. <https://doi.org/10.1016/j.gca.2011.08.026>
- Sayani, H. R., Cobb, K. M., DeLong, K., Hitt, N. T., & Druffel, E. R. M. (2019). Intercolony $\delta^{18}\text{O}$ and Sr/Ca variability among *Porites* spp. corals at Palmyra Atoll: Toward more robust coral-based estimates of climate. *Geochemistry, Geophysics, Geosystems*, 20, 5270–5284. <https://doi.org/10.1029/2019GC008420>
- Shen, G. T., & Boyle, E. A. (1988). Determination of lead, cadmium and other trace metals in annually-banded corals. *Chemical Geology*, 67(1–2), 47–62. [https://doi.org/10.1016/0009-2541\(88\)90005-8](https://doi.org/10.1016/0009-2541(88)90005-8)
- Shen, G. T., Linn, L. J., Campbell, T. M., Cole, J. E., & Fairbanks, R. G. (1992). A chemical indicator of trade wind reversal in corals from the western tropical Pacific. *Journal of Geophysical Research*, 97(C8), 12689–12697. <https://doi.org/10.1029/92JC00951>
- Smith, S. V., Buddemeier, R. W., Redalje, R. C., & Houck, J. E. (1979). Strontium–calcium thermometry in coral skeletons. *Science*, 204(4391), 404–407. <https://doi.org/10.1126/science.204.4391.404>
- Thompson, D. M., Cole, J. E., Shen, G. T., Tudhope, A. W., & Meehl, G. A. (2015). Early twentieth-century warming linked to tropical Pacific wind strength. *Nature Geoscience*, 8(2), 117–121. <https://doi.org/10.1038/ngeo2321>
- Thompson, D. M., & van Woesik, R. (2009). Corals escape bleaching in regions that recently and historically experienced frequent thermal stress. *Proceedings of the Royal Society B: Biological Sciences*, 276(1669), 2893–2901.
- Trenberth, K. E., & Fasullo, J. T. (2013). An apparent hiatus in global warming? *Earth's Future*, 1, 19–32. <https://doi.org/10.1002/2013EF000165>
- Valencia, M. J. (1977). Christmas Island (Pacific Ocean): Reconnaissance geologic observations. *Atoll Research Bulletin*, 197, 1–14. <https://doi.org/10.5479/si.00775630.197.1>
- Vecchi, G. A., & Harrison, D. E. (2000). Tropical Pacific sea surface temperature anomalies, El Niño, and equatorial westerly wind events. *Journal of Climate*, 13(11), 1814–1830. [https://doi.org/10.1175/1520-0442\(2000\)013<1814:TPSSTA>2.0.CO;2](https://doi.org/10.1175/1520-0442(2000)013<1814:TPSSTA>2.0.CO;2)
- Watanabe, T., Minagawa, M., Oba, T., & Winter, A. (2001). Pretreatment of coral aragonite for Mg and Sr analysis: Implications for coral thermometers. *Geochemical Journal*, 35(4), 265–269. <https://doi.org/10.2343/geochemj.35.265>
- Weber, J. N. (1973). Incorporation of strontium into reef coral skeletal carbonate. *Geochimica et Cosmochimica Acta*, 37(9), 2173–2190. [https://doi.org/10.1016/0016-7037\(73\)90015-X](https://doi.org/10.1016/0016-7037(73)90015-X)
- Weiner, S. (2003). An overview of biomineralization processes and the problem of the vital effect. *Reviews in Mineralogy and Geochemistry*, 54(1), 1–29. <https://doi.org/10.2113/0540001>
- Woodruff, S. D., Slutz, R. J., & Jenne, R. L. (1987). A comprehensive ocean–atmosphere data set. *Bulletin of the American Meteorological Society*, 68(10), 1239–1250. [https://doi.org/10.1175/1520-0477\(1987\)068<1239:ACOADS>2.0.CO;2](https://doi.org/10.1175/1520-0477(1987)068<1239:ACOADS>2.0.CO;2)
- Wu, R., & Xie, S. -P. (2003). On equatorial Pacific surface wind changes around 1977: NCEP–NCAR reanalysis versus COADS observations. *Journal of Climate*, 16(1), 167–173. [https://doi.org/10.1175/1520-0442\(2003\)016<0167:OEPSWC>2.0.CO;2](https://doi.org/10.1175/1520-0442(2003)016<0167:OEPSWC>2.0.CO;2)
- Yin, J., Overpeck, J., Peyser, C., & Stouffer, R. (2018). Big jump of record warm global mean surface temperature in 2014–2016 related to unusually large oceanic heat releases. *Geophysical Research Letters*, 45, 1069–1078. <https://doi.org/10.1002/2017GL076500>
- Yu, L., Weller, R. A., & Liu, W. T. (2003). Case analysis of a role of ENSO in regulating the generation of westerly wind bursts in the Western Equatorial Pacific. *Journal of Geophysical Research*, 108(C4), 3128. <https://doi.org/10.1029/2002JC001498>