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# Identifying Hydro-Sensitive Coral $\delta^{18}\text{O}$ Records for Improved High-Resolution Temperature and Salinity Reconstructions

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## RESEARCH LETTER

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Thompson and Conroy contributed equally to this work.

### Key Points:

- Seawater  $\delta^{18}\text{O}$  contributes up to 89% of the coral  $\delta^{18}\text{O}$  variability, providing critical information about salinity variability and trends
- The inferred salinity contribution to coral  $\delta^{18}\text{O}$  values is highly dependent on the salinity- $\delta^{18}\text{O}$  linear regression slope
- Interpretation of coral  $\delta^{18}\text{O}$  values should account for both temperature and hydrological influences, which may oppose one another

### Supporting Information:

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

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## Identifying Hydro-Sensitive Coral $\delta^{18}\text{O}$ Records for Improved High-Resolution Temperature and Salinity Reconstructions

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**Abstract** Stable oxygen isotopic ratios in corals ( $\delta^{18}\text{O}_{\text{coral}}$ ) are commonly utilized to reconstruct climate variability beyond the limit of instrumental observations. These measurements provide constraints on past seawater temperature, due to the thermodynamics of isotopic fractionation, but also past salinity, as both salinity and seawater  $\delta^{18}\text{O}$  ( $\delta^{18}\text{O}_{\text{sw}}$ ) are similarly affected by precipitation/evaporation, advection, and other processes. We use historical observations, isotope-enabled model simulations, and the PAGES Iso2k database to assess the potential of  $\delta^{18}\text{O}_{\text{coral}}$  to provide information on past salinity. Using “pseudocorals” to represent  $\delta^{18}\text{O}_{\text{coral}}$  as a function of observed or simulated temperature and salinity/ $\delta^{18}\text{O}_{\text{sw}}$ , we find that  $\delta^{18}\text{O}_{\text{sw}}$  contributes up to 89% of  $\delta^{18}\text{O}_{\text{coral}}$  variability in the Western Pacific Warm Pool. Although uncertainty in the  $\delta^{18}\text{O}_{\text{sw}}$ -salinity relationship influences the inferred salinity variability, corals from these sites could provide valuable  $\delta^{18}\text{O}_{\text{sw}}$  reconstructions. Coordinated in situ monitoring of salinity and  $\delta^{18}\text{O}_{\text{sw}}$  is vital for improving estimates of hydroclimatic change.

**Plain Language Summary** Seawater salinity provides valuable information about the global water cycle, including changes in precipitation, evaporation, and ocean currents. However, scientists' understanding of recent salinity change is hampered by the limited coverage of salinity measurements. Tropical corals incorporate environmental information in their skeletons as they grow, providing indirect evidence of past ocean salinity. Quantitatively estimating salinity variations requires accounting both for temperature- and salinity-driven influences on the stable oxygen isotope composition ( $\delta^{18}\text{O}$ ) of the coral skeleton, as well as changes in the relationship between salinity and seawater  $\delta^{18}\text{O}$ . Through comparison with instrumental records and climate models, we find that corals in the western Pacific Ocean and eastern Indian Ocean are most likely to provide reliable salinity information across seasons, years, and decades. Finally, we find that direct seawater  $\delta^{18}\text{O}$  observations are critical to improve the salinity information obtained from corals.

## 1. Introduction

Tropical sea surface temperature (SST) and sea surface salinity (SSS), variables driven by large-scale oceanic-atmospheric interactions, are recorded in the stable oxygen isotopic ratio of coral skeletal aragonite ( $\delta^{18}\text{O}_{\text{coral}}$ ). Coral  $\delta^{18}\text{O}$  values thus preserve key information on past ocean-atmosphere variability on interannual to centennial timescales, such as the interannual El Niño-Southern Oscillation (ENSO) in the tropical Indo-Pacific (e.g., Cobb et al., 2013; Cole and Fairbanks, 1990; Grothe et al., 2020; McGregor et al., 2013). A sound understanding of how  $\delta^{18}\text{O}_{\text{coral}}$  values record changes in SST and SSS is vital for understanding past climate variability. Coral  $\delta^{18}\text{O}$  values co-vary positively with the  $\delta^{18}\text{O}$  of the seawater from which the skeleton forms ( $\delta^{18}\text{O}_{\text{sw}}$ ), and co-vary negatively with the water temperature at the time of skeletal precipitation due to the thermodynamics of isotope fractionation (Emiliani et al., 1978; Epstein et al., 1953; Weber & Woodhead, 1972). Further, SSS has a strong positive relationship with  $\delta^{18}\text{O}_{\text{sw}}$  in the tropical-subtropical oceans, as precipitation leads to freshening and lower  $\delta^{18}\text{O}_{\text{sw}}$  values, whereas evaporation leads to increased salinity and higher  $\delta^{18}\text{O}_{\text{sw}}$  values (Craig & Gordon, 1965; Fairbanks et al., 1997; LeGrande & Schmidt, 2006). Ocean currents and upwelling advect surface and subsurface waters with particular SSS- $\delta^{18}\text{O}_{\text{sw}}$  signatures imparted by the precipitation-evaporation (P-E) balance of

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the source region, resulting in further regional-scale SSS- $\delta^{18}\text{O}_{\text{sw}}$  coherence (Stevenson et al., 2018) that may not covary with local SST (Watanabe et al., 2019).

SST and SSS typically contribute constructively to  $\delta^{18}\text{O}_{\text{coral}}$  values in the tropical-subtropical oceans. Where warmer and wetter conditions co-occur, the  $\delta^{18}\text{O}_{\text{coral}}$  signal is additive, since precipitation results in lower salinity and  $\delta^{18}\text{O}_{\text{sw}}$ , and warmer temperatures also lower  $\delta^{18}\text{O}_{\text{coral}}$  values. For example, the co-occurrence of warm, wet conditions in the central Pacific region during El Niño events amplifies the signal in  $\delta^{18}\text{O}_{\text{coral}}$ , providing clearly detectable and measurable ENSO anomalies over the Holocene (e.g., Cobb et al., 2013; Cole and Fairbanks, 1990; Grothe et al., 2020; McGregor et al., 2013). However, in other locations, such as the eastern equatorial Pacific, seasonal temperature and precipitation extremes may lag each other by several months or may interfere destructively, adding uncertainty to the interpretation of  $\delta^{18}\text{O}_{\text{coral}}$  values (Cahyarini et al., 2008; Russon et al., 2013). Paired coral Sr/Ca and  $\delta^{18}\text{O}$  measurements provide a means of determining the contribution of SST and SSS/ $\delta^{18}\text{O}_{\text{sw}}$  to  $\delta^{18}\text{O}_{\text{coral}}$  values since Sr/Ca is primarily sensitive to SST (Corrège, 2006). However, most published  $\delta^{18}\text{O}_{\text{coral}}$  records to date lack paired Sr/Ca data (Carré et al., 2021; Konecky et al., 2020).

An extensive body of work has focused on isolating the SST and ENSO signals in  $\delta^{18}\text{O}_{\text{coral}}$  (e.g., Cobb et al., 2013; Cole and Fairbanks, 1990; Hereid et al., 2013; Lawman et al., 2020; Tierney et al., 2015), but less attention has been paid to the  $\delta^{18}\text{O}_{\text{sw}}$  signal, despite its local significance at some coral sites (e.g., Cahyarini et al., 2008; Cahyarini et al., 2014; Dassié et al., 2018; Gorman et al., 2012; Murty et al., 2018). An inquiry into the role of  $\delta^{18}\text{O}_{\text{sw}}$  is especially timely, as trends in SSS since the mid-20th century (when SSS measurements became more common) echo trends in atmospheric P-E and are a fingerprint of anthropogenic hydroclimatic change (Durack et al., 2012).

Given the limited temporal range of SSS measurements, paleo- $\delta^{18}\text{O}_{\text{sw}}$  estimates from corals have potential value as proxies for past SSS. Although robust paleo-SSS reconstructions from corals may be limited by uncertainties in the slope of the  $\delta^{18}\text{O}_{\text{sw}}$ -SSS relationship, a systematic investigation into the potential of coral records to provide robust SSS information has not yet been performed. In this paper, we comprehensively explore the relationship between  $\delta^{18}\text{O}_{\text{coral}}$  and SSS using synthetic  $\delta^{18}\text{O}_{\text{coral}}$  records, or “pseudocorals” (Thompson et al., 2011), modeled from observed and simulated temperature, SSS, and  $\delta^{18}\text{O}_{\text{sw}}$ . This approach permits a detailed investigation of the relative role of temperature and SSS/ $\delta^{18}\text{O}_{\text{sw}}$  in modern  $\delta^{18}\text{O}_{\text{coral}}$  interannual to multidecadal variability across the tropics, and identifies optimal sites for reconstructing SSS. Applying this approach to coral sites in the new PAGES Iso2k database (Konecky et al., 2020) with records spanning the instrumental period, we identify hydro-sensitive  $\delta^{18}\text{O}_{\text{coral}}$  records that can provide critical salinity information.

## 2. Methods

### 2.1. Identification of Hydro-Sensitive Coral Sites From Observed or Simulated SST and SSS/ $\delta^{18}\text{O}_{\text{sw}}$

To identify sites where  $\delta^{18}\text{O}_{\text{sw}}$  contributes strongly to  $\delta^{18}\text{O}_{\text{coral}}$  variability,  $\delta^{18}\text{O}_{\text{coral}}$  was first predicted from historical or simulated SST and  $\delta^{18}\text{O}_{\text{sw}}$ /SSS over the 1950–2009 period using a coral proxy system model (PSM, Thompson et al., 2011):

$$\delta^{18}\text{O}_{\text{coral}} = a_1\text{SST} + b\delta^{18}\text{O}_{\text{sw}} \quad (1a)$$

$$\delta^{18}\text{O}_{\text{coral}} = a_1\text{SST} + a_2\text{SSS}b + \varepsilon \quad (1b)$$

where the coefficient  $a_1$  was set to  $-0.22 \text{‰/}^\circ\text{C}$  based on empirical and theoretical estimates of the  $\delta^{18}\text{O}_{\text{coral}}$ -SST relationship (Epstein et al., 1953; Evans et al., 2000; Lough, 2004). In model output, where  $\delta^{18}\text{O}_{\text{sw}}$  estimates were available,  $\delta^{18}\text{O}_{\text{coral}}$  was calculated directly from  $\delta^{18}\text{O}_{\text{sw}}$  using the relationship between the Vienna Pee Dee Belemnite (VPDB) and Vienna Standard Mean Ocean Water reference standards for  $\delta^{18}\text{O}_{\text{carbonate}}$  and  $\delta^{18}\text{O}_{\text{sw}}$ , respectively ( $b = 0.97002$ ; Equation 1a). SSS was used in place of  $\delta^{18}\text{O}_{\text{sw}}$  for estimates over the historical period, due to the paucity of *in situ*  $\delta^{18}\text{O}_{\text{sw}}$  observations. In these cases,  $a_2$  was defined at each site by the regional slopes of the  $\delta^{18}\text{O}_{\text{sw}}$ -SSS relationship (LeGrande & Schmidt, 2006), and the resulting  $\delta^{18}\text{O}_{\text{sw}}$  was converted to VPDB (Equation 1b).

We identified sites where  $\delta^{18}\text{O}_{\text{sw}}$  contributes strongly to  $\delta^{18}\text{O}_{\text{coral}}$  variability using two metrics derived from this forward-modeled coral  $\delta^{18}\text{O}_{\text{coral}}$ . The first metric, the  $F_{\text{sw}}$  (“fraction seawater”) statistic, quantifies the fraction

of total  $\delta^{18}\text{O}_{\text{coral}}$  variance driven by both  $\delta^{18}\text{O}_{\text{sw}}$  variance and the covariance of  $\delta^{18}\text{O}_{\text{sw}}$  with SST ( $F_{\text{cov}}$ ; Russon et al., 2013). The second metric,  $F_{\text{cov}}$  (“fraction covariance”), assesses the fraction of  $\delta^{18}\text{O}_{\text{coral}}$  due solely to SST- $\delta^{18}\text{O}_{\text{sw}}$  covariance (Russon et al., 2013). As in Equations 1a, 1b,  $\delta^{18}\text{O}_{\text{sw}}$  was replaced by SSS, using the regional  $\delta^{18}\text{O}_{\text{sw}}$  - SSS relationship in the absence of sufficient  $\delta^{18}\text{O}_{\text{sw}}$  observations over the historical period.

$$F_{\text{cov}} = \frac{2R_{\text{SST-coral}} \text{cov}(\text{SST}, \delta^{18}\text{O}_{\text{sw}})}{\text{var}(\delta^{18}\text{O}_{\text{coral}})} \quad (2)$$

$$F_{\text{sw}} = \frac{\text{var}(\delta^{18}\text{O}_{\text{sw}}) + 2R_{\text{SST-coral}} \text{cov}(\text{SST}, \delta^{18}\text{O}_{\text{sw}})}{\text{var}(\delta^{18}\text{O}_{\text{coral}})} \quad (3)$$

where  $R_{\text{SST-coral}}$  is the slope of the  $\delta^{18}\text{O}_{\text{coral}}$ -SST relationship of  $-0.22 \text{‰}/^\circ\text{C}$ . The  $F_{\text{cov}}$  and  $F_{\text{sw}}$  values can range from  $-1$  to  $1$ . For  $F_{\text{cov}}$ , negative values occur at sites where there is a positive covariance between SST and SSS (and thus a positive SST-SSS correlation). Correlation coefficients between annual anomalies of SST and SSS were also calculated to reveal the direction and significance of this relationship at each coral site. In turn,  $F_{\text{sw}}$  values greater than zero indicate a fraction of  $\delta^{18}\text{O}_{\text{coral}}$  variance stems from  $\delta^{18}\text{O}_{\text{sw}}$  variance and its covariance with SST. Negative values are rare, but arise if there is positive covariance between SST and  $\delta^{18}\text{O}_{\text{sw}}/\text{SSS}$  (i.e.,  $r_{\text{SST-SSS}}$  is positive and the  $F_{\text{cov}}$  term is negative) that surpasses that of  $\delta^{18}\text{O}_{\text{sw}}$  variability. In any situation where there is positive covariance between SST and  $\delta^{18}\text{O}_{\text{sw}}/\text{SSS}$ , SST and SSS destructively interfere in  $\delta^{18}\text{O}_{\text{coral}}$  and  $\delta^{18}\text{O}_{\text{coral}}$  variance is dampened relative to that of SST or SSS. For example, warmer SST coupled with higher  $\delta^{18}\text{O}_{\text{sw}}$  and salinity will reduce  $\delta^{18}\text{O}_{\text{coral}}$  variance in regions with a Mediterranean climate (i.e., dry summer, wet winter) (Russon et al., 2013), which reduces the signal-to-noise ratio and limits the ability to detect and analyze the paleoclimate signal.

## 2.2. Sensitivity Analyses (Datasets, Coefficients, and Timescales of Variability)

A series of sensitivity tests were conducted to assess the impact of parametric and observational uncertainties on predicted  $F_{\text{sw}}$  values and identify whether the inferred salinity signal varies across timescales (from interannual to multidecadal). First, multiple SST and SSS data sources were assessed, including HadISST v1.1 SST, OISST v2.0 SST, SODA v2.2.4 SST/SSS, Delcroix (tropical Pacific) SSS, IAP SSS, and ORAS v5 (ensemble members 0–4) SSS (Behringer & Xue, 2004; Carton & Giese, 2008; Cheng et al., 2020; Delcroix et al., 2011; Giese & Ray, 2011; Rayner et al., 2003; Reynolds et al., 2002; Zuo et al., 2019). Most of the SST and SSS data products are interpolated from observations to be globally complete whereas SODA and ORAS are reanalysis products that assimilate historical observations into a numerical model. HadISST v1.1 and SODA v2.2.4 are presented in Figure 2, selected for their high spatial resolution; however, we do not advocate here for any data set as superior to the others, rather, sensitivity tests with different data sets are included in Figure S2 in Supporting Information S1. All analyses were performed on April-March annual anomalies in MATLAB, with anomalies calculated relative to the long-term monthly mean (i.e., removing the seasonal cycle) over the 1950–2009 period prior to averaging over the tropical year. The only exception was the “seasonal to interannual” anomaly analysis, Figure S8 in Supporting Information S1, which was performed on anomalies calculated by removing the full timeseries mean from annual tropical averages.

We then assessed the impact of uncertainties in the  $\delta^{18}\text{O}_{\text{sw}}$ -SSS relationship in two key ways. First, we model  $\delta^{18}\text{O}_{\text{coral}}$  directly from  $\delta^{18}\text{O}_{\text{sw}}$ , rather than converting SSS data to  $\delta^{18}\text{O}_{\text{sw}}$  using a proportionality constant, thus bypassing this uncertainty in SSS-based estimates. Although no spatiotemporally complete  $\delta^{18}\text{O}_{\text{sw}}$  reanalysis product exists to date, the isotope-enabled Regional Ocean Modeling System (isoROMS; Stevenson et al., 2015, 2018) provides the closest approximation, with a nominal resolution of approximately 50 km spanning the Pacific basin. We also compare isoROMS results with those from  $\delta^{18}\text{O}_{\text{sw}}$  simulated by an isotope-enabled simulation of the Community Earth System Model (iCESM) (Nusbaumer et al., 2017; Zhang et al., 2017; Zhu et al., 2017). We note that these comparisons were performed over the 1965–2005 period, due to the presence of minor model drift in the early portion of the isoROMS simulation.

We then assessed the dependence of the predicted  $F_{\text{sw}}$  values on coefficient  $a_2$ . At each site, we randomly perturbed the  $a_2$  coefficient using 1,000 random draws of a Gaussian distribution of  $a_2$  coefficients, centered on the expected value taken from Legrande and Schmidt (2006). The 1 sigma uncertainty of the  $a_2$  coefficient was set to  $0.1\text{‰}/\text{PSU}$  based on the standard deviation of the  $\delta^{18}\text{O}_{\text{sw}}$ -SSS relationship across the limited network of

long-term seawater monitoring sites (Conroy et al., 2017). We next applied a more conservative  $a_2$  uncertainty of 0.2‰/PSU (Figure S4 in Supporting Information S1) and identified the impact of this parametric uncertainty on the inferred  $\delta^{18}\text{O}_{\text{coral}}$  trends for the late 20th century (Figure S5 in Supporting Information S1). We then tested spatially modified slopes based on the east-to-west differences in the  $\delta^{18}\text{O}_{\text{sw}}$ -SSS slope identified by Conroy et al. (2017) and compared the  $F_{\text{sw}}$  values with those obtained with the Pacific-wide slopes of LeGrande and Schmidt (2006) (Figure S6 in Supporting Information S1).

Finally, we tested the impact of timescales of SSS- $\delta^{18}\text{O}_{\text{sw}}$  variability on the  $F_{\text{sw}}$  estimates to assess the utility of  $\delta^{18}\text{O}_{\text{coral}}$  for reconstructing salinity variability across timescales. Each analysis was performed following the methods described above, but with four additional sensitivity tests (Figures S8-S12 in Supporting Information S1): (a) linear detrending, (b) removing the seasonal cycle prior to calculating the annual tropical average (“inter-annual”) versus removing the full time-series mean after calculating the annual tropical average (“seasonal to interannual”), and using the idealfilter function in MATLAB to isolate variability in (c) the ENSO band using a 2–7 years bandpass filter and in the (d) the decadal-multidecadal band using a 10–40 years bandpass filter.

### 2.3. Application to Coral $\delta^{18}\text{O}$ Records From the Iso2k Database

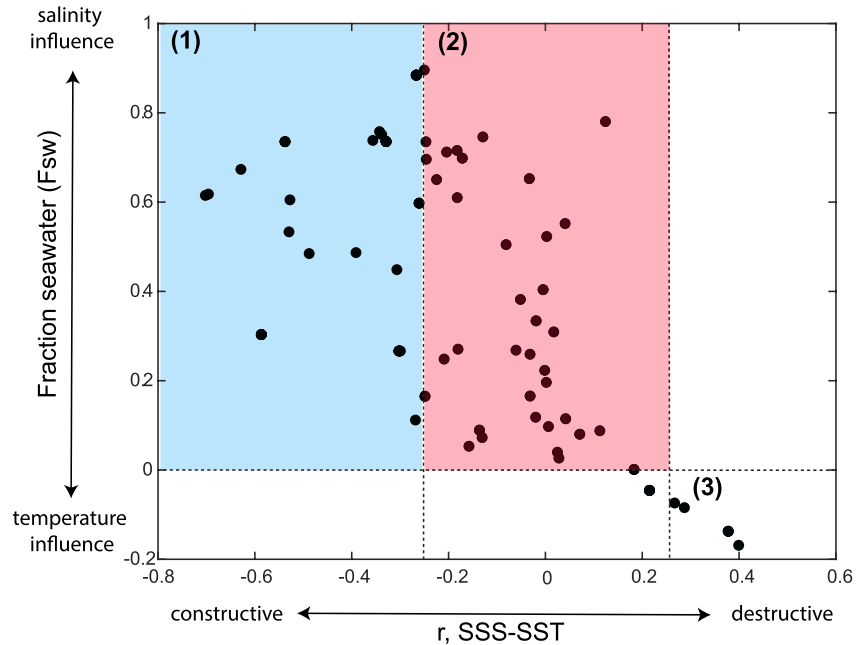
Coral  $\delta^{18}\text{O}$  records ( $N = 88$ ) that contain modern (>1950 CE) values were extracted from the Iso2k database v1.0.0 (Konecky and McKay, 2020; Konecky et al., 2020). This version of the Iso2k database contains coral  $\delta^{18}\text{O}$  records published before 4 May 2018. As with the observational and model analyses described above, all monthly  $\delta^{18}\text{O}_{\text{coral}}$  data were averaged into tropical (April-March) years before analysis (Table S1, Figure S1 in Supporting Information S1).

We first used the  $F_{\text{sw}}$  framework to identify sites expected to have a strong salinity signal in annual-averaged  $\delta^{18}\text{O}_{\text{coral}}$  that is undamped by SST variability. This approach allows us to identify targets for future paleosalinity reconstruction. Partial correlation coefficients between annual averages of SSS and Iso2k  $\delta^{18}\text{O}_{\text{coral}}$  from 1950 to 2009, after removing the influence of SST, were also assessed to reveal which actual records have a significant relationship with historical SSS. Finally, we calculated the slope of the temporal trend in  $\delta^{18}\text{O}_{\text{coral}}$  records from 1900 (or the beginning of the record, if later) to 2009 at sites where  $F_{\text{sw}} > 0.5$  and the coral record has a significant, positive partial correlation with SSS (“hydro-sensitive coral sites”). We exclude sites with <75 years of data during this time interval from the trend analysis.

## 3. Results

Pseudocoral  $F_{\text{sw}}$  values are positive in a majority (89%) of coral sites, and above 0.5 in 42% of the sites, reaching 0.89 in two western Pacific sites. A negative relationship between annual SSS and SST (Figures 1 and 2c) is observed at most sites, although the correlation is often statistically insignificant ( $p > 0.05$ ). Ten pseudocorals (6 sites) have an  $F_{\text{sw}}$  value  $\leq 0$  and a positive SSS-SST relationship. These observations are broadly consistent when using different SSS and SST products (Figures S2-S3 in Supporting Information S1), but with notable differences in the Indian Ocean. Although some differences are also observed in the southeast Pacific and south Atlantic, no coral records have been collected from these regions. The value of the  $a_2$  coefficient contributes strongly to the magnitude of the  $F_{\text{sw}}$  value, with lower  $a_2$  values producing lower  $F_{\text{sw}}$  values and vice versa (Figure 3, Figure S4 in Supporting Information S1). Despite its importance in determining the absolute magnitude of  $F_{\text{sw}}$  (Figure 3, S4, S6 in Supporting Information S1), the  $a_2$  coefficient contributes little uncertainty to the temporal trends of pseudocoral  $\delta^{18}\text{O}$  values (assuming that  $a_2$  is stable through time, Figure S7 in Supporting Information S1) or to the selection of hydro-sensitive sites (although fewer sites display high  $F_{\text{sw}}$  as  $a_2$  decreases; Figure 3). Geographically, many of the high  $F_{\text{sw}}$  values are found in the Indo-Pacific Warm Pool (IPWP, i.e., the western tropical Pacific and eastern Indian Ocean; Figure 2a).

Many modern  $\delta^{18}\text{O}_{\text{coral}}$  records from the Indo-Pacific Warm Pool also have a significant, positive relationship with SSS after removing the influence of SST ( $r_p$ , Figure 2d). Across all sites,  $F_{\text{sw}}$  and  $r_p$  display a significant positive correlation ( $r = 0.26$ ,  $N = 61$ ,  $p < 0.05$ ), and mean  $r_p$  is significantly higher at sites with  $F_{\text{sw}} > 0.5$  ( $t = 2.55$ ,  $df = 86$ ,  $p = 0.0126$ ; Figure S5 in Supporting Information S1). There is also a greater spread in  $r_p$  at sites where  $F_{\text{sw}} < 0.5$ , with the lower quartile extending into negative values (Figure S5 in Supporting Information S1). Considering the  $\delta^{18}\text{O}_{\text{coral}}$  temporal trends in the 21 records from hydro-sensitive coral sites, most (17/21)



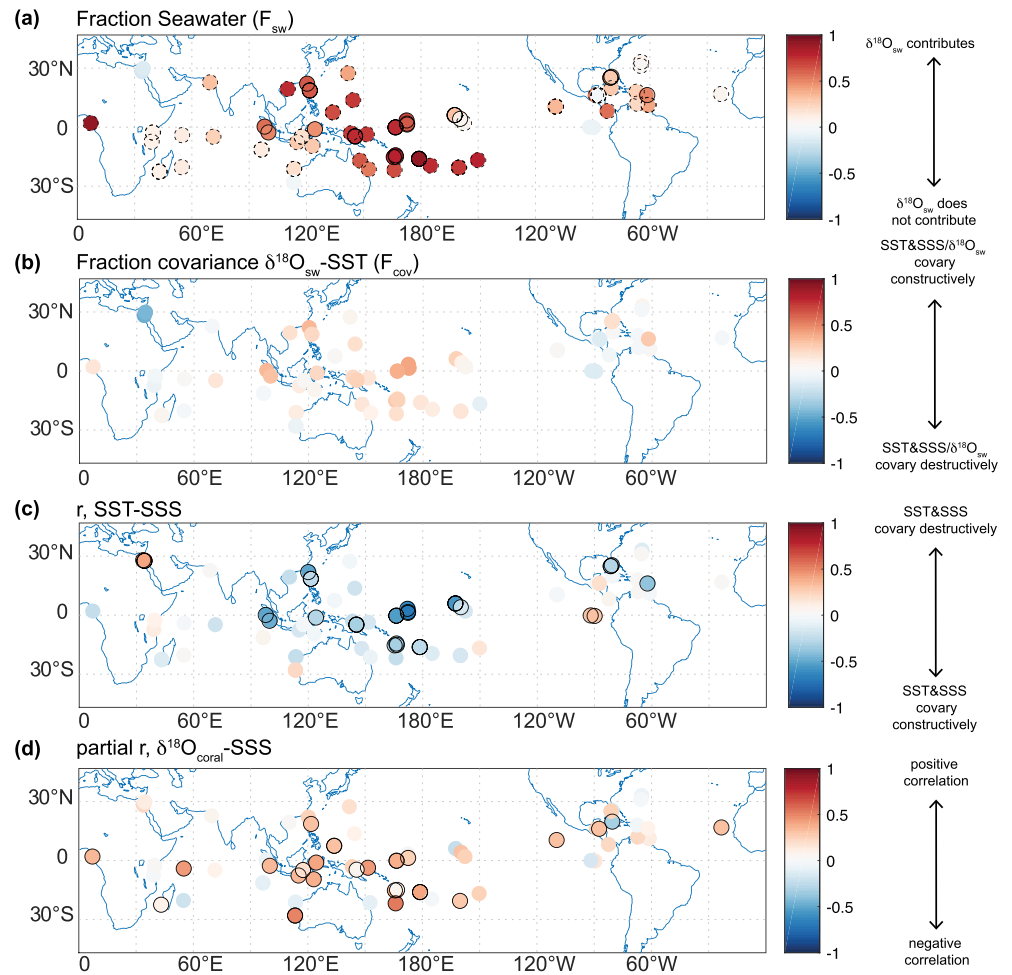
**Figure 1.** Scatterplot of correlation coefficients of HadISST v1.1 and SODA v2.2.4 sea surface salinity (SSS) annual anomalies versus pseudocoral  $F_{sw}$  values at grids approximating coral proxy locations, calculated over the 1950–2009 period. The area shaded blue (1) indicates sites where  $\delta^{18}O_{sw}$  contributes to  $\delta^{18}O_{coral}$  variance and there is a significant negative correlation between SSS and sea surface temperature (SST). The area shaded red (2) indicates sites where  $\delta^{18}O_{sw}$  contributes to  $\delta^{18}O_{coral}$  variance and there is no significant correlation between SSS and SST. In area (3),  $F_{sw}$  values are  $<0$  and  $\delta^{18}O_{sw}$ -SSS contributes destructively to  $\delta^{18}O_{coral}$ .

have a negative trend and are located in the IPWP (Figure 4). The length of these records commonly extends beyond the limits of the reliable, instrumental SSS record (i.e.,  $>50$  years).

$F_{sw}$  displays similar spatial patterns across seasonal and interannual timescales (Figure S8 in Supporting Information S1), and among historical data products (Figure S2 in Supporting Information S1) and isotope-enabled simulations (Figure S9 in Supporting Information S1). Interannual  $\delta^{18}O_{sw}$  variability contributes strongly to high  $F_{sw}$  values in the South Pacific Convergence Zone (SPCZ) region (Figure S8b in Supporting Information S1), whereas strong negative correlations between SST and  $\delta^{18}O_{sw}$  contribute to the high  $F_{sw}$  values in the central-western equatorial Pacific on seasonal timescales (Figure S8f in Supporting Information S1, and to a lesser extent, on interannual timescales (Figure S10f in Supporting Information S1).  $F_{sw}$  in the 2–7 years ENSO band and 10–40 years band shows no major differences to those calculated from unfiltered data in Figure 2 (Figures S10–S11 in Supporting Information S1). ENSO-related  $\delta^{18}O_{sw}$  variability and SST- $\delta^{18}O_{sw}$  covariance contribute to  $F_{sw}$  in the central-western equatorial Pacific, whereas decadal-multidecadal  $\delta^{18}O_{sw}$  variability and SST- $\delta^{18}O_{sw}$  covariance contribute to  $F_{sw}$  in the ITCZ region (and to a lesser extent the SPCZ, Figure S10 in Supporting Information S1). Finally,  $F_{sw}$  values are greater when the long-term trend is removed, particularly in the subtropics (Figure S12 in Supporting Information S1). As these analyses of temporal variability in  $F_{sw}$  used the same regional  $a_2$  coefficients, the observed differences in  $F_{sw}$  arise from differences in SSS/ $\delta^{18}O_{sw}$  and SST variability and their covariance.

#### 4. Discussion

Substantial information on  $\delta^{18}O_{sw}$  and SSS is likely recorded in modern and fossil coral  $\delta^{18}O$  values in the locations where  $F_{sw} > 0.5$ . High  $F_{sw}$  values ( $F_{sw} > 0.5$ ) are found across the tropics, but many of the sites with especially high  $F_{sw}$  values ( $F_{sw} > 0.6$ – $0.7$ ) are found in the western tropical Pacific and eastern Indian Ocean, in a broad region stretching from the SPCZ, across the Maritime Continent, and northward into the South China and the Philippine Seas. Across this same region, many coral  $\delta^{18}O$  records also have a positive, significant correlation

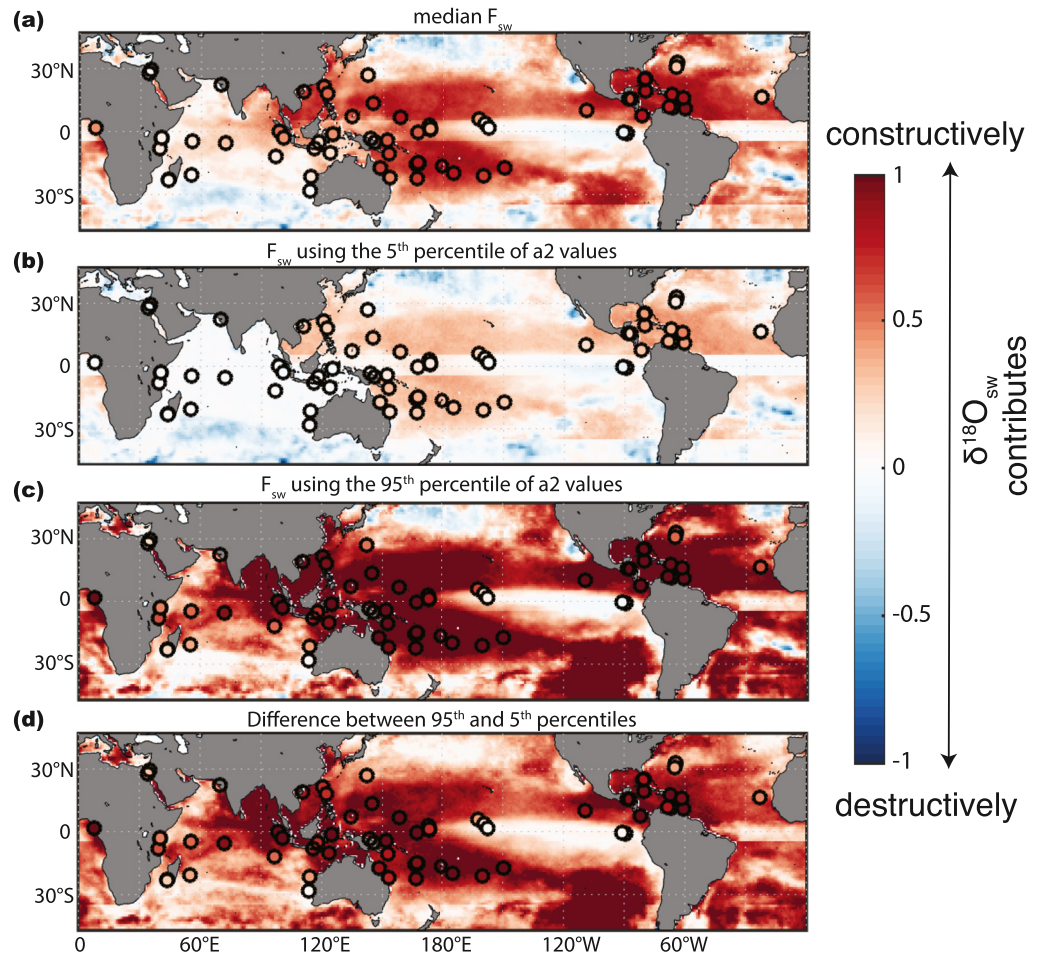


**Figure 2.** (a) Fraction seawater ( $F_{sw}$ ) in pseudocorals at coral proxy sites, calculated from HadISST v1.1 and SODA v2.2.4 sea surface salinity (SSS) as in Figure 1. Higher values indicate a greater fraction of pseudocoral  $\delta^{18}O$  variance is controlled by  $\delta^{18}O_{sw}$ . Sites with  $F_{sw} > 0$  and a significant SSS-sea surface temperature (SST) correlation are outlined in black solid lines (blue shaded region in Figure 1). Sites with  $F_{sw} > 0$  and an insignificant SSS-SST correlation are outlined in dashed lines (red shaded region in Figure 1). (b) Fraction of annual coral  $\delta^{18}O$  variance due to  $\delta^{18}O_{sw}$ -SST covariance at each coral site, calculated over the 1950–2009 period. (c) Correlation coefficient between SSS and SST, calculated over the 1950–2009 period. Correlations with  $p < 0.05$  are outlined in black. (d) Partial  $r_p$ , the  $\delta^{18}O_{coral}$ -SSS correlation between annual  $\delta^{18}O$  in real corals from the Iso2k database (sites where annual  $N > 10$ ) and SODAv2.2.4 SSS 1950–2009, after removing the influence of HadISST v1.1. Correlations with  $p < 0.05$  are outlined in black.

with SSS from 1950 to 2009 after removing the influence of SST. Thus, this region is a compelling target for paleosalinity reconstructions.

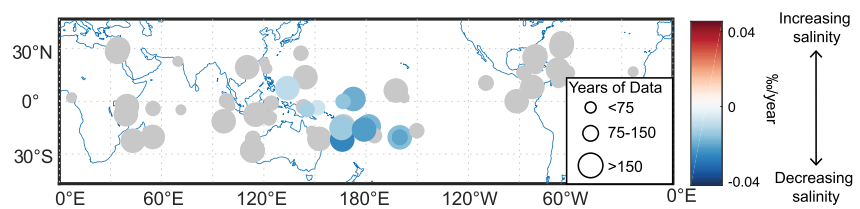
In some sites, however, the contribution of SSS or  $\delta^{18}O_{sw}$  is notably different in pseudocorals (Figure 2a) and actual corals (Figure 2d), which may arise from differences between local and large-scale marine conditions, errors in the historical salinity data, and/or non-climatic noise in the  $\delta^{18}O_{coral}$  data. We therefore caution that the identification of hydro-sensitive coral sites using a pseudocoral approach is only as robust as the observed or simulated data and the PSM used to predict the  $\delta^{18}O_{coral}$  response. Nevertheless, the agreement in hydro-sensitive sites among input datasets and the significant SSS signal in observed  $\delta^{18}O_{coral}$  data at most sites supports the general utility of our approach.

The lack of a strong or significant correlation between annual average SSS and SST at many of these sites implies that stationary SSS-SST covariance should not be assumed for interannual and longer timescales (i.e., lower  $\delta^{18}O_{coral}$  anomalies may not necessarily always imply both warmer and fresher conditions, and vice versa). SST- $\delta^{18}O_{sw}$  correlations on interannual timescales are only weakly negative across much of the tropical



**Figure 3.** Impact of  $a_2$  uncertainty on  $F_{sw}$ : (a) median  $F_{sw}$ , (b) 5th percentile, (c) 95th percentile, (d) the confidence interval (CI, difference between the 5% and 95%), calculated from 1,000 random draws of a Gaussian distribution of  $a_2$  values, with the mean value from LeGrande and Schmidt (2006) and standard deviation of 0.1. Pseudocoral  $F_{sw}$  estimates were calculated from HadISST v1.1 and SODA v2.2.4 sea surface salinity, as in Figure 1. Coral sites are outlined in black.

Indo-Pacific Ocean (Figure S8d in Supporting Information S1), whereas a strongly negative SST- $\delta^{18}O_{sw}$  relationship plays an important role in  $\delta^{18}O_{coral}$  variability in the central-western Pacific on seasonal to interannual timescales (Figures S8f, S10f in Supporting Information S1). Nevertheless, very few sites display destructive interference between SSS and SST in the form of a positive, significant correlation coefficient that confounds  $\delta^{18}O_{coral}$  variability. We do note that this analysis is confined to recent decades; the SST-SSS relationship may vary greatly on millennial timescales with large geographical shifts in the location of convergence zones (LeGrande & Schmidt, 2011) leading to changes in coral response to ENSO across the Holocene (Carré et al., 2021). For



**Figure 4.** Slope of Iso2k  $\delta^{18}O_{coral}$  z-score per year, over the 1900–2009 period for sites with  $F_{sw} > 0.5$ , a  $\delta^{18}O_{coral}$ -sea surface salinity partial correlation coefficient with  $p < 0.1$ , and at least 75 years of annual  $\delta^{18}O_{coral}$  values from 1900 to 2009. Sites that do not meet these criteria are shaded gray. Marker size denotes the length of the Iso2k coral record. Negative  $\delta^{18}O_{coral}$  trends (blue) imply local freshening, whereas positive  $\delta^{18}O_{coral}$  trends (red) suggest local salinification.



example, Corrège et al. (2004) report seasonal salinity minima occurring in winter during the Younger Dryas in New Caledonia instead of summer as it does today. Further, the approach described here assumes linear relationships and covariance among variables, assumptions that may break down at some sites (e.g., where extreme precipitation drives a non-linear relationship between SST and SSS). Nevertheless, our results demonstrate the important contribution of  $\delta^{18}\text{O}_{\text{sw}}$  variability to  $\delta^{18}\text{O}_{\text{coral}}$  records from many sites—variability which may covary with local temperature in complex (non-linear, non-stationary, or destructive) ways; therefore  $\delta^{18}\text{O}_{\text{sw}}$  variability cannot be ignored in  $\delta^{18}\text{O}_{\text{coral}}$ -based temperature or salinity reconstructions.

The  $F_{\text{sw}}$  values do not vary appreciably on interannual to multidecadal timescales relative to the entire 1950–2009 period. Importantly, sites with high  $F_{\text{sw}}$  values maintain high  $F_{\text{sw}}$  values in different frequency bandwidths, indicating that hydro-sensitive coral sites should preserve salinity information across timescales. Detrended and raw  $F_{\text{sw}}$  values are also broadly similar, though slightly higher  $F_{\text{sw}}$  values are obtained with detrended time series in some regions, particularly the subtropical Pacific and throughout the Indian Ocean. Nevertheless, the difference is small, and our results suggest that on the interannual to multidecadal timescales, SSS information in  $\delta^{18}\text{O}_{\text{coral}}$  values should remain consistent in sites where  $F_{\text{sw}}$  is high.

The regions where a large portion of coral  $\delta^{18}\text{O}$  variance is driven by  $\delta^{18}\text{O}_{\text{sw}}$  are areas of convergence and intense convection, resulting in high rates of regional precipitation. As a result, SSS and  $\delta^{18}\text{O}_{\text{sw}}$  values are notably lower in these areas (LeGrande & Schmidt, 2006). Local  $a_2$  coefficients are also relatively high (0.3–0.4‰/PSU), compared to the tropical Pacific mean of 0.27‰/PSU and eastern tropical Pacific value  $\sim 0.1$ ‰/PSU (Benway & Mix, 2004; Conroy et al., 2017). High  $a_2$  coefficients in the western tropical Pacific are hypothesized to be a result of the lower  $\delta^{18}\text{O}$  value of precipitation, a result of the isotope ‘‘amount effect,’’ a complex phenomenon that is the result of moisture recycling and rain re-evaporation in storms, among other processes (Conroy et al., 2016; Dansgaard, 1964; Risi et al., 2008).

The coefficient  $a_2$  plays a key role in setting  $F_{\text{sw}}$ , and higher  $a_2$  coefficients likely amplify the inferred  $\delta^{18}\text{O}_{\text{sw}}$ –SSS signal in  $\delta^{18}\text{O}_{\text{coral}}$  values in the western tropical Pacific. Future work should prioritize seawater  $\delta^{18}\text{O}_{\text{sw}}$ –SSS monitoring to better constrain the  $a_2$  coefficient and thus the inferred hydroclimate signal within these  $\delta^{18}\text{O}_{\text{coral}}$  records. Monitoring efforts should include long time series from key reef sites to assess the space-for-time assumption often made in paleoclimate studies (i.e., that the spatial relationship across sites is representative of the relationship through time at individual sites). Such data could be obtained by installing networks of OsmoSamplers, which do not require power and can be deployed for up to a year collecting water samples on daily to monthly time intervals (Jannasch et al., 2004; Khare et al., 2021), or by making continuous shipboard measurements with spectroscopic water isotope analyzers fed seawater from the intake line (Munksgaard et al., 2012). In each case, precise SSS measurements must also be obtained. Furthermore, there is a critical need for an updated, actively maintained, and community-based seawater isotope database where laboratories can upload  $\delta^{18}\text{O}_{\text{sw}}$  data.

Circumventing this uncertainty by modeling  $\delta^{18}\text{O}_{\text{coral}}$  directly from  $\delta^{18}\text{O}_{\text{sw}}$  simulated from isoROMS and iCESM, we demonstrate that the spatial pattern of  $F_{\text{sw}}$  is consistent with that of observational and reanalysis-based estimates, emphasizing the utility of this approach in identifying hydro-sensitive coral sites. Nevertheless, we find that the values are notably weaker in iCESM due to weak  $\delta^{18}\text{O}_{\text{sw}}$  variability and  $F_{\text{cov}}$  (Figure S13 in Supporting Information S1). These results imply that iCESM underestimates  $\delta^{18}\text{O}_{\text{sw}}$  variability and its covariance with SST, or that the uncertainty in  $a_2$  causes an overestimation of  $F_{\text{sw}}$  when calculated from observational SSS. The strong correspondence between isoROMS and observational estimates suggests that these differences are likely attributable to biases in iCESM, particularly in the WPWP where iCESM shows negative  $F_{\text{cov}}$  values (i.e., a positive SST–SSS/ $\delta^{18}\text{O}_{\text{sw}}$  relationship). Nonetheless, these modeling approaches are necessary in order to fully quantify the complex relationships between SST and  $\delta^{18}\text{O}_{\text{sw}}$  noted above, and eventually to understand the dynamics responsible for their variation.

This work highlights sites where  $\delta^{18}\text{O}_{\text{coral}}$  values can provide critical insights into SSS, and thus tropical hydroclimate variability and change. It also emphasizes the importance of site selection and screening methods to identify hydro-sensitive sites where the signal is not dampened by SST variability. Many hydro-sensitive coral records identified have long records that predate the beginning of reliable SSS data (Figure 4), and thus can provide much needed context on the anomalous nature of late-20th century SSS trends. Indeed, all 1900–2009 trends in the hydro-sensitive IPWP records are negative, and thus a sizable portion of these trends is likely reflecting ocean

freshening, rather than warming alone. These results are consistent with historical data (e.g., Durack et al., 2012), and suggest an intensification of the hydrological cycle and/or the Pacific Walker circulation.

At such sites where  $\delta^{18}\text{O}_{\text{sw}}$  contributes a significant portion of the  $\delta^{18}\text{O}_{\text{coral}}$  variability (e.g.,  $F_{\text{sw}} > 0.2$ ), independent Sr/Ca-SST estimates are necessary for reconstructing temperature, as SSS may constructively or destructively contribute to the inferred  $\delta^{18}\text{O}_{\text{coral}}$ -SST values in these locations. Although constructive SST-SSS covariance may be leveraged to assess changes in climate variability (e.g., associated with ENSO or IOD) to natural and anthropogenic forcing, the spatially varying importance of  $\delta^{18}\text{O}_{\text{sw}}$  (i.e.,  $F_{\text{sw}}$ ) and its covariance with SST (i.e.,  $F_{\text{cov}}$ ) complicate the interpretation of variance estimates among sites (e.g., among atolls in the Line Islands, see Grothe et al., 2020).

The  $\delta^{18}\text{O}_{\text{coral}}$  records from the hydro-sensitive coral sites identified here hold tremendous potential for SSS reconstruction. In sites where  $F_{\text{sw}}$  is high ( $>0.7$ – $0.8$ ),  $\delta^{18}\text{O}_{\text{coral}}$  variations can be confidently attributed to  $\delta^{18}\text{O}_{\text{sw}}$  and used as evidence of salinity change. Future data synthesis and sample collection efforts should prioritize these regions for robust hydroclimate reconstructions. In sites where  $F_{\text{sw}}$  is positive but not as high,  $\delta^{18}\text{O}_{\text{sw}}$  and SST both contribute to the coral record and cannot be simply separated. The framework presented here therefore provides a means to quantify the relative influence of temperature and salinity on  $\delta^{18}\text{O}_{\text{coral}}$  values, improving both temperature and salinity reconstructions from these critical high-resolution climate archives.

## Data Availability Statement

There was no new data generated in this study. Coral data can be accessed through the Iso2k database at: <https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/noaa-recon-29593/html>. Coral metadata (both previously published and calculated in this study) can be found in Table S1 in Supporting Information S1 and on the NCEI paleoclimate database (<https://www.ncei.noaa.gov/access/paleo-search/study/36273>); the code is available at 10.5281/zenodo.6450406.

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