What do past climates really tell us about El Niño?

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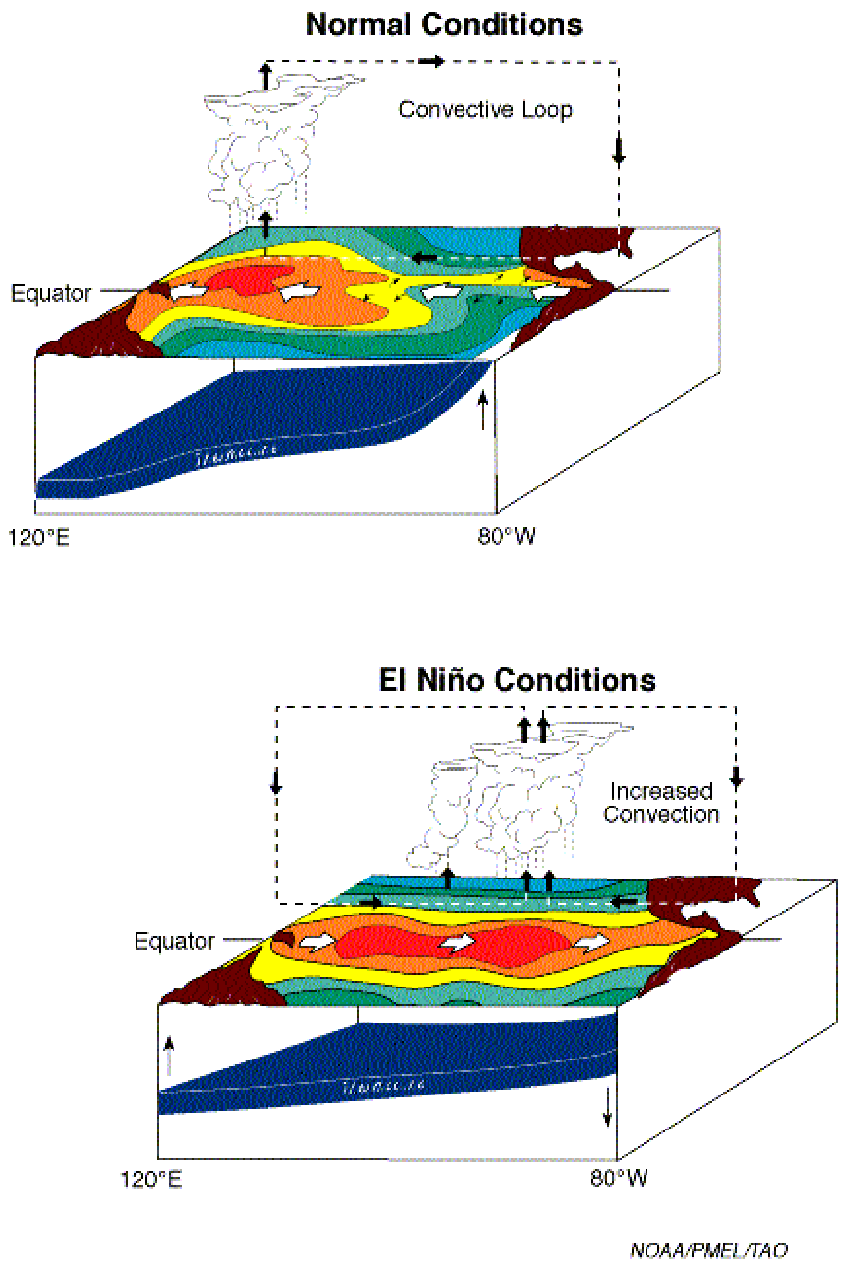
Overview

- El Niño and global climate change
- What do past climates *really* tell us?
- A cautionary tale regarding wavelet spectra

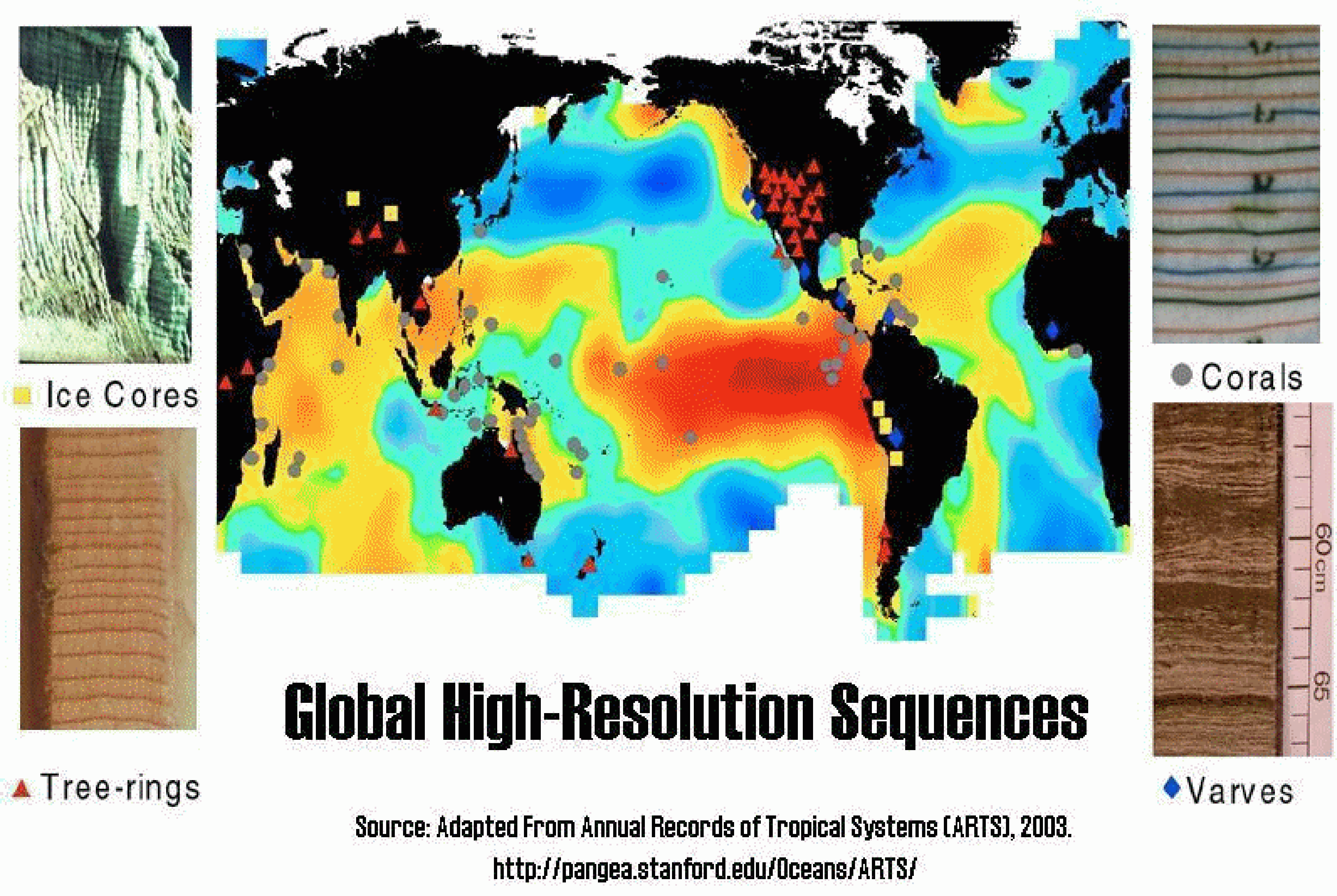
El Niño and global climate change

What is El Niño?

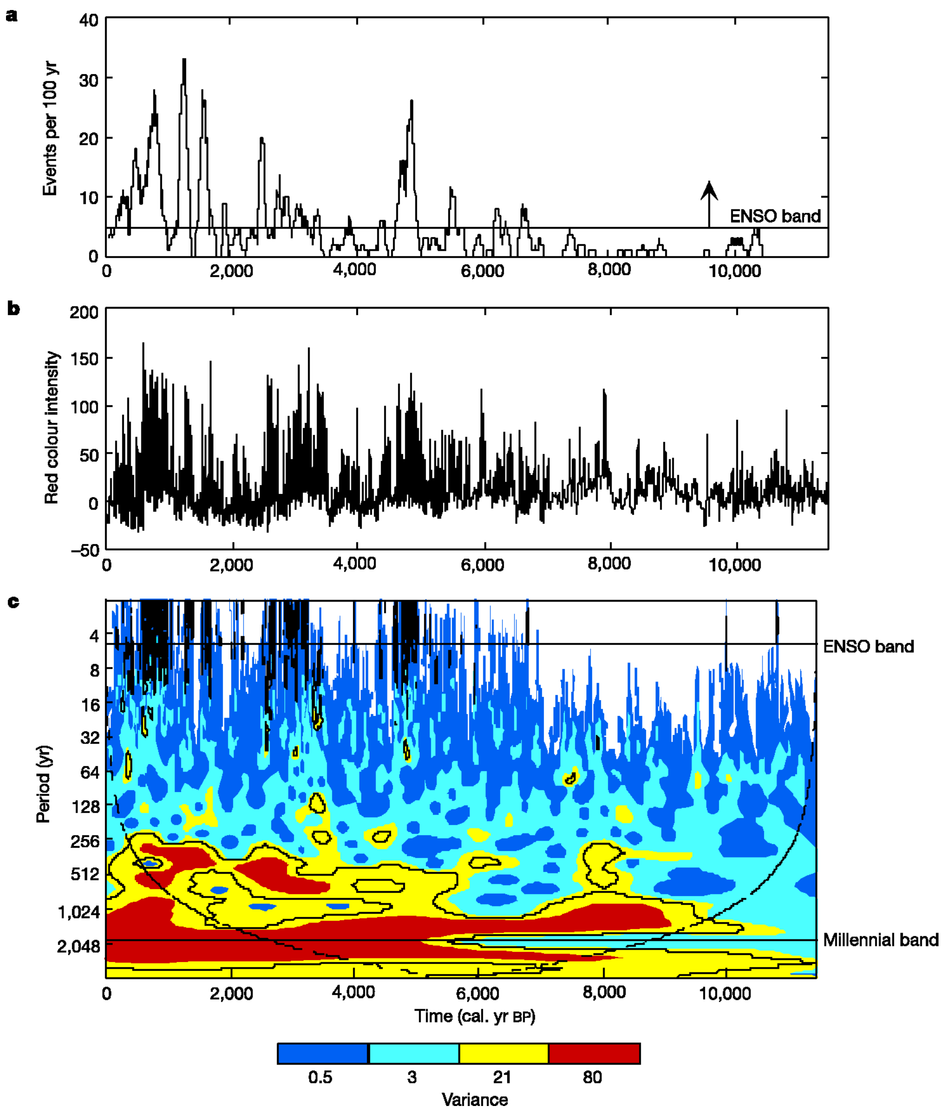


- El Niño–Southern Oscillation (ENSO) is the dominant mode of internal variability within the coupled atmosphere-ocean system
- Irregular period of ∼2–7 years
- Average state of the system involves strong easterly trade winds pushing warm water to the east
- In an El Niño event, these winds slacken and the warm water flows eastwards
- Increased rainfall in the eastern Pacific, reduced rainfall in the west

Evidence of past El Niño events is all around us



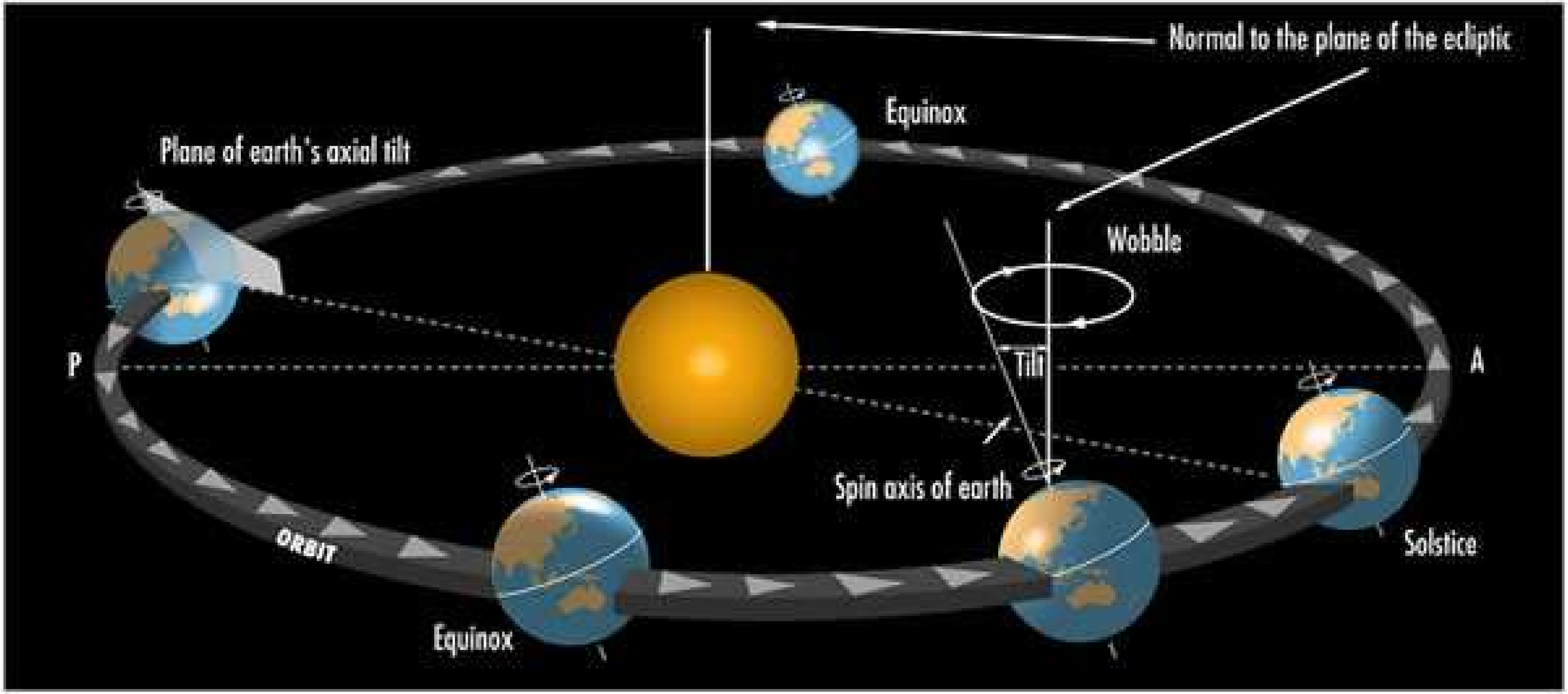
El Niño has changed ...



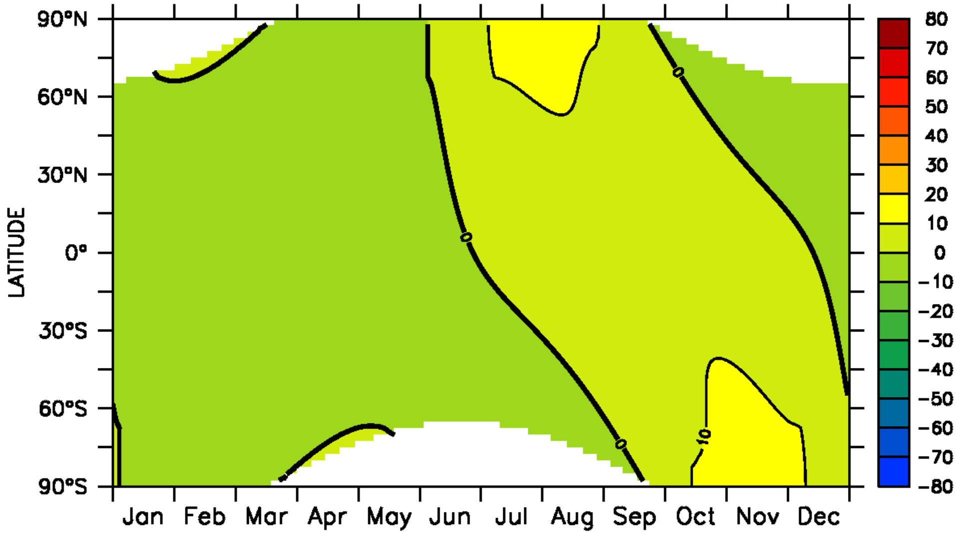
Moy et al. (2002), *Nature*

- "Modern" El Niño began 7–5 ka BP, with only weak decadal-scale variability beforehand
- El Niño was 15–60% weaker at 6 ka BP than at present
- Gradual strengthening of El Niño thereafter
- Evidence of a peak in variability at 2–1 ka, possibly earlier in the western Pacific than in the east

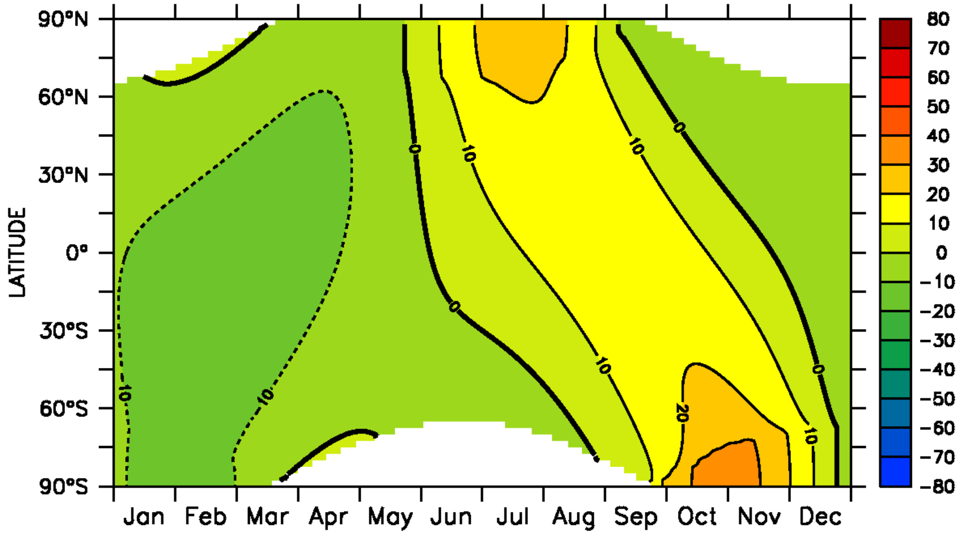
... driven by changes in the Earth's orbital geometry ...



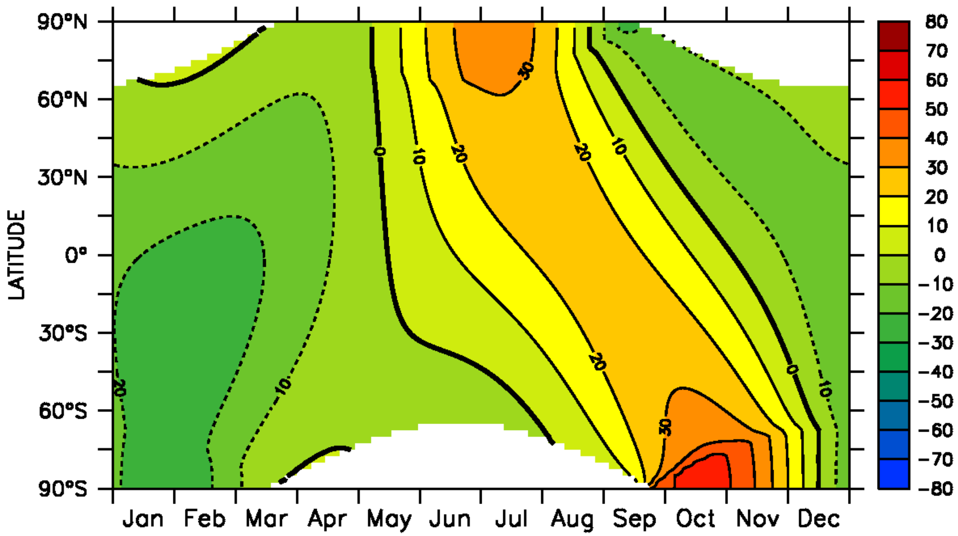
… which cause large changes in seasonal insolation



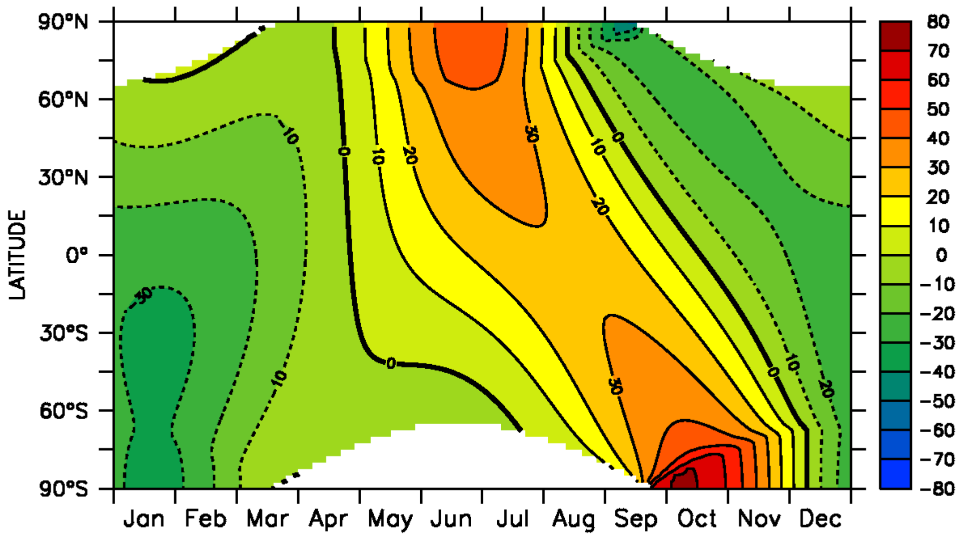
Insolation anomaly (Wm^{-2}): 2 ka BP



Insolation anomaly (Wm^{-2}): 4 ka BP



Insolation anomaly (Wm^{-2}): 6 ka BP



Insolation anomaly (Wm^{-2}): 8 ka BP

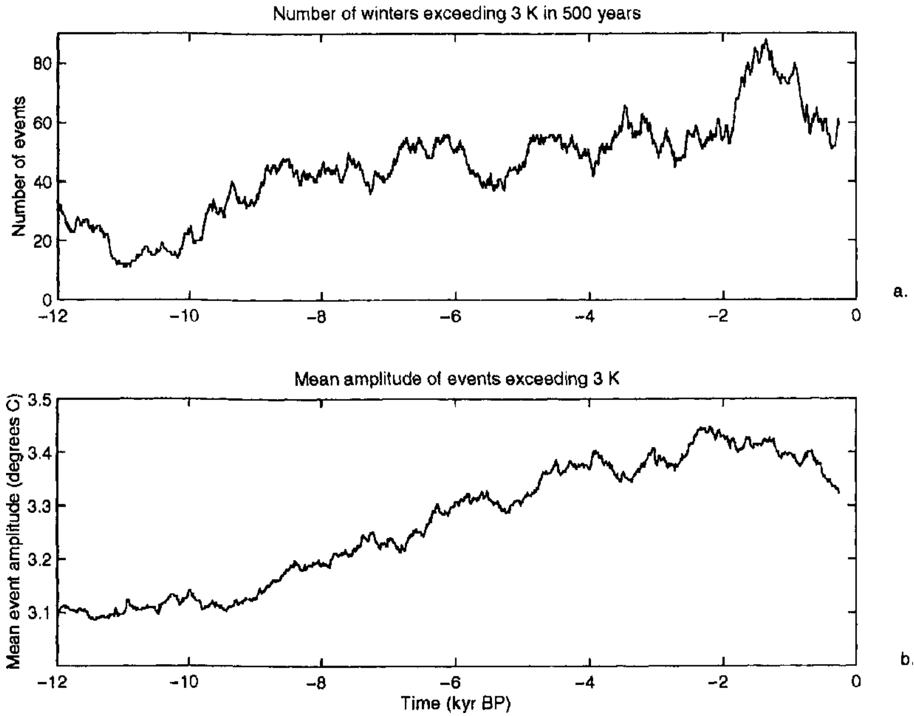
Coral records: mid-Holocene versus present day

	Age (ka)	**Location**	**% change in ENSO variance**
Tudhope et al (2001)	6.5	Papua New Guinea	-60
McGregor and Gagan (2004)	7.6–5.4	Papua New Guinea	-15

- ENSO variance is derived by calculating the standard deviation of the $\delta^{18}O$ ratio, and then applying a bandpass filter
- These two studies form the basis for the quoted uncertainty range of 15–60% (e.g. Brown et al, 2008)

Early modelling work

- Clement et al. (2000):
  - Used the Zebiak-Cane model to simulate the past 12 ka
  - Simple atmosphere-ocean model; restricted to the tropical Pacific
  - Established that orbitally-driven changes in the seasonal cycle of insolation in the tropics can alter ENSO behaviour



Coupled modelling studies: 6 ka versus 0 ka BP

	Model	Diagnostic	% change
Otto-Bliesner (1999)	CSM	Niño 3	$\sim$0
Liu et al. (2000)	FOAM	Niño 3.4	-20
Phipps (2006)	Mk3L-1.0	Niño 3.4	-13
Brown at al. (2006)	HadCM3	Niño 3	-12
Brown et al. (2008)	HadCM3	Niño 3	[-14, +19]
Zheng et al. (2008) (PMIP2)	CCSM3	Niño 3	-18.6
	FGOALS-1.0g		-14.6
	FOAM		-11.6
	IPSL-CM4		-2.9
	MIROC3.2		-22.5
	MRI-CGCM2.3.4fa		+3.3
	MRI-CGCM2.3.4nfa		-12.9

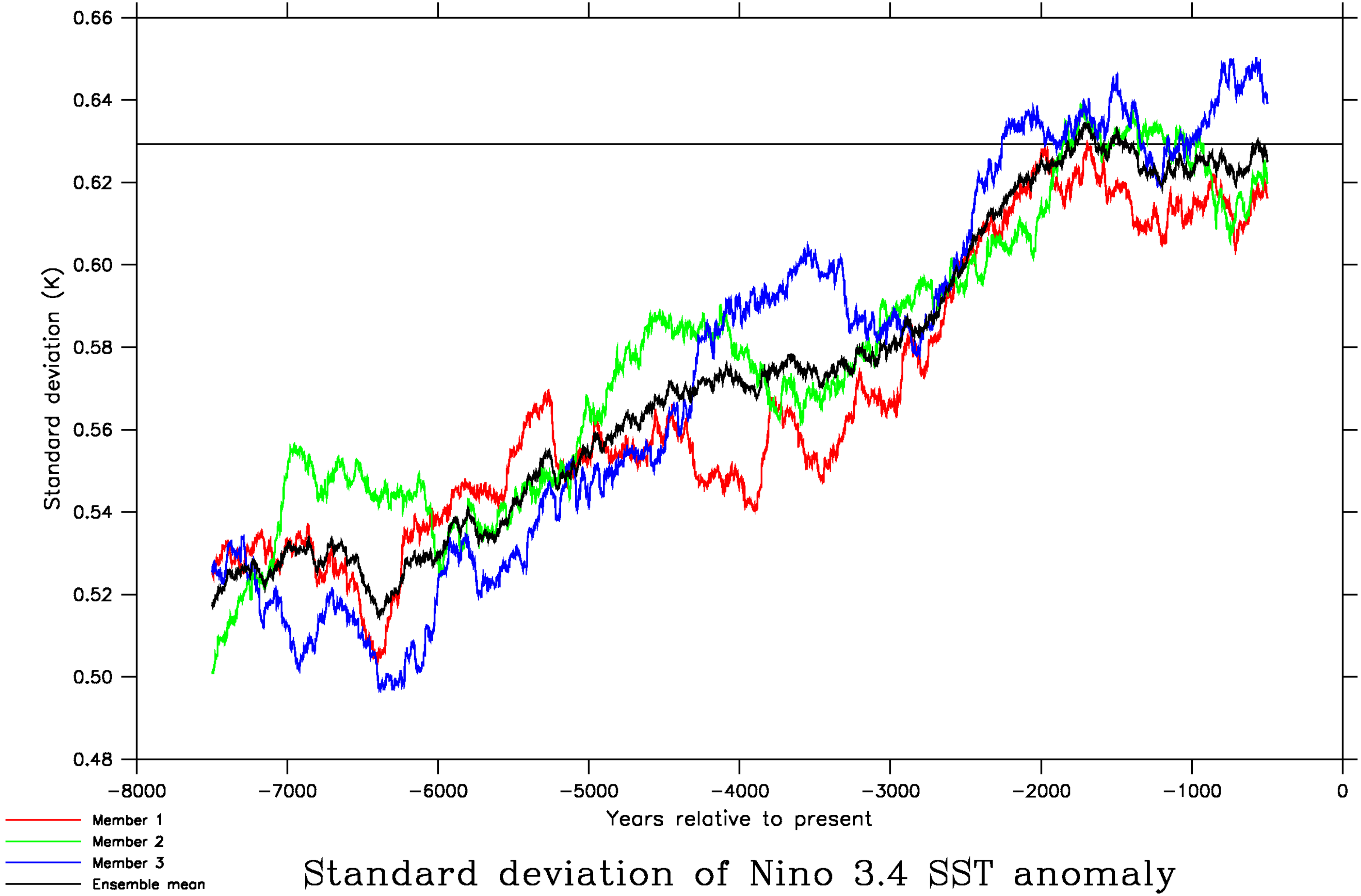
A picture begins to emerge?

- Broadly consistent mechanism found to explain weaker mid-Holocene ENSO:
  - Insolation changes result in enhanced seasonal cycle in NH
  - Intensification of summer monsoon system
  - Enhanced Walker circulation
  - Stronger easterly trade winds in central and western Pacific
  - Steeper thermocline/increased upwelling in central and eastern Pacific
  - Suppresses development of El Niño events
- However, this proposed mechanism is qualitative in nature and has yet to be rigorously tested

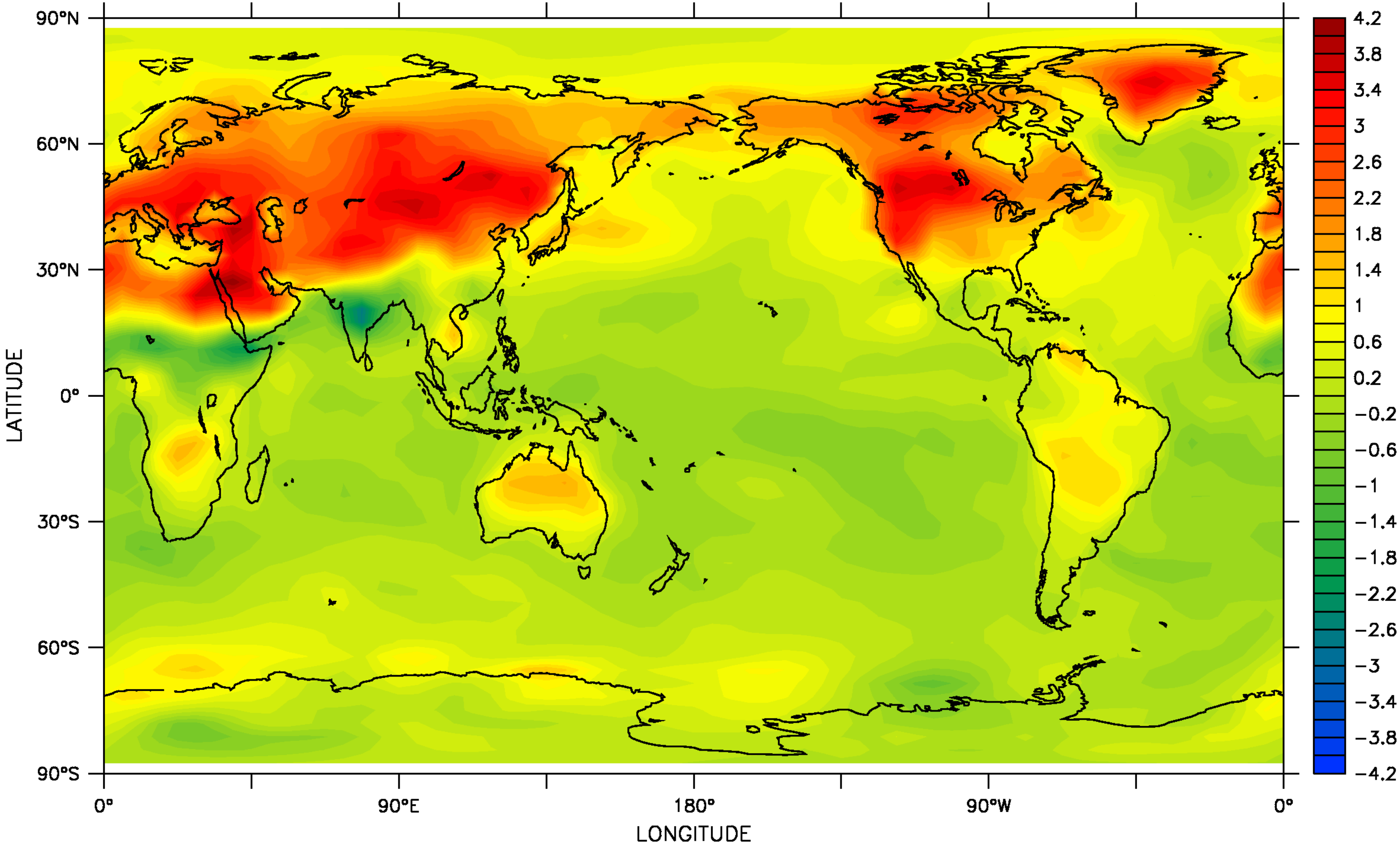
Exploring ENSO in a climate system model

- CSIRO Mk3L climate system model v1.1:
  - Atmosphere: $5.6^\circ \times 3.2^\circ$, 18 vertical levels
  - Ocean: $2.8^\circ \times 1.6^\circ$, 21 vertical levels
  - Sea ice: Dynamic-thermodynamic
  - Land surface: Static vegetation
  - Can simulate 1000 years in a month
- Three transient simulations of the past 8,000 years:
  - Only the Earth's orbital geometry is varied
  - Atmospheric CO_2 concentration = 280ppm
  - Solar constant = 1365 Wm^{-2}
  - The three ensemble members differ only in the initial conditions

Simulated changes in ENSO variability

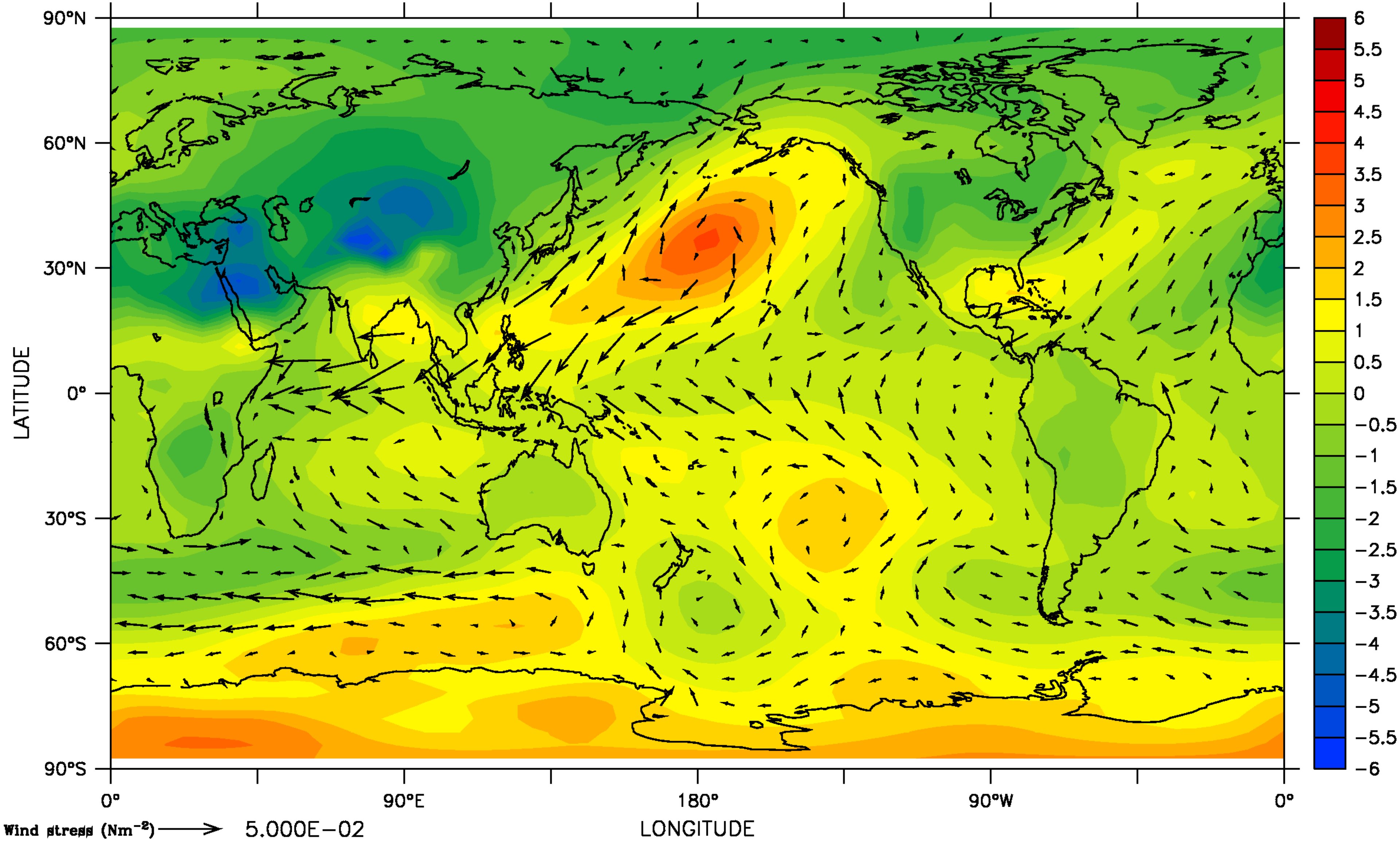


Northern Hemisphere summers were warmer at 8 ka BP ...



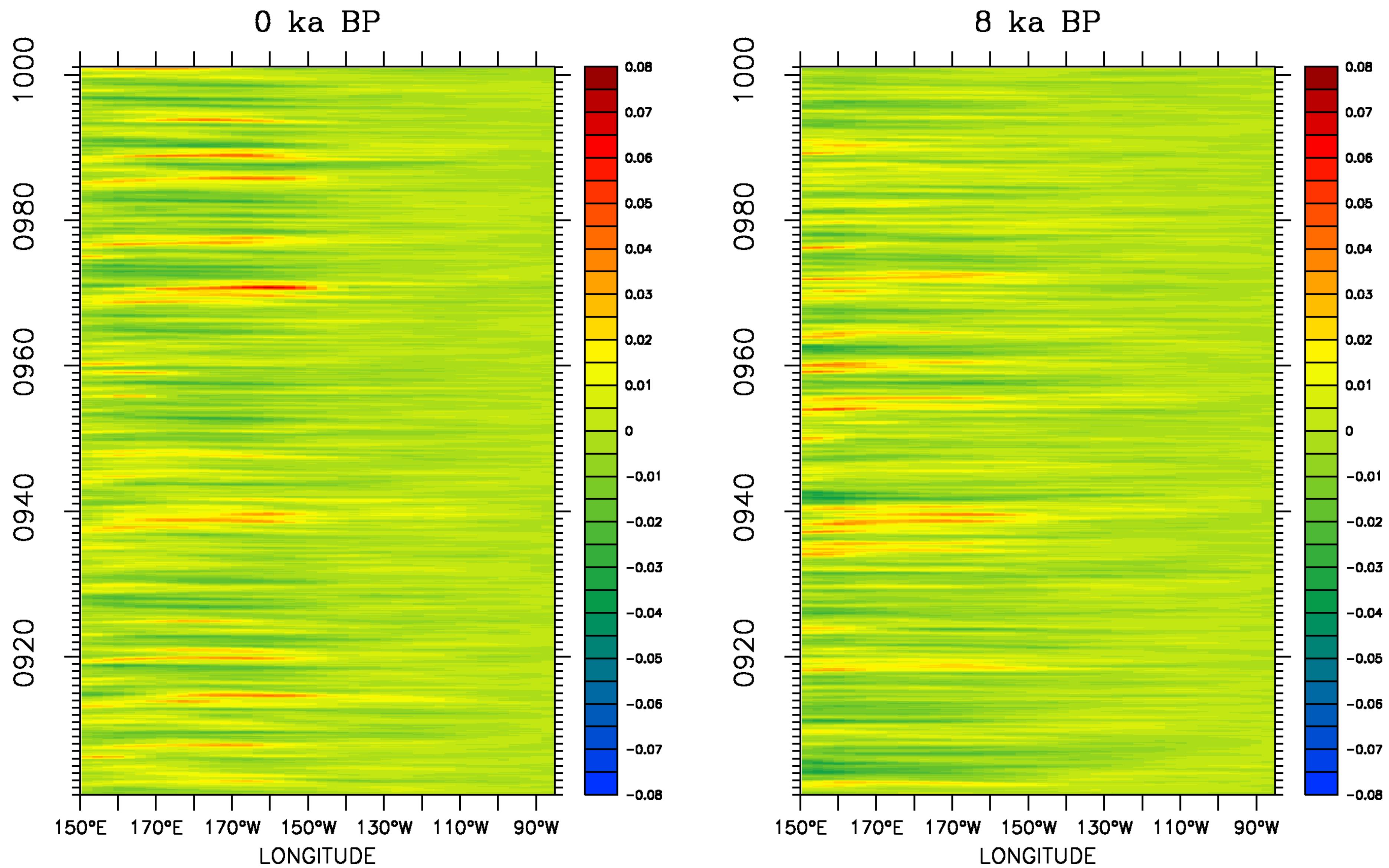
June–July–August surface air temperature, 8 ka minus 0 ka BP (K)

… which enhanced the Asian summer monsoon system



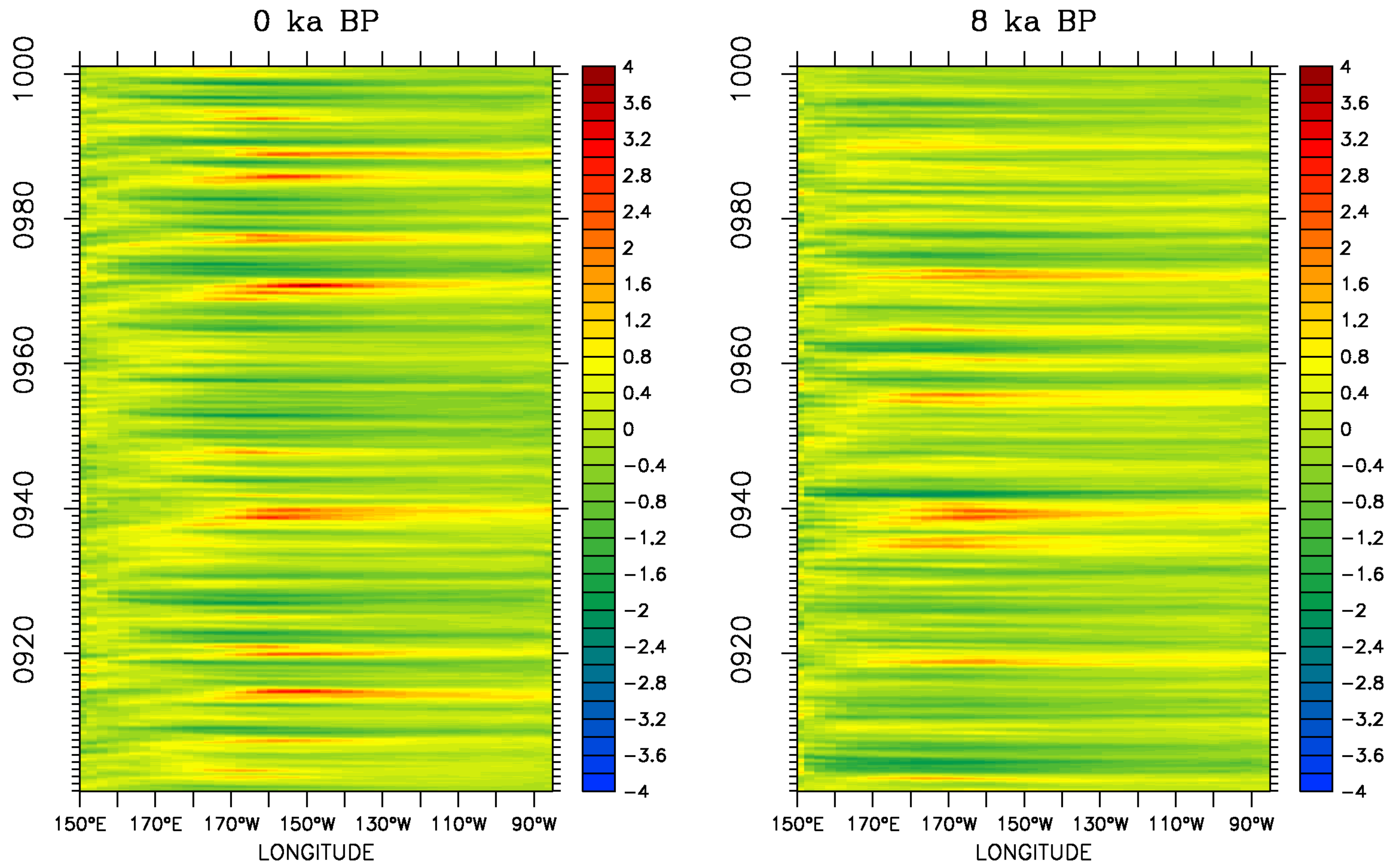
June–July–August mean sea level pressure, 8 ka minus 0 ka BP (hPa)

Westerly wind bursts were "blocked" at 8 ka BP ...



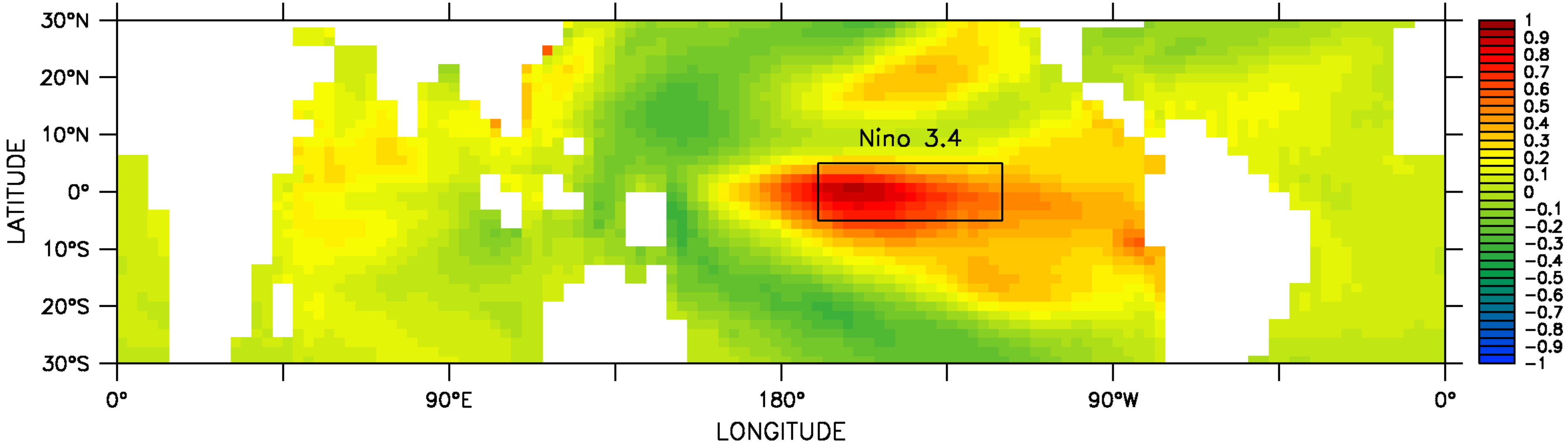
Zonal wind stress anomaly (Nm^{-2})

… which made it harder for El Niño events to develop

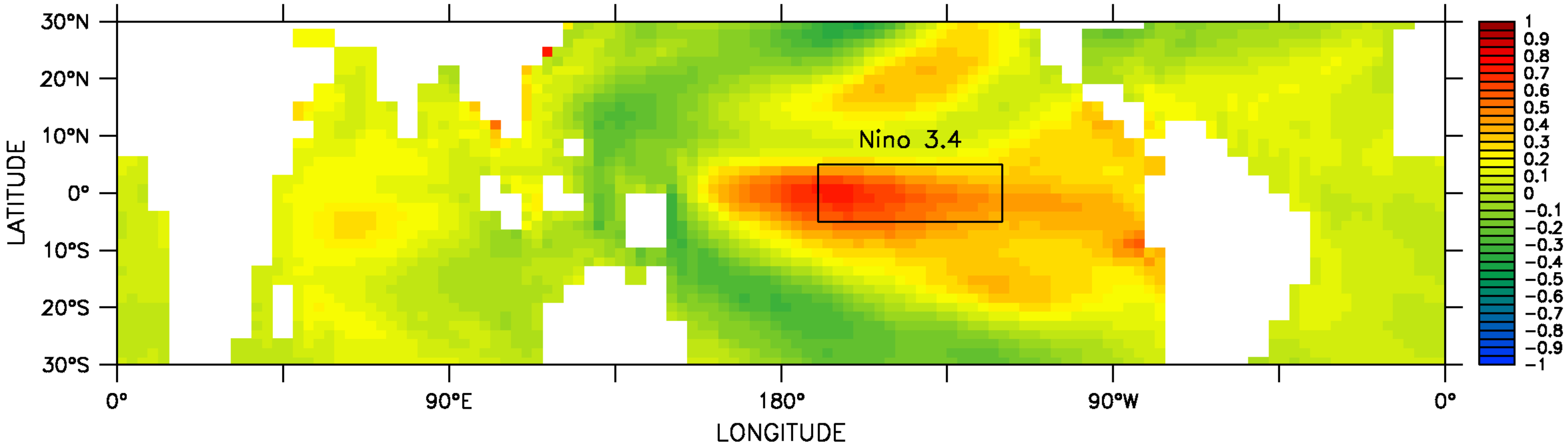


SST anomaly (K)

ENSO has shifted eastwards, as well as strengthening



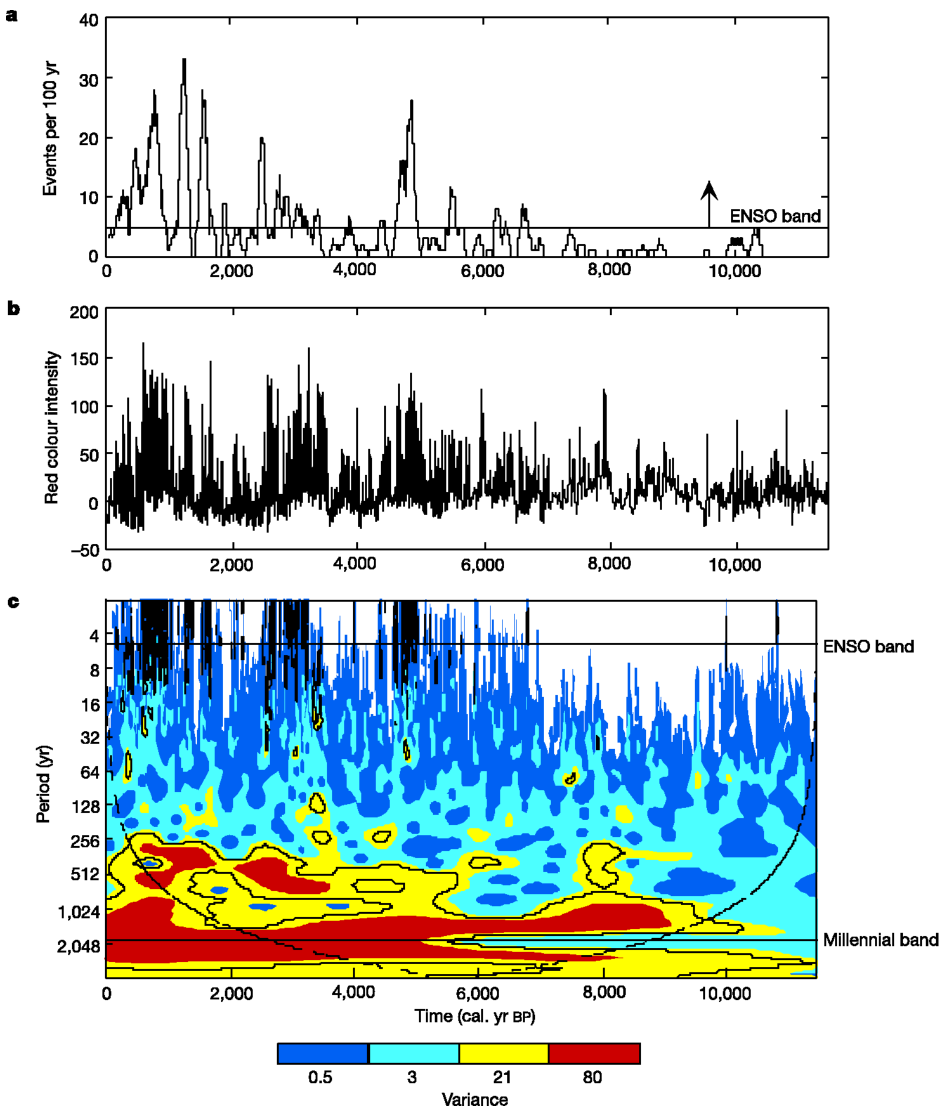
EOF1 of monthly SST anomalies (K): 0 ka BP



EOF1 of monthly SST anomalies (K): 8 ka BP

What do past climates *really* tell us?

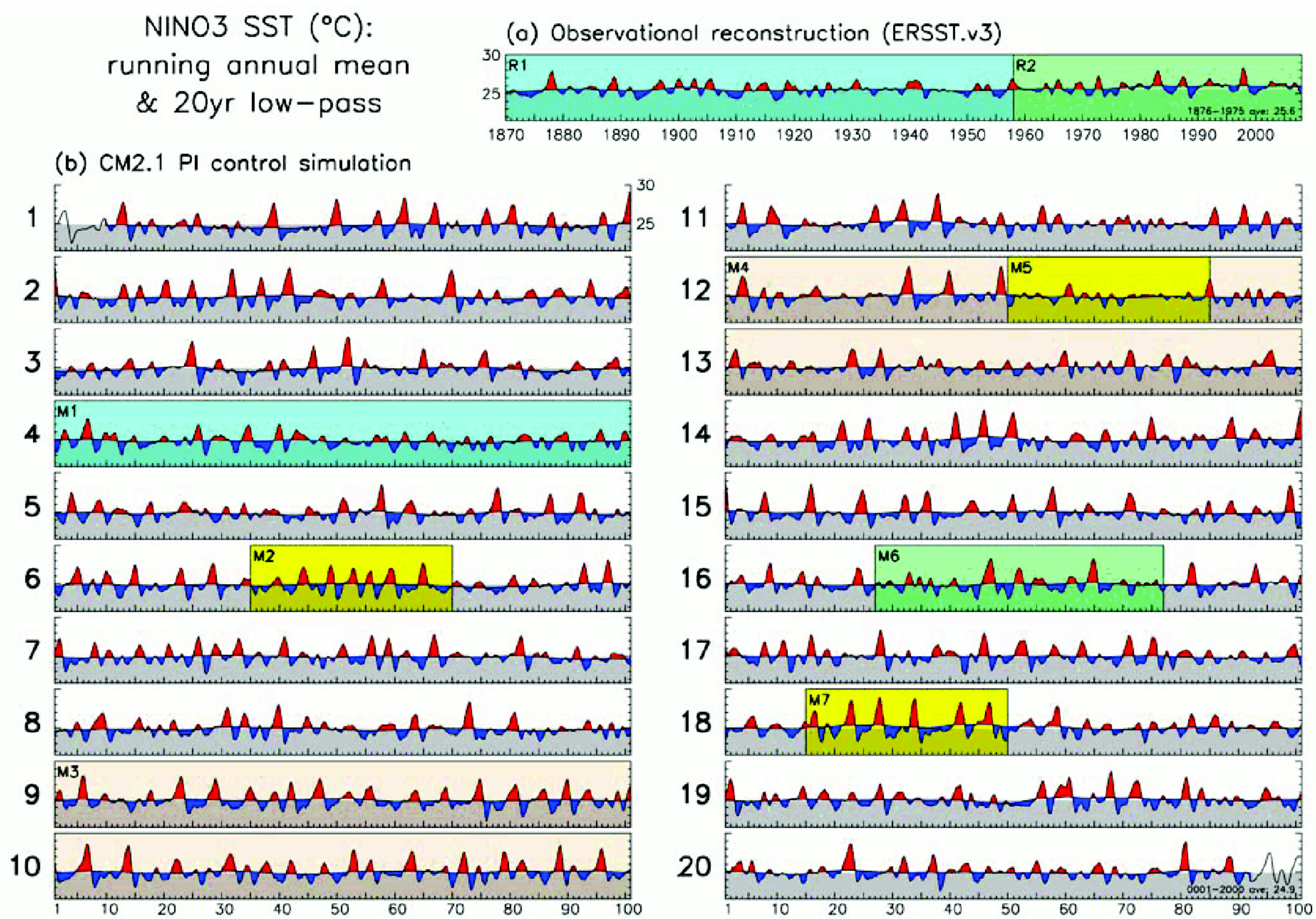
El Niño exhibits strong low-frequency variability



Moy et al. (2002), *Nature*

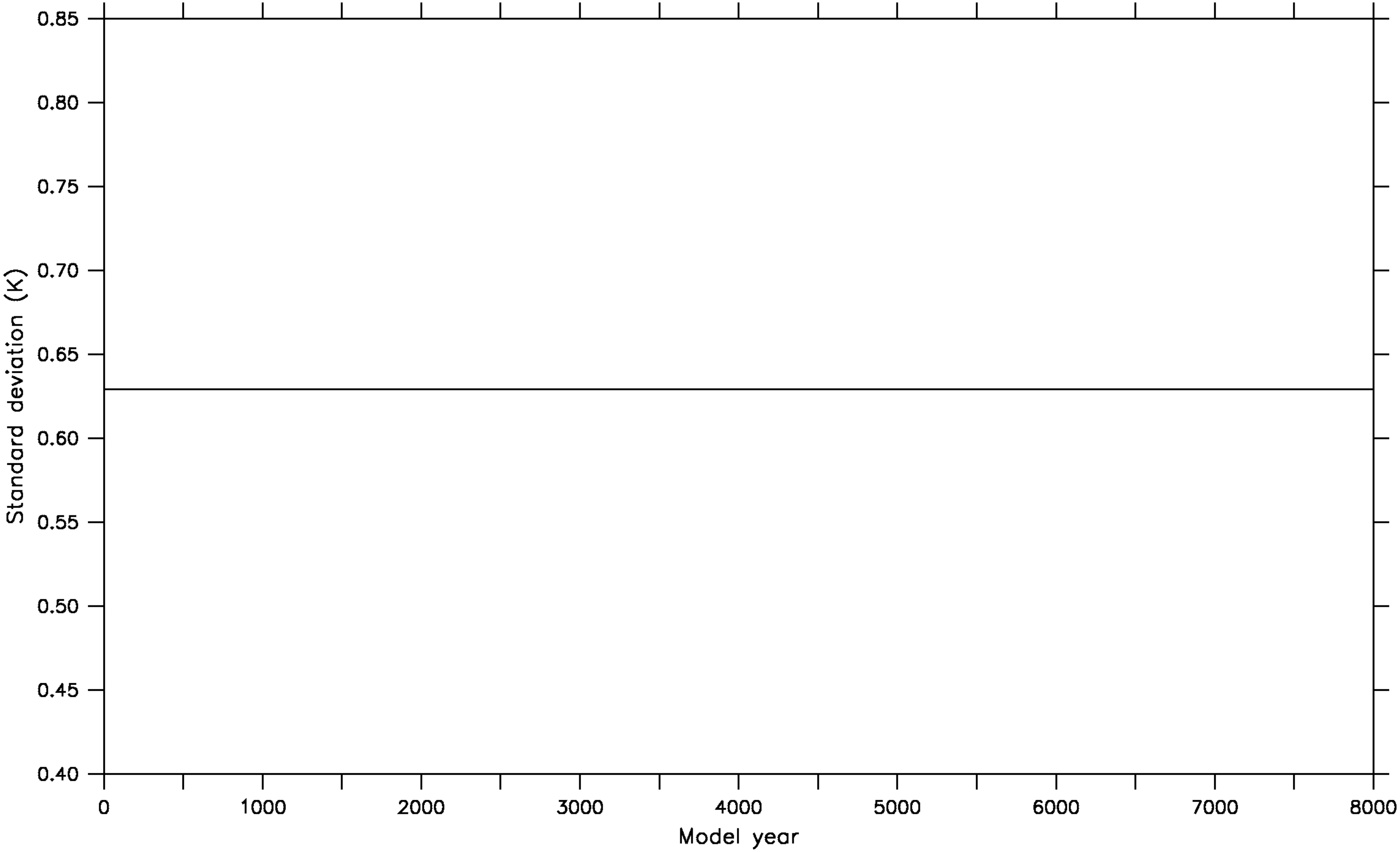
- Strong variability on centennial and millennial timescales is apparent from the palaeoclimate record
- In this alpine record from Ecuador, El Niño activity completely disappears in some centuries
- Only on very long timescales is any trend apparent
- Power spectrum shows that millennial-scale variability is dominant

At least one climate model agrees



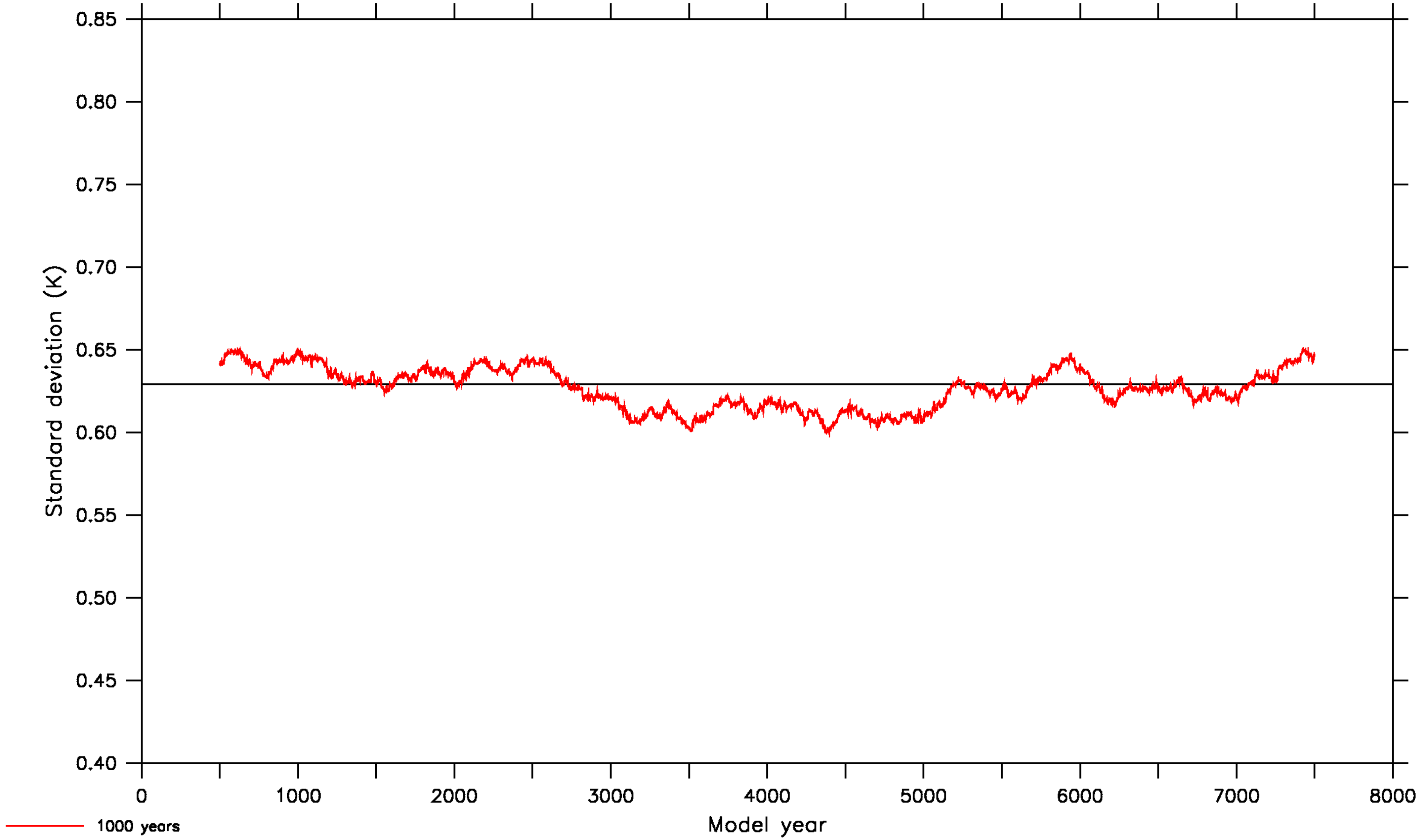
Wittenberg (2009), *GRL*

Variability as a function of sampling period within Mk3L



Standard deviation of Nino 3.4 SST anomaly

Variability as a function of sampling period within Mk3L



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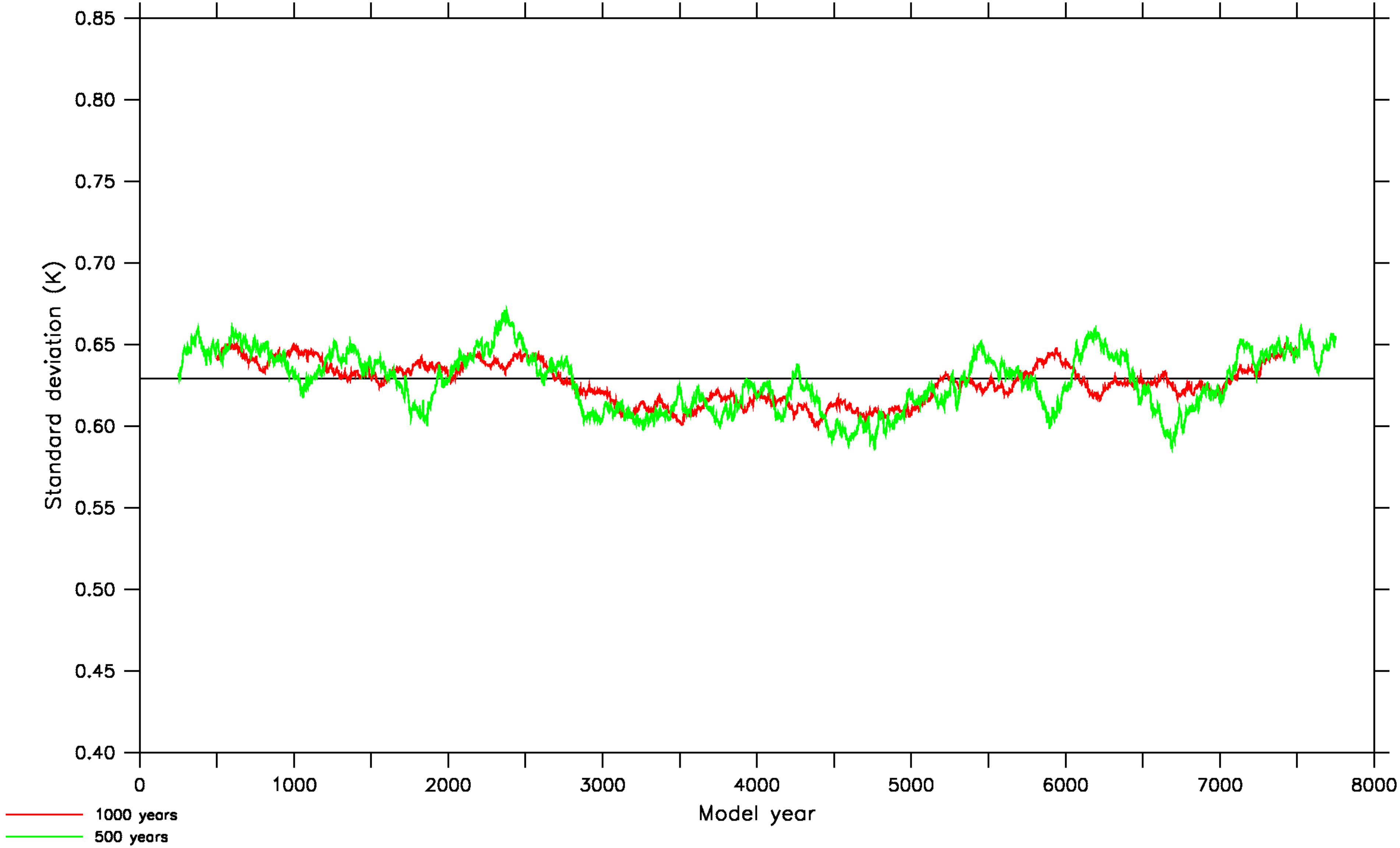

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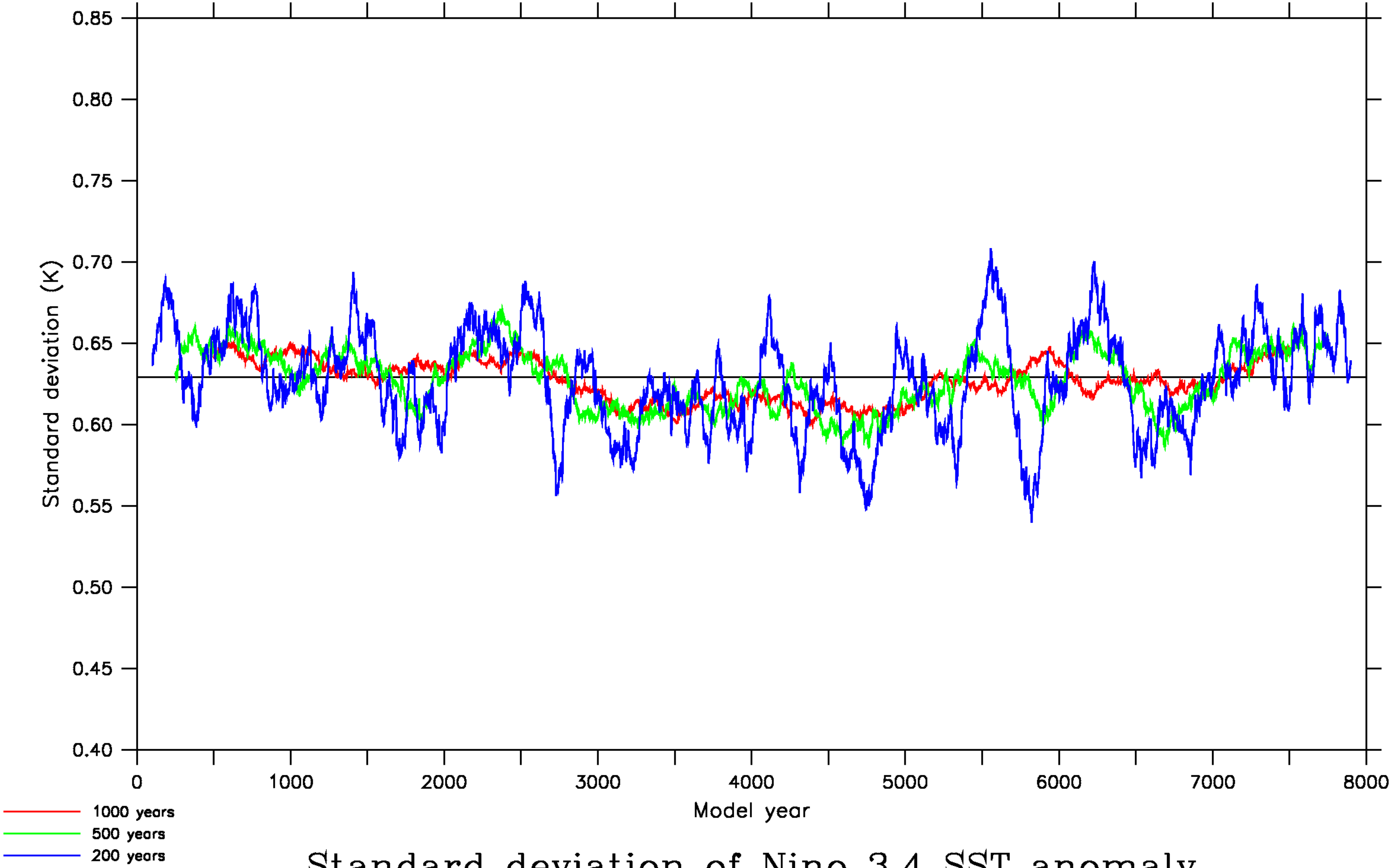

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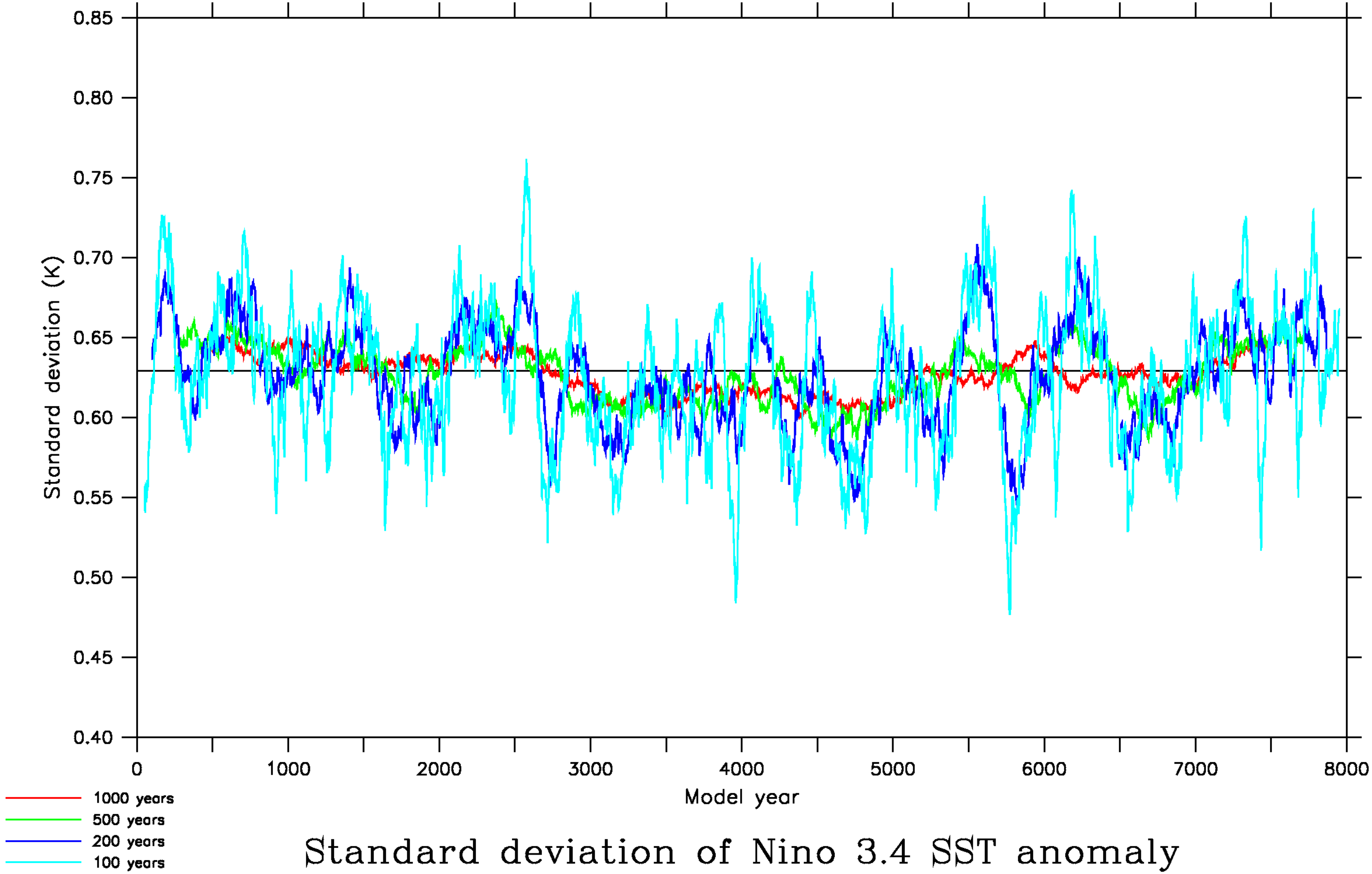
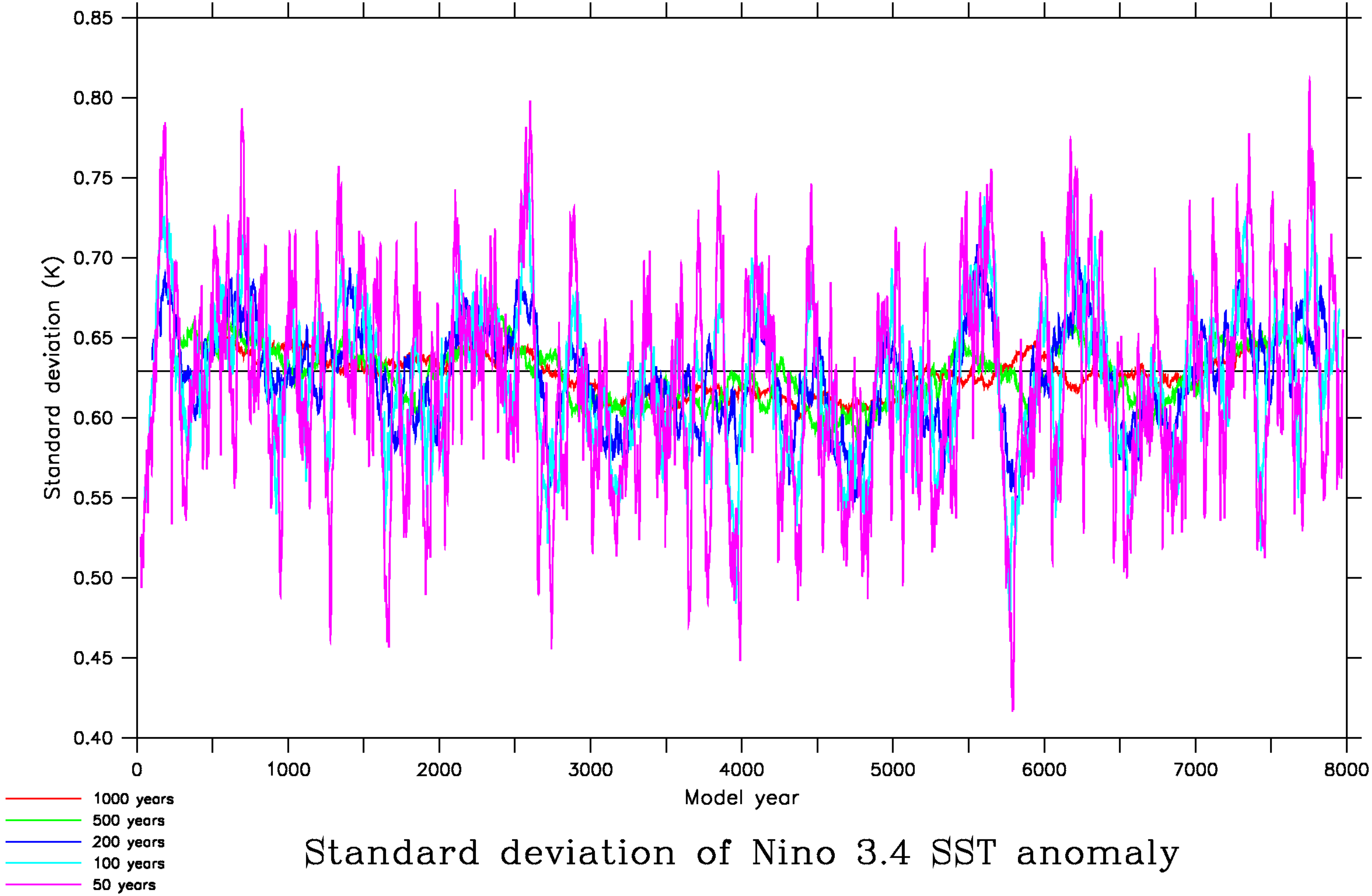


Variability as a function of sampling period within Mk3L



Standard deviation of Nino 3.4 SST anomaly

Accuracy of ENSO amplitude as a function of sampling period

Sampling period (years)	Maximum error in ENSO amplitude (%)
10	65
20	51
50	34
100	24
200	14
500	7
1000	5

- Collins et al. (2001), using a 2000-year HadCM3 simulation, note variations of ±20% and ±40% for sampling periods of 100 years and 20 years respectively

Coral records: mid-Holocene versus present day

	Age (ka)	**Location**	**% change in ENSO variance**	**Years**
Tudhope et al (2001)	6.5	PNG	-60	49
McGregor and Gagan (2004)	7.6–5.4	PNG	-15	9–89

- Brown et al. (2008) also finds that the choice of measure of ENSO amplitude results in substantial differences in the estimate of mid-Holocene ENSO changes

Coupled modelling studies: 6 ka versus 0 ka BP

	Model	Diagnostic	% change	Years
Otto-Bliesner (1999)	CSM	Niño 3	$\sim$0	50
Liu et al. (2000)	FOAM	Niño 3.4	-20	120
Phipps (2006)	Mk3L-1.0	Niño 3.4	-13	700
Brown at al. (2006)	HadCM3	Niño 3	-12	100
Brown et al. (2008)	HadCM3	Niño 3	[-14, +19]	50–100
Zheng et al. (2008) (PMIP2)	CCSM3	Niño 3	-18.6	50
	FGOALS-1.0g		-14.6	100
	FOAM		-11.6	100
	IPSL-CM4		-2.9	100
	MIROC3.2		-22.5	100
	MRI-CGCM2.3.4fa		+3.3	100
	MRI-CGCM2.3.4nfa		-12.9	100

ARC Discovery Project DP1092945

Untangling the links between El Niño and the changing global climate

1. Reconstruct ENSO frequency, magnitude and duration over the past 6,000 years
2. Produce quantitative, spatial reconstructions of individual ENSO events at around 2,000 years before present
3. Use multiple climate system models to explore the links between ENSO dynamics and the changing global climate
4. Integrate the ENSO reconstructions and model simulations with ENSO theory

Microatolls

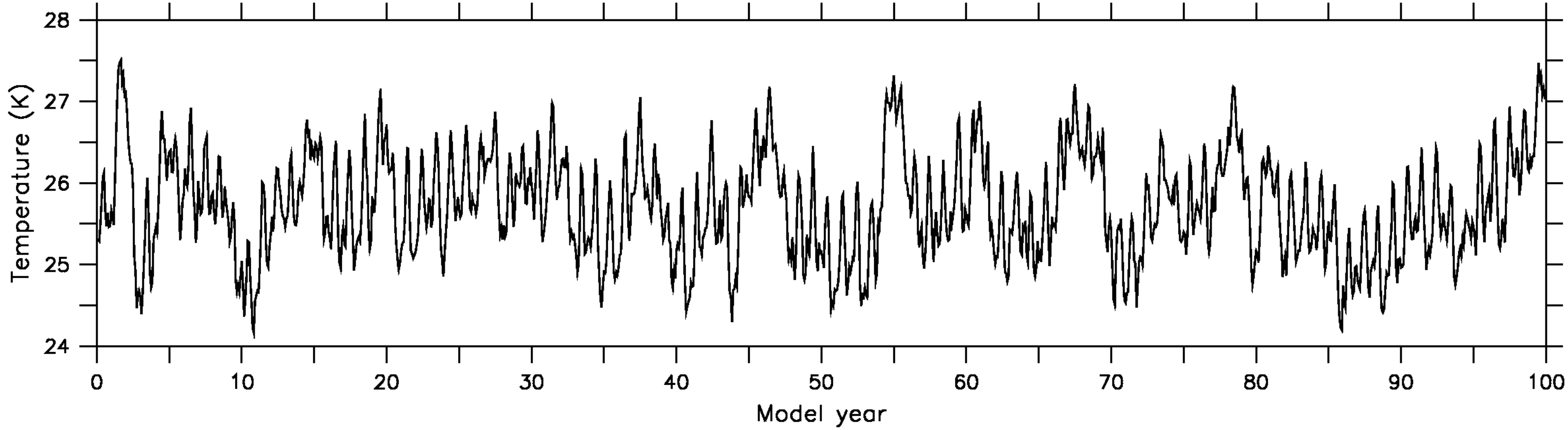
- Grow for at least 100 years
- Record sea surface temperature and precipitation
- Can be sampled at monthly resolution

Christmas Island fossil corals

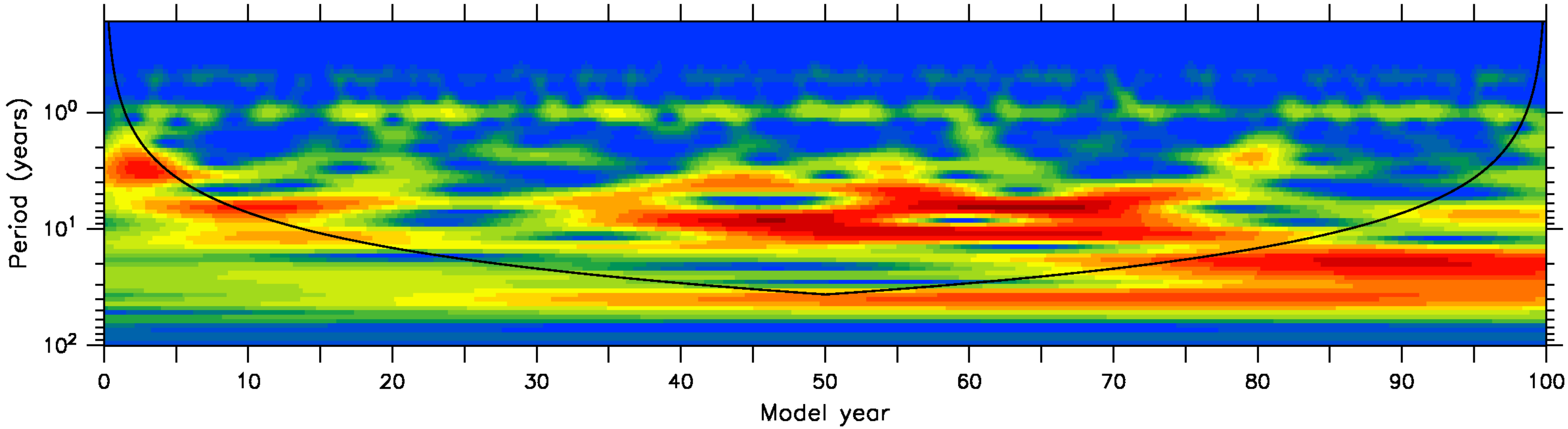
Christmas Island fossil corals

A cautionary tale regarding wavelet spectra

Does this power spectrum look right?

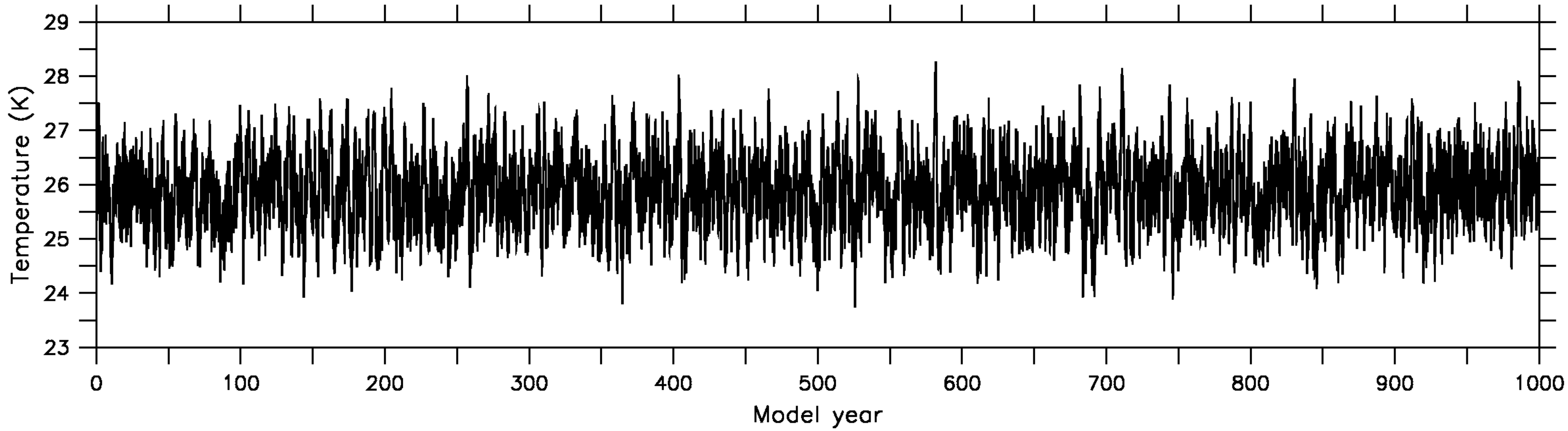


Nino 3.4 sea surface temperature

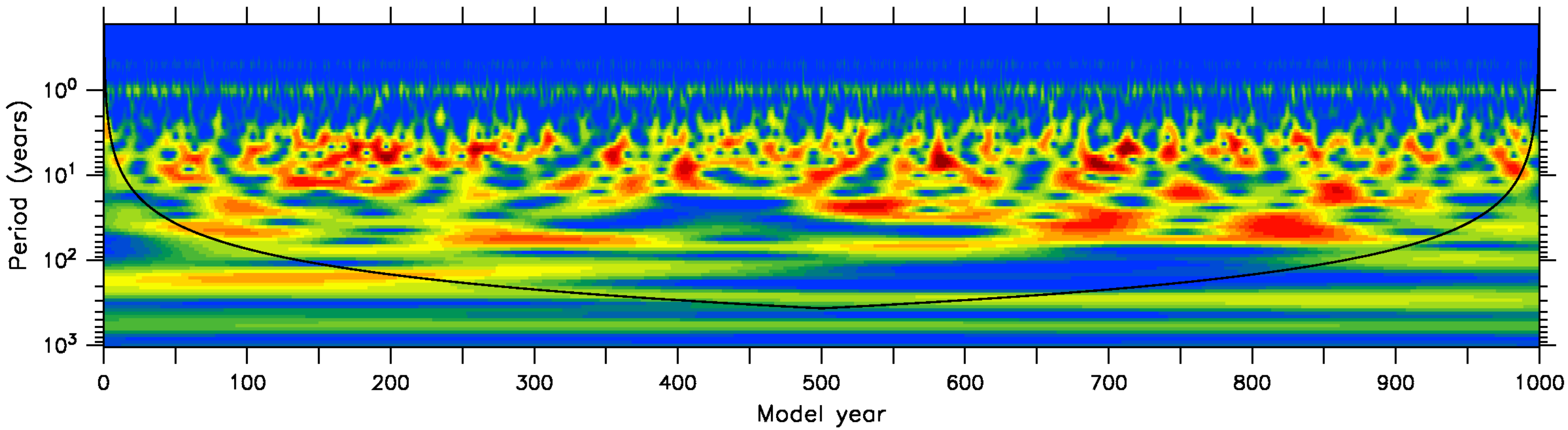


Power spectrum

How about this one?



Nino 3.4 sea surface temperature



Power spectrum

A Practical Guide to Wavelet Analysis

Christopher Torrence and Gilbert P. Compo
Program in Atmospheric and Oceanic Sciences, University of Colorado, Boulder, Colorado

ABSTRACT

A practical step-by-step guide to wavelet analysis is given, with examples taken from time series of the El Niño–Southern Oscillation (ENSO). The guide includes a comparison to the windowed Fourier transform, the choice of an appropriate wavelet basis function, edge effects due to finite-length time series, and the relationship between wavelet scale and Fourier frequency. New statistical significance tests for wavelet power spectra are developed by deriving theoretical wavelet spectra for white and red noise processes and using these to establish significance levels and confidence intervals. It is shown that smoothing in time or scale can be used to increase the confidence of the wavelet spectrum. Empirical formulas are given for the effect of smoothing on significance levels and confidence intervals. Extensions to wavelet analysis such as filtering, the power Hovmöller, cross-wavelet spectra, and coherence are described.

The statistical significance tests are used to give a quantitative measure of changes in ENSO variance on interdecadal timescales. Using new datasets that extend back to 1871, the Niño3 sea surface temperature and the Southern Oscillation index show significantly higher power during 1880–1920 and 1960–90, and lower power during 1920–60, as well as a possible 15-yr modulation of variance. The power Hovmöller of sea level pressure shows significant variations in 2–8-yr wavelet power in both longitude and time.

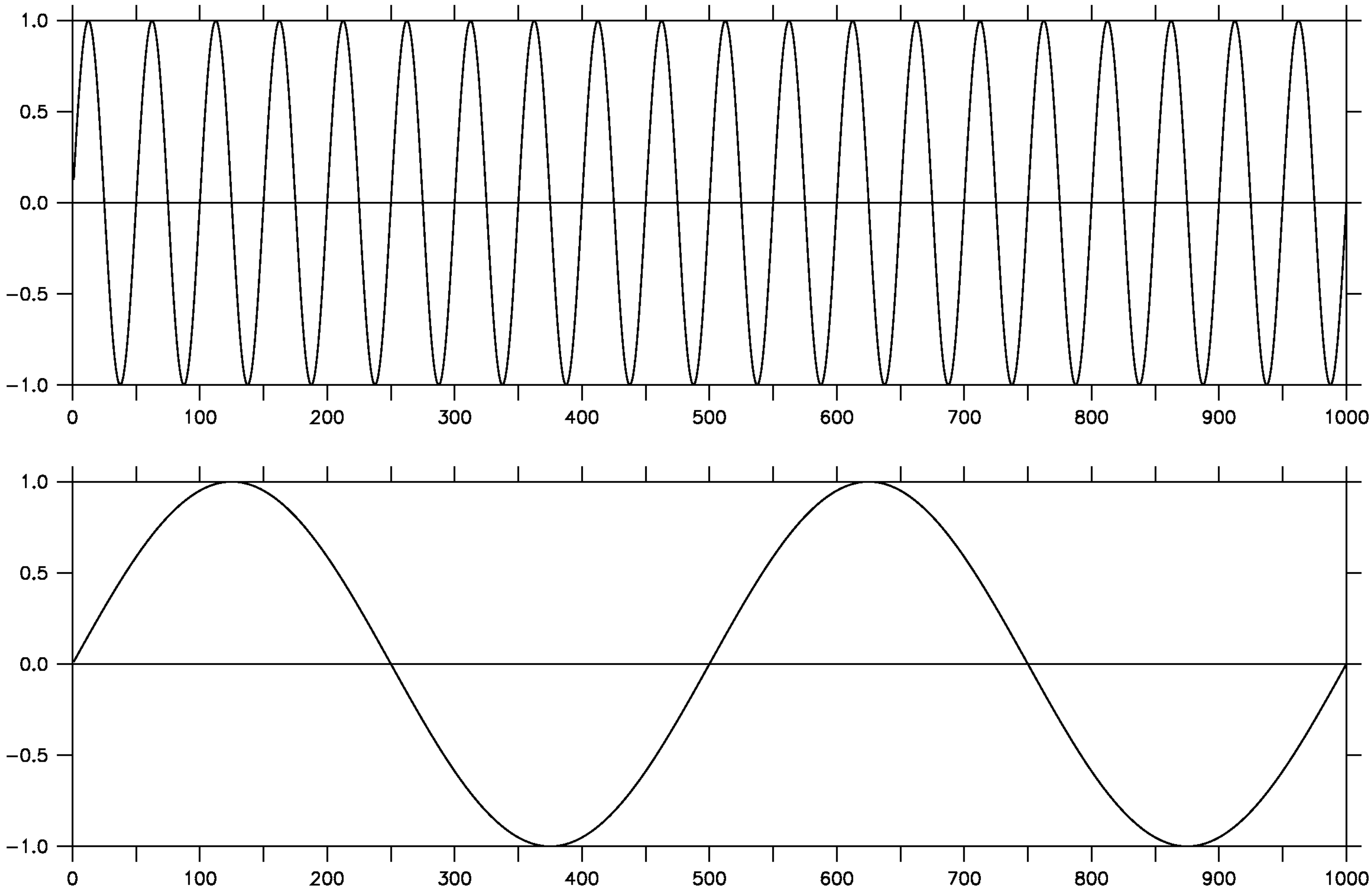
Torrence and Compo (1998), *Bulletin of the American Meteorological Society* *c. Normalization*

To ensure that the wavelet transforms (4) at each scale s are directly comparable to each other and to the transforms of other time series, the wavelet function at each scale s is normalized to have unit energy:

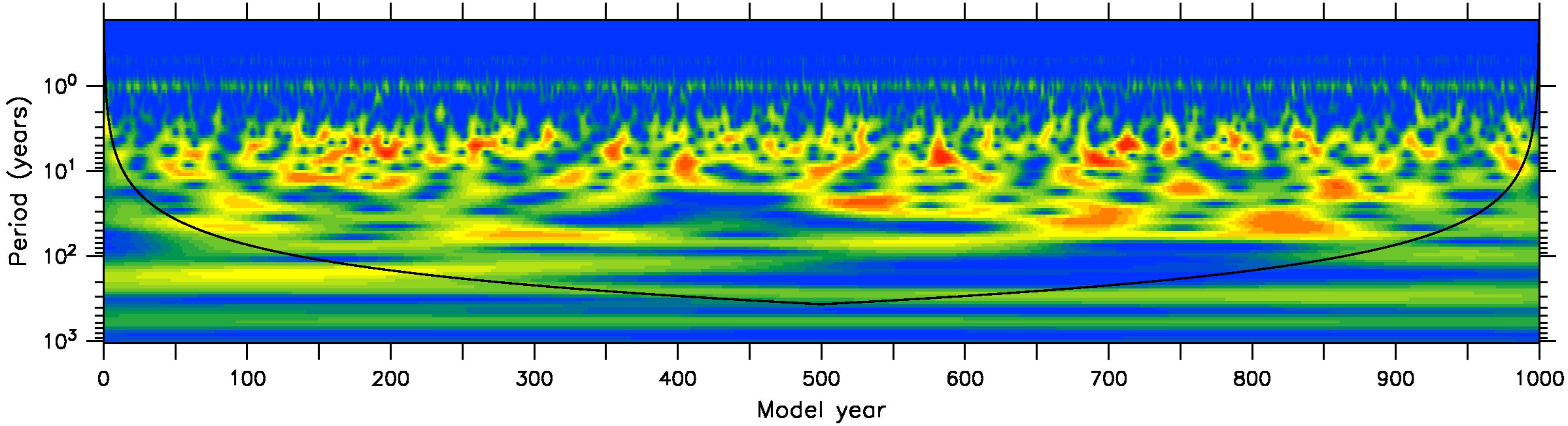
$$\hat{\psi}(s\omega_k) = \left(\frac{2\pi s}{\delta t}\right)^{1/2} \hat{\psi}_0(s\omega_k). \qquad (6)$$

- Appears to normalise the wavelets such the wavelet spectrum generated is an *energy* spectrum, not a *power* spectrum

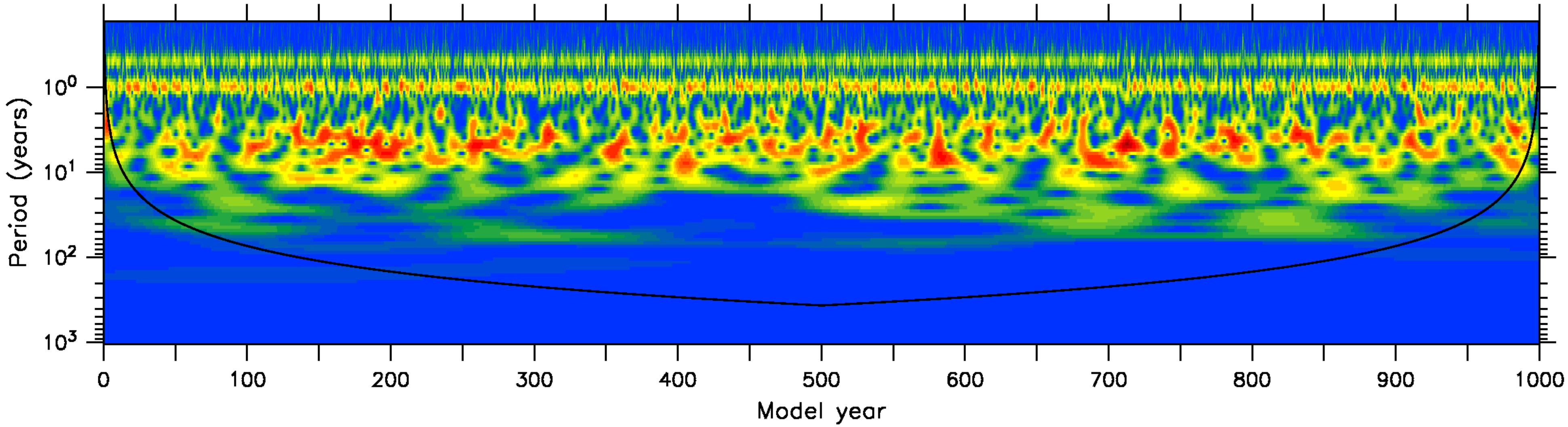
Energy versus power



“Energy” versus “power” spectrum



Energy spectrum



Power spectrum

Conclusions

- The study of past climates allows us to learn more about ENSO dynamics, and to explore the links between ENSO and the global climate system.
- Decreasing summer insolation over the past 8,000 years has resulted in a weakening of the Asian monsoon. This has reduced the stability of the background state of the tropical Pacific, making it easier for El Niño events to develop.
- ENSO exhibits strong modulation on centennial and millennial timescales. Care must be taken to ensure that observational and modelled timeseries are of sufficient duration.
- The choice of metric for ENSO amplitude is also critical.
- Wavelet spectra are very powerful tools for timeseries analysis, but must be used with caution.