Modelling of past climates

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Why model past climates?

There are three primary motivations for modelling past climates:

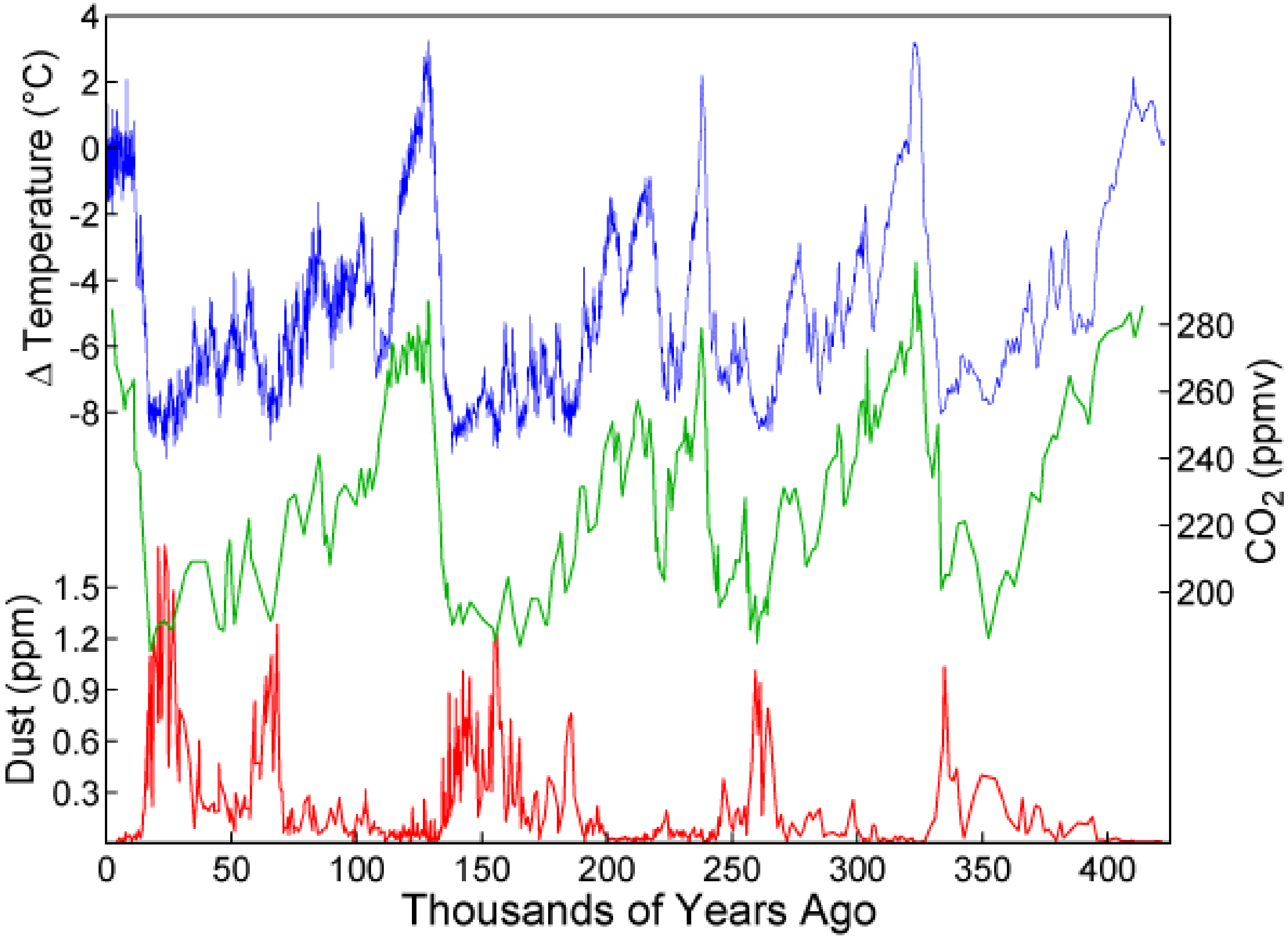
- To explore the sensitivity of the climate system to external forcing
- To explore climate dynamics
- To evaluate the ability of models to simulate climatic changes

Exploring the sensitivity of the climate system to external forcing

External forcings

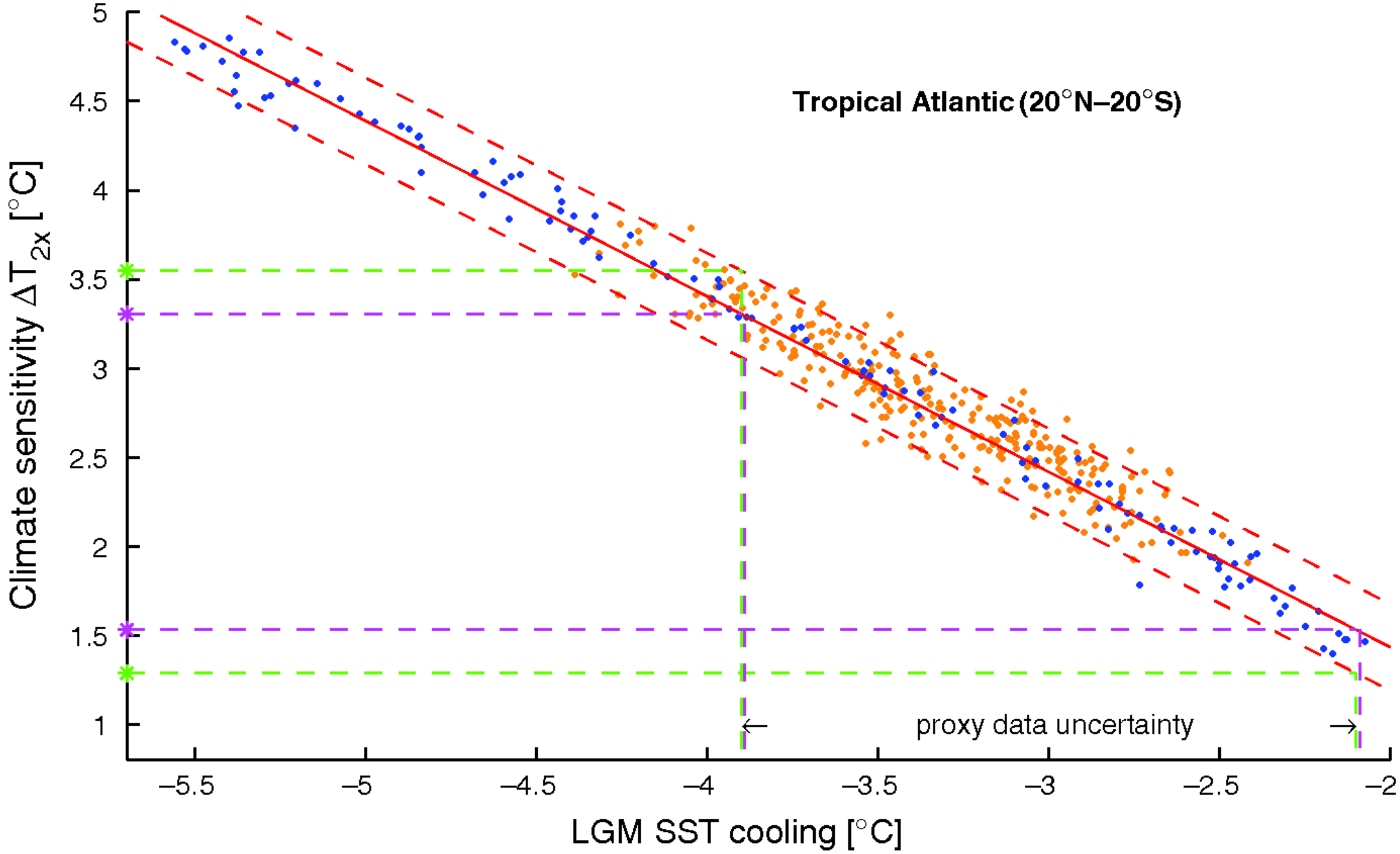
- $\leq 10^3$ years:
  - Volcanic eruptions
  - Solar output
- 10^4–10^5 years:
  - Earth's orbital geometry
- $\geq 10^6$ years:
  - Tectonic processes
  - Sun's evolution
  - Solar system's orbital path through the galaxy

The palaeoclimate record gives us past forcing *and* the response of the climate system



Petit et al. (1999)

We can use this to constrain the climate sensitivity



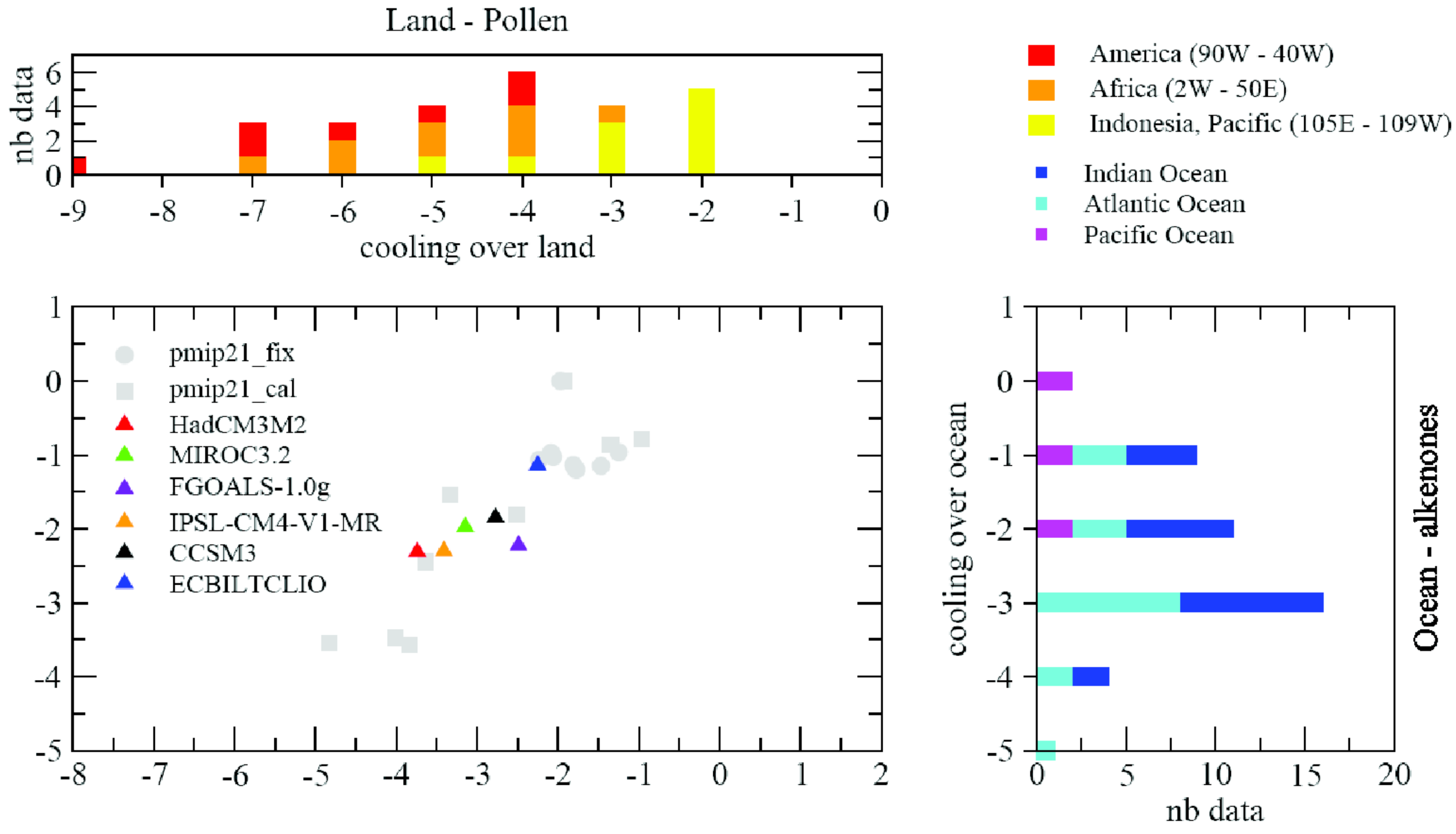
von Deimling et al. (2006)

Evaluating the ability of models to simulate climatic changes

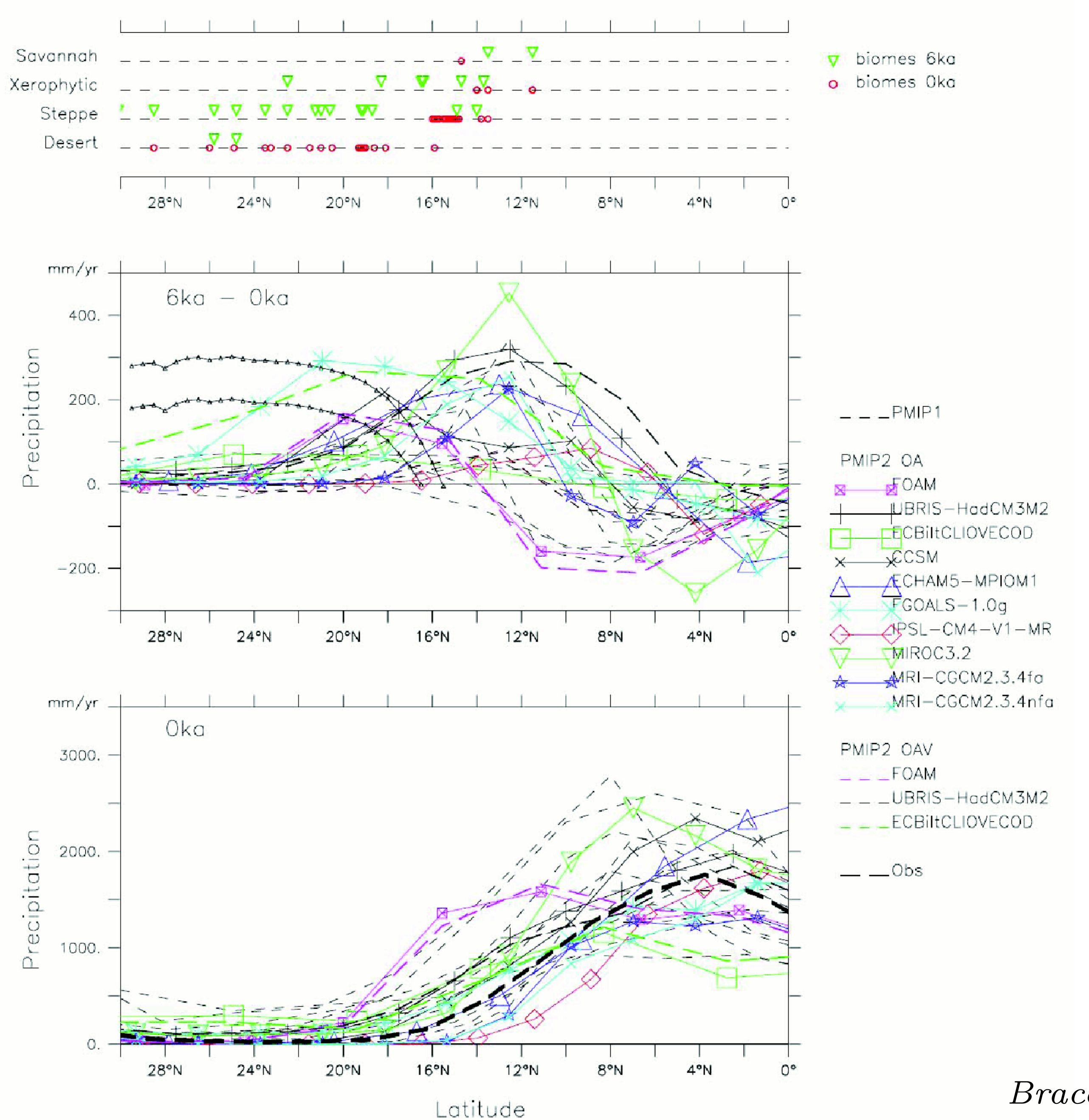
Palaeoclimate Modelling Intercomparison Project

- Phase 1 (1991–2001) :
  - Atmospheric GCMs
  - Primary experiments were 6 ka (mid-Holocene) and 21 ka (LGM)
  - 22 models participated
  - Contributed towards IPCC TAR
- Phase 2 (2002–2007) :
  - Atmosphere-ocean(-vegetation) GCMs
  - Primary experiments were 6 ka (mid-Holocene) and 21 ka (LGM)
  - 18 models participated
  - Contributed towards IPCC AR4

The models are good at temperature, but ...



Braconnot et al. (2007)



Braconnot et al. (2007)

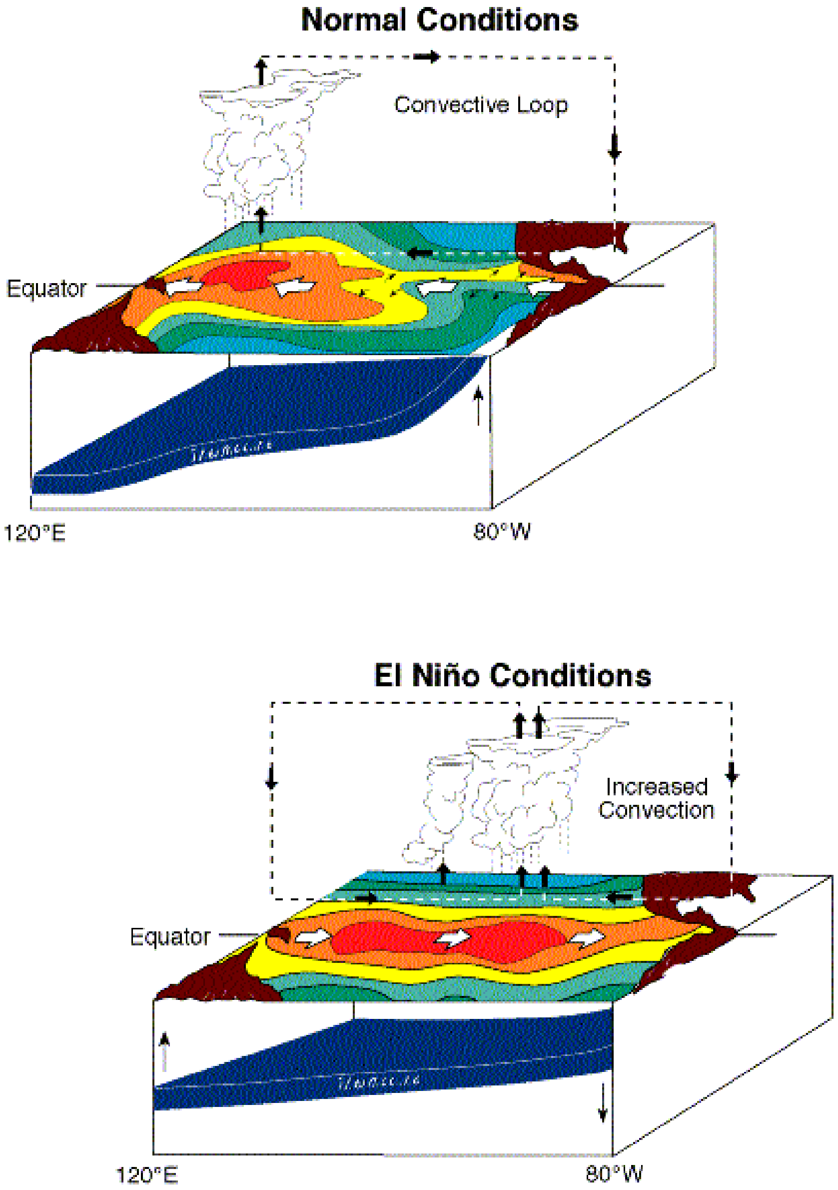
PMIP3 (2008–)

- Theme 1: Evaluation of earth system models at 6 ka and 21 ka
  - Vegetation, biogeochemical cycles, chemistry, ice sheets...
  - Use of new data syntheses for model evaluation
- Theme 2: Interglacials and warm periods
  - Last interglacial ($\sim$130–115 ka) - snapshot and transient
  - Mid-Pliocene ($\sim$3.3–3.0 Ma) - snapshot (PlioMIP)
- Theme 3: Abrupt climate changes
  - Transient simulations of last deglaciation, 8.2 ka event...
- Theme 4: Uncertainties: characterisation and understanding
  - Uncertainties in reconstructions, boundary conditions...
  - Weight models according to a palaeoclimate skill index?
- Will contribute towards IPCC AR5

The ghost of El Niño past

A palaeoclimate detective story

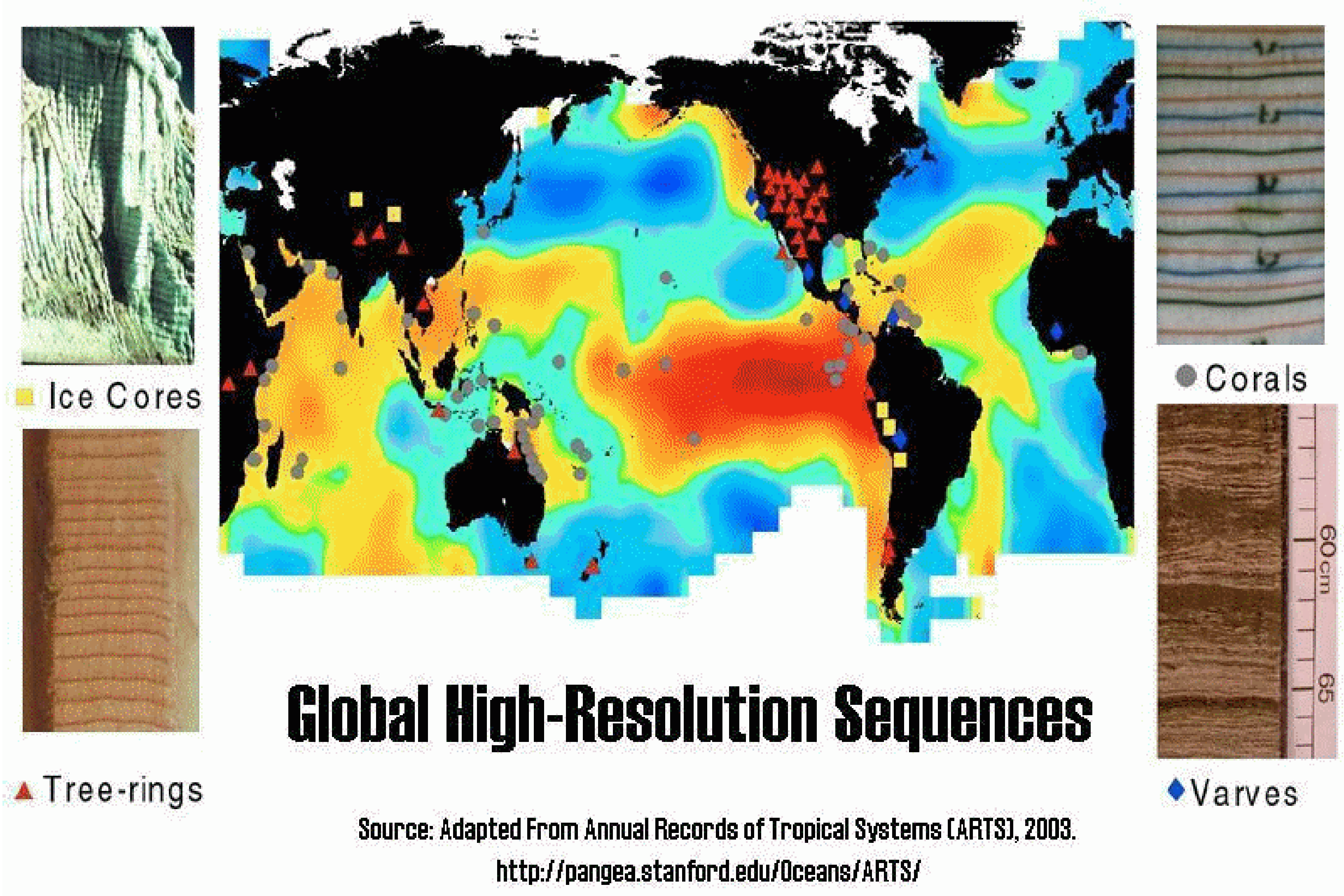
What is El Niño?



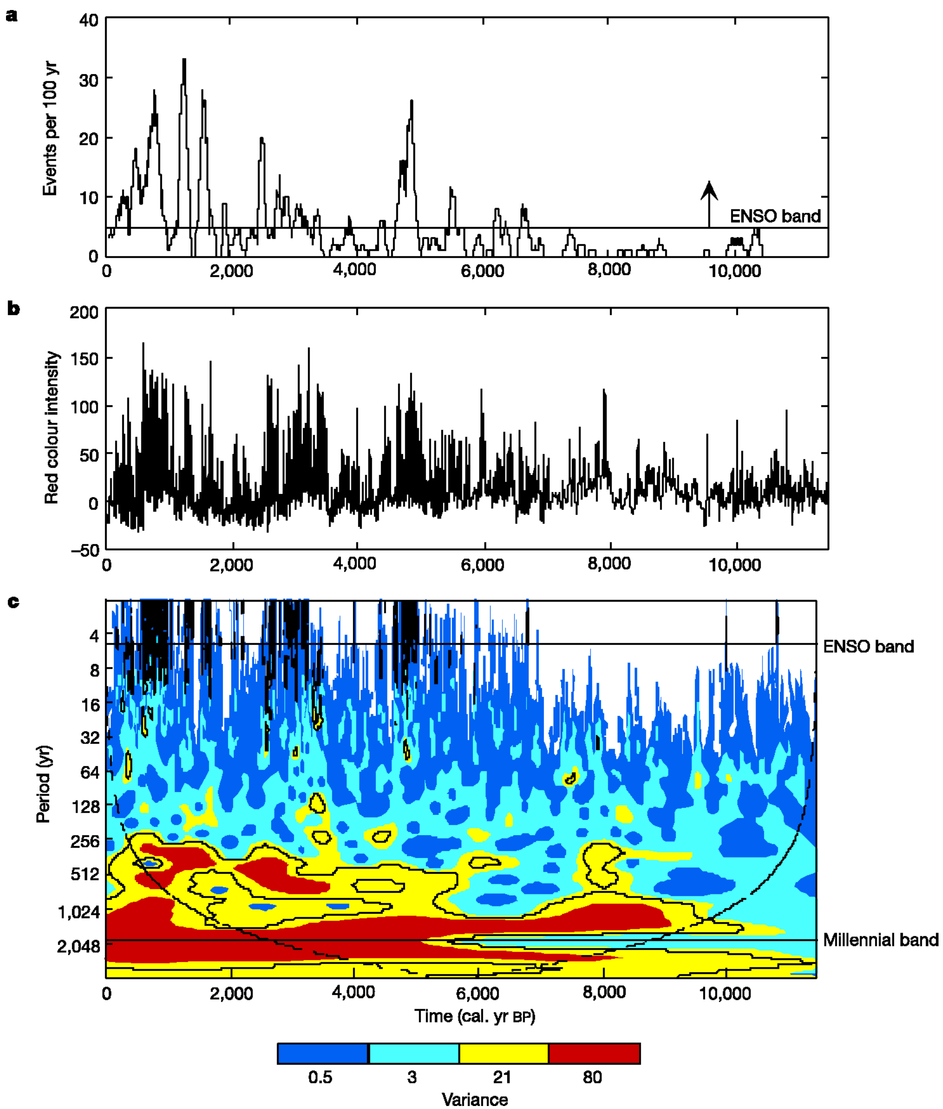
NOAA/PMEL/TAO

- 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



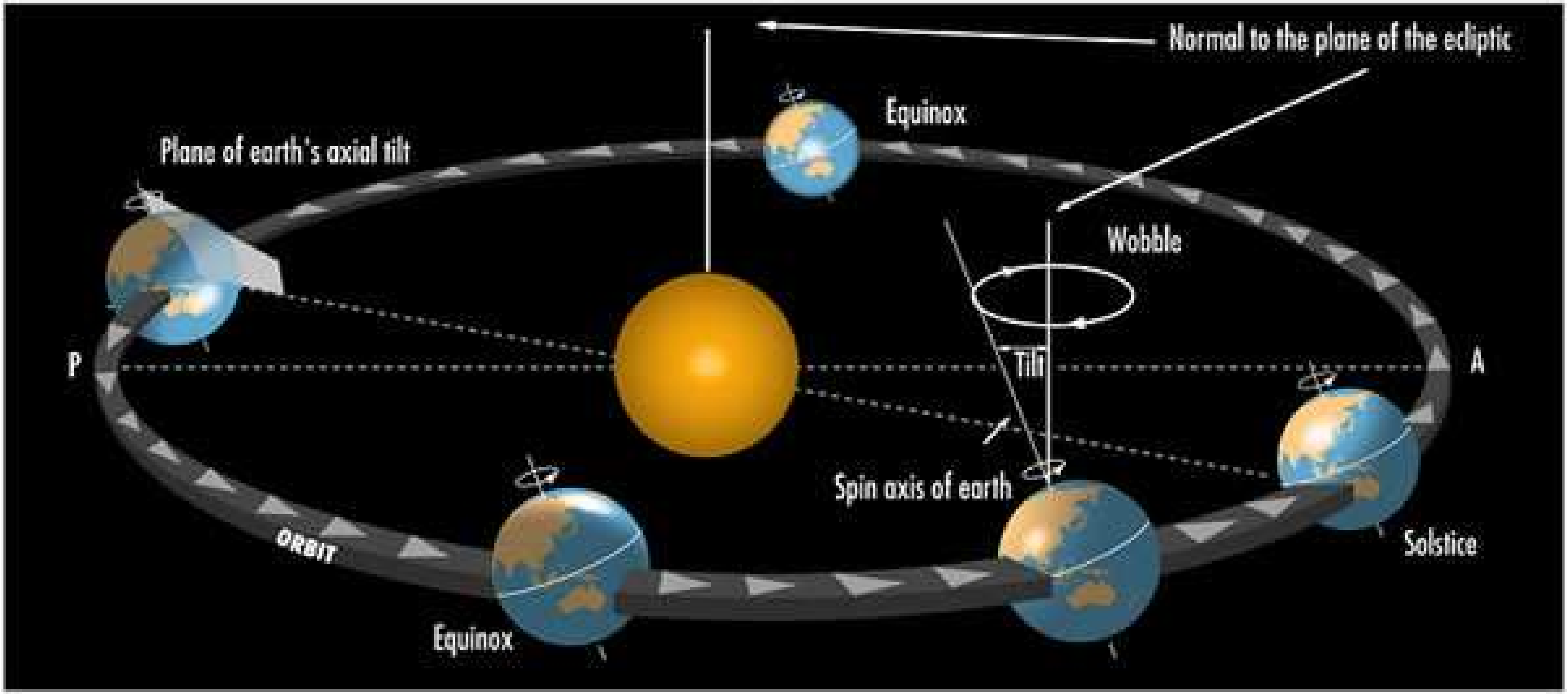
El Niño has changed ...



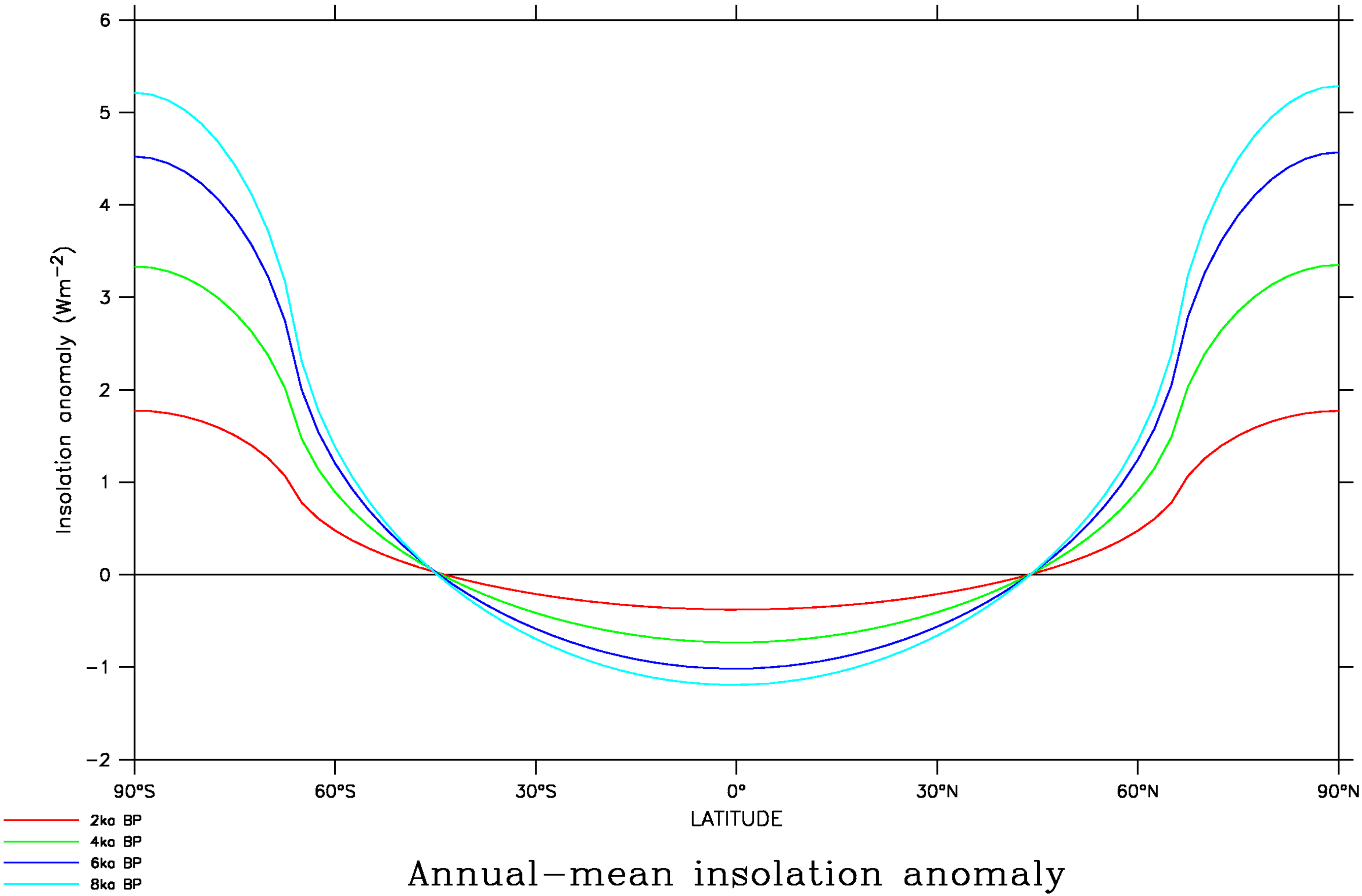
Moy et al. (2002), *Nature*

- "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

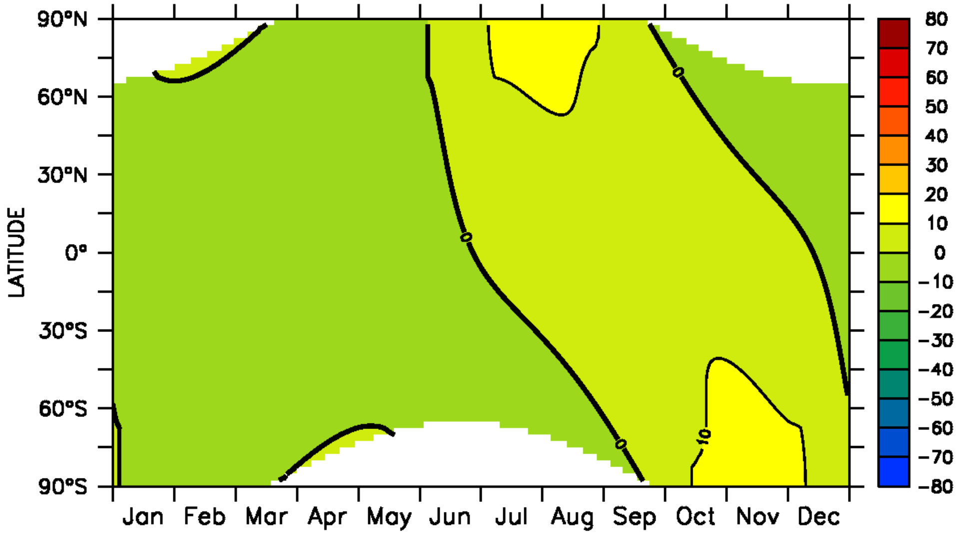
… driven by changes in the Earth's orbital geometry



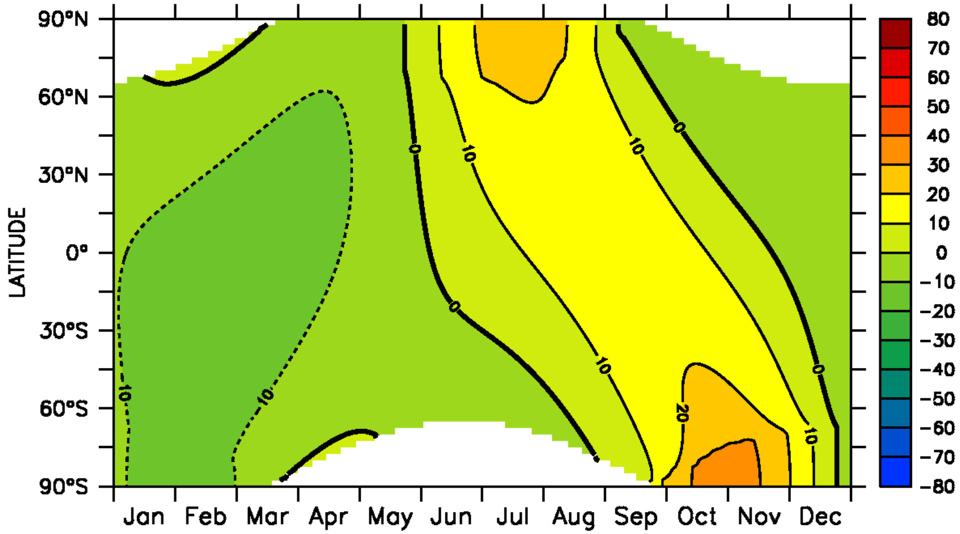
The changes in annual-mean insolation are small...



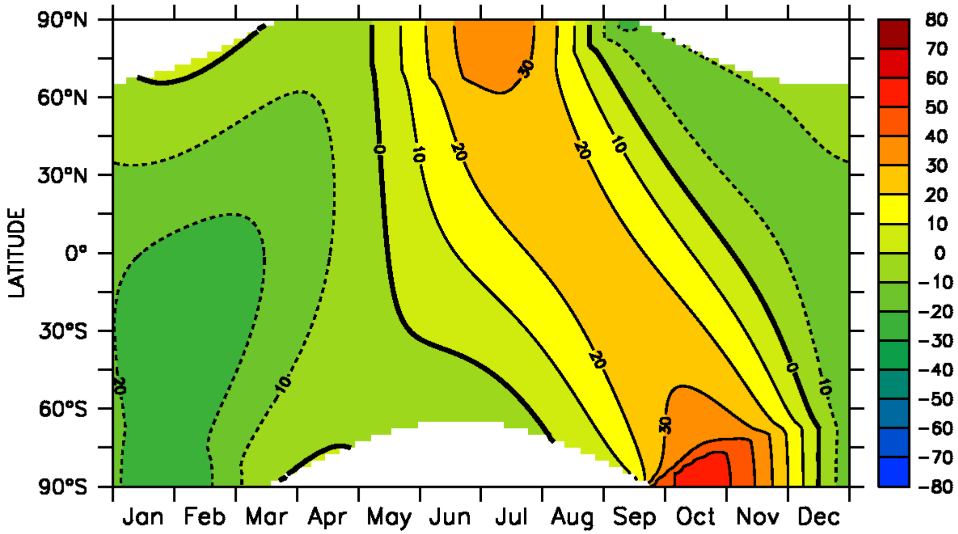
… but the seasonal changes are large



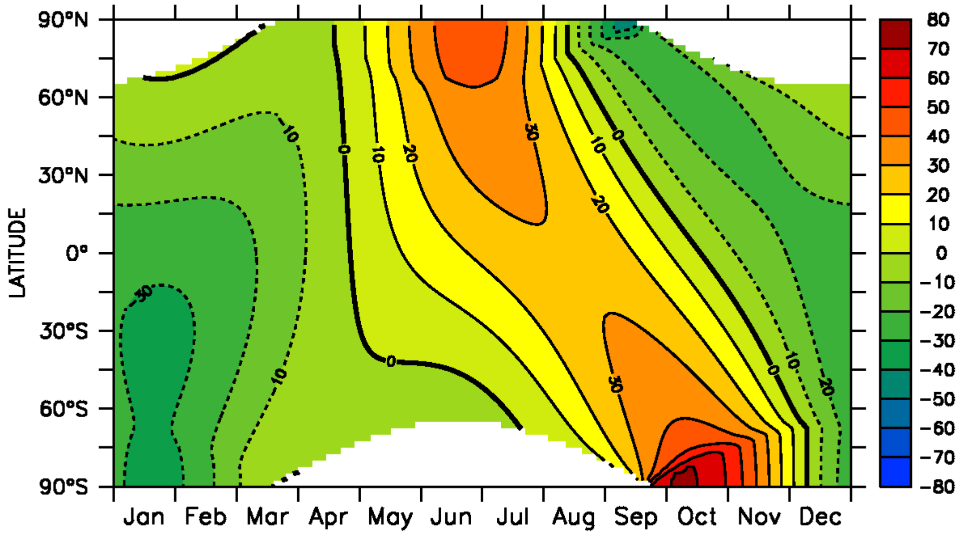
Insolation anomaly (Wm^{-2}): 2 ka BP



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



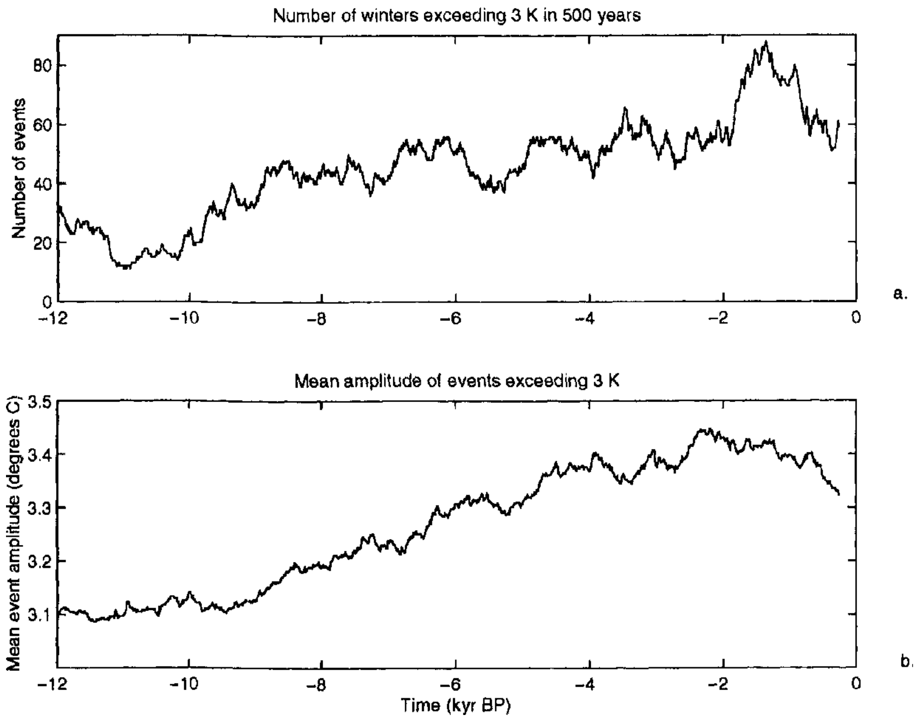
Insolation anomaly (Wm^{-2}): 6 ka BP



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

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

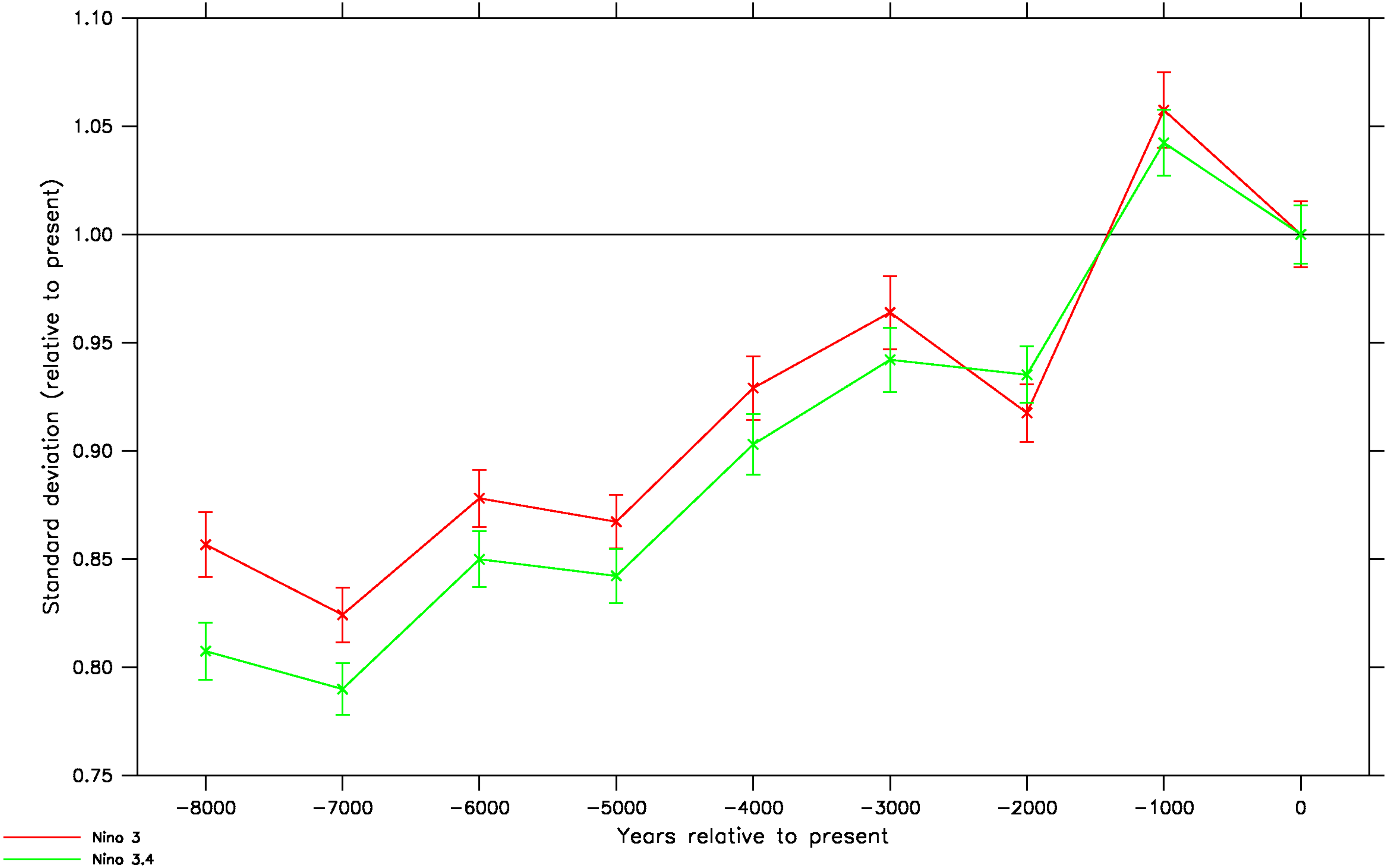
A picture begins to emerge?

- 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

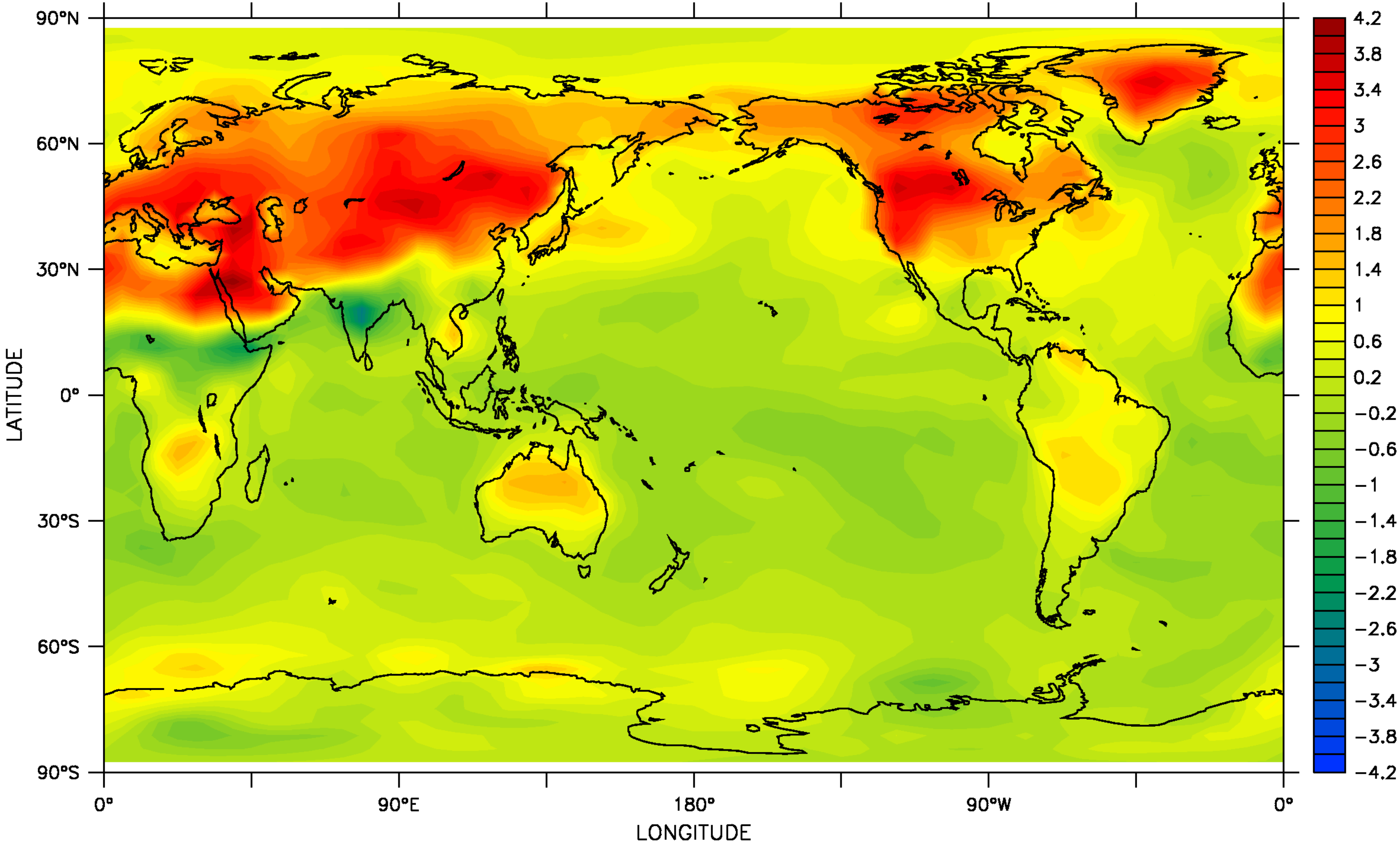
- CSIRO Mk3L climate system model v1.1:
  - Atmosphere: $5.6^\circ \times 3.2^\circ$, 18 vertical levels
  - Ocean: $2.8^\circ \times 1.6^\circ$, 21 vertical levels
  - Sea ice: Dynamic-thermodynamic
  - Land surface: Static vegetation
  - Can simulate 1000 years in a month
- Simulations for 8, 7, 6, 5, 4, 3, 2, 1 and 0 ka BP:
  - Only the Earth's orbital geometry is varied
  - Atmospheric CO_2 concentration = 280ppm
  - Solar constant = 1365 Wm^{-2}
  - Integrated for 1000 years

Simulated changes in ENSO variability



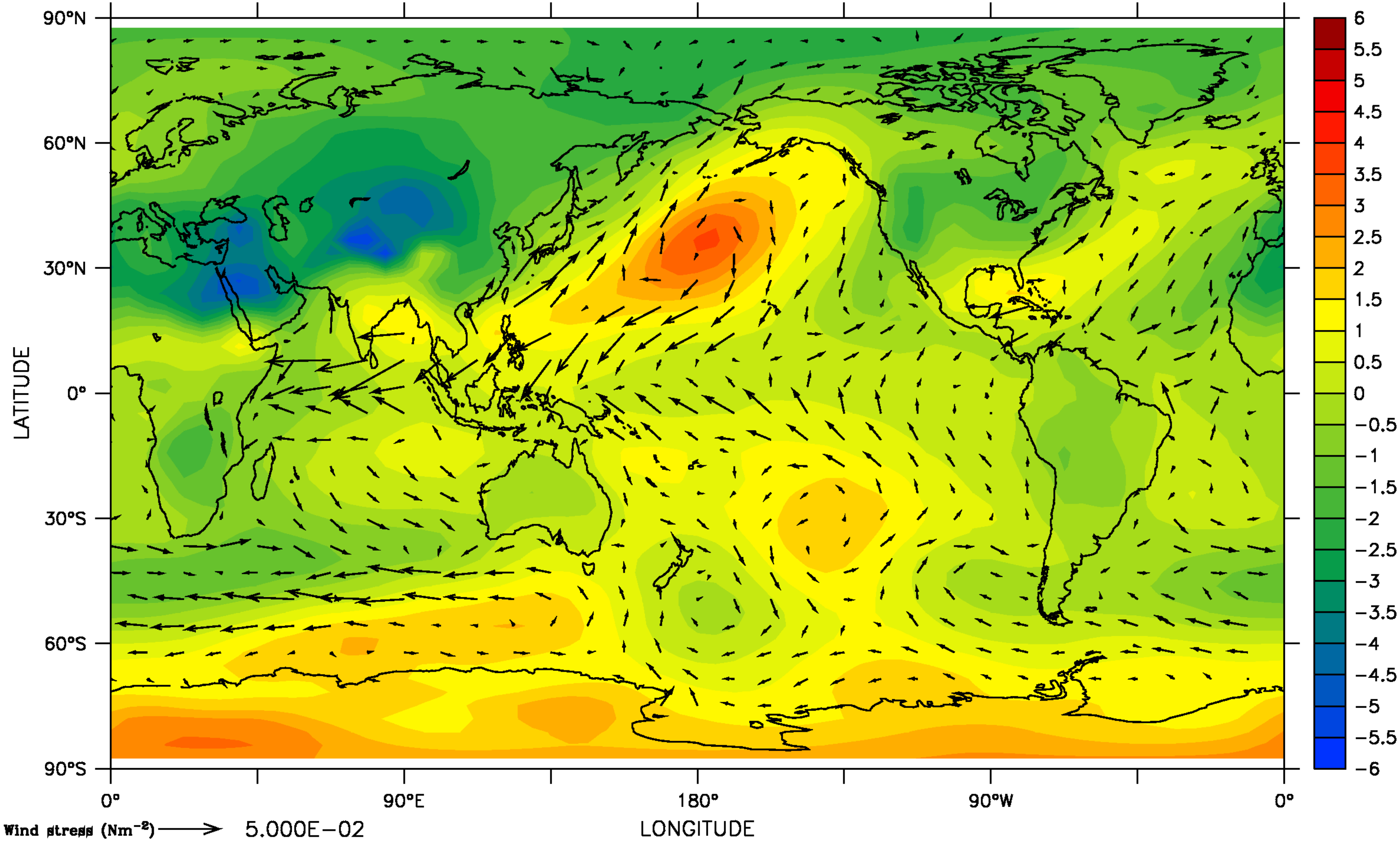
Standard deviation of Nino SST anomaly

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



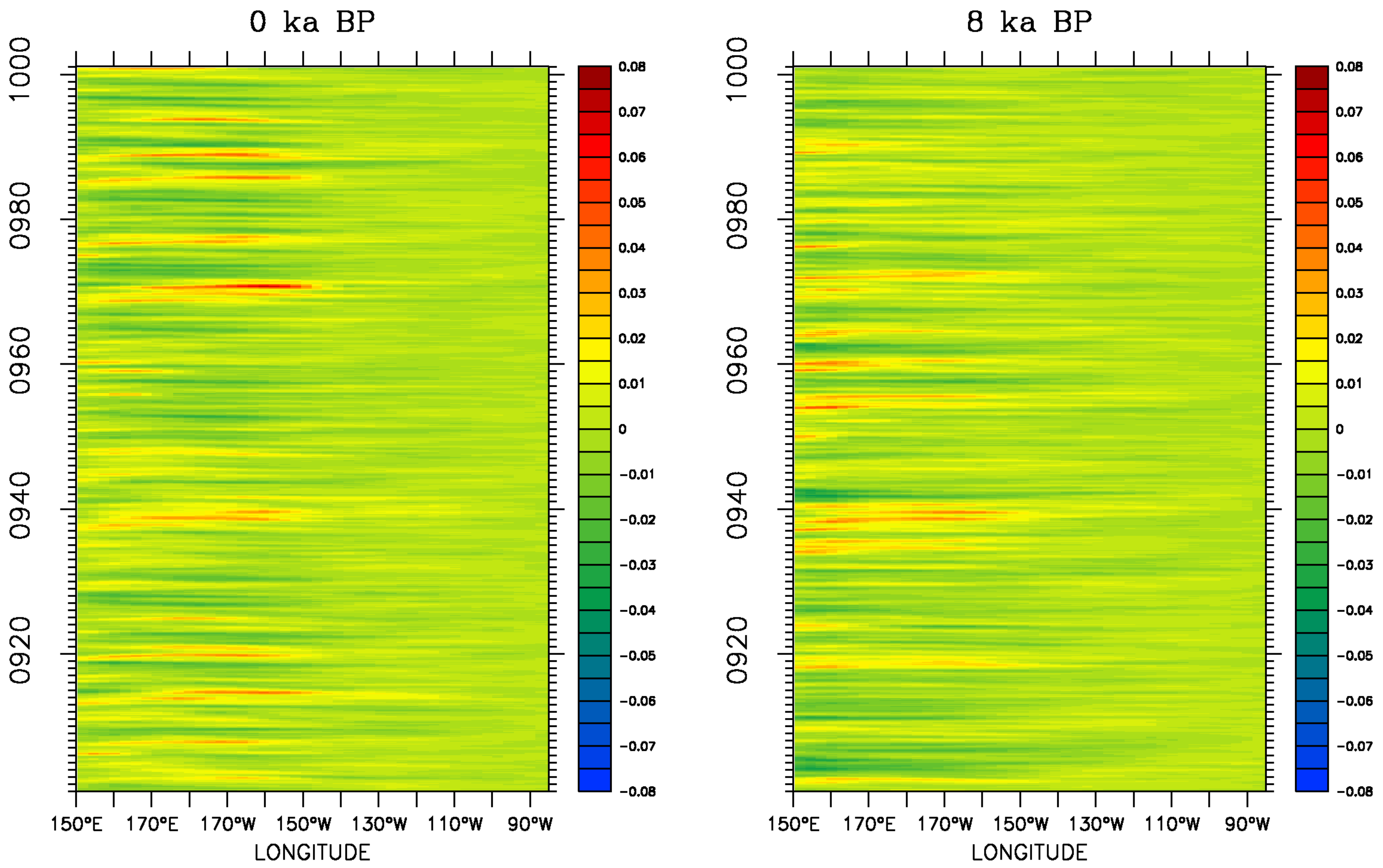
June–July–August surface air temperature, 8 ka minus 0 ka BP (K)

… which enhanced the Asian summer monsoon system



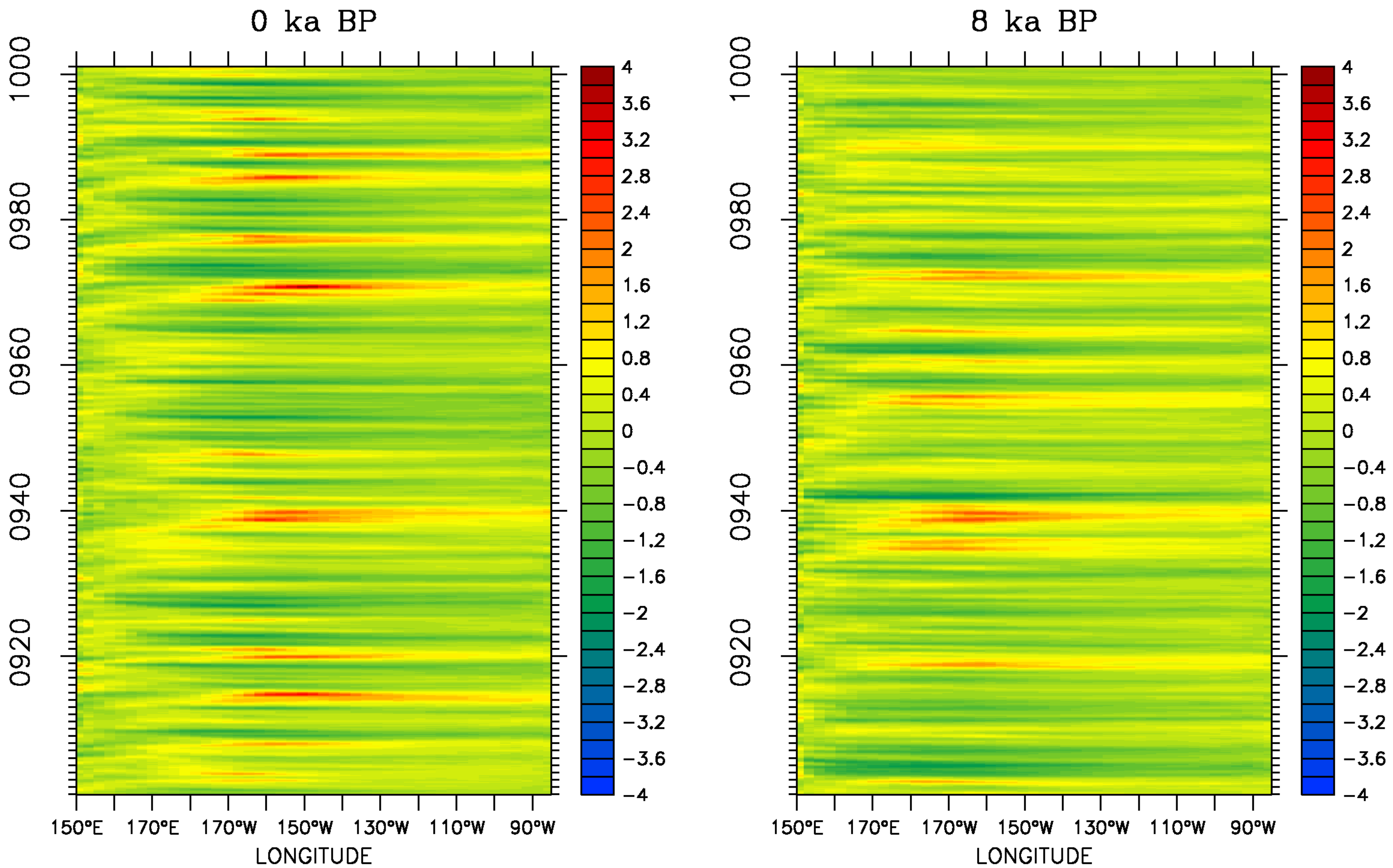
June–July–August mean sea level pressure, 8 ka minus 0 ka BP (hPa)

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



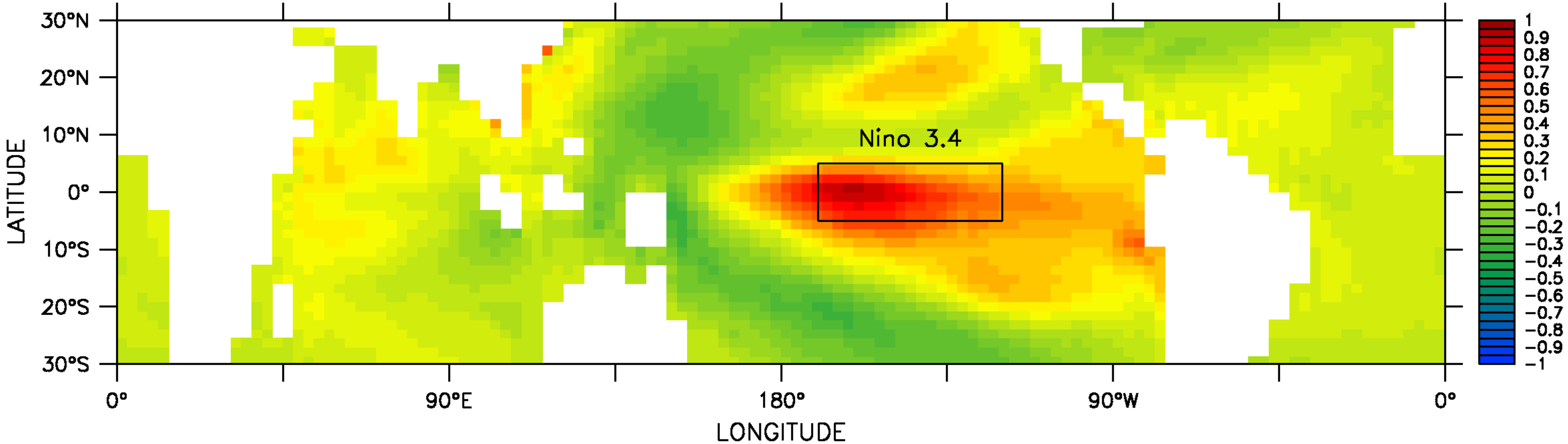
Zonal wind stress anomaly (Nm^{-2})

… which made it harder for El Niño events to develop

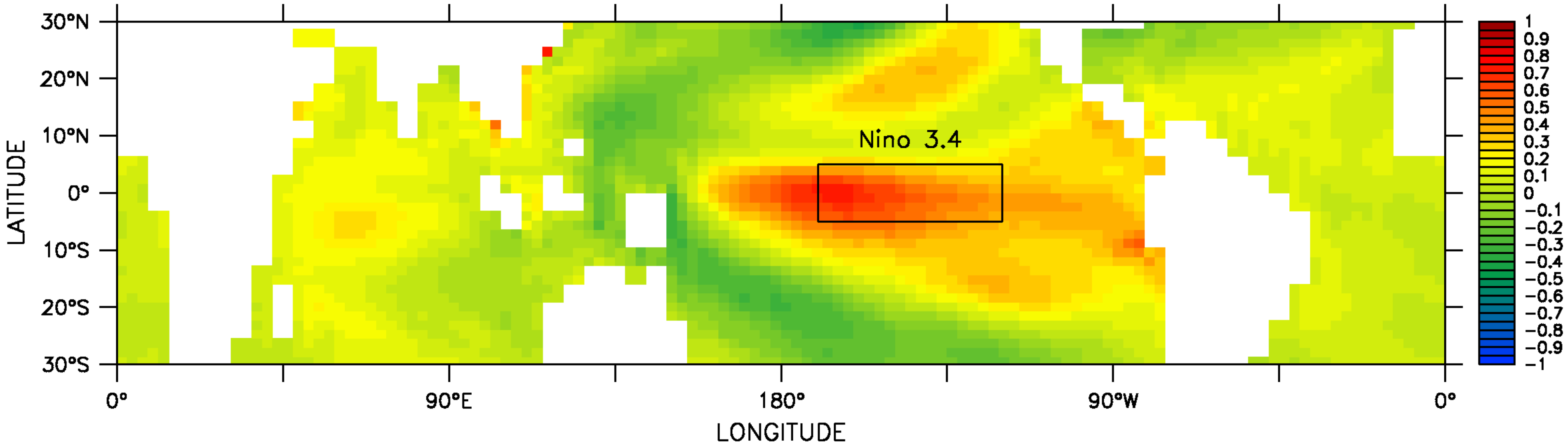


SST anomaly (K)

ENSO has strengthened and shifted eastwards ...

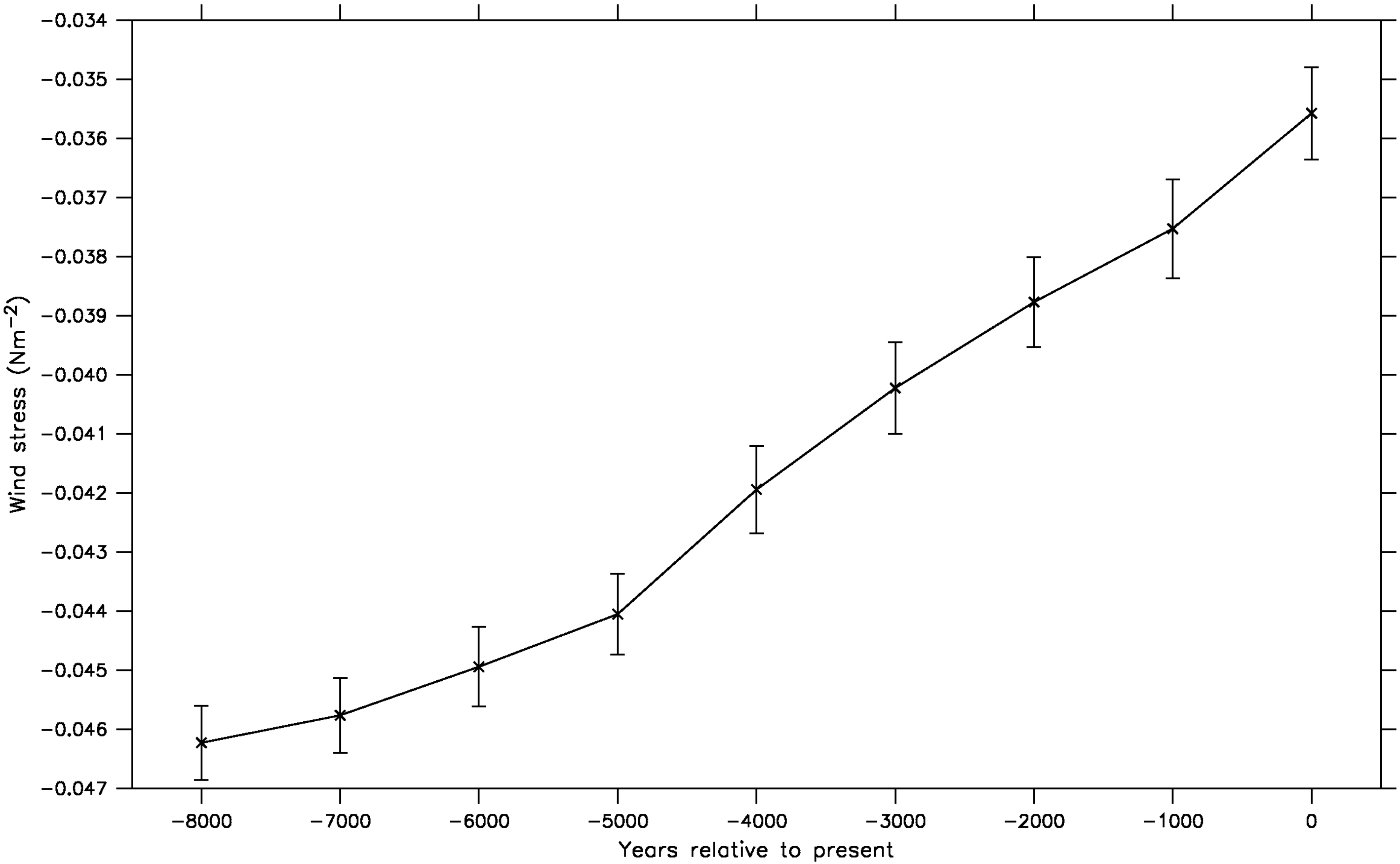


EOF1 of monthly SST anomalies (K): 0 ka BP



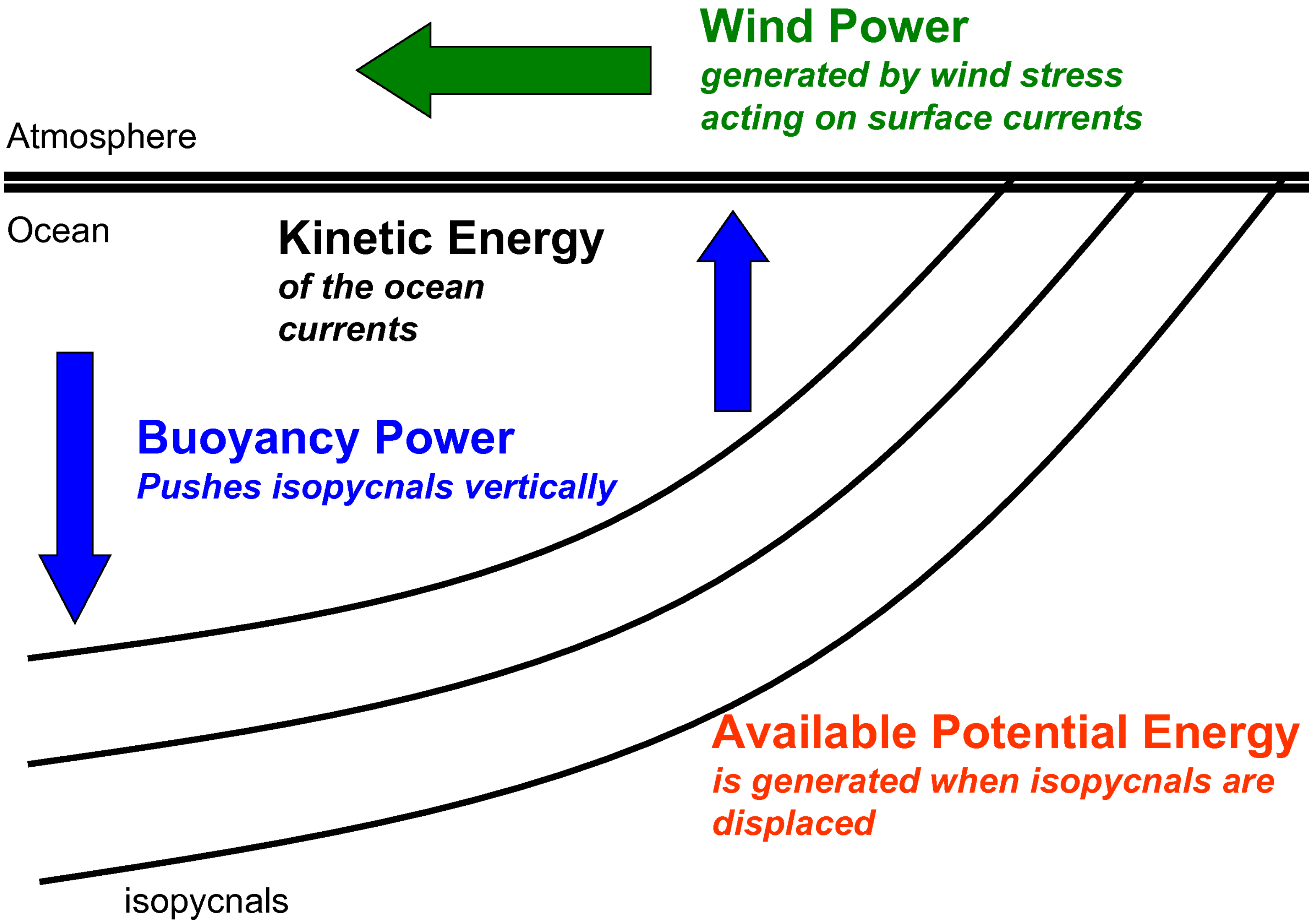
EOF1 of monthly SST anomalies (K): 8 ka BP

... as the Walker Circulation has weakened



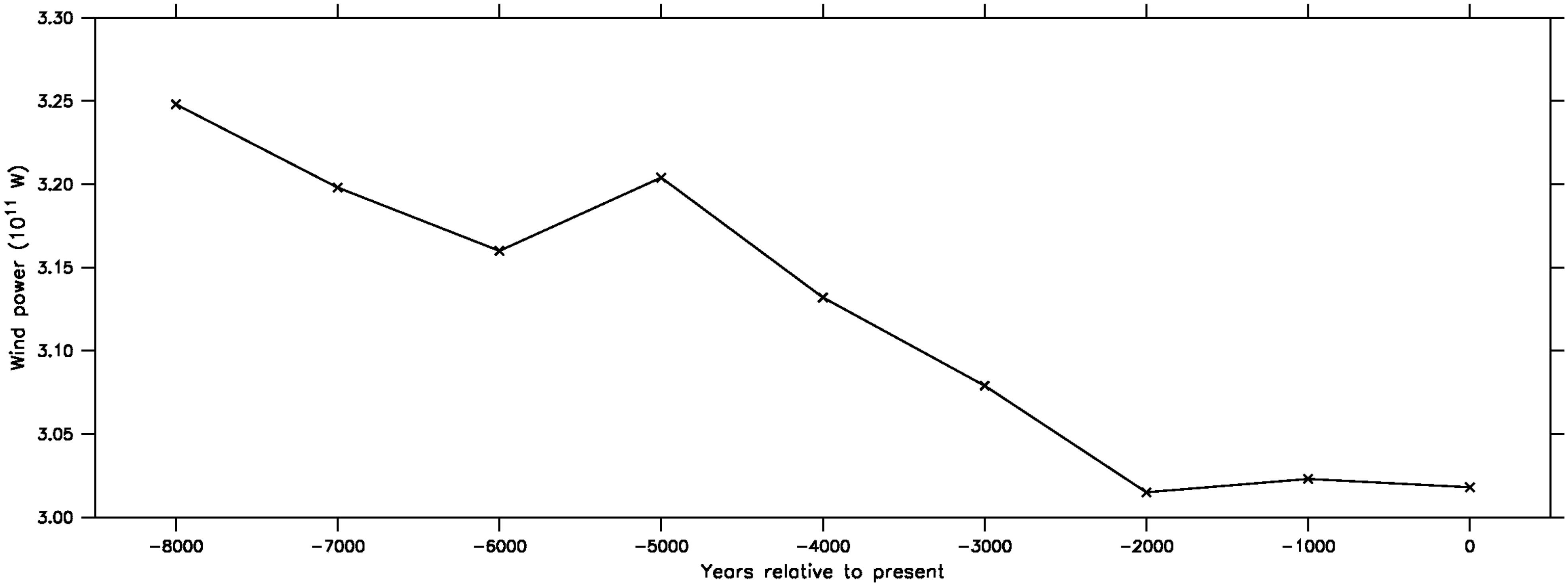
July–August–September–October zonal wind stress in Nino 4 region

Ocean energetics



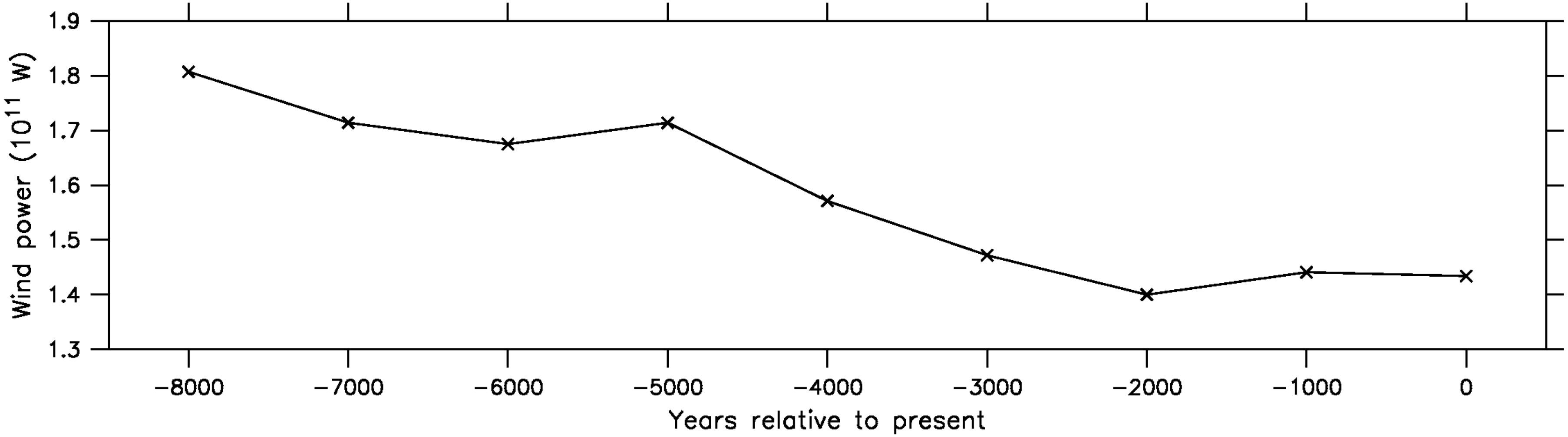
The changes in annual-mean wind power are small...

$$W = \iint_{z=0} \underline{u}.\underline{\tau}\, dxdy$$

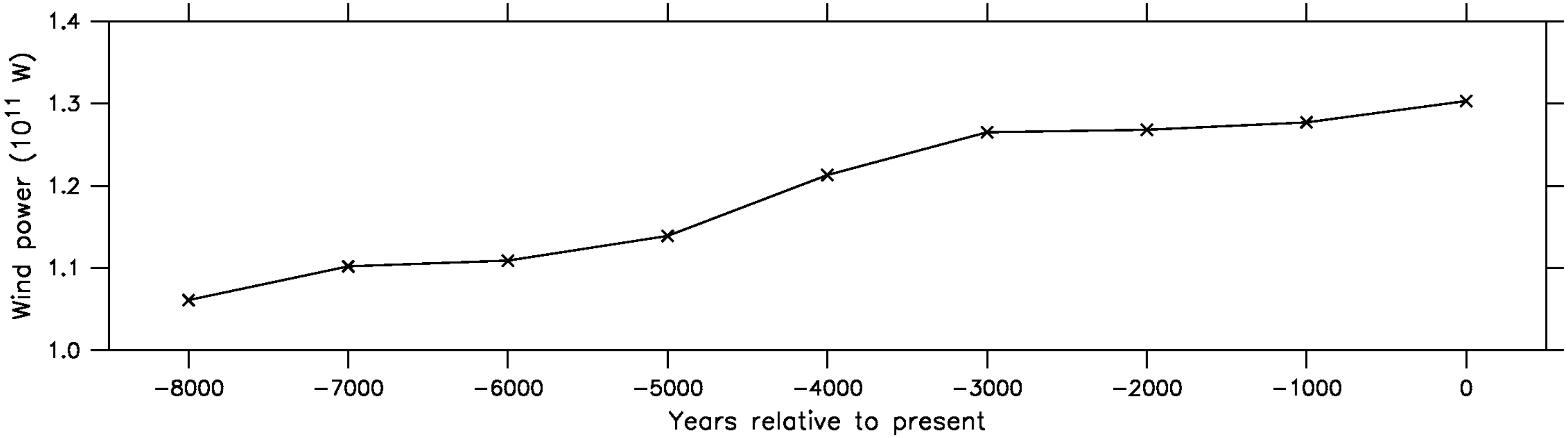


Annual−mean wind power

… but the seasonal changes are larger

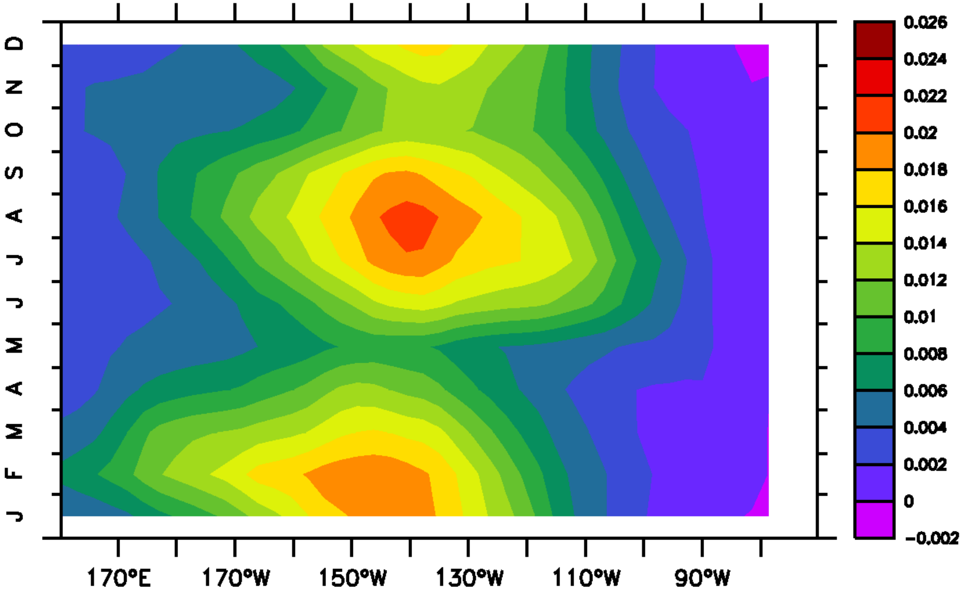


June−July−August−September wind power

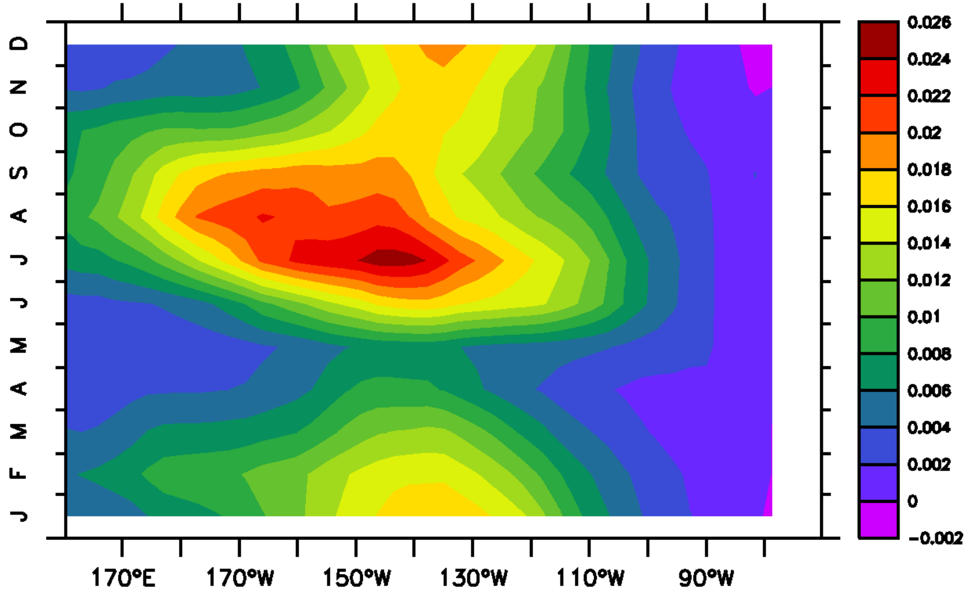


January−February−March−April wind power

Annual cycle in wind power on the equator



0 ka



8 ka

Wind power (Wm^{-2})

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.
- By forcing a climate system model with orbitally-driven insolation changes only, we have been able to reproduce the trends in ENSO variability over the past 8,000 years.
- Decreasing summer insolation over this period 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.
- However, other mechanisms also appear to be at work.
- A full understanding of the processes that drive changes in ENSO variability may be within grasp. However, this will require an approach that integrates the data, modelling and theory communities.