The response of pseudo-corals to ENSO in an isotope-enabled climate model

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Coral stable isotope records provide information on past ENSO variability. However, separating the contributions from variability in ocean temperature and the hydrological cycle to such records remains challenging. Model simulations using water isotope-enabled climate models provide powerful tools to explore this.

The stable oxygen isotopic composition of the aragonite of reef-dwelling corals ($\delta^{18}O_{coral}$) relates to both the temperature, taken here as being the sea surface temperature (SST), and the isotopic composition of the seawater ($\delta^{18}O_{sw}$) in which calcification occurred. The relationship between $\delta^{18}O_{coral}$ and SST, derived from modern calibrations, generally has a slope that is close to the value of -0.2‰ K^{-1} found for inorganically precipitated carbonates (e.g. Gagan et al. 2000; Zhou and Zheng 2003). Some long-lived corals generate sufficiently high growth rates as to allow measurement of $\delta^{18}O_{coral}$ at sub-annual resolution over multiple decades (e.g. Carré et al., this issue). These properties provide a strong basis for using fossil corals $\delta^{18}O_{coral}$ to reconstruct SST variability associated with the El-Niño Southern Oscillation (ENSO) over the Holocene and LGM (e.g. Tudhope et al. 2001; Cobb et al. 2003).

However, $\delta^{18}O_{coral}$ also depends directly on $\delta^{18}O_{sw}$, which is in turn influenced by a range of factors. Some of these factors may be closely coupled to ENSO, such as the local precipitation-evaporation balance, but others relate instead to the integrated hydrological history of the precipitation. In regions with a very active hydrological cycle, where the $\delta^{18}O_{sw}$ contribution is thought to dominate the overall $\delta^{18}O_{coral}$ signal, records have been used to infer past changes in precipitation, rather than SST (Cole and Fairbanks 1990). Fully quantifying the spatial pattern of relative contributions from SST and $\delta^{18}O_{sw}$ to $\delta^{18}O_{coral}$ remains a challenge for interpreting these records.

Limitations of the instrumental record

Instrumental records of $\delta^{18}O_{sw}$ are not available for most coral bearing locations and those that do exist are typically too short to allow robust quantification of inter-annual changes in $\delta^{18}O_{sw}$ (Schmidt 1999; LeGrande and Schmidt 2006). However, the $\delta^{18}O_{sw}$ contribution can be estimated empirically from an instrumental SST record, provided that (1) the ENSO-related $\delta^{18}O_{sw}$ fluctuations relate linearly to those in SST and (2) this relationship remains stationary throughout the period of interest. An example of a case in which the first assumption may be compromised is if the source region for precipitation changes with the magnitude of ENSO events. The second assumption may be compromised if the dominant spatial "modes" of ENSO variability change through time (Yeh et al. 2009; Capotondi et al., this issue). Climate model realizations of the response of $\delta^{18}O_{sw}$ to ENSO fluctuations have the potential to better constrain the validity of such assumptions.

Representing pseudo-corals in an isotope-enabled climate model

Only a few coupled Ocean/Atmosphere General Circulation Models (GCMs) include the additional hydrological cycle processes required to directly simulate water isotope variables such as $\delta^{18}O_{sw}$. Modeling pseudo-coral records based on the use of $\delta^{18}O_{sw}$ proxy variables such as salinity, provide a strategy to avoid this limitation (Thompson et al. 2011, this

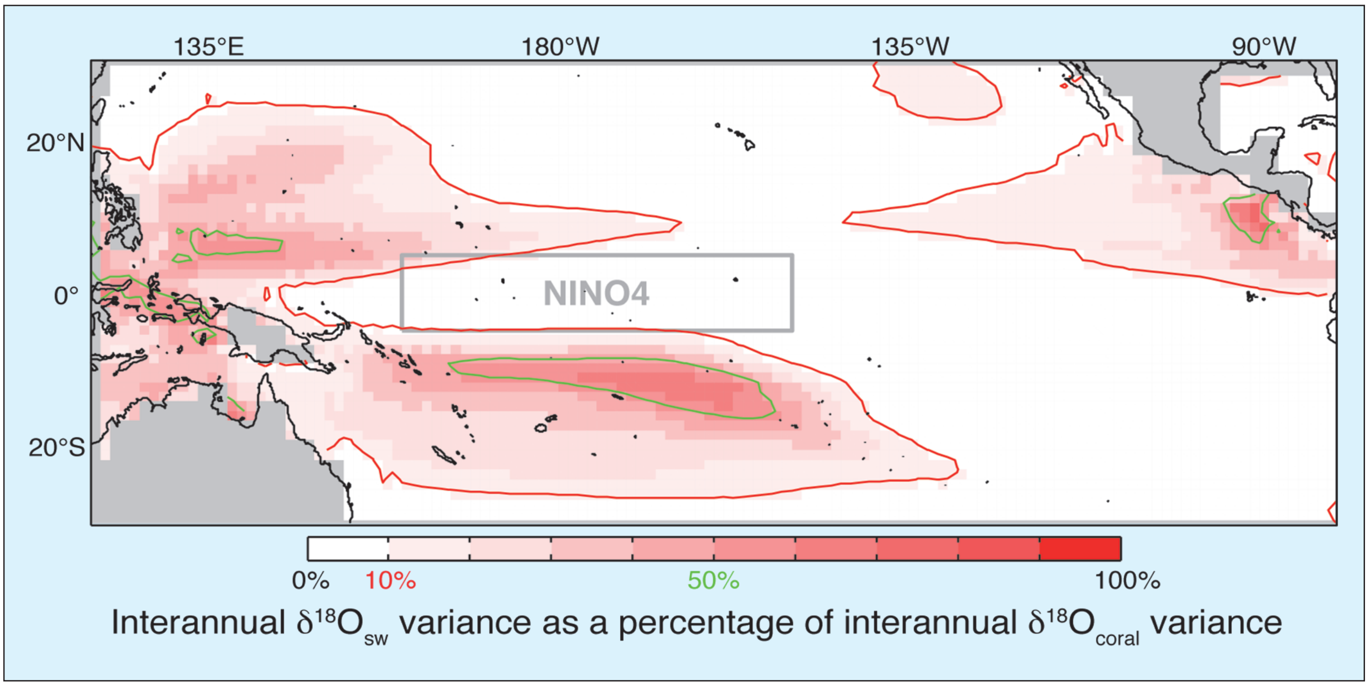

Figure 1: The percentage of modeled interannual $\delta^{18}O_{coral}$ variance accounted for by $\delta^{18}O_{sw}$, assuming a SST - $\delta^{18}O_{coral}$ slope of -0.2‰ K^{-1}. The 10% and 50% levels are contoured in red and green respectively and the location of the NINO4 region is highlighted in gray.

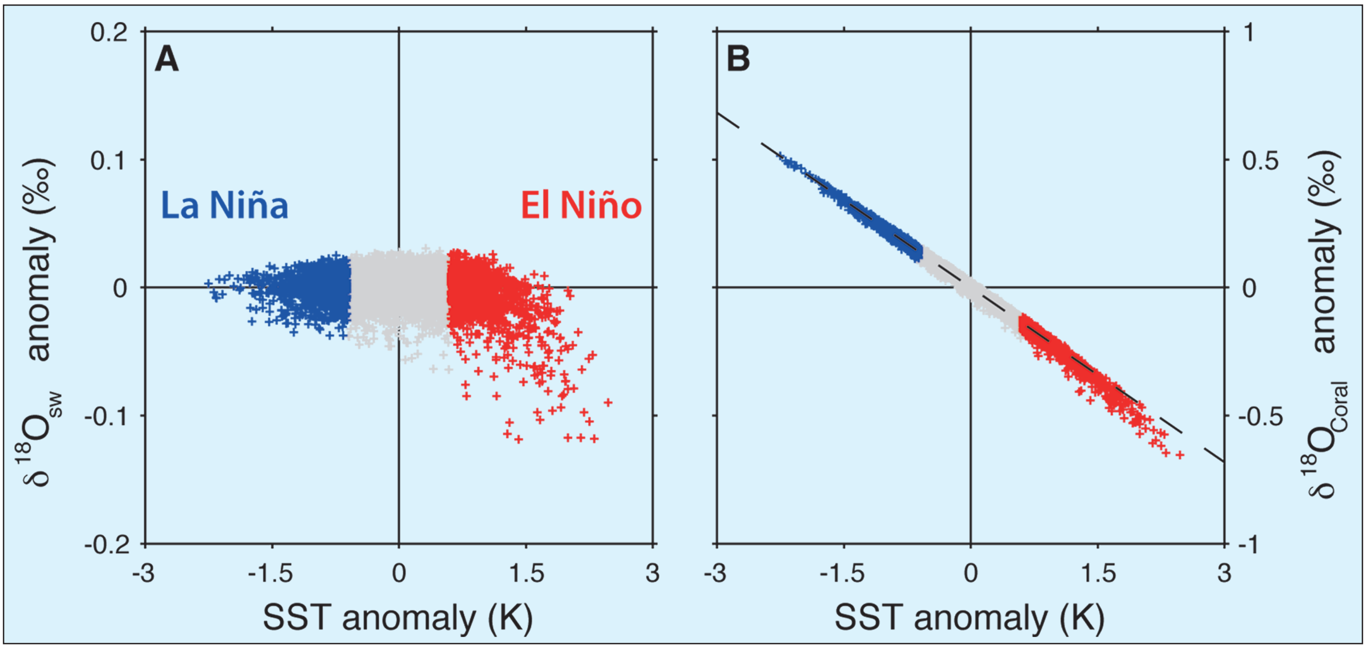

Figure 2: Scatter plots of modeled monthly inter-annual anomaly data within the NINO4 box. ***A)*** *$\delta^{18}O_{sw}$ plotted against SST.* ***B)*** *$\delta^{18}O_{coral}$ plotted against SST, with the assumed slope of -0.2‰ K^{-1} used to calculate $\delta^{18}O_{coral}$ shown as a dashed line. Points are color coded according to their SST anomaly values, such that those lying in the upper and lower standard deviations of the SST data are highlighted red and blue, and are associated with El-Niño and La-Niña events respectively.*

issue). However, work with the isotope-enabled Goddard Institute for Space Studies ModelE-R shows that the slopes of the $\delta^{18}O_{sw}$-salinity relationships may differ when calculated over temporal and spatial patterns of variability (LeGrande and Schmidt 2009). The results presented here are based on a 750-year long pre-industrial control simulation of another isotope-enabled coupled GCM, the UK Met Office's HadCM3 (Russon et al. 2013; Tindall et al. 2009). The inter-annual variability of the tropical climate in HadCM3 is known to be dominated by processes exhibiting spatial and temporal patterns resembling, albeit with significant biases, those of the observed ENSO phenomenon (Collins et al. 2001; Guilyardi et al. 2006). For this study, the water isotope regimes were brought to equilibrium by first running the model for an additional 300 years from an assumed initialization state. The pseudo-coral $\delta^{18}O_{coral}$ field is then calculated directly by inputting the monthly-mean SST and $\delta^{18}O_{sw}$ data for the ocean grid resolution of 1.25° by 1.25° over the tropical Pacific (30°S-30°N and 120°E-80°W) into a linear formulation of the standard isotope paleo-temperature equation, with an assumed $\delta^{18}O_{coral}$ to SST slope of -0.2‰ K^{-1}.

Quantifying the $\delta^{18}O_{sw}$ contribution

Modeled inter-annual fluctuations in $\delta^{18}O_{sw}$ vary inversely with those in SST across almost the entire tropical Pacific region such that they combine positively. The fraction of the inter-annual variance of pseudo-coral $\delta^{18}O_{coral}$ that could be accounted for by the inter-annual variance of modeled $\delta^{18}O_{sw}$ is less than 10% (red contour in Fig. 1) across much of the subtropical eastern and equatorial Pacific, but higher in the Warm Pool, South Pacific Convergence Zone, and central American coastal regions. This affirms that the $\delta^{18}O_{sw}$ contribution is indeed important in regions of high precipitation variability (Tudhope et al. 2001; Cole and Fairbanks 1990). Consequently, whilst eastern Pacific pseudo-coral $\delta^{18}O_{coral}$ could be reasonably used as a proxy of SST fluctuations, this is not the case for all locations. However, only in very limited regions does the $\delta^{18}O_{sw}$ contribution exceed 50% (green contour in Fig. 1). Even within the high precipitation regions, there are no locations where one would expect the SST contribution to be negligible. Therefore, interpreting western Pacific corals as solely (or even predominantly) dependent on either temperature or precipitation appears misguided for many locations in the model.

Non-linearity between SST and $\delta^{18}O_{sw}$

The regional relationships between modeled SST and $\delta^{18}O_{sw}$ are not always simple. For example, in the western equatorial Pacific NINO4 region (grey rectangle in Fig. 1), little relationship is seen between modeled SST and $\delta^{18}O_{sw}$ during La-Niña (blue crosses), neutral (grey crosses) and even moderate El-Niño (red crosses) regimes (Fig. 2a). This results in pseudo-coral $\delta^{18}O_{coral}$ values that lie close to the imposed $\delta^{18}O_{coral}$ -SST slope (Fig. 2b). In such situations, the $\delta^{18}O_{sw}$ variability effectively adds (a relatively small degree of) noise to the $\delta^{18}O_{coral}$ record. However, during larger El-Niño events a weak anti-correlation between SST and $\delta^{18}O_{sw}$ becomes evident (lower right quadrant of Fig. 2a), such that for SST anomalies exceeding ~1.5K, a deviation from the imposed slope of the $\delta^{18}O_{coral}$ -SST relationship becomes noticeable (lower right quadrant of Fig. 2b). For large El-Niño events, estimating NINO4 SST directly from $\delta^{18}O_{coral}$ would result in a relative overestimation of the true SST anomaly by over 20%. This effect would complicate attempts to accurately infer the relative magnitudes of the SST anomalies during El-Niño events of different magnitude from proxy records of $\delta^{18}O_{coral}$ alone.

Acknowledgements

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Note

The model data presented here are available upon request from the corresponding author.

Selected references

Full reference list online under:
http://www.pages-igbp.org/products/newsletters/ref2013_2.pdf

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