# Coral-model comparison highlighting the role of salinity in long-term trends

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**We use a simple proxy model to compare climate model simulations and coral records over the 20th century. While models and observations agree that the tropical oceans have warmed, they disagree on the extent and origin of freshening.**

The response of the tropical Pacific Ocean to anthropogenic climate change remains uncertain, in part because we do not fully understand how the region has responded to anthropogenic change over the 20th century. Analysis of 20th century temperature and salinity trends is hindered by limited historical data, lack of long-term in situ measurements, and disagreement among coupled general circulation model (CGCM) hindcasts. High-resolution paleoclimate records, particularly the large network of tropical Pacific coral oxygen isotope records, are an alternate means of assessing tropical climate trends. However, these natural archives of past climate are biased by their limited spatial and temporal distribution and their biologically mediated response to climate. By converting native climate variables (e.g. temperature and net freshwater flux) into synthetic ("pseudo") proxy records via an explicit proxy system model ("forward model"), we can directly compare historical climate data and climate model simulations with coral records, and assess biases and uncertainties associated with each.

## Pseudocoral modeling

The stable oxygen isotope ratio ($\delta^{18}O$) of coral aragonite is a function of the temperature and the oxygen isotopic ratio of seawater ($\delta^{18}O_{sw}$) at the time of growth; the latter is in turn strongly related to sea-surface salinity (SSS). As direct measurements of $\delta^{18}O_{sw}$ are scarce, we model the expected $\delta^{18}O$ anomalies of corals ($\delta^{18}O_{pseudocoral}$) as a function of sea-surface temperature (SST) and salinity anomalies:

$$\Delta\delta^{18}\mathrm{O}_{\mathrm{pseudocoral}} = a_1\Delta\mathrm{SST} + a_2\Delta\mathrm{SSS}$$

We define coefficient $a_1$ as -0.22 ‰ °C$^{-1}$ based on the relationship between temperature and the isotopic composition of the skeleton in well-studied coral genera (e.g. Evans et al. 2000). Coefficient $a_2$ is estimated from basin-scale regression analysis of available observations of $\delta^{18}O_{sw}$ on SSS (LeGrande and Schmidt 2006; LeGrande and Schmidt 2011). Uncertainty in the application of the resulting bivariate model arises from the assumed independence and linearization of $a_1$ and $a_2$ and substitution of the second term for a direct dependence on $\delta^{18}O_{sw}$.

We apply this simple forward model of $\delta^{18}O_{pseudocoral}$ to generate synthetic coral (pseudocoral) records from historical observations and CGCM simulations of temperature and salinity (Thompson et al. 2011). When driven with historical climate data, we found that this simple model was able to capture the spatial and temporal pattern of ENSO and the linear trend observed in corals from 1958 to 1990. Modeling pseudocorals with temperature and salinity individually also demonstrated that although warming accounts for the majority of the observed $\delta^{18}O_{coral}$ trend (60% of trend variance), salinity also plays an important role (40% of trend variance). The addition of the SSS term improved agreement between modeled pseudocoral and observed coral $\delta^{18}O$ trends over pseudocoral trends modeled from SST only (Thompson et al. 2011).

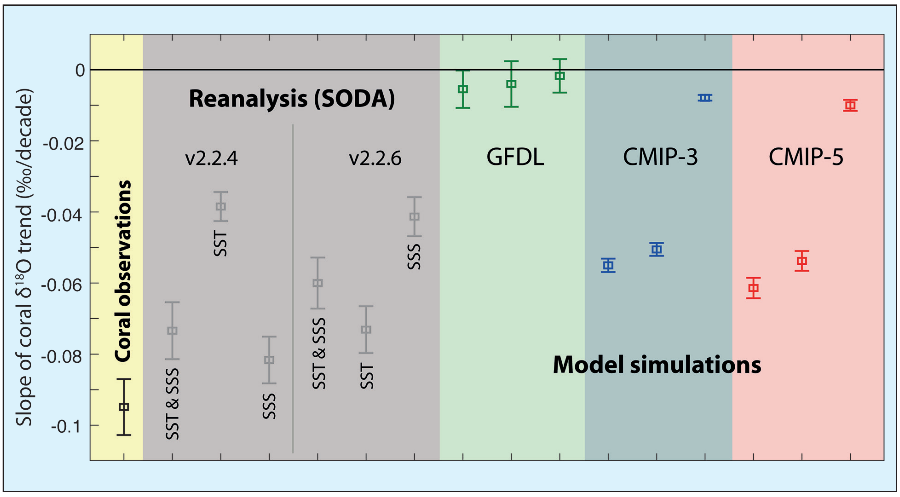


*Figure 1: Magnitude of the trend slope (‰ per decade), computed by linear regression through the trend principal component (PC) in corals (far left) and pseudocorals modeled from Simple Ocean Data Assimilation (SODA) 20th century reanalysis (Carton and Giese 2008; Compo et al. 2011), a 500-year control run from the CGCM version CM2.1 of the Geophysical Fluid Dynamics Laboratory (GFDL cm2.1) (Wittenberg et al. 2009), and all CMIP-3 and CMIP-5 model ensembles (average of all models from each modeling group). In each case, $\delta^{18}O_{coral}$ was modeled from SST and SSS (1), SST only (2), and SSS only (3). Error bars depict ± 1 standard deviation of the regression estimate.*

## 20th century trends

When driven with the output from 20th century simulations of a subset of CGCMs from the third phase of the Coupled Model Intercomparison Project (CMIP3) sampled at the coral locations, none of the pseudocoral networks reproduced the magnitude of the secular trend, the change in mean state, or the change in ENSO-related variance observed in the actual coral network from 1890 to 1990 (Thompson et al. 2011). Applying this same approach to the newer (CMIP5) suite of historical climate simulations, we find that large discrepancies still remain in the magnitude (Fig. 1), spatial pattern and ENSO-related variance of the simulated and observed trends. Differences between observed and simulated $\delta^{18}O_{coral}$ trends may stem from the simplicity of our forward model of $\delta^{18}O_{coral}$, biological bias in the coral records, or model-inherent bias in the CGCM SST and SSS fields.

Although we cannot yet completely rule out a non-climatic origin for the amplitude of the observed $\delta^{18}O_{coral}$ trend, previous work highlights biases in simulated salinity fields as a potential source of the observed-simulated trend discrepancy (Thompson et al. 2011). We found that the suite of CMIP3 and CMIP5 CGCMs simulate weak and heterogeneous salinity trends that are indistinguishable in magnitude from that of unforced control runs (Fig. 1). Further, the pseudocoral simulations (Fig. 1) illustrate that the magnitude of the simulated $\delta^{18}O_{coral}$ trend can be less than the sum of

| Region | Observed slope | Monthly ModelE2 | Annual ModelE2 | Decadal ModelE2 | ModelE2 at observations |
|---|---|---|---|---|---|
| Tropical Pacific | 0.27 | 0.35 | 0.35 | 0.36 | 0.32 |
| South Pacific | 0.45 | 0.33 | 0.33 | 0.37 | 0.30 |
| Indian Ocean | 0.16 | 0.33 | 0.35 | 0.35 | 0.27 |

*Table 1: Slope of the regional $\delta^{18}O_{sw}$-SSS relationship calculated from observations (LeGrande and Schmidt 2006) and the GISS ModelE2 control simulation. Annual and decadal series were calculated by averaging the monthly data at yearly and 10-year intervals.*

the individual trends arising from temperature and salinity when the temperature and salinity trends are confounding at the coral sites (as observed for SODA modeled pseudocorals). However, given the limited number of historical SSS observations, much uncertainty remains in the sign and magnitude of the 20th century salinity trend. When forward-modeling pseudocorals with data from two recent versions of an extended reanalysis (SODA v2.2.4 and v2.2.6; Ray and Giese 2012), we found that even the relative contribution of temperature and salinity to the observed pseudocoral trend differs (Fig.1); this discrepancy likely arises from the choice of wind field used in the reanalyses (G. Compo, personal communication). These results suggest a need for improved simulation of moisture transport and additional proxy reconstructions of salinity and $\delta^{18}O_{sw}$ to better understand their relationship and the sign and magnitude of their change.

## $\delta^{18}O_{sw}$ vs SSS: insights from isotope enabled simulations

In substituting the $\delta^{18}O_{sw}$-SSS relationship calculated from the limited observational dataset for $\delta^{18}O_{sw}$, our simple forward model assumes that this relationship is not only a valid approximation for $\delta^{18}O_{sw}$, but also that this relationship does not vary significantly through time or within regions. Although this assumption does not likely hold at the millennial timescale (e.g. LeGrande and Schmidt 2011), it may be appropriate for simulating tropical variability during the past century. Here we assess the stability of the $\delta^{18}O_{sw}$-SSS relationship through space and time on monthly to decadal timescales using a control simulation of an isotope-enabled version of the Goddard Institute for Space Studies model (GISS ModelE2, provided by A. LeGrande). In these simulations, the relationship between $\delta^{18}O_{sw}$ and SSS was generally regionally consistent over monthly to decadal timescales (Table 1), suggesting that the substitution of SSS for $\delta^{18}O_{sw}$ is unlikely to impose low-frequency variability on the modeled pseudocorals. However, we find that the slope of the $\delta^{18}O_{sw}$-SSS relationship and its sensitivity to timescale varies within the broad regions of Table 1, particularly between the eastern and western Pacific (Fig. 2). Similar regional variability in the slope of the $\delta^{18}O_{sw}$-SSS relationship was observed in an isotope enabled version of the UK Met Office model (HadCM3; Russon et al. 2013). Additionally, the slopes of the $\delta^{18}O_{sw}$-SSS relationship simulated for the tropical regions in the GISS model were generally higher and more spatially consistent than those calculated from the limited observations (LeGrande and Schmidt 2006; Table 1). If we analyze only model output corresponding to the location and time of observations, the data-model discrepancy is reduced but not eliminated (Table 1). These discrepancies likely arise from the scarcity of paired $\delta^{18}O_{sw}$ and SSS observations as well as from the modeling of precipitation processes, and will be reduced by a combination of continued seawater sampling and model development.

If the current observational dataset underestimates the true magnitude of the $\delta^{18}O_{sw}$-SSS slope, our simple forward model will underestimate the magnitude of the true $\delta^{18}O_{coral}$ trend when a significant freshening is observed. Estimates of uncertainty in the $\delta^{18}O_{sw}$-SSS slope should be incorporated in future work simulating pseudocoral trends. Nonetheless, the salinity trend in CMIP3 and CMIP5 models is weak, and near zero, suggesting that the uncertainty in the $\delta^{18}O_{sw}$-SSS relationship is not likely the source of the difference in the coral and pseudocoral trend magnitude. The presence of a significant freshening in historical observations suggests that this discrepancy is more likely due to an underestimation of the 20th century freshening in the CGCMs.

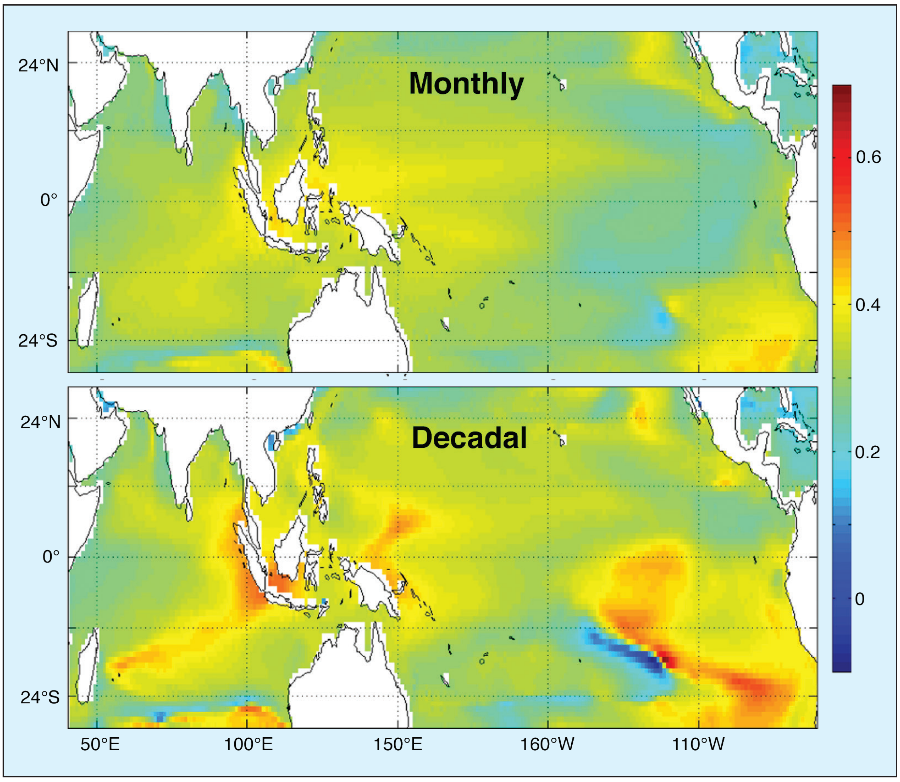


*Figure 2: Slope of the GISS ModelE2 simulated $\delta^{18}O_{sw}$ vs. salinity relationship at each gridbox on monthly **(top)** and decadal **(bottom)** timescales. Decadal series were calculated by averaging the monthly data at 10-year intervals.*

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http://www.pages-igbp.org/products/newsletters/ref2013_2.pdf

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