Paleoclimate Dynamics-identifying driving mechanisms of climate change

Gerrit Lohmann (AWI, Uni)

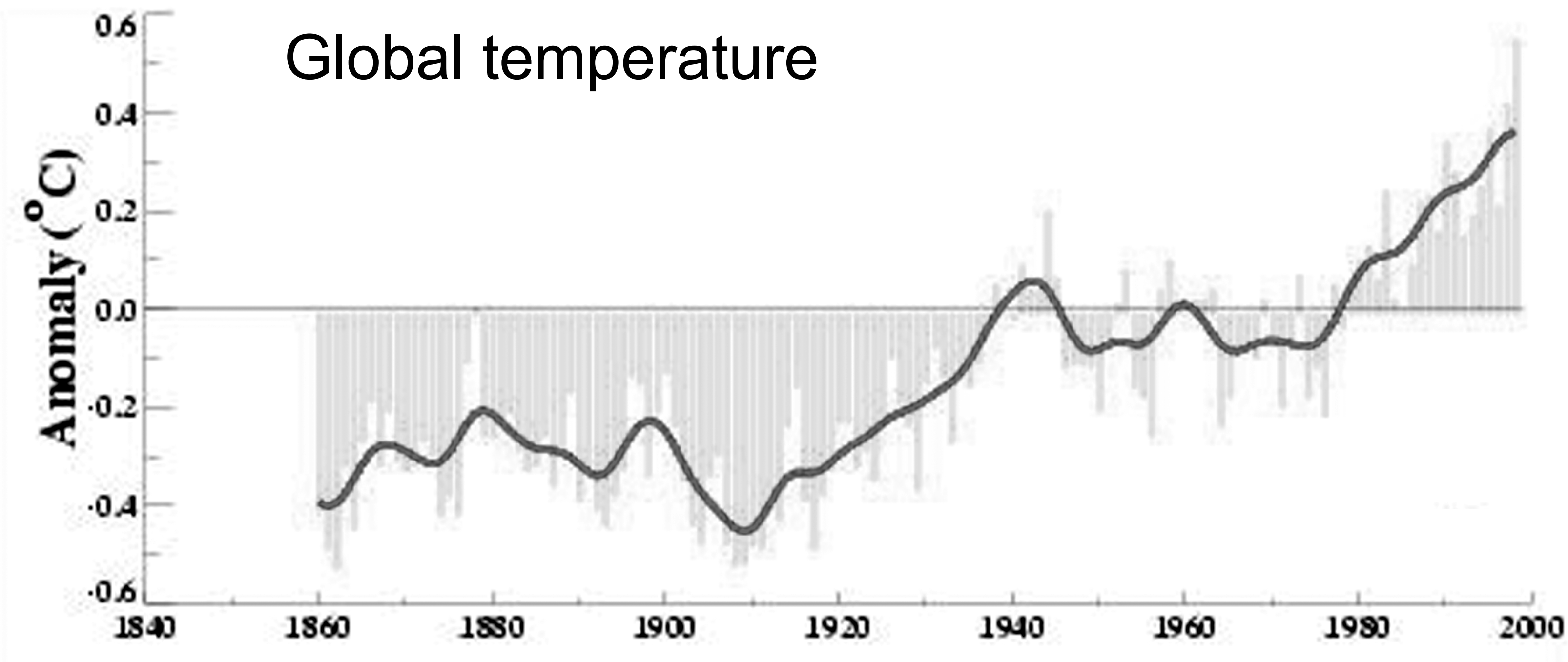
ESSReS course

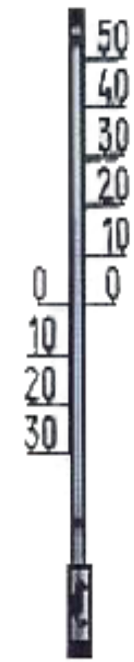
10th October 2011, 11:00-12:30

- **Broaden the view of the climate system**
- **Interpretation of past environmental changes**
- **Data and Modelling**
- **Climate variability: North Atlantic Oscillation**
- **Driving mechanisms**

Climate Trends at different Timescales

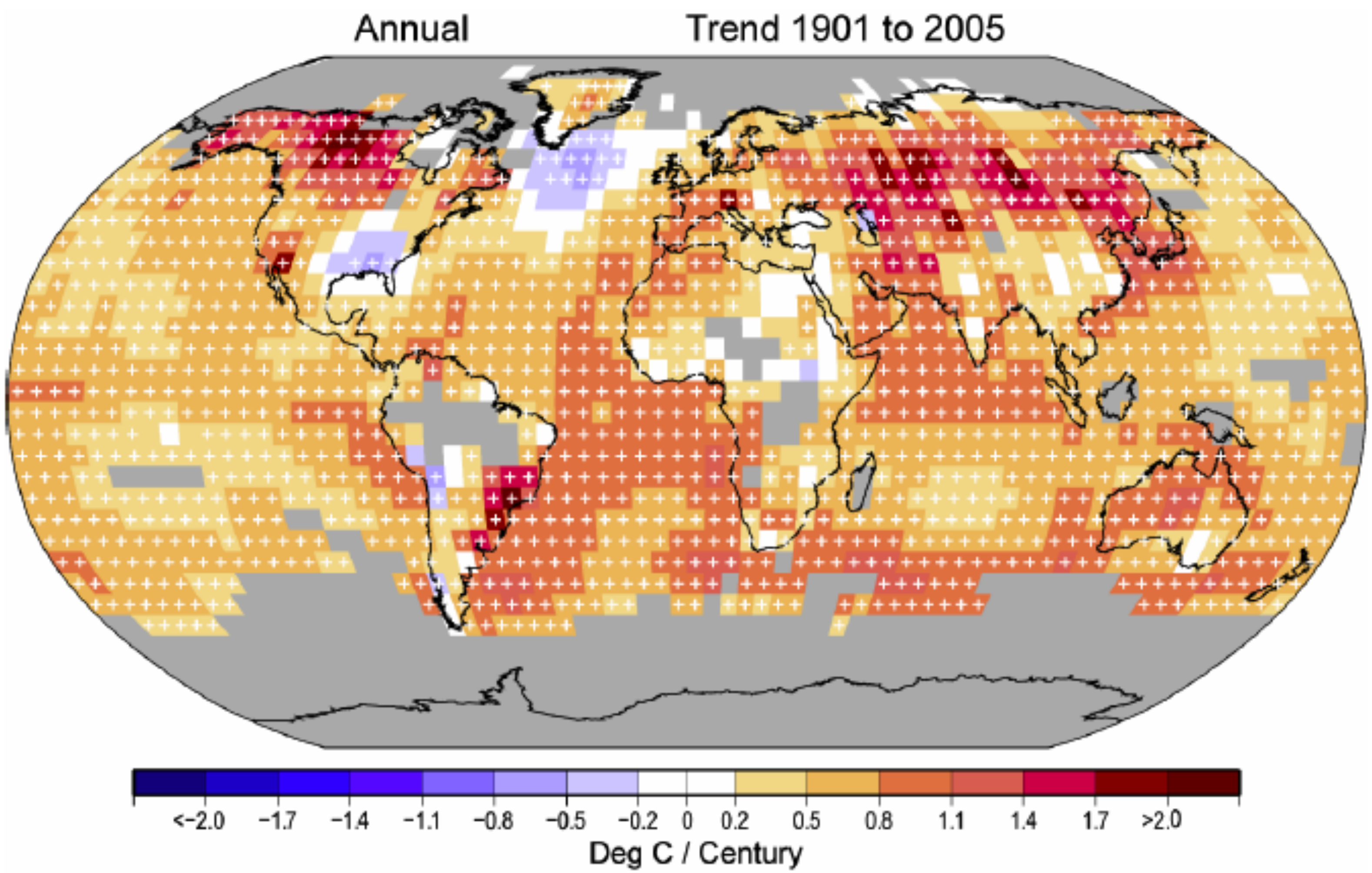
Temperature of the last **150 years** (instrumental data)





Hadley Centre, UK 2000

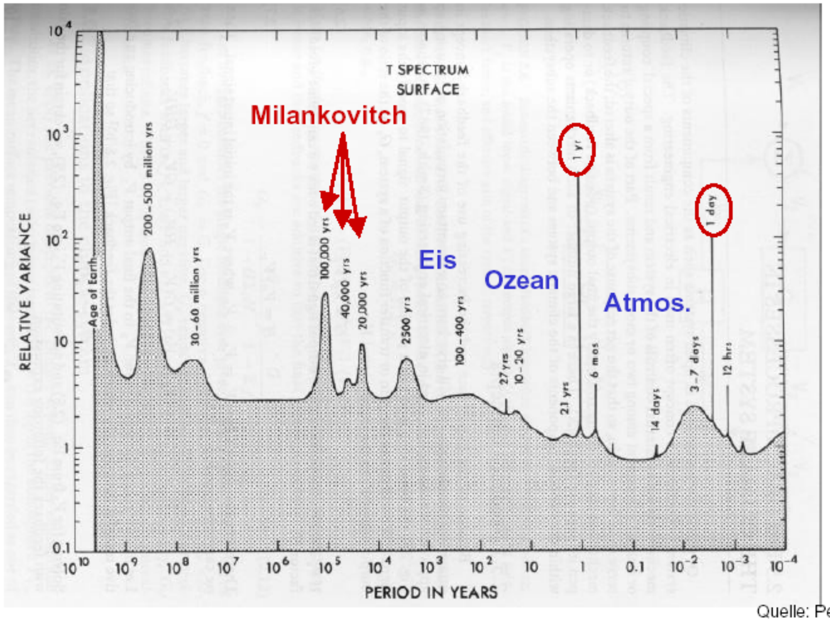
Observations: Temperature trend since 1901



External: Solar – Orbital focing

- 20000, 40000, 100000 years
- 0.5, 1 year

- Geometry of the Sun-Earth configuration



Quelle: Peixoto & Oort

Early instrumental Data

- Anfänge physikalischer Messtechnik
  - ca. 1650 erste Luftdruckmessungen (Italien, Frankreich, Schweden)
  - 1654-1670 erste aufgezeichneten Lufttemperaturmessungen (Pisa)
  - 1677-1704 erste Niederschlagsmessreihen (England)
  - ca. 1700 erste Windmessungen in Deutschland (Leibniz)

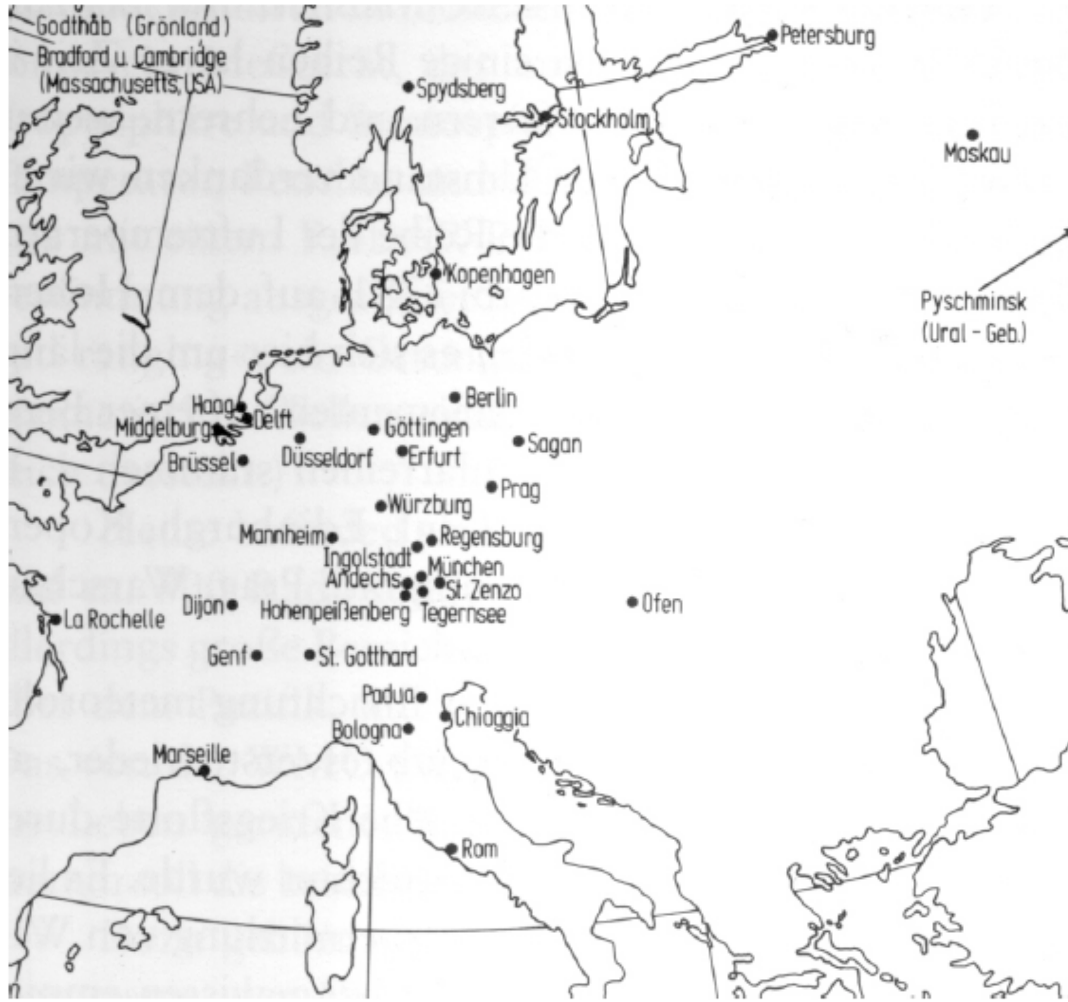
- Vieljährige (lückenlose) Messreihen
  - Längste lückenlose und homogene Lufttemperaturmessreihe der Erde: „Zentral-England“-Reihe seit 1659
  - Längste Niederschlagsreihe: Kew (bei London) seit 1697
  - Längste Luftdruckreihe: De Built (Holland) seit 1740
  - Längste Windreihe: Hohenpeißenberg seit 1781

Data sources

Stations in Europe:

„Pfälzische Meteorologischen Gesellschaft“

Societas Meteorologica Palatina
(1781-1795)



Quelle: Schönwiese

Climate Change

Detection

Understanding

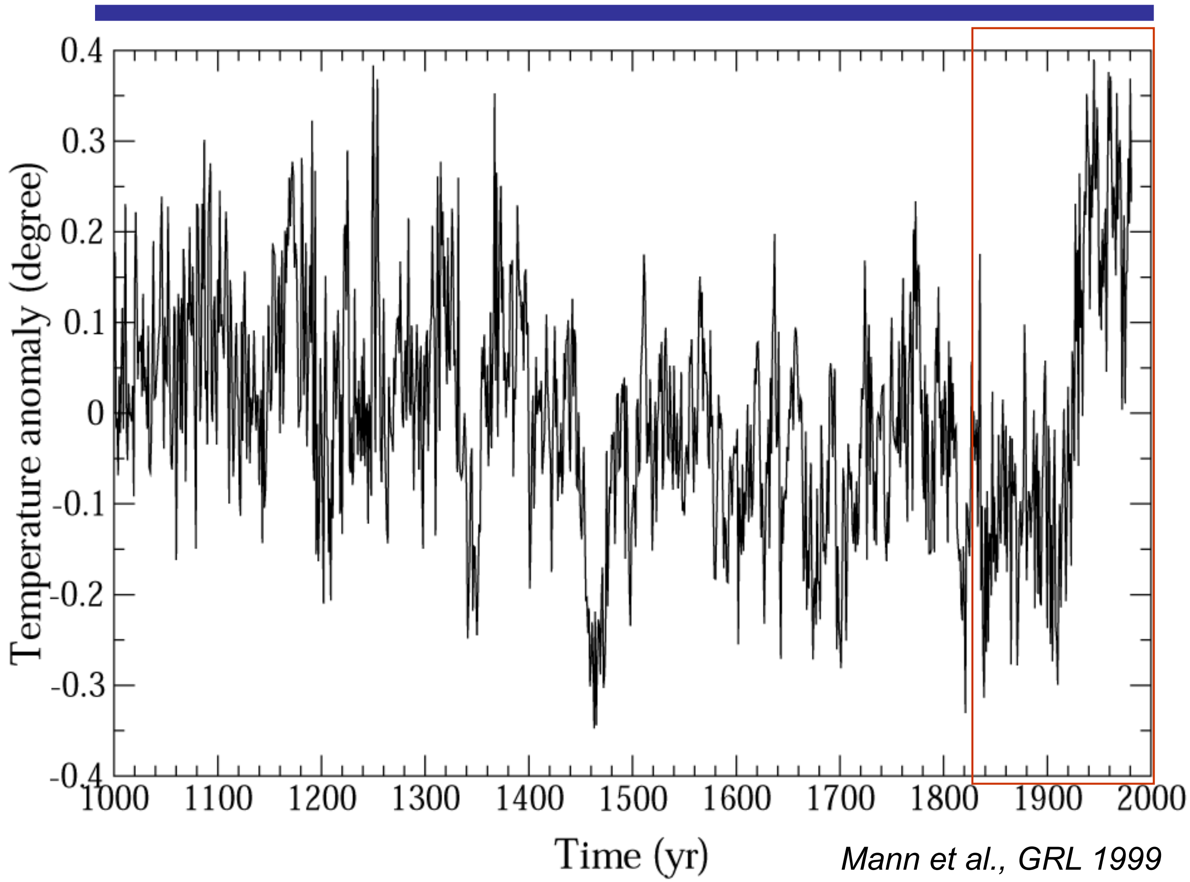
1911

2001

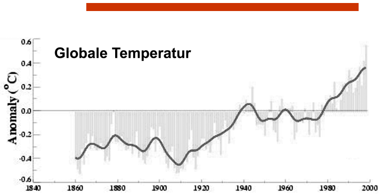
mountain glaciers (Morteratsch)

Climate Trends at different Timescales

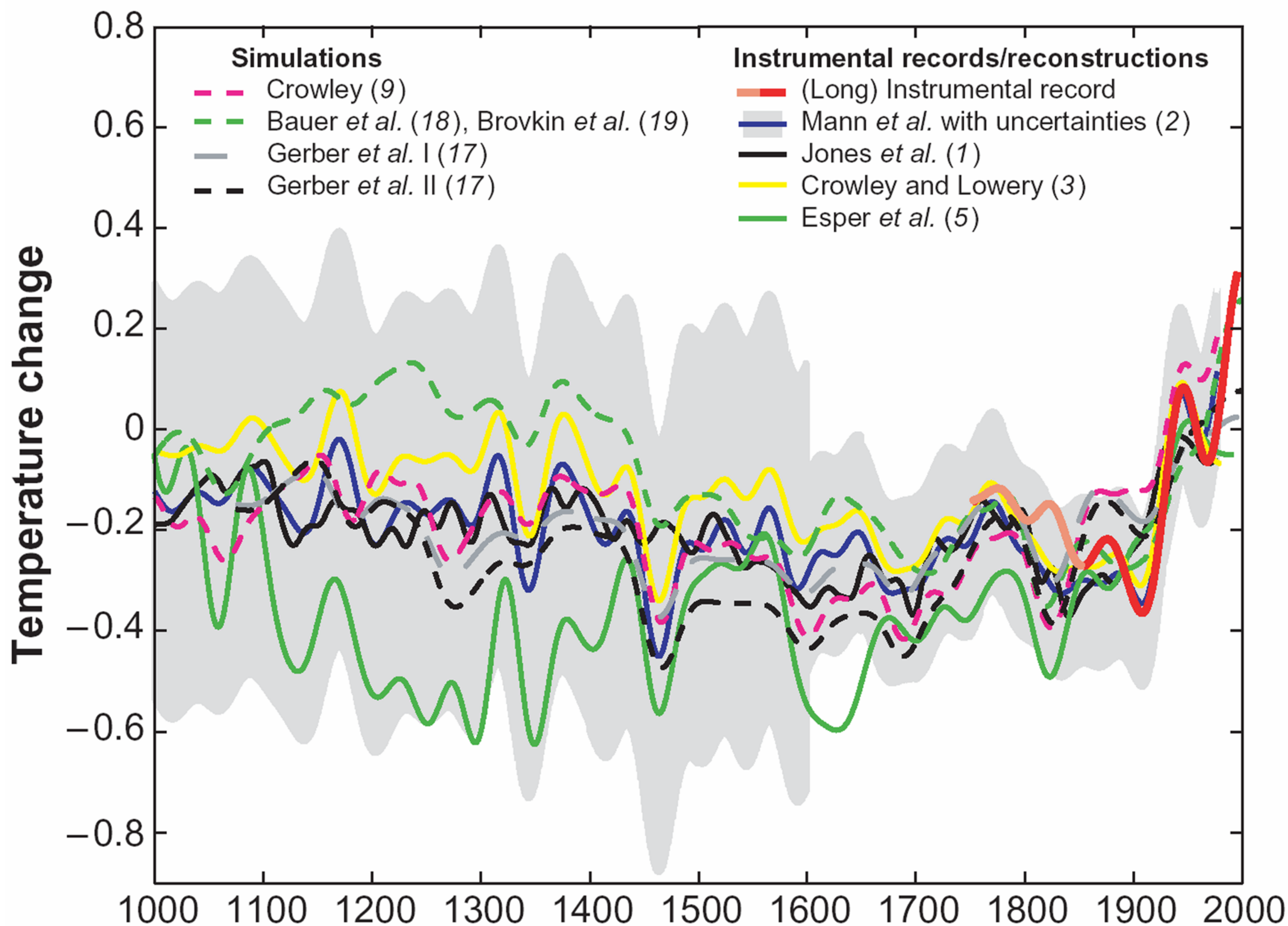
Temperature of the last **1000 years**



Mann et al., GRL 1999



Temperature of the last 1000 years

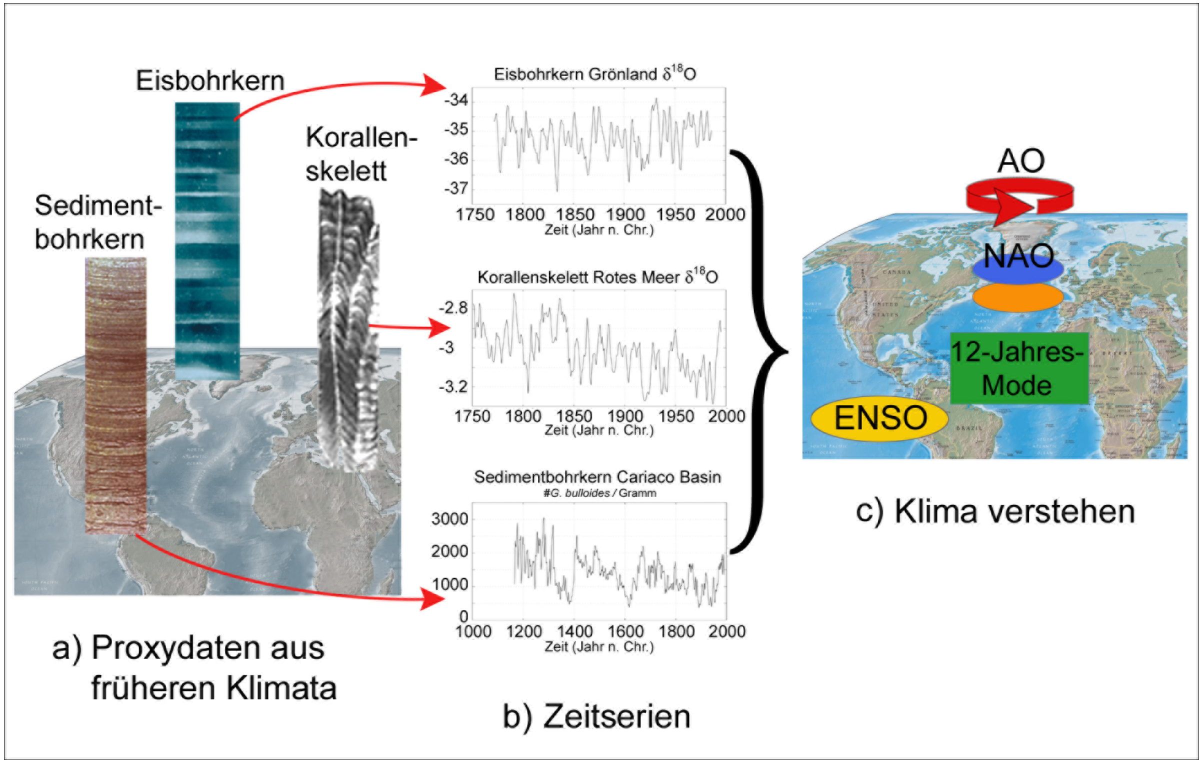


„Hockey Stick“

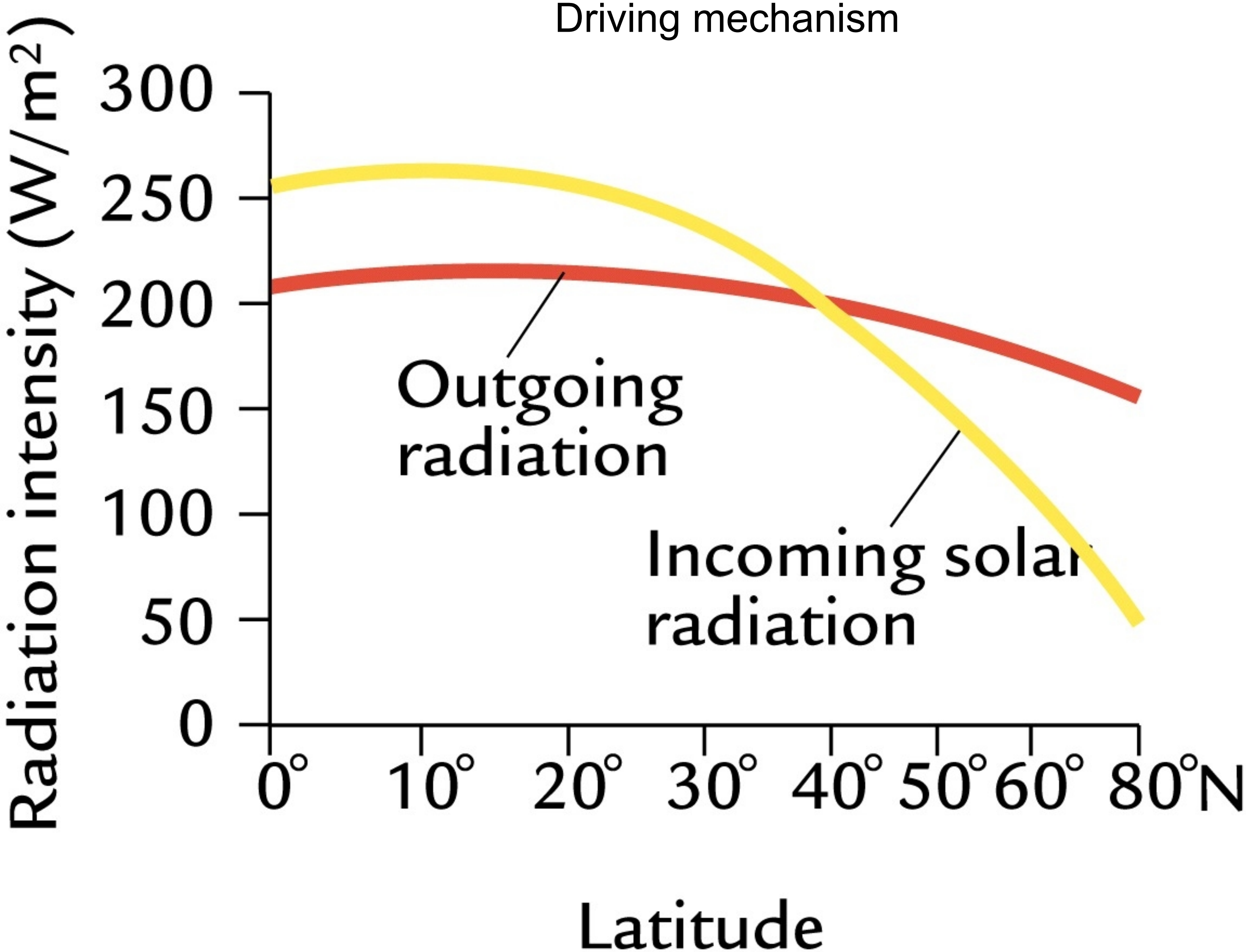
Compilation of Mann, 2002

Proxy Data

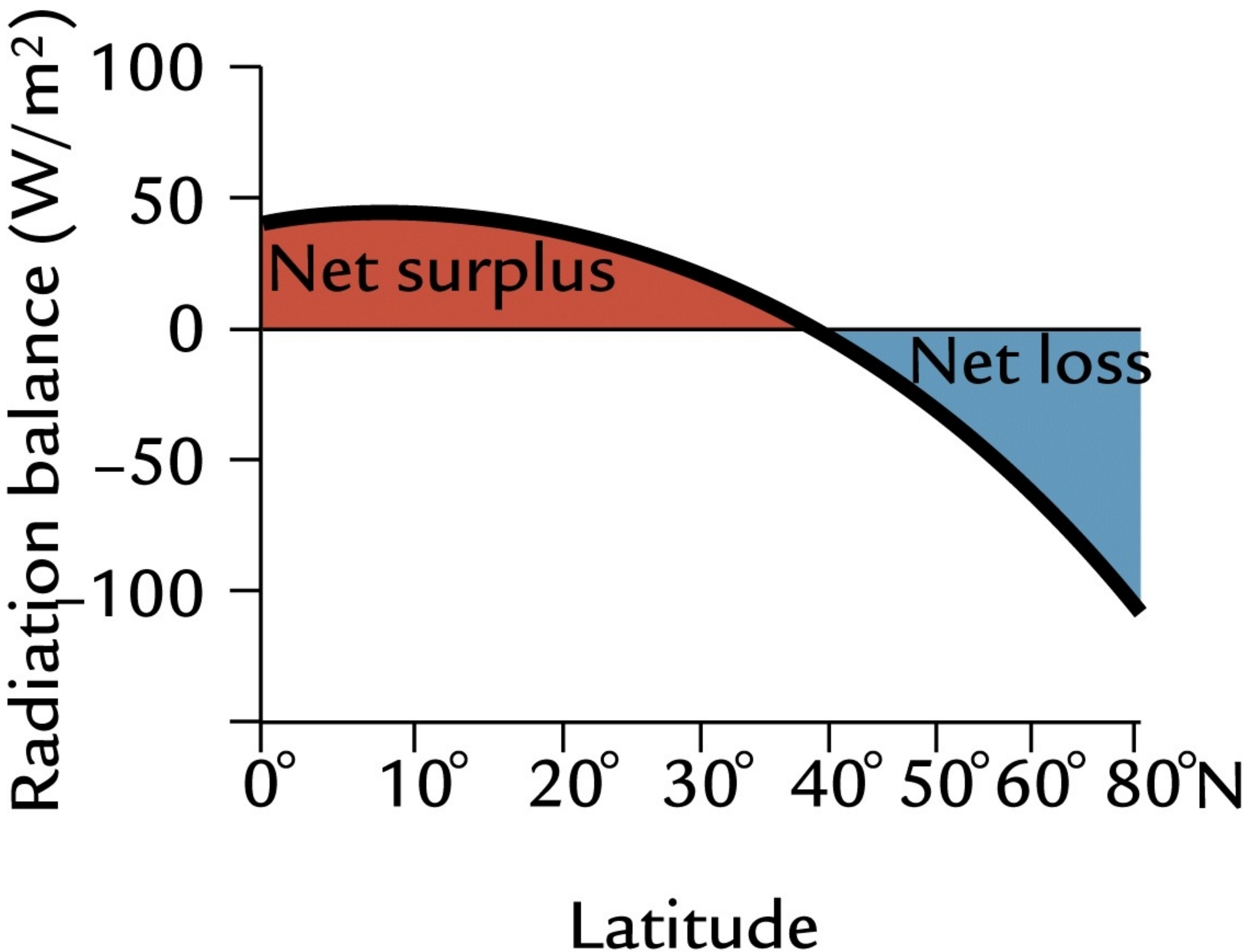
- Indirect data, often qualitative
- Long time series from archives
- Information beyond the instrumental record



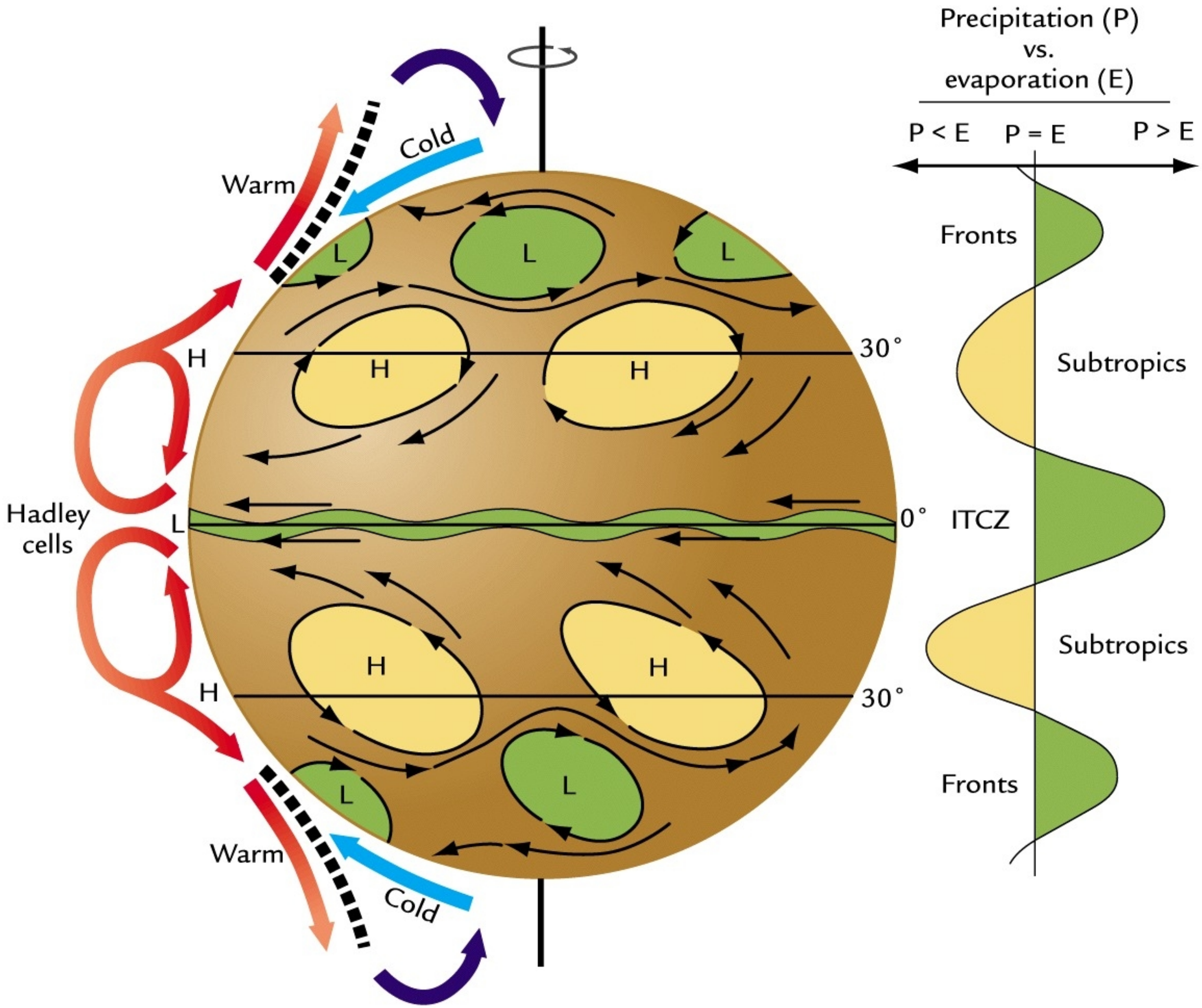
Driving mechanism

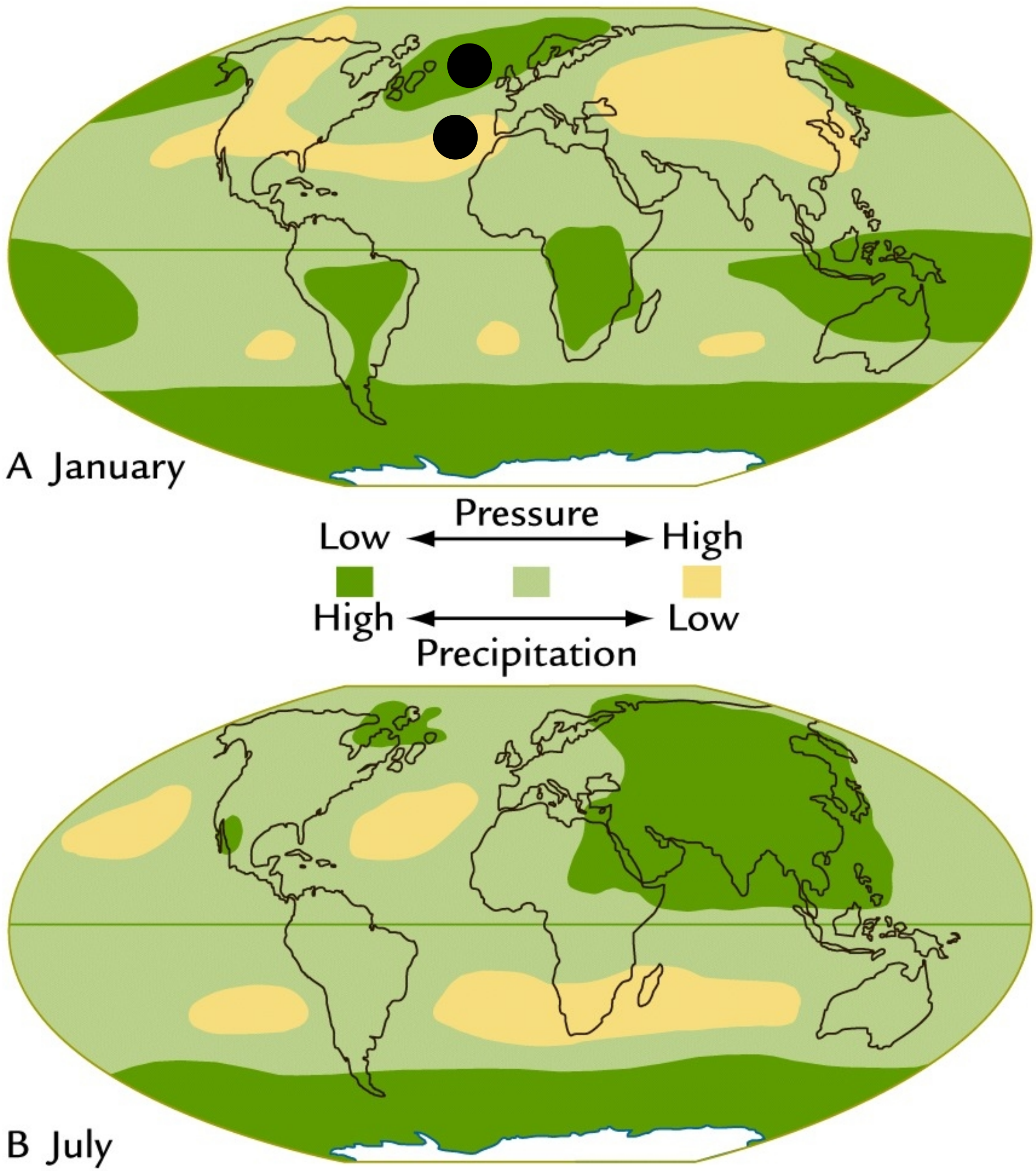


A


Radiation balance (W/m²)
100
50
0
−50
−100
Net surplus
Net loss
0°
10°
20°
30°
40°
50°
60°
80°N
Latitude

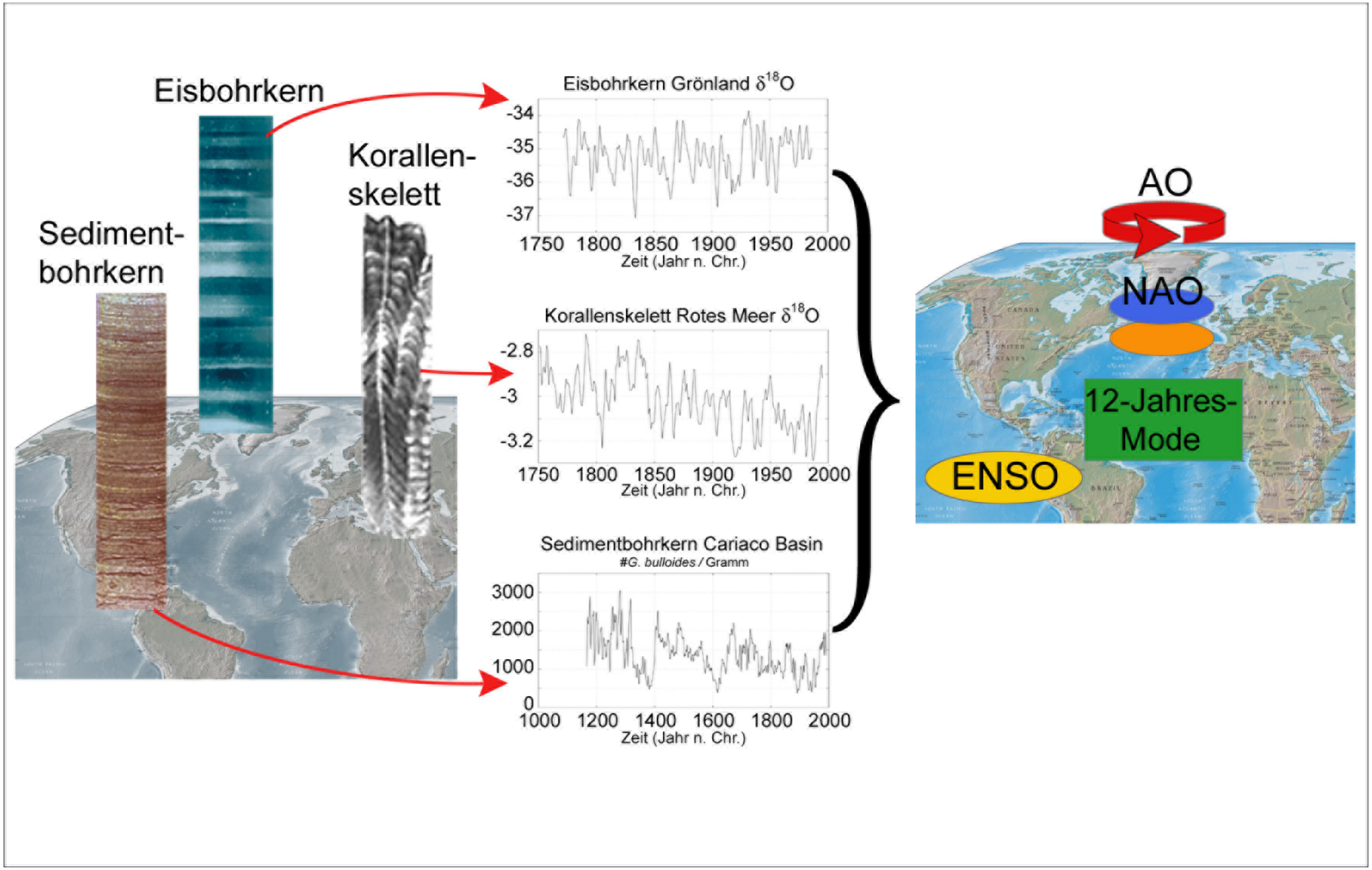
B


Precipitation (P)
vs.
evaporation (E)
P < E
P = E
P > E
Fronts
Subtropics
ITCZ
Subtropics
Fronts
Warm
Cold
Hadley
cells
H
L
H
L
L
L
H
H
30°
0°
H
H
30°
L
L
Warm
Cold


A January
Pressure
Low
High
High
Low
Precipitation
B July

Upscaling

Interpretation of Proxy Data



Statistic

Covariance (cross, auto)

$$\gamma(\Delta) = E\Big((x(t) - \bar{x}) \, (y(t+\Delta) - \bar{y}) \Big)$$

e.g. coral   e.g. meteorol. data

Correlation (cross, auto)

$$\rho_{xy} = \frac{\gamma(\Delta)}{\text{normalized}}$$

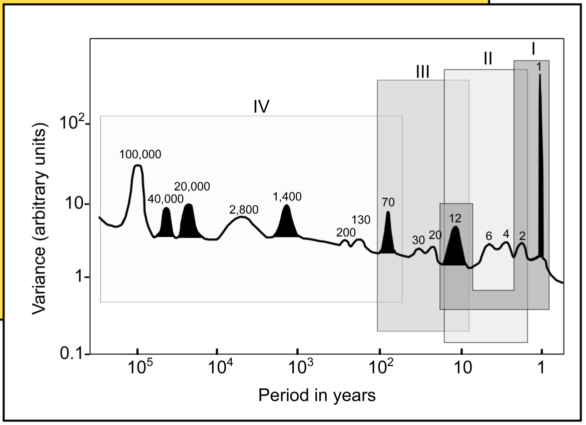
measures the tendency of x (t) and y (t) to covary

Spectrum (cross, auto)

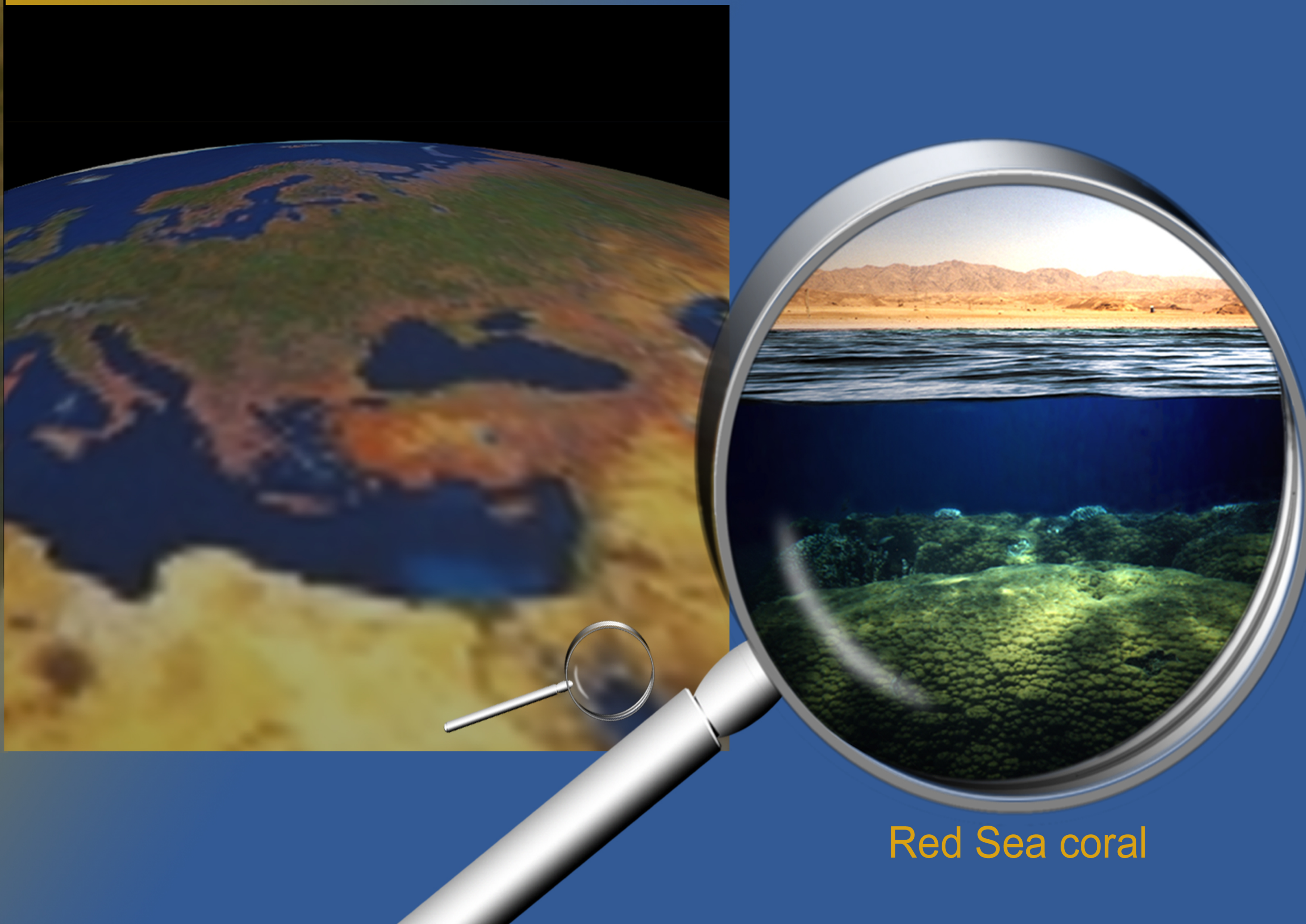
(spectral density)

$$\Gamma(\omega) = \sum_{\Delta=-\infty}^{\infty} \gamma(\Delta) \, e^{-2\pi i \Delta}$$

measures variance

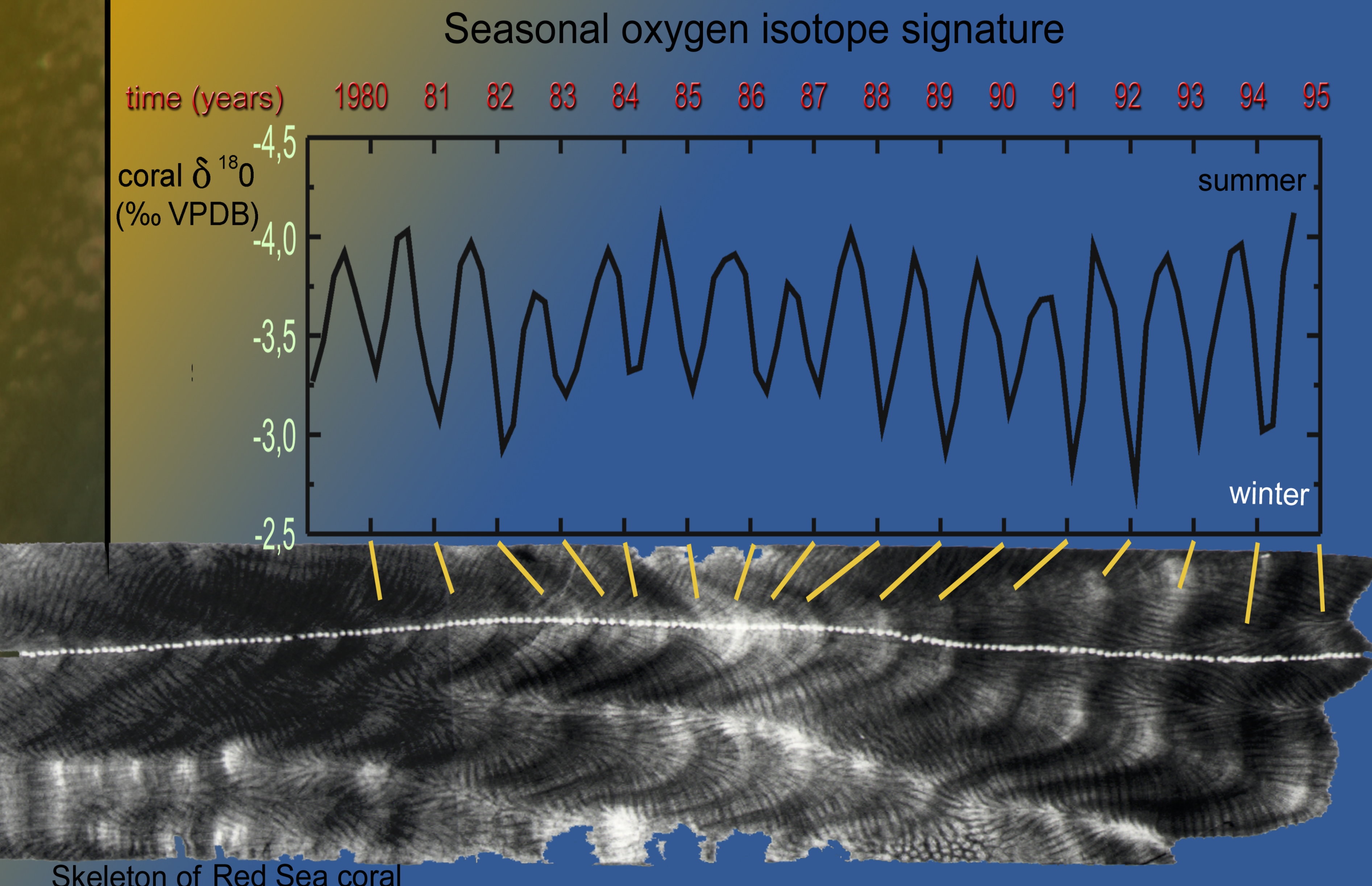


Climate Modes from Proxy Data



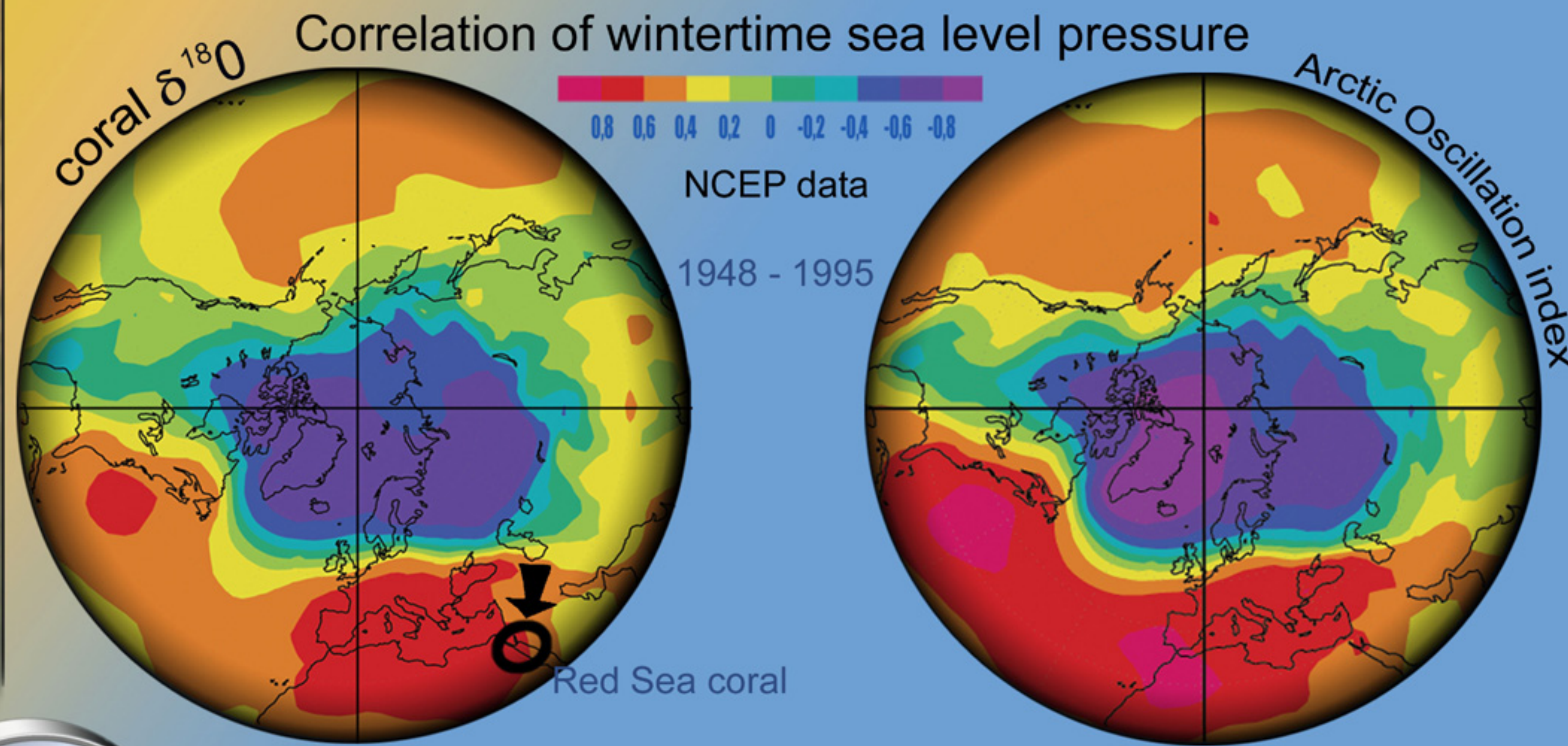
Red Sea coral

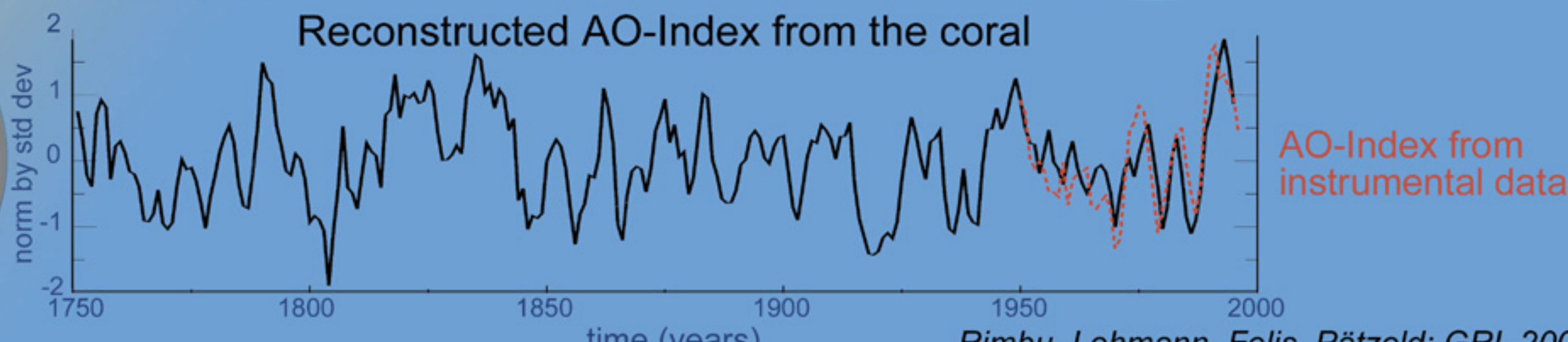
ARCTIC OSCILLATION SIGNATURE IN A RED SEA CORAL



Felis et al. Paleoceanography 2000

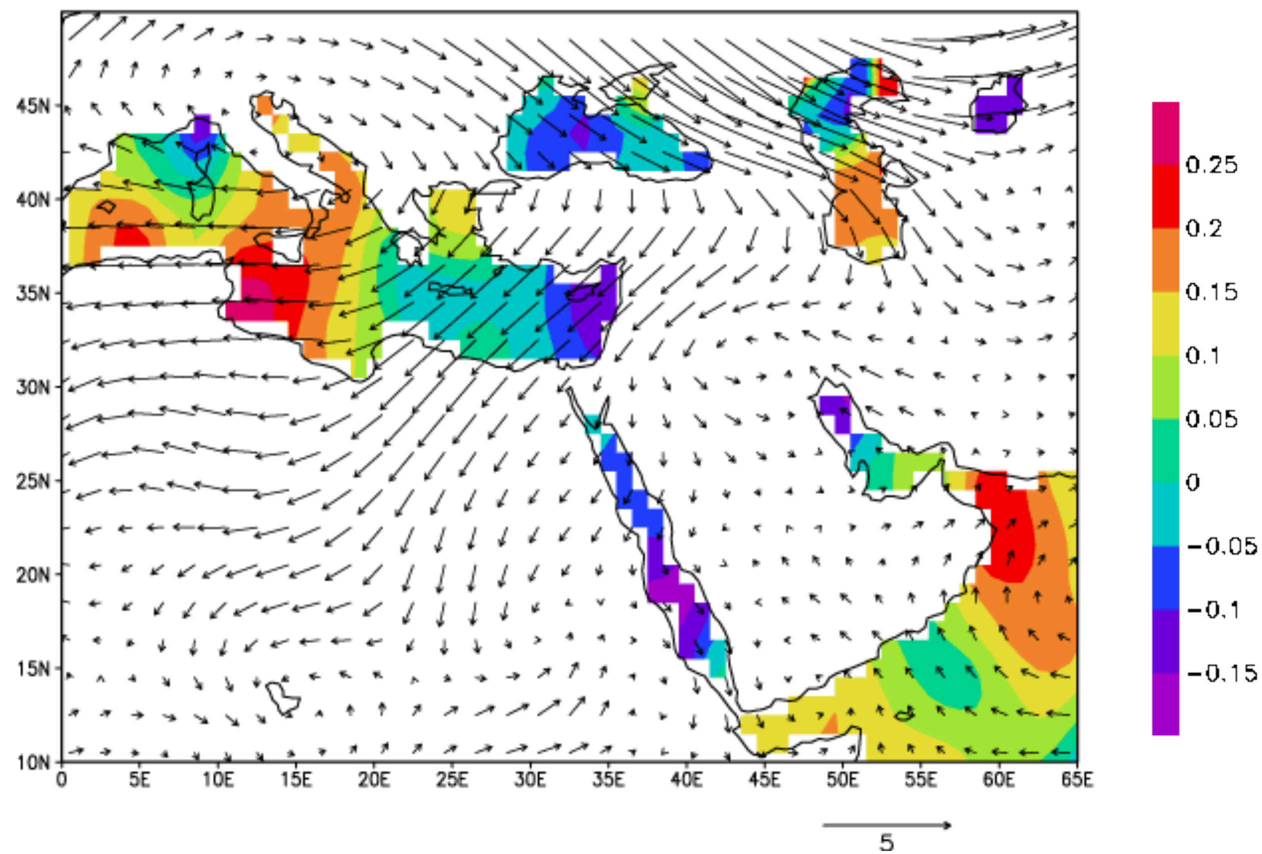
ARCTIC OSCILLATION SIGNATURE IN A RED SEA CORAL





Rimbu, Lohmann, Felis, Pätzold; GRL 2001

ARCTIC OSCILLATION SIGNATURE IN A RED SEA CORAL



Composite Map of SST [° C] and 925 hPa wind [m/s] for 1948 -1995, January - February

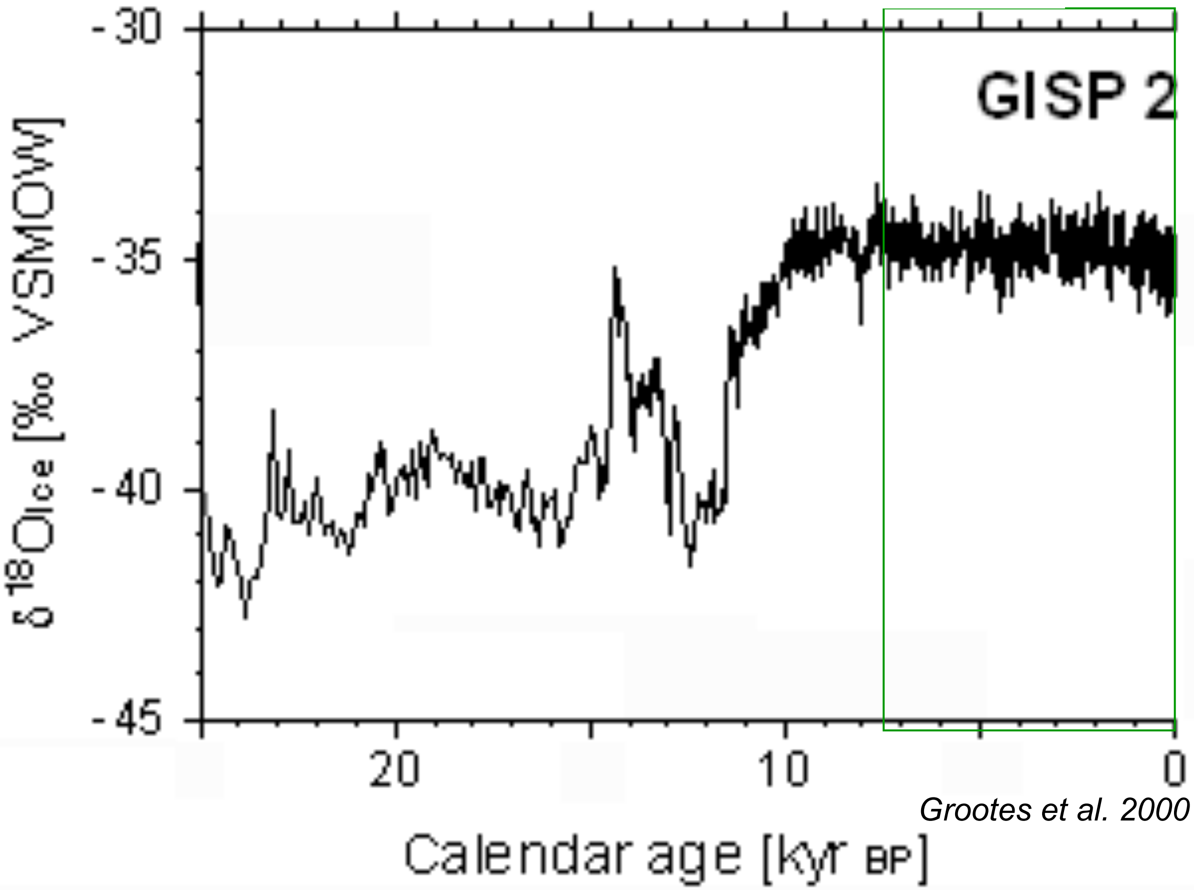
mechanistic understanding

Longer timescales

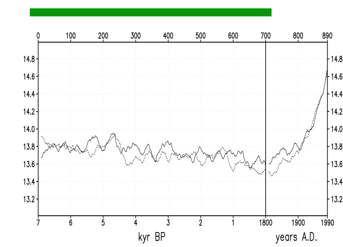
- Holocene
- Glacial-interglacial
- Role of the ocean
- Role of ice sheets
- feedbacks

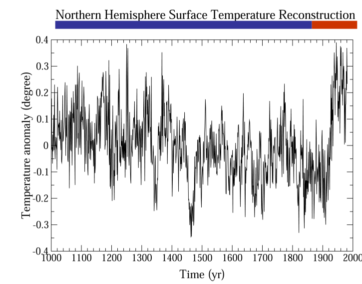
Climate Trends at different Timescales

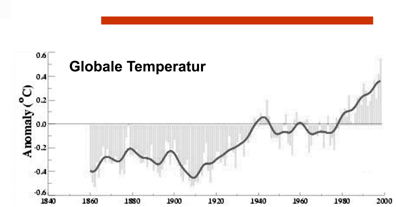
Deglaciation – Greenland ice core

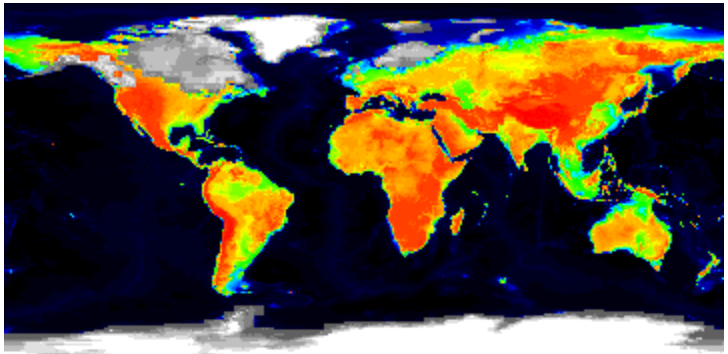


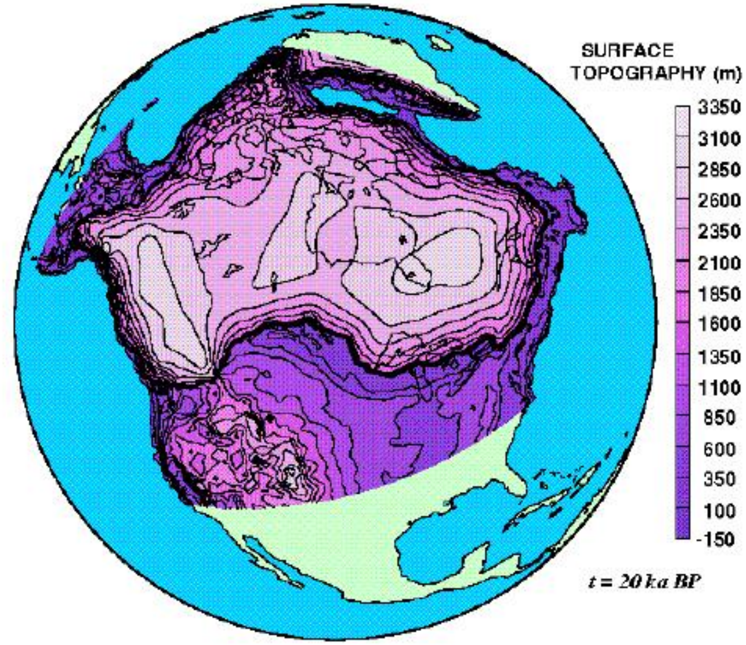
Grootes et al. 2000











Deglaciation

Schematic view of North Atlantic Deep water formation

Modelling

Circulation Models

Fluid dynamical equations

Momentum equations:

$$
\begin{aligned}
u_t + Adv(u) - \left(f + \frac{u\tan\phi}{a}\right) v &= -\frac{1}{a\cos\phi}\left(\frac{p}{\rho_0}\right)_\lambda + F^\lambda \\
v_t + Adv(v) + \left(f + \frac{u\tan\phi}{a}\right) u &= -\frac{1}{a}\left(\frac{p}{\rho_0}\right)_\phi + F^\phi \\
0 &= -\left(\frac{p}{\rho_0}\right)_z - g\rho
\end{aligned}
$$

Continuity equation:

$$\frac{1}{a\cos\phi}\left[(u)_\lambda + (v\cos\phi)_\phi\right] + (w)_z = 0 \qquad .$$

Equation for tracers χ**,** temperature T, salinity (humidity) S:

$$\chi_t + Adv(\chi) = A_{HH}\nabla^2\chi + A_{HV}\chi_{zz} \qquad ,$$

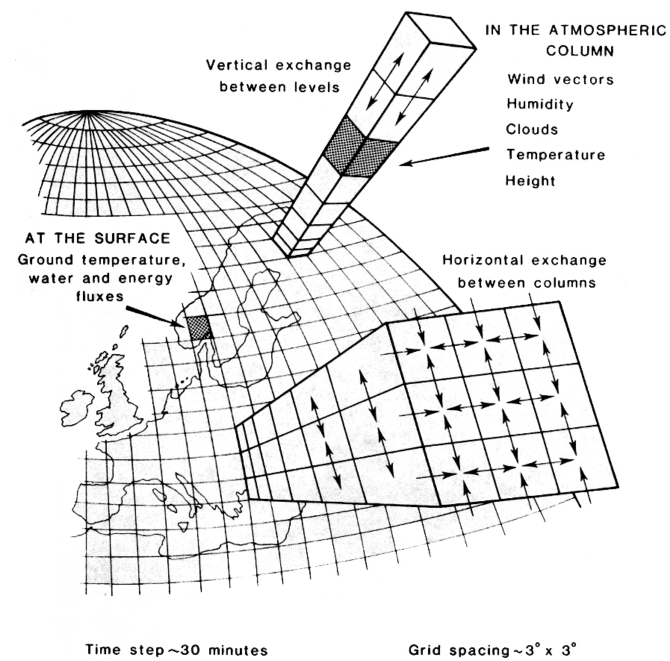
Equation of state:

$$\rho = \rho(\Theta, S, z) \qquad .$$

The equations are **"coarse grained"** in space and time.

Subgrid scale processes are **parameterized** by diffusive mixing.

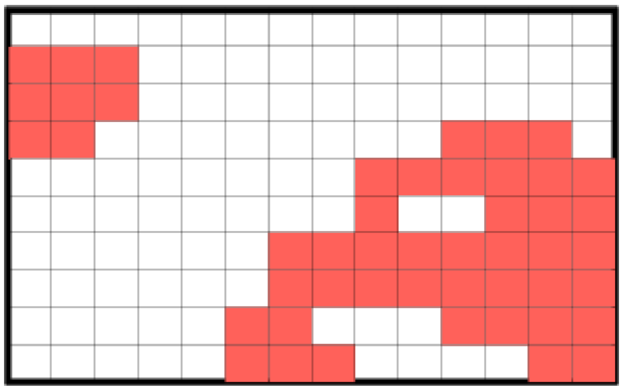
Cartesian Grid GCM



Grid resolution

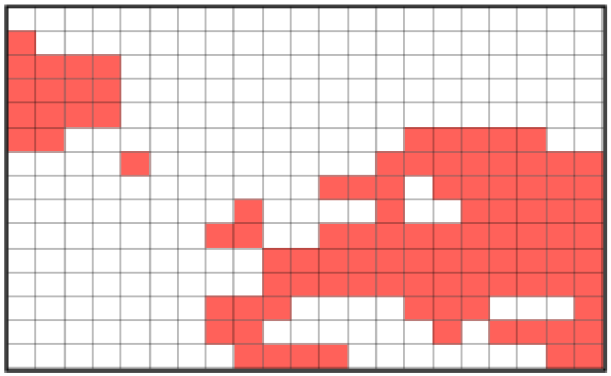
atmosphere

T 21



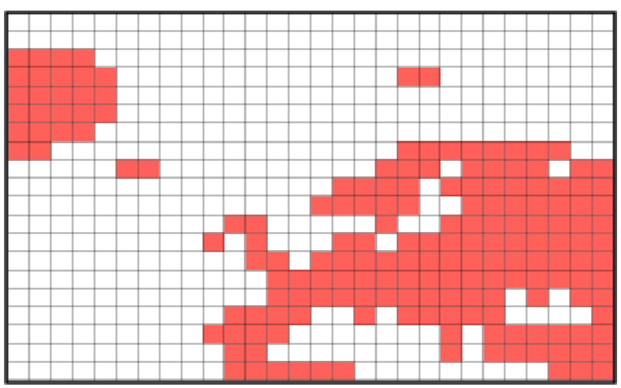
ca. 500 km Gitterabstand

T 42



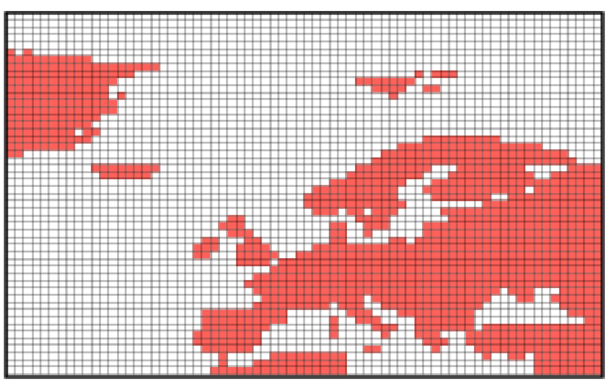
ca. 250 km Gitterabstand

T 63



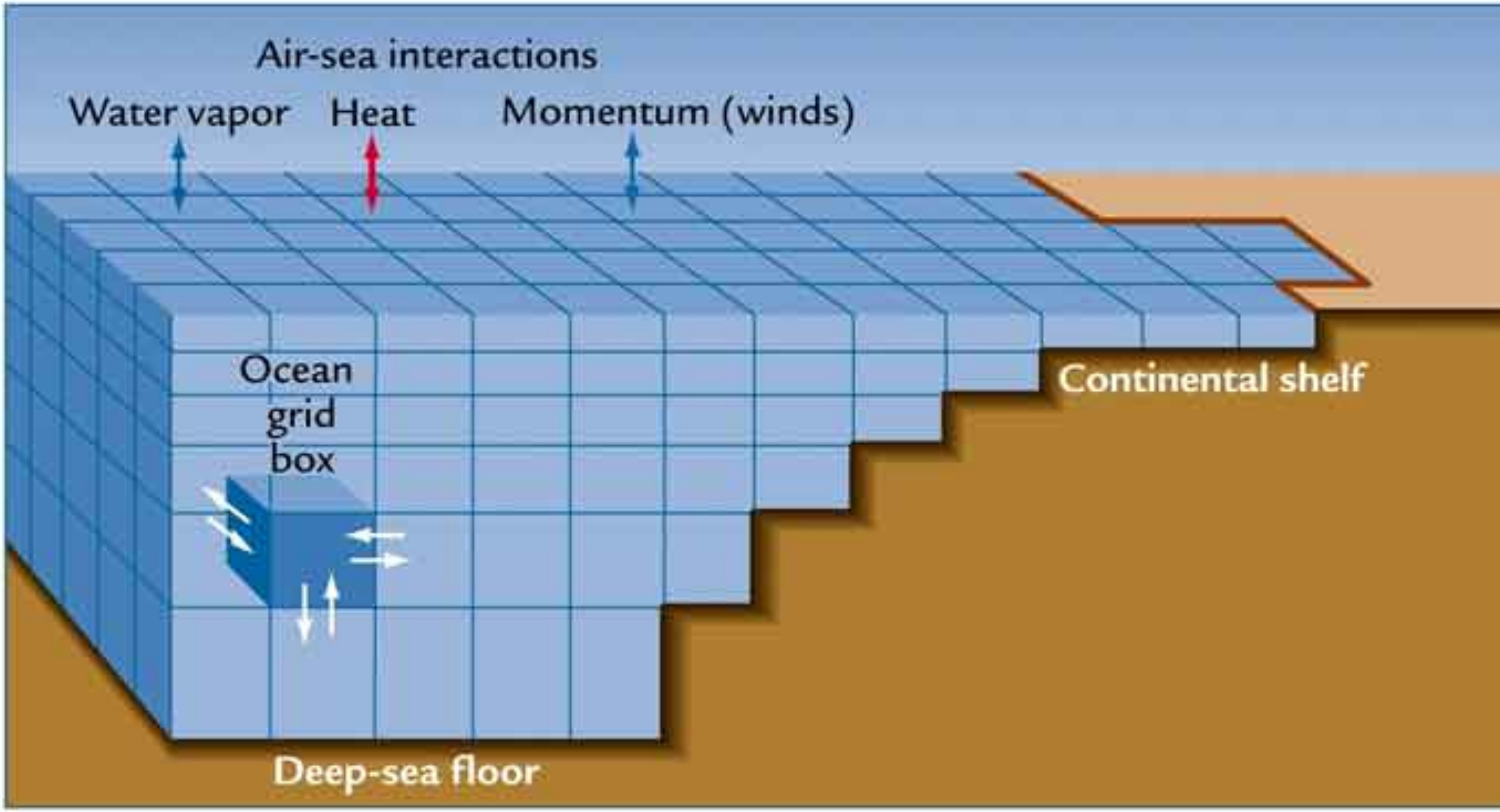
ca. 180 km Gitterabstand

T 106

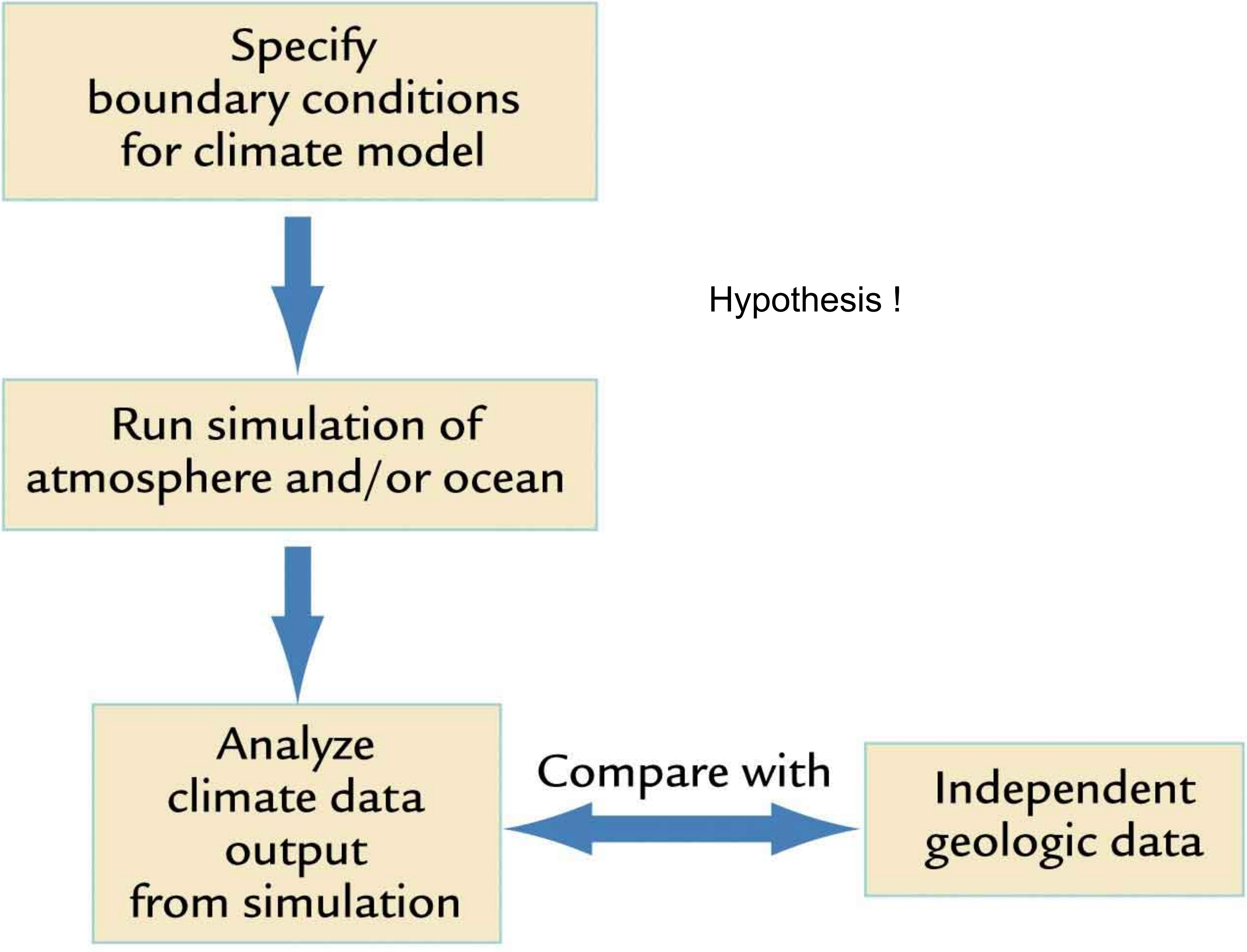


ca. 110 km Gitterabstand

ocean

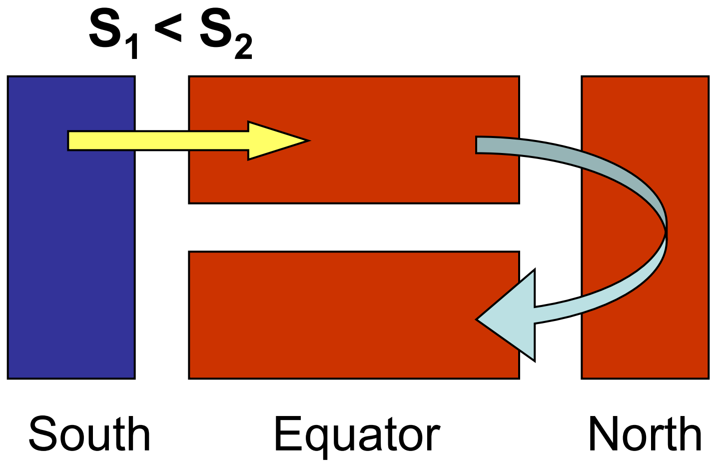


Air-sea interactions
Water vapor
Heat
Momentum (winds)
Ocean grid box
Continental shelf
Deep-sea floor


Specify boundary conditions for climate model
Run simulation of atmosphere and/or ocean
Analyze climate data output from simulation
Compare with
Independent geologic data

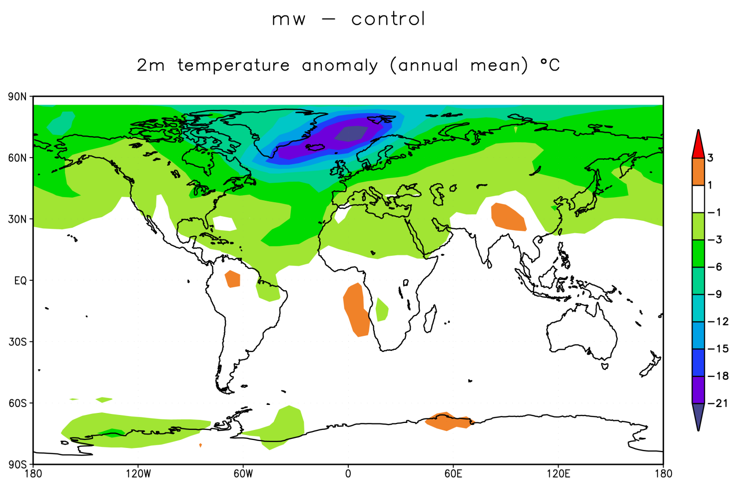
Hypothesis !

Conceptual model of the Atlantic THC



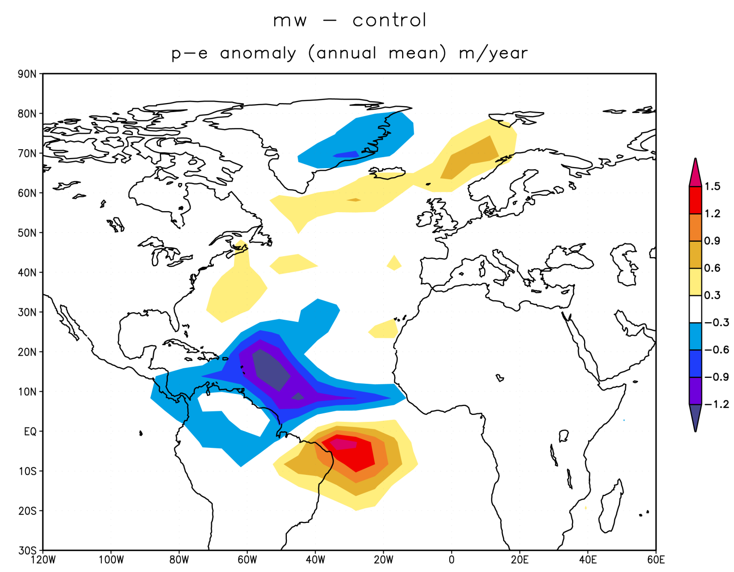
H-events
Recovery of the THC

Detecting THC changes by surface quantities



2 meter temperature

interhemispheric Seesaw



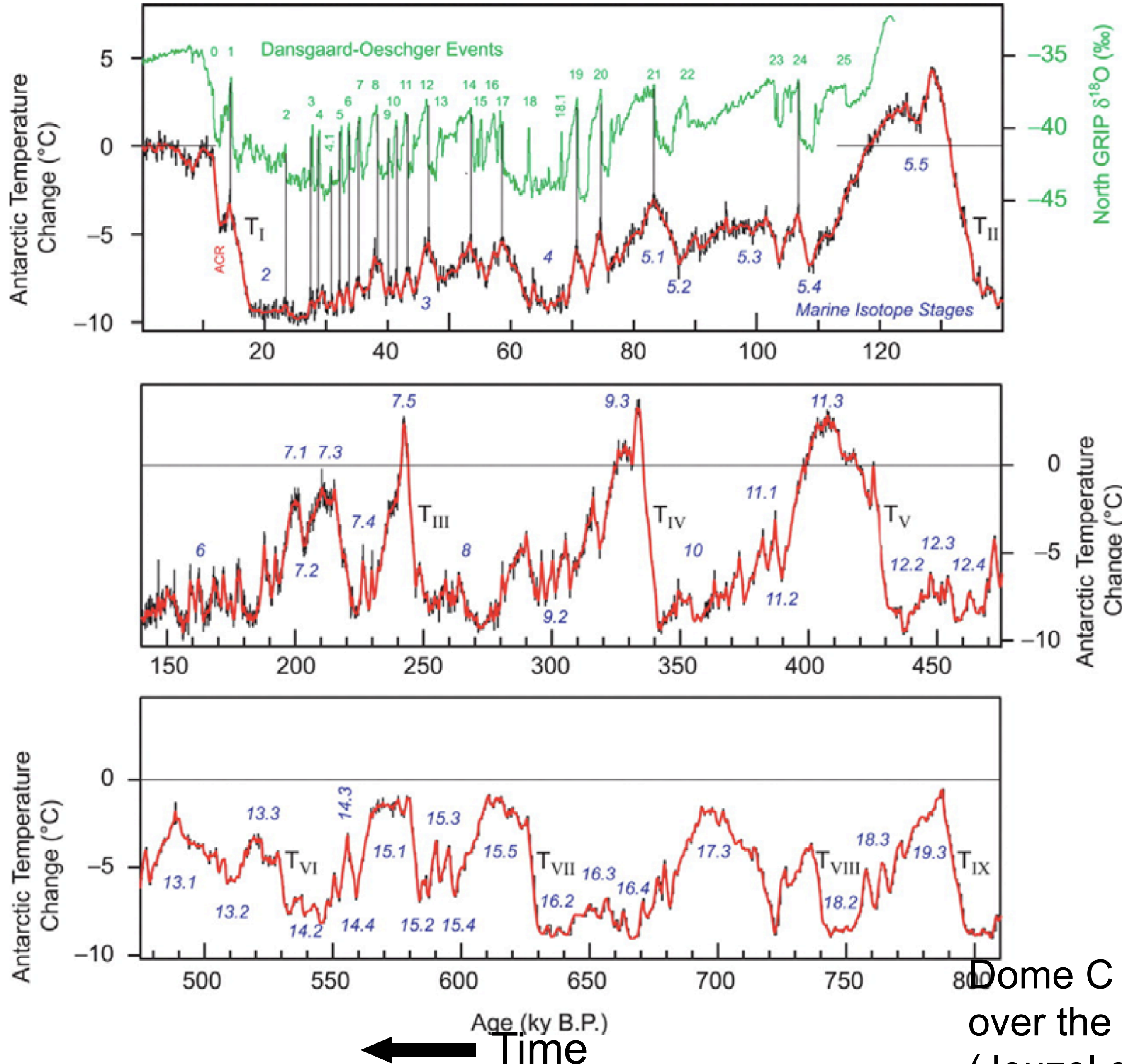
Southward Shift of the ITCZ

→ **high Noise level**

→ **Projection onto several Phenomena**

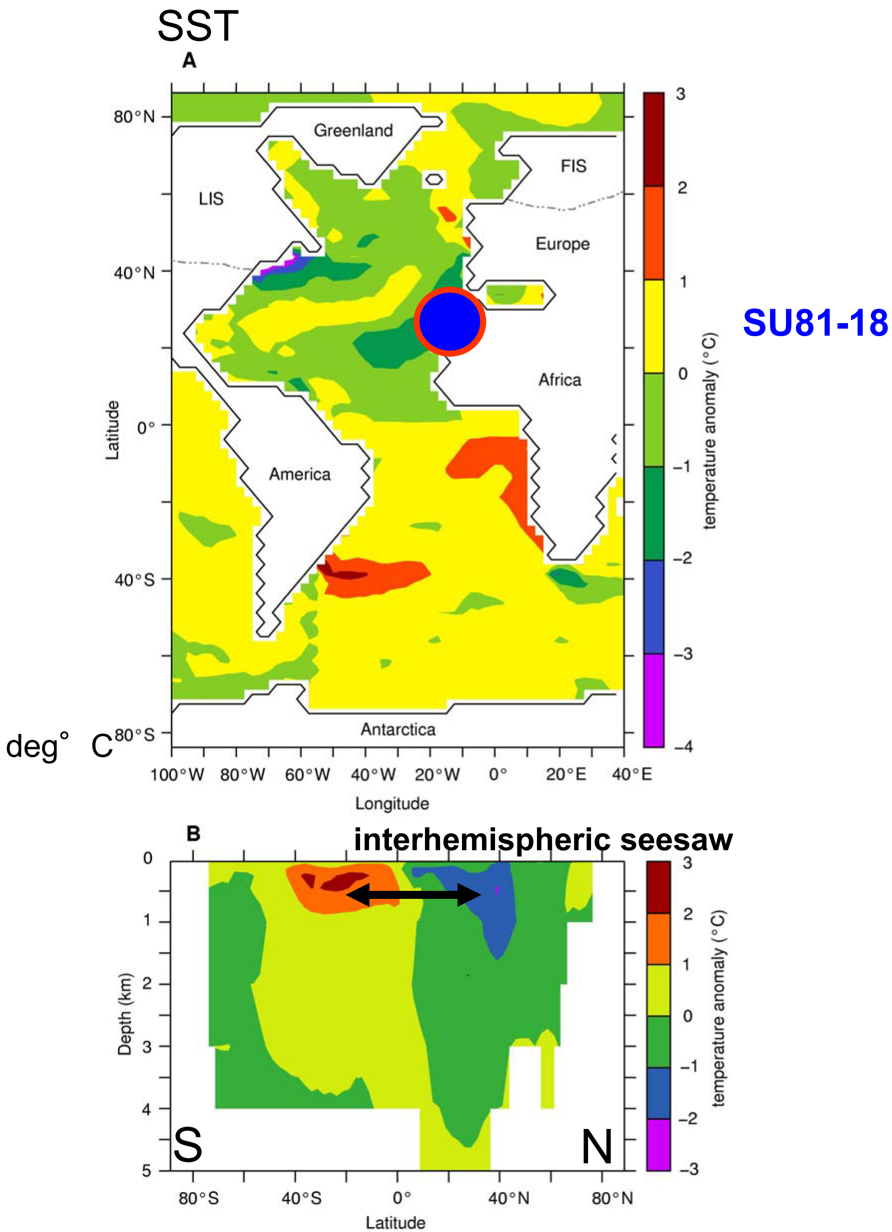
Lohmann 2003

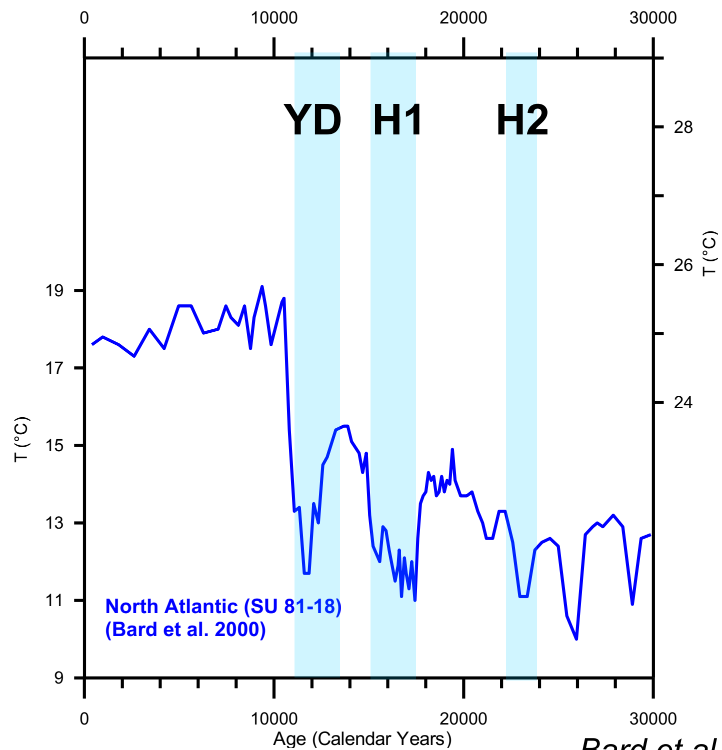
Millenial variability



Dome C temperature over the past 810 ky (Jouzel et al., 2007)

Signature at the end of a meltwater pertubation

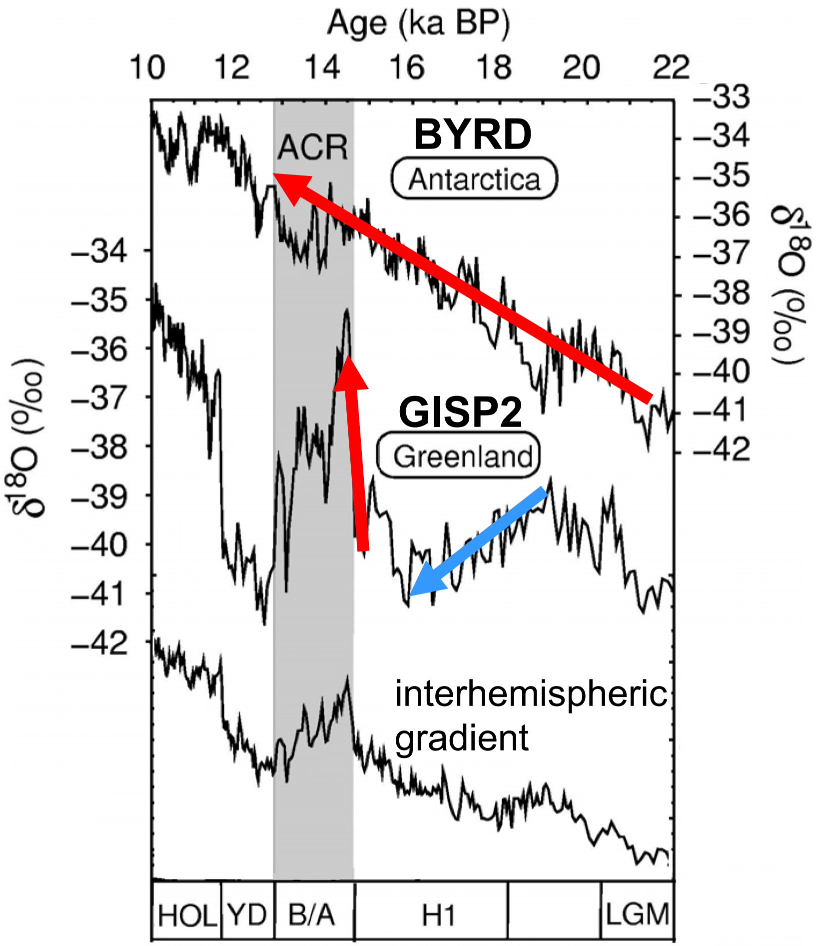


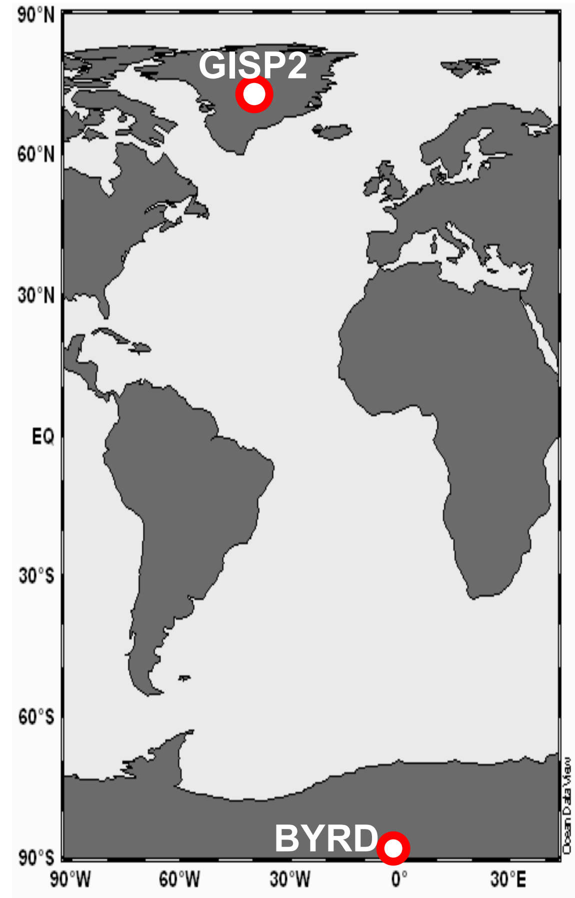


Bard et al. 2000

Motivation: Geological Data

Transition Glacial-Interglacial






Time

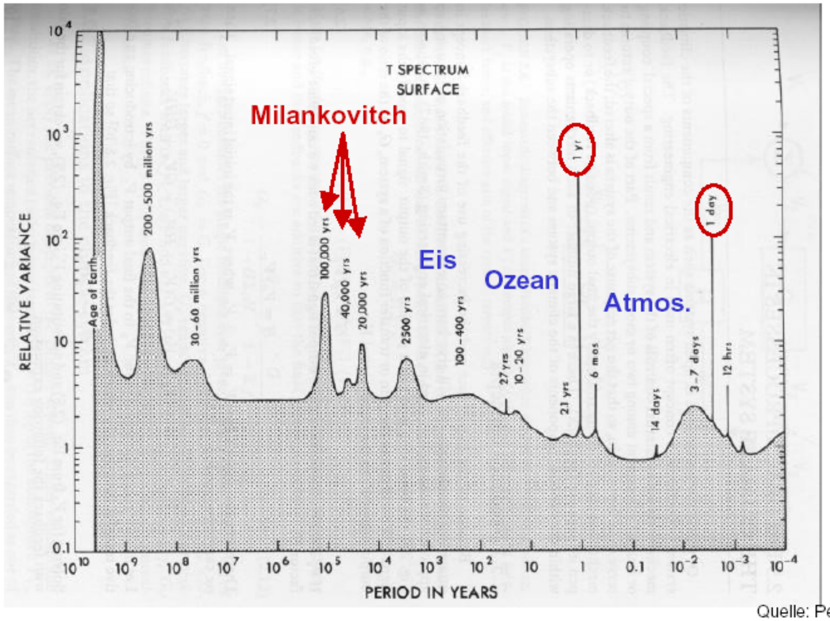
Blunier und Brook 2001

Glacial-Interglacial

Solar – Orbital focing

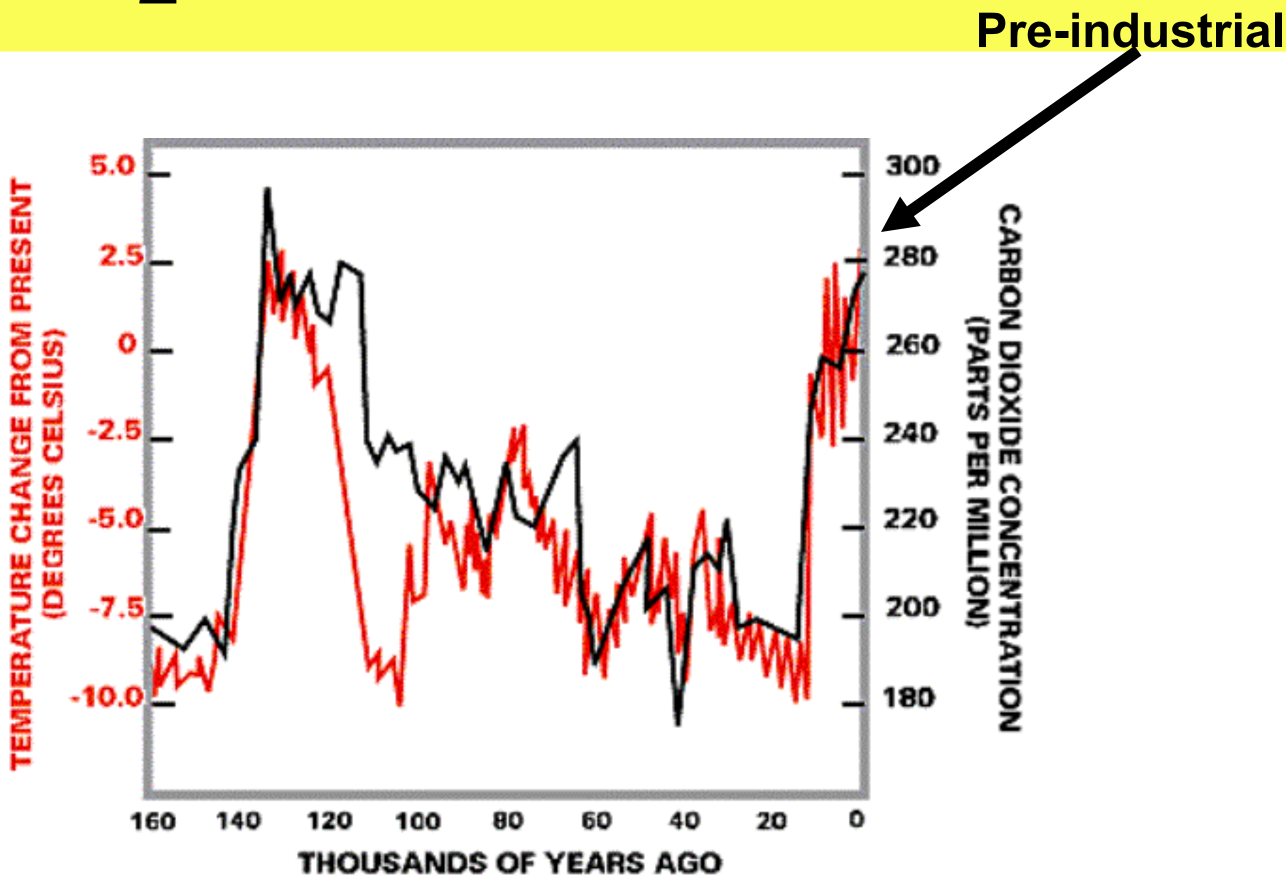
- 20000, 40000, 100000 years
- 0.5, 1 year

- Geometry of the Sun-Earth configuration



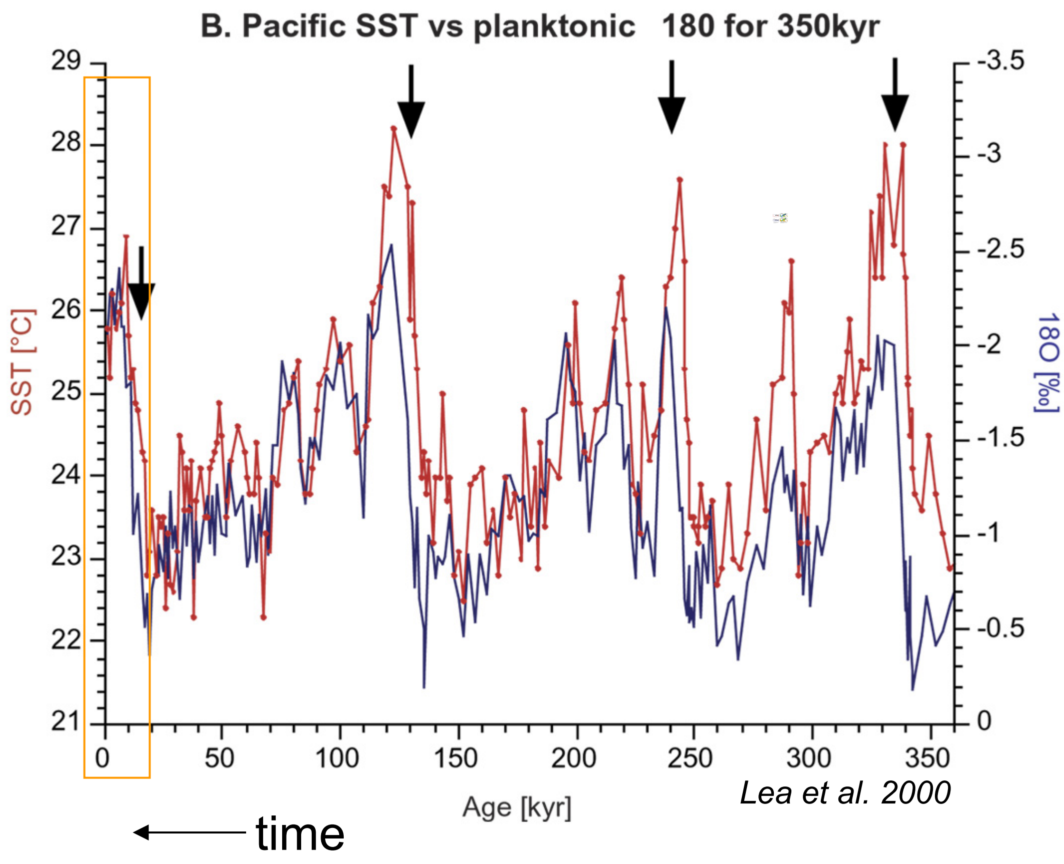
Quelle: Peixoto & Oort

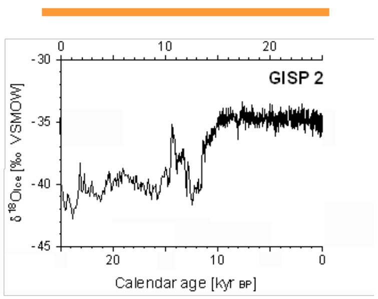
CO_2 and temperature

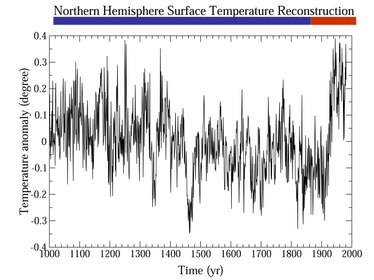


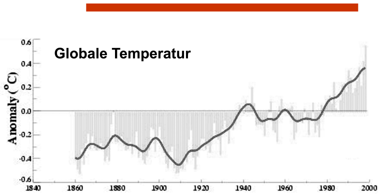
Climate Trends at different Timescales

Glacial-Interglacial

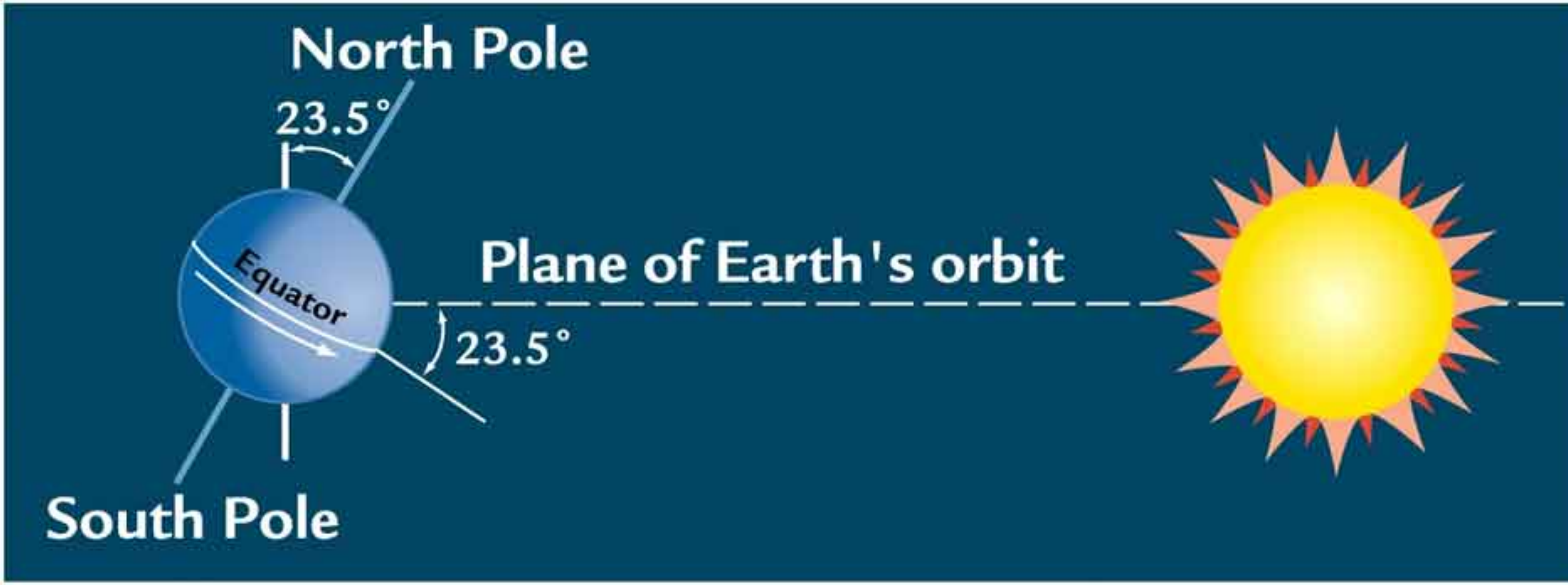








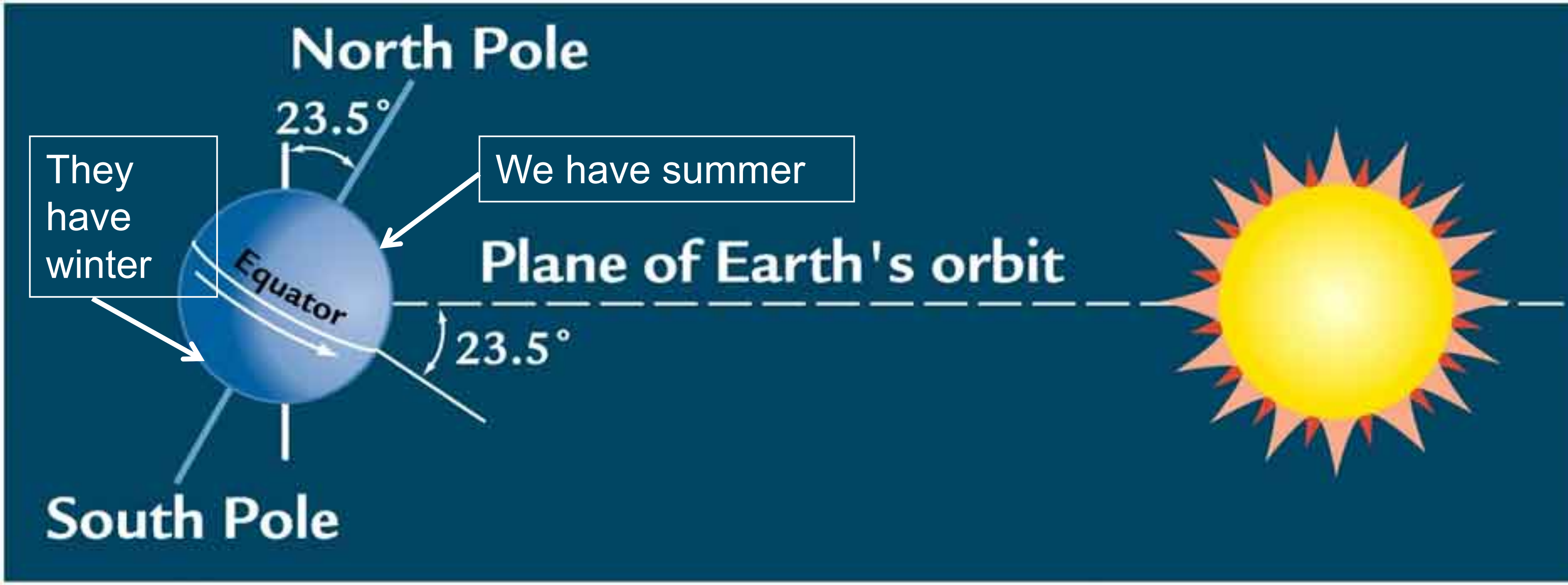
Annual Cycle



Northern Hemisphere Summer

Boreal Summer

Annual Cycle

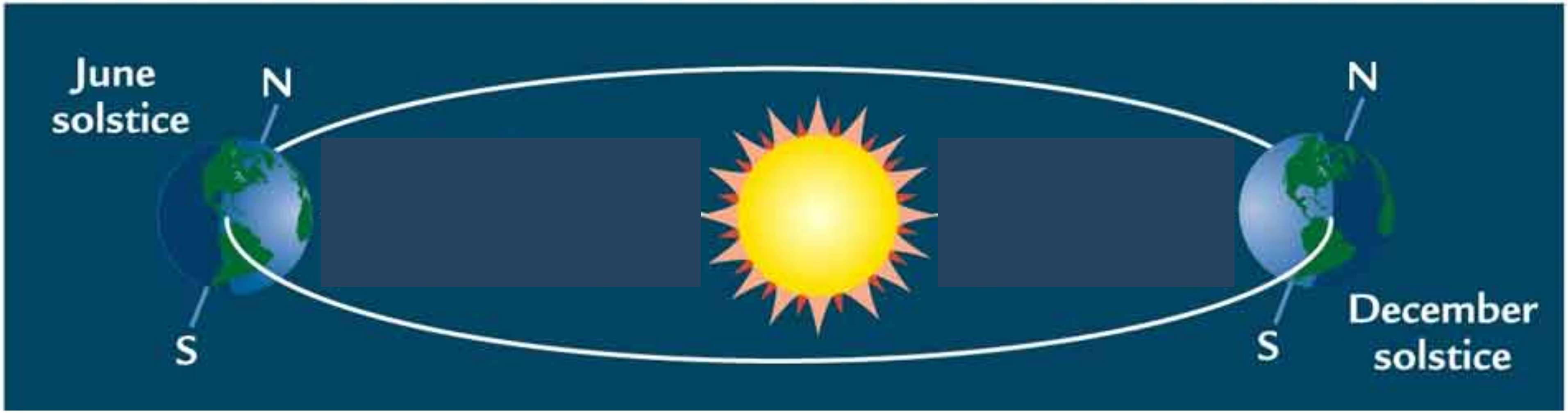


Northern Hemisphere Summer

Boreal Summer

Annual Cycle

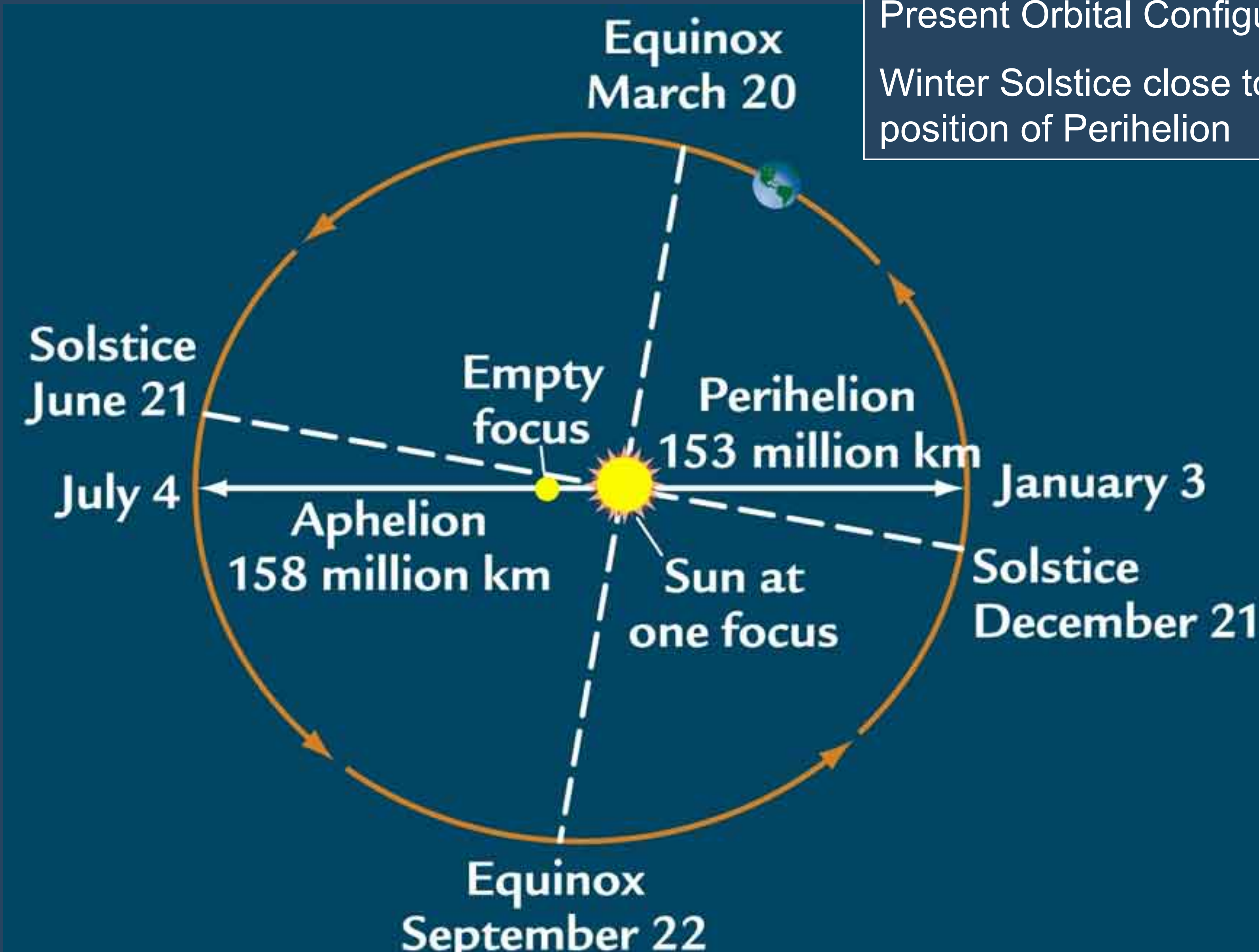
Fixed axis of Earth rotation



Precession & Eccentricity

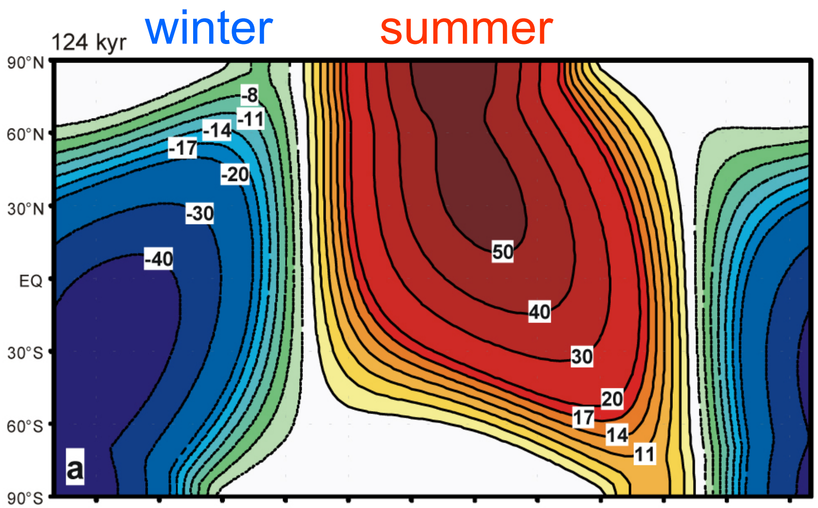
Present Orbital Configuration:

Winter Solstice close to the position of Perihelion



Example for astronomical (Milankovitch) forcing

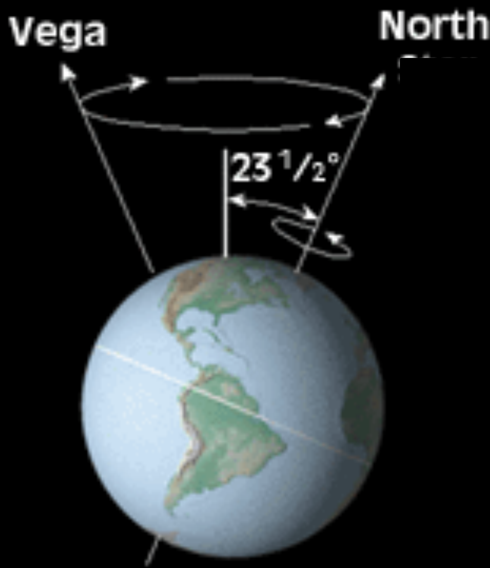
The Eemian climate (the last interglacial, 124 000 years)



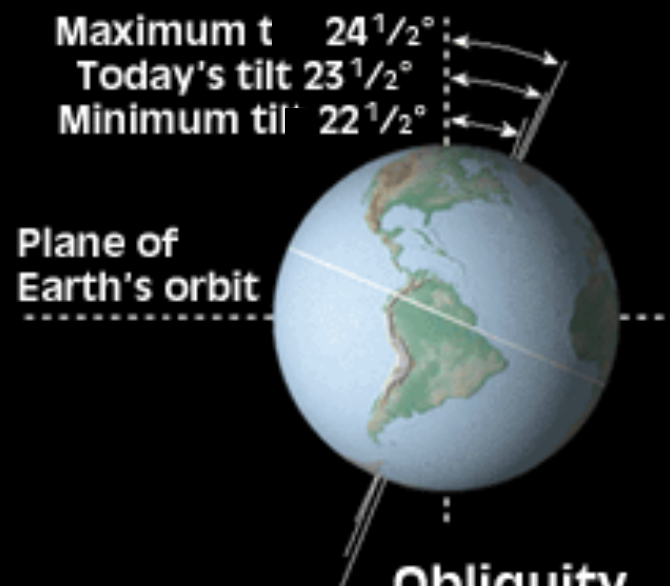
insolation anomaly form today

Jan–Feb-Mar-Apr-May-Jun-Jul-Aug-Sep-Oct-Nov-Dec

Different from Sunspots !   Photo: Nasa



Precession

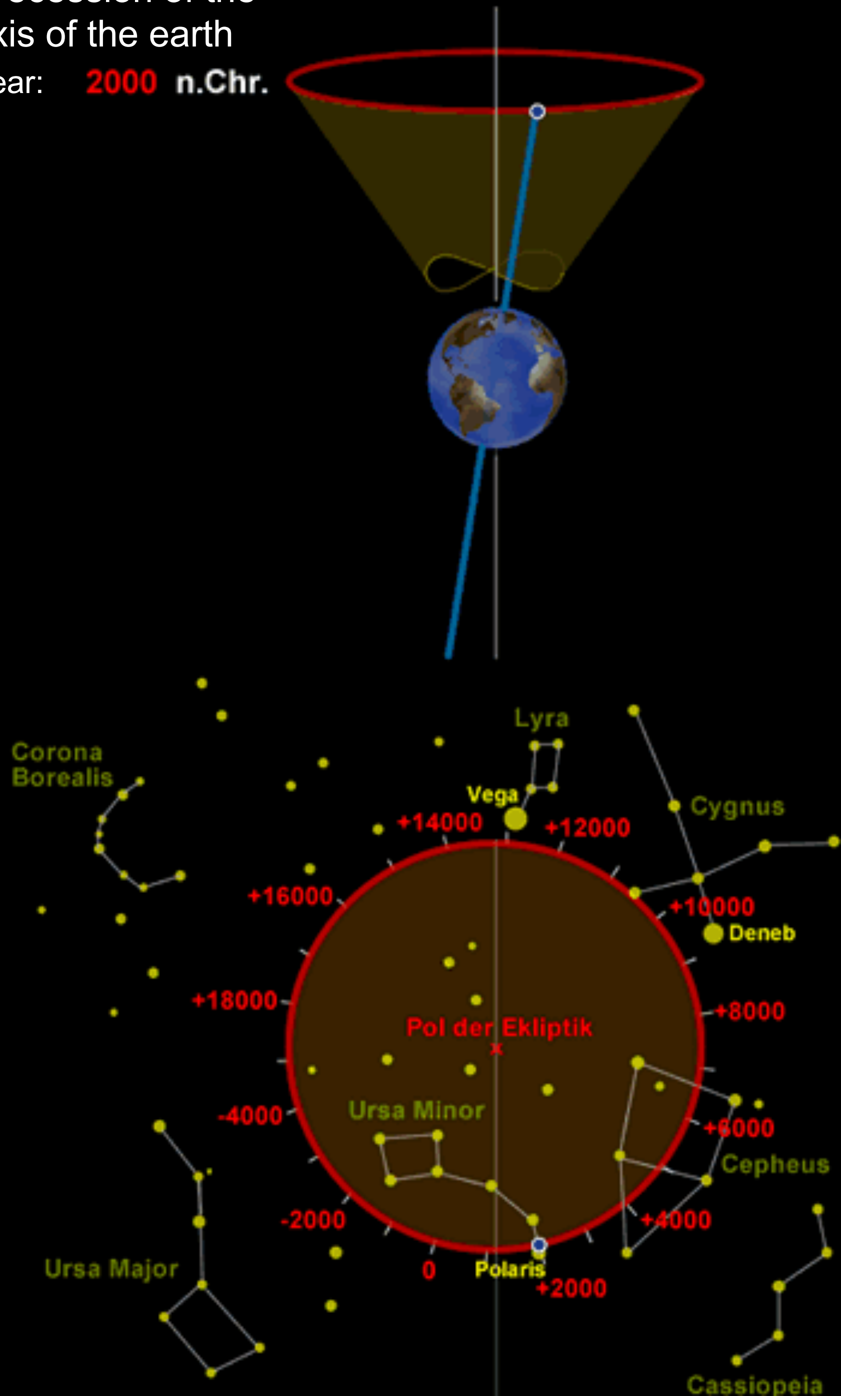


Obliquity

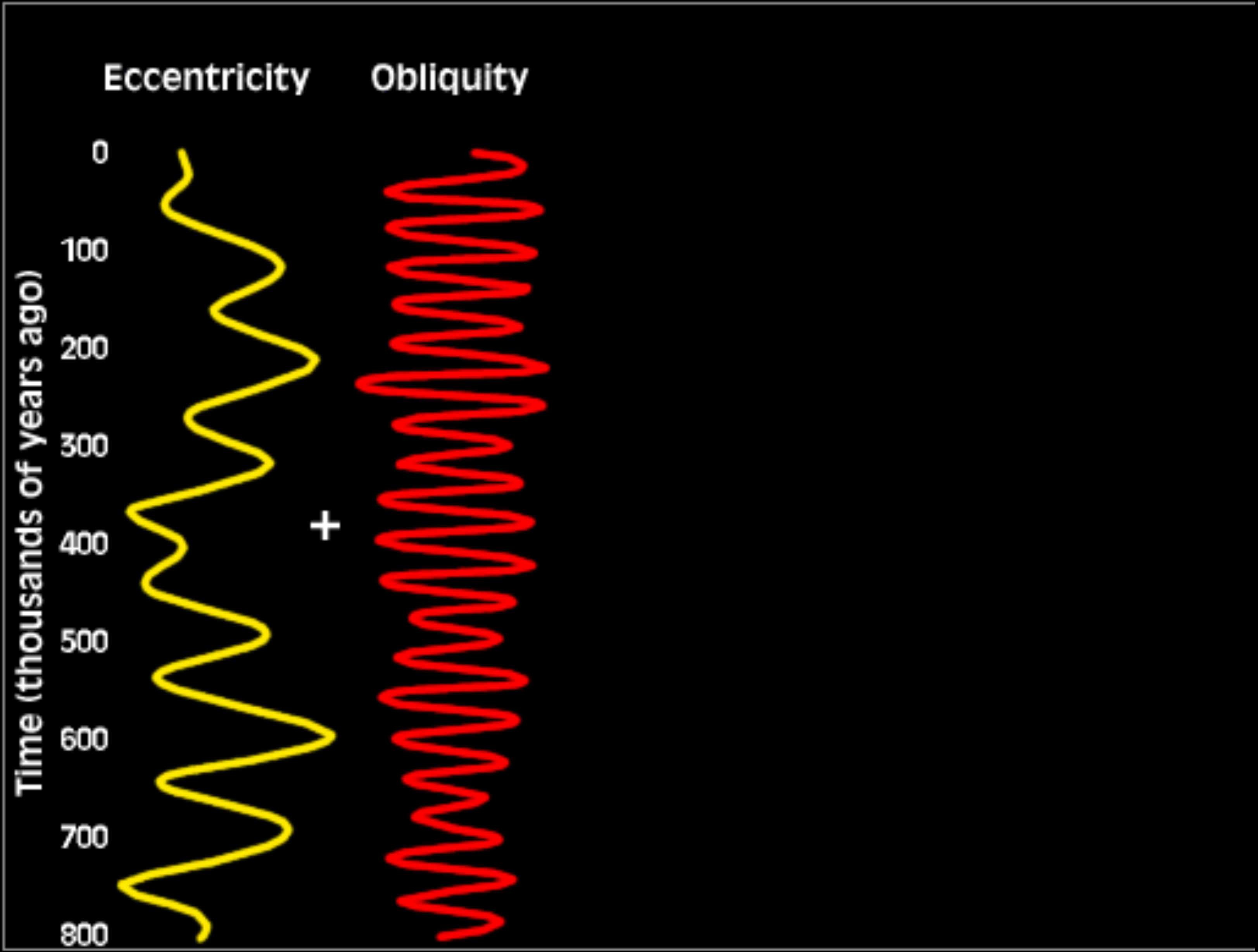
Eccentricity

Precession of the axis of the earth

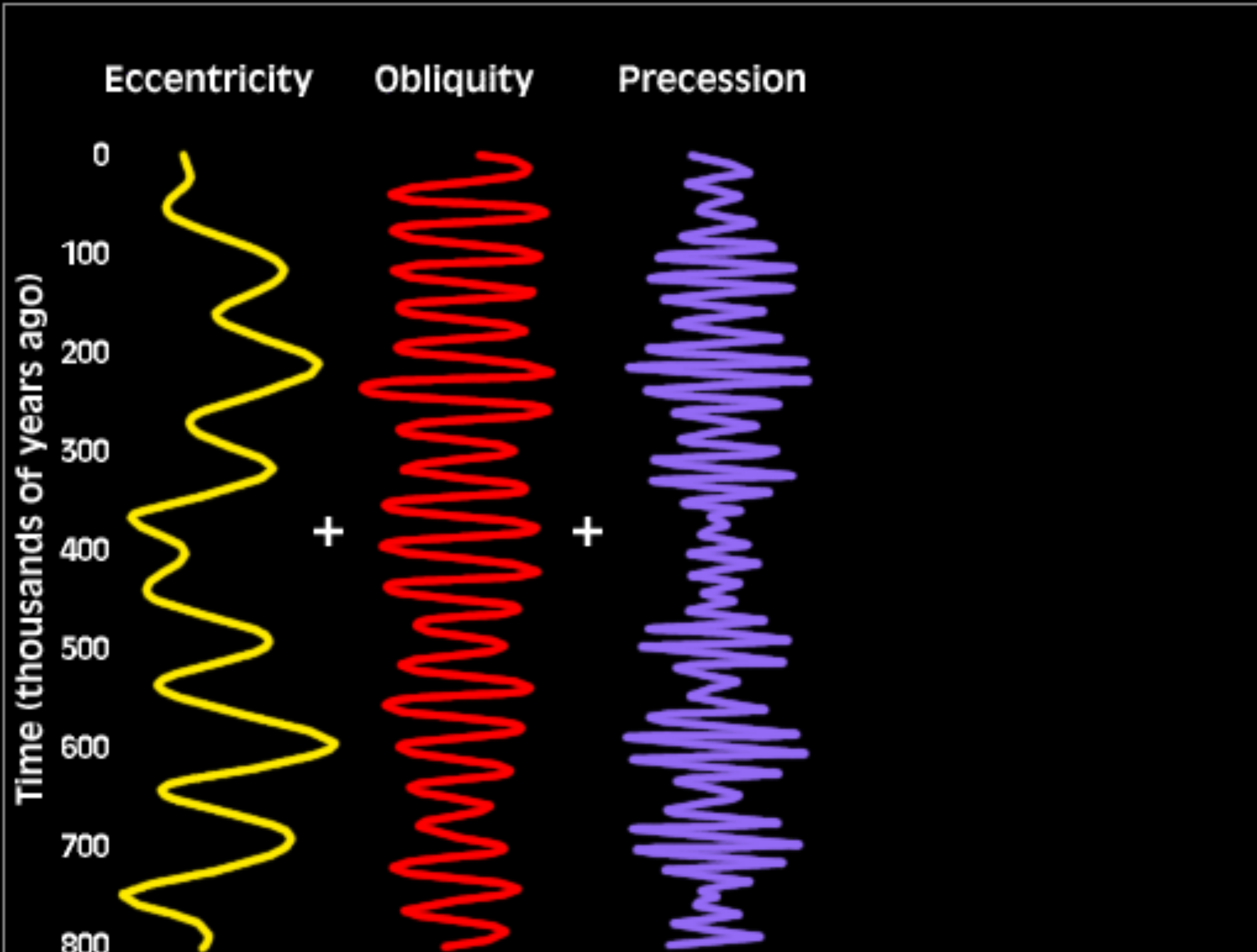
Year: 2000 n.Chr.



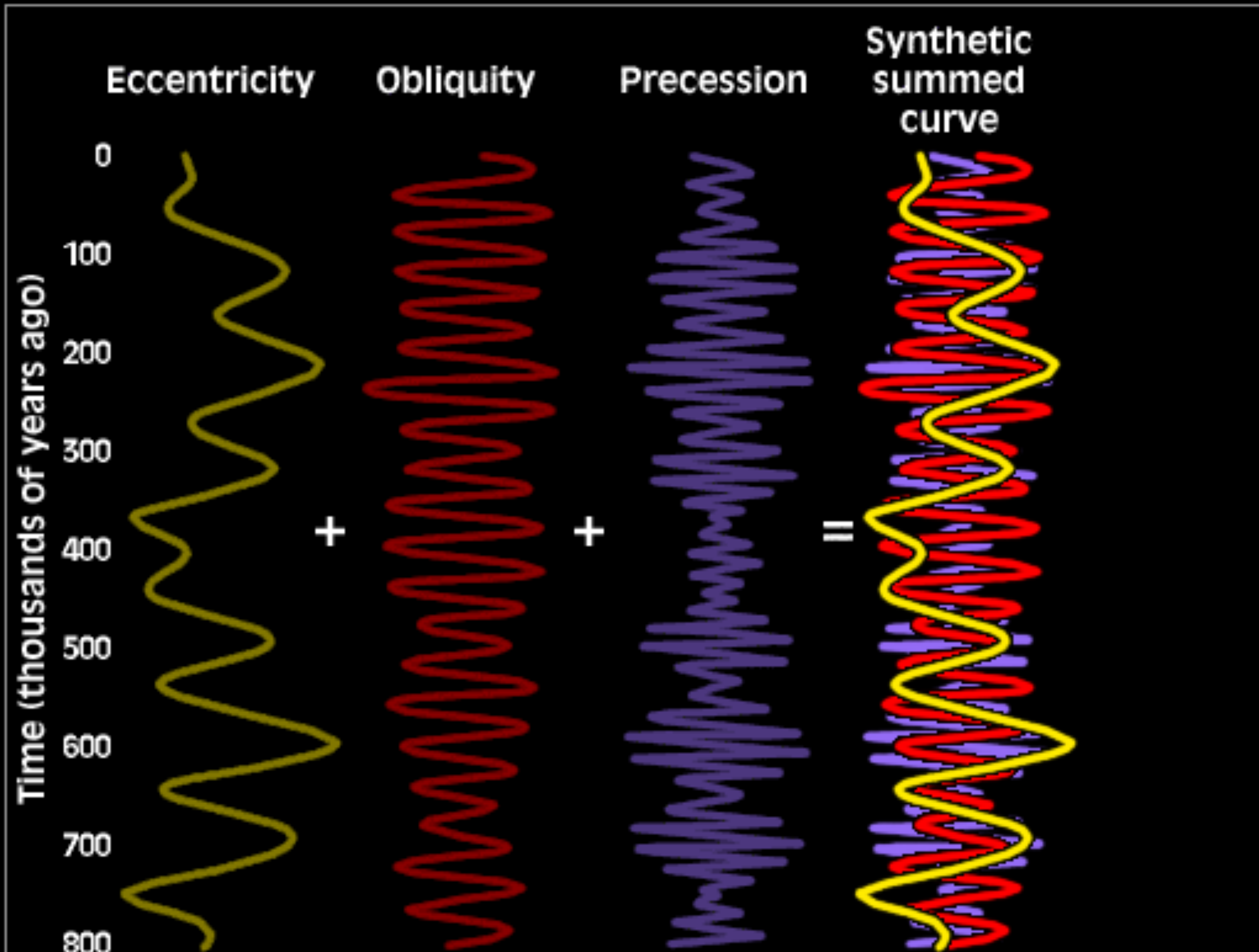
Eccentricity
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800



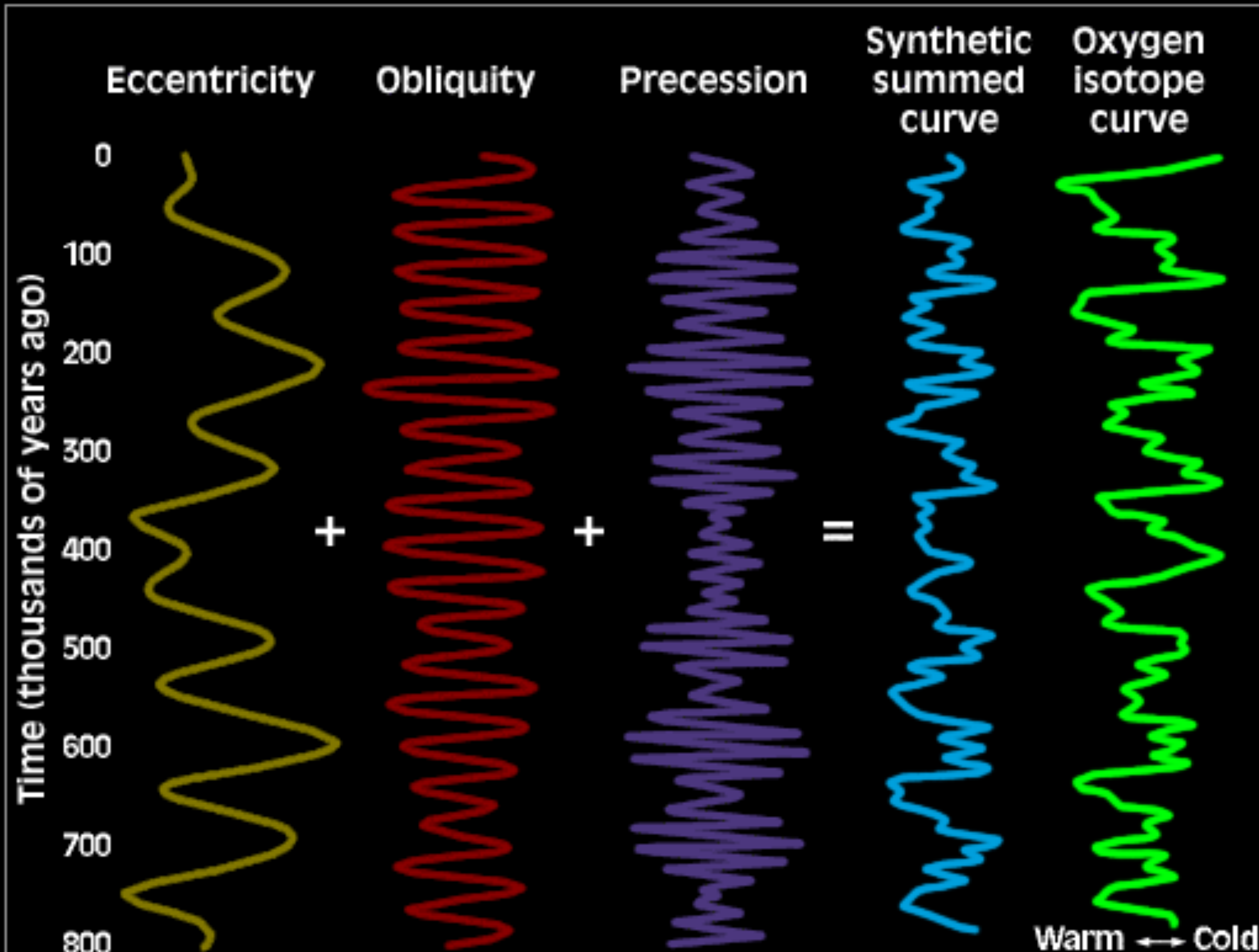
Eccentricity
Obliquity
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800
+



Eccentricity
Obliquity
Precession
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800
+
+

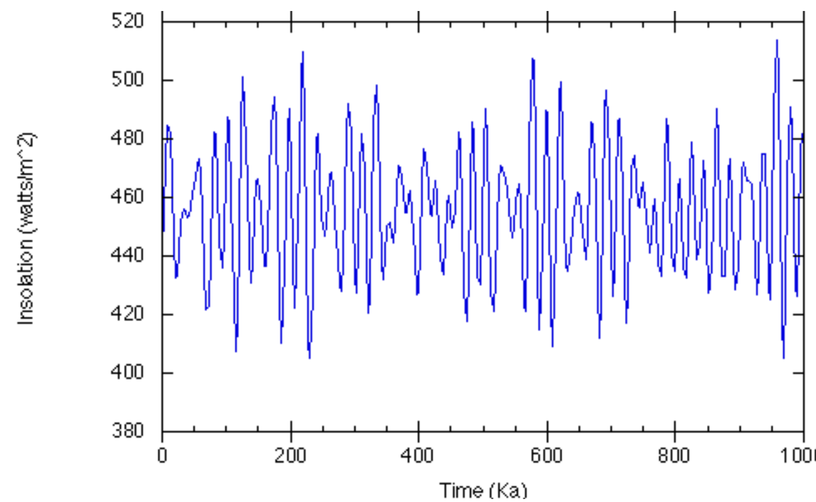


Eccentricity
Obliquity
Precession
Synthetic summed curve
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800
+
+
=

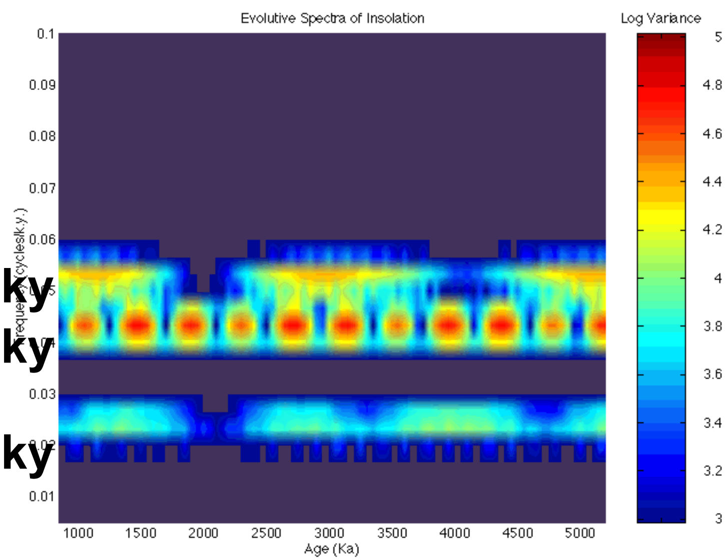

Eccentricity
Obliquity
Precession
Synthetic summed curve
Oxygen isotope curve
+
+
=
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800
Warm ⟷ Cold

Frequencies

65 degrees north latitude from the present to 1 million years ago.



Spectral analysis: examine the frequency distribution of these oscillations over the last 6 million years. With this method one can see how the strength of the orbital frequencies varies over time.

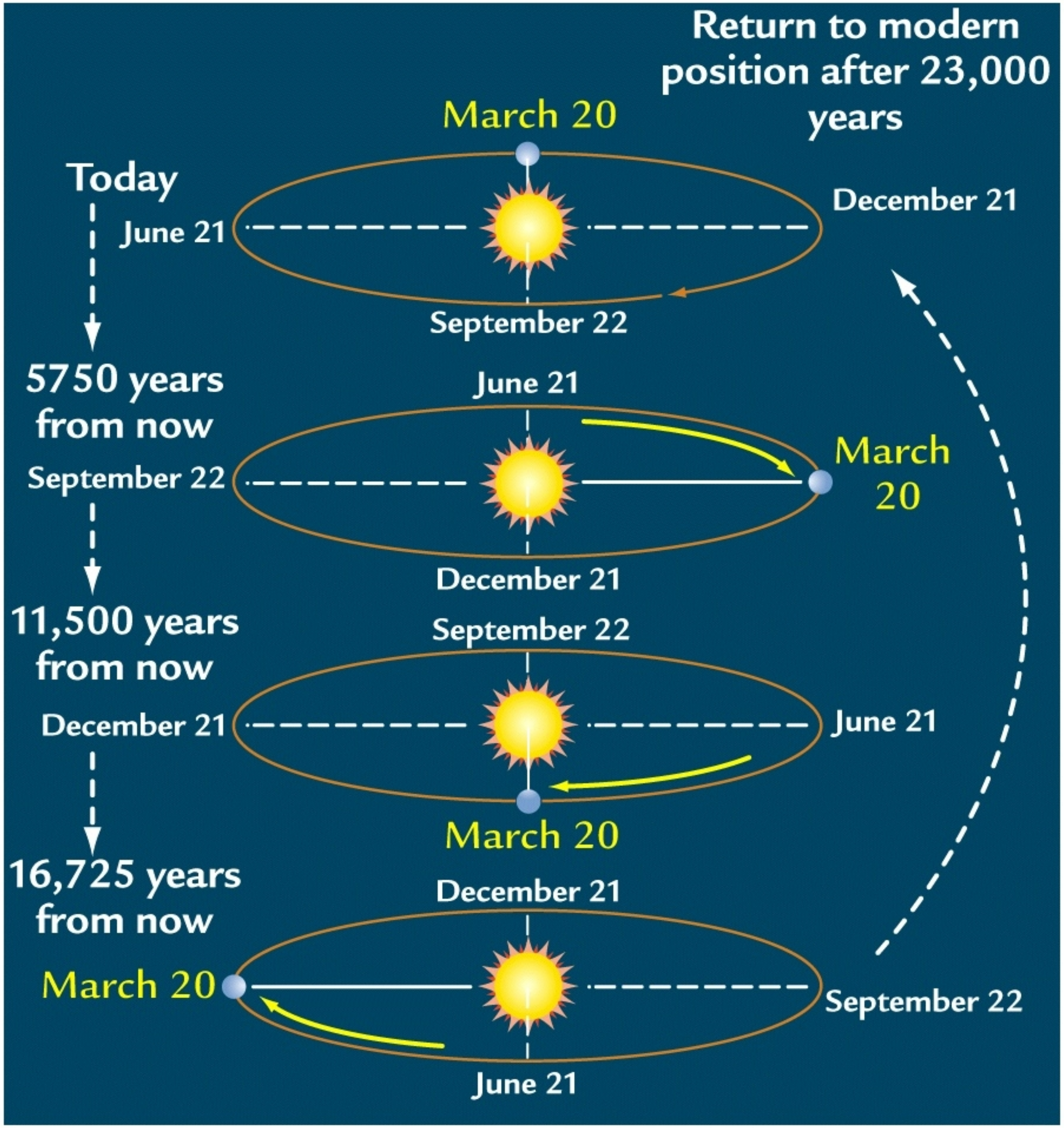


0.052 = 19 ky

0.043 = 23 ky

0.024 = 41 ky

Precession

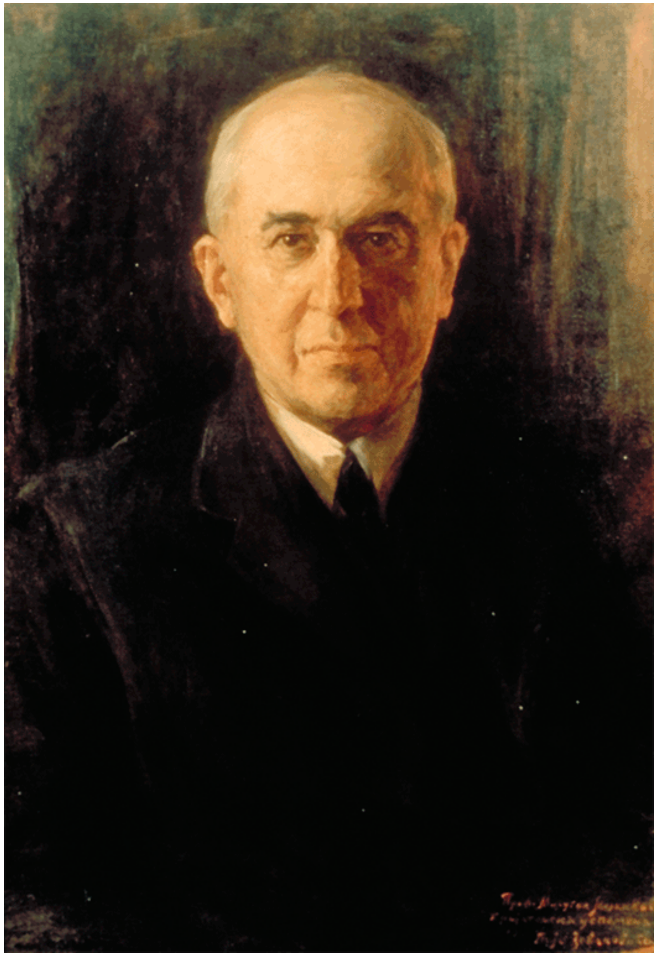


Return to modern position after 23,000 years
March 20
Today
June 21
December 21
September 22
5750 years from now
June 21
September 22
March 20
December 21
11,500 years from now
September 22
December 21
June 21
March 20
16,725 years from now
December 21
March 20
September 22
June 21

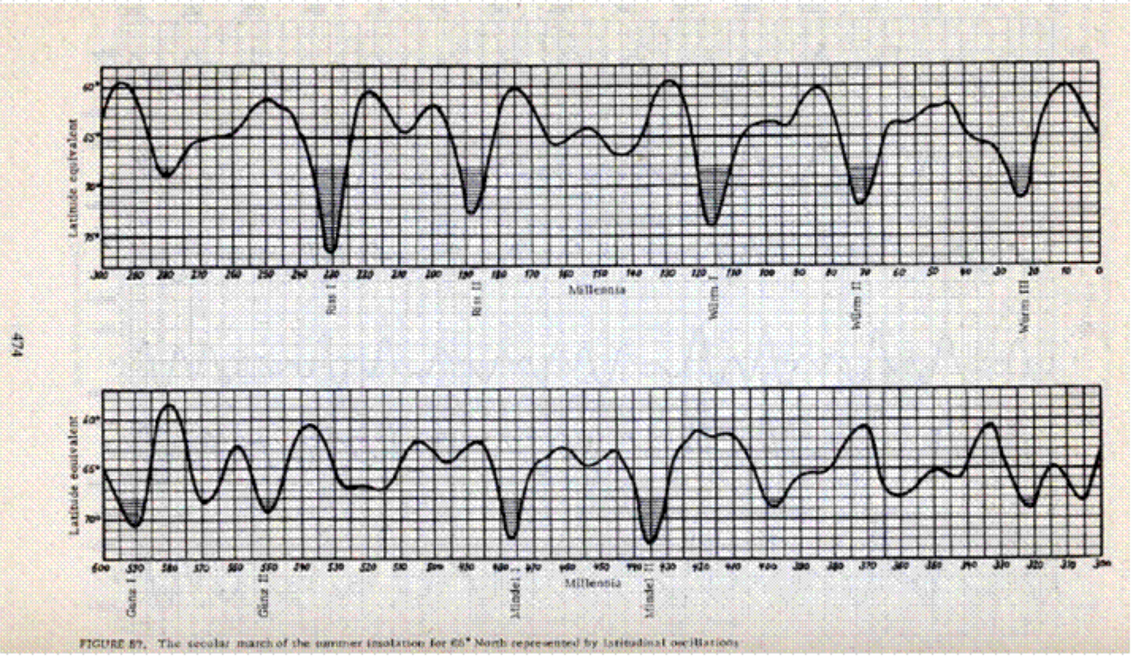
Reasons

- **Obliquity:** caused by the gravitational pull of large planets, including Jupiter. Earth's obliquity varies cyclically with a period of 41,000 years.
- **Eccentricity** of the orbit ~100,000 years due mostly to the gravitation perturbations due to Venus.
- **Precession** (~20,000) due to the **equatorial bulge of the Earth, caused by the centrifugal force of the Earth's rotation**. That rotation changes the Earth from a perfect sphere to a slightly flattened one, thicker across the equator. **The attraction of the Moon and Sun on the bulge is then the "nudge" which makes the Earth precess.**

Portrait of Milutin Milankovitch by Paja Jovanovic, 1943



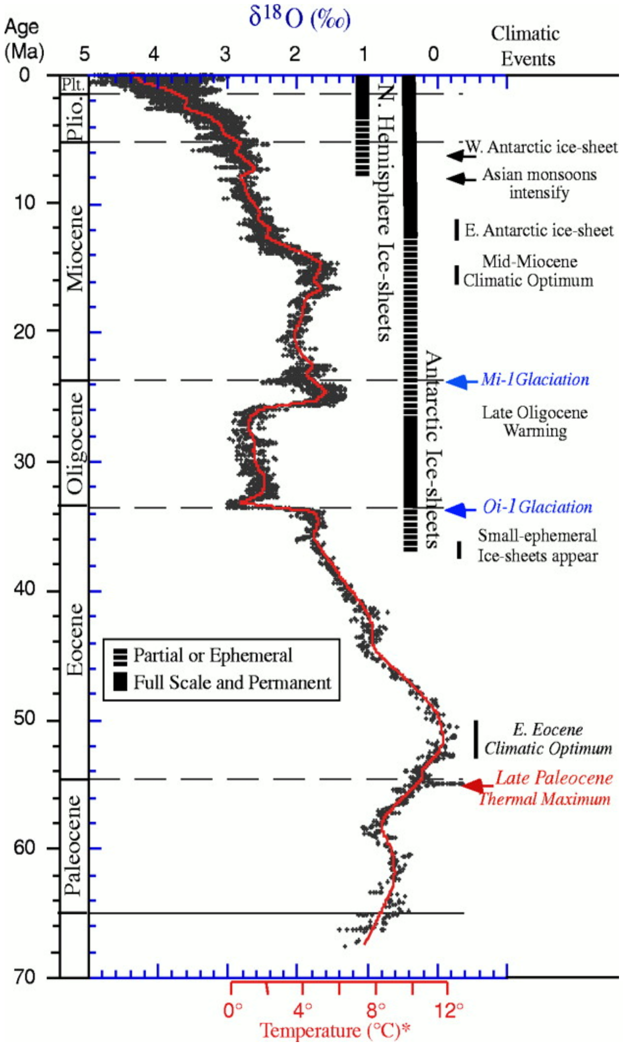
Milutin Milankovitch (1879 - 1958)



(Milankovitch, 1941)

- Glaciations correspond to summer insolation minima…

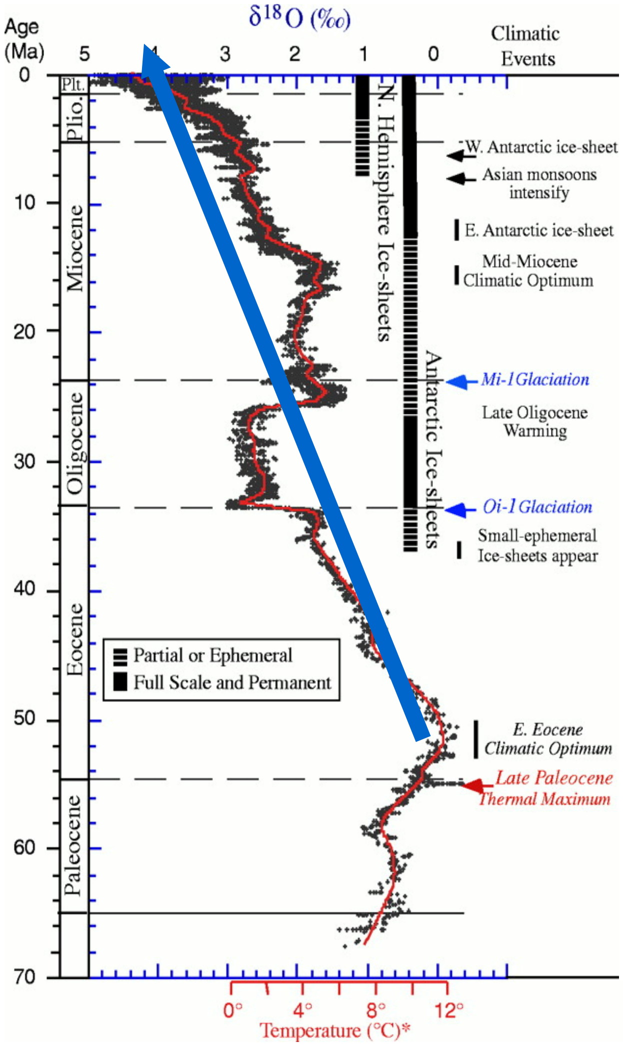
Transitions from Greenhouse to Icehouse Climate: Evidence from Marine Sediments



Global deep-sea O-18

(Zachos et al. 2001)

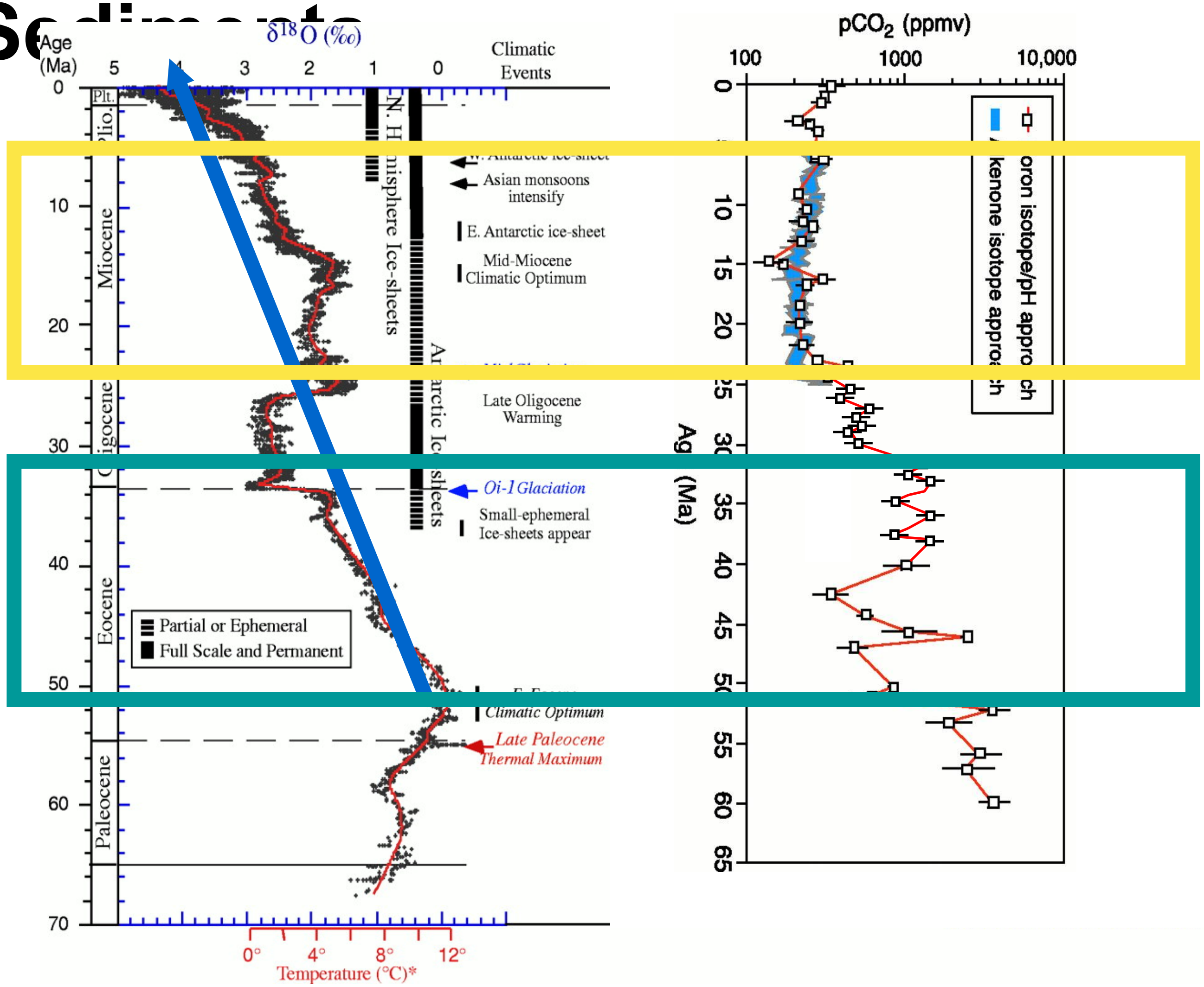
Transitions from Greenhouse to Icehouse Climate: Evidence from Marine Sediments



Global deep-sea O-18

(Zachos et al. 2001)

Transitions from the Greenhouse to the Icehouse Climate: Evidences from Marine Sediments



Global deep-sea O-18

(Zachos et al. 2001)

Proxy estimates of atmosph. pCO2

(Pearson & Palmer 2000; Pagani et al. 1999, 2005)

Miocene

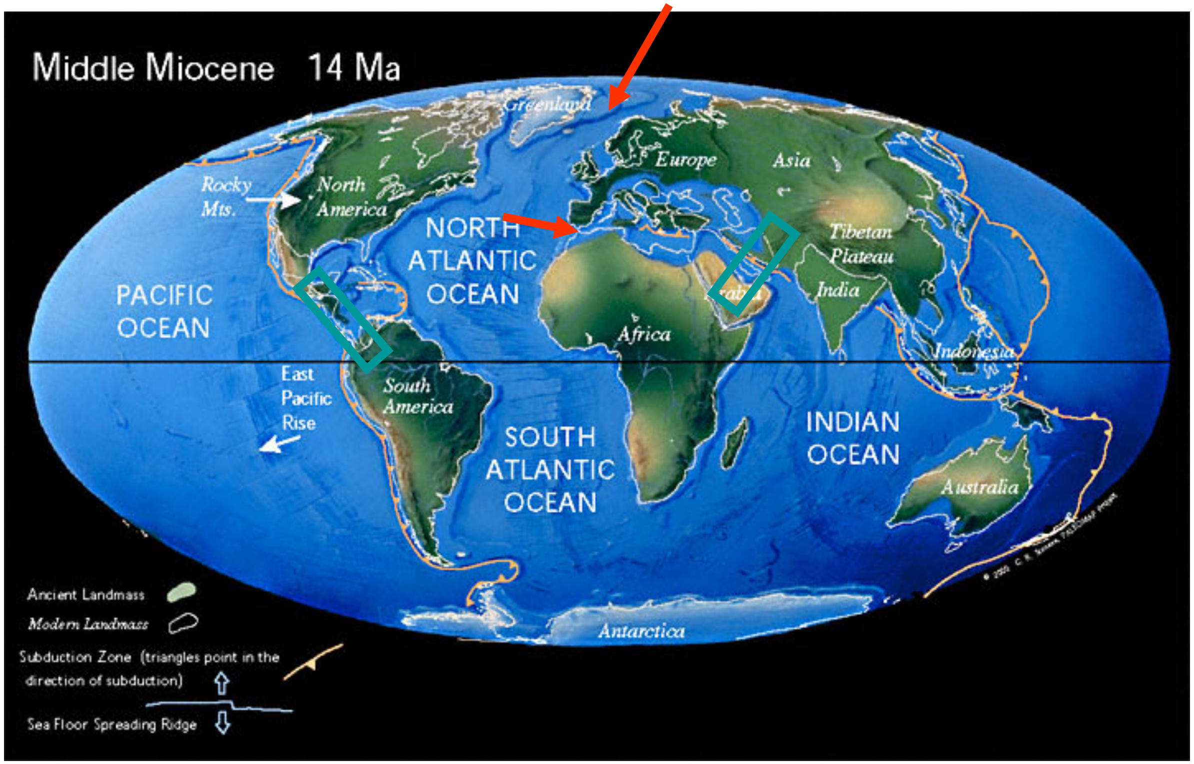
Temperature, ice volume independent on CO2 ?

Eocene/Oligocene

Paleogeography : The Mid-Miocene World

Similar to present day, <u>but</u>:

- Central American Isthmus open
- Tethys
- No deepwater connection North Atlantic & Arctic Ocean



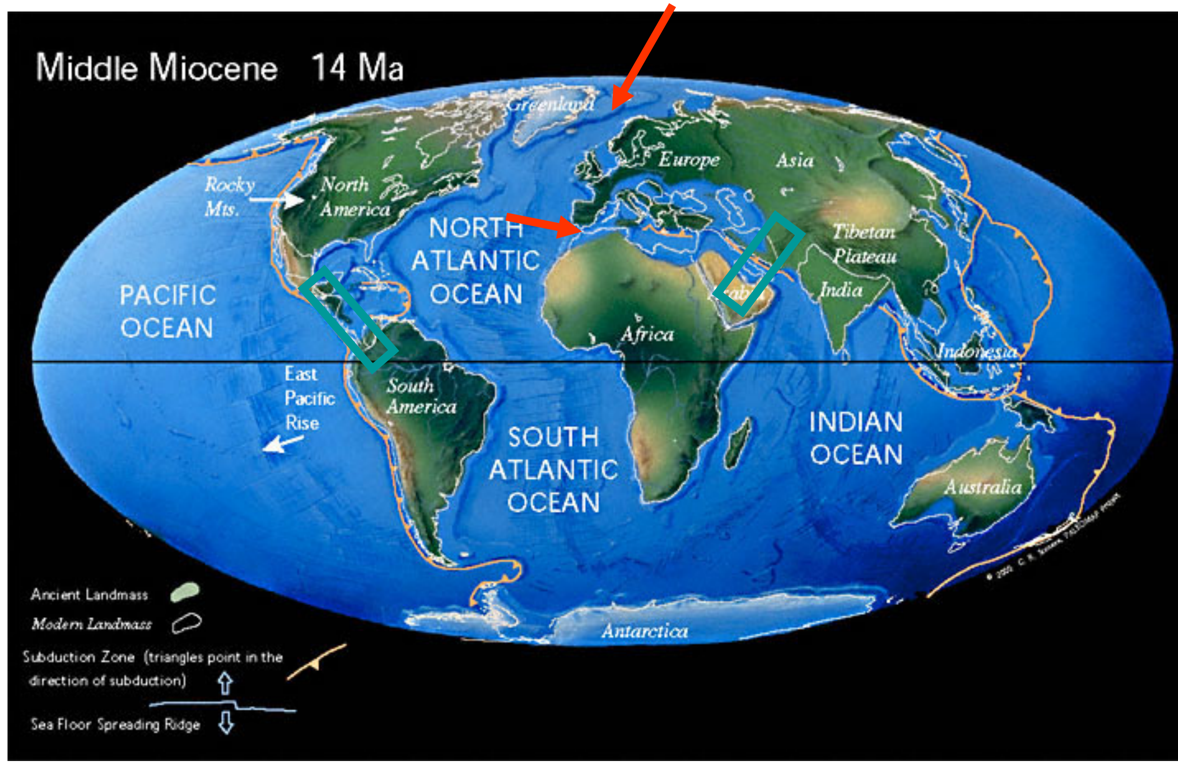
Scotese, paleomap project

Paleogeography : The Mid-Miocene World

Similar to present day, but:

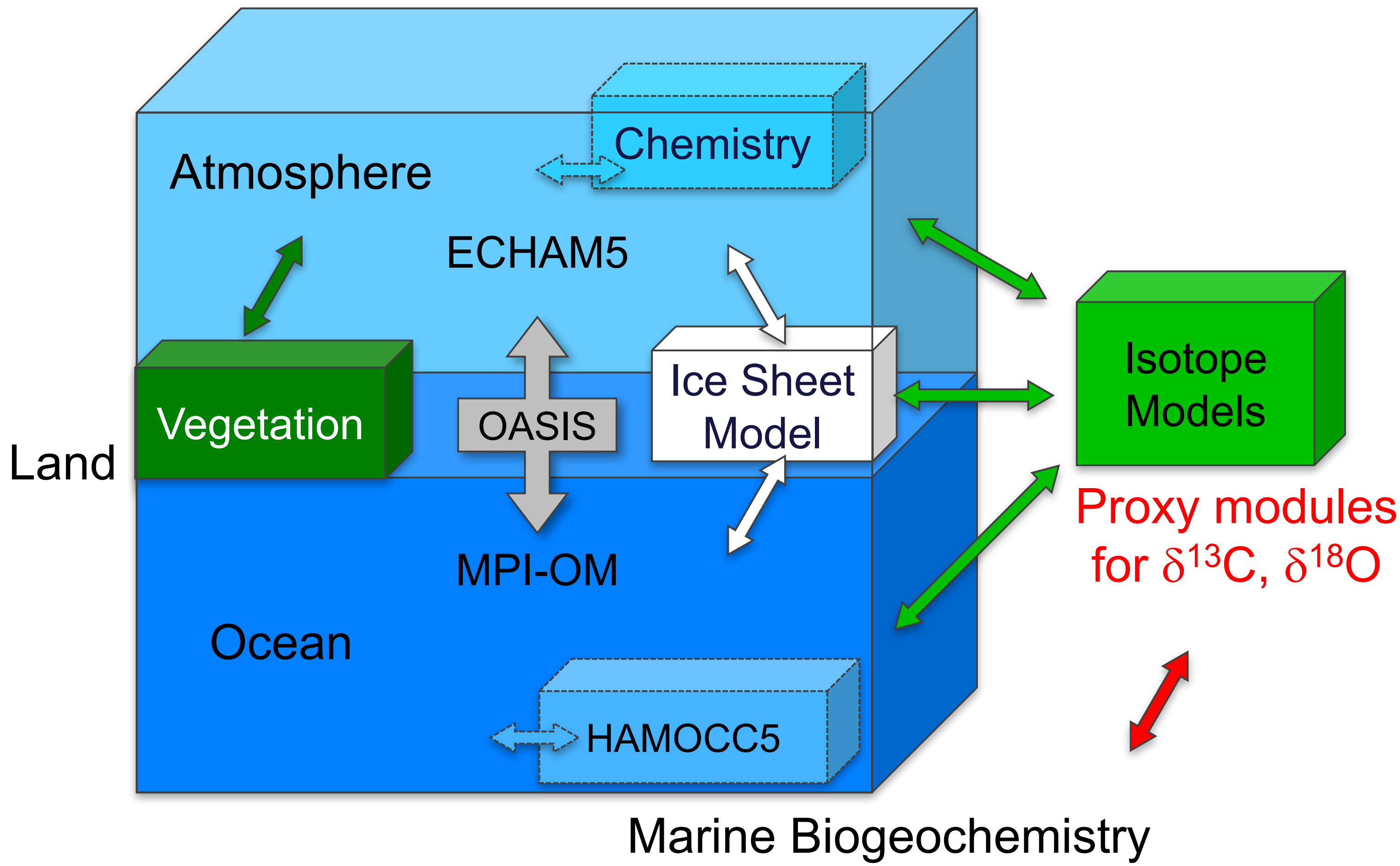
- Central American Isthmus open
- Tethys
- No deepwater connection
  North Atlantic & Arctic Ocean

- Mountain ranges are elevating
  (Andes, Alps, Tibet, etc.)
- Greenland without ice



Scotese, paleomap project

Earth System Models
New developments within COSMOS:



Paleoclimate Dynamics-identifying driving mechanisms of climate change

Gerrit Lohmann (AWI, Uni)

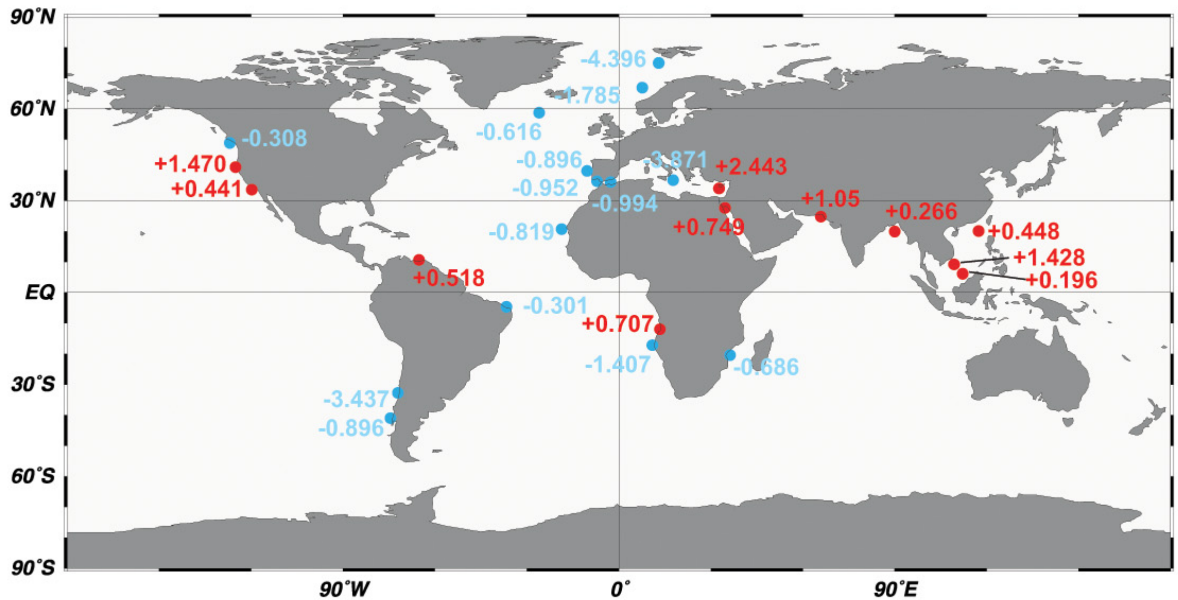
ESSReS course

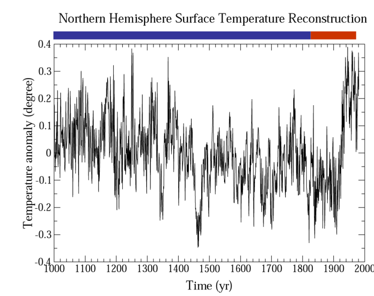
2 June 2010

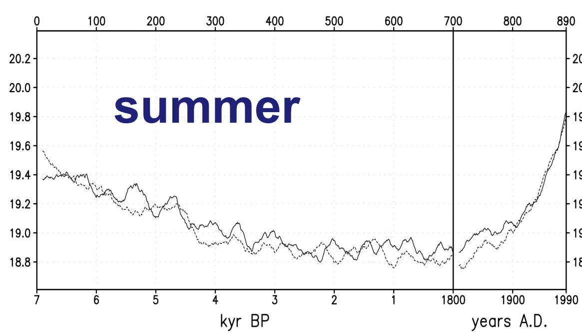
- **Broaden the view of the climate system**
- **Interpretation of past environmental changes**
- **Data and Modelling**
- **Climate variability: North Atlantic Oscillation**
- **Driving mechanisms**

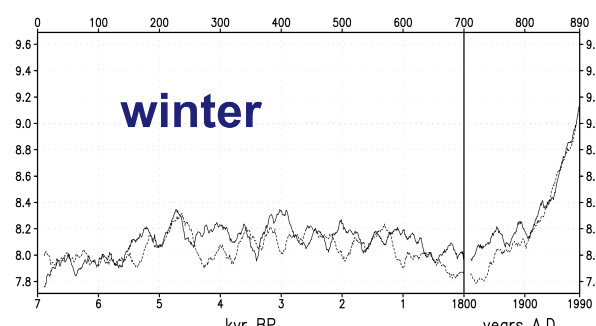
Climate Trends at different Timescales

Holocene: Temperature proxy for the last 7000 years

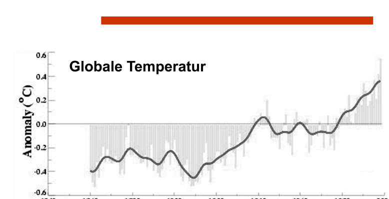




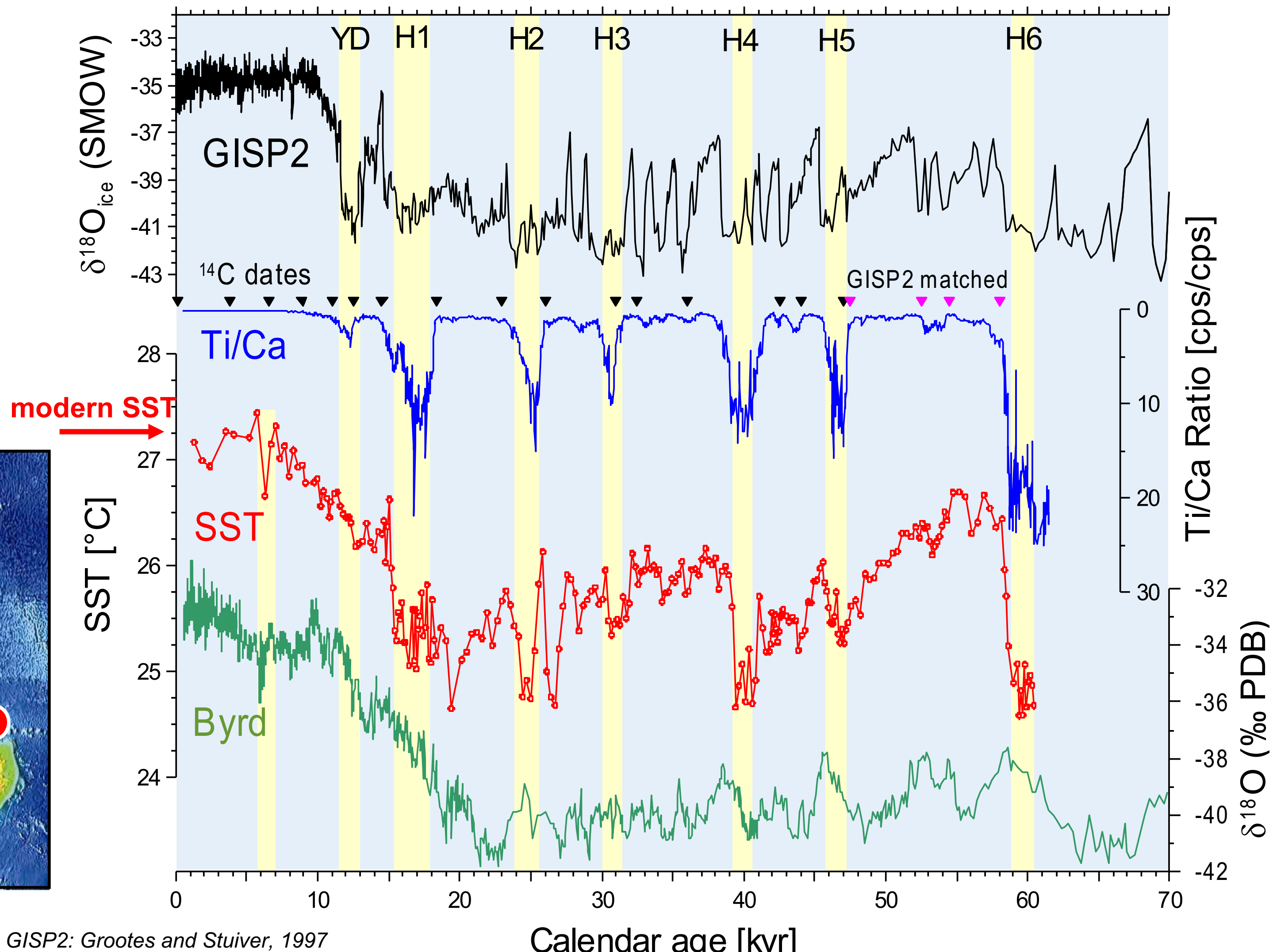




Lorenz & Lohmann 2004



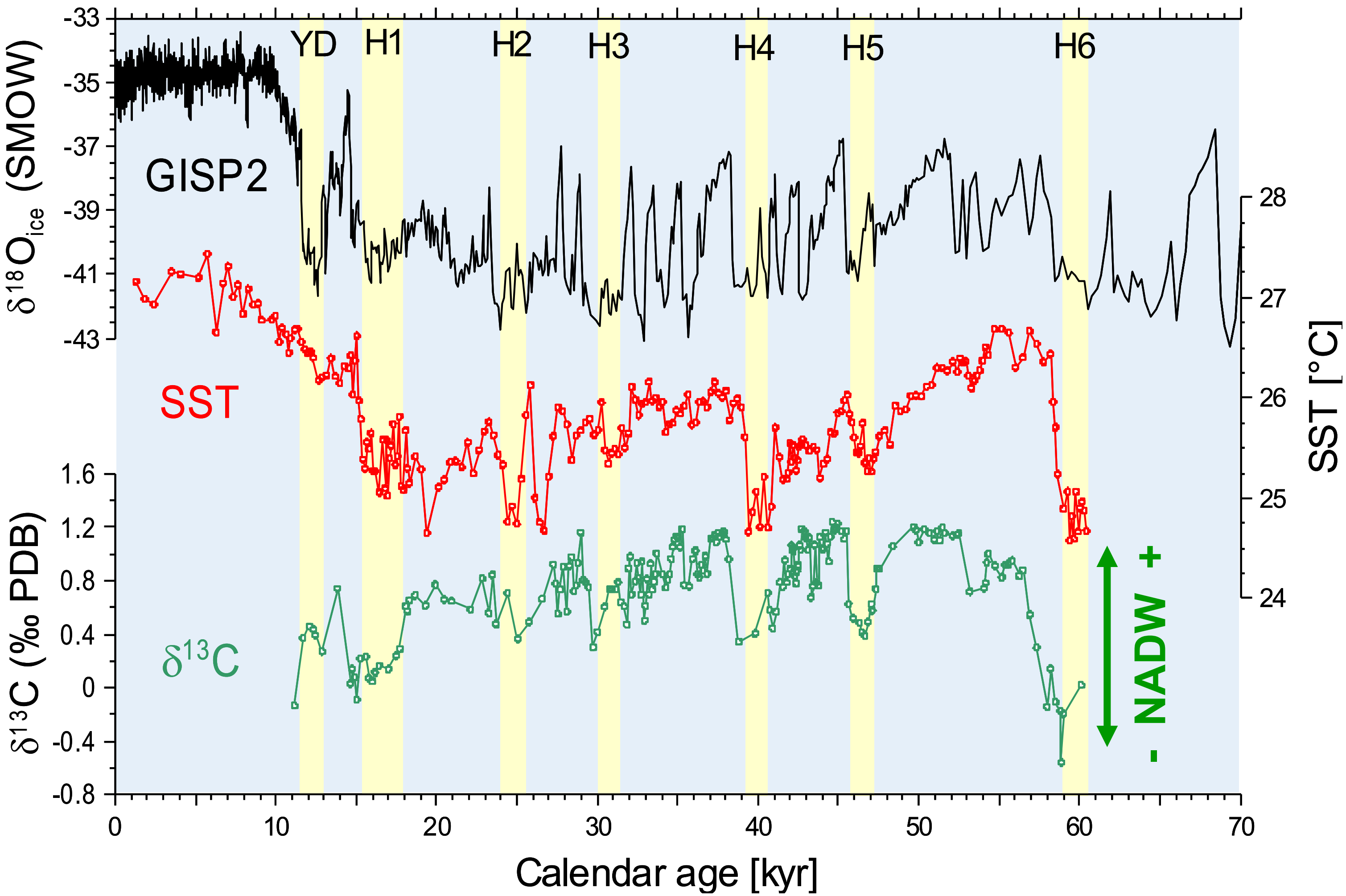
Surface temperatures & terrigenous input (Ti/Ca) recorded in GeoB 3910-2



GISP2: Grootes and Stuiver, 1997
Byrd: Johnsen et al., 1972

Jaeschke et al. 2007

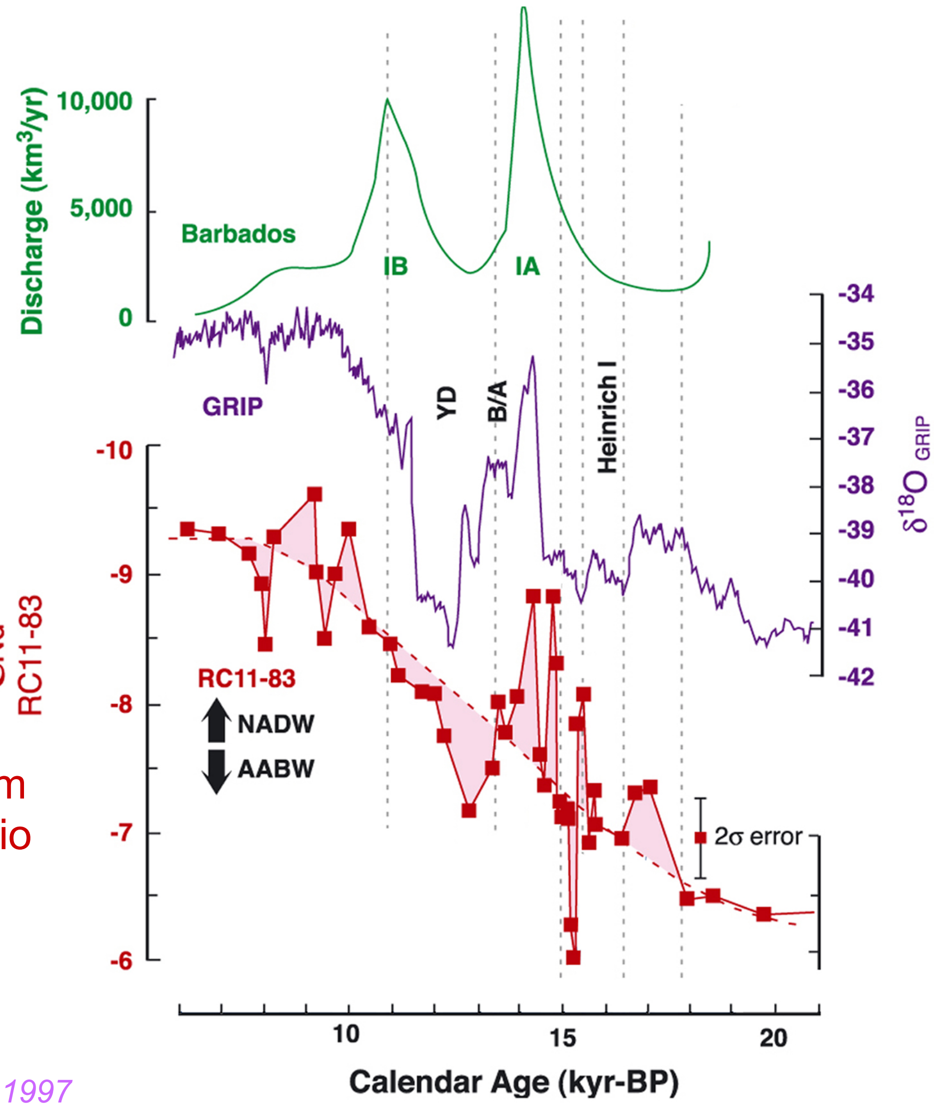
Surface temperatures and benthic $\delta^{13}C$ in GeoB 3910-2



GISP2: Grootes and Stuiver, 1997

Meltwater and Climate

weak glacial, strong interglacial THC



Neodymium isotope ratio

Fairbanks 1992,

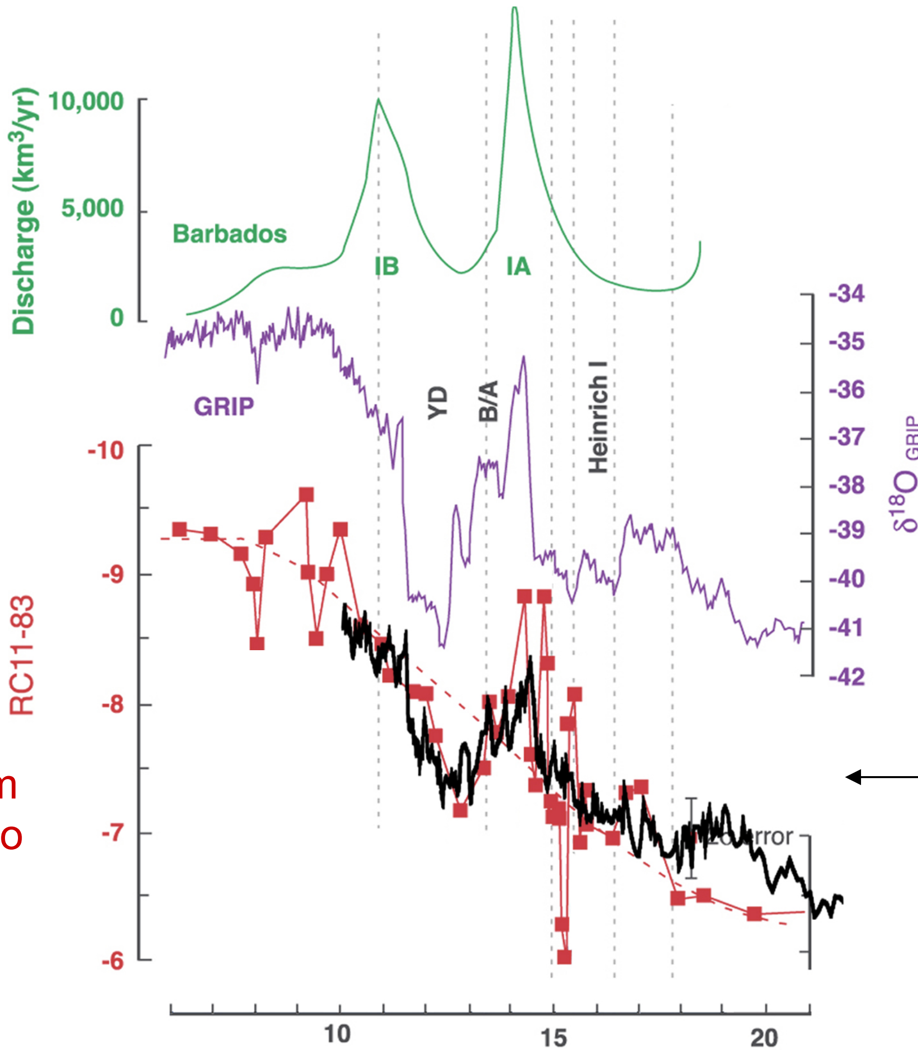
Grootes & Stuiver 1997

Piotrowski et al. 2004

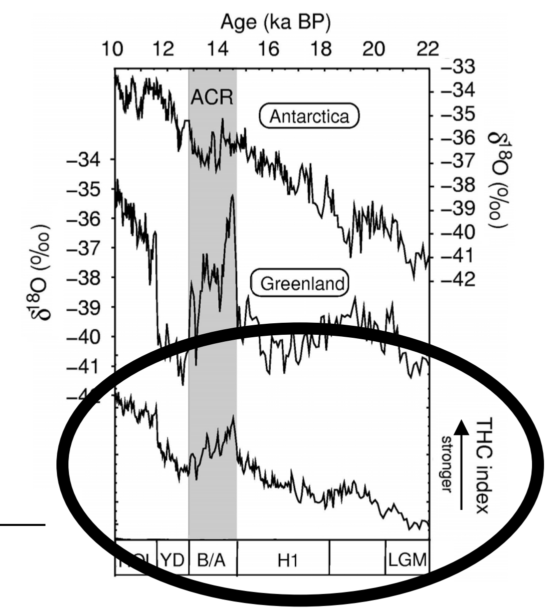
weak glacial THC:

C^{13} benthic forams
Cd/Ca
Nd isotopes
Pa/Th

Meltwater and Climate



Neodymium isotope ratio



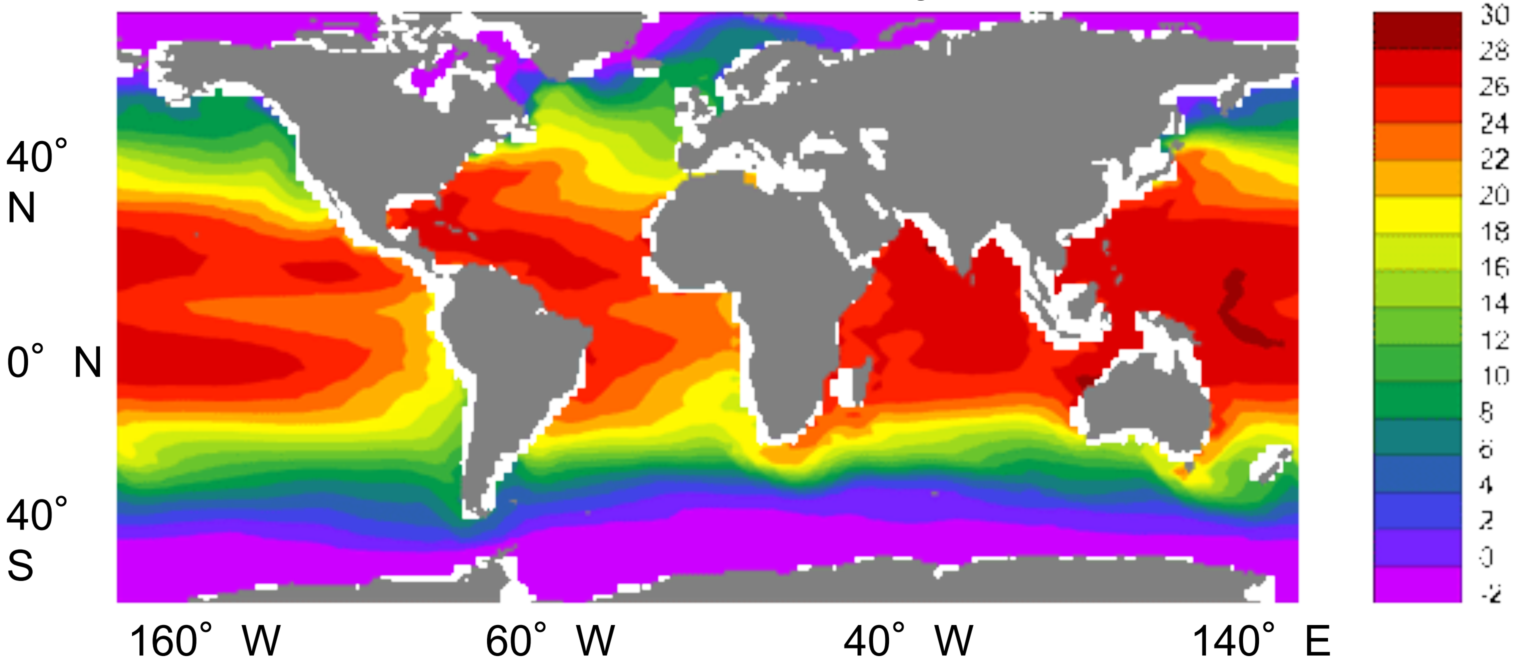
Interhemispheric temperature gradient ≈THC proxy

What causes the abrupt warming in the North?

Ocean Model LSG

- Dynamical equations for T, S, u, v, ^{14}C, …
- 3.5° horizontal resolution, 11 vertical levels
- Parameterization of overflow; ‘‘Quick‘‘ advection scheme
- Background climate: ECHAM3/ T42 for present-day and glacial conditions
- Coupling: air temperature, hydrological cycle and wind; EBM

modeled SST for present-day climate



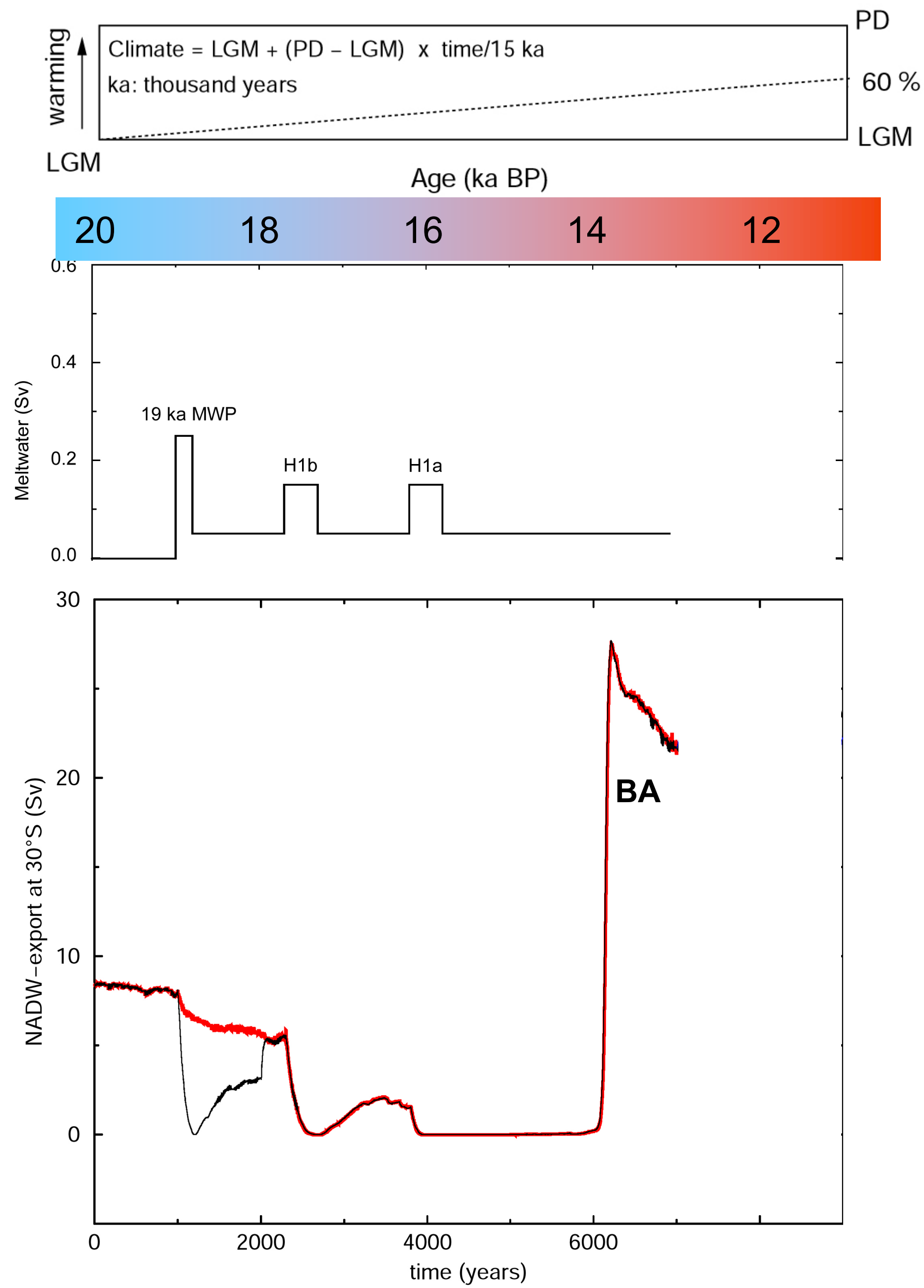
JGR 2000
JPO 2003

Global deglacial warming

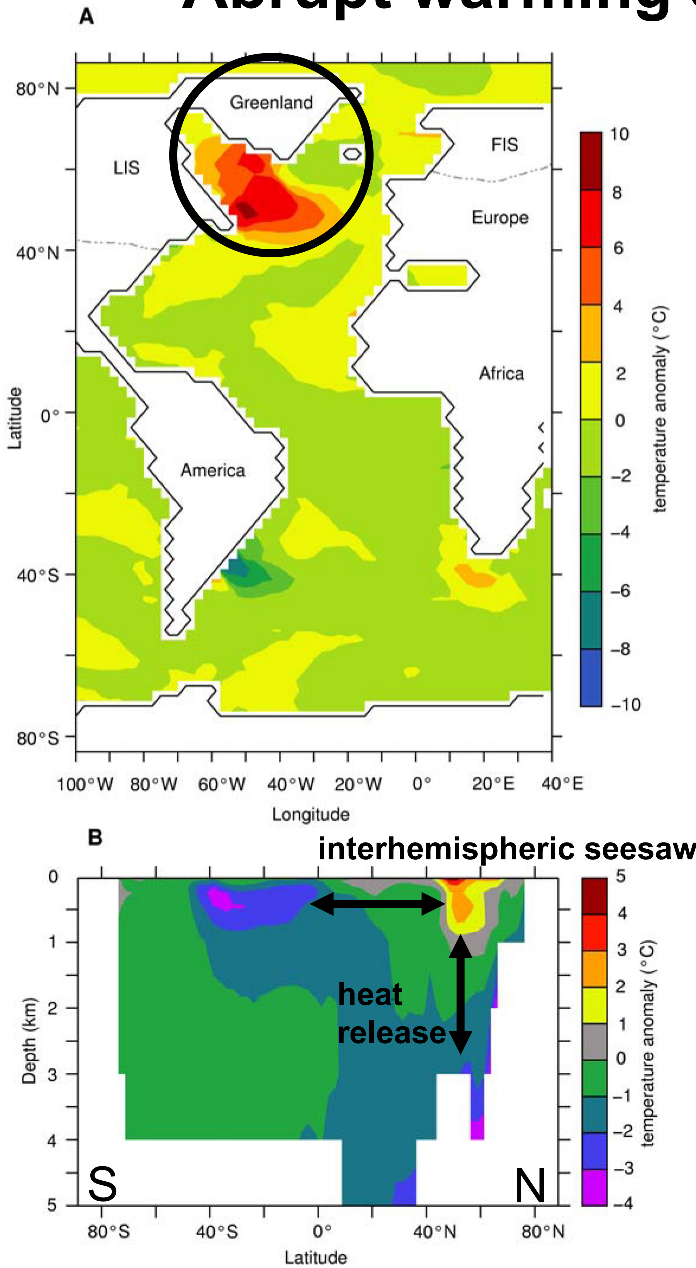
Thermal forcing

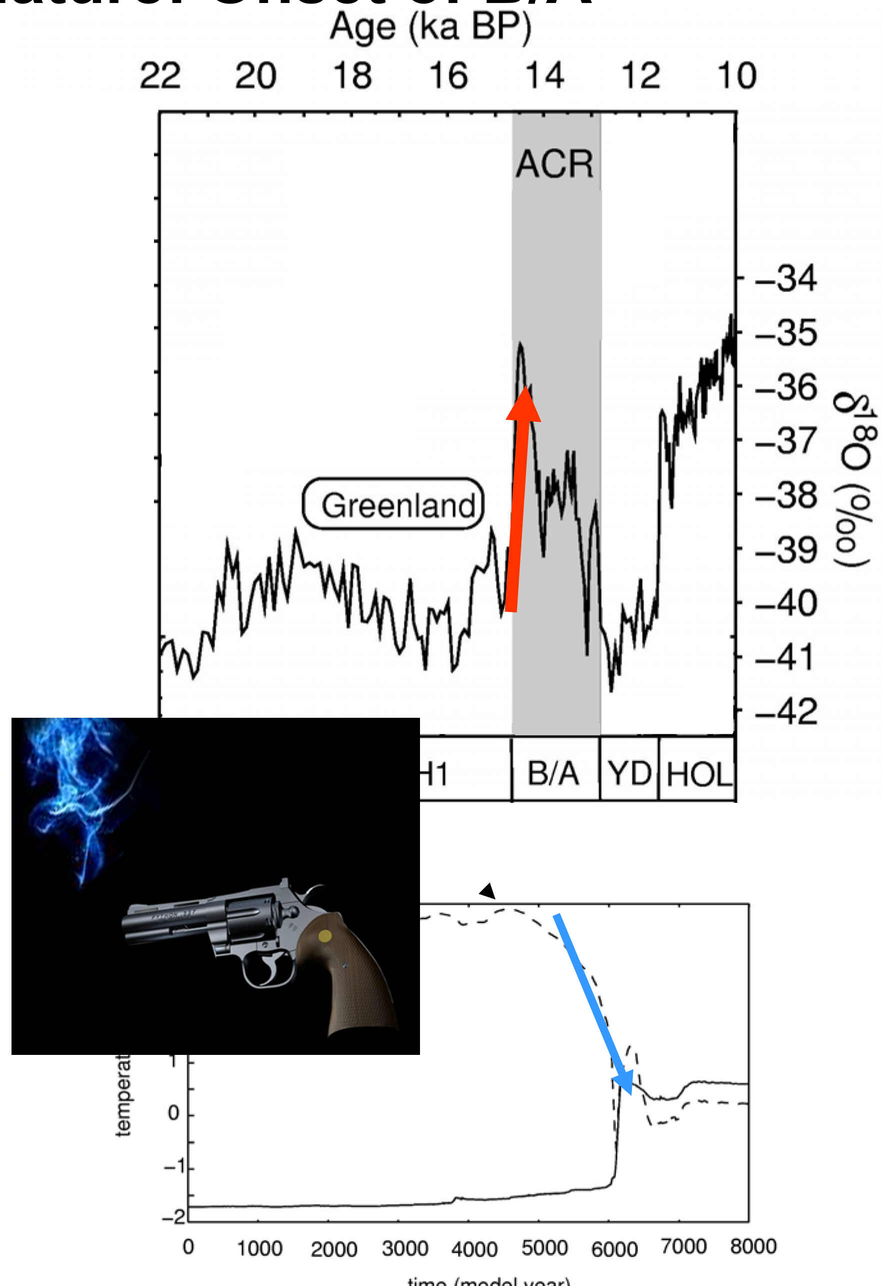
Freshwater forcing

simulated climate



Abrupt warming signature: Onset of B/A





Key elements of James Croll's Astronomical Theory Ice Ages

1. Earth's climate was influenced by changes in its orbit around the sun
2. Croll focused on changes in precession and eccentricity.
3. He was aware of changes in the Earth's tilt but had no means of quantifying it.
4. He hypothesized that ice sheets would grow during severe winters resulting from the interacting effects of precession and eccentricity.
5. To explain how very small changes in eccentricity could influence climate he formulated the concept of a **"climatic feedback"**, specifically the **Ice-Albedo Feedback**.

Key elements of Milankovitch's Astronomical Theory Ice Ages

1. Quantified variations in the Earth's obliquity, precession and eccentricity.
2. Determined the seasonal and latitudinal distribution of solar radiation (insolation) on Earth.
3. Argued that obliquity, followed by precession forcing, should dominate the climate response, with less influence due to eccentricity.
4. Argued that summer insolation at mid-latitudes rather than winter insolation was the critical forcing for ice sheet growth.

Despite these considerable advances, Milankovitch's theory was not widely accepted in his day. It's major limitation was the lack of a well dated, continuous climate curve to test the hypothesis.

The modern rebirth of the Milankovitch Hypothesis required several advances

1. Continuous sedimentary sequences
2. A reliable means of extracting continuous climate information from these sediments
3. Improved dating methods (chronology)
4. Quantitative analysis methods