Course Air-Sea Interaction

Paleoclimatology

- Introductory material
  - Online introduction:

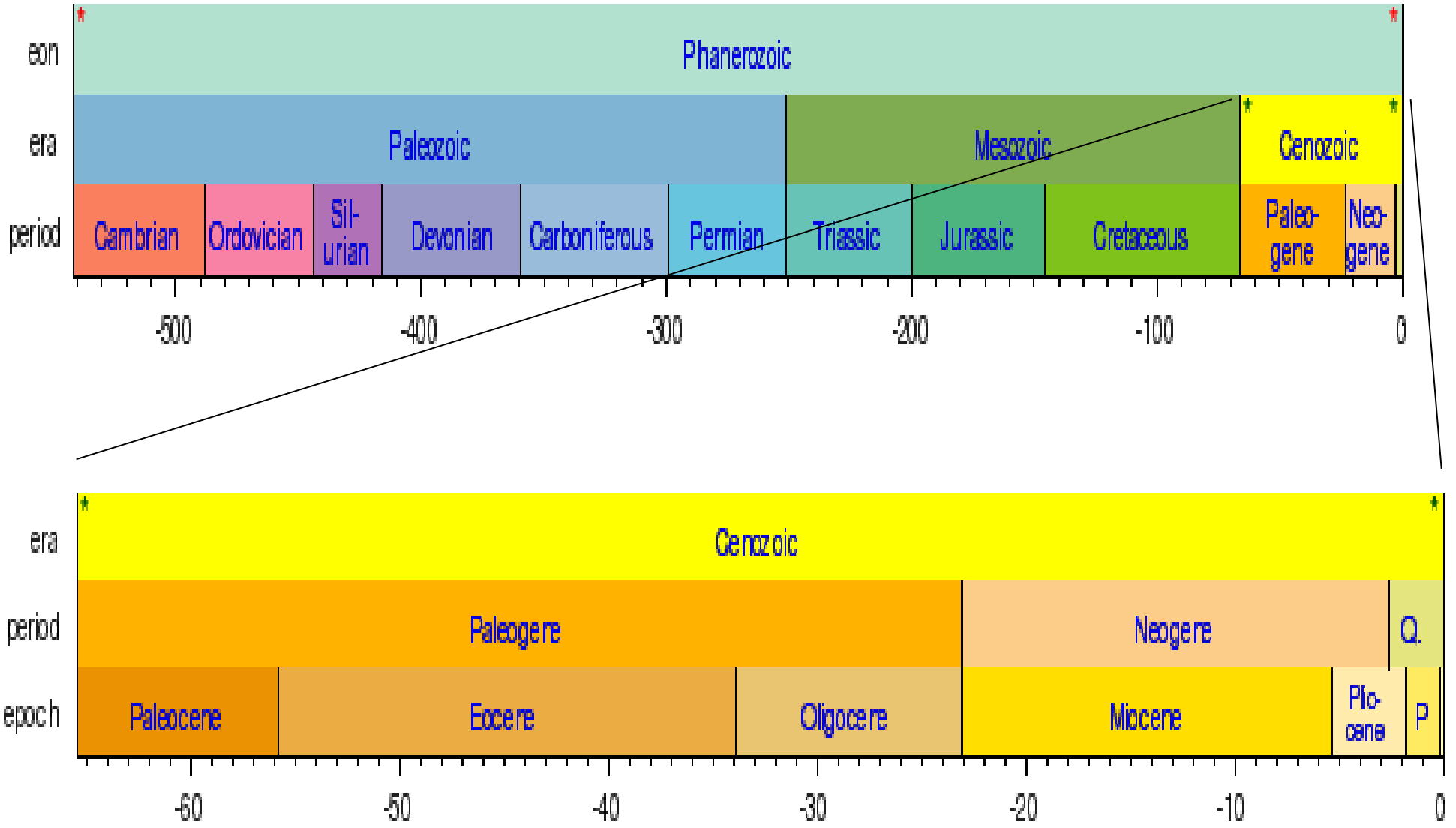
    http://www.ncdc.noaa.gov/paleo/primer.html
  - Textbooks:
    - Bradley, R.S., 1999. "Paleoclimatology: Reconstructing Climates of the Quaternary". Academic Press, San Diego.
    - Saltzmann, B. :Dynamical Paleoclimatology: Generalized Theory of Global Climate Change

Suggested Reading

- Cobb et al., El Niño/Southern Oscillation and tropical Pacific climate during the last millennium, Nature, 424(6946), 271-276, 2003
- Jones, P.D., Osborn, T.J, Briffa, K.R. The Evolution of Climate Over the Last Millennium, Science, 292(5517), pp. 662-667, 2001
- Jones, P.D., Mann, M.E., Climate Over Past Millennia, Rev. Geophysics, 42(2),RG2002, 2004 (doi:10.1029/2003RG000143)

Introductory:

Earth Geologic time scale



Geologic time scale

- Taxonomy (Classification)
  - Eon
  - Era
  - Period
  - Epoch
  - Age
  - (Chronozone)

Geologic time scale

http://www.stratigraphy.org

- Taxonomy (Classification): Where are we now?
  - Eon: Phanerozoic
    - Era: Cenozoic (“new life” after dinosaurs' extinction)
      - Period: Quaternary (glacial-interglacial cycles)
        - Epoch: Holocene (some call the time since the industrial revolution Anthropocene)
        - Age: (Climate Change age?!?)
          (previous age: “Little Ice Age”, “Medieval Warm Period”)

We will look at the last 1000 years of the Holocene and the last 100,000-1,000,000 years of Quaternary Period.

Sources of climatic information: climate proxies

What are climate proxies?

- Any indirect information about the past climate!
  - Tree ring width reflects climate of the growth season
  - Isotopes and trace metals from coral skeletons, speleothems
  - Ice cores: isotopes, trace metals, annual layer thickness
  - Marine sediment cores: foraminifera assemblages, isotopes, trace metals, grain size, pollen
  - (Historical records: weather descriptions, harvest reports, famines etc.)

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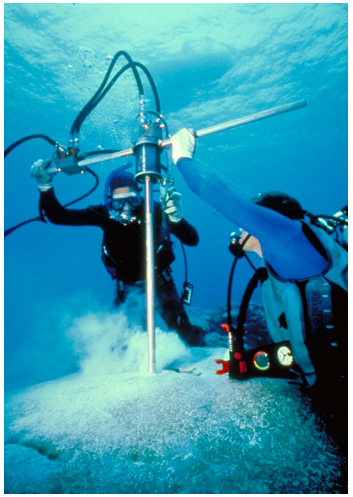
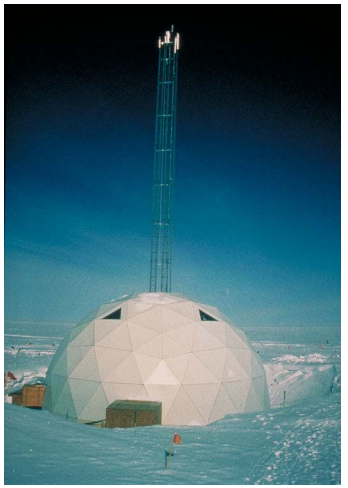
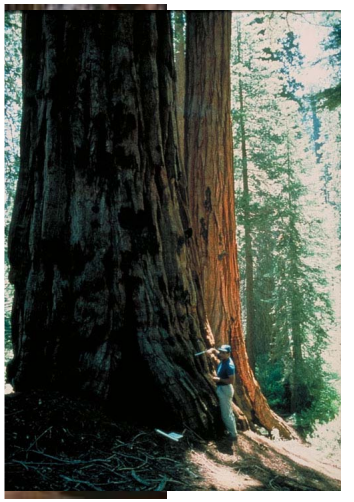
Definition: natural climate proxy ("proxy")

A physical or chemical property of a given medium that is influenced by one or more components of the climate system.

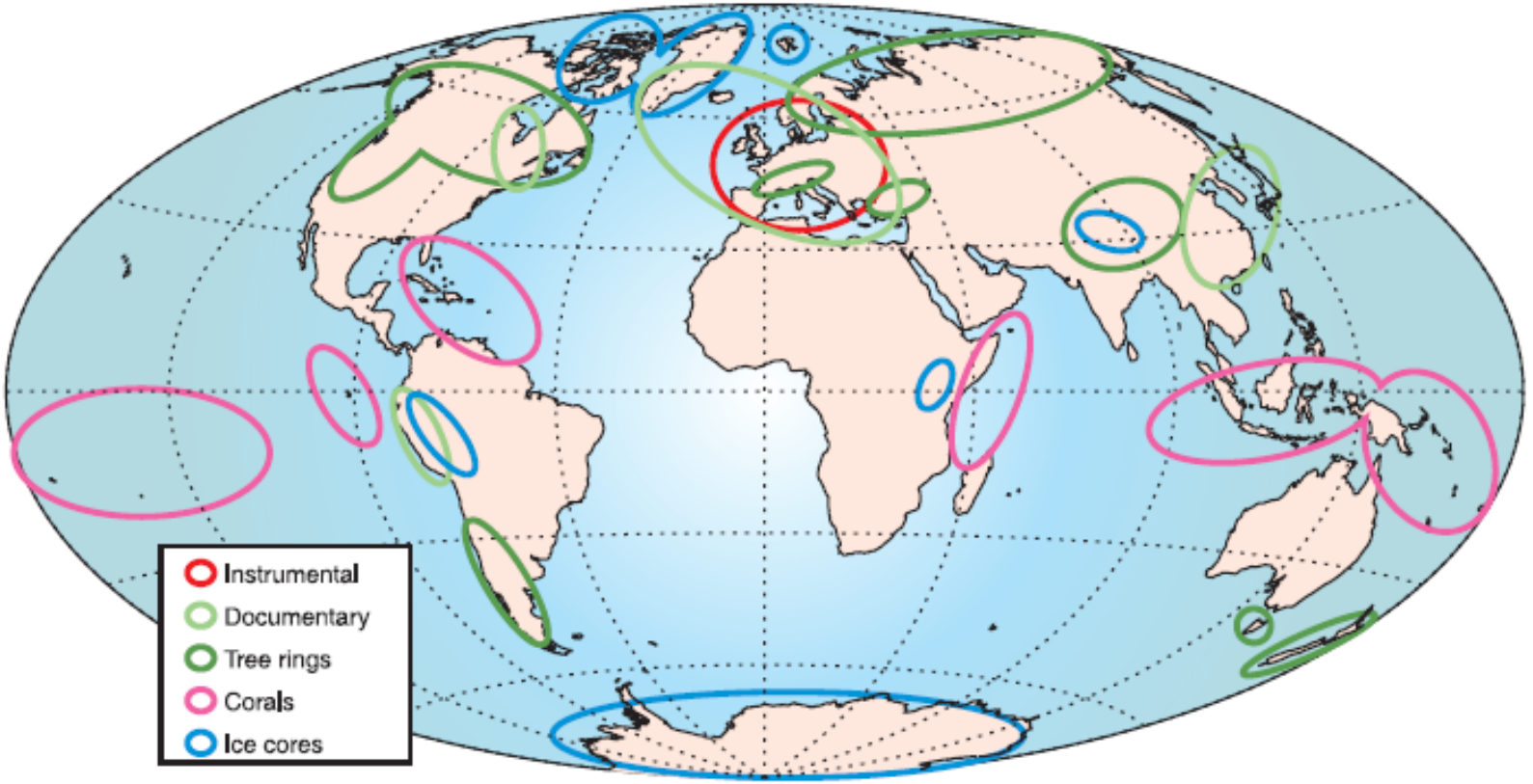





Climate of the last millennium

- Goals in Paleoclimatology:
  - develop continuous records of climate variability (with annual resolution)
- Scientific value:
  - understanding of natural climate variability in particular decadal and multidecadal variability!
  - providing a basis for the detection of anthropogenic climate change, model validation etc.
  - interdisciplinary studies (archeology, anthropology ...)

Regions with high-resolution paleoclimatic archives



From Jones (2001)

General tasks in paleoclimatology

- Development of accurate timescales
  - Dating methods rely on several methods
    - Clearly distinguished annual layers
    - Reference points such as historically documented volcanic eruptions

General tasks in paleoclimatology

- Estimating the response function of proxies [mechanistic linkage between climate and proxies]
  - Tree ring width: temperature and/or rainfall, seasonality, biological growth factors.
  - Ice core oxygen isotopes: interpreted as local temperatures but other factors such as climatic conditions over the oceanic source regions (the water source of the snow)
  - Corals: biological growth factors, oxygen isotopes reflect temperature and salinity signals (mixed signals)

Statistical concepts in paleoclimatology

- A set of proxies $Y=(y_1,y_2,...y_m)$ is responding to climate signals $X=(x_1,x_2,...x_n)$ in a systematic way given by its response function f
  - $Y = f(X)$
    - We try to find a transfer function g that recovers the climate state from the proxy state
    - $\hat{X}=g(Y)$
  - Usually we don't know the exact form of f and g and/or all the relevant climate signals X !

Linear response function

$$Y = \mathbf{H}X + N$$

$\mathbf{H}$ is a (m * n) matrix
N is a noise vector (m * 1)
Multiple linear regression,
(Principal Component
Regression)
are used to estimate the climate
state from proxy data

$$\hat{X} = (\mathbf{H}^t \mathbf{H})^{-1} \mathbf{H}^t Y$$

(Best Linear Unbiased Estimator)

Linear response function

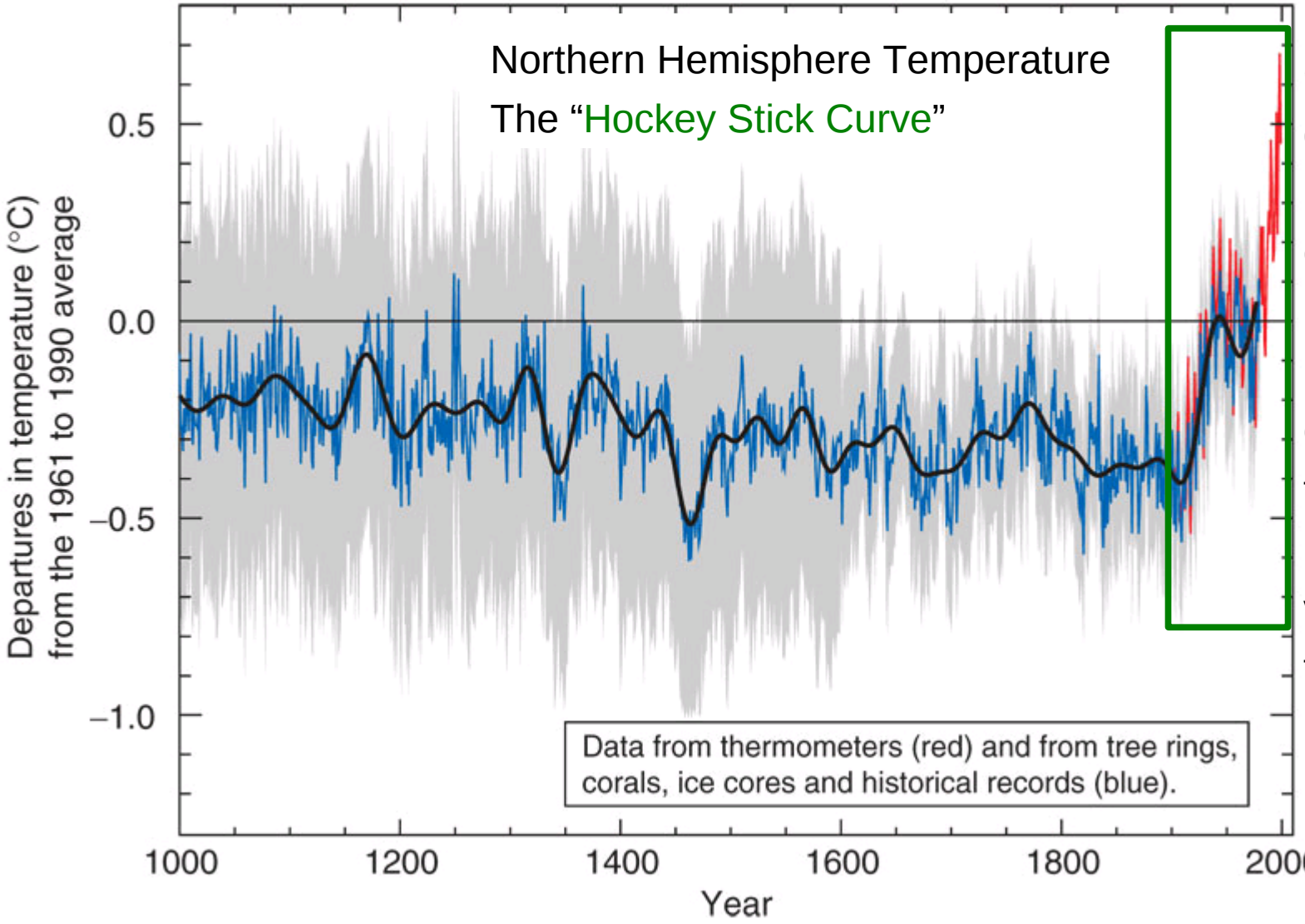
$$Y = \mathbf{H}X + N$$

- The **uniformitarian** principle is assumed
  - Contemporary climatic variations from a modern analog apply for paleoclimatic changes
  - equivalent to stationarity of response function/ transfer function
  - equivalent to **statistical stationarity** (**covariance** terms do not change)

$$\hat{X} = (\mathbf{H}^t \mathbf{H})^{-1} \mathbf{H}^t Y$$

The climate of the last 1,000 years

http://en.wikipedia.org/wiki/Hockey_stick_controvers



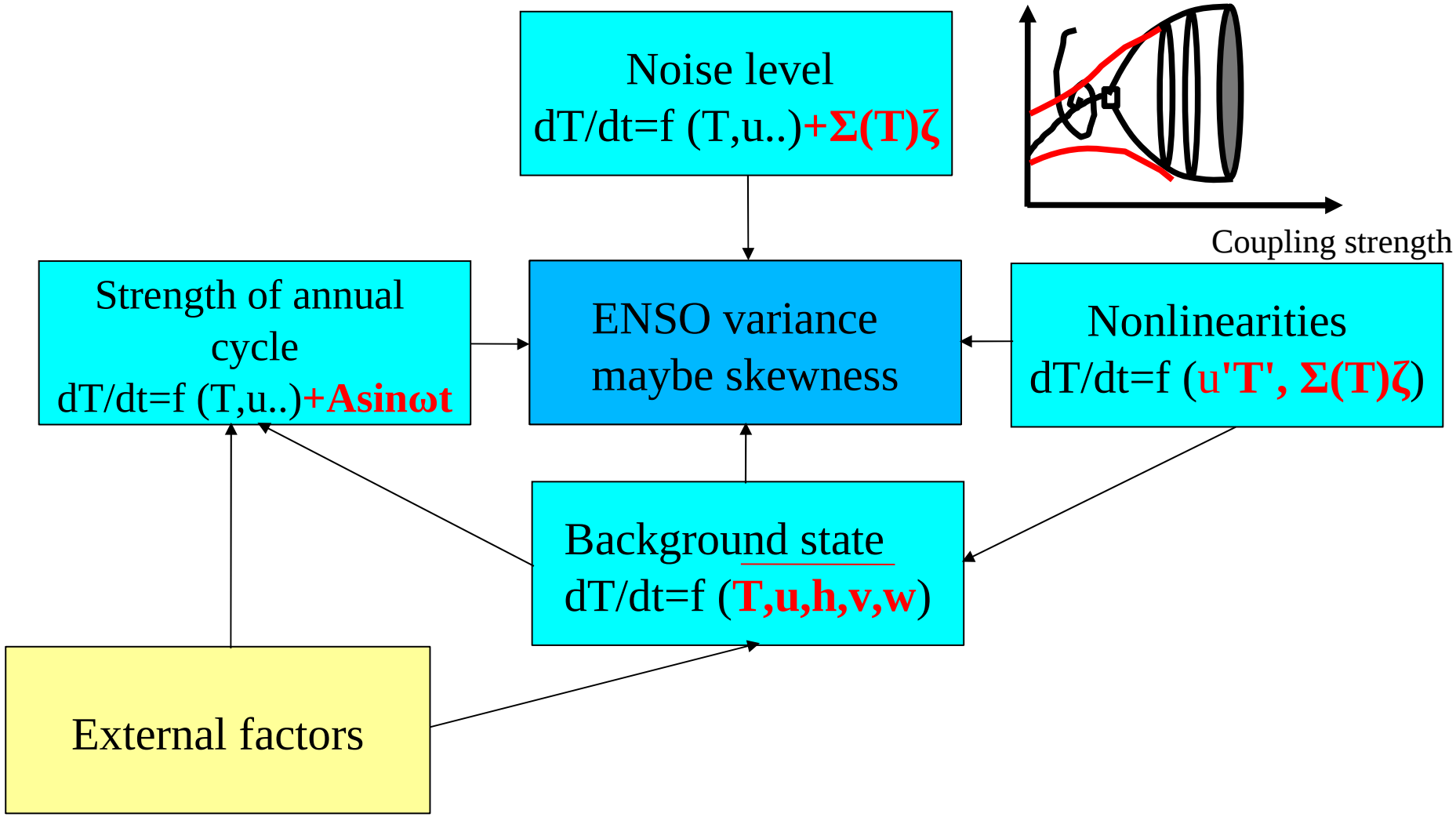
Overlapping data interval:

estimating response function

calibration of transfer model

valildation transfer model

What controls the amplitude of ENSO



(slide from A. Timmermann)

ENSO: **positive air-sea feedback**

The Gill model:

$$\frac{\partial u}{\partial t} - fv + \frac{\partial \phi}{\partial x} = -ru$$

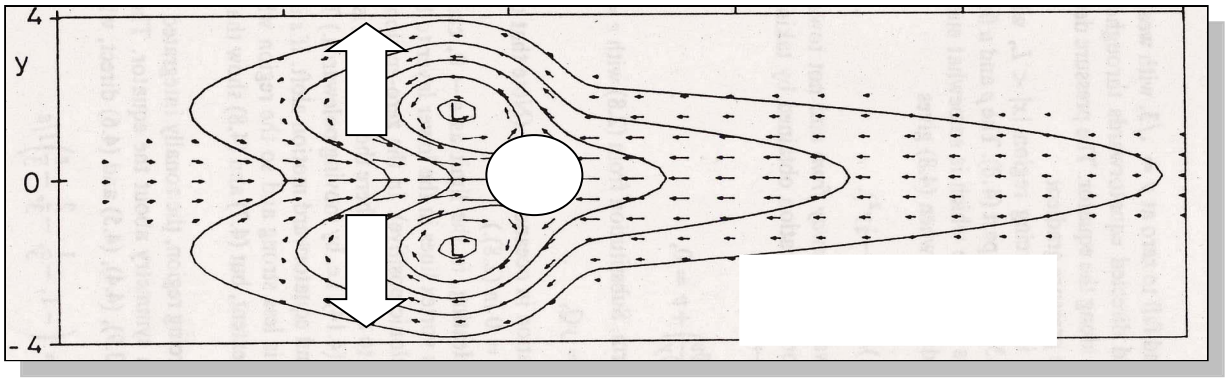
$$\frac{\partial v}{\partial t} + fu + \frac{\partial \phi}{\partial y} = -rv$$

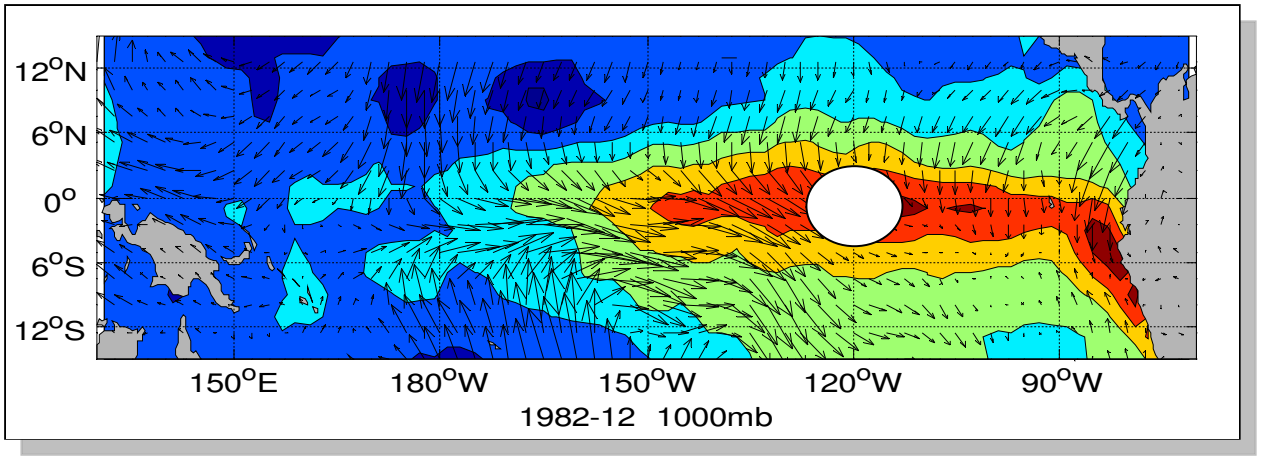
$$\frac{\partial}{\partial t}\phi + gH_e\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = -Q_a - \varepsilon\phi$$

$$-yv/2 + \frac{\partial \phi}{\partial x} = -\varepsilon u$$

$$+yu/2 + \frac{\partial \phi}{\partial y} = -\varepsilon v$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -Q_a - \varepsilon\phi$$





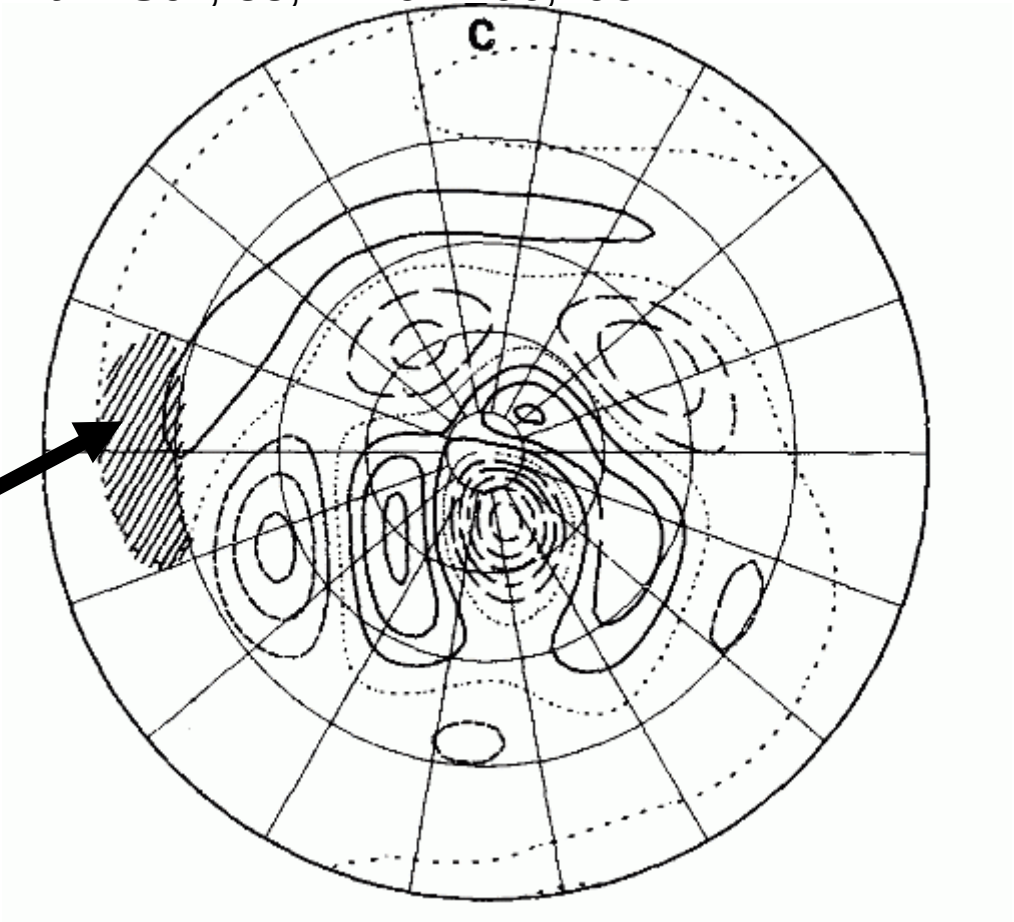
Rossby wave trains form global teleconnection pattern

Atmospheric Teleconnection Pattern

Rossby Wave Trains

Hoskins and Karoly, J. Atm. Sci., 38, 1179-1196,1981

subtropical heating source in the middle troposphere



300 hPa geopotential height anomalies

(contour interval 2 dam)

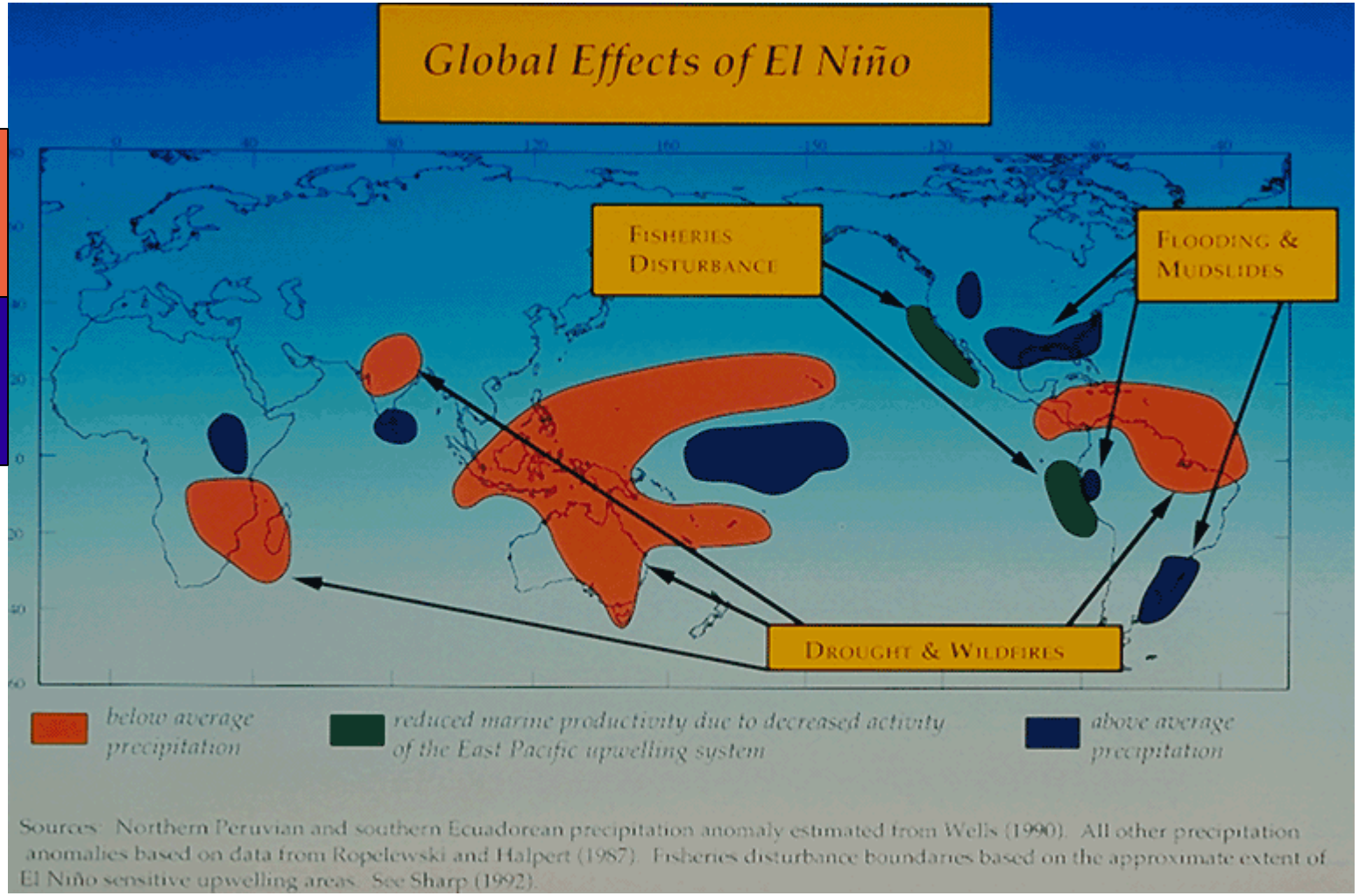
ENSO reconstructions

Global teleconnection pattern --- regions with reconstruction potential

During El Nino

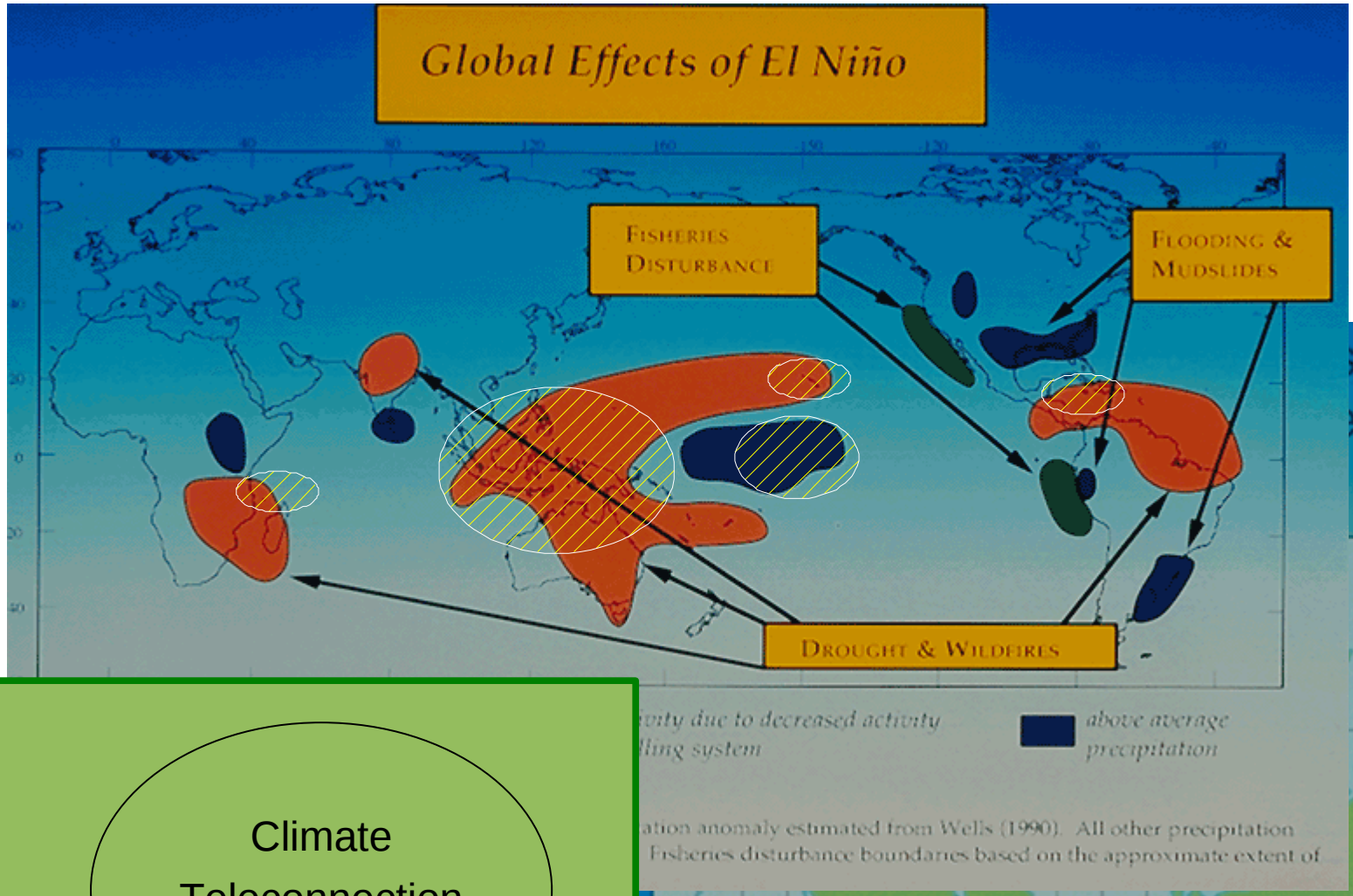
dryer

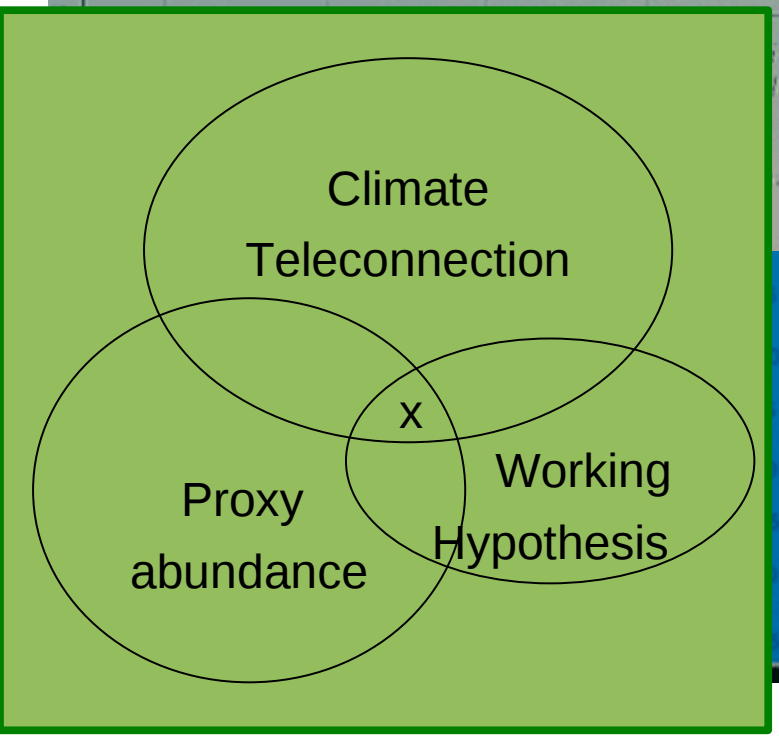
wetter



http://www.ncdc.noaa.gov/paleo/slides/slideset/13/13_226_bslide.html

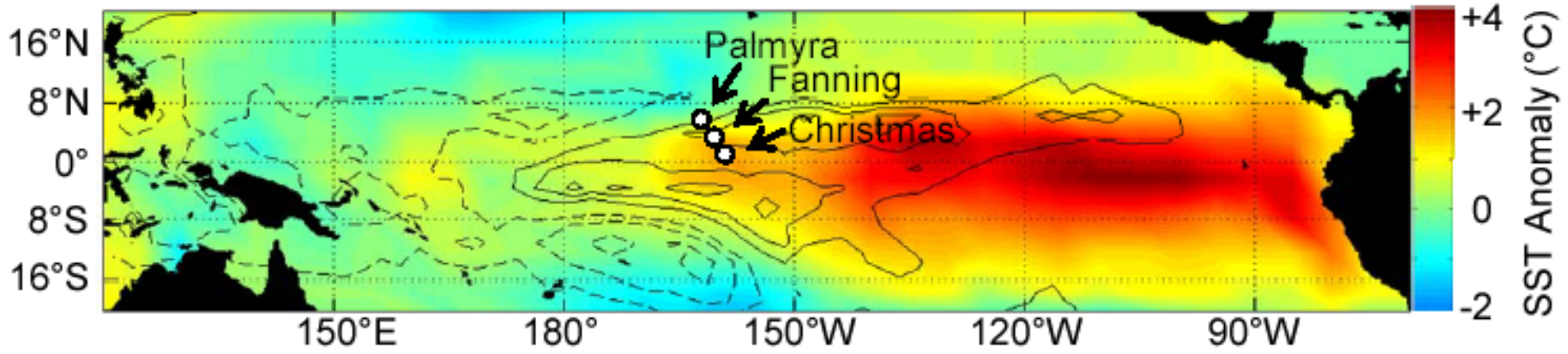
ENSO reconstruction with coral proxies


Global Effects of El Niño
Fisheries Disturbance
Flooding & Mudslides
Drought & Wildfires
above average precipitation


Climate Teleconnection
x
Working Hypothesis
Proxy abundance


only where the
n 20°-28° C
60
90
120
150

Coral-based reconstruction of ENSO

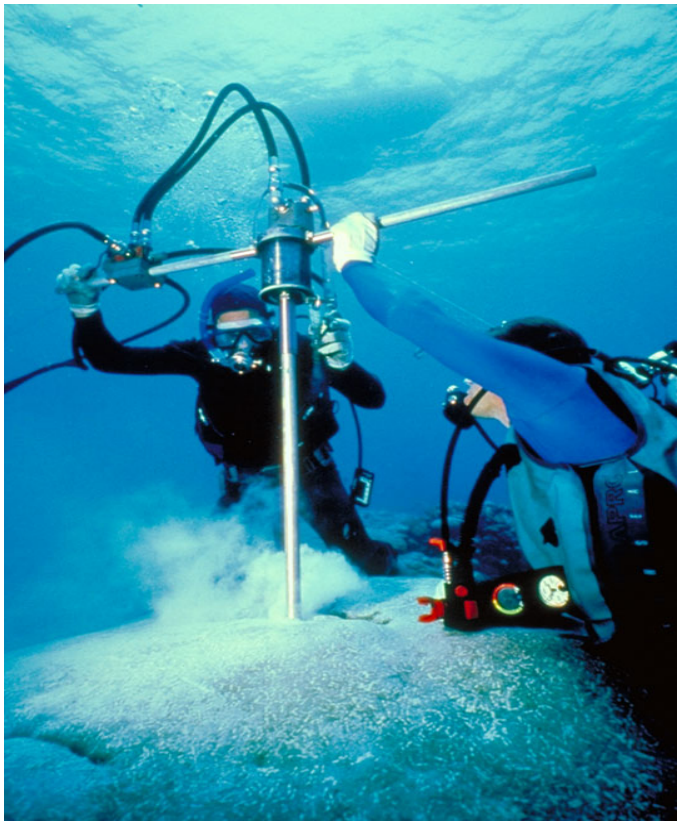


Source: Kim Cobb's paper (2003) and presentation
at the Workshop on
Climatic Changes in the Last 1500 Years: Their Impact on Pacific Islands, East West Center, Nov 2007

http://www.soest.hawaii.edu/~timm/files/workshop2007/Workshop200711.ht

Coral proxies:

Isotopes and trace elements



Climatic state:

SST, SSS

---

proxies:

oxygen isotope

$^{18}O/^{16}O$ ratio, $\delta^{18}O$

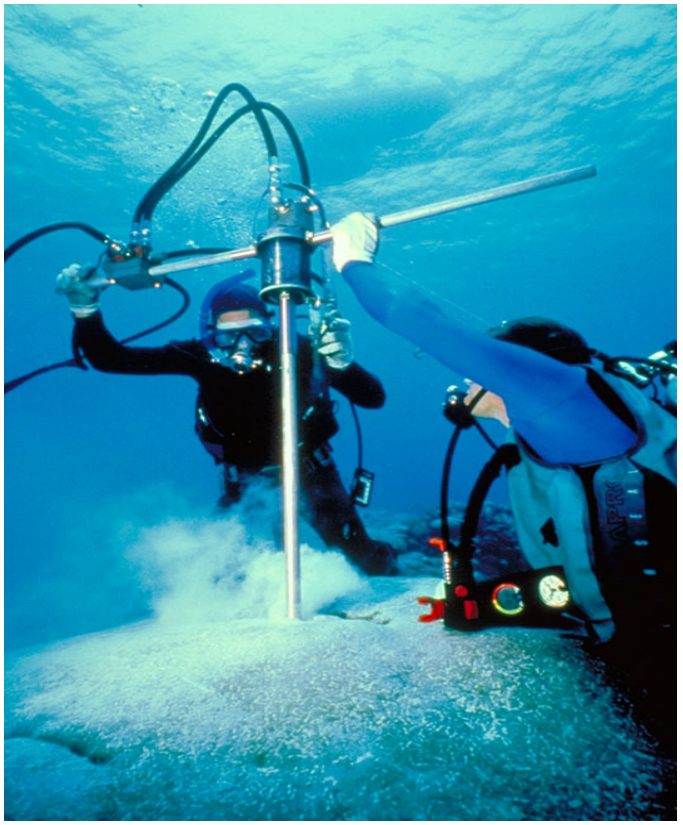
Strontium/Calcuim ratio

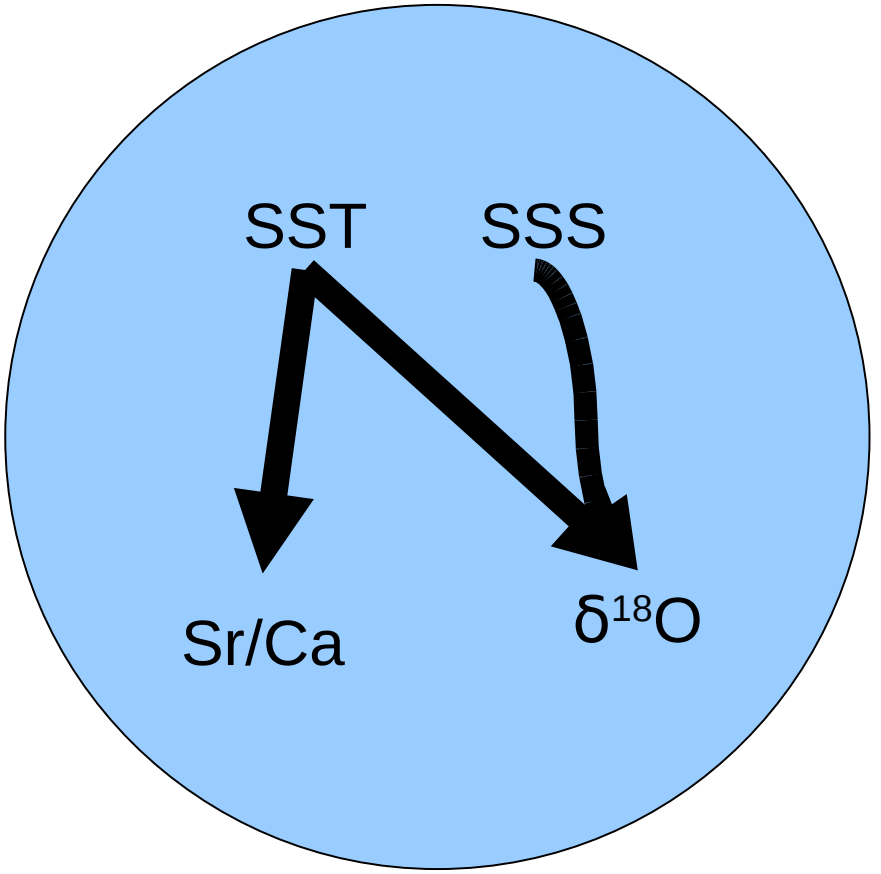
(Sr/Ca)

Gagan, M.K. et al, Science, 279, 1998

Cahyarini, S. Y. et al., Geochimica et Cosmochimica Acta, 72(12), 2841-2853

Unmixing SST and SSS signals from isotopes and trace elements





Gagan, M.K. et al, Science, 279, 1998

Cahyarini, S. Y. et al., Geochimica et Cosmochimica Acta, 72(12), 2841-2853

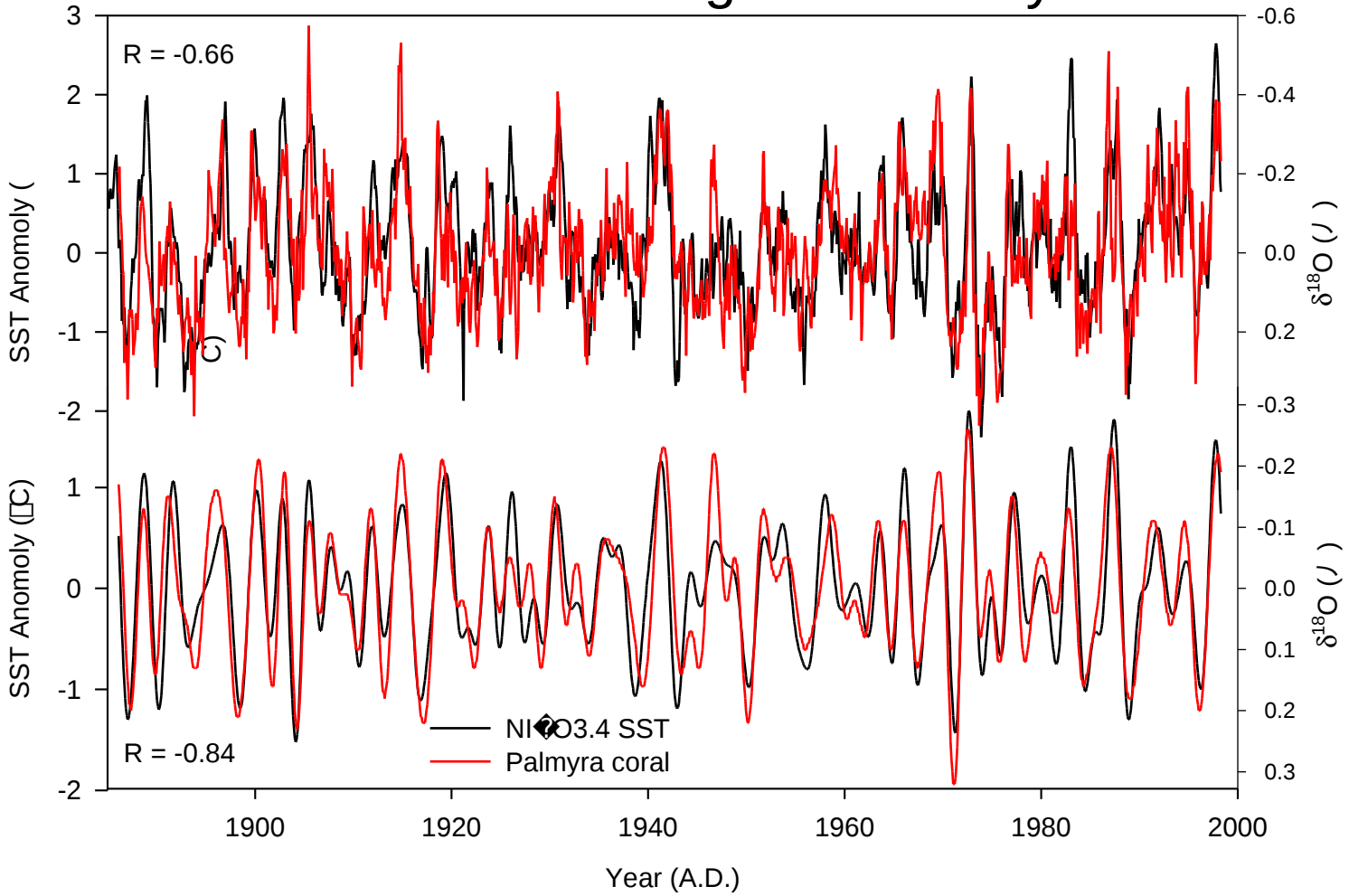
Palmyra coral proxies

Calibration of the transfer model:

NINO3.4 index --- oxygen isotopes

oxygen isotopes:

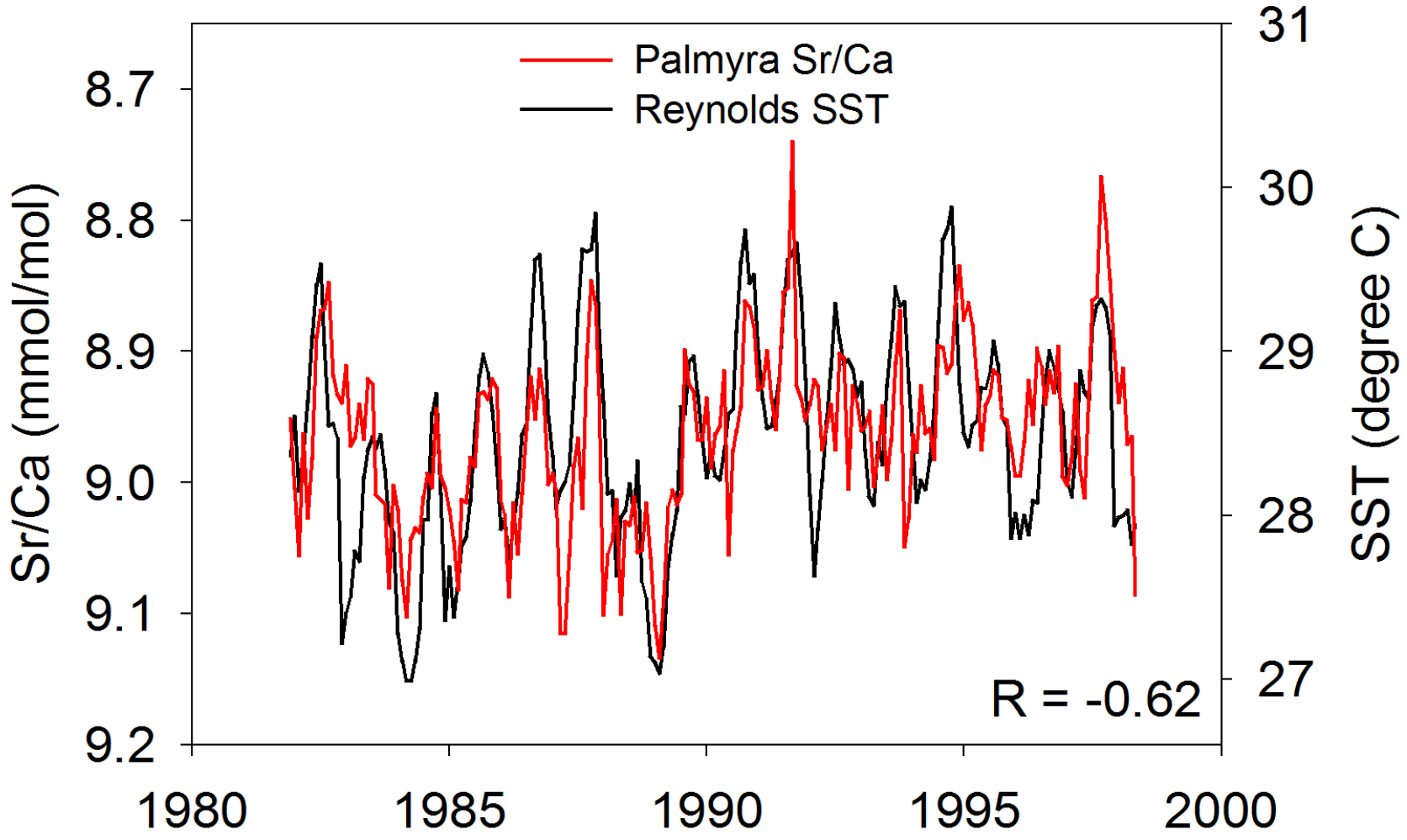
MAINLY SST signal at Palmyra



$\delta^{18}O$

$\delta^{18}O$

Strontium-Calcium ratios in corals: Proxies for SST, exclusively



ENSO reconstruction

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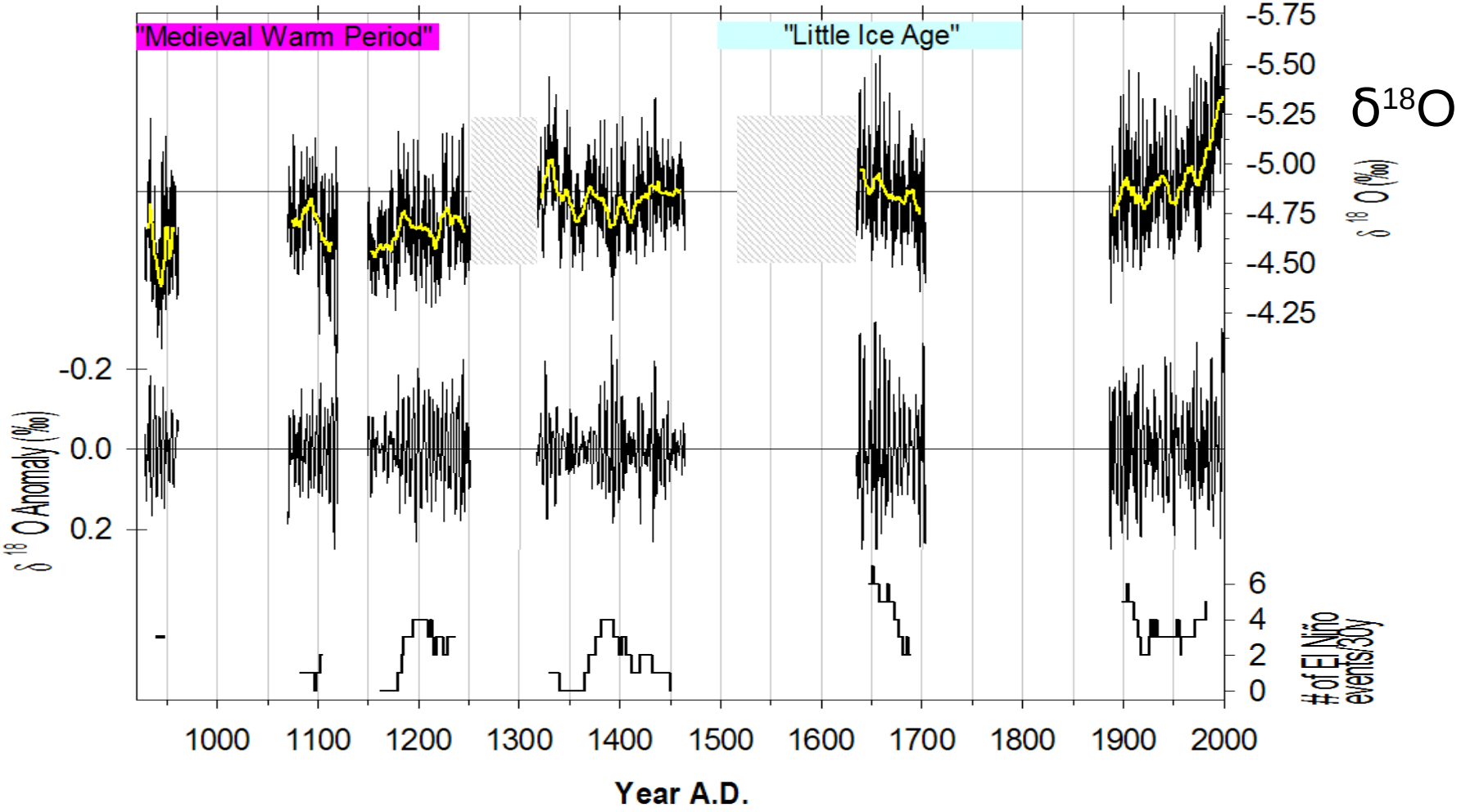
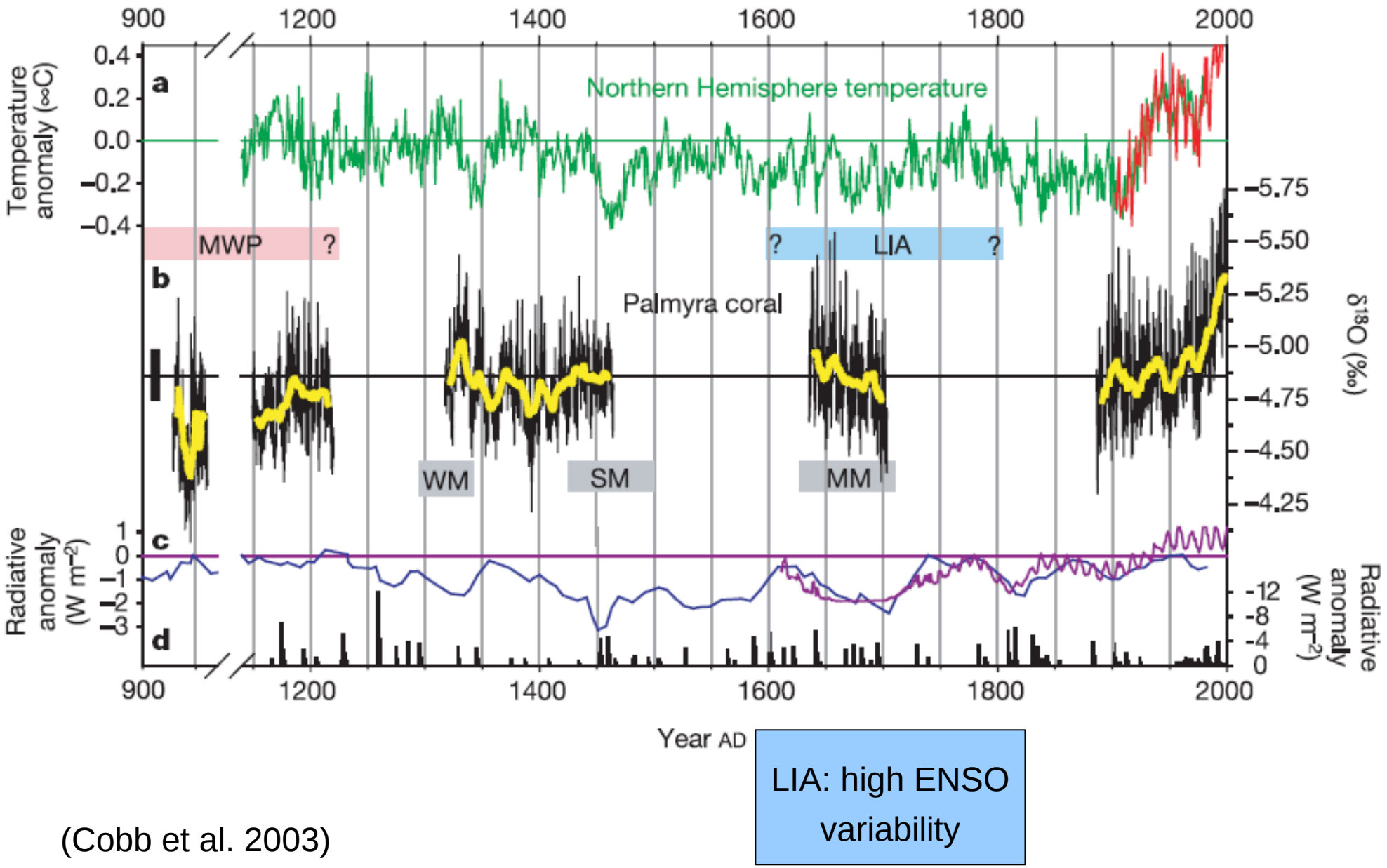
  - Contemporary climatic variations form a modern analog apply for paleoclimatic changes



ENSO reconstruction



LIA: high ENSO variability

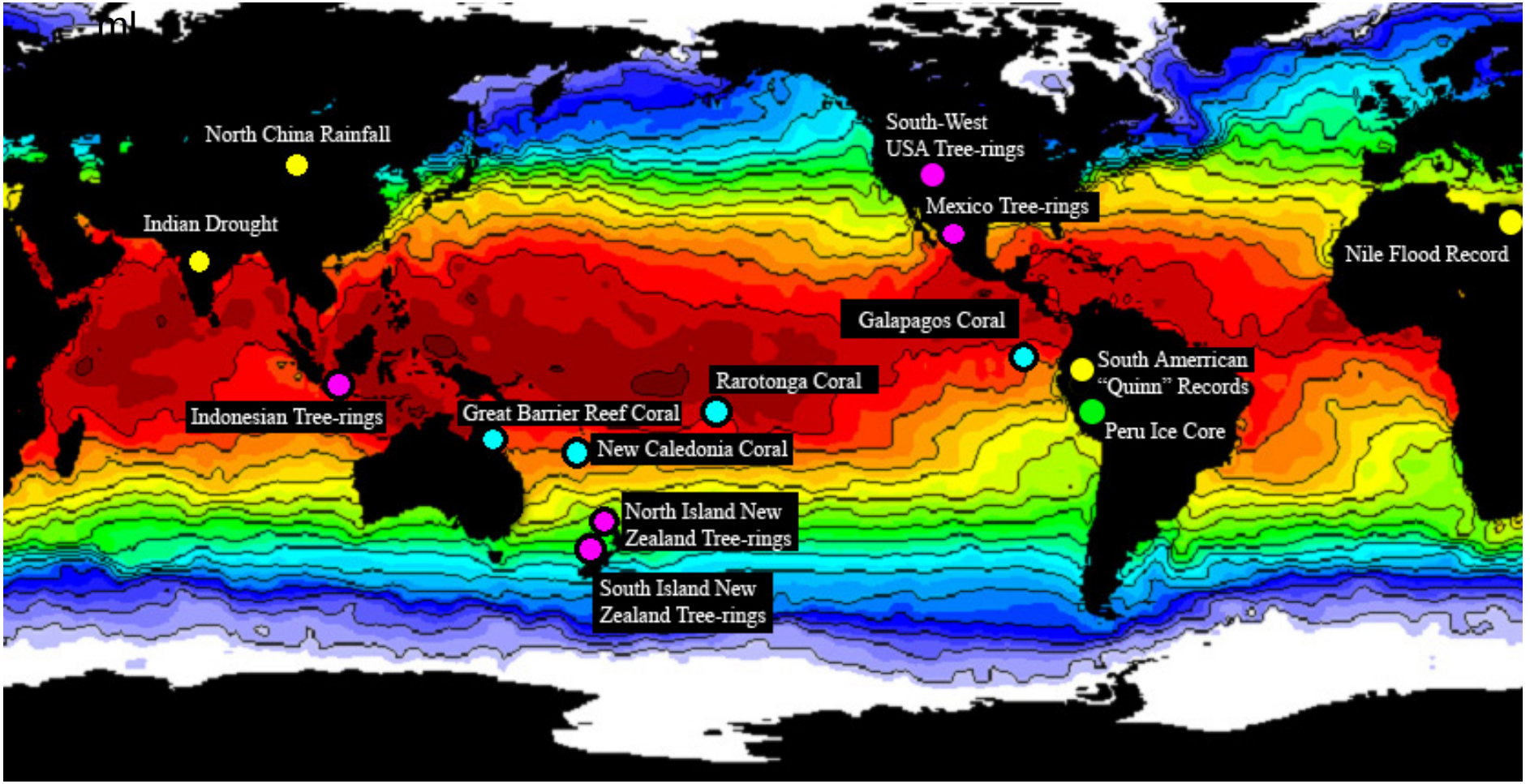
(Cobb et al. 2003)

ENSO index reconstruction

Multiproxy network

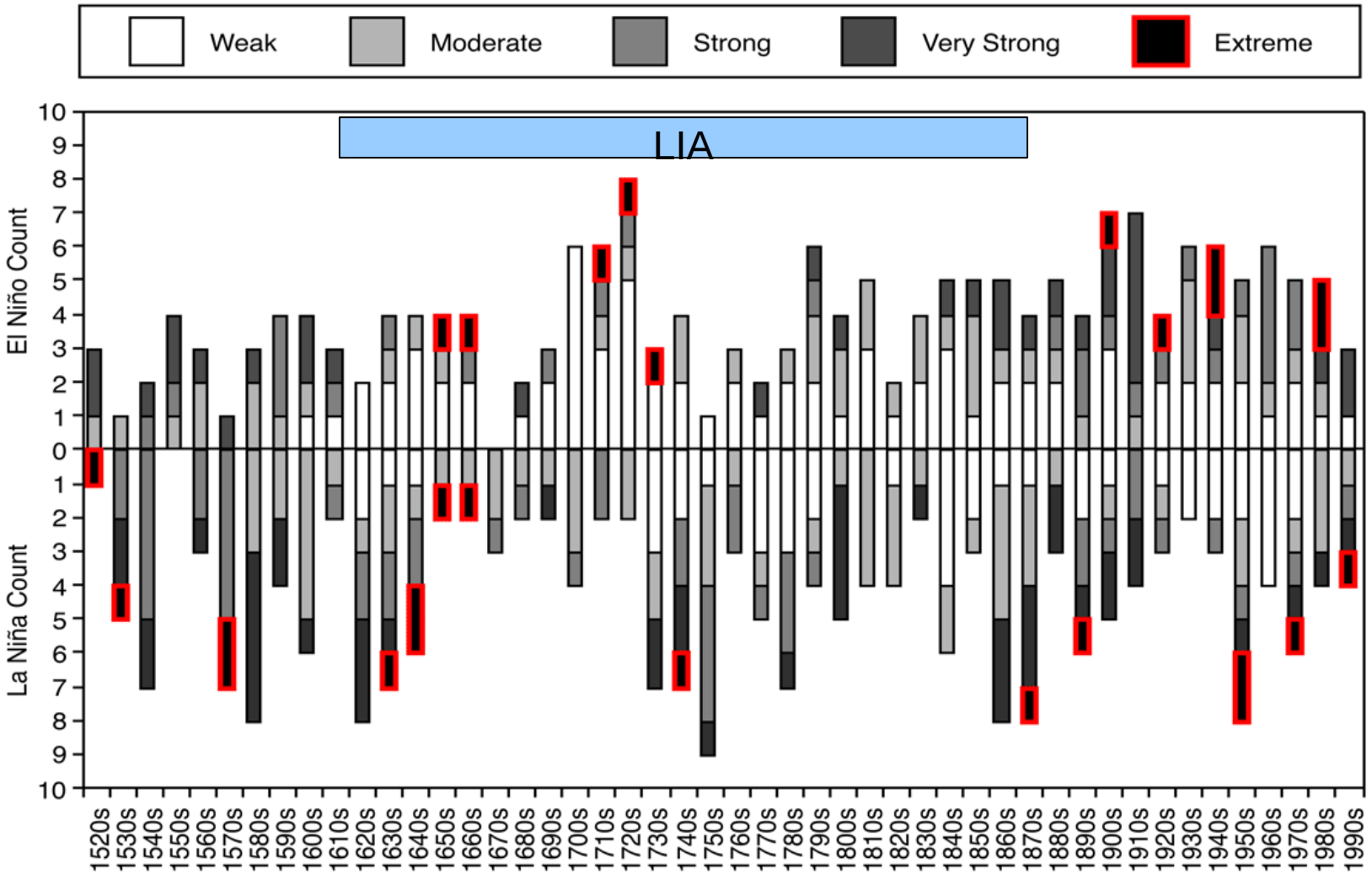
Joelle Gergis presentation , 2007

http://www.soest.hawaii.edu/~timm/files/workshop2007/Workshop200711.html



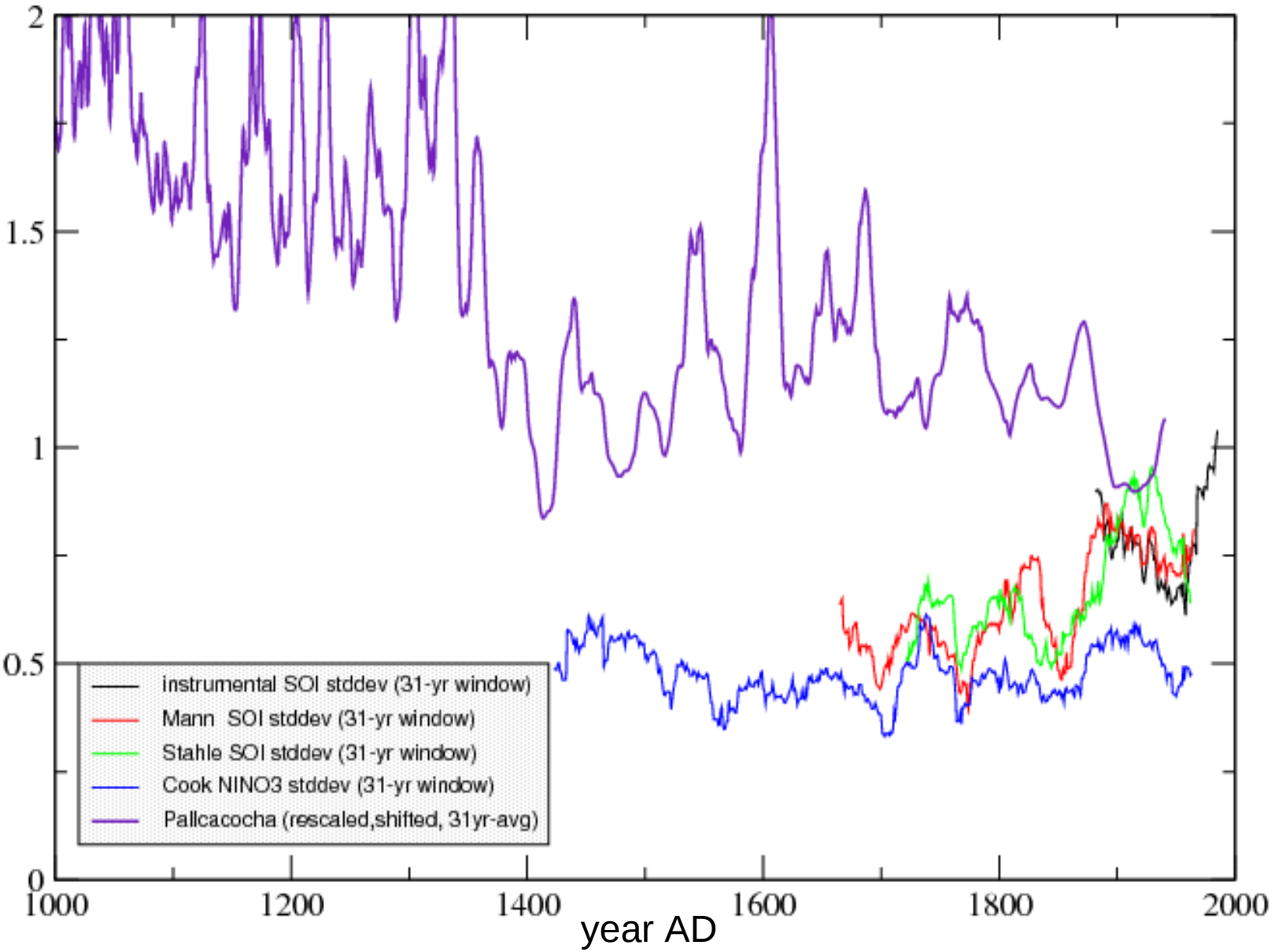
Gergis et al. (2006,2007)

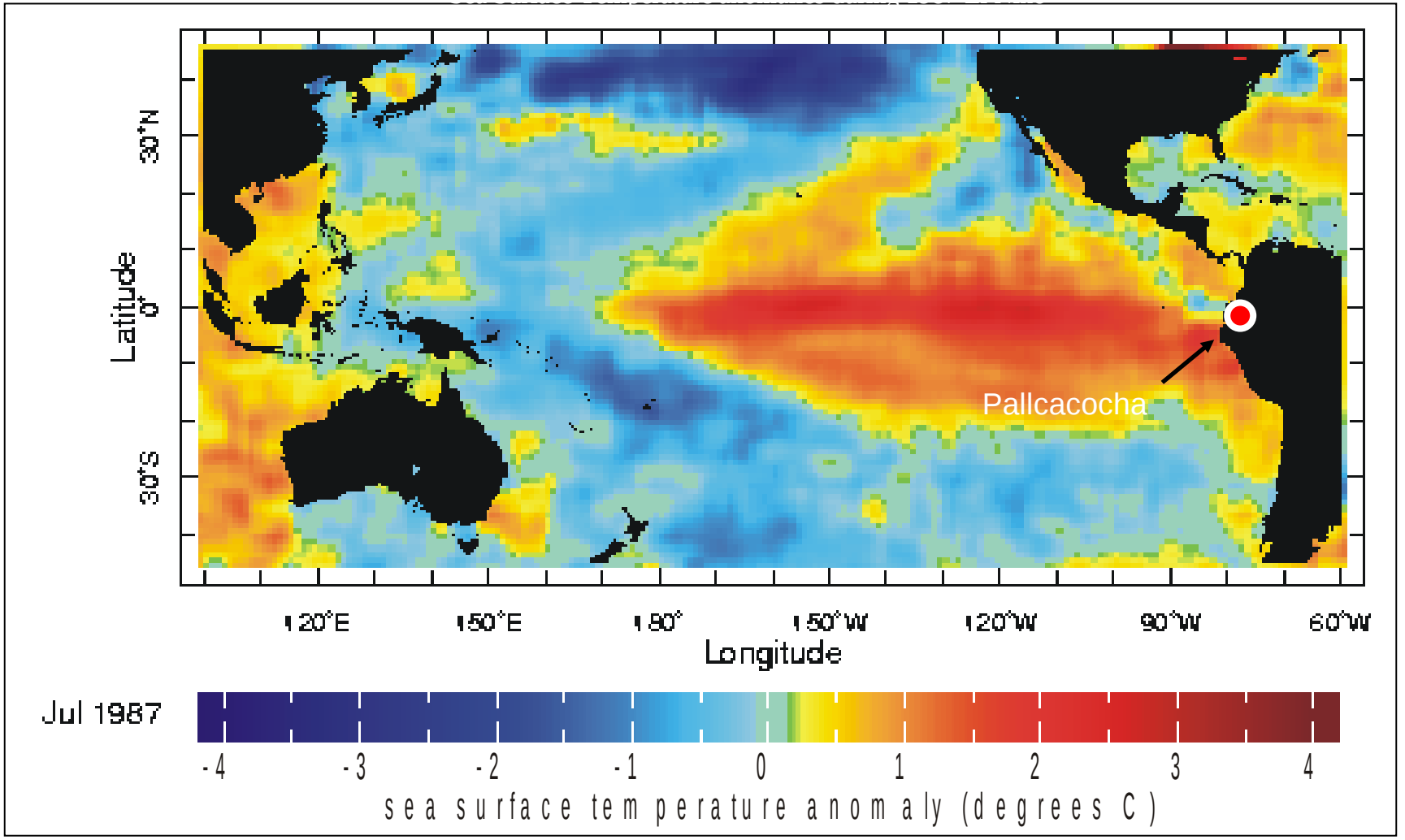
ENSO index reconstruction: multiproxy network



Gergis et al. (2006,2007)

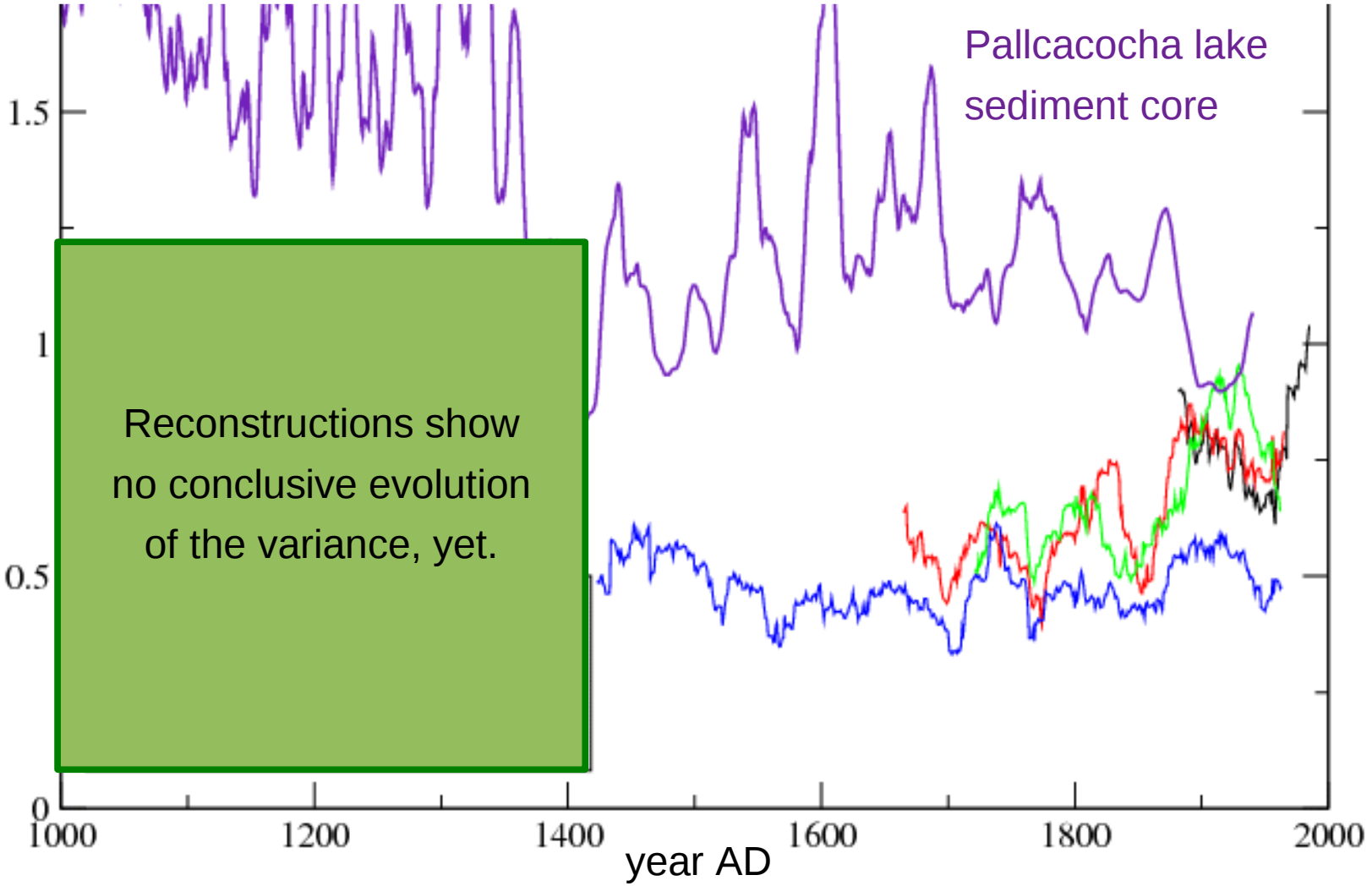
Reconstruction of ENSO variance




30°N
0°
30°S
Latitude
120°E
150°E
180°
150°W
120°W
90°W
60°W
Longitude
Pallcacocha
Jul 1987
-4
-3
-2
-1
0
1
2
3
4
sea surface temperature anomaly (degrees C)

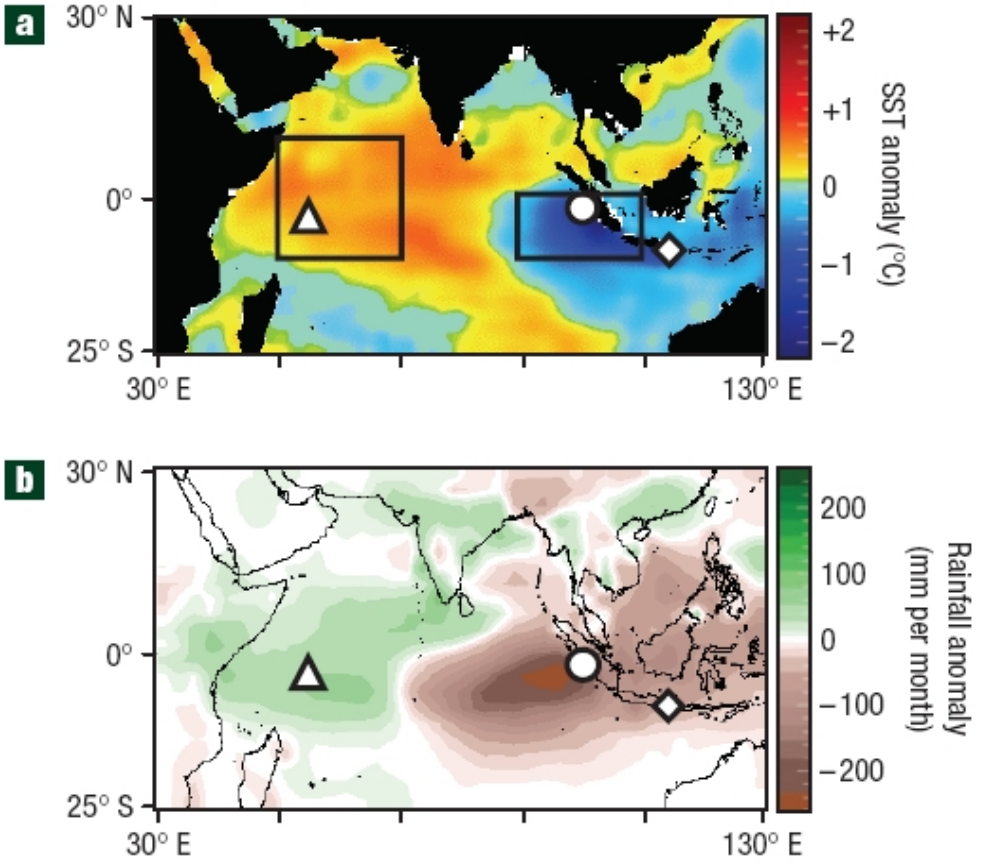
Dynamical Interpretation of ENSO reconstructions:

Variance estimates



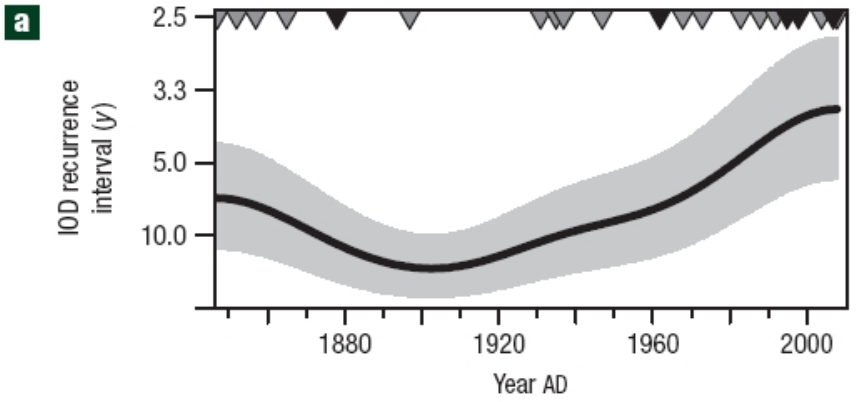
Other Modes of Variability

Indian Ocean Dipole



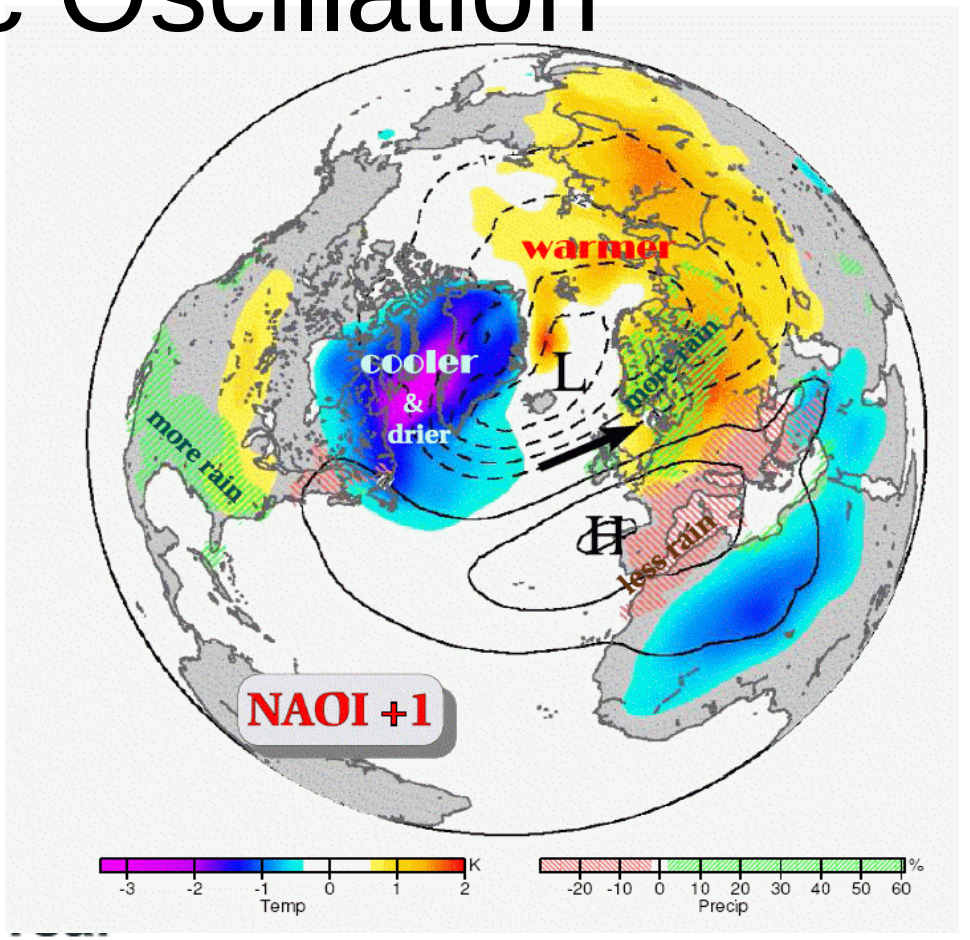
Composite SST/ Rainfall over IOD events 1994,1997, 2006.

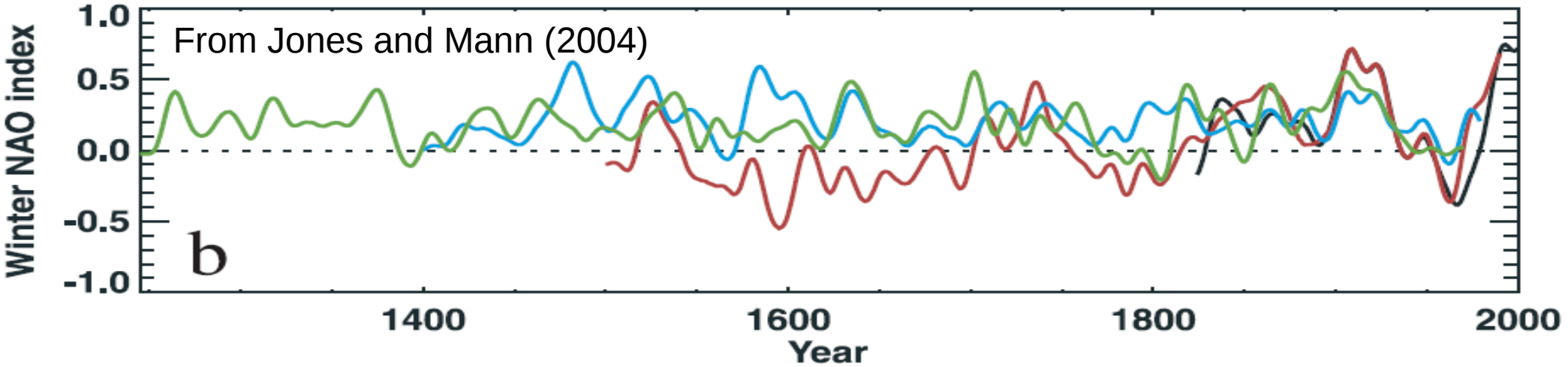
Coral proxies capture the warmer/wetter and cooler/dryer conditions => reconstructed the Dipole Mode Index.



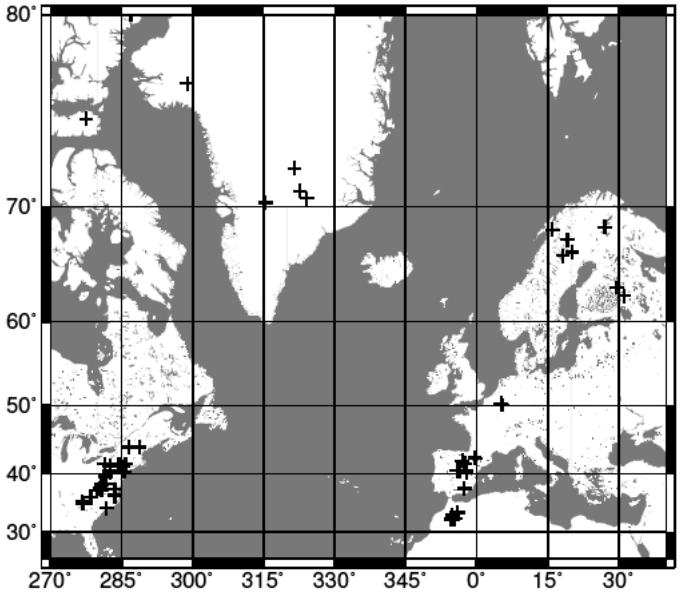
Abram N.J. et al, Nature Geoscience, Nov. 2008

North Atlantic Oscillation

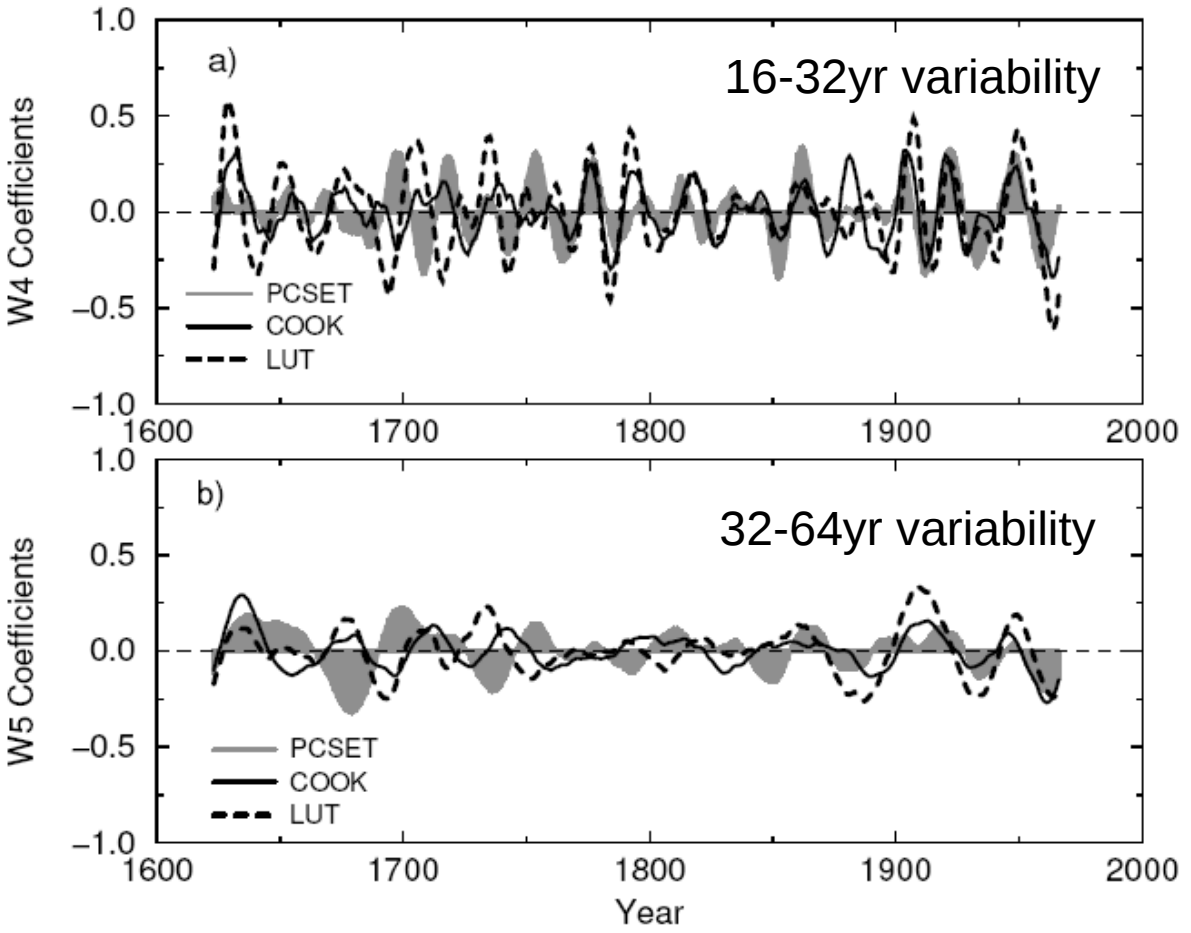




NAO reconstructions on multidecadal time scale

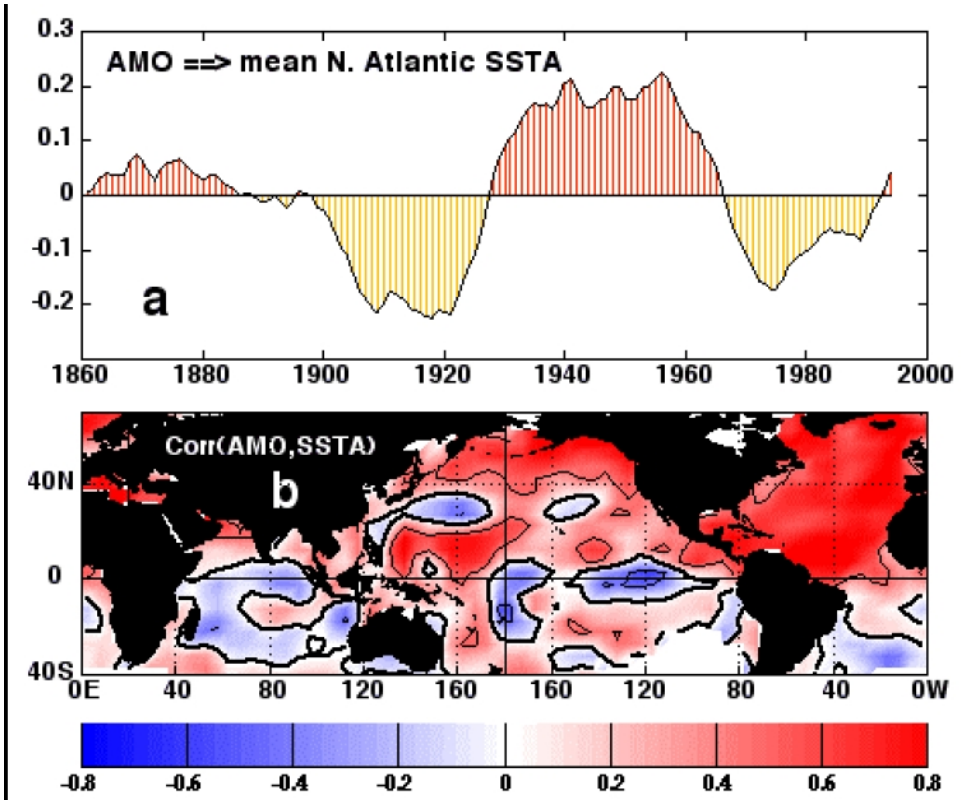


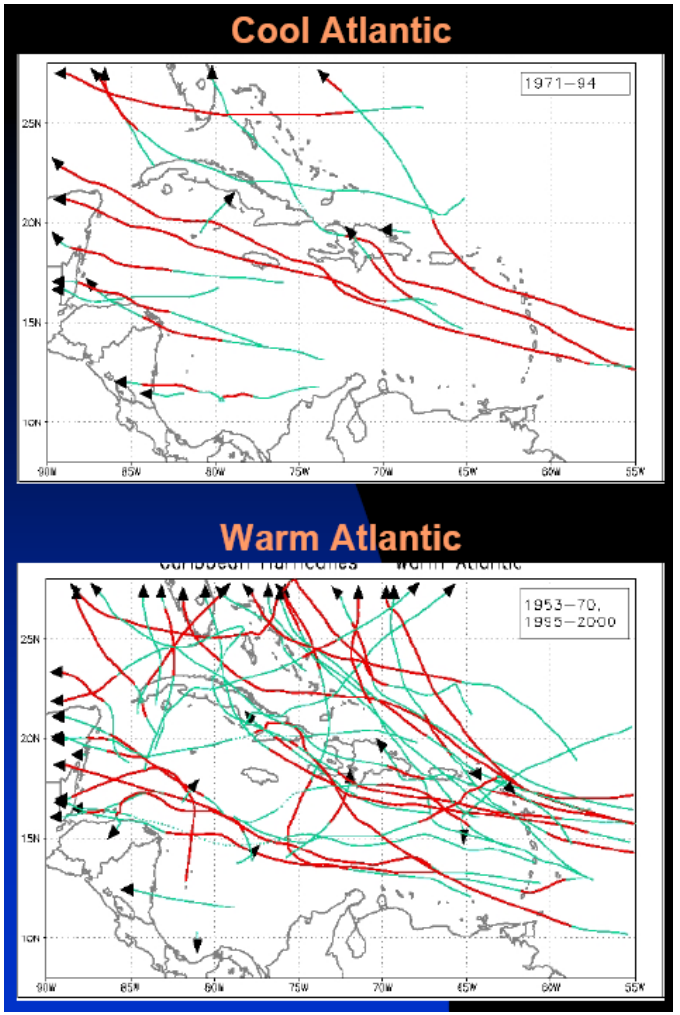
Proxy (trees, ice cores) locations



Timm, 2004 http://www.soest.hawaii.edu/~timm/files/disseration.pdf

AMO reconstructions

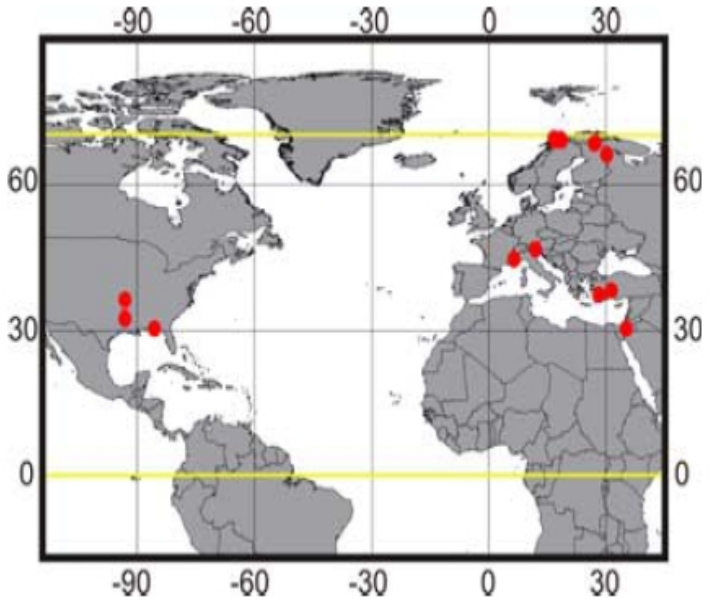


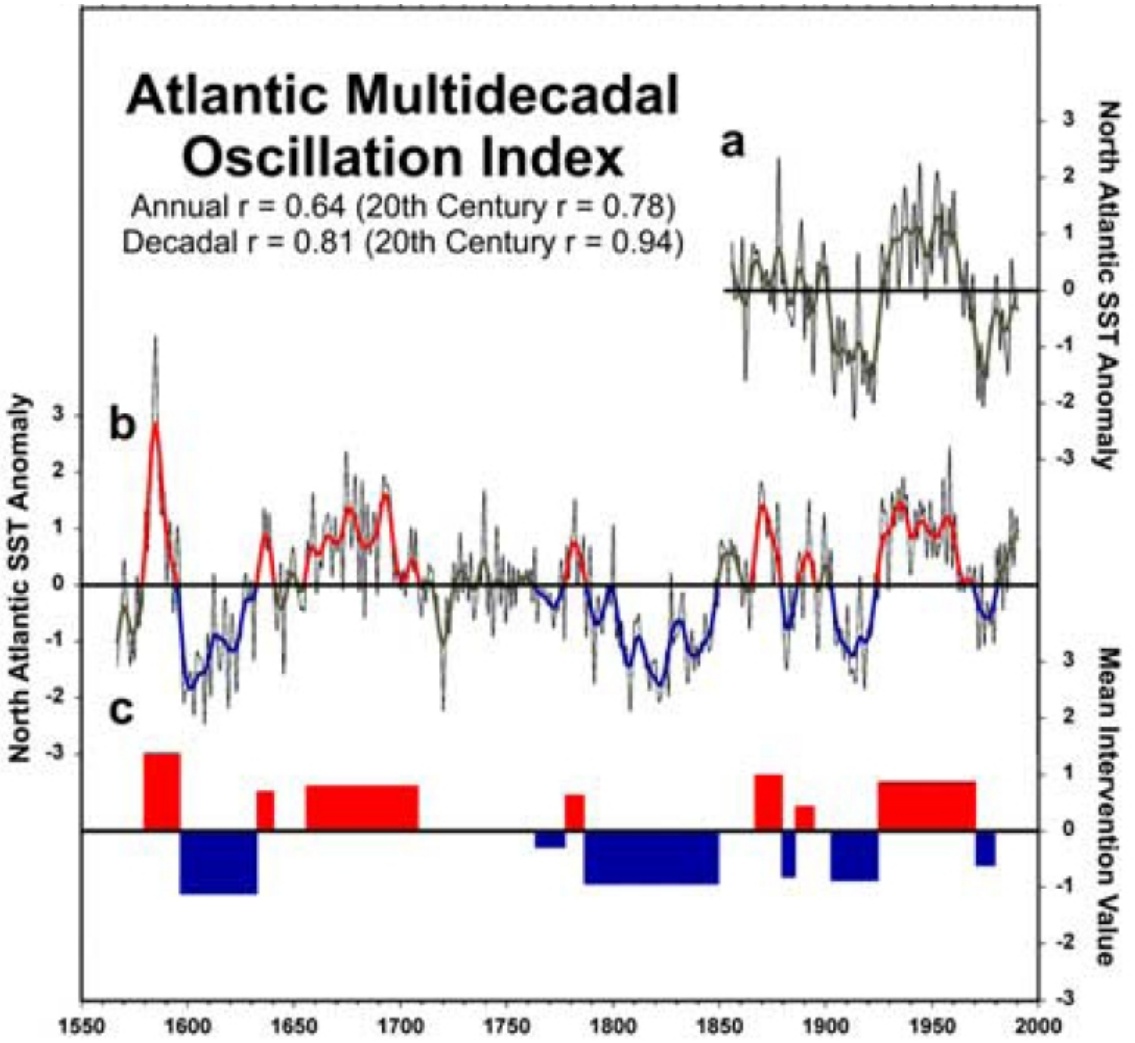


Goldenberg et al., Science, 2001:

Relation Hurricanes - Atlantic SST

AMO reconstructions

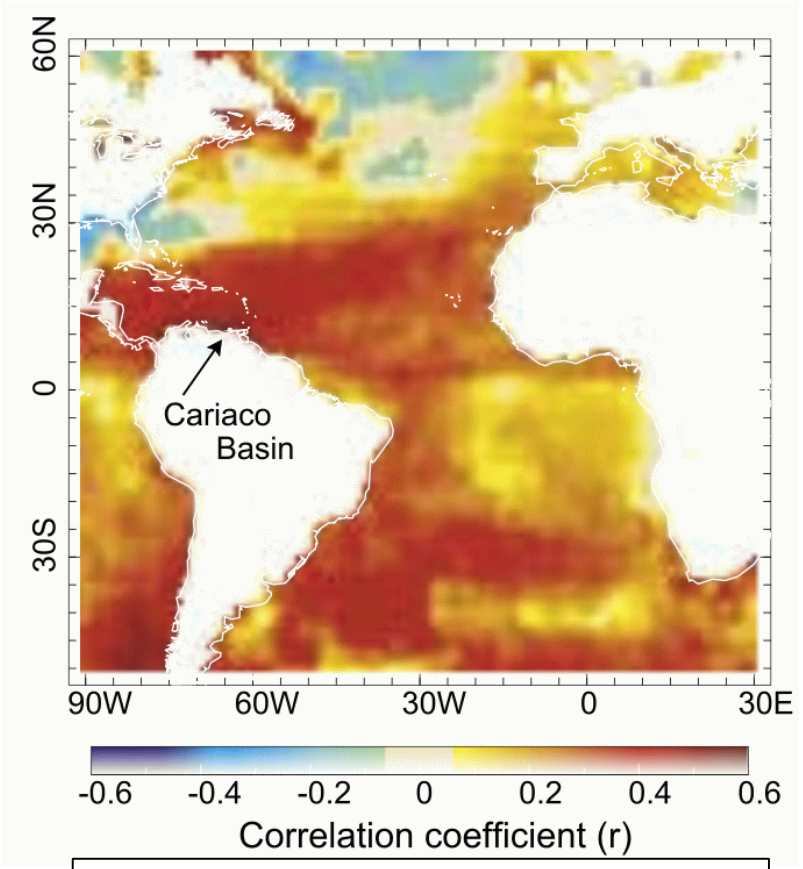




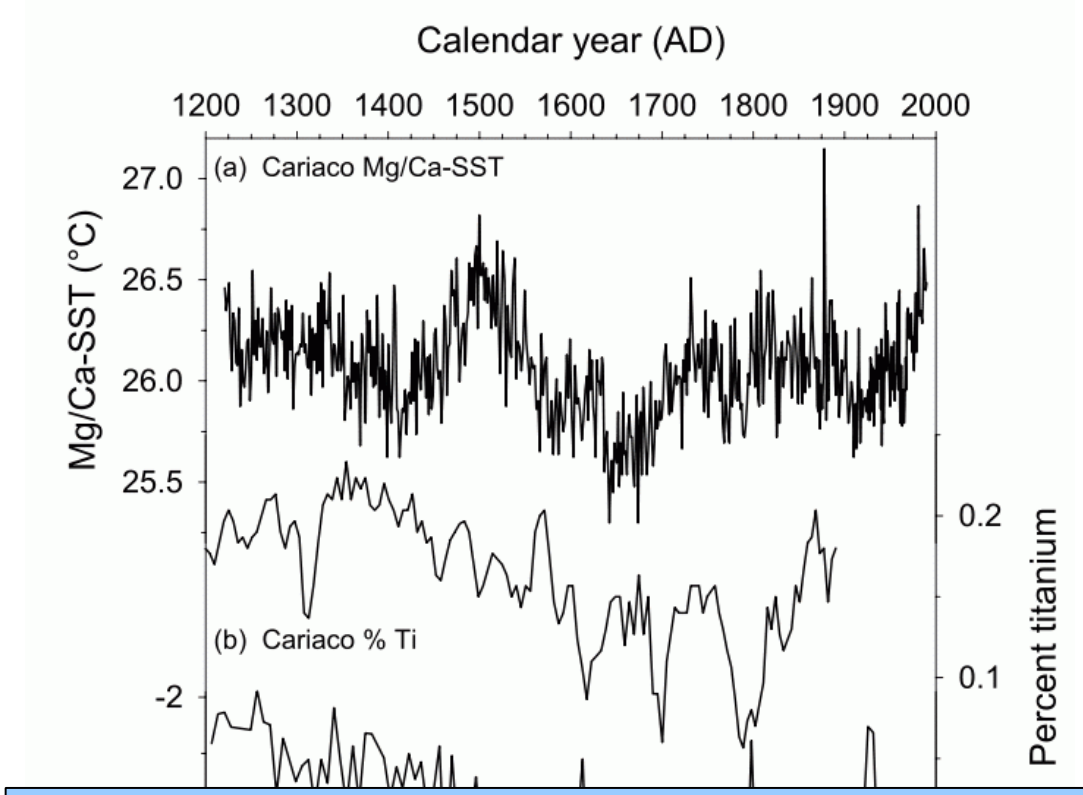
Gray et al.,GRL, 2004

Oceanic Records of Multidecadal Variability

Cariaco Basin: 800-yr high resolution sediment cores (Black et al, Paleoceanography, 2007)



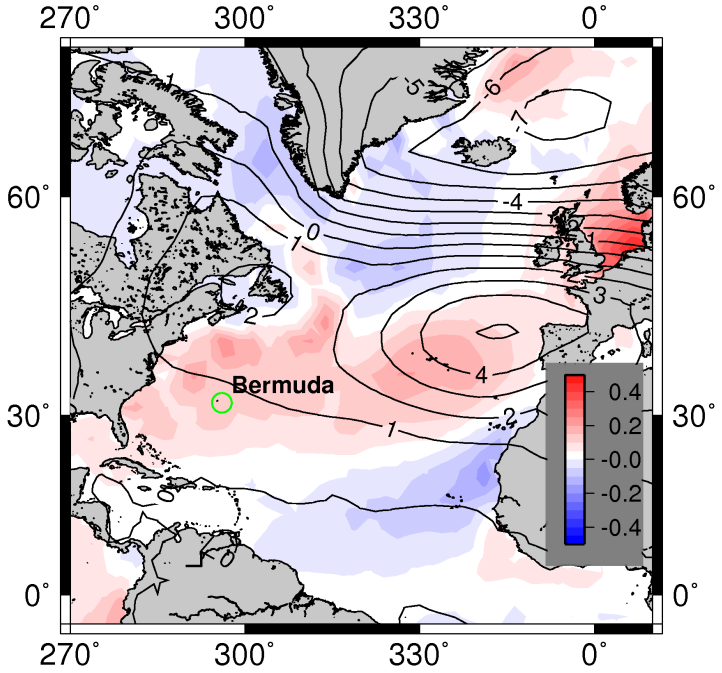
Correlation Mg/Ca with spring SST



No dominant decdal to multidecadal variability in SST temperature

How are NAO and AMO connected

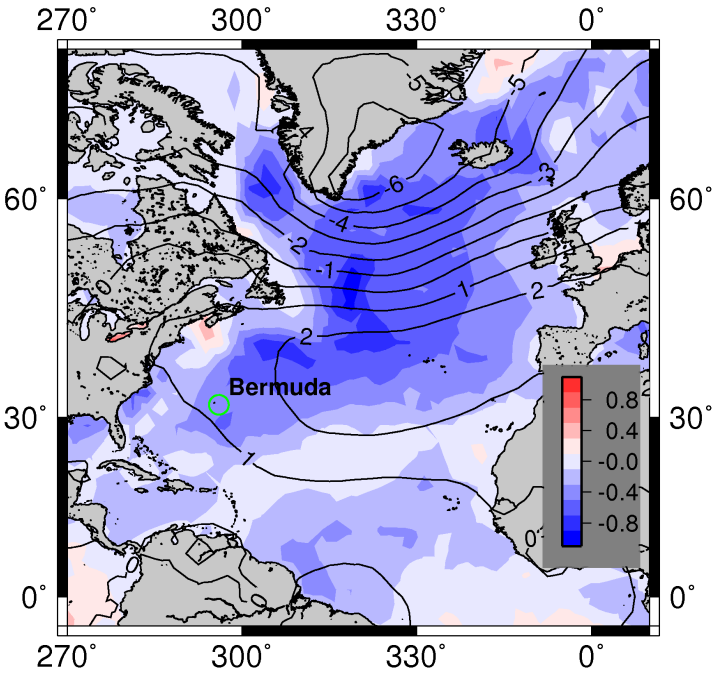
composites of high-low NAO phases



interannual timescales

SLP contours in hPa

SST shaded in K



multidecdal timescales

SLP contours in hPa

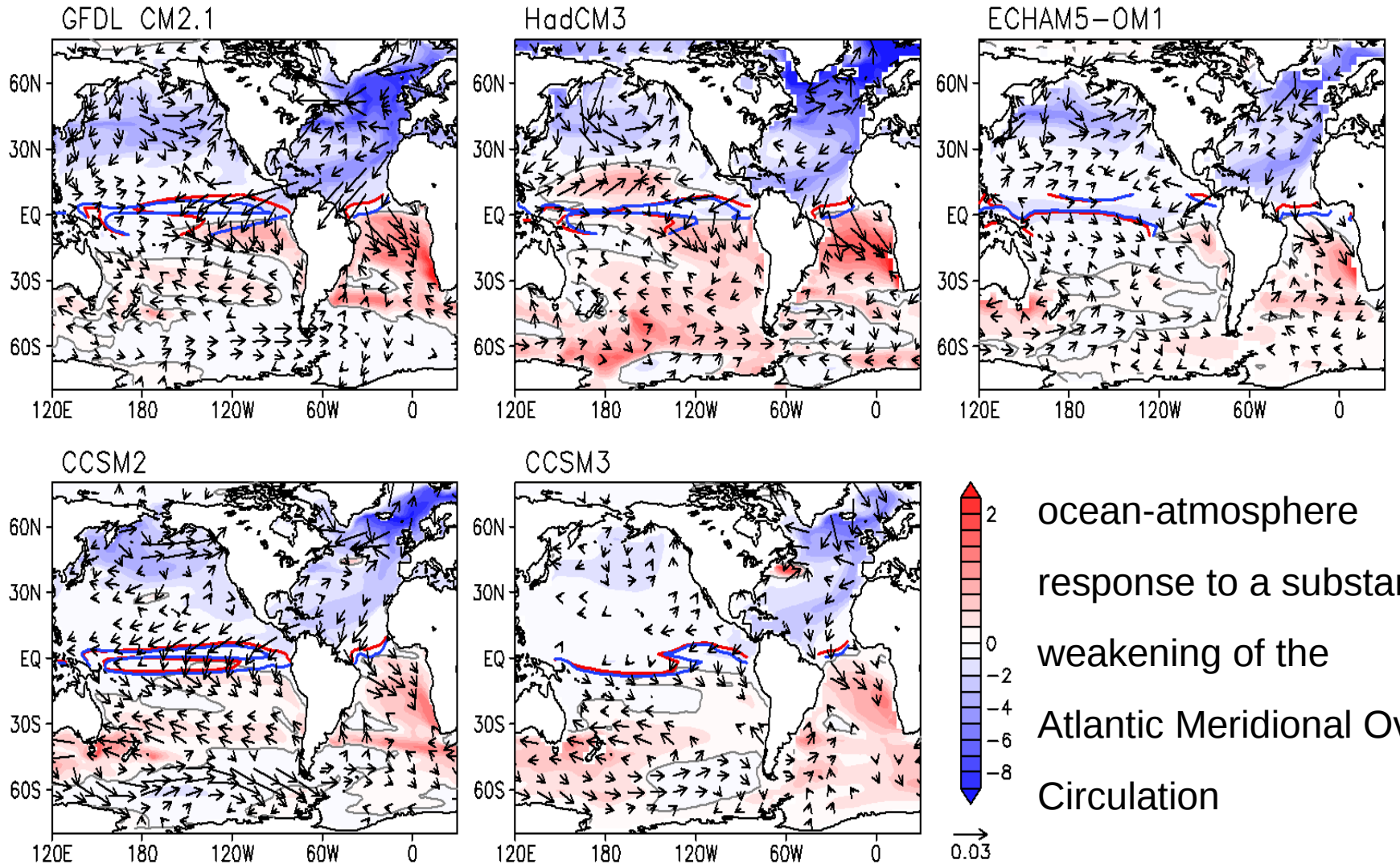
SST shaded in K

[SST composite based on AMO index]

How are ENSO-NAO-AMO-AMOC connected?

(Timmermann et al, J. Clim., 20, 4899-4919, 2007,

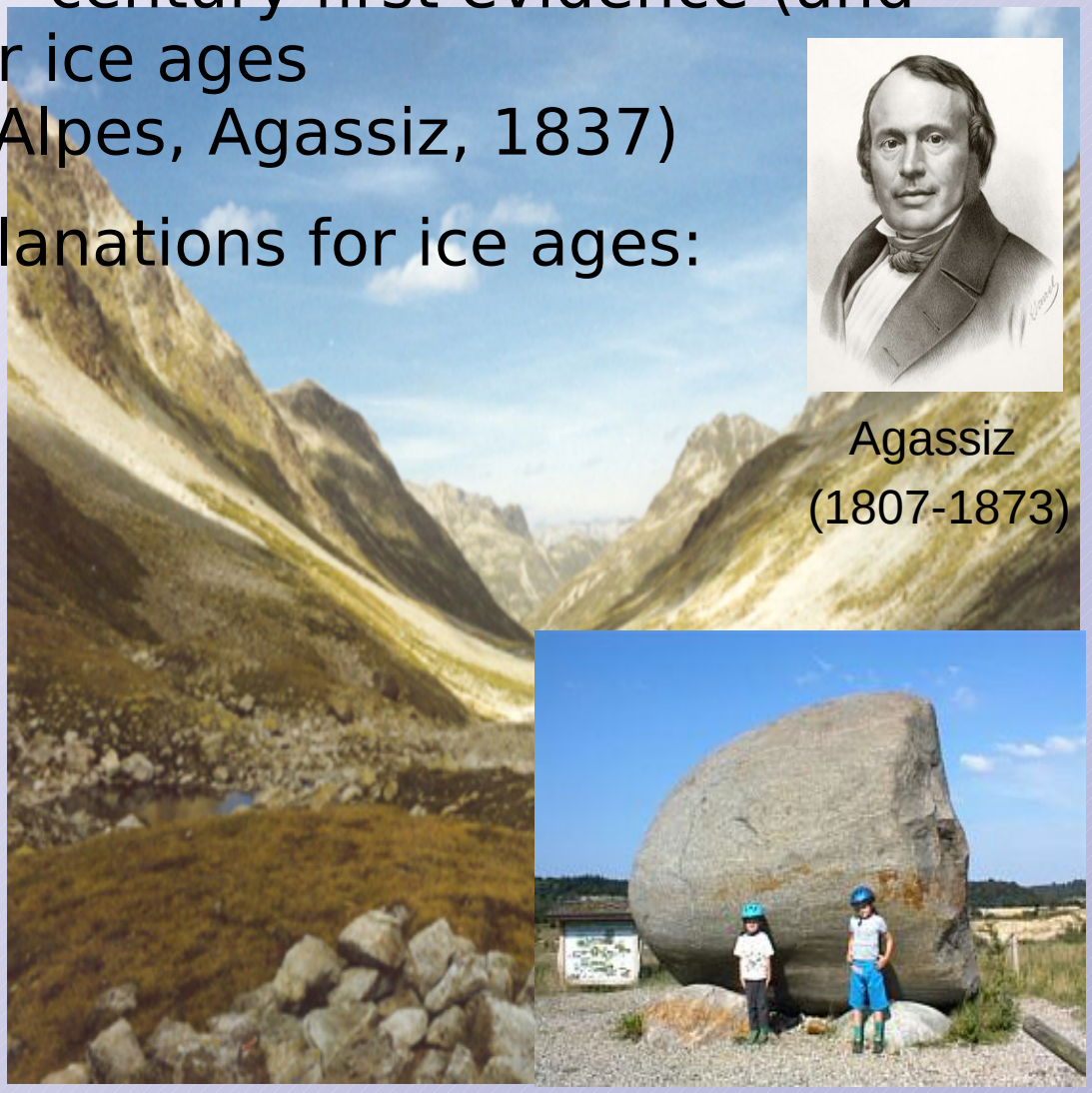
Xie et al, J. Clim, 21, 3914-3928, 2008)



ocean-atmosphere response to a substantial weakening of the Atlantic Meridional Overturning Circulation

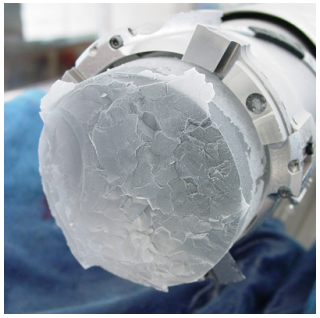
Glacial-interglacial cycles

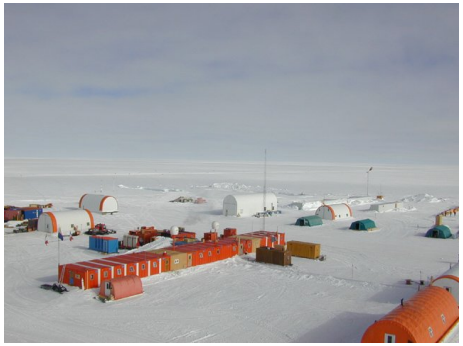
- In the 18th and early 19th century first evidence (and acceptance as proof) for ice ages (rock formations in the Alpes, Agassiz, 1837)
- Early (19th century) explanations for ice ages:
  - CO2-Effect
  - Orbitally forcing

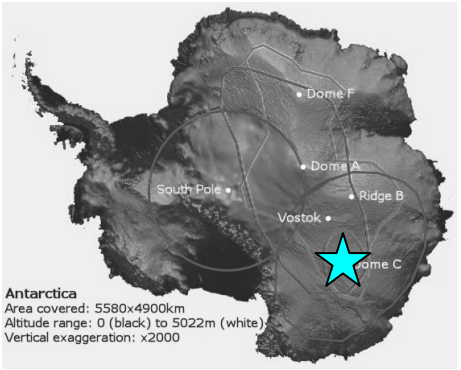


Agassiz
(1807-1873)

Antarctic ice core record from EPICA

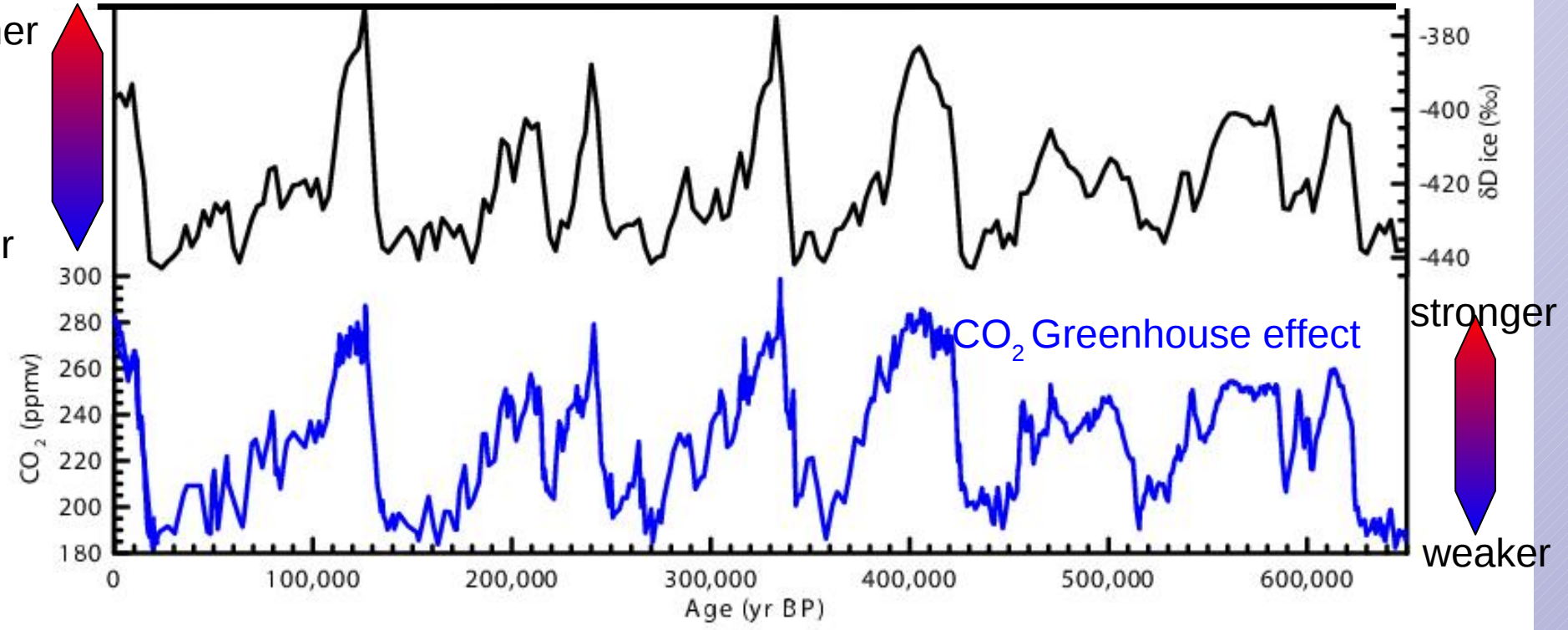






warmer

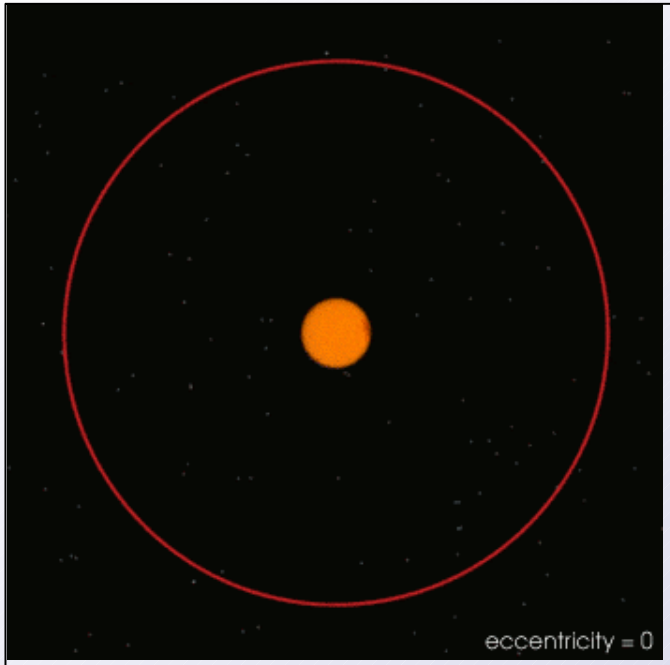
cooler

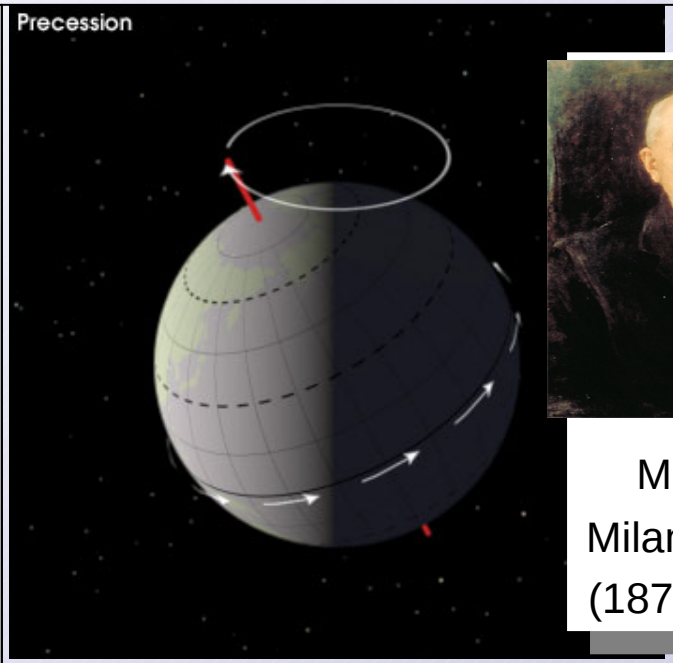


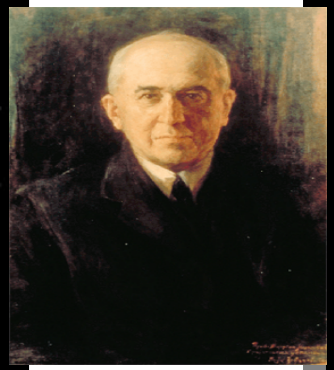
stronger

weaker

Figure from http://www.realclimate.org/index.php?p=221







Milutin Milankovitch (1879-1958)

Eccentricity

- 100,000 years
- Weak effect on annual insolation

Precession

- 19,000+23,000 years
- Strong seasonal effect

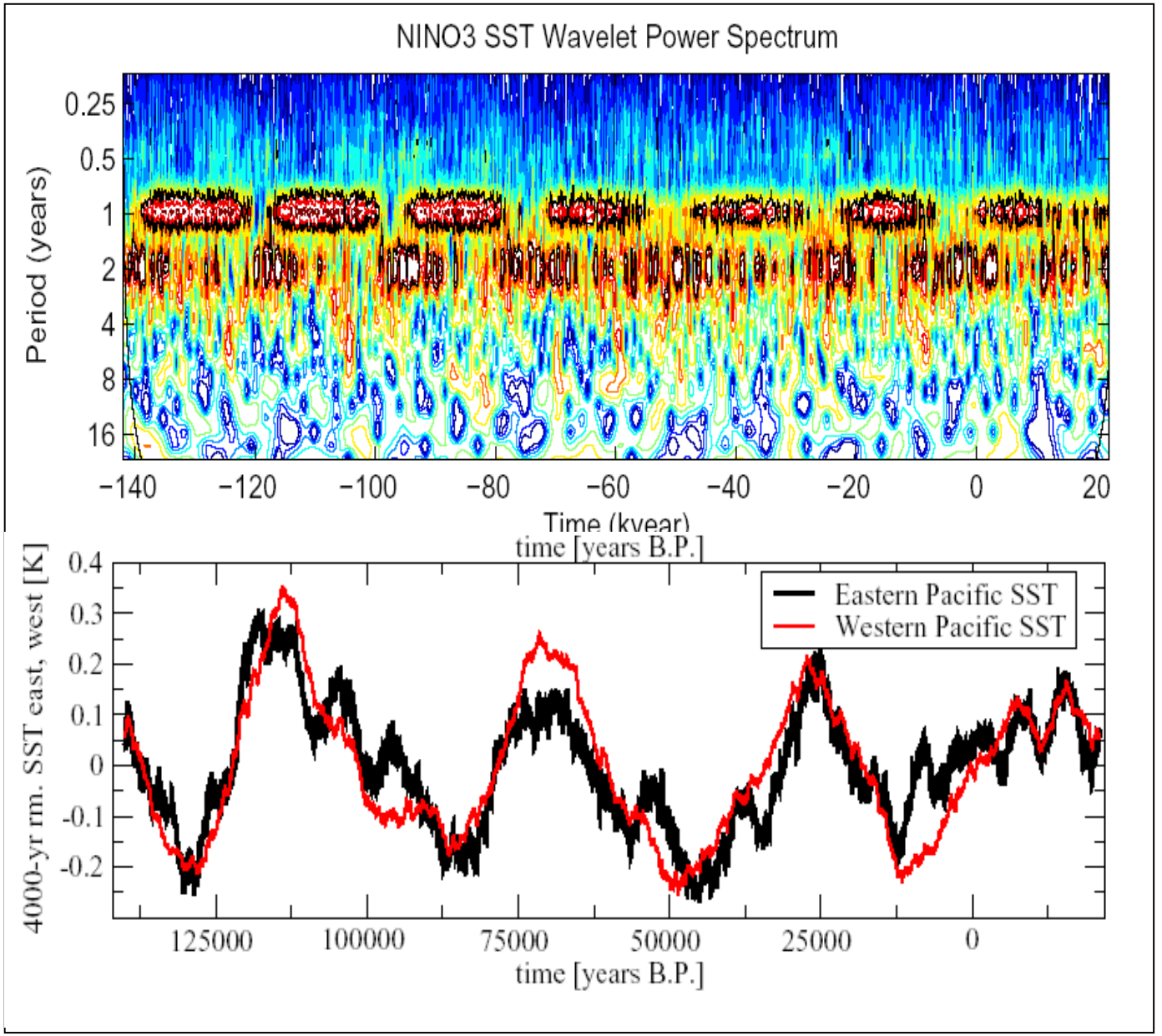
Obliquity

- 41,000 years
- pole-equator contrast in insolation
- seasonal changes

Precession depends on eccentricity

Images: http://earthobservatory.nasa.gov/Library/Giants/Milankovitch/

Paleoclimate modeling



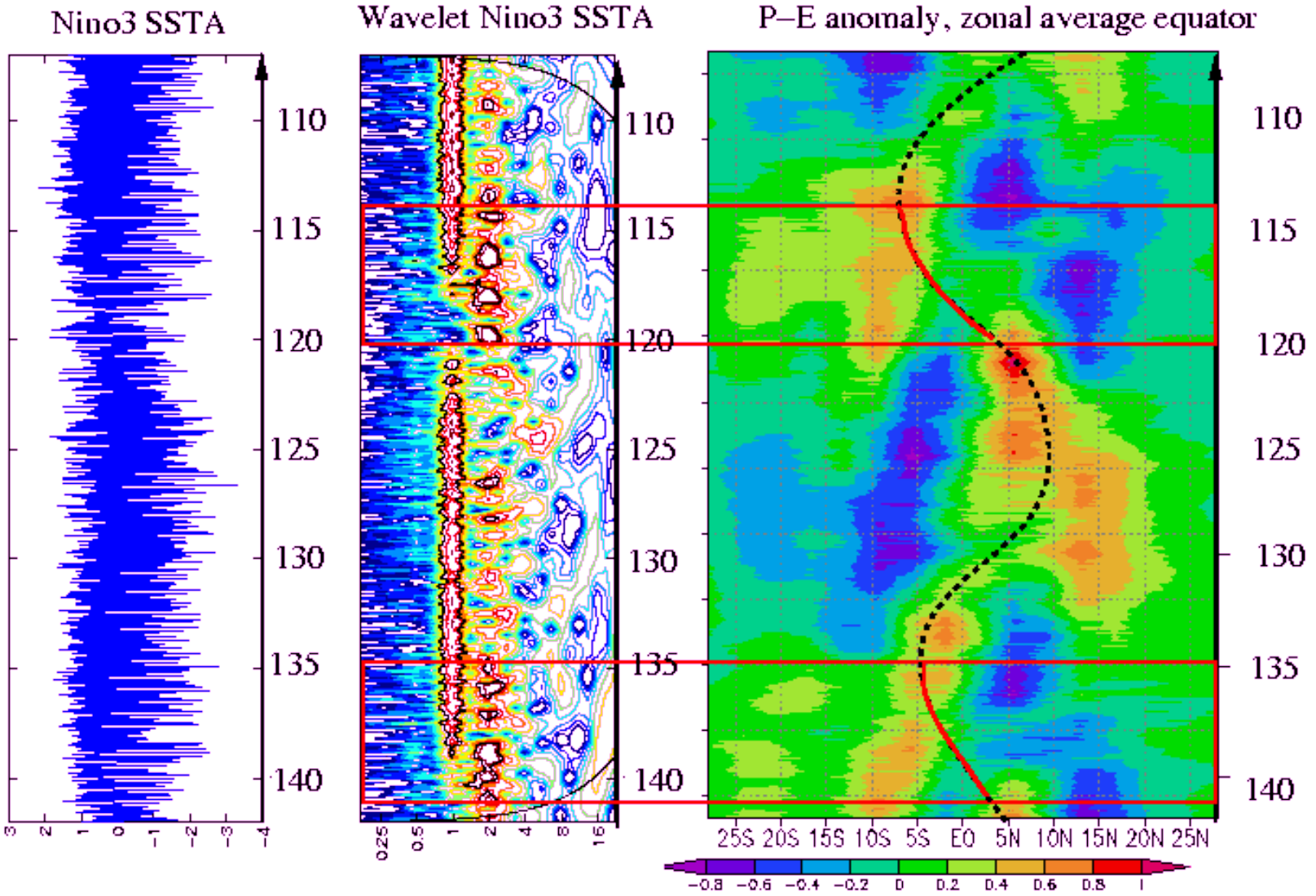
Timmermann et al, J. Climate, 20, 4147-4159, 2007.

ECHO-G model

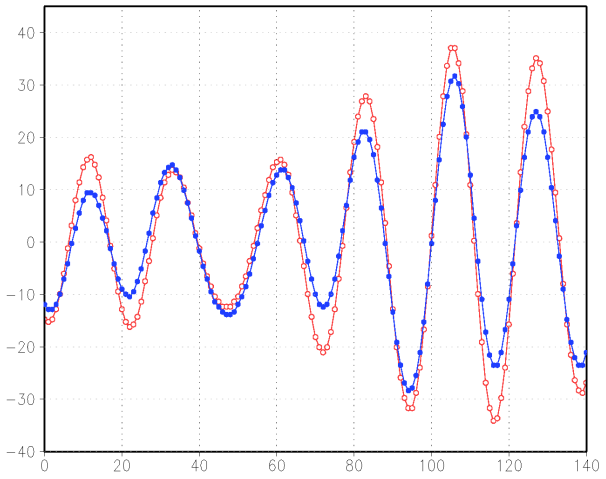
Zonal SST gradient: obliquity cycle

ACY and ENSO amplitude: precessional cycle

Paleoclimate modeling



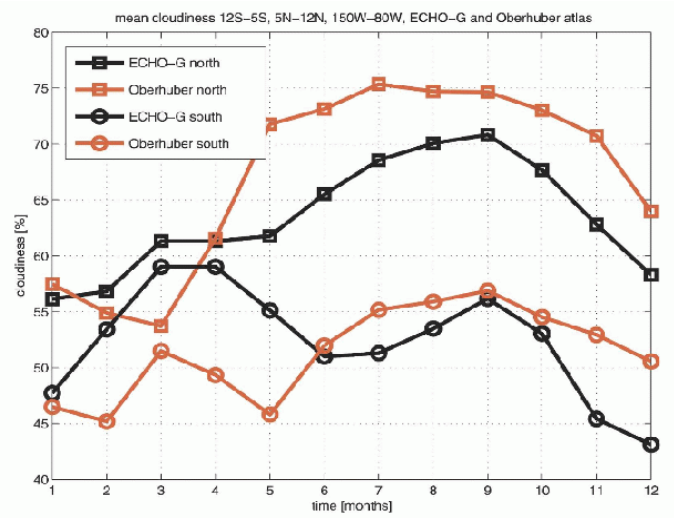
How can Precession Forcing change the meridional SST gradient? Importance of the seasonal cycle of cloud cover!



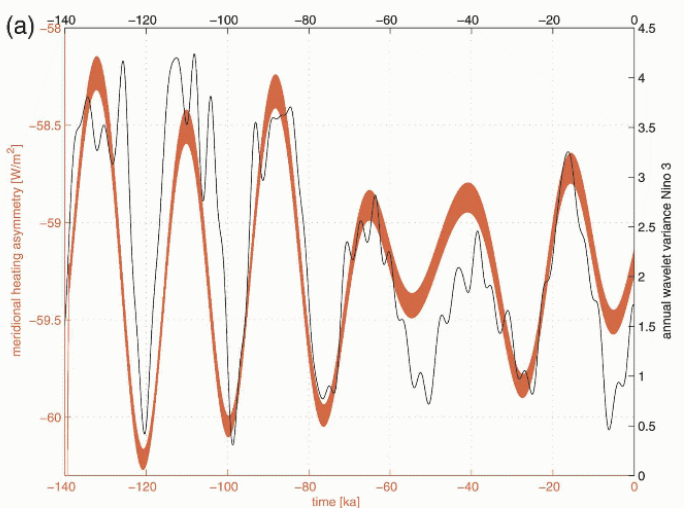
June Insolation

0-140,000 yrs ago

(10N red, 10S blue)

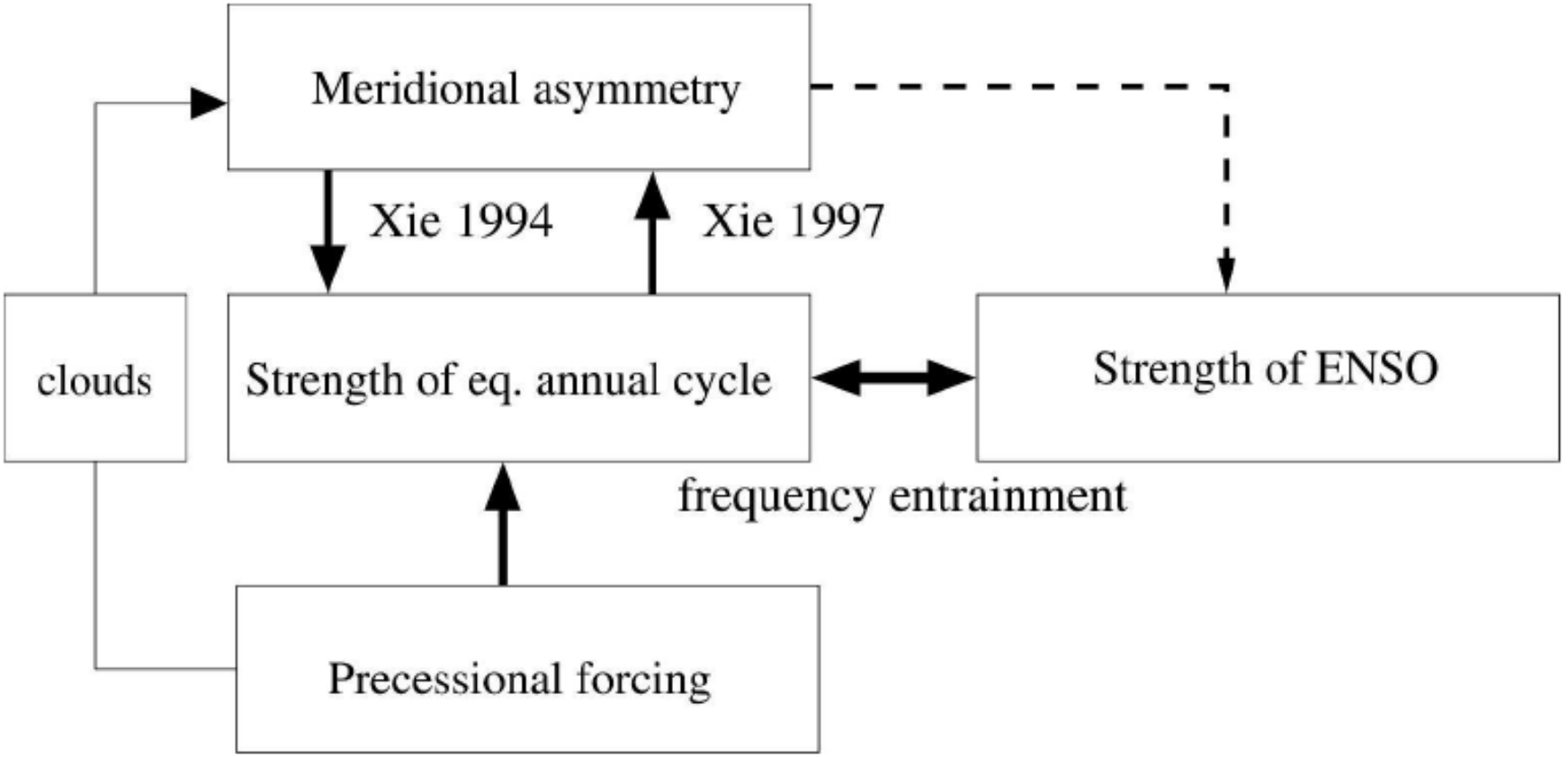


seaonal cycle of cloud cover



meridional heating gradient

Conceptual models for orbitally-driven climate variability



Timmermann et al, J. Climate, 20, 4147-4159, 2007.

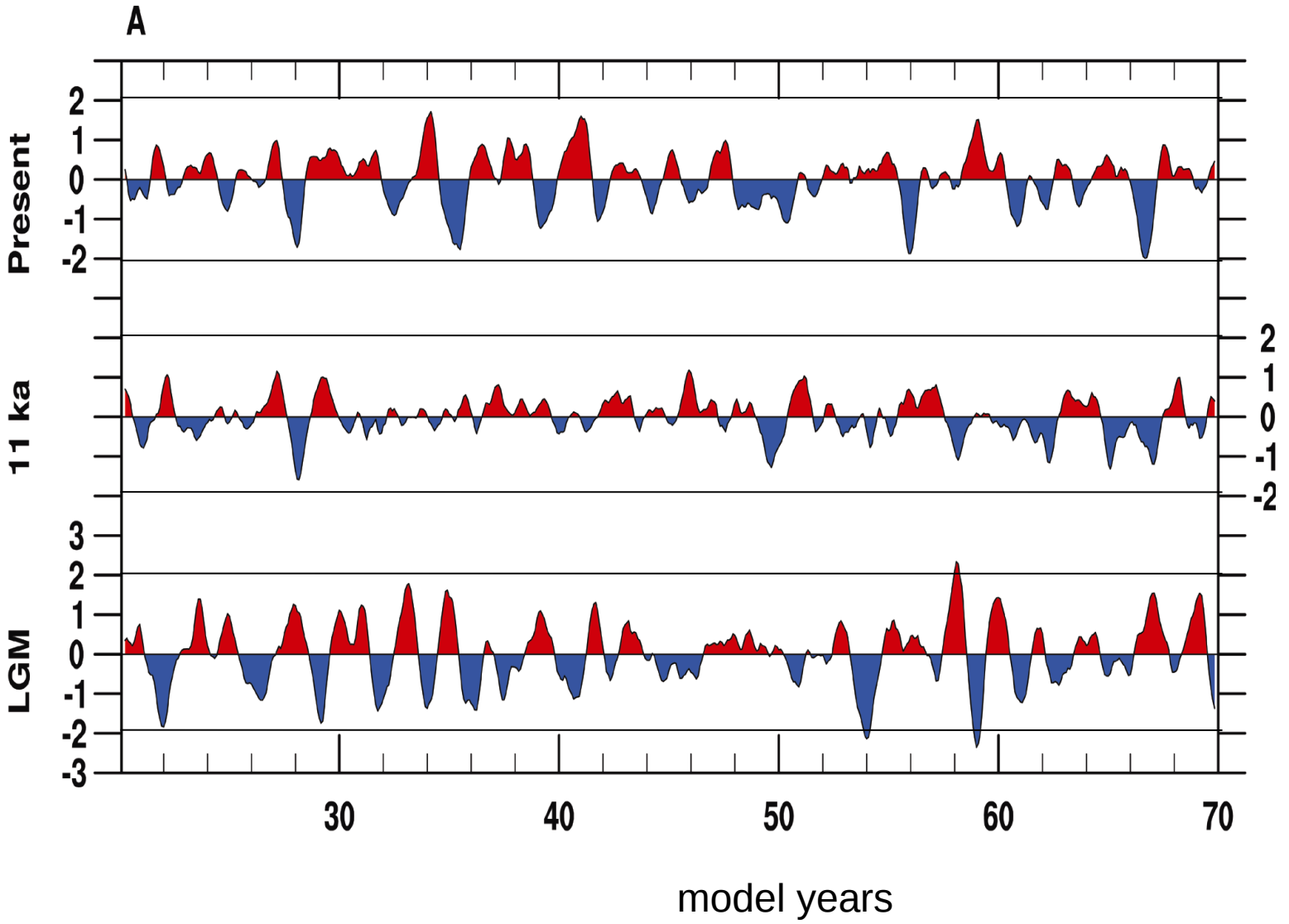
ENSO amplitude during the Last Glacial Maximum

CSM 1.4 climate model (Shin et al. 2003)

- Atmosphere model: spectral model, T31, L18
- Ocean model: primitive equations
- Resolution : ~0.9°x 3.6° Tropics otherwise 1.8x3.6°, L25
- Sea-ice model: thermodynamic-dynamic
- Land model: Dynamic vegetation, Hydrology

- Glacial greenhouse gas concentration
- Glacial land albedo
- Glacial topography
- Glacial land-sea distribution

ENSO variability



Course Air-Sea Interaction

Paleoclimatology

- References:
  - Online introduction:

    http://www.ncdc.noaa.gov/paleo/primer.html
  - Textbooks:
    - Bradley, R.S., 1999. "Paleoclimatology: Reconstructing Climates of the Quaternary". Academic Press, San Diego.
    - Saltzmann, B. :Dynamical Paleoclimatology: Generalized Theory of Global Climate Change