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Strontium to calcium ratio and oxygen isotopic coral records can exaggerate past decadal tropical climate variability

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Geochemical tracers measured in corals are a key archive for reconstructing past variations in tropical climate and provide unique information on the complex nature of global climate dynamics. However, reconstructions from many tropical corals contain much greater decadal to centennial climate variability than evident from models or instrumental records, suggesting either biases in climate models or enhanced preindustrial climate variability. Using a method to distinguish climate from non-climate variations, on a recently compiled coral dataset covering the tropics and subtropics, we show that records from single corals contain a strongly autocorrelated non-climate noise component. This noise inflates the variance of reconstructed temperature by a factor of two to seven across a large range of timescales, implying that past studies may have exaggerated decadal to centennial temperature variations.

Understanding the spatial and temporal structure of climate variability is essential for testing physical models of Earth's climate system in order to predict the impacts of global warming and develop regional and national adaptation strategies in response to projected changes. It has become clear that natural temperature variability has a complex temporal structure, with the magnitude of variations increasing from inter-annual to longer timescales^{1–4}. However, the amplitude of natural local climate variability remains uncertain, with considerable disagreement between instrumental data, proxy-based climate reconstructions, and climate model simulations on decadal and longer timescales^{5–8}. Given that these timescales are crucial for implementing significant changes in infrastructure and behaviour in response to climate change, they hold particular relevance for human society.

Records of temperature sensitive geochemical tracers from tropical corals, such as the ratio of strontium to calcium (Sr/Ca) and the isotopic composition of oxygen ($\delta^{18}\text{O}$) in their aragonitic skeletons, are particularly suited to studying past climate variability on societally relevant timescales as they have up to monthly resolution, and can be well dated^{9–13}. They extend the sparse pre-satellite instrumental record in tropical regions back several hundred years, with additional floating snapshots from fossil corals from e.g. the last deglaciation¹⁴ and further back in time¹⁵. Corals have been used to reconstruct tropical sea surface temperature¹⁶ (SST), investigate decadal to centennial variability in the El Niño-Southern Oscillation^{10,17–19}, and to study the local impact and temporal dynamics of volcanic forcing^{10,16,17,20,21}.

Despite their high resolution, precise dating, and fidelity to the local annual temperature cycle, there are challenges to using coral records to

reconstruct past climate variability on inter-annual to decadal timescales. When temperature sensitive tracers are calibrated based on monthly values (effectively calibrating to the amplitude of the annual cycle), inter-annual to decadal-scale fluctuations in reconstructed temperature are typically much larger than those represented in gridded instrumental data^{22–27} (Supplementary Fig. 1). For $\delta^{18}\text{O}$ records, some of this excess variance could be explained by variation in the $\delta^{18}\text{O}$ of seawater, however, as the phenomenon is similar for Sr/Ca records, variation in the hydroclimate cannot be a general explanation, and forward modelling has shown that the degree of excess variation in $\delta^{18}\text{O}$ is too large to be explained by seawater composition changes alone⁸.

This exaggeration of coral derived SST changes on longer timescales has so far been addressed by adjusting the calibration, either after observing steeper calibration slopes for annual mean data^{23,24} or spatial calibrations²⁸, or to correct for a hypothesised time-scale dependence of temperature sensitivity due to damping of monthly scale variation by biosmoothing²⁹. However, correlation between local SST and geochemical tracers is also often much lower for annual- than monthly-resolution data^{23,24,30,31}. While replication studies have shown good reproducibility of the recorded annual cycle^{32–34}, larger discrepancies can emerge for some^{25,32,35–38} but not all coral colonies^{39,40} when looking at inter-annual changes in SST. The difference between resolutions is in large part because the strong signal of the annual cycle is absent in annual data. However, this implies that the strong correlation at monthly resolution is high, not because the noise is low, but because the signal from the annual cycle is very strong for most locations. This may indicate that slow, non-climatic variations, or noise, in addition to the

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climate signal, are responsible for the excess variation in the geochemical tracers at longer timescales.

Results

Excess variability in coral temperature records

To further quantify the ability of corals to record temperature changes at different timescales, we analyse the PAGES (Past Global Changes) CoralHydro2k database⁴¹, a recent compilation of coral Sr/Ca and $\delta^{18}\text{O}$ records from across the tropics and subtropics (Fig. 1a). We first compare the amplitude of variations (standard deviation) of coral Sr/Ca and $\delta^{18}\text{O}$ records with the amplitude of co-located gridded SST (specifically OISSTv2.1 and

ERSSTv5) at monthly (within-year) and annual mean (between-year) resolutions. There is a clear difference between these timescales in how well the amplitude of gridded instrumental SST fluctuations are reflected in individual Sr/Ca and $\delta^{18}\text{O}$ records given the typical temperature sensitivity of these tracers (Fig. 1b-c, Supplementary Fig. 2). Within-year standard deviations of monthly instrumental SST and tracer records correspond well across most of the spatial variation in annual cycle amplitude; coral Sr/Ca and $\delta^{18}\text{O}$ only under-record variation in SST at locations with the highest annual cycle variation (Fig. 1b), perhaps due to a cessation or slowing of calcification during either the coldest or hottest months⁴². In contrast, the standard deviations of annual mean Sr/Ca and $\delta^{18}\text{O}$ records far exceed what

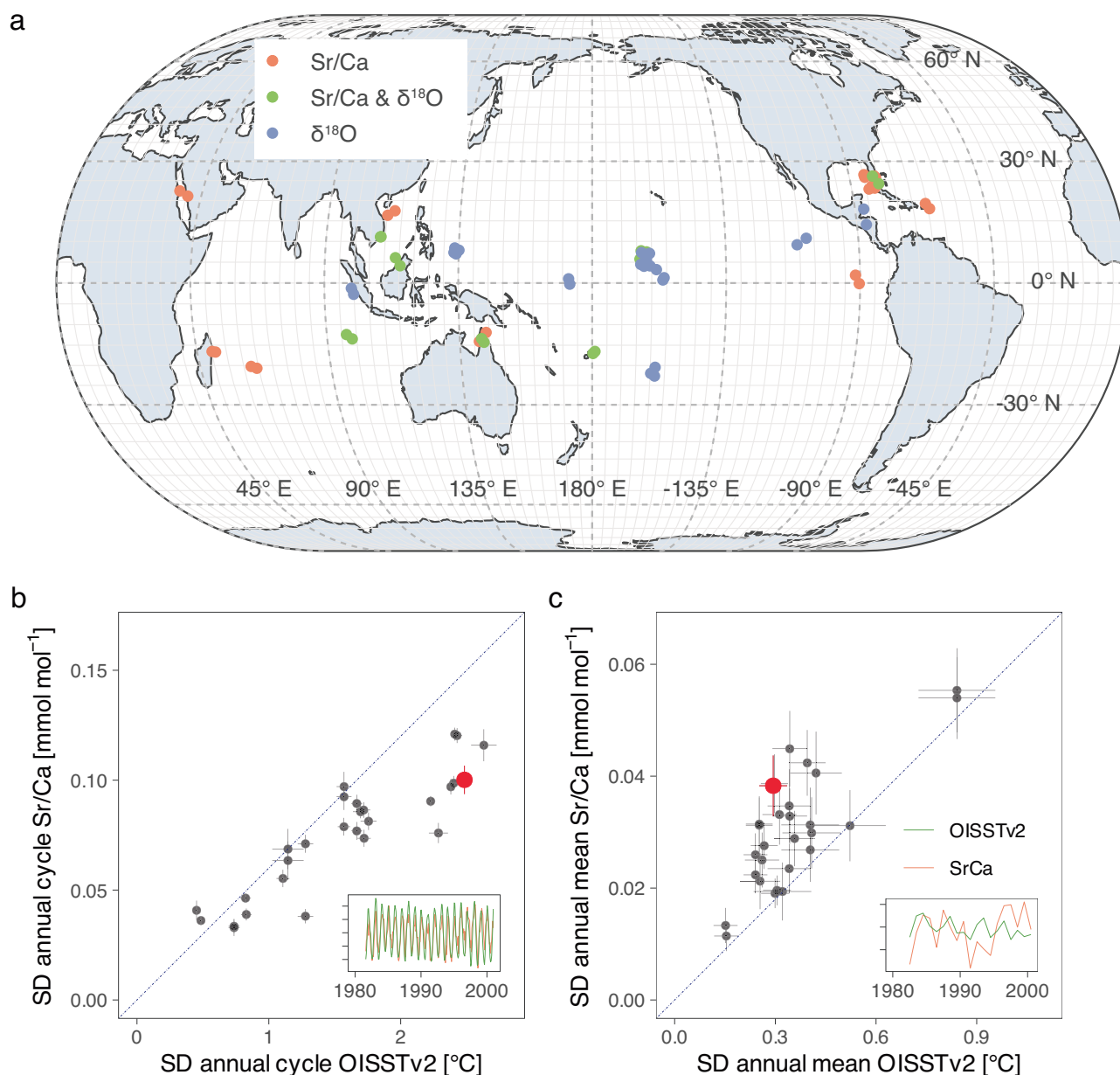


Fig. 1 | Map of study sites and a comparison across space between the standard deviation of coral Sr/Ca and gridded SST at short and long timescales. a Locations of Sr/Ca and $\delta^{18}\text{O}$ records used in the main analysis of this study. Precise positions have been adjusted to avoid over-plotting. **b** The mean standard deviation of the annual cycle in monthly coral Sr/Ca values and OISSTv2.1 from corresponding locations. **c** as **b** but showing the standard deviation of annual mean SST and coral Sr/Ca. For **b**, **c**: error bars indicate standard errors of the estimated standard deviations; the dashed blue lines indicate the consensus mean sensitivity of coral Sr/

Ca to temperature ($-0.06 \text{ mmol mol}^{-1} \text{ K}^{-112}$); a section of the red-highlighted record is used for the inset figures illustrating the monthly **b** versus annual **c** coral Sr/Ca and OISSTv2.1 timeseries. At the annual timescale the SD of Sr/Ca is on average similar to that expected given the SD of gridded SST and the mean sensitivity of Sr/Ca to temperature in coral aragonite; however, at longer timescales Sr/Ca is more variable than expected given local gridded SST variation. For coral $\delta^{18}\text{O}$ results see Supplementary Fig. 2.

would be expected given the typical temperature sensitivity of these tracers (Fig. 1c, Supplementary Fig. 2).

To study this timescale dependent behaviour in a more systematic way, we analyse the power spectra of the coral and instrumental records. Uncorrected power spectra of coral Sr/Ca and $\delta^{18}\text{O}$ records (S_{proxy}) are higher than instrumental SST spectra by a factor of at least 2 across all timescales (Fig. 2a), corresponding to at least 40% higher standard deviation, except at the annual cycle (Supplementary Fig. 3).

Separating the climate signal from the noise

To characterise the magnitude and temporal structure of the non-climate noise component of coral Sr/Ca and $\delta^{18}\text{O}$, we make use of the fact that nearby records should record similar temperature variations, as surface temperatures are highly correlated across several hundred kilometres⁴³. By analysing pairs of closely located records (median separation <1 km) that overlap in time (Fig. 1a) we decompose the variance of coral records into shared (climate), and non-shared (non-climate) components using a frequency resolved version of analysis of variance (see Methods⁴⁴). From this analysis we obtain corrected power-spectra representing the shared signal, which we interpret as the climate signal S_{clim} , and the non-shared component, which we consider as the non-climate noise, S_{noise} , showing the timescale dependence of both components (Fig. 2c). For individual pairs the separation of the common and noise components is inherently noisy; therefore, we present only averages across all pairs (Fig. 2). For comparison with the power spectra of instrumental SST, the coral Sr/Ca and $\delta^{18}\text{O}$ temperature proxies have been scaled with their mean sensitivities, $-0.06 \text{ mmol mol}^{-1} \text{ K}^{-1}$ for Sr/Ca¹², $-0.22\text{‰} \text{ K}^{-1}$ for $\delta^{18}\text{O}$ ³⁶, values obtained from many empirical studies and with support from inorganic precipitation experiments.

Amplitude and correlation structure of the noise

The separation of signal and noise indicates a large and strongly autocorrelated noise component for both coral Sr/Ca and $\delta^{18}\text{O}$ (Fig. 2c). S_{noise} increases from inter-annual (2–5 years) to multi-decadal (10–100 years) timescales, indicating that, unlike for many other climate archives such as water isotopes in ice-cores⁴⁴, or $\delta^{18}\text{O}$ in marine sediment cores⁴⁵, the magnitude of error on individual coral records is larger at longer timescales.

There are several lines of evidence that our separation of climate and non-climatic variations is meaningful:

Firstly, although the noise component was estimated without reference to any SST product, after subtracting the noise (Eqs. 3–4), the resulting corrected proxy spectra, S_{clim} , correspond well in pattern and amplitude to power-spectra of instrumental SST (ERSSTv5 and OISSTv2.1) evaluated at the locations of these coral records (Fig. 2a). Although gridded SST products represent temperature variations at a much larger spatial scale, at inter-annual to decadal timescales they agree in amplitude with variations recorded by temperature loggers located on coral reefs⁴⁶ (Supplementary Fig. 5) and so we should expect agreement between corals and gridded SST at these timescales. We note however that gridded SST products become less reliable further back in time, and we have little independent logger data prior to 1996, so comparisons on decadal to centennial timescales need to be treated with more caution. After correction, the spatial pattern across locations with varying SST amplitudes also matches the expectation given average temperature sensitivity (Fig. 3), further supporting our interpretation of the shared component as primarily climate signal. Remaining scatter around the mean sensitivity line is due in part to uncertainty in the separation of signal and noise, which could be reduced by using spatial clusters rather than pairs of coral colonies with more records per cluster.

Secondly, power spectra of the residuals from regression models of coral tracers onto SST support the idea that the non-climate component is strongly autocorrelated, as indicated by the steep increase in power with timescale (Supplementary Fig. 4). For Sr/Ca, regression-based residuals spectra and S_{noise} from the stacking method have similar magnitudes, while for $\delta^{18}\text{O}$ the residuals spectra lie above S_{noise} . This is consistent with the coral $\delta^{18}\text{O}$ signal containing additional variance from changes in seawater $\delta^{18}\text{O}$,

likely from variations in the hydrological cycle^{11,47}, and promising regarding community efforts to reconstruct tropical hydroclimate changes over the Common Era^{41,48}.

Thirdly, while relative time uncertainty between coral colonies due to missing or double counted annual bands or cycles⁴⁹ could inflate the apparent noise component⁴⁴, time uncertainty itself does not affect the shape or amplitude of power-spectra⁵⁰, and therefore cannot explain the excess power in the uncorrected proxy spectra (Fig. 2). Simulations show that relative time uncertainty would produce a very different noise spectrum than the one we estimate from stacking (Supplementary Fig. 6) and cannot explain the estimated noise spectrum, S_{noise} , at multidecadal timescales, even if we were to assume a counting error rate that would imply all noise at inter-annual timescales is due to time uncertainty.

Finally, by analysing pairs of records with a maximum spatial separation of less than 54 km (median distance 0.74 km), and for which there is a high correlation between sites in satellite based annual mean temperature (Pearson correlation ≥ 0.99), we have limited the extent to which true spatial variation might be mis-attributed as noise. This is further supported by the small effect of spatial separation on the signal-to-noise ratio (SNR) at timescales longer than the annual cycle, with SNR for Sr/Ca of only around 1 even at separations of less than 1 km (Supplementary Fig. 7).

While, individual corals might capture local climate variation not represented by the grid cells of the ERSSTv5 and OISST products, such as influences from shallow lagoonal versus reef slope settings that are more affected by the open ocean, or sites affected by local upwelling of colder waters versus non-upwelling sites, such variations would still be considered noise in the context of regional climate reconstructions.

Discussion

The presence of highly autocorrelated noise on individual coral records has significant implications for the interpretation of existing coral paleo-climate studies and the use of coral records in climate research. At timescales longer than the annual cycle, uncorrected coral Sr/Ca and $\delta^{18}\text{O}$ variance is 2–7 times larger than after correction (1.4 to 2.6 times in terms of standard deviation, Fig. 4). The inflated variance implies that past studies of decadal to centennial temperature variability using individual coral records^{2,8,51–53} are biased towards showing too much variability and thus have exaggerated the mismatch between proxy-based variability estimates and model simulations of tropical climate. This may imply that other high-resolution marine proxies are biased in a similar way, as their variability is currently thought to be consistent with that of coral records^{5,54,55}.

Strongly autocorrelated error may be a common feature of climate archives where proxy timeseries come from single organisms (e.g. trees⁵⁶, bivalves⁵⁷) rather than from separate samples of short-lived individuals (e.g. foraminifera in marine sediment cores), or ice, where the noise is predominantly independent between samples^{44,45}. For corals, in addition to sampling issues, it is plausible that physiological and/or metabolic processes that affect the incorporation of Sr/Ca and $\delta^{18}\text{O}$ into coral skeletons, described as vital effects, are responsible for this strongly temporally correlated error. For pragmatic reasons, when reconstructing past climate, vital effects are typically treated as if fixed for a given coral colony when in fact there are indications that they have the potential to vary over time, for example as side effects of growth rate-related kinetic effects^{58–62}, in response to changes in the composition of their symbionts^{63–65}, or thermal stress events⁶⁶. Such “wandering vital effects” would introduce strongly autocorrelated non-climate related noise consistent with our findings.

Fortunately, in contrast to the strong temporal correlation of this noise within individual records, it appears to be largely uncorrelated between colonies. This implies that averaging replicated records, or stacking, is an effective way to reduce the non-climate component and increase the signal-to-noise ratio, as is common in dendrochronology, has been demonstrated for central Greenland ice cores⁶⁷ and suggested for corals^{36,68}. Indeed, it is often noted that composite records made from stacking replicates correlate better with independent SST records than do the individual coral records^{30,32,33,35,39,68,69}. We show here that stacks of just 2 replicate records are

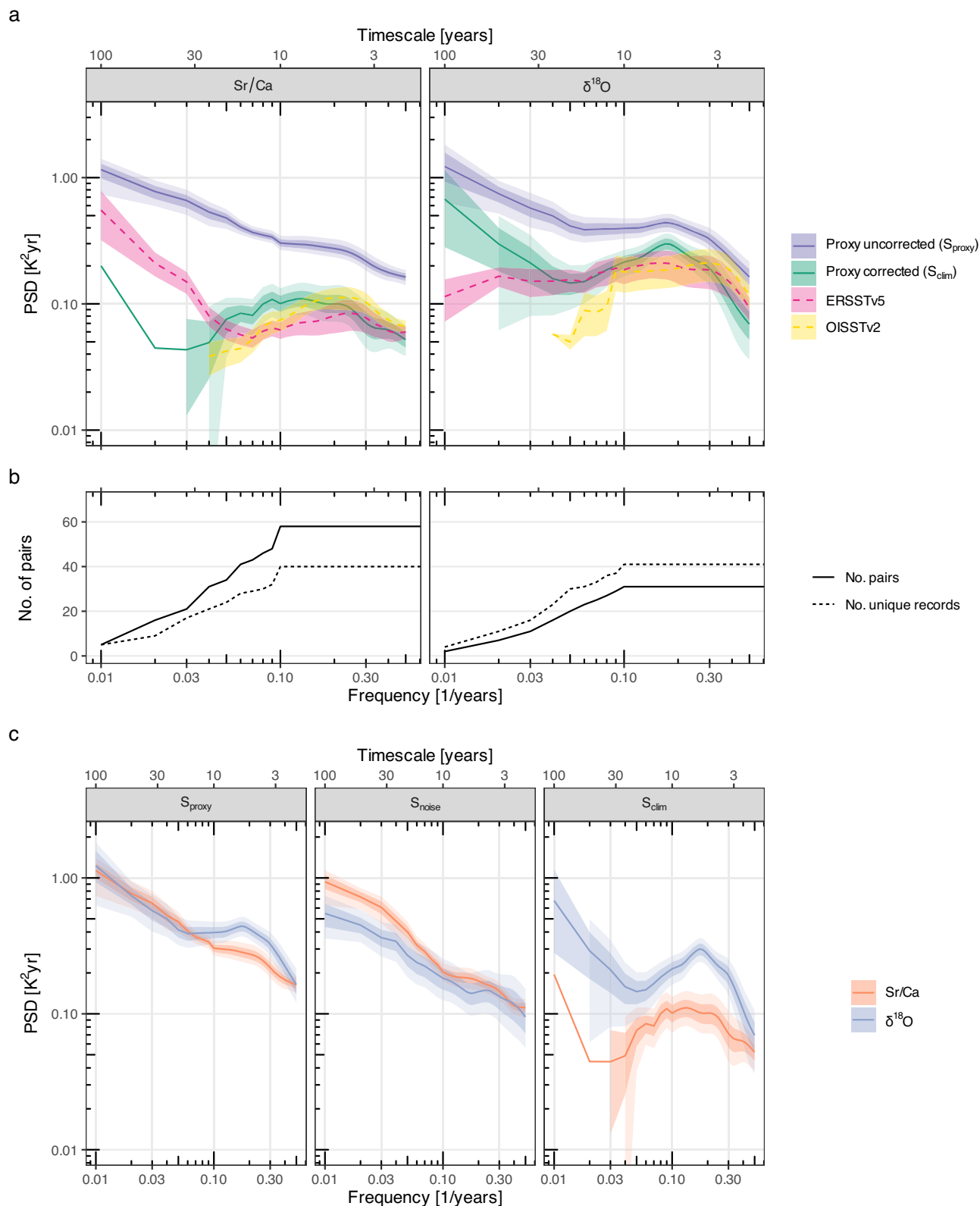
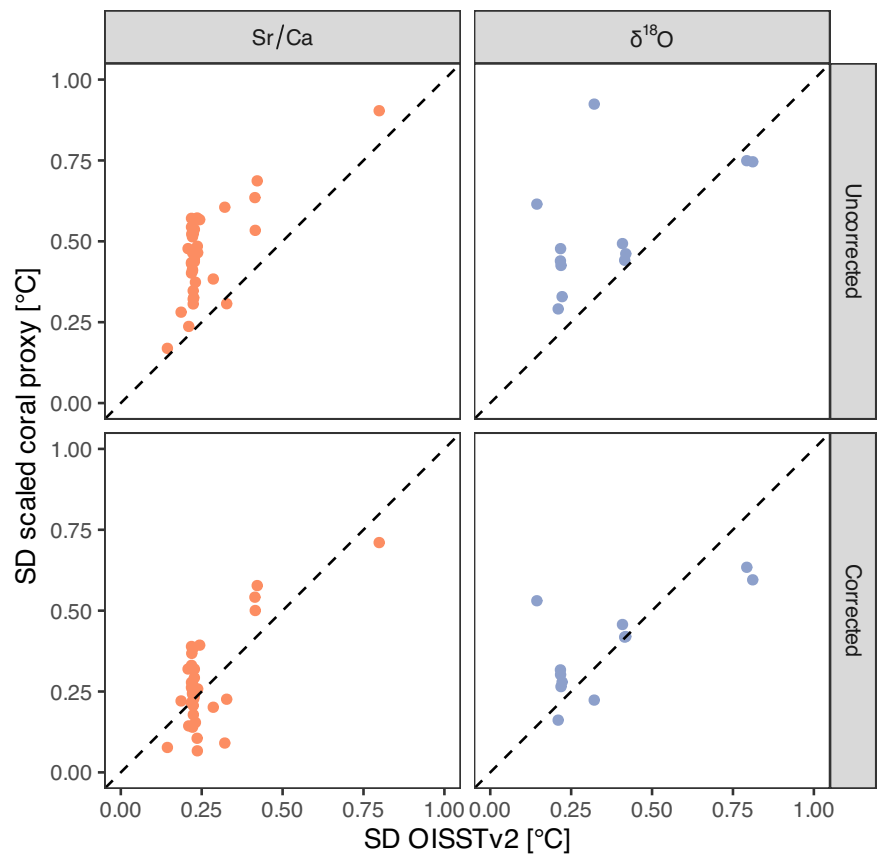


Fig. 2 | Power spectra of coral Sr/Ca, $\delta^{18}\text{O}$, and instrumental SST. a A comparison of the uncorrected (S_{proxy}) and corrected (S_{clim}) spectra estimated from coral Sr/Ca and $\delta^{18}\text{O}$ with the power spectral density (PSD) of instrumental SST (ERSSTv5 & OISSTv2) evaluated for the locations and time periods for which there were Sr/Ca and $\delta^{18}\text{O}$ data. Spectra represent averages across all pairs of coral records analyzed in this study. For **a** and **b**, units have been converted to Kelvin by multiplying Sr/Ca and $\delta^{18}\text{O}$ based spectra by $1/0.06^2$ and $1/0.22^2$ respectively. **b** No. of pairs and the number

of unique records contributing to the mean power spectra at each frequency for coral derived data. **c** Power spectral density of the uncorrected coral proxy records, shared (climate) and noise components estimated using the stacked records method. For proxy-based power spectra, shaded regions indicate 68 and 95% confidence intervals estimated by record-wise bootstrapping. Bootstrapped interval estimation was not possible for timescales with contributions from less than about 20 coral pairs (the precise number was dependent on the variation of the given statistic).

Fig. 3 | Corrected versus uncorrected estimates of climate variation from coral geochemical tracers. Standard deviation of Sr/Ca and $\delta^{18}\text{O}$ records before and after correction via the stacked records method plotted against the SD of SST from OISSTv2. Each point represents the mean across records in a pair. The diagonal lines show the accepted literature values for the mean sensitivities of the two proxies ($-0.06 \text{ mmol mol}^{-1} \text{ K}^{-1}$ for Sr/Ca¹², -0.22‰ K^{-1} for $\delta^{18}\text{O}$ ³⁶).



sufficient to fully correct estimates of past climate variability as the noise remaining after stacking can be subtracted from spectra or variance estimates (Fig. 3). While residual noise cannot be ‘removed’ from composite timeseries, we can estimate realistic noise estimates appropriate for the timescale of the analysis⁴⁵. Importantly, individual records still contain valuable information about past climate history, even when accounting for these larger uncertainties (Supplementary Fig. 9). Measurements of coral extension rate, density, and additional tracers such as Li/Ca, Li/Mg, U/Ca, B/Ca, and Mg/Ca may offer ways to statistically adjust reconstructions for biological and growth rate effects^{70–72}. However, replication will remain the most reliable way to identify and remove these effects³⁶ and can be applied to both modern and young fossil corals⁷³.

To advance our understanding and optimal use of coral-based reconstructions, it will be necessary to incorporate temporally correlated noise into proxy system models, which, at present, assume independent errors^{18,74,75}. Additionally, this correlated noise must be considered in data assimilation exercises, impacting the relative weighting of proxy and model information. Conventionally reported errors on metrics such as decadal means from individual records are likely underestimated and previous interpretations of local reconstructions from individual corals compiled in the CoralHydro2k database⁴¹ may need to be reassessed in this context. Finally, considering our findings and basing calibration on replicated corals⁷⁶ could clarify complexities in coral calibrations, including time-interval dependency⁷⁷, the timescale of the data^{23,24,29} and inter-colony variation in calibration parameters⁶⁹.

Corals remain one of the most valuable archives for tropical marine climate reconstructions^{9–11} and we reiterate previous calls to prioritise replication when developing new coral records^{36,78,79}, while recognising the substantial analytical work and cost involved, as well as the sensitive nature of coring additional centurion-aged colonies in fragile ecosystems. Strategic site selection, so that where possible new cores are located near to existing

records, which can then be re-analysed along with the new data, will optimise our use of these resources.

Methods

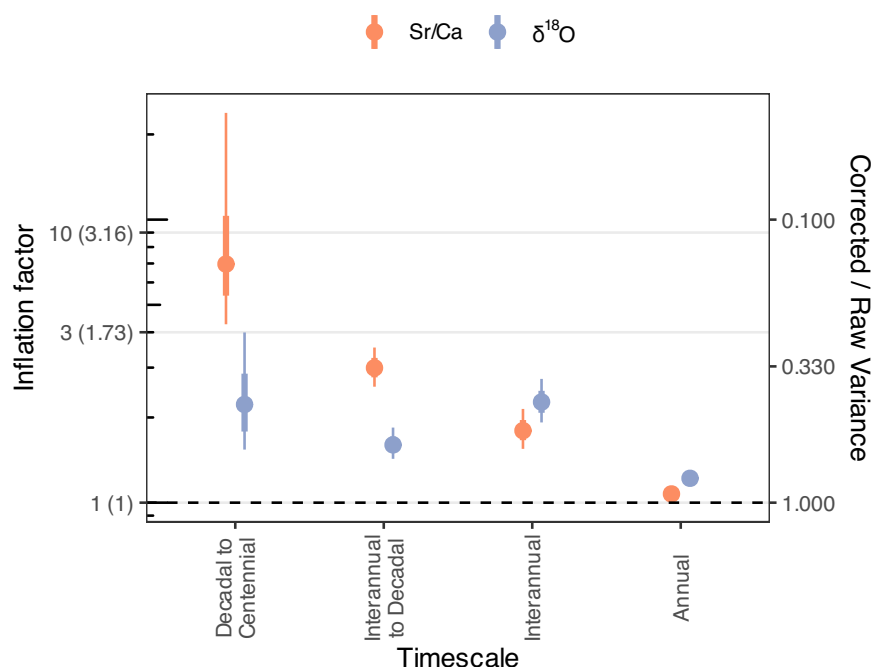
Coral Sr/Ca and $\delta^{18}\text{O}$ records

We screened the PAGES CoralHydro2k Database⁴¹ for Sr/Ca and $\delta^{18}\text{O}$ records with monthly or bi-monthly (6 per year) minimum temporal resolution. Records labelled as “monthly_uneven” and “bimonthly_uneven” were also included. The primary time variable in CoralHydro2k is decimal year “year.dec”. For most records this is a semi-regular time axis with small variations in the estimated time spacing between geochemical measurements. When converted to year and month, this results in many cases where there are two observations in a month, on say the 1st and 30th, and then no observation the following month. To avoid this, we linearly interpolated all records onto a regular time axis with 12 mid-month time-points per year, with a maximum interpolation distance of 1 month, leaving gaps where an interpolated mid-month point would be more than 1 month from the nearest observation. This interpolation will have a small low-pass filtering effect on the time series and resulting power spectra, equivalent to a sinc⁴ filter in the frequency domain affecting only the highest frequencies. The attenuation is approximately 5% at the frequency of the annual cycle. We then used singular spectrum analysis with iterative gap filling to interpolate over short gaps in records and upscale bimonthly records to monthly resolution while preserving the annual cycle implemented in the R package “Rssa”⁸⁰. No records were extrapolated past their earliest or latest data point.

Instrumental data

Instrumental SST data from the NOAA Extended Reconstructed SST V5 (ERSSTv5)⁸¹ and NOAA OI SST V2 High Resolution Datasets (OISSTv2.1)⁸² were matched to the interpolated coral Sr/Ca and $\delta^{18}\text{O}$ records by distance weighted linear interpolation and matching by year and month. Using the ERSSTv5 has the benefit that it goes back to 1854 and

Fig. 4 | Inflation of coral Sr/Ca and $\delta^{18}\text{O}$ variation by non-climate noise. Corrected versus raw variance of coral Sr/Ca and $\delta^{18}\text{O}$ proxies calculated by integrating the corrected and raw proxy spectra (S_{clim} and S_{proxy} respectively) across frequency bands corresponding to characteristic timescales. The inflation factor is a variance ratio, the ratio in terms of standard deviation is given in parentheses. Error bars show 68% (± 1 se) and 95% confidence intervals from bootstrapping.



therefore can be used to estimate variance at longer timescales, with the downside that it has a coarser spatial resolution of $2^\circ \times 2^\circ$ (approximately 110×110 km) and is based on sparse observations with the risk of increasing inaccuracies further back in time. OISSTv2.1 has a much higher $0.25 \times 0.25^\circ$ (27×27 km) resolution and is based on more spatially complete satellite data, however it only goes back as far as 1981.

For each location we estimated the power spectrum of ERSSTv5 and OISSTv2.1 data. Mean spectra of ERSSTv5 and OISSTv2.1 were then calculated by averaging across locations.

Nearby pairs of records. We identified pairs of coral $\delta^{18}\text{O}$ or Sr/Ca records from colonies which overlap in time by at least ten years, and for which detrended annual mean OISSTv2.1 time-series for the full period 1981–2024 sampled at both locations were correlated $R \geq 0.99$. This resulted in 58 Sr/Ca, and 31 $\delta^{18}\text{O}$ pairs with a maximum pairwise distance of 54 km. The mean distance was just 7 km and the median less than 1 km. This set of closely located colonies was used for the main analysis. An expanded set of pairs with maximum distance of 1000 km and no restriction on OISSTv2.1 correlation was used to examine how our results were influenced by spatial separation (Supplementary Fig. 7).

Of the 81 unique coral records in the reduced set of pairs, 60 were from colonies of the genus *Porites*, with additionally 11 *Orbicella*, 6 *Siderastrea*, 2 *Pseudodiploria* and 2 *Diplastrea*.

Comparison of instrumental and coral record variance

To illustrate that coral Sr/Ca and $\delta^{18}\text{O}$ records match the variance expected from instrument SST at annual cycle timescales but exceed it at longer timescales, at each location where we have a geochemical record we calculate the standard deviation between monthly values for the Sr/Ca or $\delta^{18}\text{O}$ record and for OISSTv2.1 matched by year and month. We calculate these separately for each year, then calculate the mean across years for each record, and the standard error of this mean as the standard deviation divided by the square root of the number of years. Only years with 12 monthly values were included in the calculations.

To compare variance at longer timescales we calculate annual mean geochemical and OISSTv2.1 values (Jan–Dec) and then the standard deviation across annual means. The standard errors of these standard

deviation estimates, σ , were estimated with the formula $\sigma/\sqrt{(2n - 2)}$, where n is the number of values from which the standard deviation was calculated.

These estimates for coral Sr/Ca or $\delta^{18}\text{O}$ and OISSTv2.1 are then plotted against each other and compared to a reference line indicating their consensus mean sensitivity to temperature ($-0.06 \text{ mmol mol}^{-1} \text{ K}^{-1}$ for Sr/Ca¹², -0.22‰ K^{-1} for $\delta^{18}\text{O}$ ³⁶ (Fig. 1b, c, Supplementary Fig. 2).

Stacking and variance decomposition in the frequency domain

For each pair we create a stacked (mean) record by averaging across coral records at each timepoint (averaging in the time domain) and estimate the power spectrum of the stack, S_{stack} . We then estimate the power spectrum of each individual record, S_{proxy} , before averaging across records at each frequency (averaging in the frequency domain) to get the mean individual record spectrum \bar{S}_{proxy} . Power spectra were estimated after linear detrending and removing the mean. We use the multitaper method with five tapers.

Assuming that the non-climate component of a coral geochemical timeseries is independent of the climate signal, the spectrum of an individual record is the spectrum of the climate S_{clim} plus the spectrum of the non-climate component, S_{noise} (Eq. 1).

Assuming that the non-climate component (noise) is independent between records, while the climate component is common across records in a stack, the power spectrum of the stack, S_{stack} is the power of the common climate signal (S_{clim}) plus the power of the noise, S_{noise} divided by the number of records in the stack, n , here always 2 (Eq. 2).

$$S_{\text{proxy}} = S_{\text{clim}} + S_{\text{noise}} \quad (1)$$

$$S_{\text{stack}} = S_{\text{clim}} + S_{\text{noise}}/n \quad (2)$$

From expressions 1 and 2 we can derive the spectrum of the noise component as the difference between \bar{S}_{proxy} and S_{stack} correcting for the fact that the stack still contains some noise unless is composed of an infinite number of records (Eq. 3). We can then obtain the spectrum of the common signal, here assumed to be climate, by subtracting the noise spectrum from \bar{S}_{proxy} .

$$S_{\text{noise}} = (\bar{S}_{\text{proxy}} - S_{\text{stack}})n/(n - 1) \quad (3)$$

$$S_{clim} = S_{proxy} - S_{noise} \quad (4)$$

The frequency dependent signal-to-noise ratio is then simply the ratio

$$S_{clim}/S_{noise} \quad (5)$$

Power spectra were estimated using the multitaper method and then smoothed to reduce noise in the spectral estimates. Because the noise component is large relative to the signal at some frequencies, and because here we have only 2 records in each stack, uncertainty in the numerical spectral estimator can mean that the S_{noise} estimate can exceed S_{stack} , resulting in non-sensical negative power estimates for S_{clim} at some frequencies. To reduce the occurrence of negative estimates we smooth the spectra at the expense of losing detail at specific frequencies, but this gives a clearer picture of the scaling of climate and noise variance with timescale.

To aid comparison of coral Sr/Ca and $\delta^{18}\text{O}$ spectra with each other, and with instrumental based SST, coral Sr/Ca and $\delta^{18}\text{O}$ were scaled by their respective mean temperature sensitivities to convert them to units of variance in temperature ($0.06 \text{ mmol mol}^{-1} \text{ K}^{-1}$ for Sr/Ca¹², $0.22\text{‰} \text{ K}^{-1}$ for $\delta^{18}\text{O}$ ³⁶).

Aggregation across pairs

Estimates of S_{clim} are by construction very noisy for individual pairs and so we stack pairs in the frequency domain to get the power spectrum of tropical SST as recorded by coral Sr/Ca and $\delta^{18}\text{O}$. To do this we interpolate the spectra from each pair onto a common frequency axis and calculate the mean across frequencies.

Time uncertainty

Age models for coral timeseries are typically generated by counting annual bands backwards from the year of core retrieval – for sub-annually sampled records they are then cross-referenced with annual cycles in the geochemical measurements (e.g. $\delta^{18}\text{O}$ and/or Sr/Ca). Bands and cycles can be missed or double counted, introducing uncertainty or error to the assigned year. This kind of time uncertainty does not affect the overall shape of power spectra for individual timeseries⁵⁰. It does however reduce coherency between records, and therefore influences the spectrum of a mean or stacked record; without correction, this time uncertainty effect could be misattributed as noise in our analysis. We assessed the magnitude of this affect by simulation using a band counting error model⁴⁹, as implemented in the proxysnr package for R¹⁴, which can be used to estimate the effect of relative time uncertainty as a transfer function⁴⁴. For each pair of records we simulated independent counting-error-perturbed age models, assuming the top-most year in a record to be the year of collection and error free, with subsequent counting error rates of 1 in 50, 100, 200, and 400 years. The probabilities of double counting or missing a year were assumed to be equal. Where the records in a pair started in a different year (i.e., had a different number of years before the start of their overlapping period) we modelled from the mean of the starting dates. The perturbed records were then stacked, as in our main analysis (Eqs. 1–4) which allows the artefactual time-uncertainty noise component to be estimated. This was repeated 1000 times to get a stable estimate (Supplementary Fig. 6).

Sub-annual geochemical measurements are typically assigned to specific months by matching one or both of the peak and trough of the annual cycle to the climatologically coldest and warmest months at the location of the coral colony. Intervening measurements are then assigned to the other months of the year by interpolation. The specific method varies between practitioners, but the effect on the power-spectrum is similar to that of linear interpolation, reducing power at higher frequencies and biasing the slope of the spectrum towards -2 in log-log space. We did not model this process explicitly here, but rather avoid quantitatively interpreting the power spectra at timescales faster than the annual cycle.

Variance pre- and post-correction

To assess how well the stacking method corrects variance estimates, we integrated S_{proxy} , S_{clim} across the frequency range $1/100 < f < 1/2$. We then plot the uncorrected and corrected climate SD estimates against mean instrumental SDs per pair, with reference lines indicating mean temperature sensitivities (Fig. 3).

Variance inflation factor

To show the extent to which the non-shared (non-climate) component exaggerates or inflates estimates of climate variability at different timescales, we integrated S_{proxy} and S_{clim} over the frequency ranges $1/100 \leq f \leq 1/10$ (decadal to centennial); $1/10 \leq f \leq 1/2$ (interannual to decadal); $1/2 \leq f \leq 1/1.1$ (interannual); $1/1.1 \leq f \leq 1.1/1$ (annual) and take the ratio of these variance estimates (Fig. 4).

Effect of pairwise distance

To test whether the spatial distance we allowed between records in a pair could influence our results, by allowing true spatial variation to be mis-attributed to noise, we examine the relationship between pairwise distance and apparent signal-to-noise ratio at annual cycle, interannual and inter-annual to decadal timescales. While there is a decline in SNR with distance at all timescales, this effect is small at timescales above annual for distances less than 100 km (Supplementary Fig. 7).

Record-wise bootstrapping confidence intervals

We carried out record-wise bootstrapping to estimate uncertainty in power spectra, variances and variance ratios. Individual records were resampled with replacement. For a given bootstrap sample, if a record is not sampled, then all pairs containing that missing record are then missing from the bootstrap sample. If records appear more than once, then their corresponding pairs also appear more than once in the bootstrap sample. We then used the variation across 10000 bootstrap samples to estimate uncertainties in all spectra and statistics presented (with the exception of Fig. 1). We estimate the 0.025, 0.159, 0.841, and 0.975 quantiles, which are equivalent to ± 1 and 2 standard deviations, or the 68 and 95% confidence intervals. Bootstrapped interval estimation was not possible for timescales with contributions from less than about 20 coral pairs (the precise number was dependent on the variation of the given statistic).

Monte Carlo validation

We used a Monte Carlo procedure to validate our implementation of the stacking method by simulating data with different spectral slopes for the climate and noise components and testing that the method returns unbiased estimates of the parameters used for the simulation. For each pair we simulate one pseudo climate timeseries with a power spectrum with similar scaling to that observed in S_{clim} estimated from the real data ($\beta = 0.7$). For each member of a pair, we then add a noise timeseries such that the signal-to-noise ratio declines from approximately 1 at $f = 6$ to 0.3 at $f = 0.07$ ($\beta = 0.9$), and a deterministic sinusoidal seasonal cycle. This approximates the observed SNR in the real data. We generate 1000 replicate sets of this surrogate data and for each re-run the stacking analysis, including the aggregation across pairs. We then test that the method returns unbiased estimates of the parameters used for the simulation (see Supplementary Fig. 8).

Autocorrelated noise example timeseries

To illustrate the consequences of autocorrelated noise on the interpretation of individual timeseries, we contrast uncertainty estimates based on an assumption of independent (white) noise, and the uncertainty implied by the power-spectrum of the noise we estimate here. We apply these uncertainty estimates to a 244-year bi-monthly Sr/Ca record from Ras Umm Sidd in the northern Red Sea²⁴ that we have binned to decadal resolution. For the uncertainty assuming autocorrelated noise we integrate the estimated mean noise spectrum for Sr/Ca records (S_{noise} , Fig. 2) over the frequency range $1/244$ years to $1/20$ years. To cover the frequency range $1/244$ to $1/100$ years we

extended S_{noise} assuming a power law with the same average slope as over the frequency range 1/100 to 1/20. This gives the variance of the autocorrelated noise process at decadal resolution. For the uncertainty assuming independent noise we assume a white noise process with total variance equal to the variance of the full extended S_{noise} spectrum from 1/244 to 3 years. To get the variance on annual means we divide this by 60 for the 60 Sr/Ca observations per decade. We apply these two uncertainty estimates to annual means calculated from the original monthly values, scaled to units of temperature with $1/-0.06$ (Supplementary Fig. 9).

Data availability

All Sr/Ca and $\delta^{18}O$ data used are contained in the PAGES (Past Global Changes) CoralHydro2k database⁴¹ and are available at this <https://doi.org/10.25921/yp94-v135>. The NOAA Extended Reconstructed SST V5 data product (ERSSTv5)⁸¹ is available here: <https://doi.org/10.7289/V5T72FNM>. NOAA OI SST V2 High Resolution Dataset data (OISSTv2) was provided by the NOAA PSL, Boulder, Colorado, USA, from their website at <https://www.psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>.

Code availability

All code is publicly available as a Github repository archived via a Zenodo <https://doi.org/10.5281/zenodo.10613861>.

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References

- Schmitt, F., Lovejoy, S. & Schertzer, D. Multifractal analysis of the Greenland Ice-Core Project climate data. *Geophys. Res. Lett.* **22**, 1689–1692 (1995).
- Laepple, T. & Huybers, P. Global and regional variability in marine surface temperatures. *Geophys. Res. Lett.* **41**, 2528–2534 (2014).
- Lovejoy, S. A voyage through scales, a missing quadrillion and why the climate is not what you expect. *Clim. Dyn.* **44**, 3187–3210 (2015).
- Franzke, C. L. E. et al. The structure of climate variability across scales. *Rev. Geophys.* **58**, e2019RG000657 (2020).
- Laepple, T. & Huybers, P. Ocean surface temperature variability: large model–data differences at decadal and longer periods. *Proc. Natl. Acad. Sci. USA* **111**, 16682–16687 (2014).
- Laepple, T. et al. Regional but not global temperature variability underestimated by climate models at supradecadal timescales. *Nat. Geosci.* 1–9 (2023) <https://doi.org/10.1038/s41561-023-01299-9>.
- Cheung, A. H. et al. Comparison of Low-Frequency Internal Climate Variability in CMIP5 Models and Observations. *J. Clim.* **30**, 4763–4776 (2017).
- Parsons, L. A. et al. Temperature and Precipitation Variance in CMIP5 Simulations and Paleoclimate Records of the Last Millennium. *J. Clim.* **30**, 8885–8912 (2017).
- Thompson, D. M. Environmental records from coral skeletons: A decade of novel insights and innovation. *WIREs Clim. Change* **13**, e745 (2022).
- Gagan, M. K. et al. New views of tropical paleoclimates from corals. *Quat. Sci. Rev.* **19**, 45–64 (2000).
- Felis, T. Extending the Instrumental Record of Ocean-Atmosphere Variability into the Last Interglacial Using Tropical Corals. *Oceanography* **33**, 68–79 (2020).
- Correge, T. Sea surface temperature and salinity reconstruction from coral geochemical tracers. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **232**, 408–428 (2006).
- Lough, J. M. Climate records from corals. *WIREs Clim. Change* **1**, 318–331 (2010).
- Felis, T. et al. Intensification of the meridional temperature gradient in the Great Barrier Reef following the Last Glacial Maximum. *Nat. Commun.* **5**, (2014).
- Brachert, T. C. et al. Slow-growing reef corals as climate archives: A case study of the Middle Eocene Climatic Optimum 40 Ma ago. *Sci. Adv.* **8**, eabm3875 (2022).
- Tierney, J. E. et al. Tropical sea surface temperatures for the past four centuries reconstructed from coral archives. *Paleoceanography* **30**, 2014PA002717 (2015).
- Damassa, T. D., Cole, J. E., Barnett, H. R., Ault, T. R. & McClanahan, T. R. Enhanced multidecadal climate variability in the seventeenth century from coral isotope records in the western Indian Ocean. *Paleoceanography* **21**, PA2016 (2006).
- Lawman, A. E. et al. Developing a Coral Proxy System Model to Compare Coral and Climate Model Estimates of Changes in Paleo-ENSO Variability. *Paleoceanogr. Paleoclimatol.* **35**, e2019PA003836 (2020).
- Tangri, N., Dunbar, R. B., Linsley, B. K. & Mucciarone, D. M. ENSO's Shrinking Twentieth-Century Footprint Revealed in a Half-Millennium Coral Core From the South Pacific Convergence Zone. *Paleoceanogr. Paleoclimatol.* **33**, 1136–1150 (2018).
- Dee, S. G. et al. No consistent ENSO response to volcanic forcing over the last millennium. *Science* **367**, 1477–1481 (2020).
- D'Arrigo, R., Wilson, R. & Tudhope, A. The impact of volcanic forcing on tropical temperatures during the past four centuries. *Nat. Geosci.* **2**, 51–56 (2009).
- Crowley, T. J., Quinn, T. M. & Hyde, W. T. Validation of coral temperature calibrations. *Paleoceanography* **14**, 605 (1999).
- Felis, T. et al. Subtropical coral reveals abrupt early-twentieth-century freshening in the western North Pacific Ocean. *Geology* **37**, 527–530 (2009).
- Felis, T., Ionita, M., Rimbu, N., Lohmann, G. & Kölling, M. Mild and Arid Climate in the Eastern Sahara-Arabian Desert During the Late Little Ice Age. *Geophys. Res. Lett.* **45**, 7112–7119 (2018).
- Linsley, B. K. et al. Tracking the extent of the South Pacific Convergence Zone since the early 1600s. *Geochem. Geophys. Geosystems* **7**, 1–15 (2006).
- Scott, R. B., Holland, C. L. & Quinn, T. M. Multidecadal Trends in Instrumental SST and Coral Proxy Sr/Ca Records. *J. Clim.* **23**, 1017–1033 (2010).
- Goodkin, N. F., Hughen, K. A., Curry, W. B., Doney, S. C. & Ostermann, D. R. Sea surface temperature and salinity variability at Bermuda during the end of the Little Ice Age. *Paleoceanography* **23**, (2008).
- DeLong, K. L., Quinn, T. M., Shen, C.-C. & Lin, K. A snapshot of climate variability at Tahiti at 9.5 ka using a fossil coral from IODP Expedition 310. *Geochem. Geophys. Geosystems* **11**, 1–14 (2010).
- Gagan, M. K. & Dunbar, G. B. The effect of skeletal mass accumulation in *Porites* on coral Sr/Ca and $\delta^{18}O$ Paleothermometry. *Paleoceanography* **27**, 1–16 (2012).
- Grove, C. A. et al. Confounding effects of coral growth and high SST variability on skeletal Sr/Ca: Implications for coral paleothermometry. *Geochem. Geophys. Geosystems* **14**, 1277–1293 (2013).
- Murty, S. A. et al. Spatial and Temporal Robustness of Sr/Ca-SST Calibrations in Red Sea Corals: Evidence for Influence of Mean Annual Temperature on Calibration Slopes. *Paleoceanogr. Paleoclimatology* **33**, 443–456 (2018).
- DeLong, K. L., Quinn, T. M. & Taylor, F. W. Reconstructing twentieth-century sea surface temperature variability in the southwest Pacific: A replication study using multiple coral Sr/Ca records from New Caledonia. *Paleoceanography* **22**, 1–18 (2007).
- Stephans, C. L., Quinn, T. M., Taylor, F. W. & Corrège, T. Assessing the reproducibility of coral-based climate records. *Geophys. Res. Lett.* **31**, L18210 (2004).
- Felis, T. et al. Increased seasonality in Middle East temperatures during the last interglacial period. *Nature* **429**, 164–168 (2004).
- DeLong, K. L. et al. A reconstruction of sea surface temperature variability in the southeastern Gulf of Mexico from 1734 to 2008 C.E.

- using cross-dated Sr/Ca records from the coral *Siderastrea siderea*. *Paleoceanography* **29**, 403–422 (2014).
36. Lough, J. M. A strategy to improve the contribution of coral data to high-resolution paleoclimatology. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **204**, 115–143 (2004).
 37. Wu, H. C., Moreau, M., Linsley, B. K., Schrag, D. P. & Corrège, T. Investigation of sea surface temperature changes from replicated coral Sr/Ca variations in the eastern equatorial Pacific (Clipperton Atoll) since 1874. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **412**, 208–222 (2014).
 38. Reed, E. V. et al. Impacts of Coral Growth on Geochemistry: Lessons From the Galápagos Islands. *Paleoceanogr. Paleoclimatology* **36**, e2020PA004051 (2021).
 39. Flannery, J. A., Richey, J. N., Toth, L. T., Kuffner, I. B. & Poore, R. Z. Quantifying Uncertainty in Sr/Ca-Based Estimates of SST From the Coral *Orbicella faveolata*. *Paleoceanogr. Paleoclimatology* **33**, 958–973 (2018).
 40. Flannery, J. A., Richey, J. N., Thirumalai, K., Poore, R. Z. & DeLong, K. L. Multi-species coral Sr/Ca-based sea-surface temperature reconstruction using *Orbicella faveolata* and *Siderastrea siderea* from the Florida Straits. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **466**, 100–109 (2017).
 41. Walter, R. M. et al. The CoralHydro2k database: a global, actively curated compilation of coral $\delta^{18}\text{O}$ and Sr/Ca proxy records of tropical ocean hydrology and temperature for the Common Era. *Earth Syst. Sci. Data* **15**, 2081–2116 (2023).
 42. Barnes, D. J., Taylor, R. B. & Lough, J. M. On the inclusion of trace materials into massive coral skeletons. Part II: distortions in skeletal records of annual climate cycles due to growth processes. *J. Exp. Mar. Biol. Ecol.* **194**, 251–275 (1995).
 43. Hansen, J. & Lebedeff, S. Global trends of measured surface air temperature. *J. Geophys. Res.* **92**, 13345 (1987).
 44. Münch, T. & Laepple, T. What climate signal is contained in decadal-to centennial-scale isotope variations from Antarctic ice cores? *Clim* **14**, 2053–2070 (2018).
 45. Dolman, A. M., Kunz, T., Groeneveld, J. & Laepple, T. A spectral approach to estimating the timescale-dependent uncertainty of paleoclimate records – Part 2: Application and interpretation. *Clim* **17**, 825–841 (2021).
 46. Dolman, A. M. & Laepple, T. Temperature Variability on Coral Reefs Versus Gridded SST – The Long and the Short of It. *Geochem. Geophys. Geosystems* **26**, e2025GC012351 (2025).
 47. Thompson, D. M. et al. Identifying Hydro-Sensitive Coral $\delta^{18}\text{O}$ Records for Improved High-Resolution Temperature and Salinity Reconstructions. *Geophys. Res. Lett.* **49**, e2021GL096153 (2022).
 48. PAGES Hydro2k Consortium Comparing proxy and model estimates of hydroclimate variability and change over the Common Era. *Climate* **13**, 1851–1900 (2017).
 49. Comboul, M. et al. A probabilistic model of chronological errors in layer-counted climate proxies: applications to annually banded coral archives. *Climate* **10**, 825–841 (2014).
 50. Rhines, A. & Huybers, P. Estimation of spectral power laws in time uncertain series of data with application to the Greenland Ice Sheet Project 2 $\delta^{18}\text{O}$ record. *J. Geophys. Res. Atmospheres* **116**, (2011).
 51. Dee, S. G. et al. Improved spectral comparisons of paleoclimate models and observations via proxy system modeling: Implications for multi-decadal variability. *Earth Planet. Sci. Lett.* **476**, 34–46 (2017).
 52. Ellerhoff, B. & Rehfeld, K. Probing the timescale dependency of local and global variations in surface air temperature from climate simulations and reconstructions of the last millennia. *Phys. Rev. E* **104**, 064136 (2021).
 53. Calvo, E. et al. Interdecadal climate variability in the Coral Sea since 1708 AD. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **248**, 190–201 (2007).
 54. Black, D. E. et al. An 8-century tropical Atlantic SST record from the Cariaco Basin: Baseline variability, twentieth-century warming, and Atlantic hurricane frequency. *Paleoceanography* **22**, PA4204 (2007).
 55. Zhao, M., Eglinton, G., Read, G. & Schimmelmann, A. An alkenone (U37K') quasi-annual sea surface temperature record (A.D. 1440 to 1940) using varved sediments from the Santa Barbara Basin. *Org. Geochem.* **31**, 903–917 (2000).
 56. Matalas, N. C. Statistical Properties of Tree Ring Data. *Int. Assoc. Sci. Hydrol. Bull.* **7**, 39–47 (1962).
 57. Krantz, D. E., Williams, D. F. & Jones, D. S. Ecological and paleoenvironmental information using stable isotope profiles from living and fossil molluscs. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **58**, 249–266 (1987).
 58. Goodkin, N. F., Hughen, K. A., Cohen, A. L. & Smith, S. R. Record of Little Ice Age sea surface temperatures at Bermuda using a growth-dependent calibration of coral Sr/Ca. *Paleoceanography* **20**, (2005).
 59. Hayashi, E. et al. Growth-rate influences on coral climate proxies tested by a multiple colony culture experiment. *Earth Planet. Sci. Lett.* **362**, 198–206 (2013).
 60. Maier, C., Felis, T., Pätzold, J. & Bak, R. P. M. Effect of skeletal growth and lack of species effects in the skeletal oxygen isotope climate signal within the coral genus *Porites*. *Mar. Geol.* **207**, 193–208 (2004).
 61. Saenger, C., Cohen, A. L., Oppo, D. W. & Hubbard, D. Interpreting sea surface temperature from strontium/calcium ratios in *Montastrea* corals: Link with growth rate and implications for proxy reconstructions. *Paleoceanography* **23**, (2008).
 62. Suzuki, A., Hibino, K., Iwase, A. & Kawahata, H. Intercolony variability of skeletal oxygen and carbon isotope signatures of cultured *Porites* corals: Temperature-controlled experiments. *Geochim. Cosmochim. Acta* **69**, 4453–4462 (2005).
 63. Berkelmans, R. & van Oppen, M. J. H. The role of zooxanthellae in the thermal tolerance of corals: a 'nugget of hope' for coral reefs in an era of climate change. *Proc. R. Soc. B Biol. Sci.* **273**, 2305–2312 (2006).
 64. Cohen, A. L. The Effect of Algal Symbionts on the Accuracy of Sr/Ca Paleotemperatures from Coral. *Science* **296**, 331–333 (2002).
 65. Little, A. F., van Oppen, M. J. H. & Willis, B. L. Flexibility in Algal Endosymbioses Shapes Growth in Reef Corals. *Science* **304**, 1492–1494 (2004).
 66. D'Olivo, J. P. et al. Long-Term Impacts of the 1997–1998 Bleaching Event on the Growth and Resilience of Massive *Porites* Corals From the Central Red Sea. *Geochem. Geophys. Geosystems* **20**, 2936–2954 (2019).
 67. Hörhold, M. et al. Modern temperatures in central-north Greenland warmest in past millennium. *Nature* **613**, 503–507 (2023).
 68. Cahyarini, S. Y., Pfeiffer, M. & Dullo, W. Chr. Improving SST reconstructions from coral Sr/Ca records: multiple corals from Tahiti (French Polynesia). *Int. J. Earth Sci.* **98**, 31–40 (2009).
 69. Sayani, H. R., Cobb, K. M., DeLong, K., Hitt, N. T. & Druffel, E. R. M. Intercolony $\delta^{18}\text{O}$ and Sr/Ca variability among *Porites* spp. corals at Palmyra Atoll: toward more robust coral-based estimates of climate. *Geochem. Geophys. Geosyst.* **20**, 5270–5284 (2019).
 70. D'Olivo, J. P., Sinclair, D. J., Rankenburg, K. & McCulloch, M. T. A universal multi-trace element calibration for reconstructing sea surface temperatures from long-lived *Porites* corals: Removing 'vital-effects'. *Geochim. Cosmochim. Acta* **239**, 109–135 (2018).
 71. DeCarlo, T. M. et al. Coral Sr-U thermometry. *Paleoceanography* **31**, 626–638 (2016).
 72. Galochkina, M., Cohen, A. L., Oppo, D. W., Mollica, N. & Horton, F. Coral Sr-U thermometry tracks ocean temperature and reconciles Sr/Ca discrepancies caused by rayleigh fractionation. *Paleoceanogr. Paleoclimatol.* **38**, e2022PA004541 (2023).
 73. Cobb, K. M., Charles, C. D., Cheng, H. & Edwards, R. L. El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature* **424**, 271–276 (2003).

74. Dee, S. et al. PRYSM: An open-source framework for PRoxY System Modeling, with applications to oxygen-isotope systems. *J. Adv. Model. Earth Syst.* **7**, 1220–1247 (2015).
75. Thompson, D. M., Ault, T. R., Evans, M. N., Cole, J. E. & Emile-Geay, J. Comparison of observed and simulated tropical climate trends using a forward model of coral $\delta^{18}\text{O}$. *Geophys. Res. Lett.* **38**, L14706 (2011).
76. Goodkin, N. F., Hughen, K. A. & Cohen, A. L. A multicoral calibration method to approximate a universal equation relating Sr/Ca and growth rate to sea surface temperature. *Paleoceanography* **22**, (2007).
77. Quinn, T. M. et al. A multicentury stable isotope record from a New Caledonia coral: Interannual and decadal sea surface temperature variability in the southwest Pacific since 1657 A.D. *Paleoceanography* **13**, 412–426 (1998).
78. Jones, P. D. et al. High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects. *Holocene* **19**, 3–49 (2009).
79. DeLong, K. L., Quinn, T. M., Taylor, F. W., Shen, C.C. & Lin, K. Improving coral-base paleoclimate reconstructions by replicating 350 years of coral Sr/Ca variations. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **373**, 6–24 (2013).
80. Golyandina, N. & Korobeynikov, A. Basic Singular Spectrum Analysis and forecasting with R. *Comput. Stat. Data Anal.* **71**, 934–954 (2014).
81. Huang, B. et al. Extended reconstructed sea surface temperature, version 5 (ERSSTv5): upgrades, validations, and intercomparisons. *J. Clim.* **30**, 8179–8205 (2017).
82. Huang, B. et al. Improvements of the daily optimum interpolation sea surface temperature (DOISST) Version 2.1. *J. Clim.* **34**, 2923–2939 (2021).

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Conceptualization: A.M.D., T.L. Methodology: A.M.D., T.L. Formal Analysis: A.M.D. Writing – original draft: A.M.D. Writing – review & editing: A.M.D., T.L., M.Y.M., T.F.

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The authors declare no competing interests.

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