Supplementary information for: How variable are marine sea surface temperatures beyond decadal time scales?

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Proceedings of the National Academy of Sciences of the United States of America

SI-1. Overview

The supplementary information is divided into the description of the proxy calibration (SI-2), a discussion of coral based variance estimates (SI-3) an independent check of the signal/noise variance in the proxies (SI-4) and sensitivity tests of our results relative to choices in habitat depth, seasonality, bioturbation depth and our proxy-record selection (SI-5).

SI-2. Proxy calibration

All proxy records of a given type are uniformly calibrated to facilitate spatial comparison (Fig. 5). $U_{37}^{k'}$ records are calibrated using $0.033U_{37}^{K'}/^{\circ}C$; U_{37}^{k} records using $0.035U_{37}^{K'}/^{\circ}C$; and Mg/Ca records, including the Cariaco Basin record [1], using 9.35% Mg/Ca per °C. These choices are the mean of all author calibrations of the analysed datasets and are similar to other standard calibrations: $0.033U_{37}^{K'}/^{\circ}C$ [2] and 9% Mg/Ca per °C [3]. The single exception is a growth rate coral record [4] for which no independent calibration exists. For Sr/Ca and δ^{18}O in corals there is evidence that calibrations based on seasonal relationships lead to an overestimation of interannual and longer temperature variability, possibly because interannual signals are attenuated by calcification occurring at some depth into the coral [5]. We therefore recalibrate all coral estimates to 0.084 (mmol/mol SrCa)/°C and -0.23permil δ^{18}O /°C, which is consistent with interannual calibrations [5] (see also Section SI-3). The use of common calibrations that are confirmed by spatial calibrations and lab-experiments avoids issues associated with local and temporal calibrations [6]. Note, that the recalibration also affects the reported errors and replicate statistics.

SI-3. Reliability of coral-based estimates of marine variability

There are several classes of uncertainties associated with coral proxy records of sea surface temperature variability. For δ^{18}O proxies, the δ^{18}O of coral skeletons are temperature sensitive but are also influenced by the δ^{18}O of ambient seawater. Thus, changes in lateral and horizontal advection in the near surface ocean and changes in the balance of precipitation and evaporation will affect the signal. Our selection of δ^{18}O proxies reported to be mainly sensitive to temperature reduces but cannot wholly exclude this effect, perhaps especially on longer timescales [7]. The mechanistic relationship between Sr/Ca uptake and temperature involves numerous uncertainties. Sr/Ca uptake in corals may be affected by symbionts [8], growth rate [9], changes in the sea-water Sr/Ca, and the sampling process because of heterogeneity in coral ratios. See refs. [10] and [11] for more details.

Observational studies [5] indicate that seasonal signals in coral records can be attenuated because calcification occurs over a depth range that partially integrates across more than a single season. This attenuation appears to be limited to less-than-decadal timescales, however, and we use the calibiration proporsed by Gagan et al. [5] as appropriate for decadal and longer timescales. In particular, for Sr/Ca we use 0.084 (mmol/mol SrCa)/°C and for δ^{18}O we use -0.23permil/°C. The implication is that we may somewhat underestimate interannual temperature variability using this calibration, which appears to be the case in comparisons between coral and instrumental SST spectral estimates (Fig. 3B, inset, Fig. S4). The approach of a single calibration for each coral proxy type is confirmed by comparing the spatial variance pattern of the coral records and instrumental SST. The recalibrated records correlate better to the instrumental SST variance pattern (R=0.84 recalibrated) than when using the individual calibrations published along with each record (R=0.26).

To further examine the calibration and the skill of the corals in recording SST variability, we compare the variability of coral SSTs against instrumental SSTs across different sites on interannual and interdecadal timescales (Fig. S4). There is a good correspondence between these independent estimates of temperature variance, showing a correlation of 0.93 on interannual and 0.53 on interdecadal timescales, but it is also useful to discuss those records for which there are disagreements in more detail. One outlier is the Sr/Ca record of Kilbourne et al. (2008) [12] that shows significantly more variability than the instruments. Another outlier is the proxy record reported by Dunbar et al. (1994) [13] that shows lower than instrumental variance, possibly reflecting the sparse instrumental measurements available in the earlier part of the century.

To test the sensitivity of our results to uncertainties in coral-based proxy estimates of marine temperature variability, we recalculate the spectra using only Sr/Ca coral records as well as only using the five corals most consistent with the instrumental variability at interdecadal timescales (Fig. S5). The SST variability reconstructed only from Sr/Ca (6 records) is very close to the SST variability using all records. The variability reconstructed from the five records that are closer to the decadal instrumental SST variance (Fig. S4) shows somewhat less variability but a similar scaling behavior and these

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estimates remain much greater than the GCM estimates at the corresponding locations.

SI-4. Signal-to-noise estimates

One class of explanations for the model-data mismatch discussed in the main manuscript has to do with proxy noise, though this appears an unsatisfactory explanation. Such an explanation would require that proxy noise have an order of magnitude or more the variance in the proxy records as does the actual marine temperature variability signal. Below, two approaches are offered for estimating the ratio of temperature-to-noise variance, referred to as signal-to-noise ratios (SNR), and both show that the SNR is close to one.

SI-4.1 Forward model approach. The forward model of the signal and noise component described in [14] can be used to obtain an estimate of signal-to-noise ratios (SNR) for Mg/Ca and Uk37 based on our knowledge of the sampling process and instrumental temperature variability. The procedure that we use is to generate random timeseries following the spectral model with $\beta = 1$, corrupt them using the sampling regime found in the individual cores [14], and then apply the core-specific noise level, σ, and bioturbation with $\delta = 10$cm. Comparing the corrupted time-series and the original time-series after resampling both to a 250yr resolution results in a SNR estimate. An SNR of 0.5 is found as an average across all Mg/Ca records and 1.6 for Uk37. The lower proportion of signal relative to noise found for Mg/Ca records is in keeping with the greater variance correction that is applied to these records (Fig. 3).

SI-4.2 Correlation approach. An independent estimate of the SNR can be obtained from a comparison of nearby cores. Given a pair of cores with perfect time control and a signal shared entirely in common and each containing noise independent of the other, the SNR is simply $R/(1-R)$ where R is the correlation coefficient between both time series [15]. A complication, however, is that in our dataset most pairs of cores are separated in space such that the signal component cannot be expected to be closely correlated. To account for this effect we use climate model simulations to estimate the covariance of the signal component at each pair of core site locations as described further below. It is also possible that errors would be correlated, tending to bias the SNR high, but we have no evidence that this is the case. Further, temperature time series derived from sediment cores have a relative timing that is uncertain, tending to decrease the sample correlation coefficient and bias the SNR estimate low, but we do not account for either timing error or correlated noise in our estimates.

All pairs of cores that are less than 5000 km apart are examined. 5000 km approximates the centennial timescale decorrelation decay length, chosen as being somewhat larger than the 3800km decay length estimated at decadal timescales [16] under the expectation that longer timescales of variability also have larger spatial scales and because this affords sufficient samples for the statistical analysis. Note that we also include records with a mean temporal resolution of less than 150 years (Table S3) because restricting the analysis to cores with less than 100 year average sample resolution would give only three pairs of Mg/Ca separated by less that 5000 km. Every timeseries is resampled to a 250 year resolution and linearly detrended, thereby giving a consistent treatment with respect to the spectral analysis procedure.

The mean correlation of all pairs of each proxy type are computed. The null hypothesis of no relationship between records can be rejected for both Uk37 (p=0.01) and Mg/Ca records (p=0.02), which then strongly indicates that a common signal is present. To examine whether the forward modeling results presented earlier are consistent with the observed proxy correlation, we sample the 6000 year GCM simulation (orbital only) at the position of the cores using 250 year block averages. We add white noise to every model time series in order to obtain SNR between 0.1 and 10. Repeating this procedure 1000 times gives a distribution of mean correlations for the chosen SNR. An estimate of the SNR is then obtained by matching the correlation obtained from the model plus noise timeseries and the sample proxy correlation. This procedure results in a best estimate of 1.2 SNR for Mg/Ca and 1.4 SNR for Uk37. The difference between the Mg/Ca and Uk37 SNRs is qualitatively in the same direction as in the previous estimate from the forward model, though the Mg/Ca estimate is higher and the Uk37 estimate lower.

It is also possible to evaluate the uncertainty in the SNR estimates from correlation. We find that the proxy correlation is well inside the 95% range of the model plus noise correlation distribution when choosing the noise level to match an SNR of 0.5 for Mg/Ca and 1.6 for Uk37 (Fig. S1). This demonstrates consistency between our independent estimates of SNR derived variously from correlations and the forward spectral correction algorithm.

A number of choices are made in the foregoing estimates of SNR including those associated with bioturbation intervals, model derived estimates of covariance, and interpolation intervals. Although a full discussion of the robustness of these result could be provided, it suffices to say that values of SNR having a magnitude near one are consistently arrived at. SNR magnitudes of less than 0.1 would be needed to bring the proxy-observed and GCM-simulated marine variability into consistency with one another. Therefore, we conclude that both independent methodologies for estimating SNR indicate that the model-data mismatch in variance is not ascribable to noise.

SI-5. Sensitivity tests

The analysis presented here necessitates the selection of certain parameters and models. Here we discuss how the sensitivity of our results to these selections are small relative to the model-data discrepancy that is identified and that the consistency between the various proxy estimates of marine temperature variability is robust.

SI-5.1 Depth and seasonality. Foraminifera and alkenone producers do not evenly record the seasonal cycle nor do they monitor conditions exactly at the sea surface. For a more detailed discussion regarding seasonal and habitat influence on the recording of temperature see ref. [17] and references therein. To examine the influence of recording specific seasons or depths we additionally analysed GCM-produced variability in summer (JJA in the Northern Hemisphere, DJF in the Southern Hemisphere) and winter (DJF in NH, JJA in SH) as well as at 27m depth. Results show a small increase in variability at all timescales when considering seasonal temperature or considering subsurface temperature (Fig. S6). The latter is caused by the greater vertical advection of temperature anomalies. However, the scaling behavior of the variability is not affected and the magnitude of the increase is small relative to the model-proxy mismatch.

SI-5.2 Bioturbation depth assumption. Assuming no bioturbation leads to a small decrease in the estimated proxy SST variability of -18% for Uk37 and -19% for Mg/Ca. Assuming that bioturbation acts over a 20cm vertical scale increases the estimated SST variability by 32% for Uk37 and 49% for Mg/Ca. Again, these changes are small relative to the order-of-magnitude discrepancies between models and data. For both Uk37 and Mg/Ca, the misfit between observed and estimated spectra in the spectral correction process [14] is smallest when assuming a 10cm bioturbation width.

SI-5.3 Inclusion of more records. Only those records having an average sampling interval of less than 100 years were included. As discussed in [14], it is difficult to correct for sampling and measurement noise in more coarsely resolved records. Nonetheless, accepting records that have a 150 year average sampling interval (Table S3) gives 4 more Mg/Ca and 5 more Uk37 records and does not change the main results (Fig. S8) but does lead to more scatter in variance ratios (i.e. those shown in Fig. 5), as expected from the Monte Carlo experiments [14].

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Table S1. Proxy data used in the main study

Name	Ref.	Lat. $^\circ N$	Lon. $^\circ E$	sed. rate (cm/kyr)	mean Δt (yr)	interp. Δt (yr)	duration (yr)	proxy	error 1sd ($^\circ C$)
Caledonia	[18]	-22.5	166.5		1	1	333	δ^{18}O	0.22
Galapagos	[13]	-0.4	-91.2		1	1	346	δ^{18}O	0.29
Guam	[19]	13.6	144.8		1	1	208	δ^{18}O	0.10
Gr.Barrier Reef	[20]	-18.0	146.5		5	5	415	Sr/Ca	0.06
Rarotonga 2R	[21]	-21.5	-159.5		1	1	268	Sr/Ca	0.17
Bermuda	[9]	32.0	296.0		1	1	216	Sr/Ca	0.11
Flinders reef	[22]	-17.5	148.3		5	5	280	Sr/Ca	0.11
Turrumote	[12]	17.9	293.0		1	1	253	Sr/Ca	0.30
Fiji 1F	[23]	-16.8	179.2		1	1	215	Sr/Ca	0.17
Bahamas	[4]	25.8	-78.6		1	5	439	growth rate	0.07
Cariaco Mg/Ca	[1]	10.8	295.2		1.4	2	769	Mg/Ca G.bulloides	0.17
MD03-2707	[24]	2.5	9.4	55	36	100	6600	Mg/Ca G.ruber (pink)	
MD98-2176	[25]	-5.0	133.4	50	43	100	6818	Mg/Ca G.ruber (white)	
MD99-2155	[26]	57.4	-27.9	166	52	100	6440	Mg/Ca G.bulloides	
MD99-2203	[27]	35.0	-75.2	53	19	100	6374	Mg/Ca G.ruber (white)	
MD98-2181	[25]	6.3	125.8	80	43	150	6969	Mg/Ca G.ruber (white)	
MV99-GC41/PC14	[28]	25.2	247.3	79	90	150	6091	Mg/Ca G.bulloides	
SO90-39KG/56KA	[29]	24.8	65.9	123	20	100	4880	Uk'37	
GeoB6007	[30]	30.9	-10.3	65	31	100	6750	Uk'37	
MD97-2151	[31]	8.7	109.9	39	49	100	6020	Uk'37	
SSDP-102	[32]	35.0	128.9	216	61	150	6870	Uk'37	
IOW 225514	[33]	57.8	8.7	66	72	150	5980	Uk'37	
CH07-98-GGC19	[34]	36.9	-74.6	27	68	150	6470	Uk'37	
OCE326-GGC30	[34]	43.9	-62.8	30	72	150	6940	Uk'37	
KR02-06	[35]	36.0	141.8	30	51	150	7013	Uk'37	
MD952011	[36]	67.0	7.6	74	58	200	6450	UK37	
MD01-2412	[37]	44.5	145.0	95	73	200	6920	Uk'37	
D13882	[38]	38.6	-9.5	55	53	200	6530	Uk'37	
IOW 225517	[33]	57.7	7.1	52	94	200	5170	Uk'37	
JR51-GC35	[39]	67.0	-18.0	48	98	200	6880	UK37	
GeoB 3313-1	[40]	-41.0	-74.5	107	90	200	6930	Uk'37	
GeoB 5901-2	[30]	36.4	-7.1	13	80	200	5840	Uk'37	
SO139-74KL	[41]	-6.5	103.8	106	78	200	5870	Uk'37	

Errors reported above are relative to the interpolated resolution and are converted to ($^\circ C$) using the calibrations described in (Sec. SI-2). For the Guam coral, only the variability from an internal standard was reported and the mean replicate variability from the two other δ^{18}O coral studies (0.0835 permil) is assumed. For Flinders Reef a 0.1% error is assumed because the reported 0.02% only represent the analytical error. For Fiji 1F and Rarotonga 2R we understood that uncertainty rates were of 0.48% (personnel communication, Braddock Linsley 05 Jun 2012) and later that they were 0.15%, in accord with values published in Linsley et al. (2000) and Linsley et al. (2004) (personnel communication, Braddock Linsley 18 Oct 2014). We have assumed the larger uncertainty rate in all calculations, though have also calculated results for the smaller 0.15% rate, which would lead to less than a 1% change in the overall coral variance estimate, being thus unimportant for our particular results. Sedimentation rates are mean values over the last 7kyr or over the duration of the record, whichever is shorter. Duration is the length of the record inside the 7kyr BP to present day interval used in this study where BP is with respect to 1950 AD.

Table S2. Model simulations

Name	No.	Model components	Forcing	Resolution	Time	Ref.
Millennium-Forced	5	ECHAM5 (atmosphere) MPIOM (ocean) HAMOCC5 (biogeochem.) JSBACH (land)	solar, volcanic aerosols, GHG (CO2 interactive), land-cover, orbital	atmosphere (T31), ocean (22-350km)	800-2005 CE	[42]
Millennium-CTRL	1	ECHAM5 (atmosphere) MPIOM (ocean) HAMOCC5 (biogeochem.) JSBACH (land)	preindustial boundary conditions, no forcing	atmosphere (T31), ocean (22-350km)	3100yr	[42]
Orbital	1	ECHAM5 (atmosphere) MPIOM (ocean) JSBACH (land) +interactive vegetation	orbital	atmosphere (T31), ocean (22-350km)	4000BCE - 2000 CE	[43]
CMIP5/PMIP3 past1000	15	coupled ocean atmosphere models	full forcing [44]	varies	850-1850CE	[45, 46]
TraCE-21ka	1	CCSM3	GHG, orbital, ice sheets,paleogeography, meltwater	T31gx3v5	last 21kyr	[47]

Table S3. Proxy data $\Delta t \geq$100yr, used in Sec. SI4.2 and SI5.3

Name	Ref.	Lat. $^{\circ}N$	Lon. $^{\circ}E$	sed. rate (cm/kyr)	mean Δt (yr)	interp. Δt (yr)	duration (yr)	proxy
ODP1084B	[48]	-25.5	13.3	9	126	200	6916	Mg/Ca G. bulloides
A7	[49]	27.8	127.0	11	125	200	5866	Mg/Ca G. ruber
MD01-2378	[50]	-13.1	121.8	22	131	200	6300	Mg/Ca G. ruber
RAPID-12-1K	[51]	62.1	-17.8	21	100	200	6909	Mg/Ca G. bulloides
MD952015	[52]	58.8	-26.0	50	101	200	6260	UK'37
ODP 658C	[53, 54]	20.8	-18.6	21	100	200	6900	UK'37
ODP 1019C	[55]	41.7	-124.9	40	132	200	6840	UK'37
MD95-2043	[56]	36.1	-2.6	37	133	200	5980	UK'37
OCE326-GGC26	[34]	43.5	-54.9	30	128	200	6770	UK'37

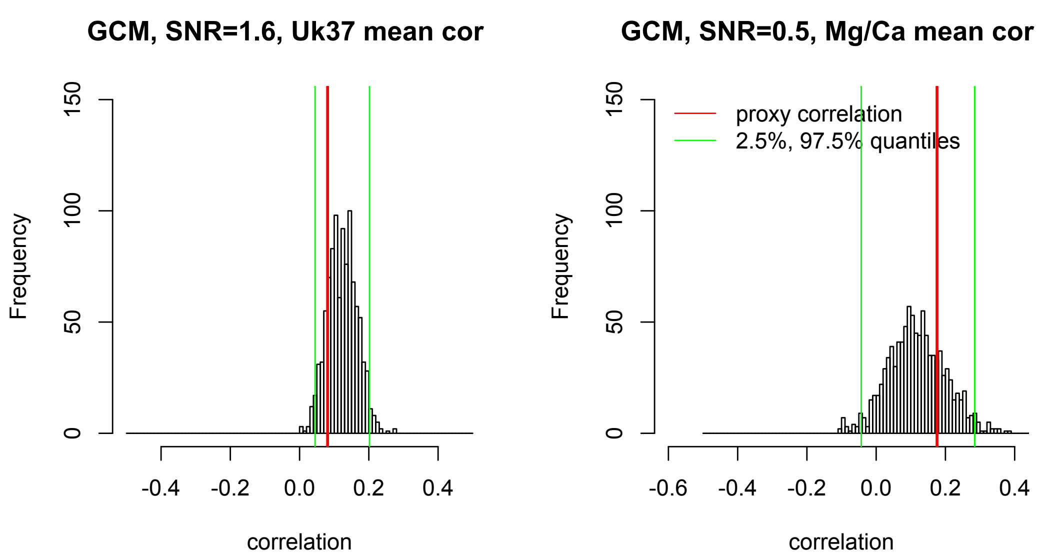

Fig. S1. Check of consistency between the forward model and correlation based approaches for estimating signal-to-noise ratios (SNRs). To obtain SNRs equivalent to those estimated from the forward model for Mg/Ca and Uk37, white noise is added to GCM temperature simulations at the proxy positions. The observed average proxy correlations, indicated by a vertical red line, are inside the distribution of the simulated correlations, showing consistency between the two different estimates of SNR. The 2.5 and 97.5 quantiles of the simulated correlations are indicated by green vertical lines.

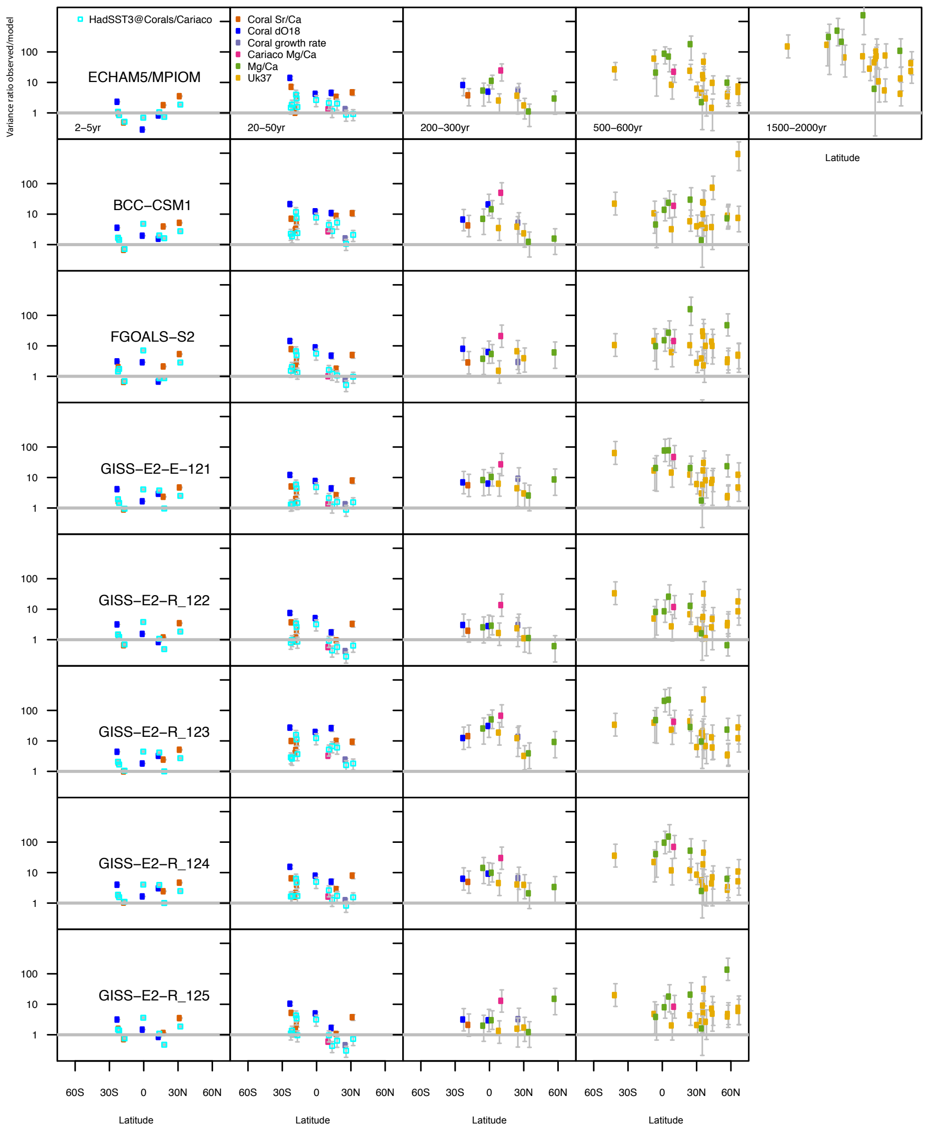

Fig. S2. Latitudinal dependence of the model-data mismatch at different timescales for the CMIP5/PMIP3 past1000 simulations. See Fig. 5 for the full caption. In the first row, ECHAM5/MPIOM is shown as a reference. As the past1000 simulations contain only the last millenium, the millenial variance ratio could not be estimated.

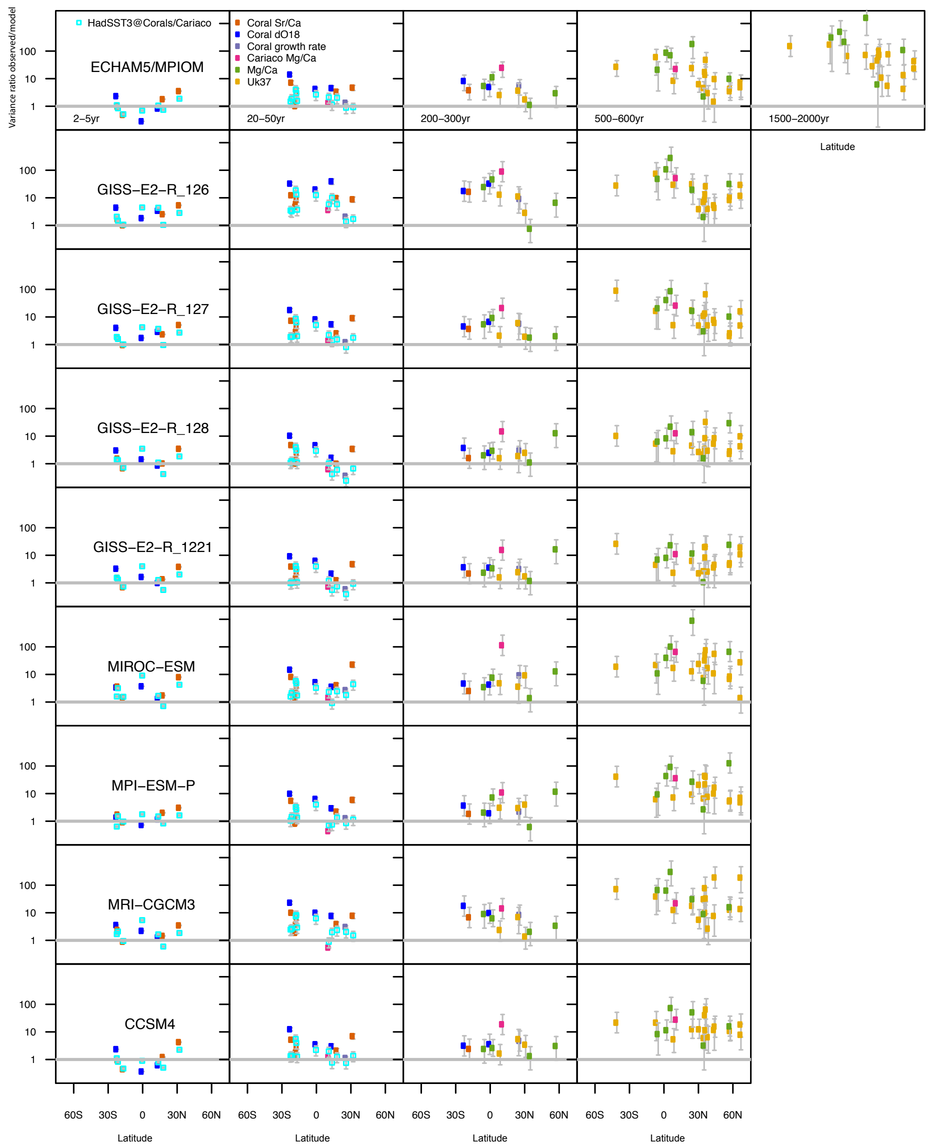

Fig. S3. Latitudinal dependence of the model-data mismatch at different timescales for the CMIP5/PMIP3 past1000 simulations, continuation

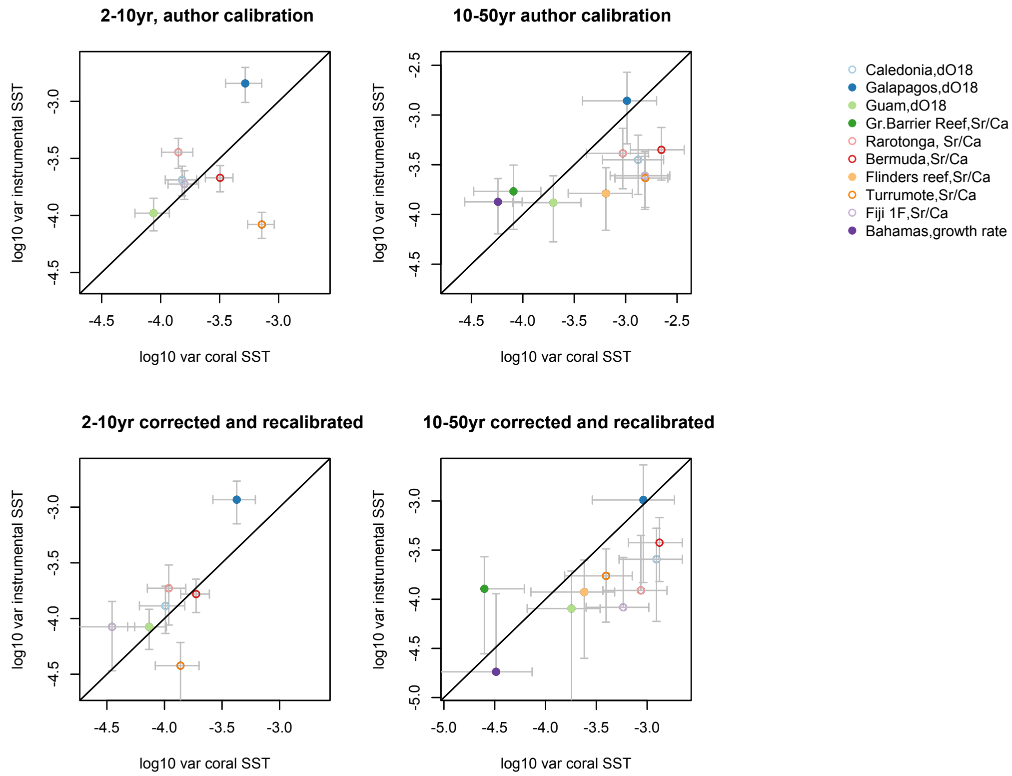

Fig. S4. Comparison of instrumental (HadSST3) and coral based SST variance for interannual (left column) and interdecadal (right column) timescales. Top row: uncorrected instrumental and proxy data using the authors calibration; lower row: variances corrected for sampling and measurement error using the common calibration. Using the common calibration increases the correlation between instrumental and coral SST variance. On interannual timescales coral proxies tend to underestimate variability, as expected from the selected calibration [5]. At interdecadal timescales some corals tend to overestimate variability, possibly because the biological-smoothing effect was underestimated or because proxy noise has been underestimated or measurement noise was overestimated. The records most consistent with the instrumental data regarding interdecadal variability are marked as filled dots and analysed separately in a sensitivity experiment (Fig. S5).

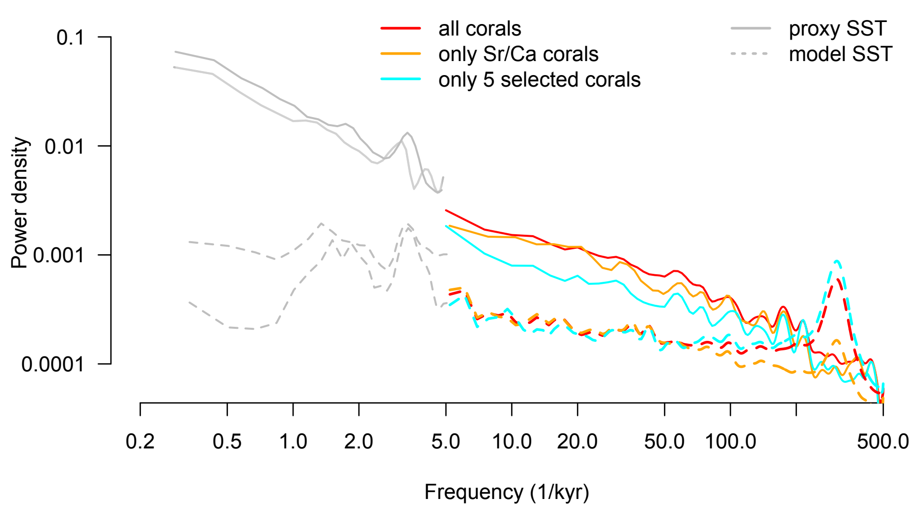

Fig. S5. Sensitivity of spectral results to the choice of coral proxies. As main Fig. 3B but only using Sr/Ca records or only using the five records that are closest in variability to their instrumental counterparts (Fig. S4). In addition, the GCM SST spectrum, sampled at the coral position is shown. In either case, the corals show a scaling similar to that of the entire collection and much greater variability than the GCM results.

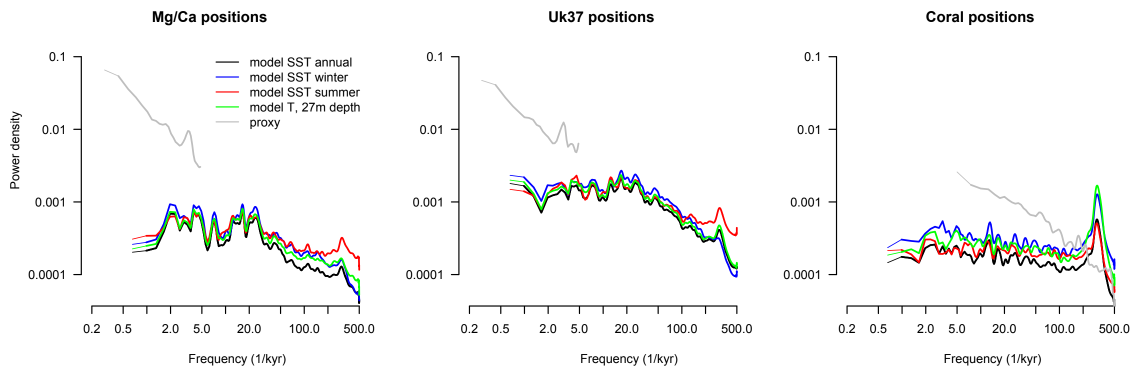

Fig. S6. Dependence of marine temperature variability on season and water depth in the ECHAM5/MPIOM unforced control simulation. Shown is variability for annual, summer, and winter surface conditions as well as annual conditions at 27m depth at the Mg/Ca core site positions (left panel) and the Uk37 core sites (right panel). A small increase in variability is observed in each case relative to the annual average surface conditions that is largely frequency independent. Depth has a greater influence at the Mg/Ca than Uk37 core positions because of the shallower mixed layer depth in the tropics where many of the Mg/Ca records are located.

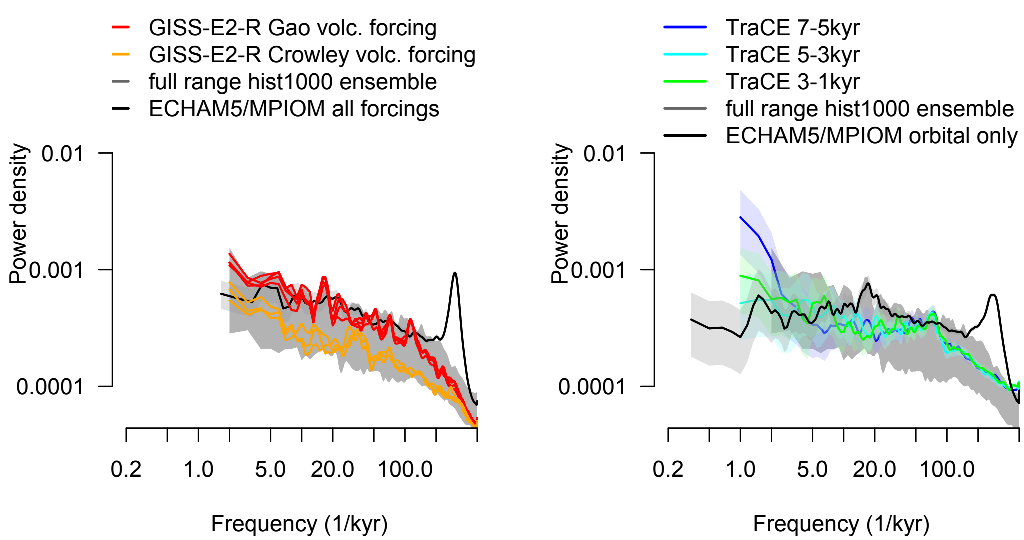

Fig. S7. Dependence of simulated marine temperature variability on the forcing. Volcanic forcing (left panel): GISS-E2-R [57] ensemble members p122,p125,p128,p1221 using the stronger Gao et al., volcanic forcing [58] are on the upper end of the CMIP5/PMIP3 model envelope (grey) whereas the ensemble members from the same model but using the Crowley et al, [59] forcing are on the lower side of the envelope. Freshwater forcing (right panel): The 7-5kyr BP section of the TraCE-21ka model simulation [47], which includes freshwater forcing, shows more variability on multicentennial and millenial timescales than later time periods without freshwater forcing

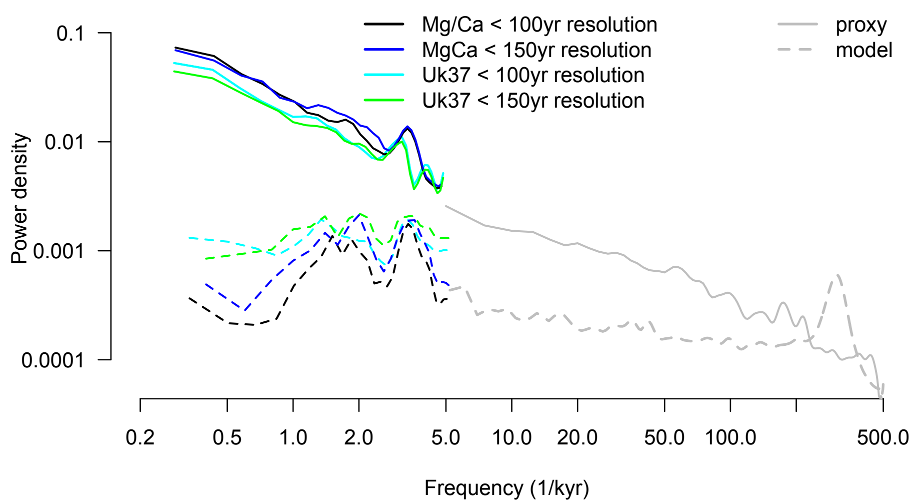

Fig. S8. Sensitivity of average spectra to inclusion of lower-resolution proxy records. Proxy spectra are after filtering for measurement and sampling errors and GCM spectra are at the proxy positions for records with a mean resolution less than 100 years and including records with an average resolution of up to 150 years (Table S3). There is little difference when these additional records are included.