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Key Points:

- Three environmental proxies were examined in skeletal composition of long-lived deep-water gorgonian corals in the SW Pacific
- The time series indicate coherent ca. 23-year periodicity at depths corresponding to the AAIW and UCDW
- Long-term trends in all three proxies reversed sign in the early to mid-1900s, along with their relationship with the SAM

Supporting Information:

Supporting Information may be found in the online version of this article.

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Apparent Periodic and Long-Term Changes in AAIW and UCDW Properties at Fixed Depths in the Southwest Pacific, With Indications of a Regime Shift in the 1930s

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Abstract Metal/calcium ratios in two long-lived deep-sea gorgonian corals (*Lepidisis* and *Corallium* spp.) in the Southwest Pacific evidence periodic decadal variability at depths that correspond to Antarctic Intermediate Water (AAIW) and shallow Upper Circumpolar Deep Water, and a shift in the mid-1930s to late-1930s in mean ambient temperatures, barium/silicate concentrations and possibly pH, the rate at which these properties change over time, and the relationship between temperatures at fixed depth and the Southern Annular Mode (SAM). The decadal periodicity, which is evident in other biological indices in the study area, can be accounted for by water mass heave on the order of 100–150 m, which is consistent with observed scales of variability in the AAIW. The proximate and ultimate causes of the midcentury shifts are unclear, but could be related to suggested mid-20th century changes in climate parameters globally and, more specifically, in the subpolar SW Pacific.

Plain Language Summary The dynamics of the Southern Ocean play a critical role in global climate and oceanography, but sparse historical instrumental data make it difficult to assess the significance of recently observed changes. We help fill this information gap by analyzing apparent proxies for ambient temperature, barium/silicate concentrations, and possibly pH in the carbonate skeletons of a pair of very long-lived deep-sea corals. The data strongly suggest a previously unreported ∼23-year periodicity in two Southern Ocean water masses (Antarctic Intermediate Water and Upper Circumpolar Deep Water), which is likely to be the result of vertical shifts in water mass distributions. The long-term data also suggest the water masses cooled, became less acidic and had declining barium/silicate concentrations from at least the early 1700s until the early to mid-1900s, after which the sign of the long-term trends reversed. The causes of the long-term trends and their reversal are not clear, but may be related to changes to climate parameters globally, but more specifically to those in the SE Pacific, where Antarctic Intermediate Water is formed.

1. Introduction

Models and recent observations confirm that the Southern Ocean plays a critical role in global climate and ocean dynamics (Fröhlicher et al., 2014; Khatiwala et al., 2009; Sarmiento et al., 2004). Key processes are the up-welling of Circumpolar Deep Water (CDW), the flux of heat and anthropogenic and natural CO_2 between the atmosphere and the surface ocean, and the export of both heat and CO_2 to the subsurface ocean in Antarctic Bottom and Intermediate Waters (Downes et al., 2009; Sarmiento et al., 2004). As well, Antarctic Intermediate Waters ventilate much of the world's oceans and are a crucial source of nutrients that support midlatitude and low latitude surface production (Loubere & Bennett, 2008; Sarmiento et al., 2004). Recent observational studies show that properties of the Intermediate Waters (Sub-Antarctic Mode Water [SAMW] and Antarctic Intermediate Water [AAIW]) have changed over the last half century, SAMW cooling and freshening while AAIW has warmed (Bindoff & Church, 1992; Bindoff & McDougall, 2000; Johnson & Orsi, 1997; Schmidtko & Johnson, 2012). These changes have been related to warming and freshening of Antarctic Surface Water (Church et al., 1991; Johnson & Orsi, 1997), and are consistent with anthropogenic climate changes in southern polar latitudes (Fyfe, 2006; Mayewski et al., 2007; Turner et al., 2005) and the contraction of the polar vortex, reflected in an increasingly positive Southern Annular Mode (SAM) (Oke & England, 2004). The significance of these changes, nonetheless, remains uncertain (Bryden et al., 2003), largely due to historically sparse instrumental records of deep water in the Southern Ocean. Here, we help fill this gap by deriving high-resolution ~140-year and 330-year records of proxies for temperature, barium/silicate concentrations, and possibly pH from the skeletal composition of two calcitic deep-water corals collected in the Southwest Pacific Ocean. One was collected just below the core depth of AAIW and the second in shallow Upper Circumpolar Deep Water (UCDW). The results provide a context for recent instrumental data on properties of both water masses, evidence episodic, ~23-years variability in all three proxies and suggest a shift in the mid-1930s to late-1930s in their mean levels, their trends over time, and possibly the relationship between the SAM and water mass temperatures.

2. Methods

The deep-water coral sample *Lepidisis* #9 (L9) (Gorgonacea: Isididae) was live-collected on January 07, 2008 from between 1,130 and 1,190 m off the Sisters Seamount (44°27′S; 147°27′E), south of Tasmania, Australia; *Corallium* #2 (C2) (Gorgonacea: Coralliidae) was live-collected by ROV at 2,173 m on January 03, 2009, at the Cascade Plateau (43°49′S, 150°20′E), in the Tasman Sea (Figure S1a). The sampling depths and locations place the corals just below the core of AAIW and in shallow UCDW, respectively (Rintoul & Bullister, 1999; Rochford, 1960) (Figures S1b and S1c). Seawater properties in this depth range close to the seamount surface match those measured 10s of kilometers from it (Thresher et al., 2010; Thresher, Adkins, et al., 2011; Thresher, Tilbrook, et al., 2011), indicating that environmental conditions experienced by corals during their lifetimes track those of the water masses in which they reside. Radiocarbon dating of L9 suggests it was ~140-years old when collected (Strzepek et al., 2014); radiocarbon dating of C2 calcite suggests a colony age of 329 ± 36 years (Figure S2). For both corals, the fit between distance from the center of the coral and age suggests relatively stationary radial growth rates, averaging 24 μm yr^{-1} for L9 (Strzepek et al., 2014) and 45 μm yr^{-1} for C2 (Figure S2).

We inferred the environmental conditions experienced by the corals during their lifetimes from metal:calcium proxies measured along the radial axes of their skeletons using laser ablation ICP-MS (for analytic details, see Strzepek et al., 2014, and supporting information). Magnesium:calcium ratios (Mg/Ca) were measured as a proxy for ambient temperature (Thresher et al., 2010, 2016; Weinbauer et al., 2000; see, however, Flöter et al., 2019) (Figure S3), barium:calcium ratios (Ba/Ca) as a proxy for ambient barium and by inference silicate, and U/Ca as a possible proxy for pH/carbonate ion concentrations. Isidid skeletal Ba/Ca has been suggested as an indirect proxy for silicates on the basis of generally covarying ambient concentrations of it and barium in seawater (Geyman et al., 2019; LaVigne et al., 2011; Thresher et al., 2016). U/Ca in marine carbonates has been validated as negatively dependent on seawater pH/carbonate ion concentrations in foraminiferan calcite (Russell et al., 2004) and in shallow and deep-water scleractinian aragonite (Anagnostou et al., 2011; Inoue et al., 2011; Raddatz et al., 2014). Three hundred and thirty-one contiguous (edge-to-edge) points were measured in L9, and 2,569 in C2, providing nominally subannual resolution in both specimens. However, microstructural heterogeneity, instrumental error, and short-term variability in growth rates due to, for example, reproduction and food availability, all suggest that analyses at less than decadal scales are likely to be unreliable (Thresher et al., 2007).

Statistical analyses were done using Statview, and spectral analysis using K-Spectra. Environmental data were obtained from the CSIRO Atlas of Regional Seas (CARS) (www.marine.csiro.au/~dunn/cars2009/), the historical SAM data from Dätwyler et al. (2018) (www.ncei.noaa.gov/pub/data/paleo/reconstructions/datwyler2017/Reconstructions_Annual_LC.txt), and the record of the Interdecadal Pacific Oscillation (IPO) over Antarctica from Vance et al. (2015).

3. Results and Discussion

Reconstructed time series for all three proxies correlate significantly between the two corals (Figure 1), despite having been collected ~250 km apart and at depths differing by ~1,000 m. All three proxies also correlate highly, if variably, within specimens (Figure S4). The similarity between sites indicates the gorgonian profiles are not idiosyncratic, but rather reflect regional oceanography. The covariance within specimens indicates all three metal:calcium ratios reflect variation in the coral's carbonate matrix. The sign of the correlation between proxies differs between specimens, however. Mg/Ca peaks and troughs in C2 are matched by those in U/Ca and Ba/Ca (which in turn match each other) throughout its life history (Figure S4). In

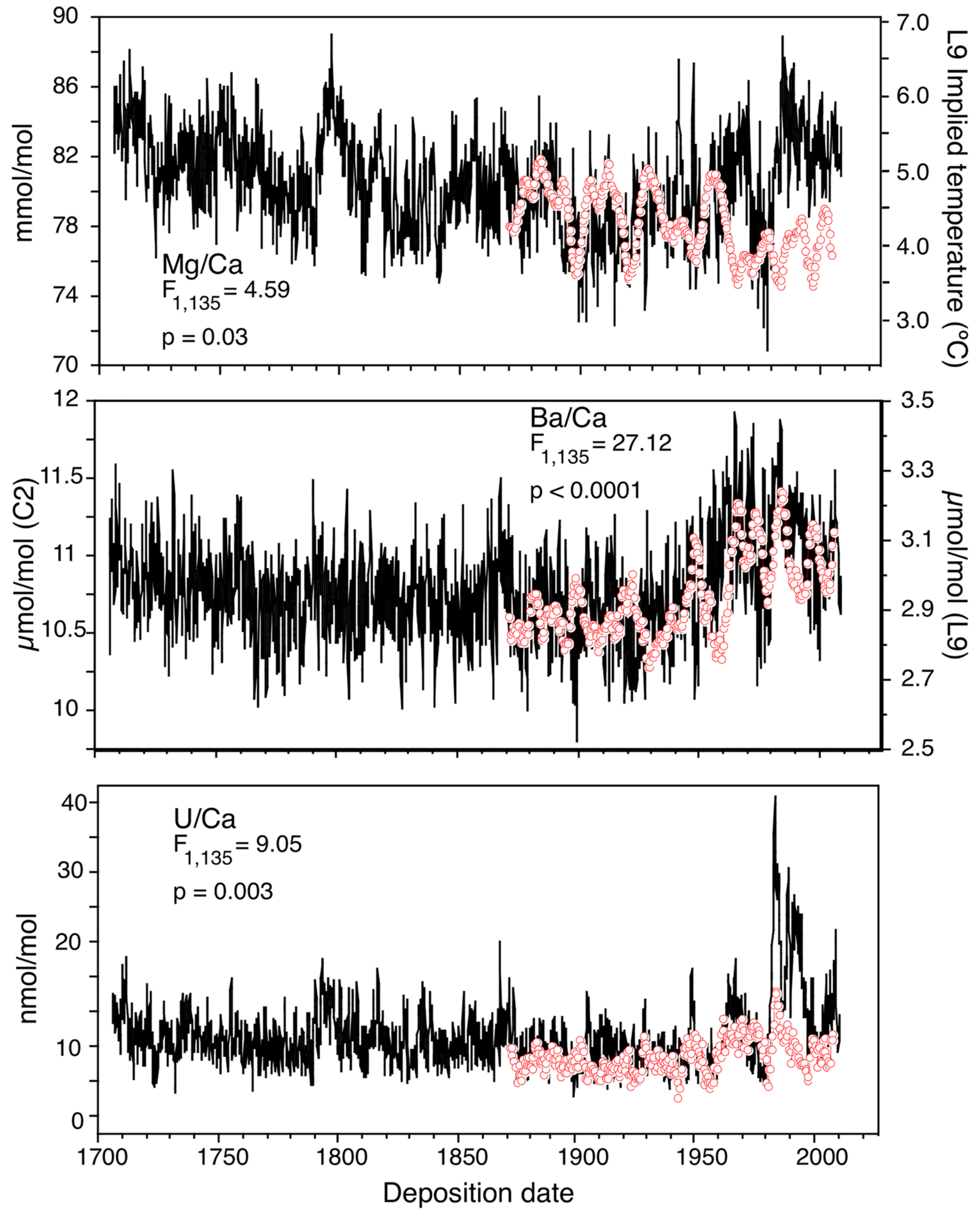

Figure 1. Mg/Ca, Ba/Ca, and U/Ca profiles for C2 (solid black line) and L9 (red circles) compared. Both data sets have been smoothed using a three-point unweighted running mean. Note the different scales for Ba/Ca for the two corals. Implied temperature for L9 is derived from supporting information; note that the range is likely to be exaggerated by the use of filtered data for the calibration.

contrast, Mg/Ca variability in L9 correlates negatively with Ba/Ca. The sign of the relationship between Mg/Ca and U/Ca varies over time. Prior to the mid-20th century, the two proxies only roughly track one another, positively; thereafter, the correlation is negative and highly significant. Break-point analysis suggests the transition is in the early 1930s (maximum postsplit correlation $F_{1,187} = 33.1$, $p < 0.0001$, for a split between 1932 and 1933) (Figure S5). A similar disjunction is evident in the relationship between U/Ca and Ba/Ca in L9, though overall the relationship is highly significant and positive. The inconsistent relationship among proxies between and within corals indicates covariance among them does not derive from possible "vital effects" (e.g., Gagnon et al., 2007; Hill et al., 2011), but rather reflects proxy-specific responses to biological or environmental drivers.

Three features are prominent in the data sets: the inconsistent relationship between proxies noted above, periodic decadal variability in all three proxies, most prominent in L9, and a shift in the mid-20th century in the baseline and trends for proxies in both corals, most prominent in Ba/Ca. Regarding the inconsistency, both barium and uranium in seawater are quasi-conservative water mass tracers, as both are sensitive to biophysical processes associated with the production and recycling of organic matter and carbonate ion concentrations (Langmuir, 1978; Peek & Clementz, 2012; Pyle et al., 2017). The inconsistent relationship between coral U/Ca and Mg/Ca argues against a dominant effect of temperature on uranium up-take (e.g., Shen & Dunbar, 1995), but rather for a long-term, biologically mediated shift in the relationship between temperature and AAIW carbonate chemistry. The opposite sign relationships between Mg/Ca and Ba/Ca in the two corals could reflect regional differences in temperature-mediated effects on the biogeochemistry of seawater barium, but can also be accounted for by shifts in water mass distributions, discussed below. Regarding periodicity, four decade-long peaks dominate the L9 Mg/Ca and Ba/Ca time series prior to about 1960, at 20–25-year intervals. After 1960, the ratios remain episodic, but at a shorter, roughly 15-year period. Spectral analysis of raw (unfiltered) Mg/Ca data confirms the periodicity, with significant ($p > 0.95$) peaks at 21.6, 14.2, and 11.3 years, as well as a cluster of significant peaks centered around apparent annual variation (periods ranging from 0.91 to 1.21 years) (Figure S6). Metal:calcium ratios are noisier in C2, but a spectral analysis of Mg/Ca ratios indicates similar multiyear periodicity, with peaks at 23–26 years ($p > 0.99$) and 8.0 years ($p > 0.95$). In the sampled region, ca. 23 year periodicity is also evident in the recruitment of a deep-sea scleractinian coral (Thresher, Adkins, et al., 2011; Thresher, Tilbrook, et al., 2011), in the temperature-sensitive variability of strontium (Sr) weight-fractions along the growth axes of orange roughy (*Hoplostethus atlanticus*) otoliths (Figure 2a) (see Thresher & Proctor, 2007, for details), and in the temperature-correlated growth rates of juvenile orange roughy (Figure 2b) (Thresher et al., 2014). The correspondence in the SW Pacific between the Mg/Ca cycles in L9 and at least three other regional indices indicates that the periodicity is manifest assemblage wide.

Regarding longer term changes and focusing on the longer C2 series, Ba/Ca ratios fall significantly from the onset of the series to ~1935, at a rate of ~0.009 μmol/mol yr^{-1} ($F_{1,1941} = 62.0$, $p < 0.0001$) and thereafter increase to the end of the series at an average rate of 0.045 μmol/mol yr^{-1} ($F_{1,625} = 29.4$, $p < 0.0001$) (Figure 1). The rise is steepest between ~1935 and ~1970. Differences in mean and the variance of Ba/Ca ratios before and after 1935 are also highly significant (means, 10.72 μmol/mol vs. 10.97, $t_{2568} = 13.8$, $p < 0.0001$; variance $F_{72, 229} = 0.49$, $p < 0.0005$, based on annual mean values). Trends are noisier and not as striking, but similar, in Mg/Ca and U/Ca (Figure 1). Both decline prior to the mid-20th century (to 1935, at a mean rate of 0.17 mmol/mol yr^{-1} for Mg/Ca [$F_{1,1941} = 431.4$, $p < 0.0001$] and 0.09 nmol/mol yr^{-1} for U/Ca [$F_{1,1941} = 53.6$, $p < 0.0001$]) and increase thereafter (at a mean rate of 0.54 mmol/mol yr^{-1} for Mg/Ca [$F_{1,626} = 71.9$, $p < 0.0001$] and 1.20 nmol/mol yr^{-1} for U/Ca [$F_{1,626} = 109.9$, $p < 0.0001$]). Mean ratios of both Mg/Ca and U/Ca are also higher after ~1935 ($t_{2568} = 3.18$, $p < 0.002$, and $t_{2568} = 12.3$, $p < 0.0001$, respectively). Variance is also higher after 1935 for U/Ca ($F_{72, 229} = 0.26$, $p < 0.0001$, based on annual mean values), but not Mg/Ca ($F_{72, 229} = 1.01$, NS). Long-term trends prior to the mid-20th century are less clear cut in the shorter L9 series, but a shift in mean ratios and variability coincident with those in C2 is evident in Ba/Ca and U/Ca (Figure 1). Means increase in both after ~1935, from an average of 9.81 to 10.27 μmol/mol ($t_{332} = 11.50$, $p < 0.0001$) and 7.60 to 9.65 nmol/mol ($t_{332} = 5.86$, $p < 0.0001$), respectively. Variances are also higher after 1935, again based on annual mean values (Ba/Ca, $F_{54,62} = 0.28$, $p < 0.0001$; U/Ca, $F_{54,62} = 0.47$, $p < 0.005$). In contrast, mean Mg/Ca declines between the two time periods from an average of 79.18 to 77.29 mmol/mol ($t_{332} = 10.24$, $p < 0.0001$), with a parallel decline in variance ($F_{54,62} = 2.25$, $p < 0.0025$). The principal drop in L9 Mg/Ca is in the 1960s.

A mechanism that could underlie the periodicity and long-term changes at fixed depths is lateral shifts in water mass distributions. The southern Tasman Sea (location of C2) and the region south of Tasmania (L9) are areas where northern and southern varieties of AAIW mix (Bostock et al., 2013; Rintoul & Bullister, 1999). The northern variety is warmer, higher in silicates, and more acidic than the southern variety (Bostock et al., 2013). Hence, under this scenario increasing temperatures at depth should track increasing silicate levels, and their proxies (Mg/Ca and Ba/Ca, respectively) should correlate positively. They correlate negatively in L9, apparently falsifying the hypothesis. An alternative physical hypothesis is that the periodicity and long-term changes reflect multidecadal variations in the properties, production or depth of AAIW and UCDW. Covariance between SO water mass properties, depth, and volume (Kolodziejczyk

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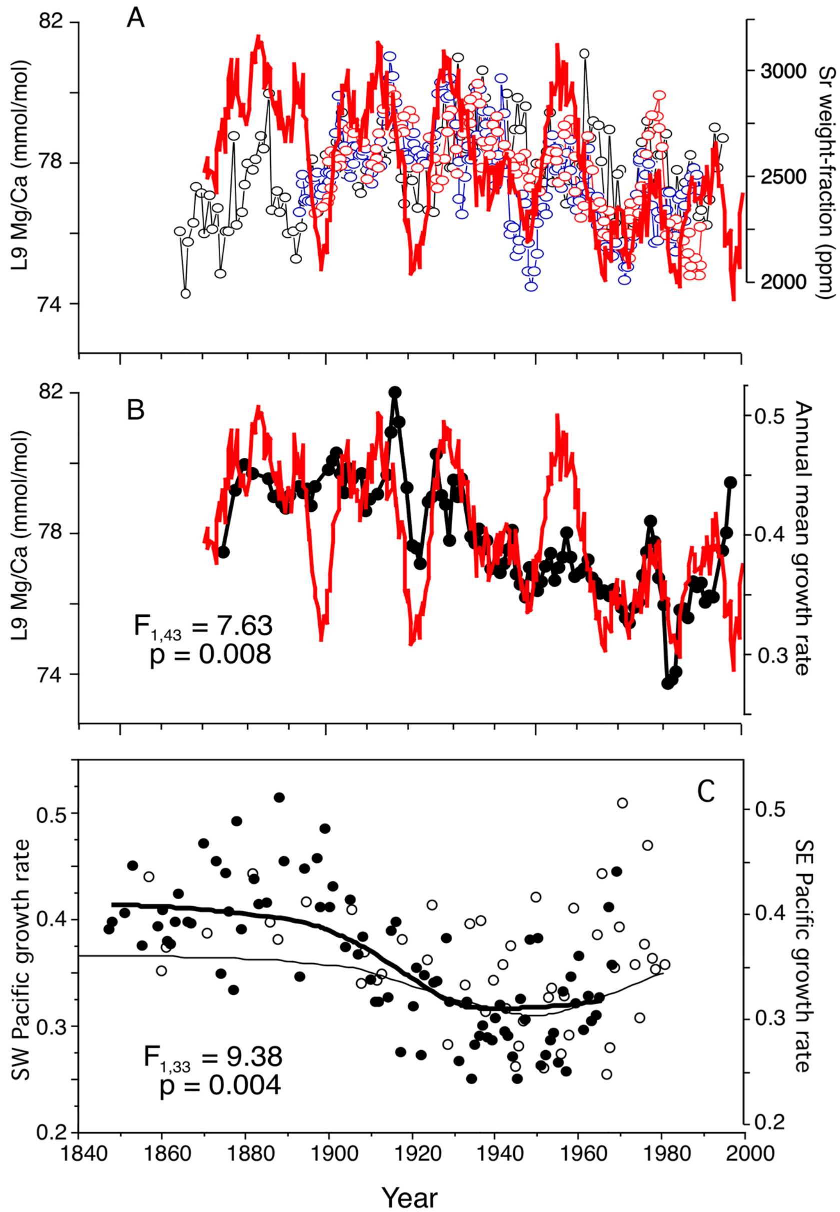

Figure 2. (a) Comparison of L9 Mg/Ca (heavy red line) with nominal temperature proxy (Strontium [Sr] weight-fraction) in the postjuvenile (posttransition zone) otoliths of three orange roughy (*Hoplostethus atlanticus*) (thin lines, circles) collected in 1996 in the area where L9 was collected. The implied ages of the fish match those demonstrated by radiometric aging. For details, see Thresher and Proctor (2007). (b) Comparison of L9 Mg/Ca (red line) with annual mean growth rates of juvenile orange roughy from the area where L9 was collected. (c) Comparison of individual orange roughy juvenile growth rates from the SE Pacific (Chile) (open circles, thin line) and SW Pacific (Tasmania) (filled circles, heavy line), the latter lagged −23 years. For details, see Thresher et al. (2014). The trend lines are Lowess 66° strain.

et al., 2019; Schmidtko & Johnson, 2012) suggests several factors could be involved simultaneously. Based on profiles near where L9 was collected (Thresher et al., 2016), deepening of the AAIW water mass increases temperature, decreases barium and silicate, and increases pH at a fixed depth. This would correspond to simultaneously increasing Mg/Ca, decreasing Ba/Ca, and decreasing U/Ca, i.e., the pattern observed in L9 (Figure S4). Based on water column profiles of the Tasman Sea (Bostock et al., 2011, 2013), deepening of UCDW regionally results in increasing temperature at a fixed depth, but increasing silicates and decreasing pH. Hence, all three proxies should correlate positively, also as observed, in C2, at both decadal and multicentury scales (Figure S4). Whether heave alone is sufficient to account for periodicity in C2's composition is uncertain, as the proxies have not yet been calibrated for that taxon. For L9, relatively small shifts in implied pH, seawater barium, and silicates would require heave of less than 100 m (Figure S7); the range of implied temperatures requires a decadal heave of ≤100–150 m, depending on the calibration. This is compatible with historical hydrographic data for the study area; hydrographic and Argo profiles in the CARS database for a 5° square centered on the location of L9 suggest the estimated depth of the salinity minimum locally averaged close to 1,000 m for 18 sampled years between 1953 and 2007, but varied interannually from an estimated 930 to 1,075 m.

For C2, the long-term trends and positive correlations among all three proxies could be accounted for by remote changes in the proportion of CDW (relatively warm, high in silicates, and low pH) that contribute each year to Antarctic Surface Water and consequently the mix that subducts to form AAIW (Santoso & England, 2004; Sloyan & Rintoul, 2001). A remote source of the long-term variability is also suggested by analysis of the temperature-correlated orange roughy growth rate. In both the SE and SW Pacific, growth rates decline in the mid-1900s, but those in the SE precedes those in the SW by 22–30 years (Thresher et al., 2016; Figure 2c). The lag matches the CFC-11 age of the southern variety of AAIW (Rintoul & Bullister, 1999) and implies a temperature decline near the AAIW source region in the 1910s that propagates to the SW Pacific and is captured in the coral proxies in the late 1930s. In contrast, however, the proxy series for L9 correspond poorly to observational time series of AAIW properties in the Drake Passage (Garabato et al., 2009) and subpolar Pacific (Schmidtko & Johnson, 2012) at any lag close to 20–30 years (Figure S8).

One means of discriminating between a remote and local source of the observed variability at either time scale is to examine the relationship between the measured properties and changes in the latitude and strength of the zonal west winds (Hall & Visbeck, 2004; Oke & England, 2004). Goodwin et al. (2004) document a ∼23-year periodicity in the Law Dome salt proxy of the Southern Annual Mode (SAM), similar to that in the two corals, since 1700, along with evidence of a quasi-decadal periodicity earlier in the reconstructed time series. With specific regard to UCDW, Santoso et al. (2006) suggests that interactions between southward flowing North Atlantic Deep Water and CDW in the South Atlantic produces an ∼30-year periodicity in UCDW properties and heave (their EOF2) that propagates eastwards along the ACC toward the Australian sector of the Southern Ocean. The periodicity is driven at least in part by basin-scale multidecadal (25–30 years) variability in SST and SLP associated with varying intensity of the SH zonal west winds (Wainer & Venegas, 2002). Possibly reflecting this, there is a rough correspondence between observed SSTs in the South Atlantic (Figure 1 of Wainer & Venegas, 2002) and Mg/Ca for both C2 and L9 (Figure S9). The correspondence is best when the South Atlantic SSTs are lagged 2 years, which is consistent with a 2.5 years lag between the South Atlantic SLP and SST variability (Wainer & Venegas, 2002).

We tested directly for an effect of the zonal winds on the fixed depth inferred UCDW and AAIW time series by comparing the Mg/Ca data sets with historical annual values of the SAM as reconstructed by Dätwyler et al. (2018). Comparisons were done at lags of 0 years and 20–25 years, corresponding to local and remote sources of the observed variability, respectively. At the longer lag, the highest correlation between the coral series and the SAM was at a lag of 24 years (Figure 3). In both corals, the lag captures a relationship between a negative SAM in the early 1940s and Mg/Ca ratios that are low in the mid-1960s, and a parallel increase in both thereafter. However, overall the correlation with C2 is only just significant ($F_{1,312} = 3.90$, $p = 0.048$) and for L9, within its range of age uncertainty, there are no significant correlations. Unlagged full-term comparisons between the SAM and coral Mg/Ca indicate no correlation for C2 ($F_{1,332} = 0.31$) and a significant ($F_{1,140} = 10.8$, $p < 0.001$), negative relationship for L9 (Figure S10). Inspection of the time series, however, suggests a significant break in the comparisons in the early to mid-1900s. Specifically, for C2, Mg/Ca inversely and closely tracks the SAM from the onset of the time series (1670) through to about 1940, thereafter appearing to track the SAM positively until the end of the comparison (2004) (Figure 3). Break-point analysis suggests the transition is between 1935 and 1936, as determined by simultaneously maximum correlations before and after the transition (<1936, $F_{1,262} = 38.4$, $p < 0.0001$, $m = -0.16 \pm 0.05$ vs. ≥1936, $F_{1,67} = 19.7$, $p < 0.0001$, $m = +0.14 \pm 0.07$). Varying the proxy series for L9 over the likely uncertainty of the age estimate (140 years, ± ∼10 years) results in correlations between the climate and Mg/Ca ranging from weakly positive to negative. However, for coral ages around 146 years, a pattern emerges that is similar to that of C2 (Figure 3). Break-point analysis suggests a shift about 1938, prior to which Mg/Ca in L9 correlates

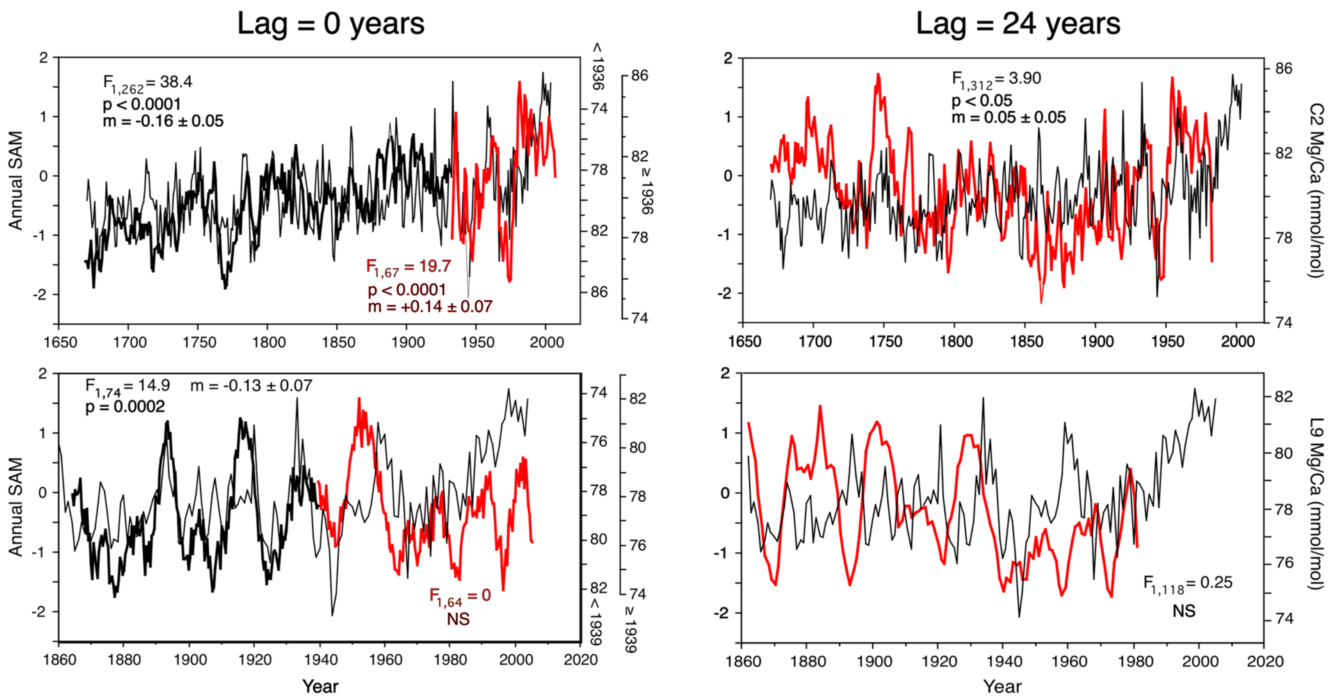

Figure 3. Comparison of annual mean Mg/Ca ratios for C2 and L9 (thick lines) with reconstructed annual mean SAM (thin black lines) (from Dätwyler et al., 2018), at two lags. At a lag of 0 years, Mg/Ca is split based on an apparent change in the sign of the relationship with the SAM in the 1930s. Heavy black lines indicate Mg/Ca is inverted (correlation between SAM and Mg/Ca is negative); heavy red lines indicate Mg/Ca is not inverted. Break-point analysis indicates the optimal split for C2 is <1936 vs. ≥1936; for L9, <1939 vs. ≥1939. The correlation between the SAM and L9 Mg/Ca ≥1939 is significant ($p < 0.05$) and positive after the two series are linearly detrended. At a lag of 24 years (to match the regional age of the AAIW since formation), the SAM correlates positively with C2 over the full time series. The correlation with L9 captures the rise in Mg/Ca since ca. 1940, but is overall not significant. SAM, Southern Annular Mode; AAIW, Antarctic Intermediate Water.

negatively from the onset of the time series (1862) with the annual SAM ($F_{1,74} = 14.9$, $p = 0.0002$) at a slope ($m = -0.13 \pm 0.07$) similar to that in C2. After 1938, there is no correlation between the SAM and L9 Mg/Ca, largely because the latter does not track upwards along with the increasing SAM. After detrending both variables, however, as in C2 they correlate positively after the 1930s ($m = +0.07 \pm 0.06$) ($F_{1,64} = 4.4$, $p < 0.05$).

The break-point analysis of the relationship between coral Mg/Ca and the SAM reinforces evidence of a mid-20th century shift in mean levels and variability in all three proxies in L9 and two of the three in C2, as well as their relationships to southern high latitude climate variability. The proximate and ultimate causes of this oceanographic shift remain uncertain, but we note it is consistent with recent suggestions of a mid-20th century change in climate parameters globally (Turney & Fogwill, 2021). Using tree-ring proxies from sub-Antarctic islands, Turney et al. (2017) reconstruct historical sea surface temperatures (SSTs) for the SW Pacific, find evidence of a mid-20th century increase in subpolar SST variance and link it to increased variability of tropical SSTs. The increased variance in subpolar SSTs parallels our observations for Ba/Ca and U/Ca, but not Mg/Ca. That all three proxies exhibit pronounced decadal variability, but only the two sensitive to ocean productivity increase in amplitude and variance suggests biogeochemical processes play a key role in the amplification.

Finally, the ~23 periodicity of the coral time series invites comparison with the 15–30-year periodicity of the Interdecadal Pacific Oscillation (IPO) (Mantua et al., 1997; Parker et al., 2007). Impacts of the IPO have been documented for the Australian region and the IPO is captured in the Law Dome Ice core climate records (Vance et al., 2015). The Vance et al. IPO reconstruction does not correlate with the periodicity of the coral proxies (Figure S11). It does correlate, weakly ($F_{1,331} = 3.91$, $p < 0.05$) and negatively, with the full C2 Mg/Ca series, but we suggest this reflects primarily the correlation between the SAM and the Vance et al. IPO ($F_{1,332} = 7.16$, $p < 0.01$) coupled with the negative relationship between the SAM and the C2 time series until the 1930s.

4. Conclusions

Analysis of metal/calcium ratios in two long-lived corals in the Southwest Pacific evidence periodic decadal variability at depths that correspond to the AAIW and shallow UCDW, and imply a shift in the mid-1930s to late-1930s in mean ambient temperatures, barium/silicate concentrations, and possibly pH and the rate at which these properties change over time. The decadal periodicity is also manifest in recruitment of a deep-sea scleractinian, in a wholly independent temperature proxy in fish otoliths, and in growth rates of deep-sea fish, indicating it is system-wide in the SW Pacific. In the longer time series (over 300 years), all three coral proxies decline slowly but significantly through to the mid-20th century, before increasing abruptly in the 1930s to the end of the series. A regime shift in the late 1930s-early 1940s is also evident in declining growth rates of deep-sea fish and in the relationship between Mg/Ca and U/Ca in L9, which changes from nonsignificant to strongly negative. The causes of the decadal and long-term variability in AAIW and UCDW in the SW Pacific are not clear. Previous studies show that contraction of the circumpolar vortex, reflected in a positive SAM, results in warming along depth strata (Oke & England, 2004) and along isopycnals below the AAIW core depth (Bindoff & Church, 1992; Bindoff & McDougall, 2000; Johnson & Orsi, 1997; Schmidtko & Johnson, 2012). Comparison of the coral series with the SAM at a lag consistent with the age of AAIW in the sampled region supports a long-term positive relationship between the zonal winds and apparent fixed depth temperature in UCDW (C2), but it fails to capture the fixed depth variability just below the AAIW core depth (L9). An alternative analysis, based on a 0 years lag between the SAM and the coral series, results in highly significant correlations in both corals, but requires a regime shift, again in the mid-1930s to late-1930s, from a negative relationship between the SAM and temperature to a positive one. “Mode switches” in Antarctic climate have previously been suggested based on analysis of ice cores (Mayewski et al., 2004), but there is nothing in the record suggestive of an event in the 1930s or, if the SW Pacific time series derives from propagated changes from the SE Pacific AAIW source region, 1910–1920. The timing of the shift approximates the onset of the 1940s positive phase of the IPO, but if the IPO is involved, it leaves unanswered why previous, stronger positive shifts (e.g., in the early 1900s) did not affect either the correlation with the SAM or proxy means and trends. The midcentury regime shifts in the deep-water proxies are also roughly concordant with apparent changes in climate parameters globally in the mid-20th century and could be mediated at least in part by changes in surface productivity.

Data Availability Statement

Environmental data are available from the CSIRO Atlas of Regional Seas (CARS) (www.marine.csiro.au/~dunn/cars2009/), coral proxy data from CSIRO Data Access Portal (https://data.csiro.au/collections/collection/CIcsiro:48512), the historical SAM data from Dätwyler et al. (2018), and the record of the Interdecadal Pacific Oscillation (IPO) over Antarctica from Vance et al. (2015).

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References

Anagnostou, E., Sherrell, R. M., Gagnon, A., LaVigne, M., Field, M. P., & McDonough, W. F. (2011). Seawater nutrient and carbonate ion concentrations recorded as P/Ca, Ba/Ca, and U/Ca in the deep-sea coral *Desmophyllum dianthus*. *Geochimica et Cosmochimica Acta*, *75*, 2529–2543. https://doi.org/10.1016/j.gca.2011.02.019

Bindoff, N. L., & Church, J. A. (1992). Warming of the water column in the Southwest Pacific Ocean. *Nature*, *357*, 59–62. https://doi.org/10.1038/357059a0

Bindoff, N. L., & McDougall, T. J. (2000). Decadal changes along an Indian ocean section at 32°S and their interpretation. *Journal of Physical Oceanography*, *30*, 1207–1222. https://doi.org/10.1175/1520-0485(2000)030<1207:dcaaio>2.0.co;2

Bostock, H. C., Hayward, B. W., Neil, H. L., Currie, K. I., & Dunbar, G. B. (2011). Deep-water carbonate concentrations in the Southwest Pacific. *Deep Sea Research Part I: Oceanographic Research Papers*, *58*, 72–85. https://doi.org/10.1016/j.dsr.2010.11.010

Bostock, H. C., Sutton, P. J., Williams, M. J. M., & Opdyke, B. N. (2013). Reviewing the circulation and mixing of Antarctic intermediate water in the south pacific using evidence from geochemical tracers and Argo float trajectories. *Deep Sea Research Part I: Oceanographic Research Papers*, *73*, 84–98. https://doi.org/10.1016/j.dsr.2012.11.007

Bryden, H. L., McDonagh, E. L., & King, B. A. (2003). Changes in ocean water mass properties: Oscillations or trends? *Science*, *300*, 2086–2088. https://doi.org/10.1126/science.1083980

Church, J. A., Godfrey, J. S., Jackett, D. R., & McDougall, T. J. (1991). A model of sea level rise caused by ocean thermal expansion. *Journal of Climate*, *4*, 438–456. https://doi.org/10.1175/1520-0442(1991)004<0438:amoslr>2.0.co;2

Dätwyler, C., Neukom, R., Abram, N. J., Gallant, A. J. E., Grosjean, M., Jacques-Coper, M., et al. (2018). Teleconnection stationarity, variability and trends of the Southern Annular Mode (SAM) during the last millennium. *Climate Dynamics*, *51*, 2321–2339. https://doi.org/10.1007/s00382-017-4015-0

Downes, S. M., Bindoff, N. L., & Rintoul, S. R. (2009). Impacts of climate change on the subduction of mode and intermediate water masses in the Southern Ocean. *Journal of Climate*, *22*, 3289–3302. https://doi.org/10.1175/2008jcli2653.1

Flöter, S., Fietzke, J., Gutjahr, M., Farmer, J., Hönisch, B., Nehrke, G., & Eisenhauer, A. (2019). The influence of skeletal micro-structures on potential proxy records in a bamboo coral. *Geochimica et Cosmochimica Acta*, *248*, 43–60. https://doi.org/10.1016/j.gca.2018.12.027

Fröhlicher, T. L., Sarmiento, J. L., Paynter, D. J., Dunne, J. P., Krasting, J. P., & Winton, M. (2014). Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. *Journal of Climate*, *28*, 862–886.

Fyfe, J. C. (2006). Southern Ocean warming due to human influence. *Geophysical Research Letters*, *33*, L19701. https://doi.org/10.1029/2006GL027427

Gagnon, A. C., Adkins, J. F., Fernandez, D. P., & Robinson, L. F. (2007). Sr/Ca and Mg/Ca vital effects correlated with skeletal architecture in a scleractinian deep-sea coral and the role of Rayleigh fractionation. *Earth and Planetary Science Letters*, *261*, 280–295. https://doi.org/10.1016/j.epsl.2007.07.013

Garabato, A. C. N., Jullion, L., Stevens, D. P., Heywood, K. J., & King, B. A. (2009). Variability of subantarctic mode water and Antarctic intermediate water in the drake passage during the late-twentieth and early-twenty-first centuries. *Journal of Climate*, *32*, 3661–3688.

Geyman, B. M., Ptacek, J. L., LaVigne, M., & Horner, T. J. (2019). Barium in deep-sea bamboo corals: Phase associations, barium stable isotopes, & prospects for paleoceanography. *Earth and Planetary Science Letters*, *525*, 115751. https://doi.org/10.1016/j.epsl.2019.115751

Goodwin, I. D., van Ommen, T. D., Curran, M. A. J., & Mayewski, P. A. (2004). Mid latitude winter climate variability in the South Indian and Southwest Pacific regions since 1300 AD. *Climate Dynamics*, *22*, 783–794. https://doi.org/10.1007/s00382-004-0403-3

Hall, A., & Visbeck, M. (2004). Synchronous variability in the Southern Hemisphere atmosphere, sea ice and ocean resulting from the annular mode. *Journal of Climate*, *15*, 3043–3057.

Hill, T. M., Spero, H. J., Guilderson, T., LaVigne, M., Clague, D., Macalello, S., & Jang, N. (2011). Temperature and vital effect controls on bamboo coral (Isididae) isotope geochemistry: A test of the "lines method". *Geochemistry, Geophysics, Geosystems*, *12*, Q04008. https://doi.org/10.1029/2010GC003443

Inoue, M., Suwa, R., Suzuki, A., Sakai, K., & Kawahata, H. (2011). Effects of seawater pH on growth and skeletal U/Ca ratios of *Acropora digitifera* coral polyps. *Geophysical Research Letters*, *38*, L12809. https://doi.org/10.1029/2011GL047786

Johnson, G. C., & Orsi, A. H. (1997). Southwest Pacific Ocean water-mass changes between 1968/69 and 1990/91. *Journal of Climate*, *10*, 306–316. https://doi.org/10.1175/1520-0442(1997)010<0306:spowmc>2.0.co;2

Khatiwala, S., Primeau, F., & Hall, T. (2009). Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. *Nature*, *462*, 346–349. https://doi.org/10.1038/nature08526

Kolodziejczyk, N., Llovel, W., & Portela, E. (2019). Interannual variability of upper ocean water masses as inferred from Argo array. *Journal of Geophysical Research: Oceans*, *124*, 6067–6085. https://doi.org/10.1029/2018JC014866

Langmuir, D. (1978). Uranium solution-mineral equilibria at low temperatures with applications to sedimentary ore deposits. *Geochimica et Cosmochimica Acta*, *42*, 547–569. https://doi.org/10.1016/0016-7037(78)90001-7

LaVigne, M., Hill, T. M., Spero, H. J., & Guilderson, T. P. (2011). Bamboo coral Ba/Ca: Calibration of a new deep ocean refractory nutrient proxy. *Earth and Planetary Science Letters*, *312*, 506–515. https://doi.org/10.1016/j.epsl.2011.10.013

Loubere, P., & Bennett, S. (2008). Southern Ocean biogeochemical impact on the tropical ocean: Stable isotope records from the Pacific for the past 25,000 years. *Global and Planetary Change*, *63*, 333–340. https://doi.org/10.1016/j.gloplacha.2008.08.001

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, *78*, 1069–1079. https://doi.org/10.1175/1520-0477(1997)078<1069:apicow>2.0.co;2

Mayewski, P. A., Maasch, K. A., White, J. W. C., Steig, E. J., Meyerson, E., Goodwin, I., et al. (2004). A 700 year record of Southern Hemisphere extratropical climate variability. *Annals of Glaciology*, *39*, 127–132. https://doi.org/10.3189/172756404781814249

Mayewski, P. A., Meredith, M. P., Summerhayes, C. P., Turner, J., Worby, A., Barrett, P. J., et al. (2007). State of the Antarctic and Southern Ocean climate system. *Reviews of Geophysics*, *47*, RG1003. https://doi.org/10.1029/2007RG000231

Oke, P. R., & England, M. H. (2004). Oceanic response to changes in the latitude of the Southern Hemisphere subpolar westerly winds. *Journal of Climate*, *17*, 1040–1054. https://doi.org/10.1175/1520-0442(2004)017<1040:ortcit>2.0.co;2

Parker, D., Folland, C., Scaife, A., Knight, J., Colman, A., Baines, P., & Dong, B. (2007). Decadal to multidecadal variability and the climate change background. *Journal of Geophysical Research*, *112*, D18115. https://doi.org/10.1029/2007JD008411

Peek, S., & Clementz, M. T. (2012). Sr/Ca and Ba/Ca variations in environmental and biological sources: A survey of marine and terrestrial systems. *Geochimica et Cosmochimica Acta*, *95*, 36–52. https://doi.org/10.1016/j.gca.2012.07.026

Pyle, K. M., Hendry, K. R., Sherrell, R. M., Meredith, M. P., Venables, H., Lagerström, M., & Morte-Ródenas, A. (2017). Coastal barium cycling at the West Antarctic Peninsula. *Deep Sea Research Part II: Topical Studies in Oceanography*, *139*, 120–131. https://doi.org/10.1016/j.dsr2.2016.11.010

Raddatz, J., Rüggeberg, A., Flögel, S., Hathorne, E. C., Liebetrau, V., Eisenhauer, A., & Dullo, W.-C. (2014). The influence of seawater pH on U/Ca ratios in the scleractinian cold-water coral *Lophelia pertusa*. *Biogeosciences*, *11*, 1863–1871. https://doi.org/10.5194/bg-11-1863-2014

Rintoul, S. R., & Bullister, J. L. (1999). A late winter hydrographic section from Tasmania to Antarctica. *Deep Sea Research Part I: Oceanographic Research Papers*, *46*, 1417–1454. https://doi.org/10.1016/s0967-0637(99)00013-8

Rochford, D. (1960). The intermediate depth waters of the Tasman and coral seas. I. The 27.20 σt surface. *Marine and Freshwater Research*, *11*, 127–147. https://doi.org/10.1071/mf9600127

Russell, A. D., Hönisch, B., Spero, H. J., & Lea, D. W. (2004). Effects of seawater carbonate ion concentration and temperature on shell U, Mg, and Sr in cultured planktonic foraminifera. *Geochimica et Cosmochimica Acta*, *68*, 4347–4361. https://doi.org/10.1016/j.gca.2004.03.013

Santoso, A., & England, M. H. (2004). Antarctic intermediate water circulation and variability in a coupled climate model. *Journal of Physical Oceanography*, *34*, 2160–2179. https://doi.org/10.1175/1520-0485(2004)034<2160:aiwcav>2.0.co;2

Santoso, A., England, M. H., & Hirst, A. C. (2006). Circumpolar deep water circulation and variability in a coupled climate model. *Journal of Physical Oceanography*, *36*, 1523–1552. https://doi.org/10.1175/jpo2930.1

Sarmiento, J. L., Gruber, N., Brzezinski, M. A., & Dunne, J. P. (2004). High-latitude controls of thermocline nutrients and low latitude biological productivity. *Nature*, *427*, 56–60. https://doi.org/10.1038/nature02127

Schmidtko, S., & Johnson, G. C. (2012). Multidecadal warming and shoaling of Antarctic intermediate water. *Journal of Climate*, *25*, 207–221. https://doi.org/10.1175/jcli-d-11-00021.1

Shen, G. T., & Dunbar, R. B. (1995). Environmental controls on uranium in reef corals. *Geochimica et Cosmochimica Acta*, *59*, 2009–2024. https://doi.org/10.1016/0016-7037(95)00123-9

Sloyan, B. M., & Rintoul, S. R. (2001). Circulation, renewal, and modification of Antarctic mode and intermediate water*. *Journal of Physical Oceanography*, *31*, 1005–1030. https://doi.org/10.1175/1520-0485(2001)031<1005:cramoa>2.0.co;2

Strzepek, K. M., Thresher, R. E., Revill, A. T., Smith, C. I., Komugabe, A. F., & Fallon, S. F. (2014). Preservation effects on the isotopic and elemental composition of skeletal structures in the deep-sea bamboo coral *Lepidisis* spp. (Isididae). *Deep Sea Research Part II: Topical Studies in Oceanography*, *99*, 199–206. https://doi.org/10.1016/j.dsr2.2013.07.010

Thresher, R., Morrongiello, J., Sloyan, B. M., Krusic-Golub, K., Shephard, S., Minto, C., et al. (2014). Parallel decadal variability of inferred water temperatures for Northern and Southern Hemisphere intermediate water masses. *Geophysical Research Letters*, *41*, 1232–1237. https://doi.org/10.1002/2013GL058638

Thresher, R., Tilbrook, B., Fallon, S., Wilson, N., & Adkins, J. (2011). Effects of chronic low carbonate saturation levels on the distribution, growth and skeletal chemistry of deep-sea corals and other seamount megabenthos. *Marine Ecology Progress Series*, *442*, 87–99. https://doi.org/10.3354/meps09400

Thresher, R. E., Adkins, J., & Thiagarajan, N. (2011). Modal analysis of the deep-water solitary scleractinian, *Desmophyllum dianthus*, on SW Pacific seamounts: Inferred recruitment periodicity, growth, and mortality rates. *Coral Reefs*, *30*, 1063–1070. https://doi.org/10.1007/s00338-011-0806-7

Thresher, R. E., Fallon, S. J., & Townsend, A. T. (2016). A "core-top" screen for trace element proxies of environmental conditions and growth rates in the calcite skeletons of bamboo corals (Isididae). *Geochimica et Cosmochimica Acta*, *193*, 75–99. https://doi.org/10.1016/j.gca.2016.07.033

Thresher, R. E., MacRae, C. M., Wilson, N. C., & Gurney, R. (2007). Environmental effects on the skeletal composition of deep-water gorgonians (*Keratoisis* spp.; Isididae). *Bulletin of Marine Science*, *81*, 409–422.

Thresher, R. E., & Proctor, C. H. (2007). Population structure and life history of orange roughy (*Hoplostethus atlanticus*) in the SW Pacific: Inferences from otolith chemistry. *Marine Biology*, *152*, 461–473. https://doi.org/10.1007/s00227-007-0705-1

Thresher, R. E., Wilson, N. C., MacRae, C. M., & Neil, H. (2010). Temperature effects on the calcite skeletal composition of deep-water gorgonians (Isididae). *Geochimica et Cosmochimica Acta*, *74*, 4655–4670. https://doi.org/10.1016/j.gca.2010.05.024

Turner, J., Colwell, S. R., Marshall, G. J., Lachlan-Cope, T. A., Carleton, A. M., Jones, P. D., et al. (2005). Antarctic climate change during the last 50 years. *International Journal of Climatology*, *25*, 279–294. https://doi.org/10.1002/joc.1130

Turney, C., & Fogwill, C. (2021). The implications of the recently recognized mid-20th century shift in the Earth system. *The Anthropocene Review*. https://doi.org/10.1177/2053019621995526

Turney, C. S. M., Fogwill, C. J., Palmer, J. G., van Sebille, E., Thomas, Z., McGlone, M., et al. (2017). Tropical forcing of increased Southern Ocean climate variability revealed by a 140-year subantarctic temperature reconstruction. *Climate of the Past*, *13*, 231–248. https://doi.org/10.5194/cp-13-231-2017

Vance, T. R., Roberts, J. L., Plummer, C. T., Klem, A. S., & van Ommen, T. D. (2015). Interdecadal Pacific variability and eastern Australian megadroughts over the last millennium. *Geophysical Research Letters*, *42*, 129–137. https://doi.org/10.1002/2014GL062447

Wainer, I., & Venegas, S. A. (2002). South Atlantic multidecadal variability in the climate system model. *Journal of Climate*, *15*, 1408–1420. https://doi.org/10.1175/1520-0442(2002)015<1408:samvit>2.0.co;2

Weinbauer, M. G., Brandstätter, F., & Velimirov, B. (2000). On the potential use of magnesium and strontium concentrations as ecological indicators in the calcite skeleton of the red coral (*Corallium rubrum*). *Marine Biology*, *137*, 801–809. https://doi.org/10.1007/s002270000432

References From the Supporting Information

Fallon, S. J., McCulloch, M. T., van Woesik, R., & Sinclair, D. J. (1999). Corals at their latitudinal limits: Laser ablation trace element systematics in Porites from Shirigai Bay, Japan. *Earth and Planetary Science Letters*, *172*, 221–238. https://doi.org/10.1016/s0012-821x(99)00200-9

Ridgway, K. R., Dunn, J. R., & Wilkin, J. L. (2002). Ocean interpolation by four-dimensional weighted least squares-application to the waters around Australasia. *Journal of Atmospheric and Oceanic Technology*, *19*, 1357–1375. https://doi.org/10.1175/1520-0426(2002)019<1357:oibfdw>2.0.co;2