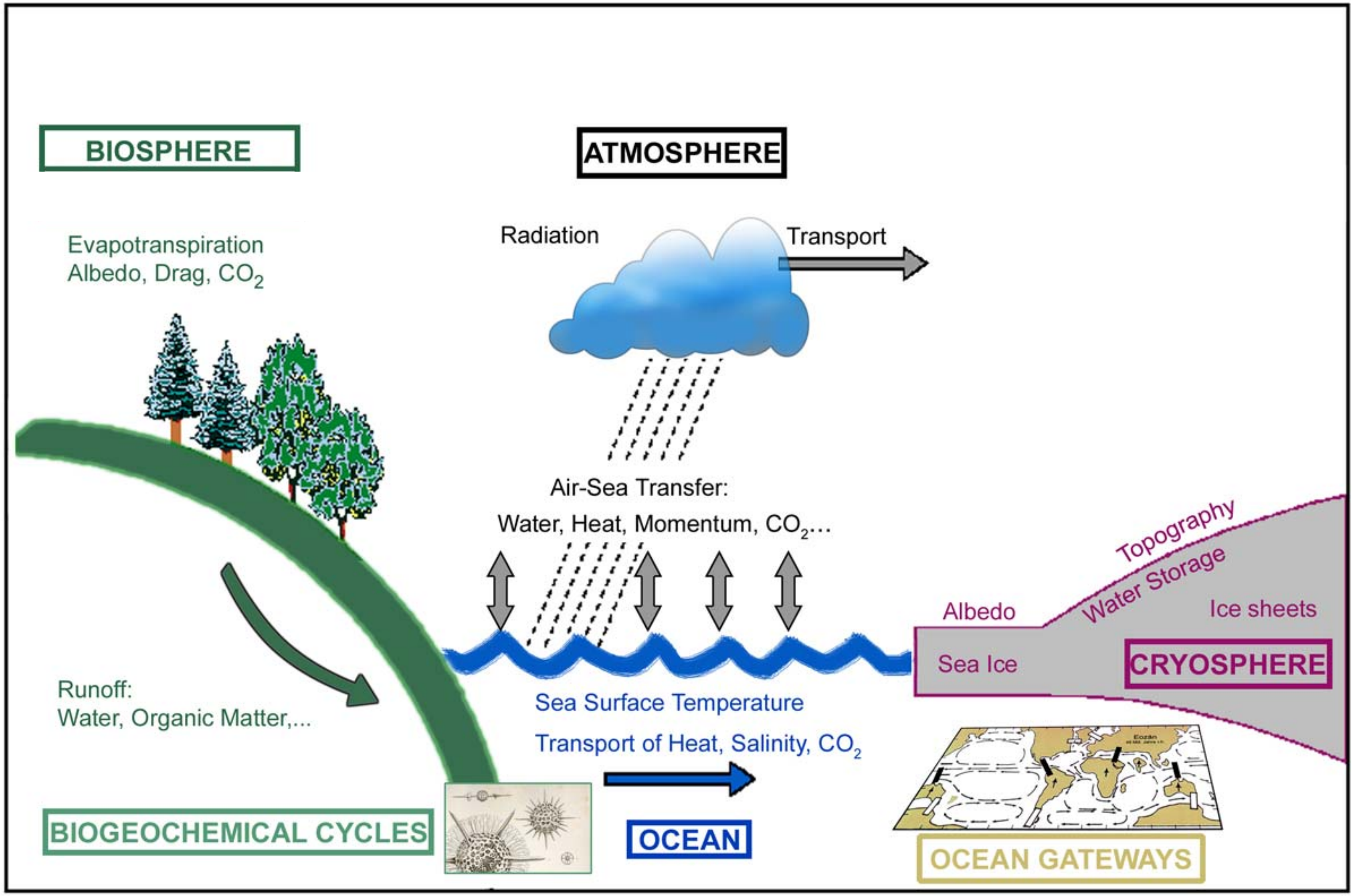
Earth System Science Research School

Paleoclimate Dynamics

AWI
Universität Bremen
JACOBS UNIVERSITY

High complexity → multi-disciplinary approach

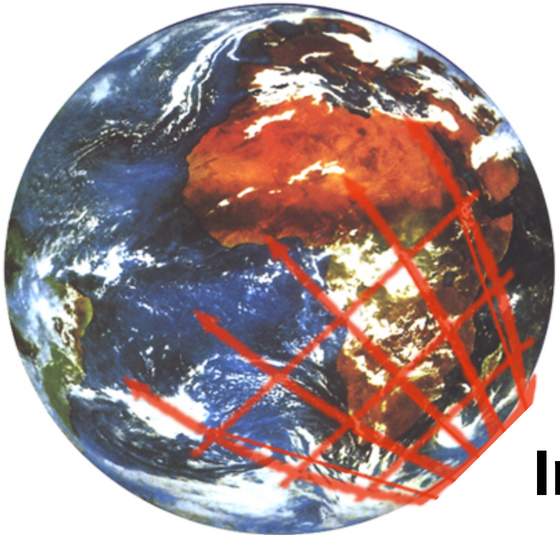


Modified after Hasselmann

Bridging the gap between disciplines

Data exploration

& analysis



Processes

Lab experiments

Interpretation

Models

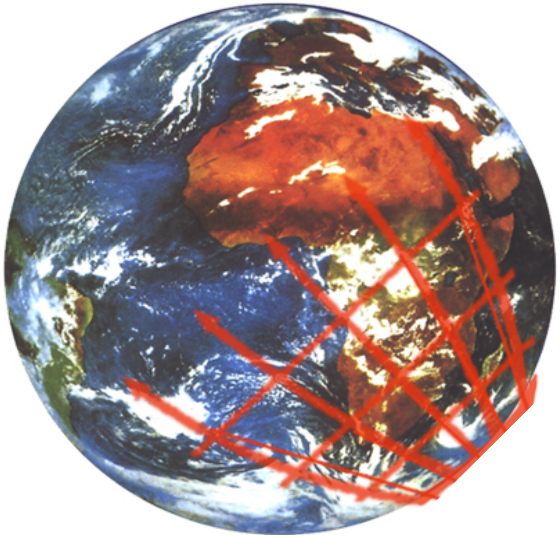
Bridging the gap between disciplines

Data exploration

& analysis

Examples:

Carbon cycle
Proxies
Modelling



Processes

Lab experiments

Interpretation

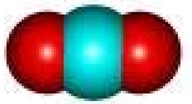
Models

Example: Carbon Cycle

Satellites
Data Analysis

Transport Models

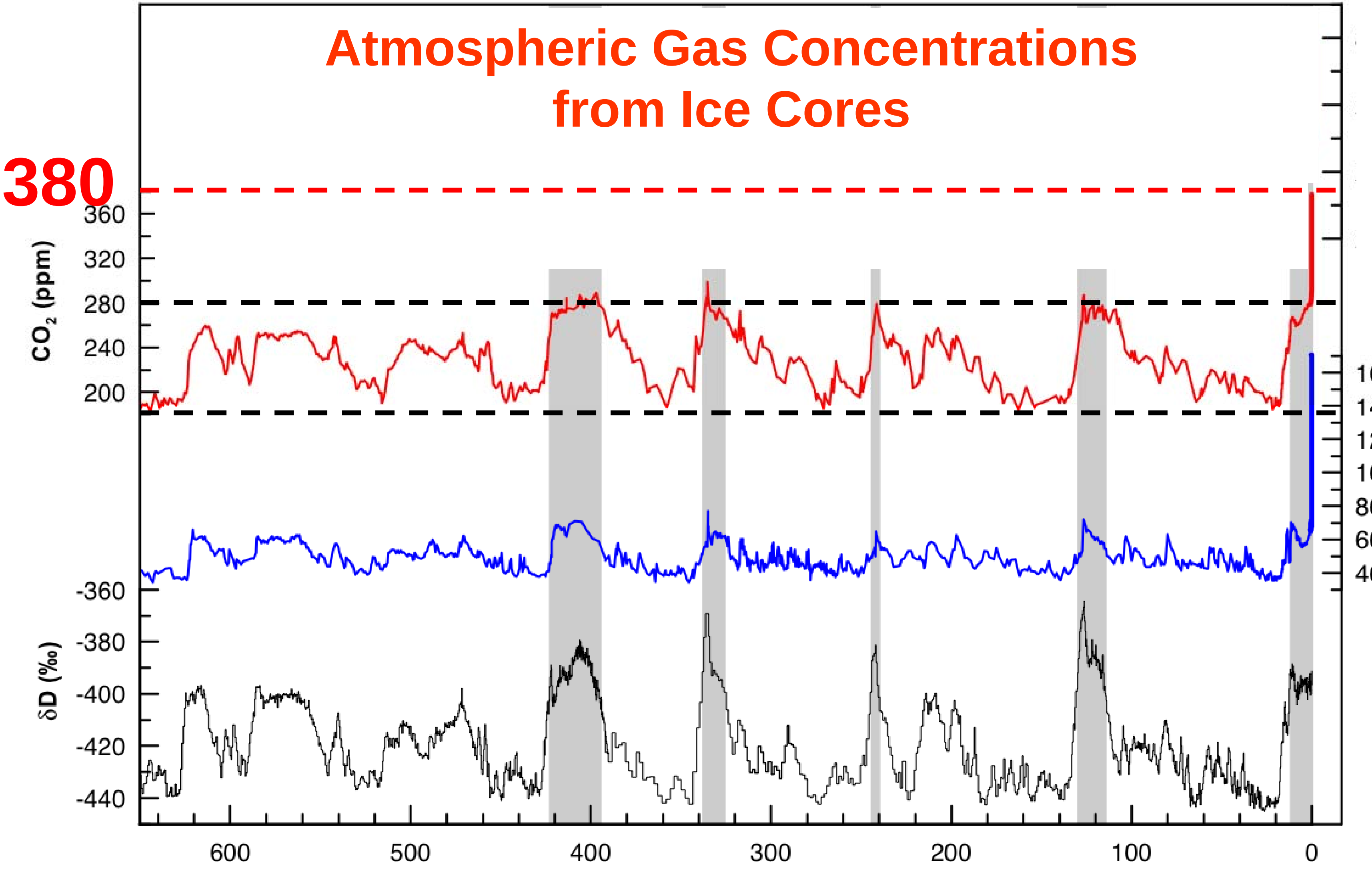
Carbon: sources & sinks



Measurements
Lab Work

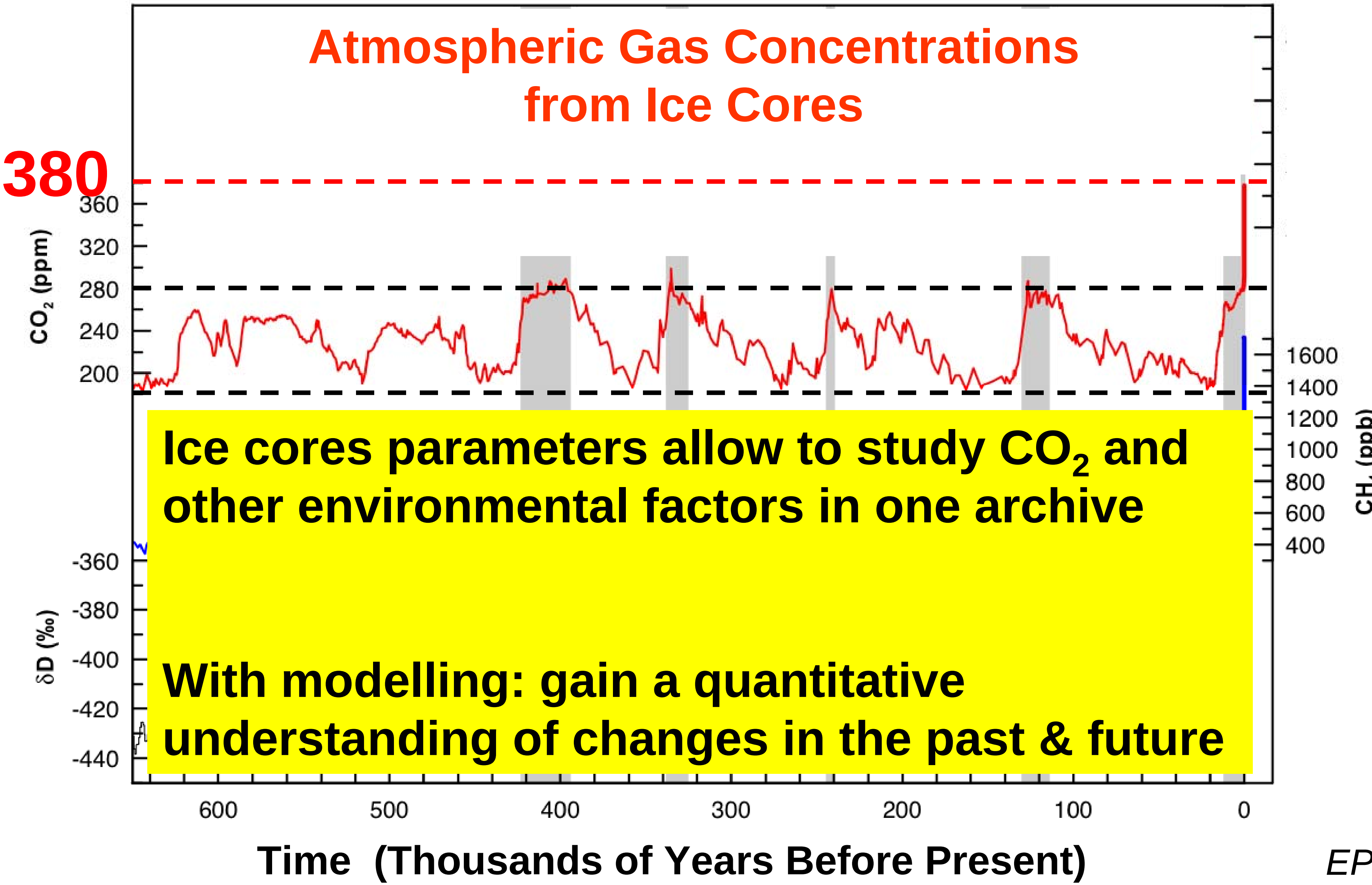
Ground-based Observations

Carbon cycle: long time scales



EPICA

Carbon cycle: long time scales

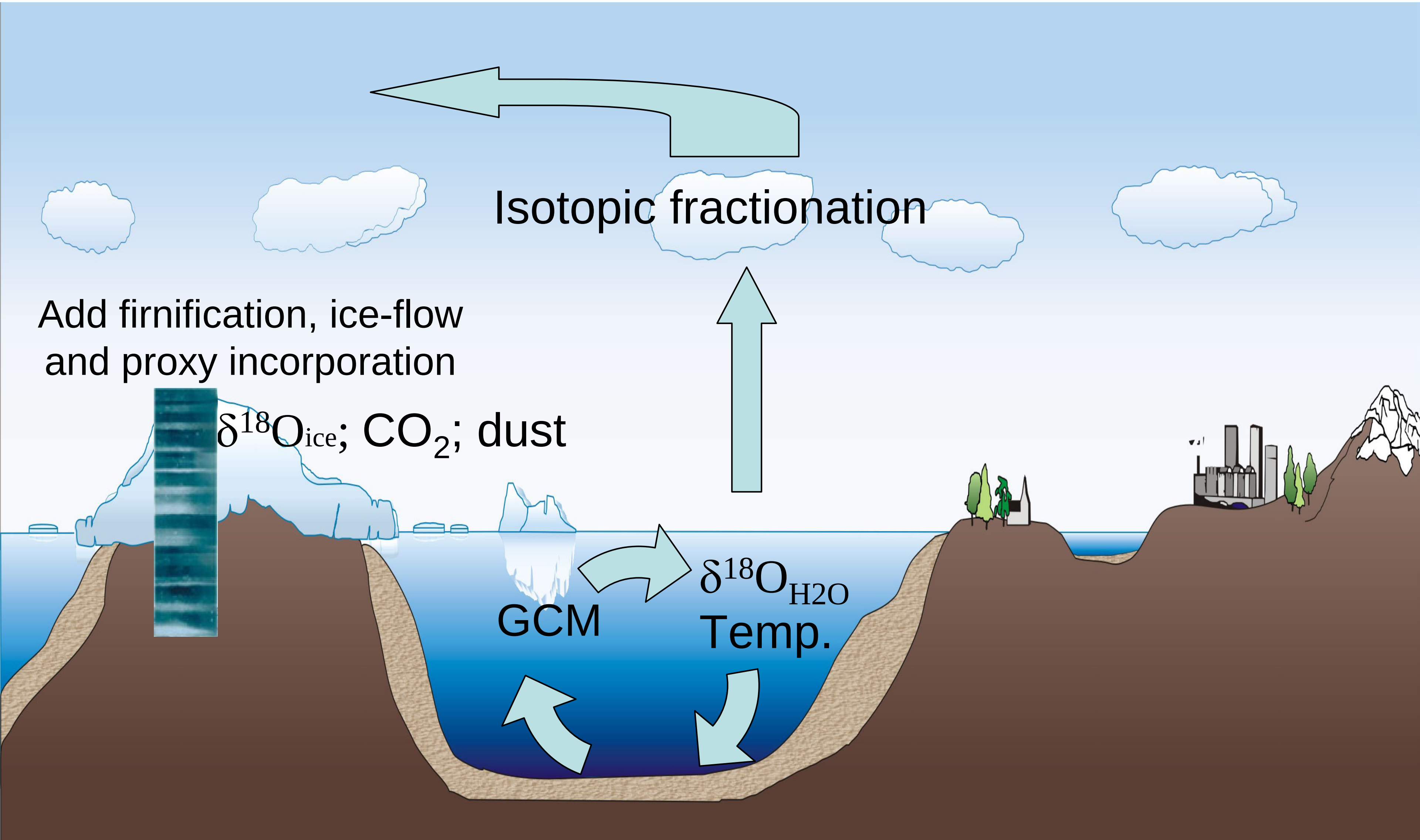


Ice cores parameters allow to study CO_2 and other environmental factors in one archive

With modelling: gain a quantitative understanding of changes in the past & future

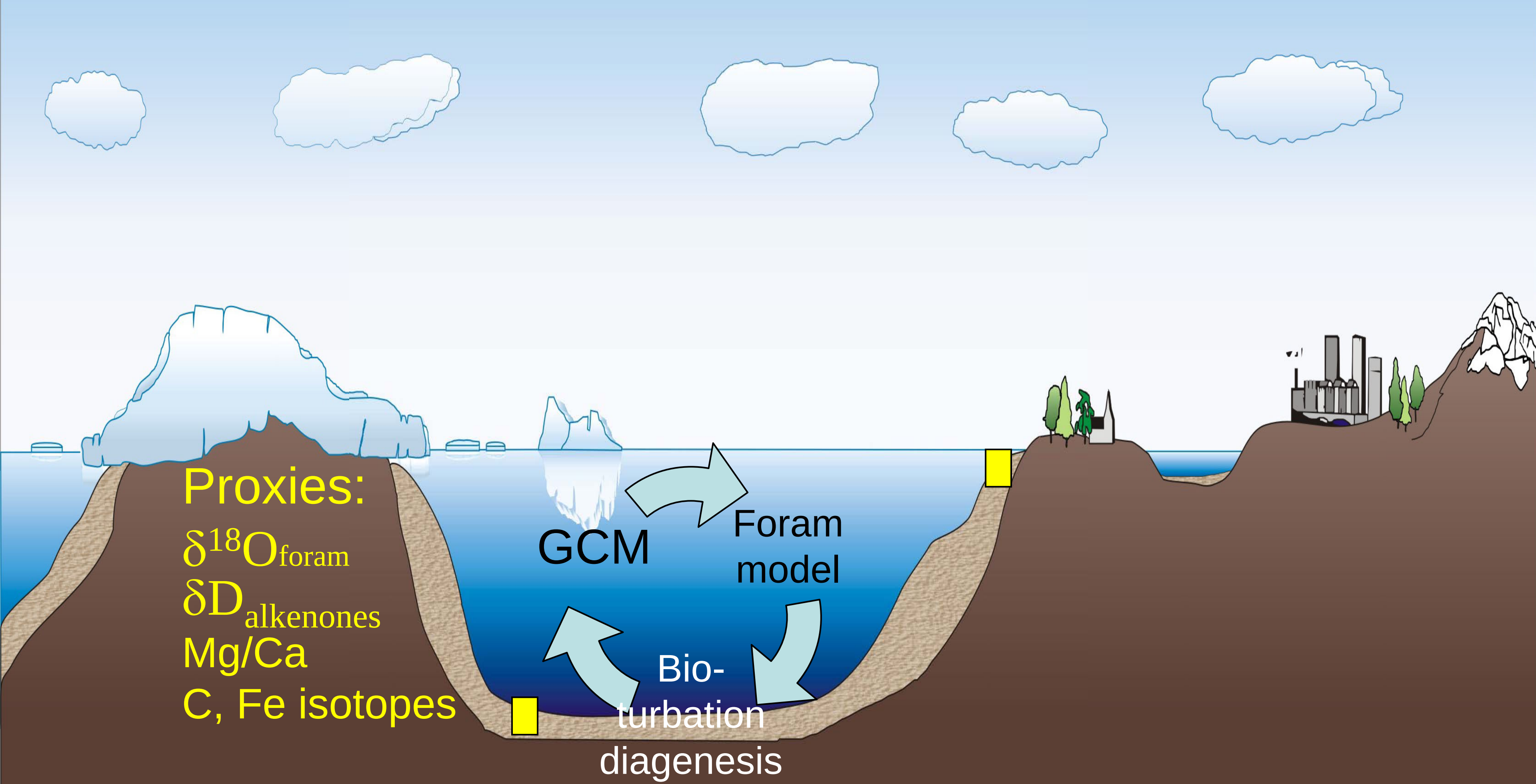
EPICA

Climate Archives & Modelling: Ice Cores

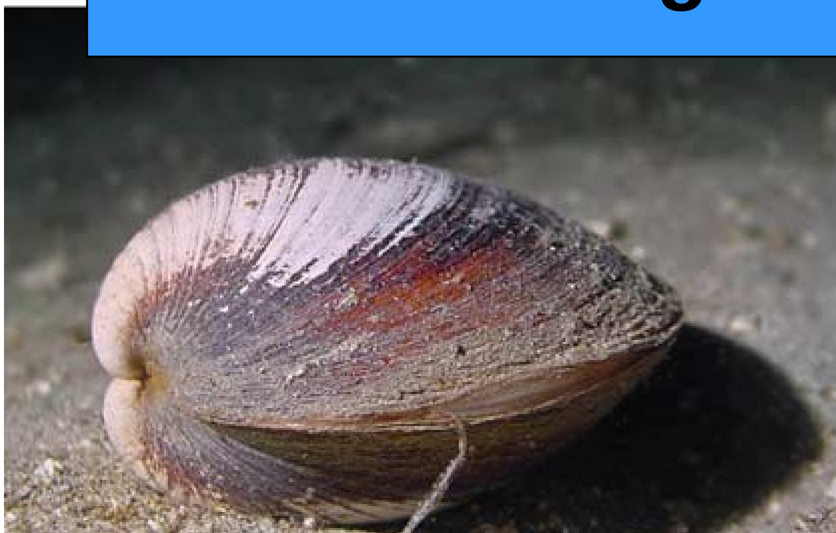


Marine Proxies

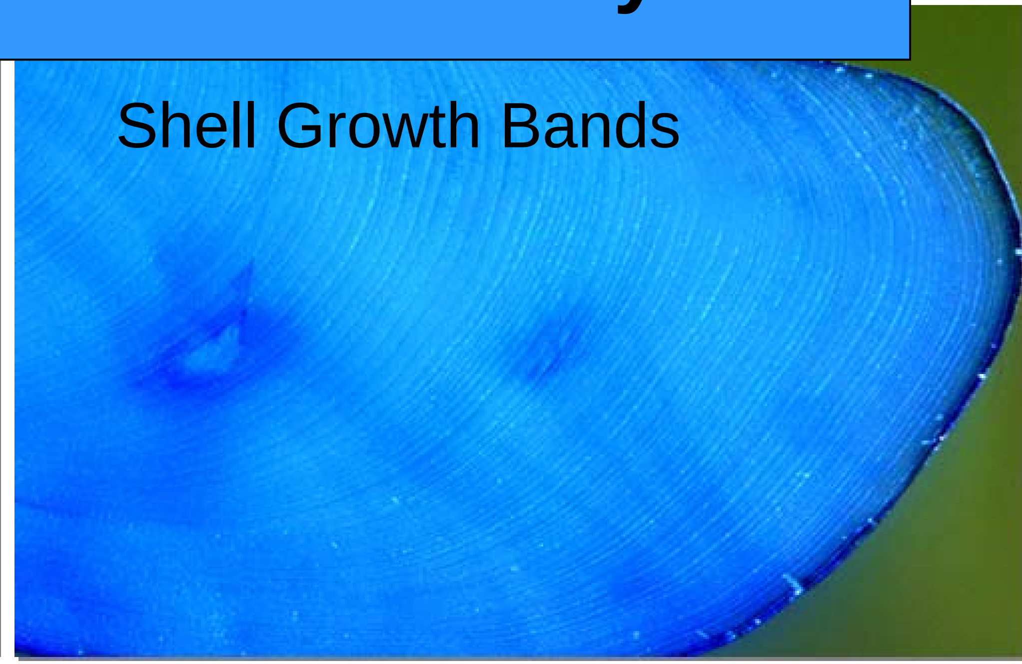
Compare simulations with real cores

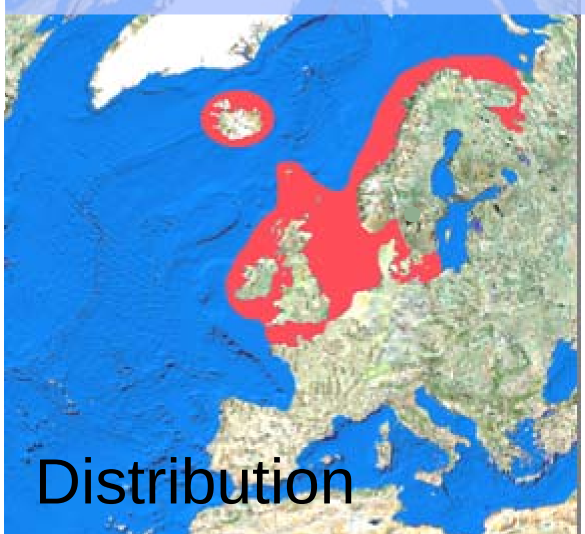


Climate change over the last 100 years

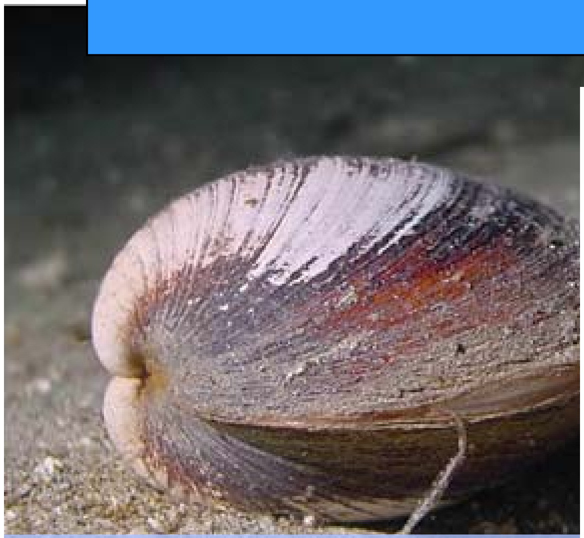


Bivalve Bioarchive
Arctica islandica



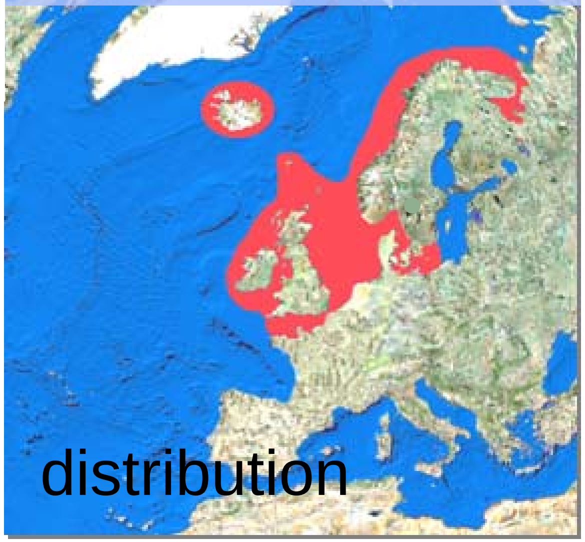


Climate change over the last 100 years

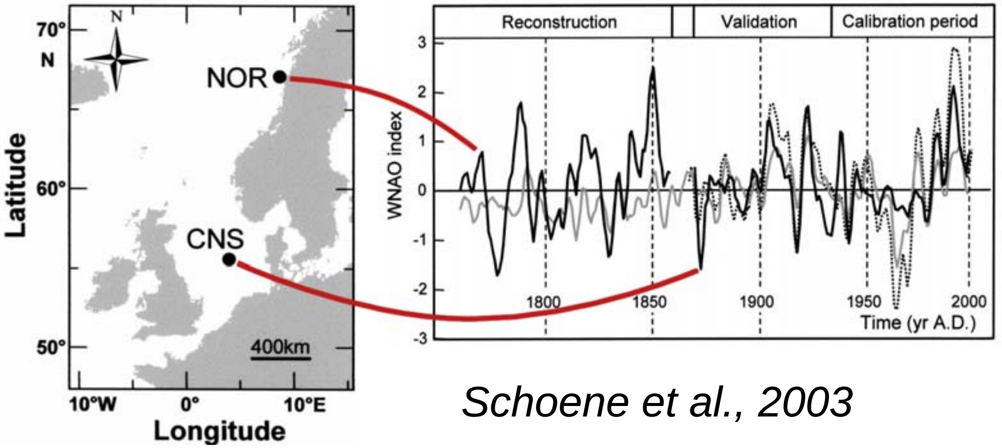


Bivalve Bioarchive

Arctica islandica

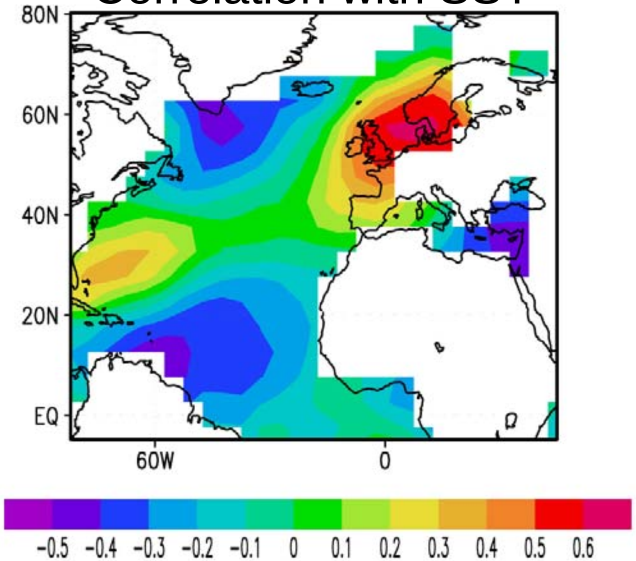


distribution



Schoene et al., 2003

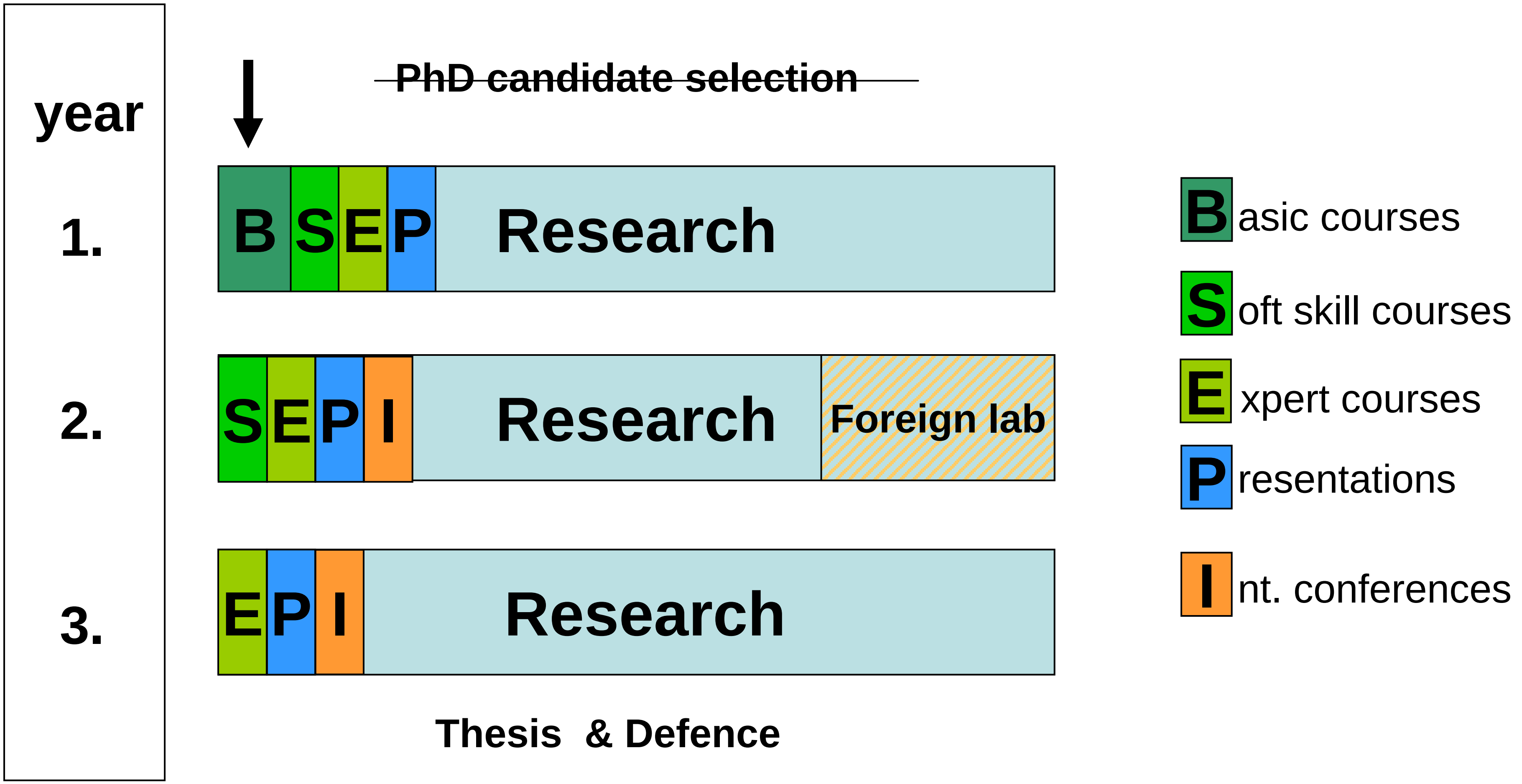
Correlation with SST



NAO-Signature

Lohmann et al., 2006

Study Programme

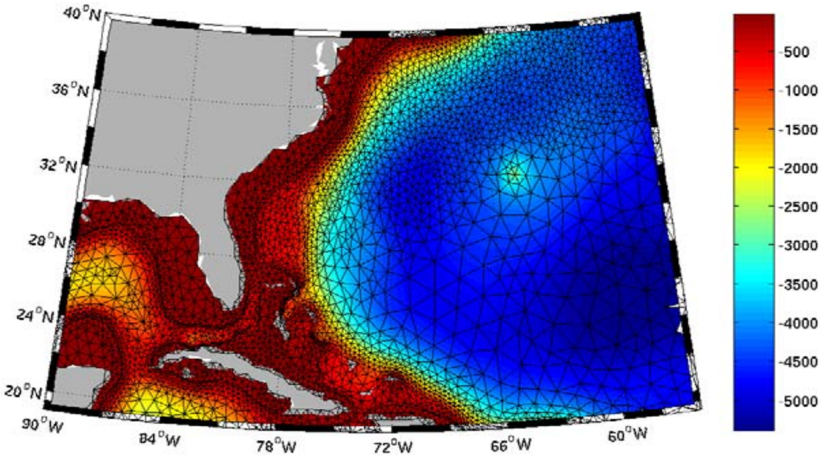


Self-organised units:

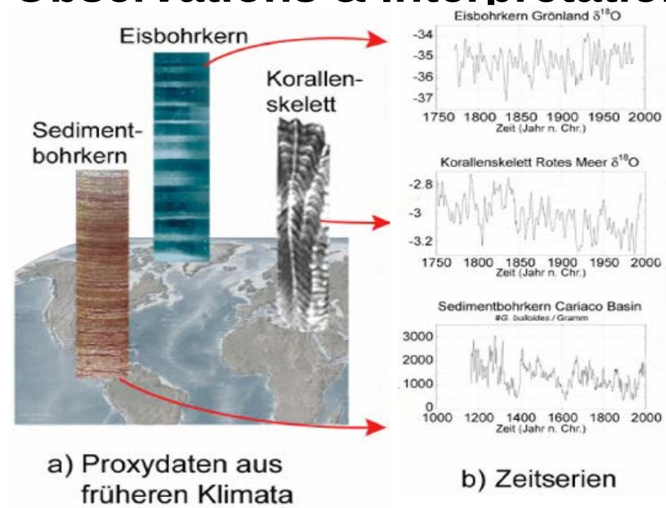
- **literature seminars**
- **students teach students**

What shall you learn?

Complex Models



Observations & Interpretation



Data Analyses Tools

Measurement Techniques

Collaborating Institutes

www.awi.de

Paleoclimate Dynamics (G. Lohmann, K. Grosfeld)
Ocean Dynamics (S. Danilov)
Glaciology (S. Kipfstuhl, H. Fischer)
Geophysics (K. Gohl, G. Uenzelmann-Neben)
Marine Geology (R. Tiedemann, R. Schlitzer)
Sea Ice Physics (Chr. Haas, P. Lemke)
Geo-Biology (D. Wolf-Gladrow, J. Bijma)
Marine Animal Ecology (T. Brey)

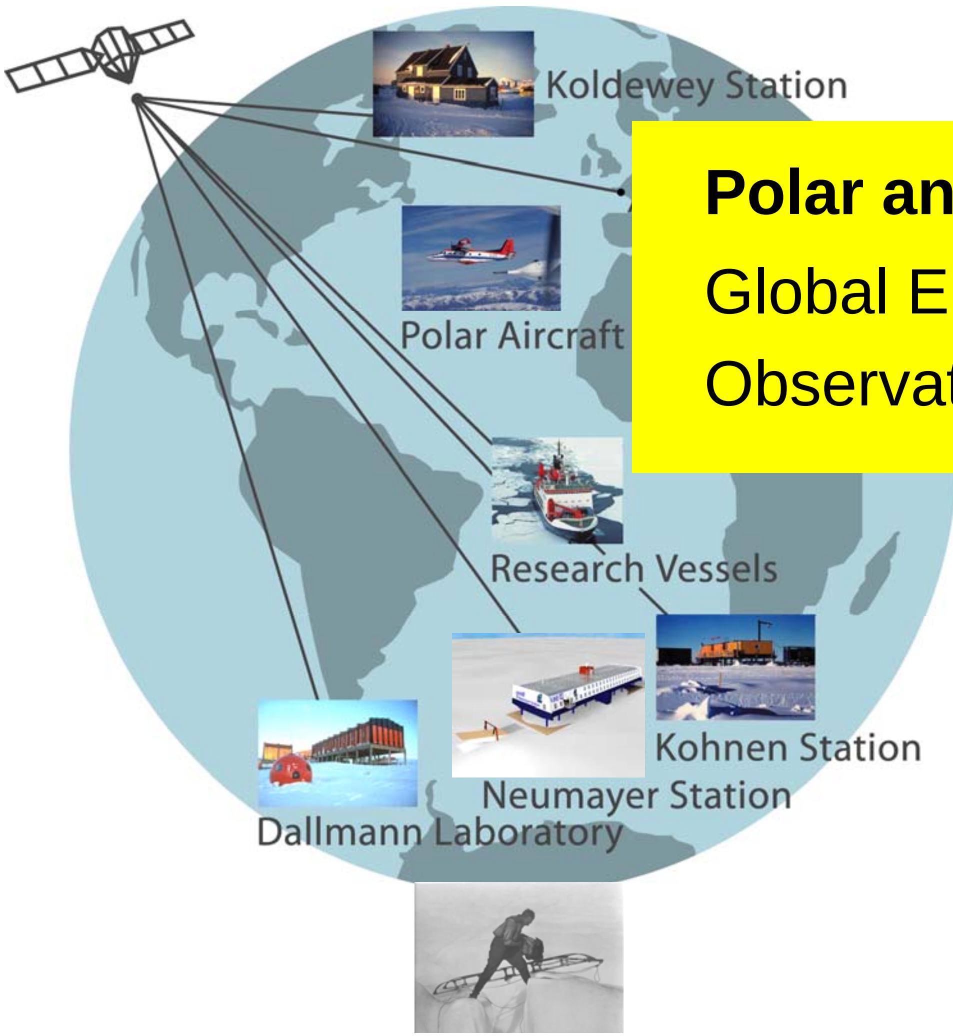
Universität Bremen

Remote Sensing (J. Notholt, G. Heygster)
Physics and Chemistry of the Atmosphere (J. P. Burrows, A. Ladstätter-Weißenmayer)

JACOBS UNIVERSITY

Earth and Space Sciences (A. Schaefer, V. Unnithan)
Computational Science (P. Baumann, L. Linsen)

Research



Polar and Marine Research:

Global Environment & the Earth System

Observations - Models - Applications

Education

Universities Bremen, Potsdam, Kiel, Jacobs, Oldenburg, Hamburg, FH Bremerhaven

Guest Scientists & Lecturers at AWI and
Hanse Wissenschaftskolleg Delmenhorst (HWK)

Block Courses at 'Biologische Anstalt Helgoland' (Helgoland & Sylt)

Paleoclimate Dynamics

Gerrit Lohmann (AWI, Uni)

6. October 2008

- **Broaden the view of the climate system**
- **Interpretation of past environmental changes**
- **Data and Modelling**
- **Climate variability: North Atlantic Oscillation, El Niño – Southern Oscillation**

Paleoclimate Dynamics

Gerrit Lohmann

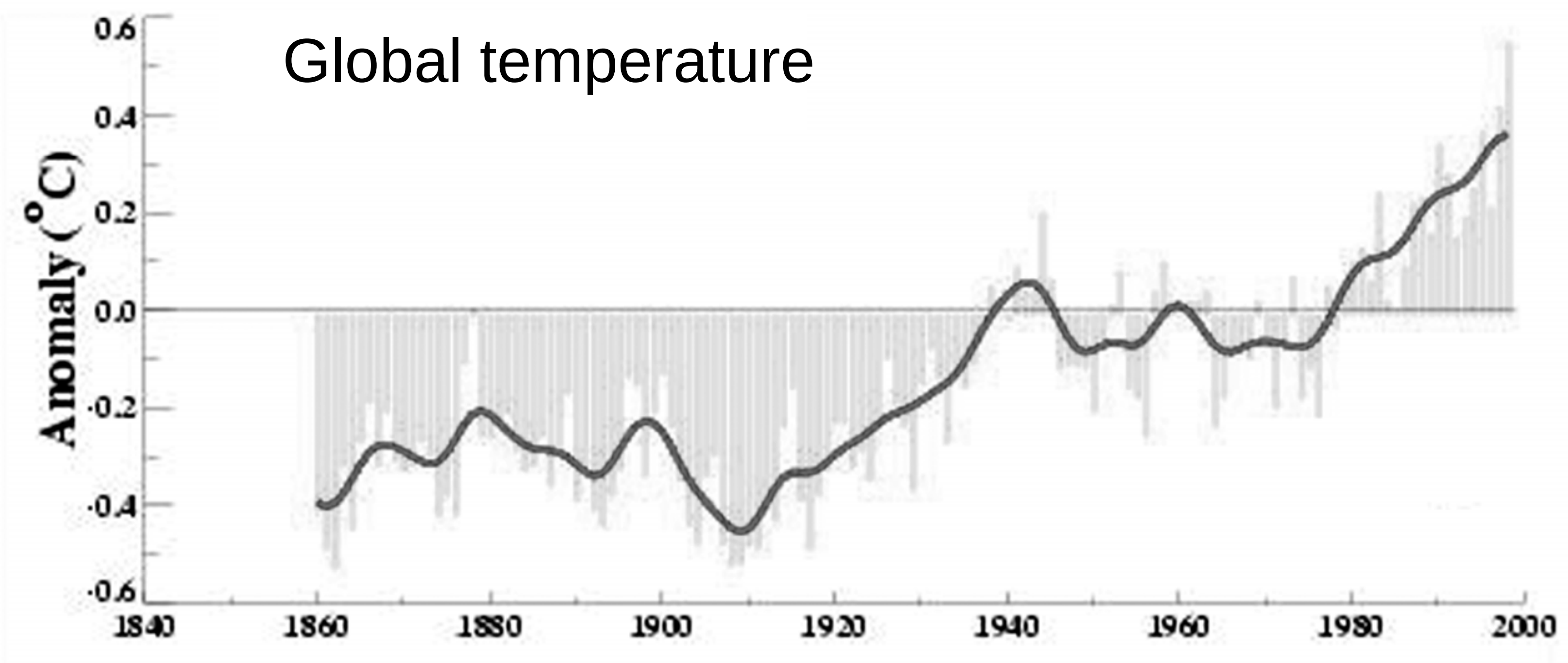
6. October 2008

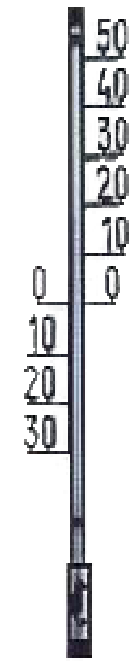
- **Broaden the view of the climate system**
- **Interpretation of past environmental changes**
- **Data and Modelling**
- **Climate variability: North Atlantic Oscillation, El Niño – Southern Oscillation**

- 2008: Overview
- 2009: Statistical Interpretation with practical units

Climate Trends at different Timescales

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

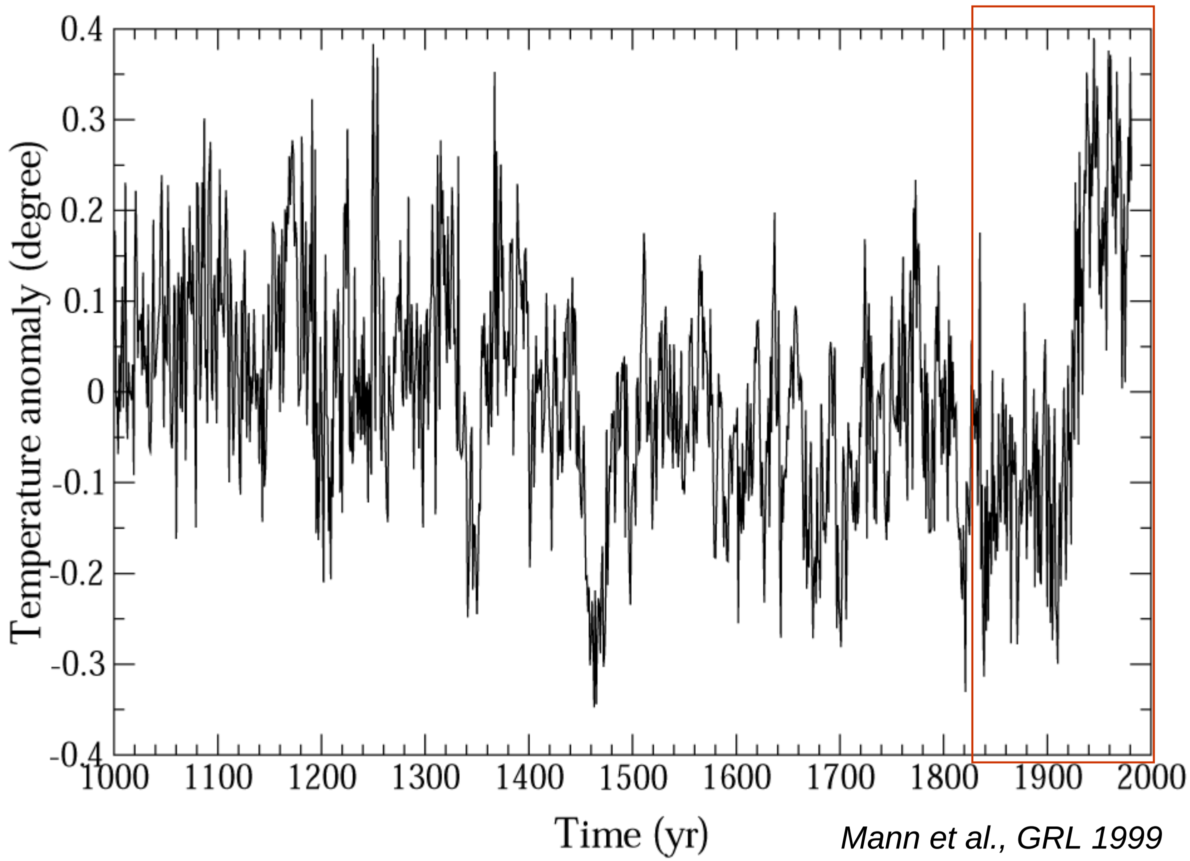




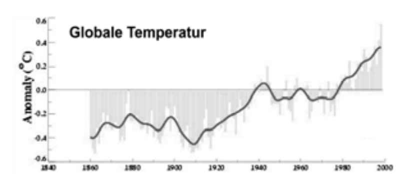
Hadley Centre, UK 2000

Climate Trends at different Timescales

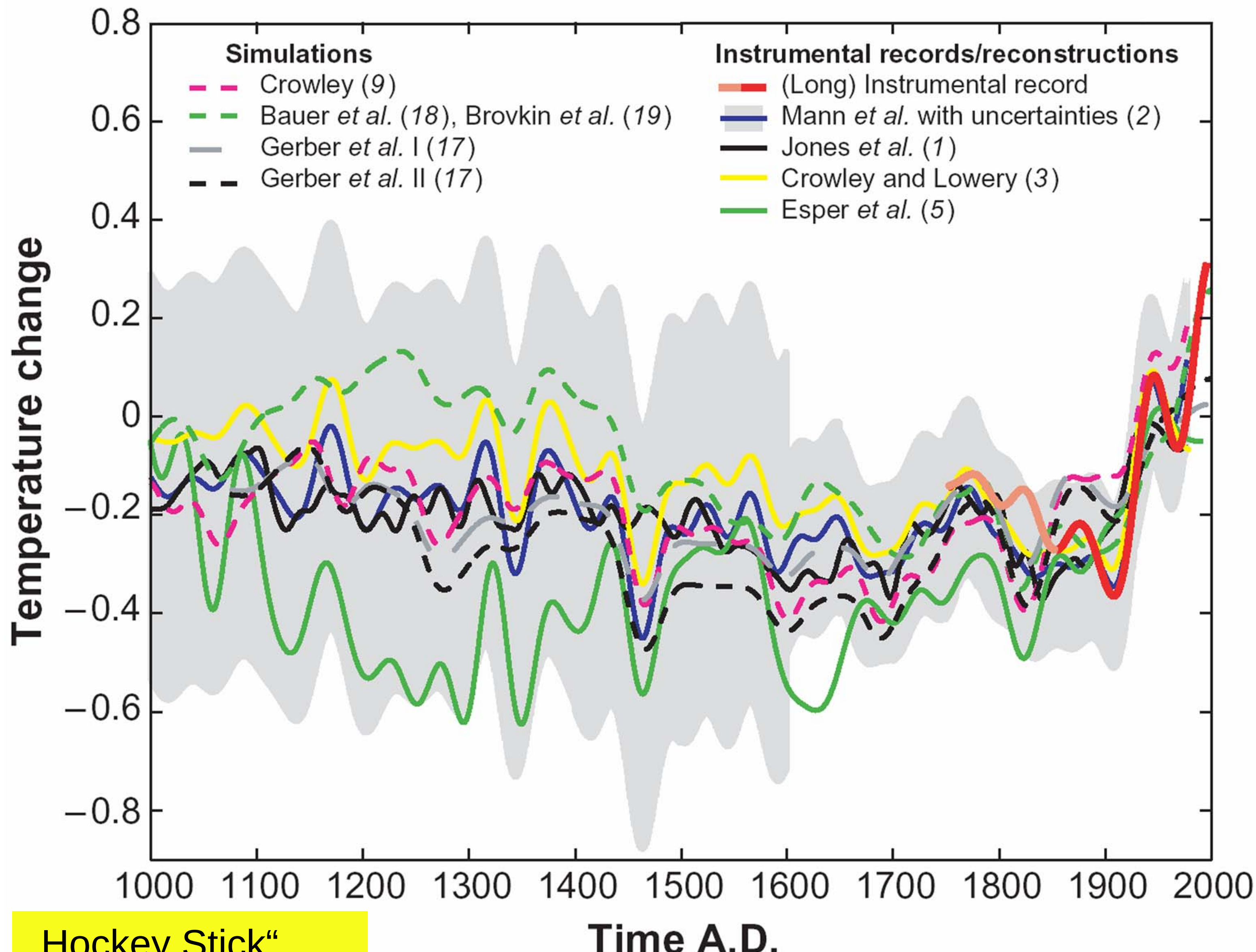
Temperature of the last **1000 years**



Mann et al., GRL 1999



Temperature of the last 1000 years

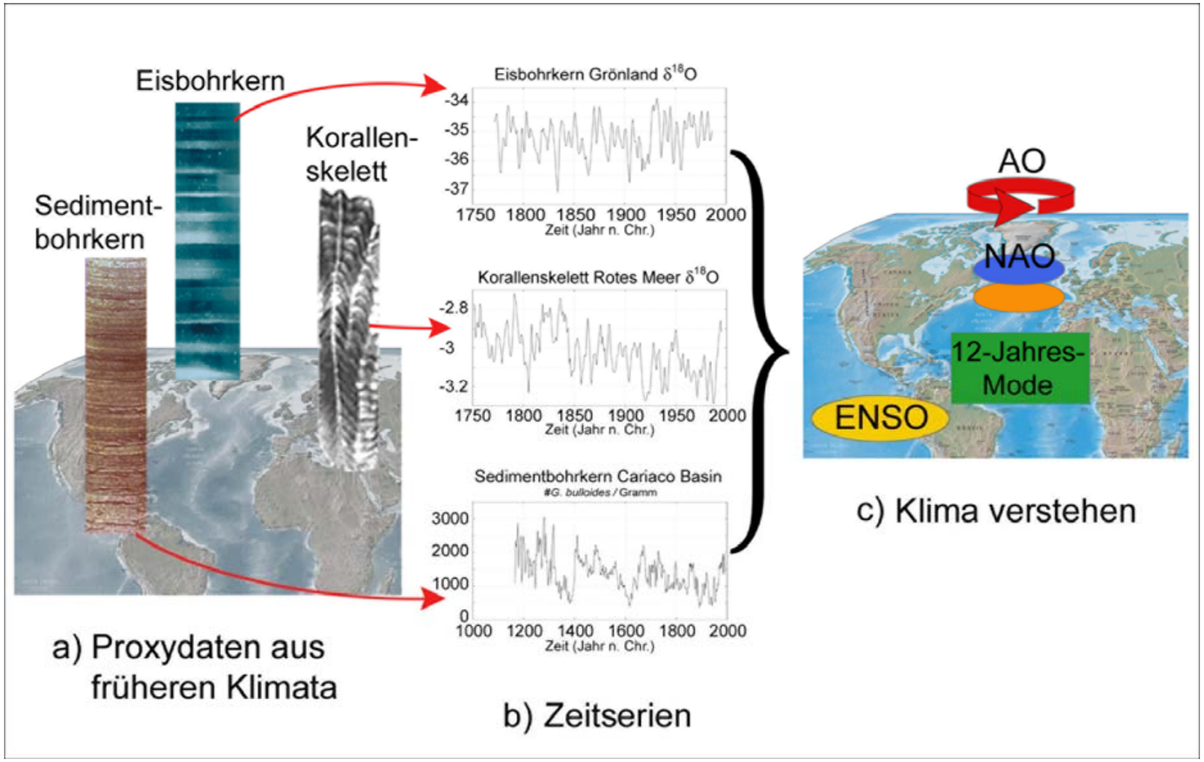


„Hockey Stick“

Compilation of Mann, 2002

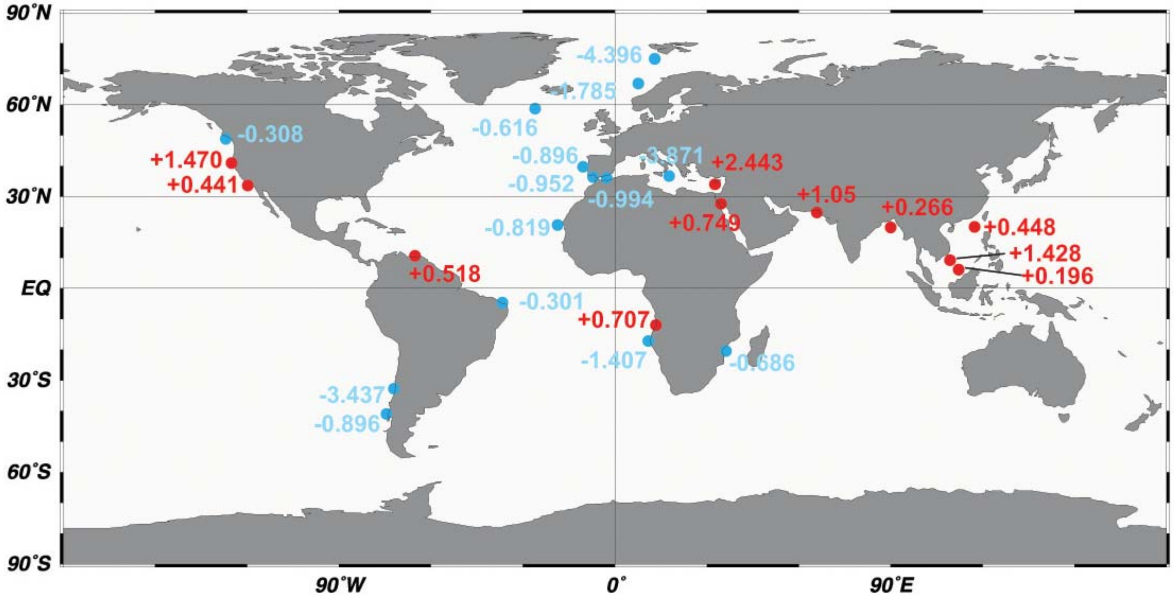
Proxy Data

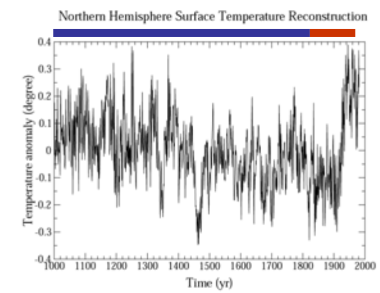
- Indirect data, often qualitative
- Long time series from archives
- Information beyond the instrumental record

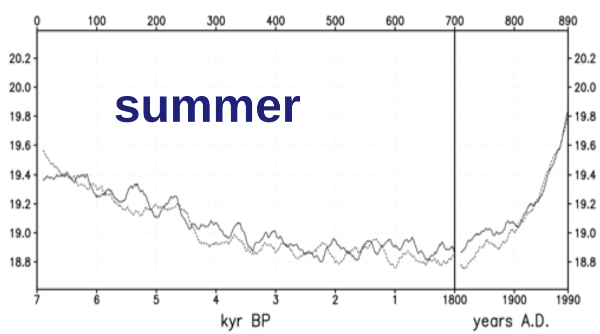


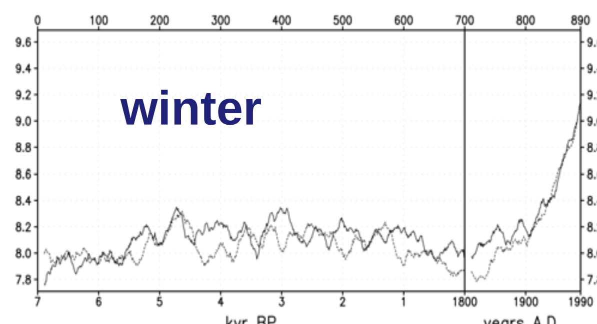
Climate Trends at different Timescales

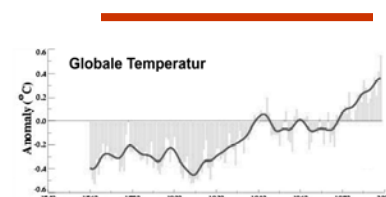
Holocene: Temperature proxy for the last 7000 years







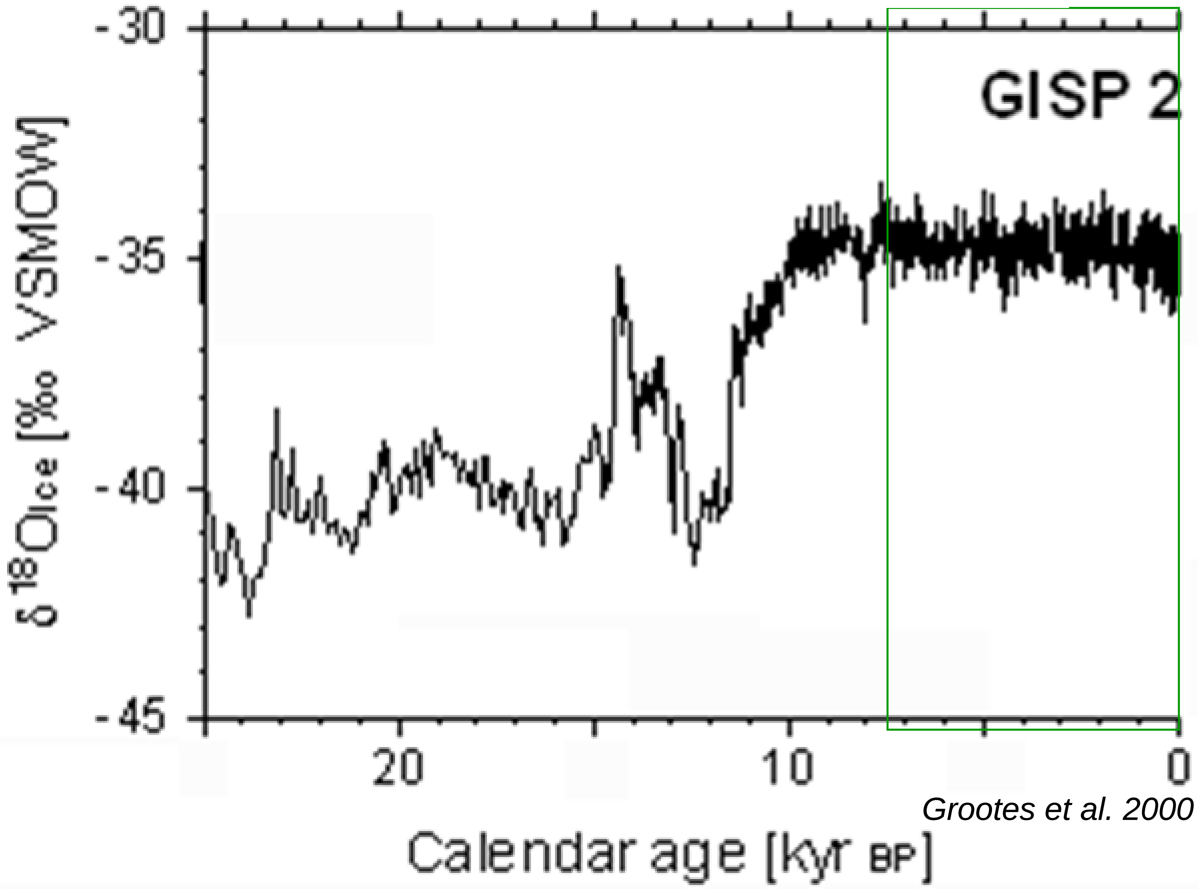




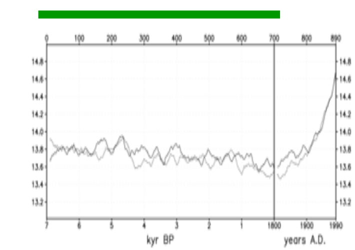
Lorenz & Lohmann 2004

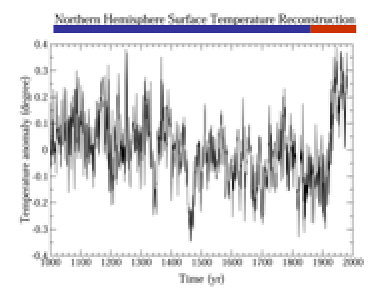
Climate Trends at different Timescales

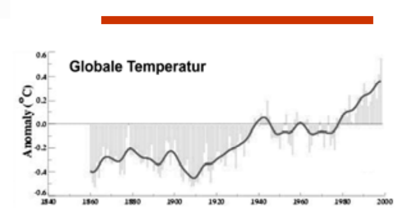
Deglaciation – Greenland ice core

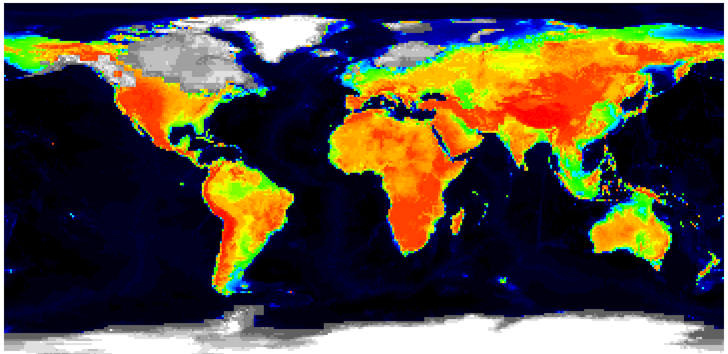


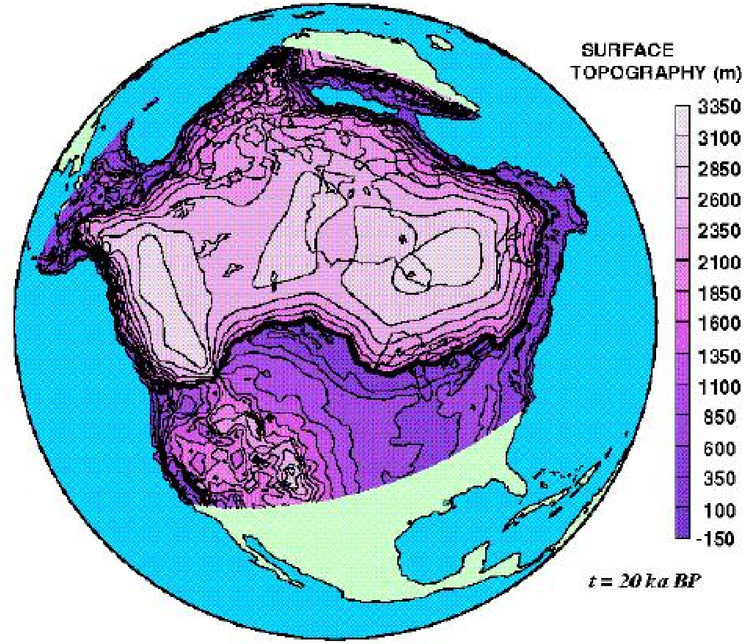
Grootes et al. 2000







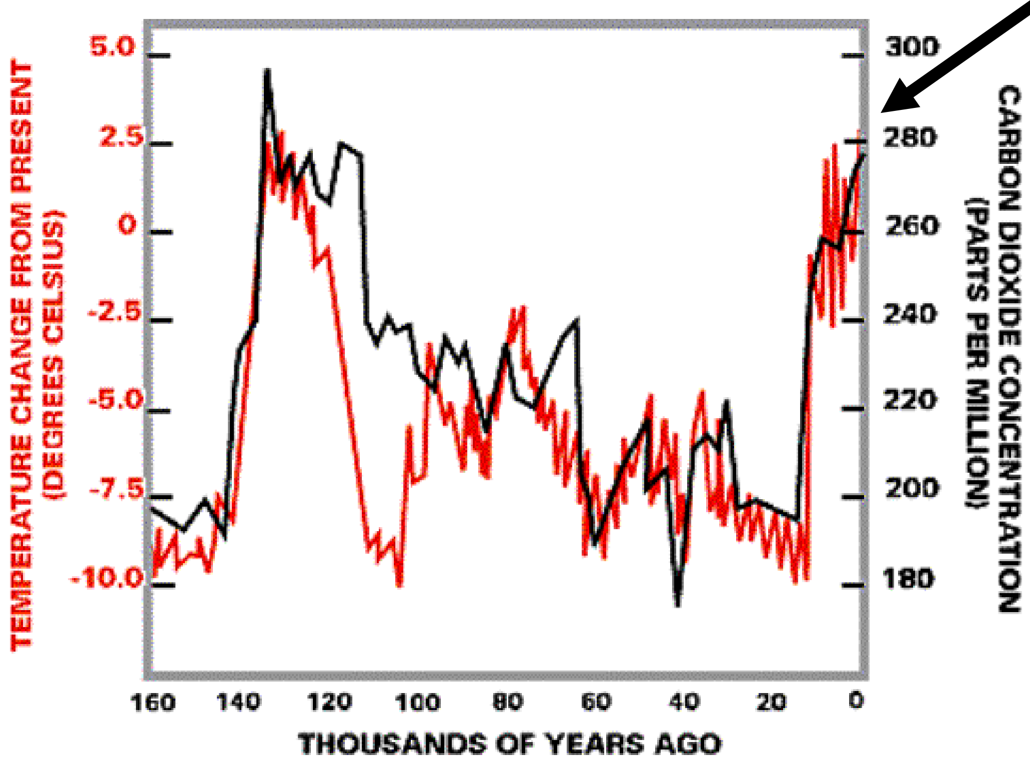




Deglaciation

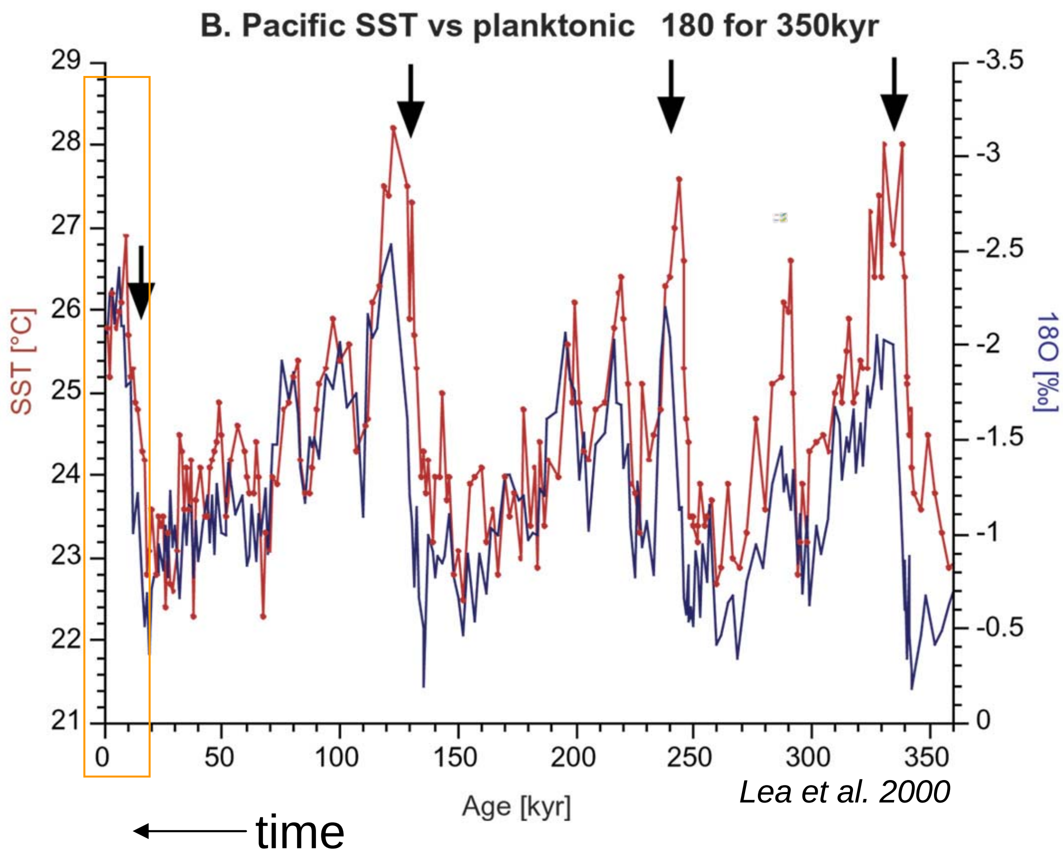
CO_2 and temperature

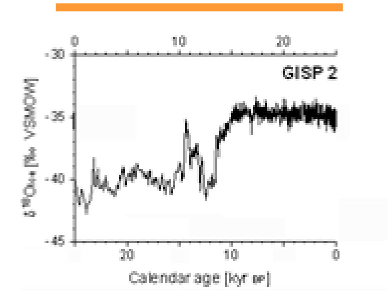
Pre-industrial

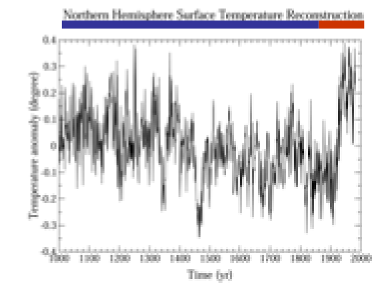


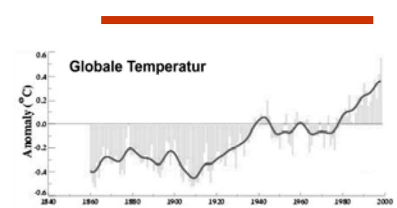
Climate Trends at different Timescales

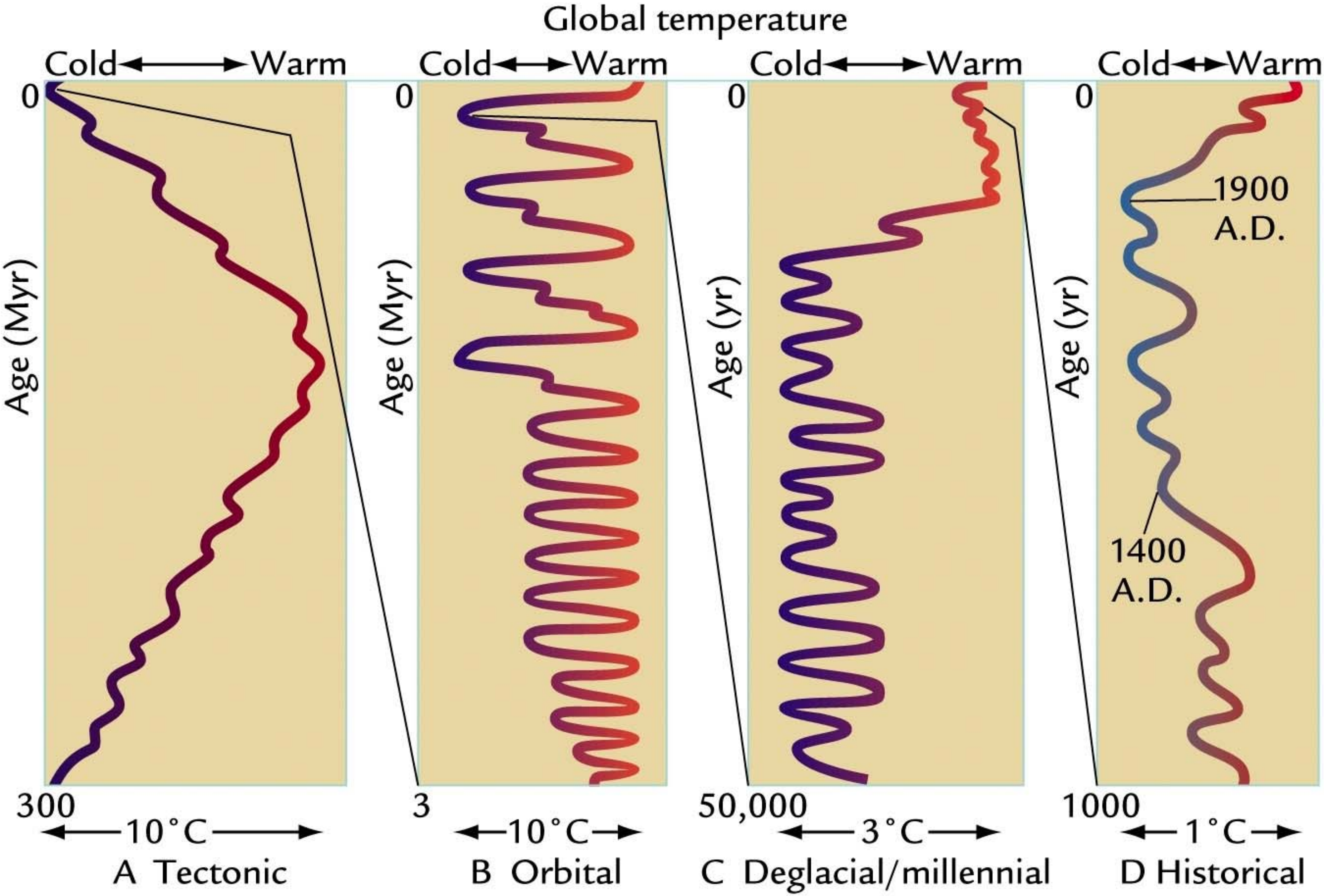
Glacial-Interglacial





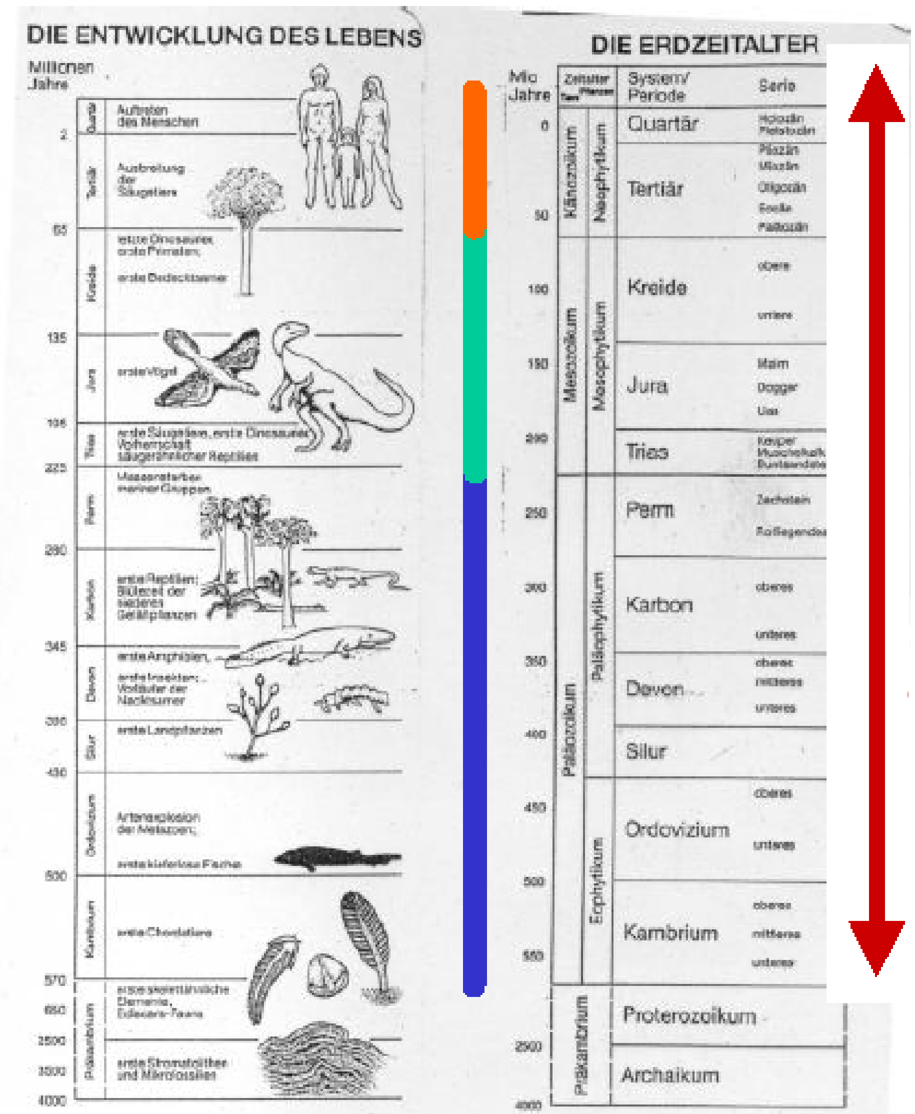






Ruddiman, 2000

Global Climate



450 000 years

First Humans: ca. 30 million years

Homo sapiens: 160 000 years

4 billion years
(German: Milliarden Jahre !)

Data

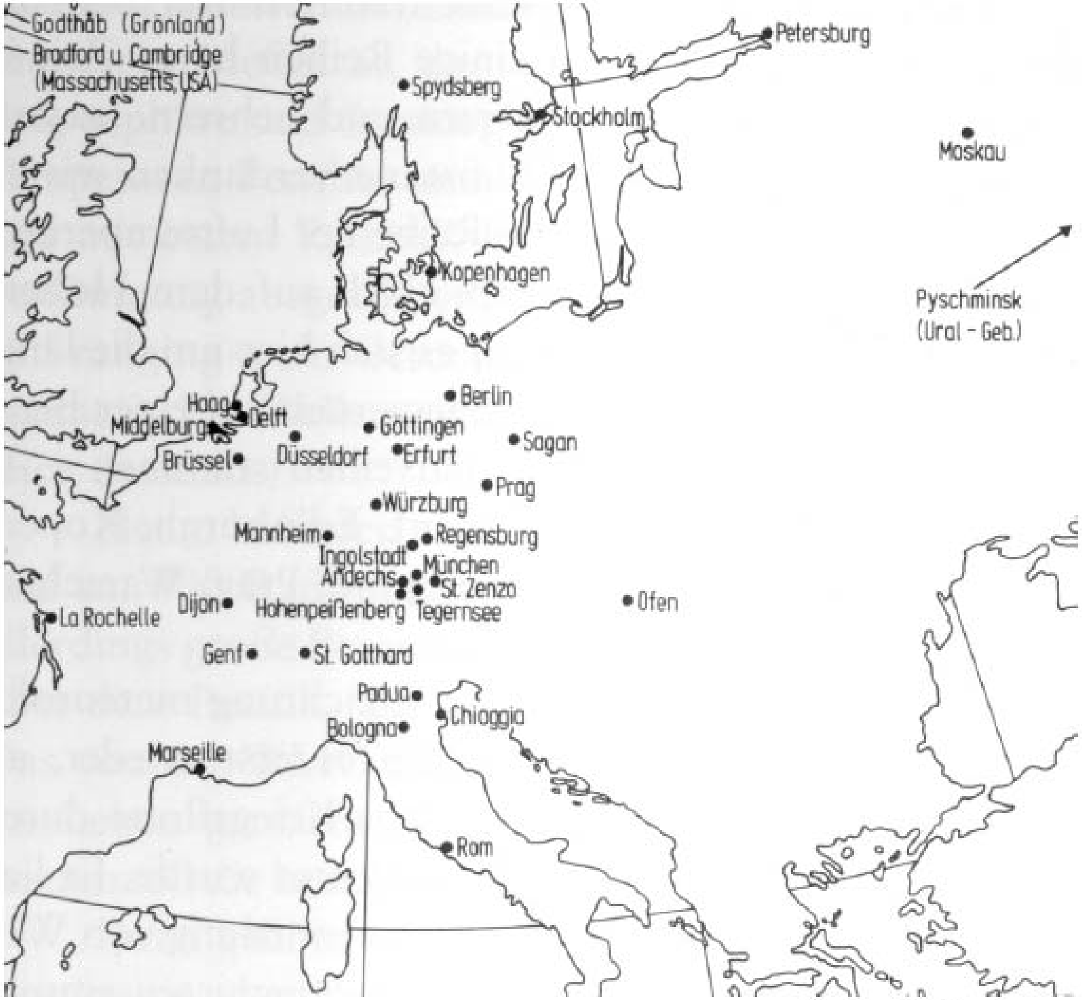
- Anfänge physikalischer Messtechnik
  - ca. 1650 erste Luftdruckmessungen (Italien, Frankreich, Schweden)
  - 1654-1670 erste aufgezeichneten Lufttemperaturmessungen (Pisa)
  - 1677-1704 erste Niederschlagsmessreihen (England)
  - ca. 1700 erste Windmessungen in Deutschland (Leibniz)
- Vieljährige (lückenlose)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

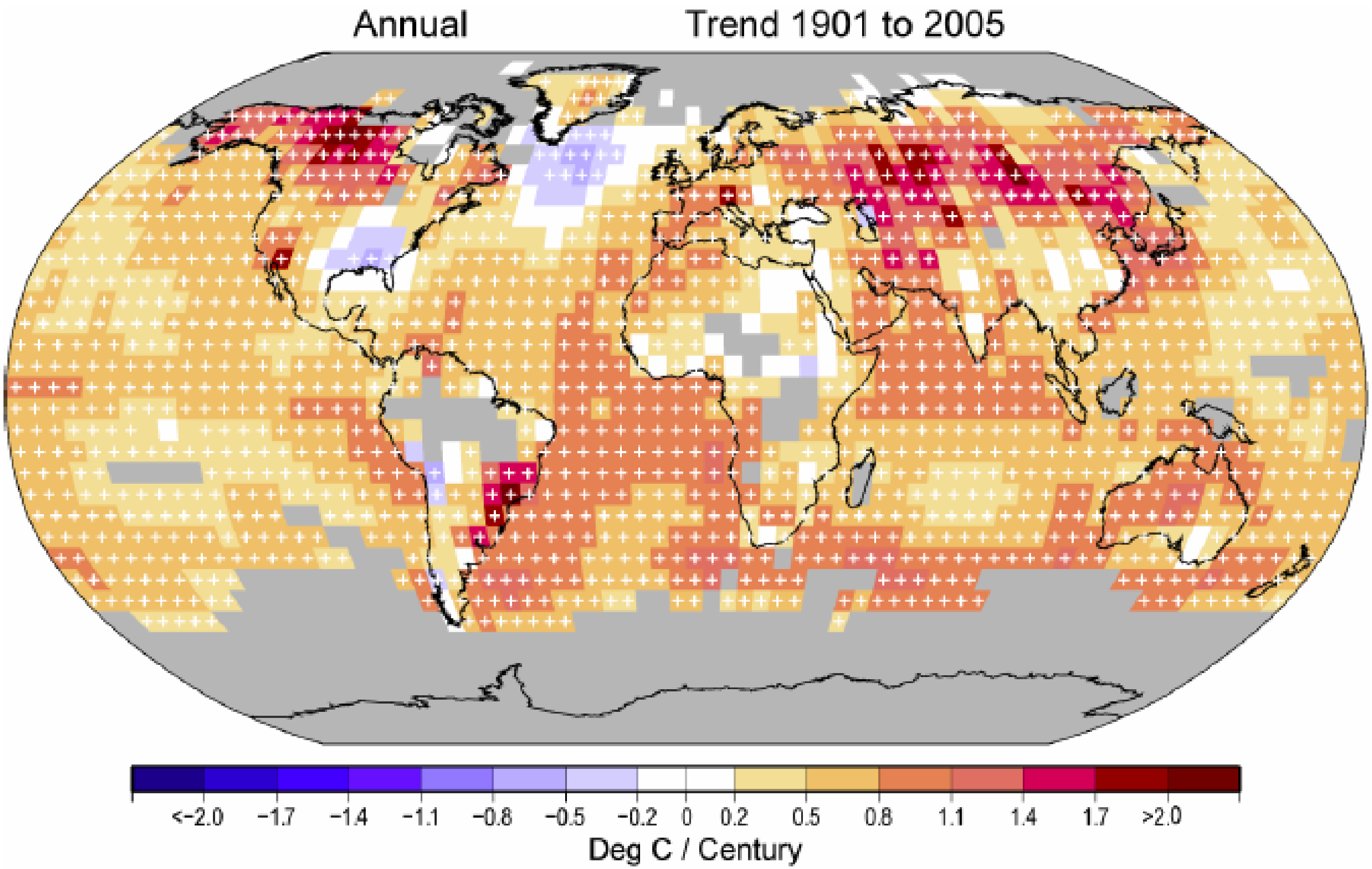
„Pfälzische Meteorologischen Gesellschaft“

Societas Meteorologica Palatina
(1781-1795)

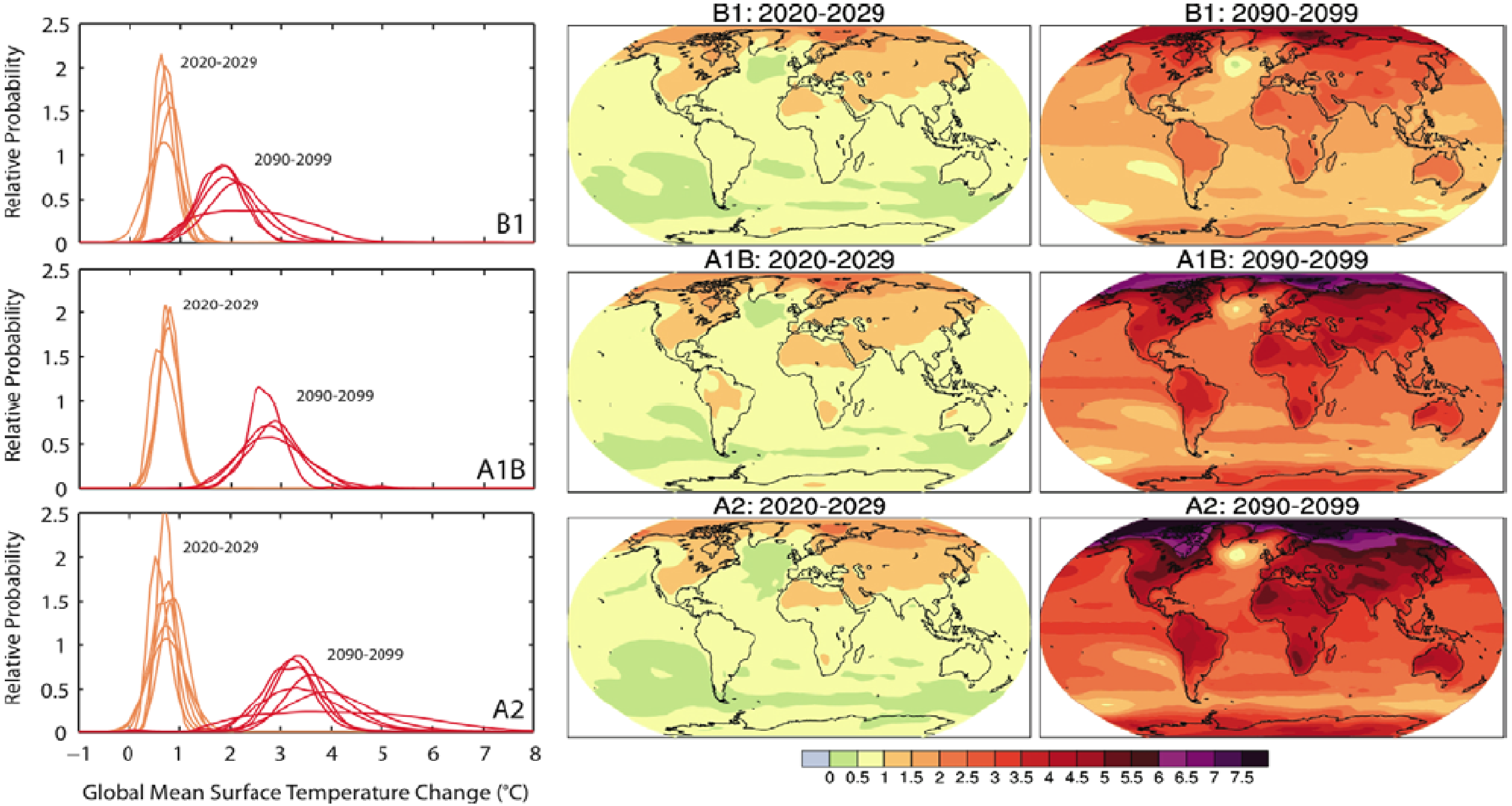


Quelle: Schönwiese

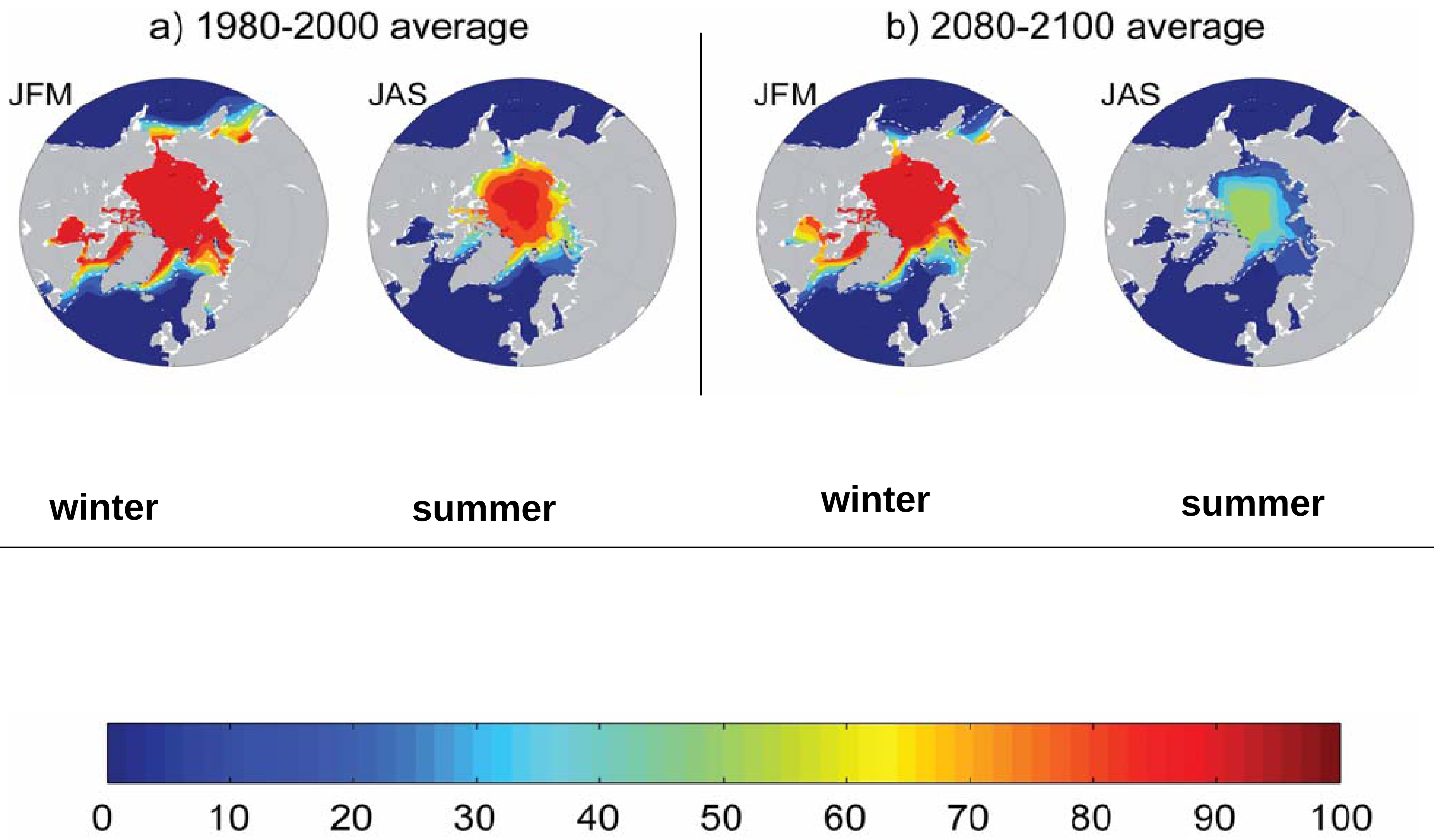
Observations: Temperature trend since 1901



CO_2–Climate-Scenarios

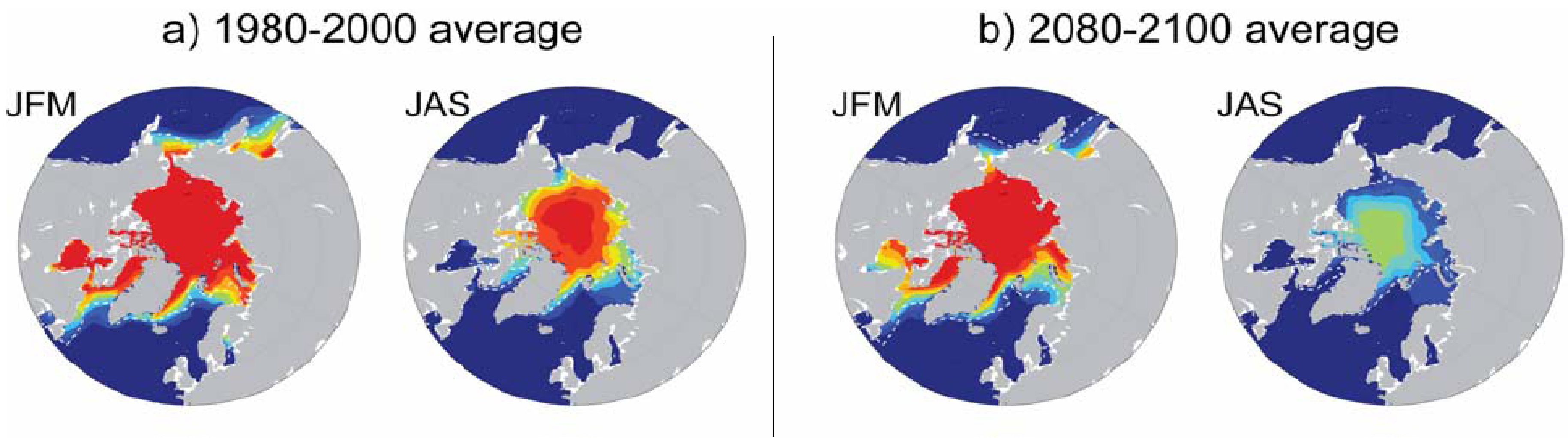


Scenarios: sea ice extent



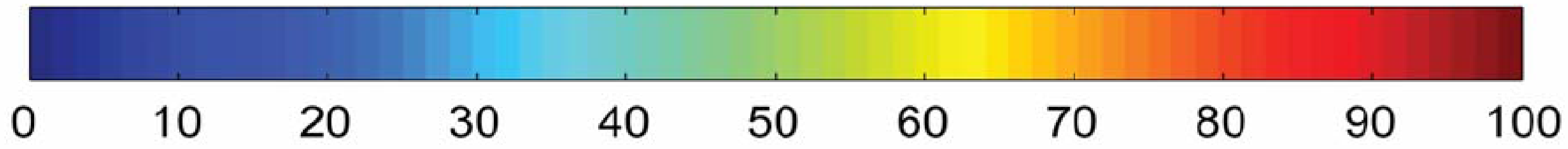
IPCC AR4 (2007)

Scenarios: sea ice extent



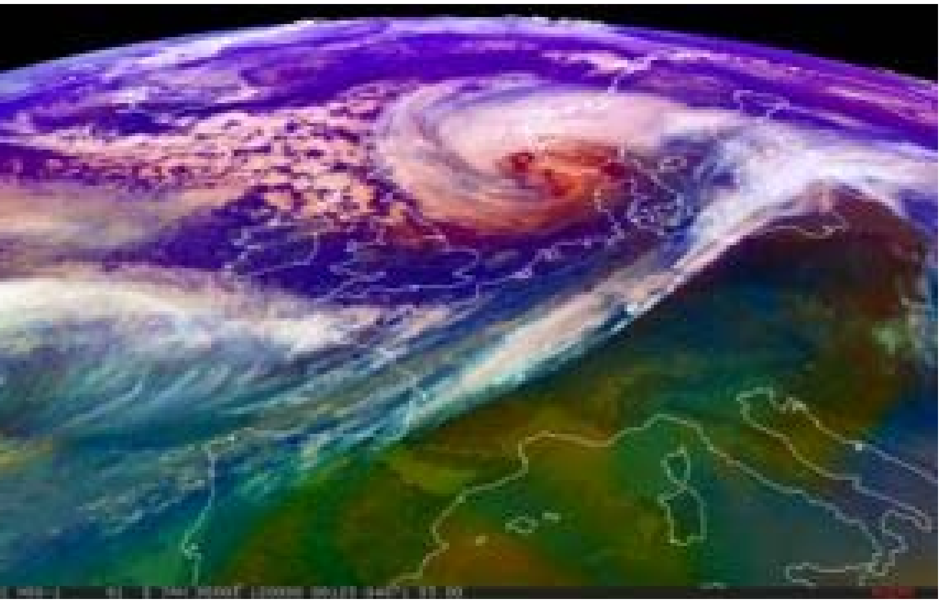
winter summer winter summer

Ecosystem change -> Biologists



IPCC AR4 (2007)

Economic damage:
European windstorms during winter

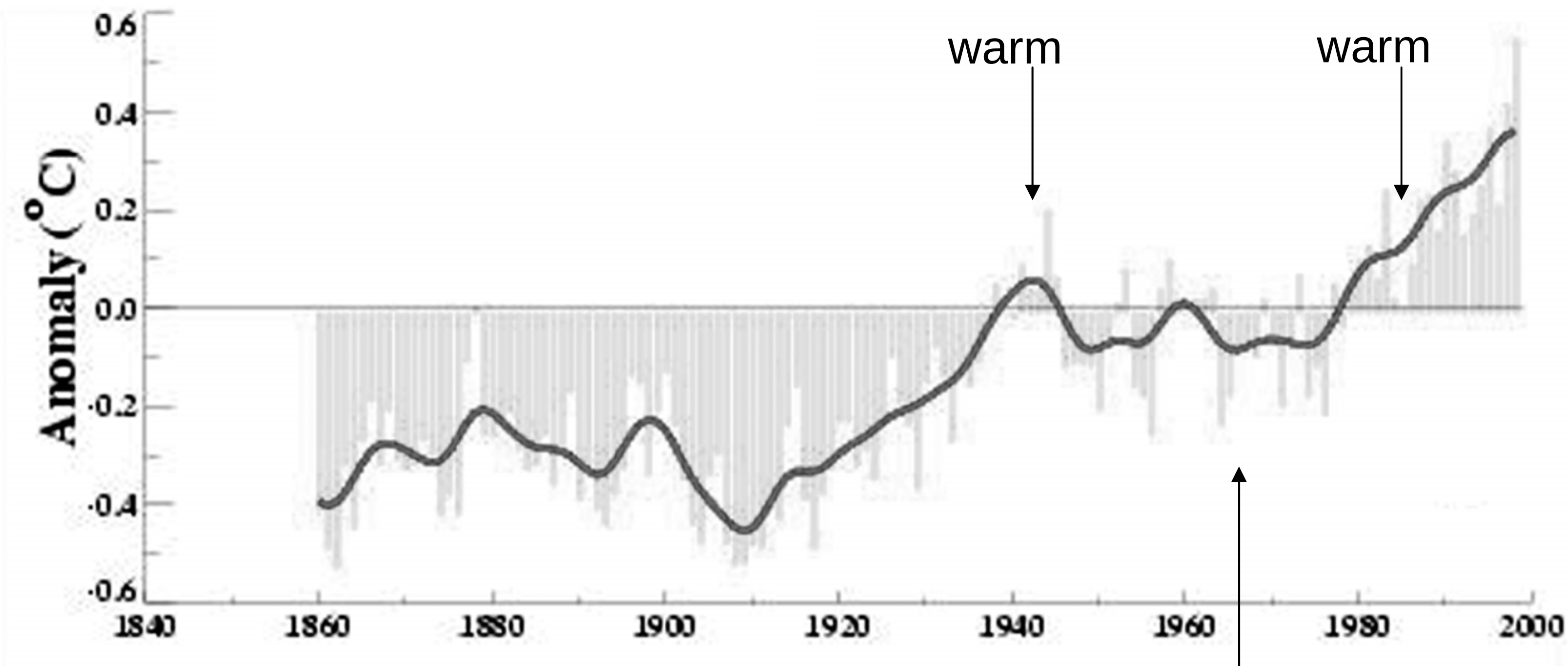


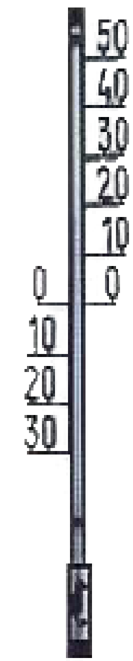
Economic damage: €1.9 billion per year, insurance losses: €1.4 billion per year (1990-1998).

Second highest cause of global natural catastrophe insurance loss after U.S. hurricanes.

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

Global temperature

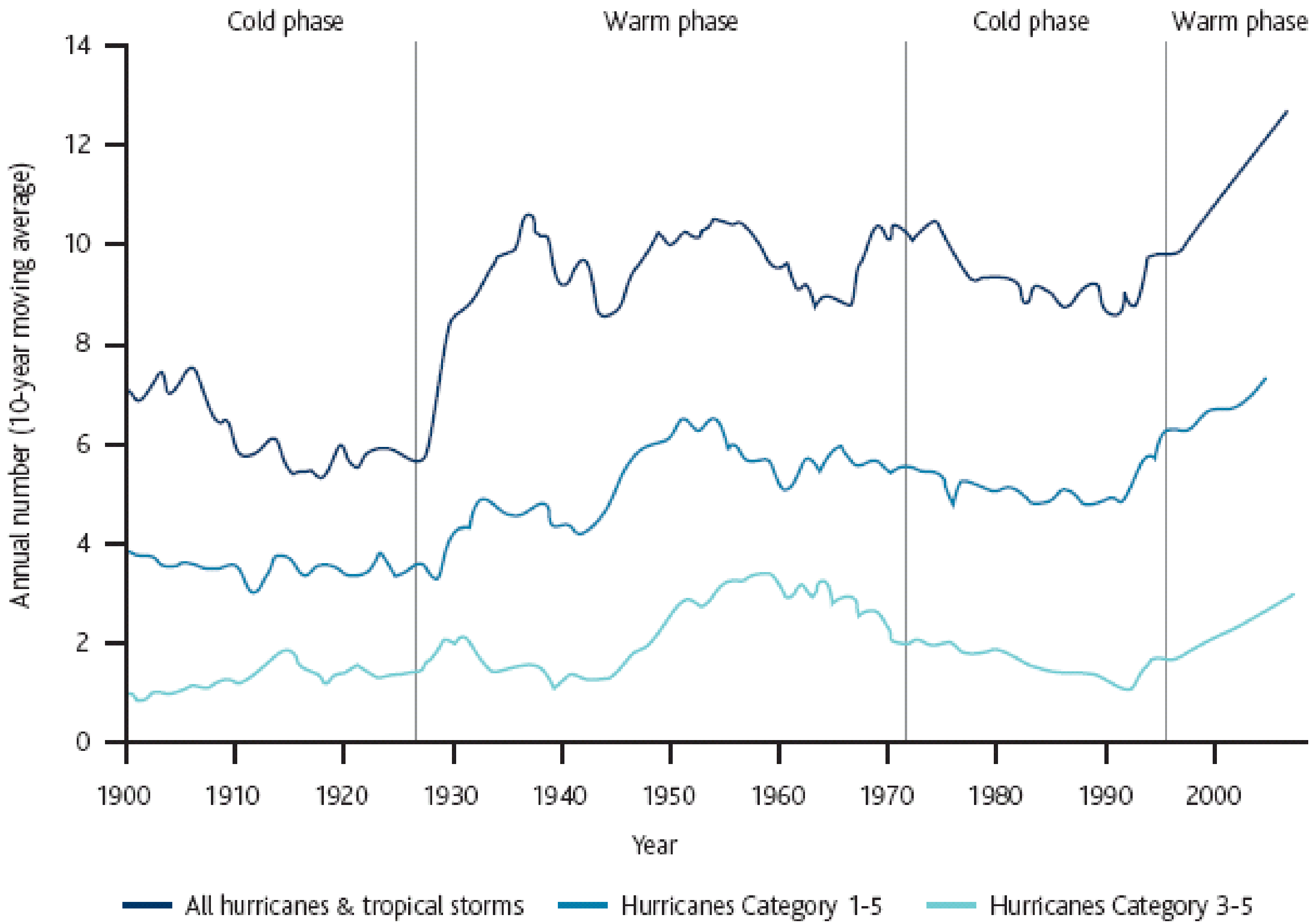




Hadley Centre, UK 2000

Hurricans:
Decadal Oscilations plus trend

(b) Ten-year moving average for tropical cyclones formed in the North Atlantic Basin



Source: NOAA, with re-handling and calculations by Munich Re.

Climate Change

Detection

Understanding

1911

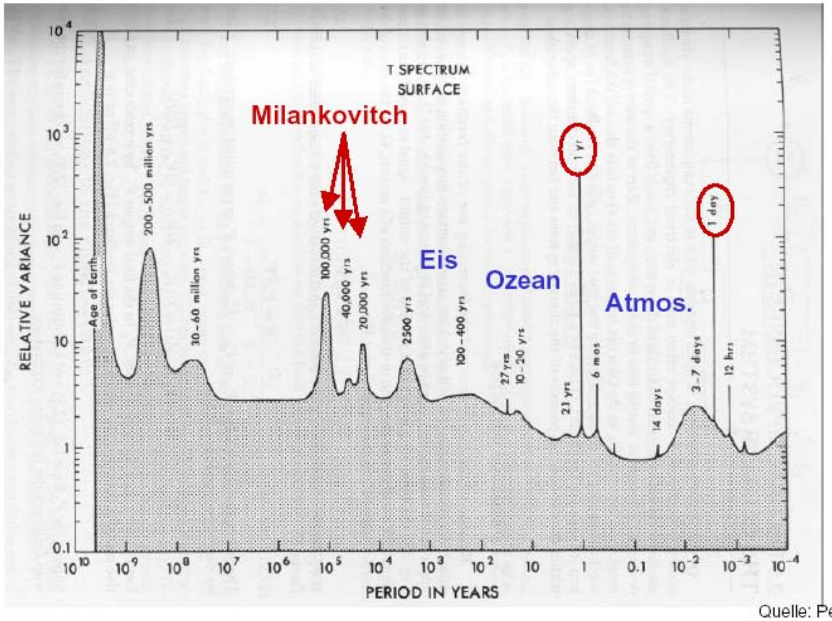
2001

mountain glaciers (Morteratsch)

Solar – Orbital focing

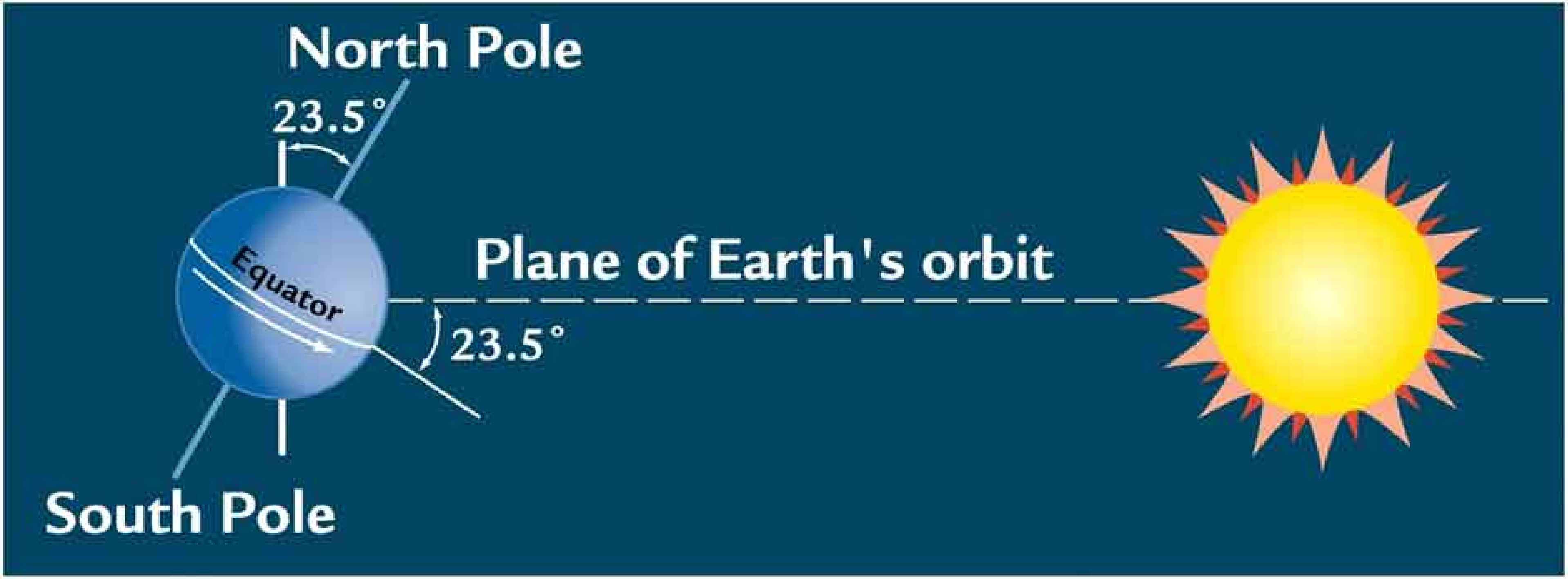
- 20000, 40000, 100000 years
- 0.5, 1 year

- Geometry of the Sun-Earth configuration



Quelle: Peixoto & Oort

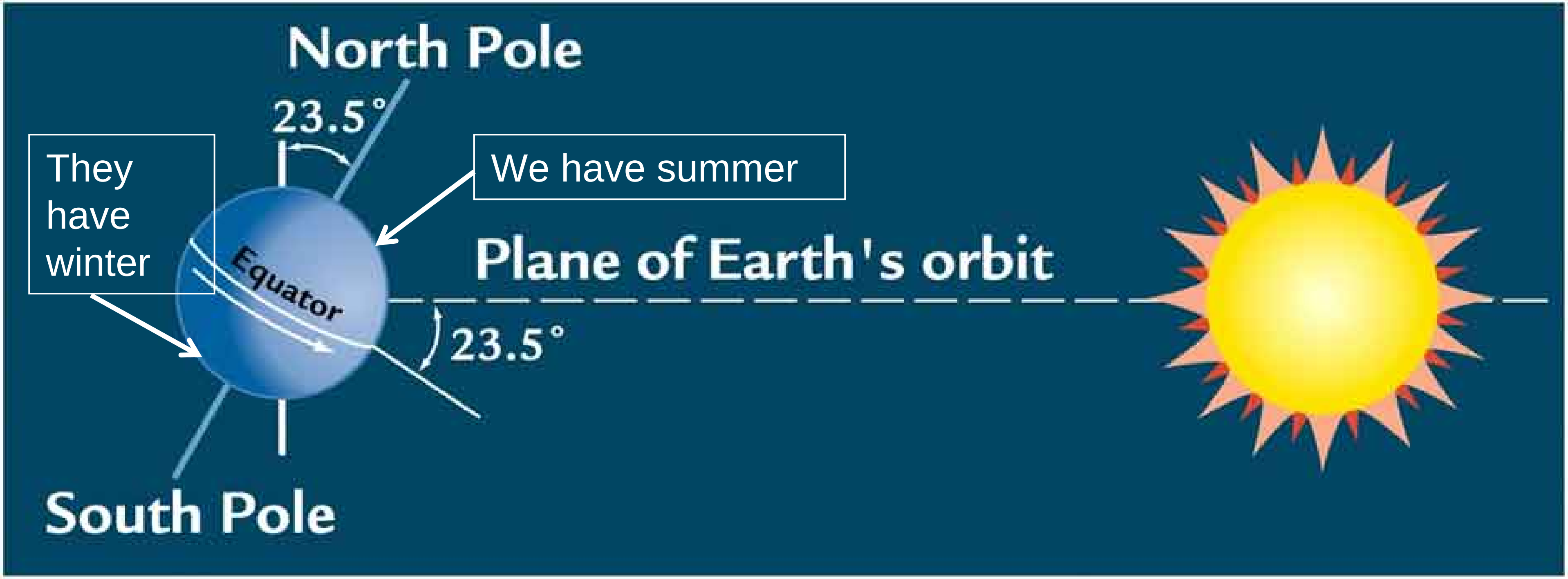
Annual Cycle



Northern Hemisphere Summer

Boreal Summer

Annual Cycle

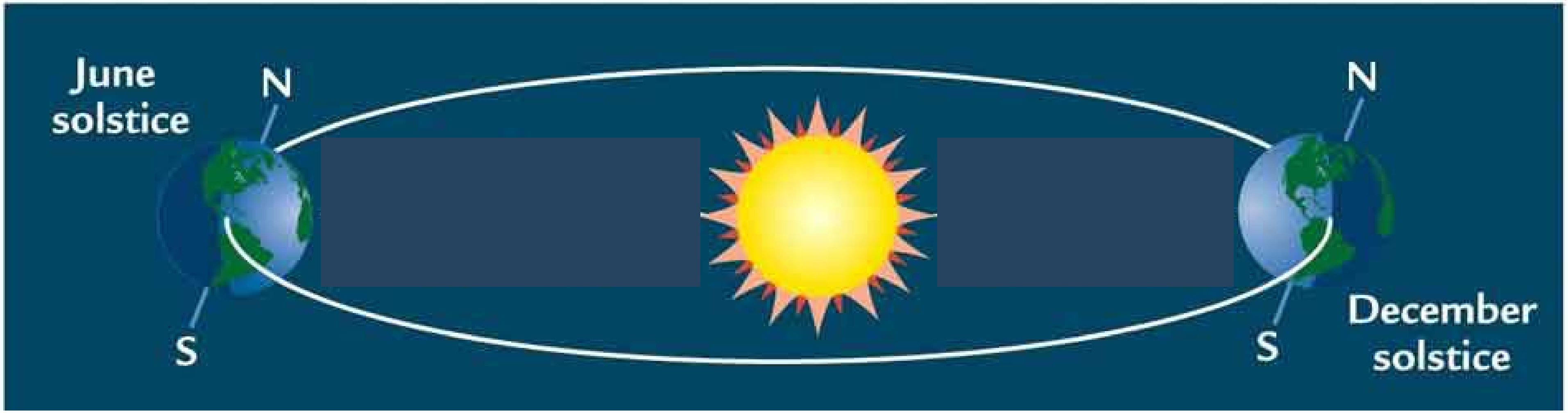


Northern Hemisphere Summer

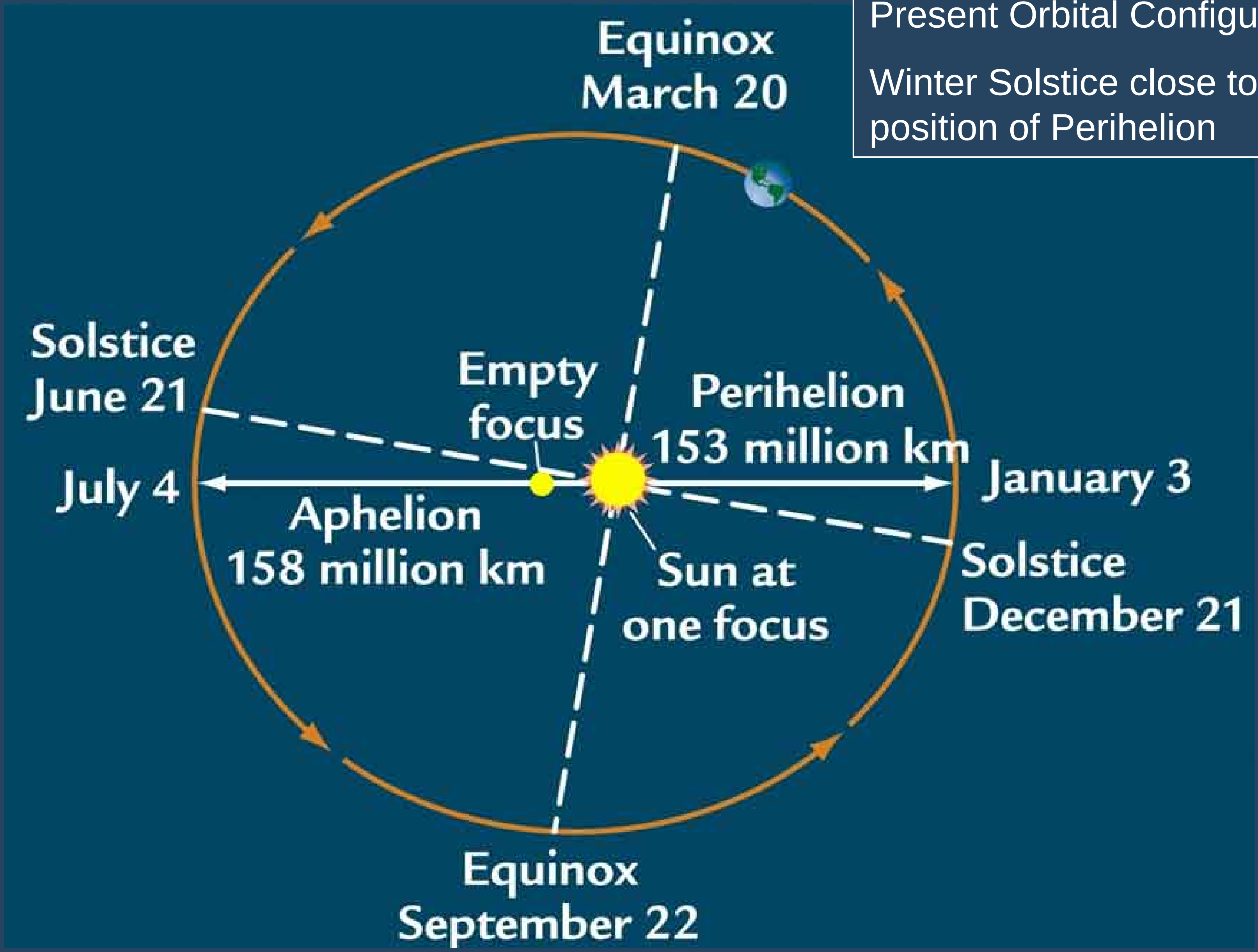
Boreal Summer

Annual Cycle

Fixed axis of Earth rotation



Precession & Eccentricity

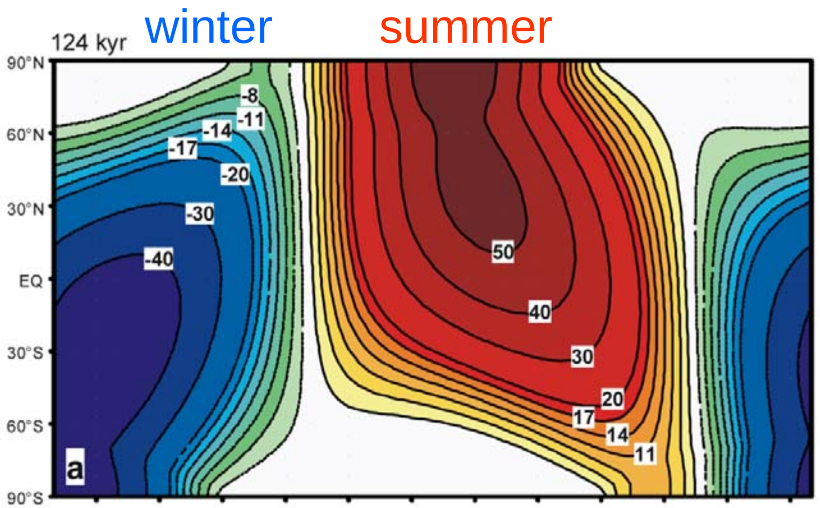


Present Orbital Configuration:

Winter Solstice close to the position of Perihelion

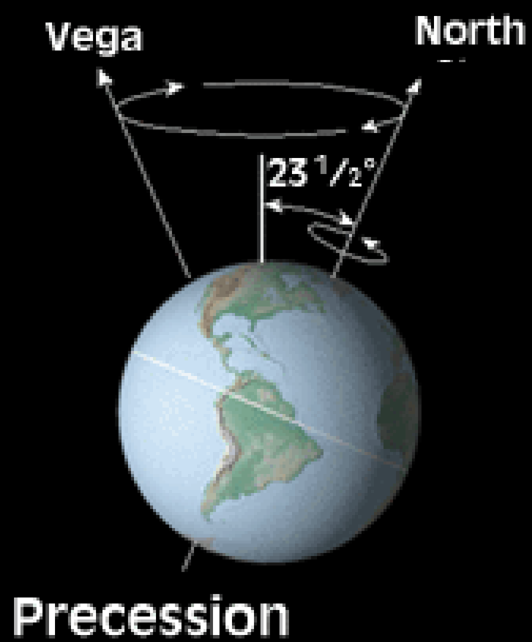
Example for Milankovitch forcing

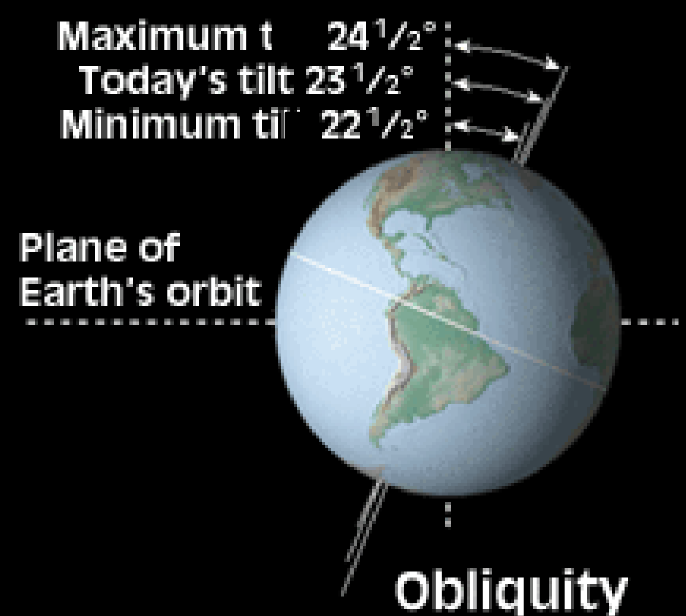
The Eemian climate (the last interglacial, 124 000 years)

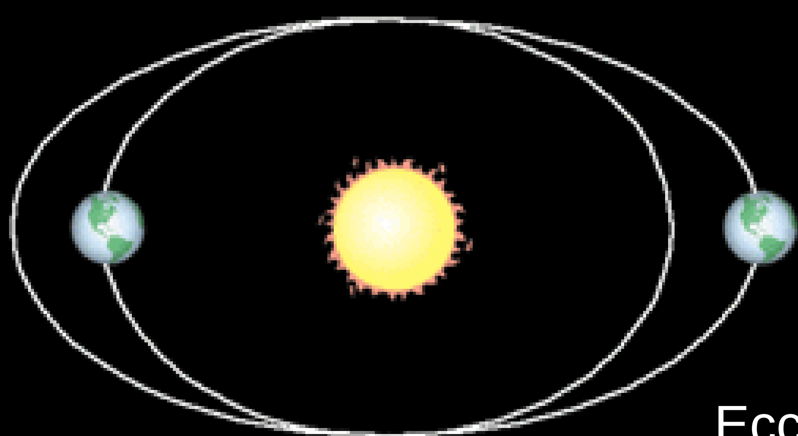


insolation anomaly form today

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



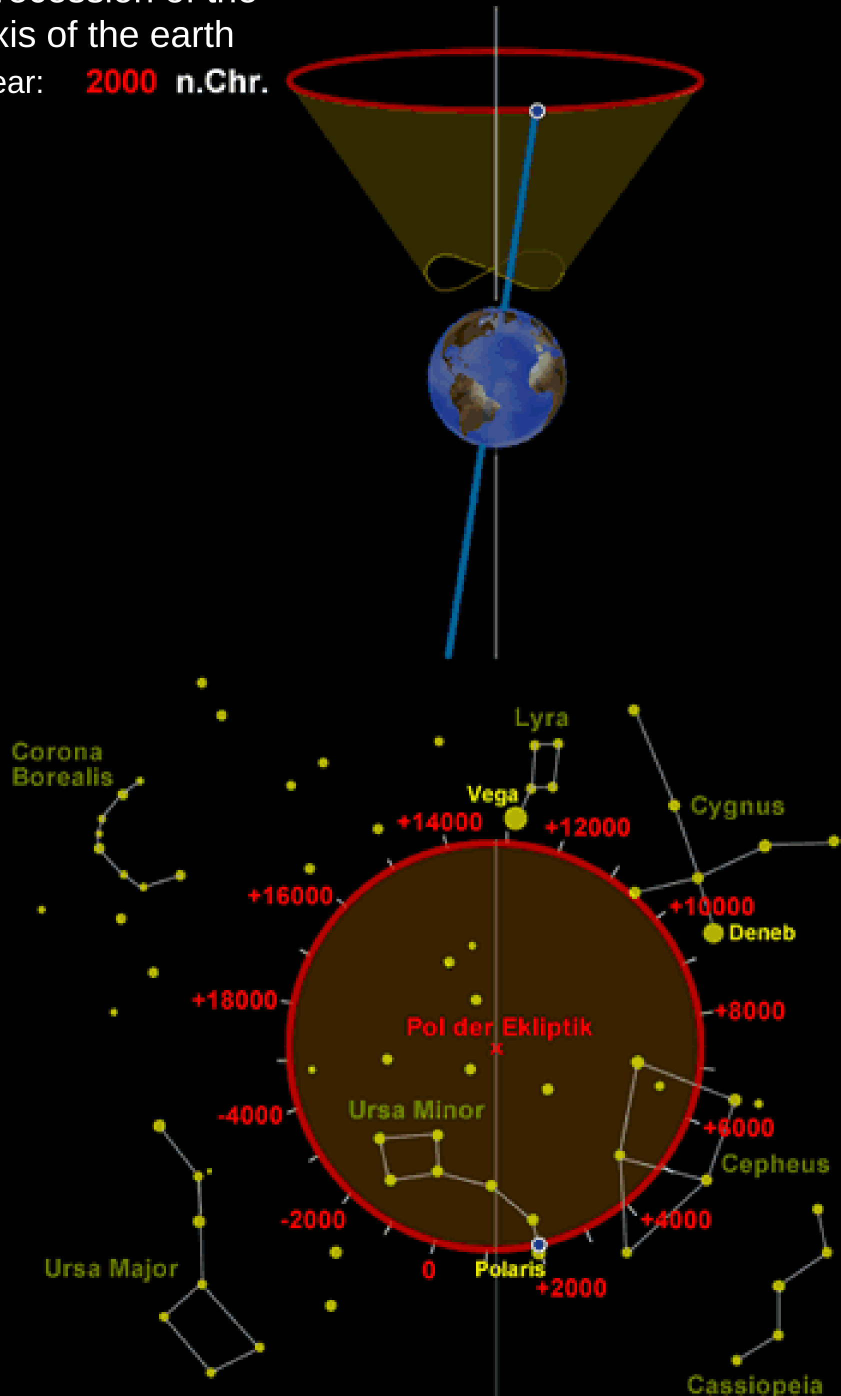


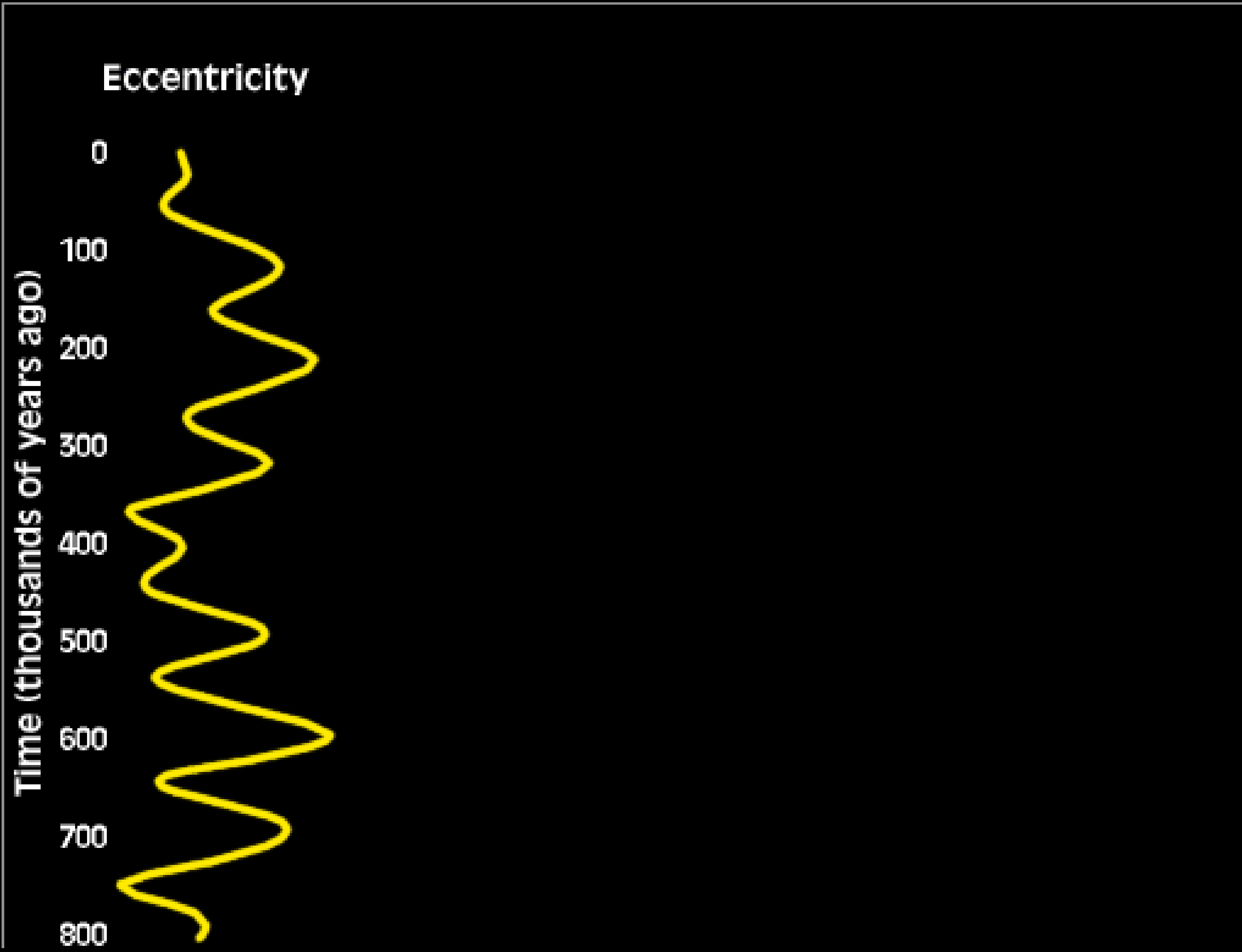


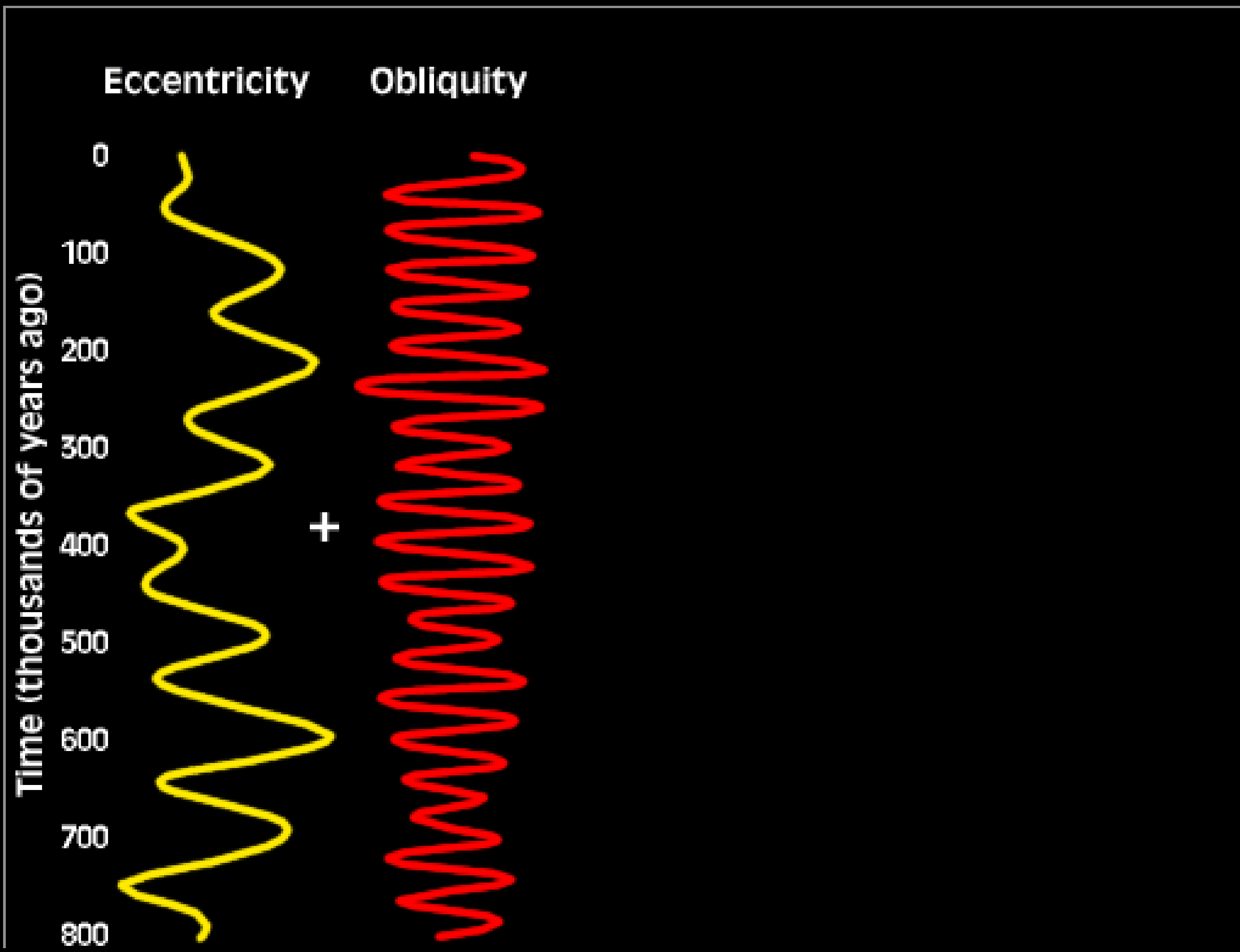
Eccentricity

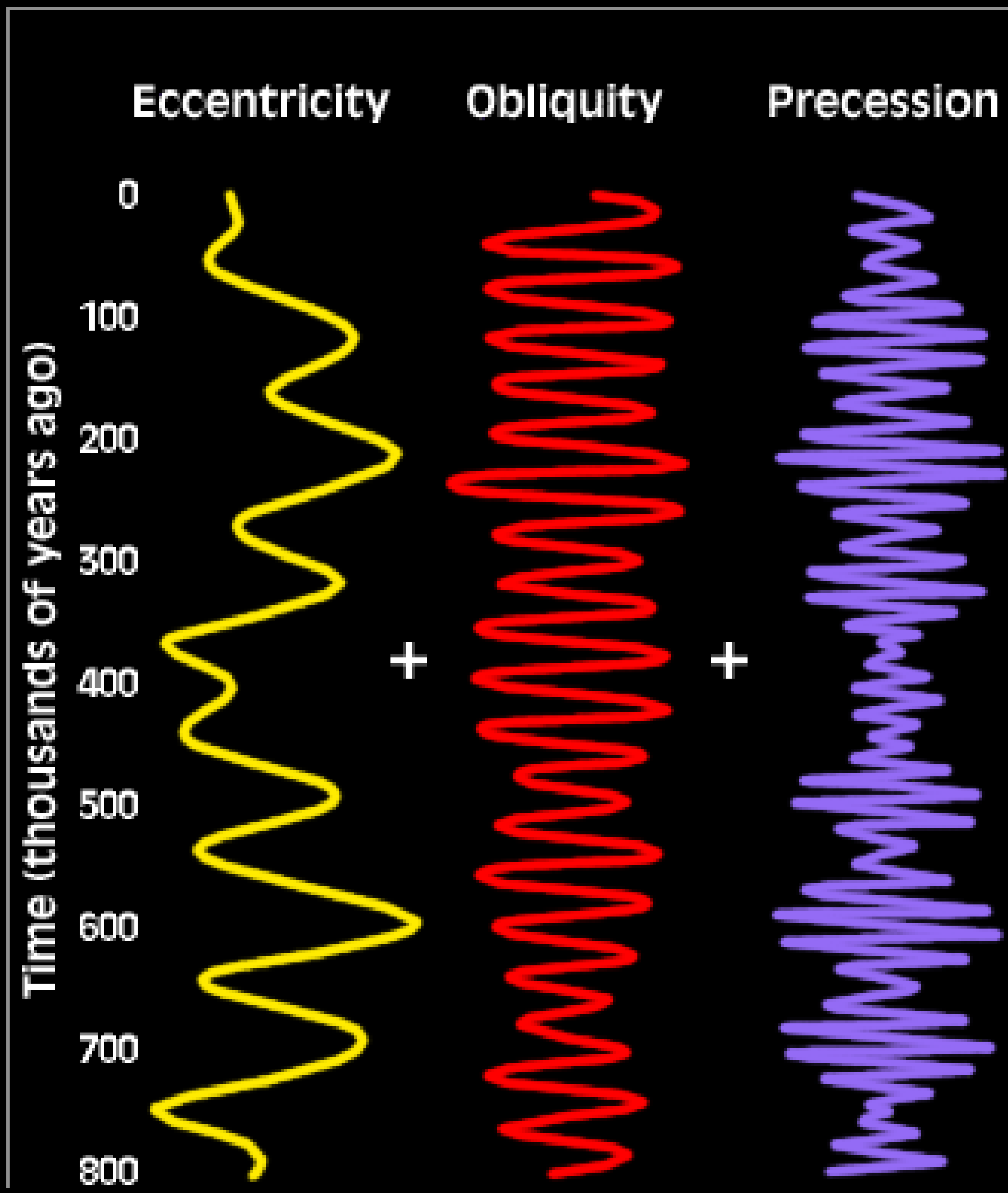
Precession of the axis of the earth

Year: 2000 n.Chr.

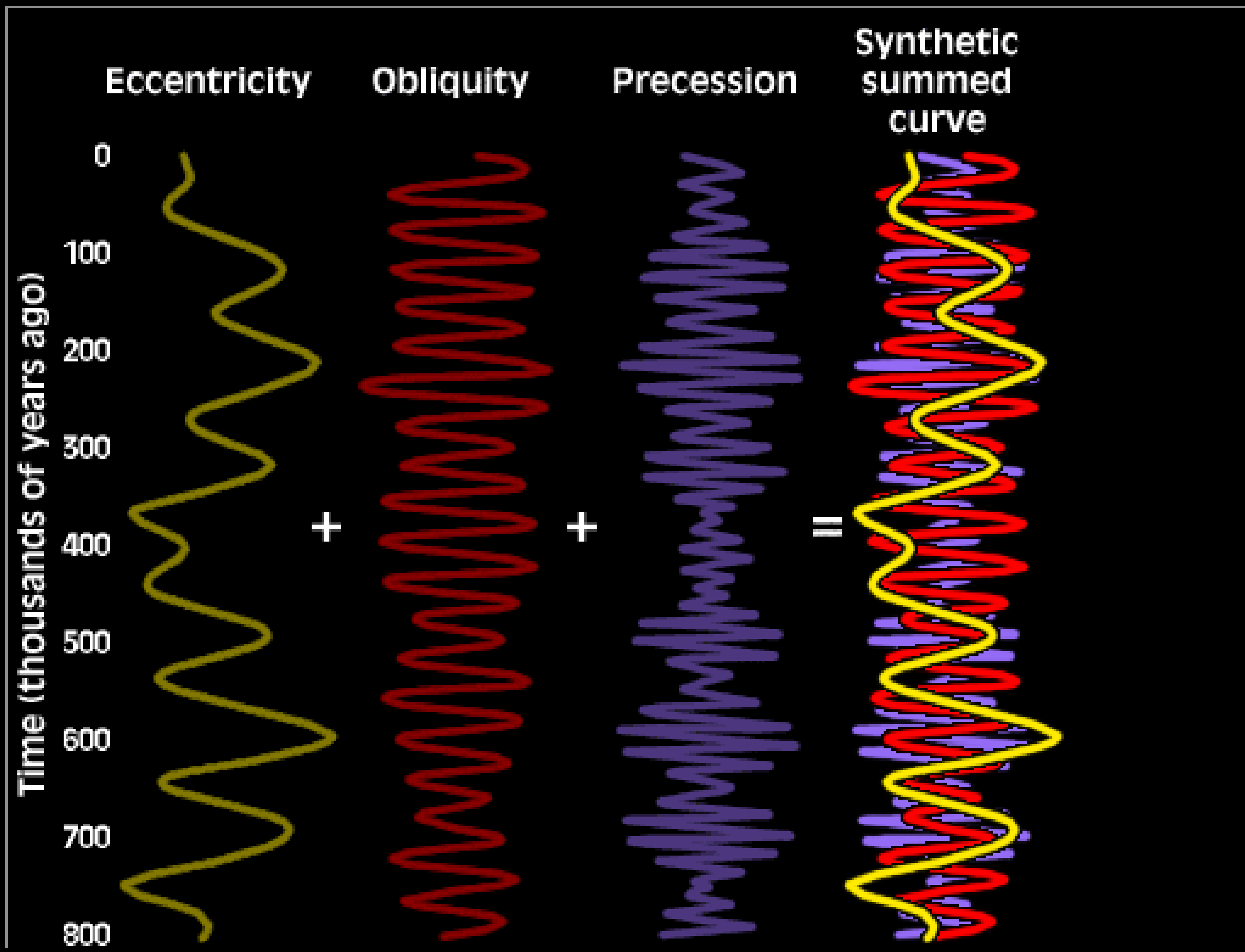



Eccentricity
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800

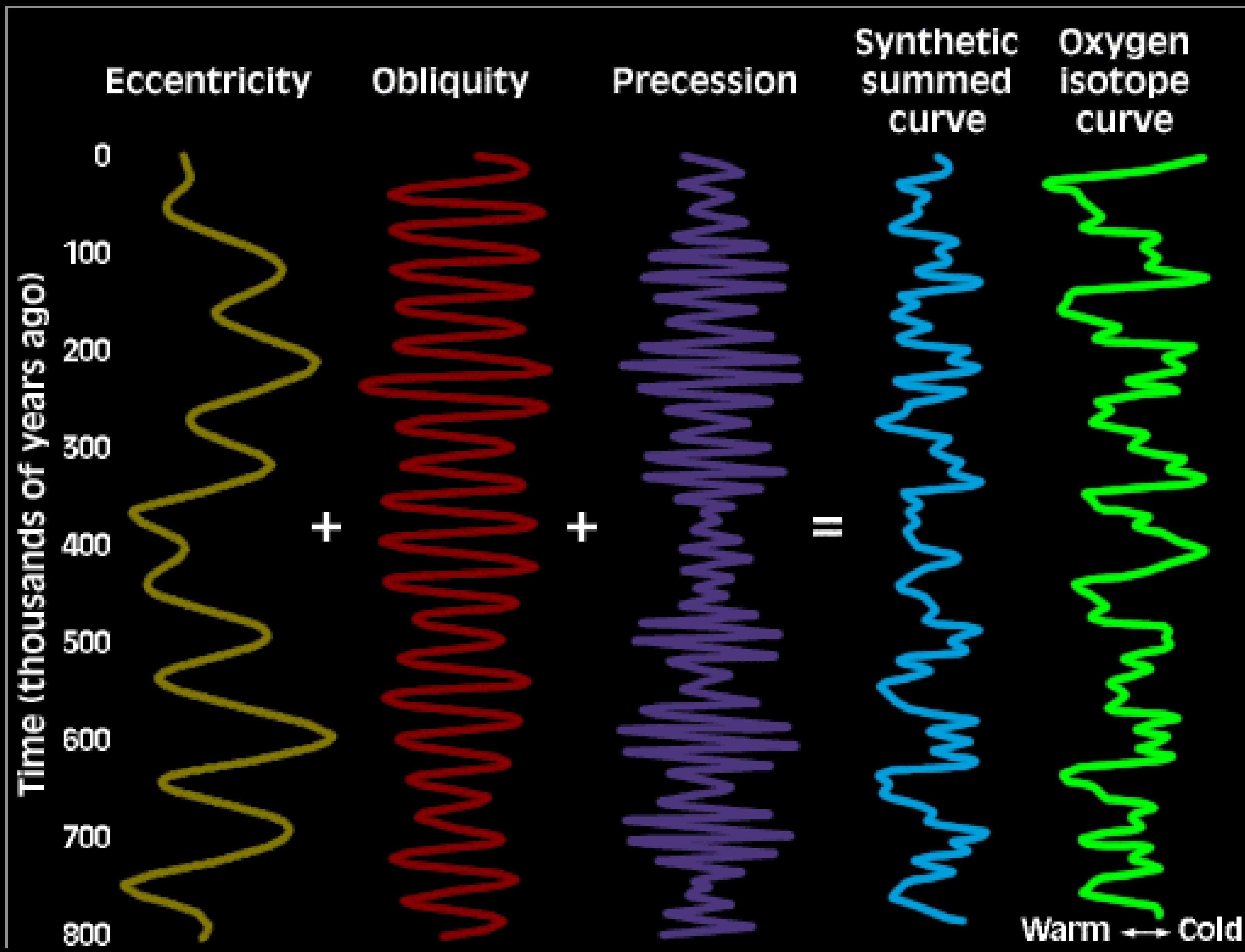

Eccentricity
Obliquity
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800
+



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



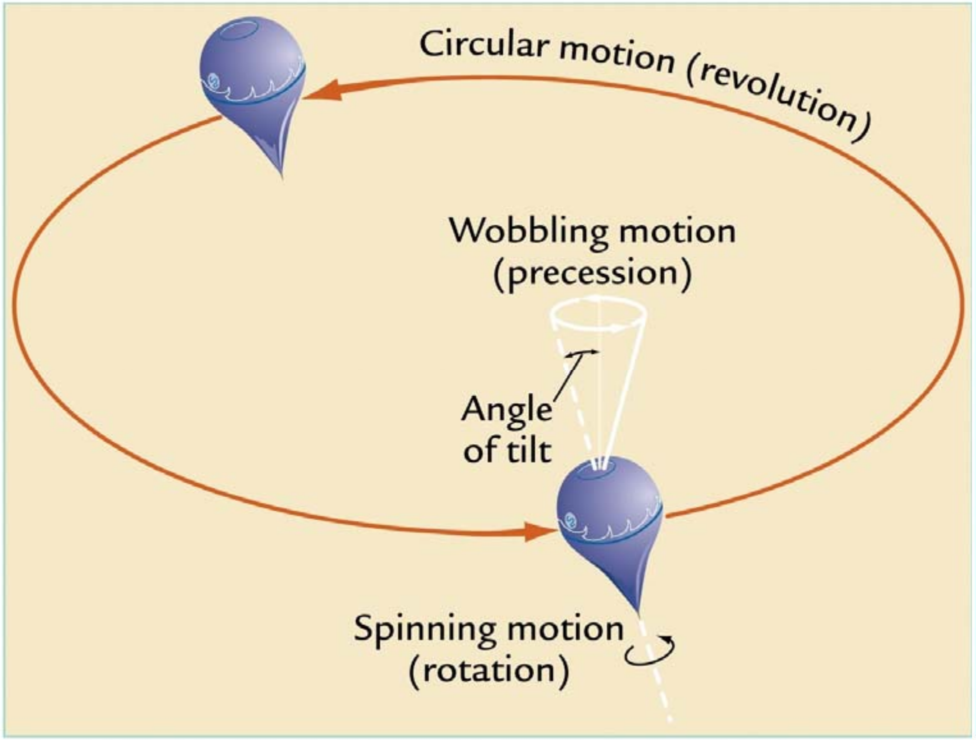
Eccentricity
Obliquity
Precession
Synthetic summed curve
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800
+
+
=



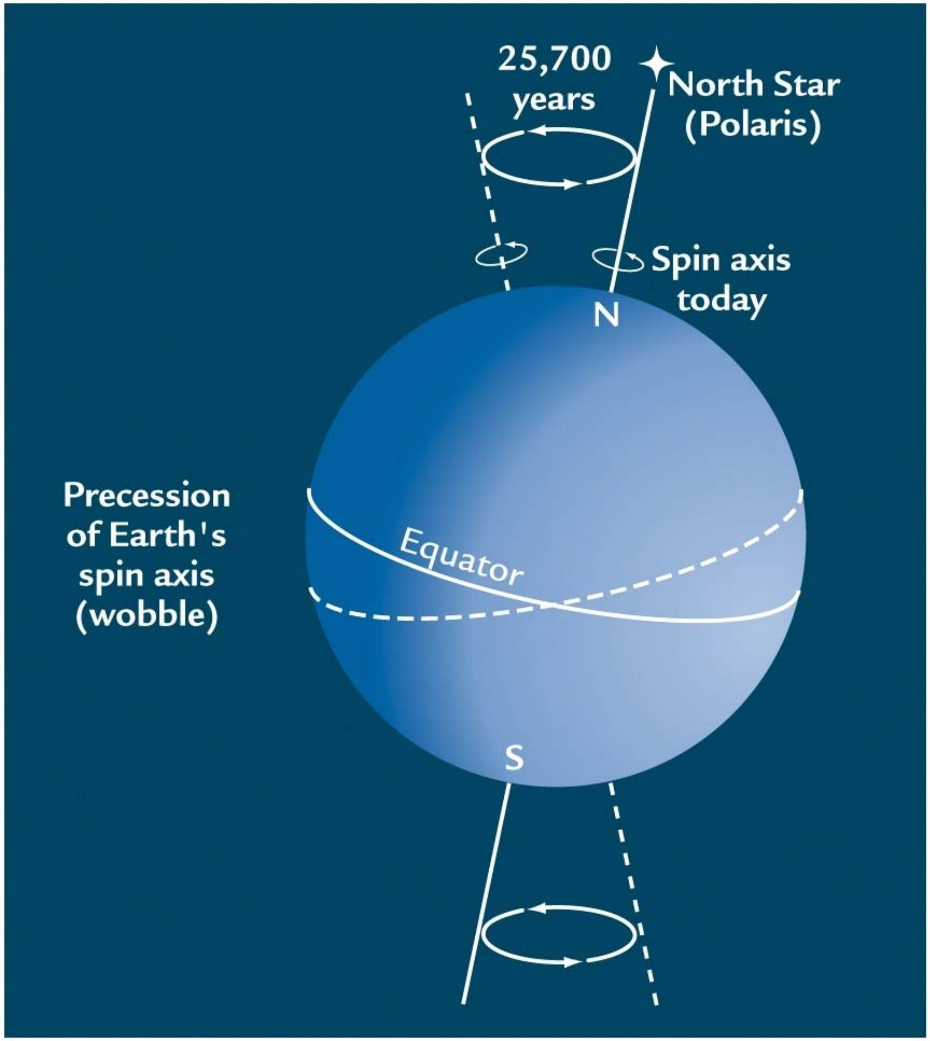
Eccentricity
Obliquity
Precession
Synthetic summed curve
Oxygen isotope curve
Time (thousands of years ago)
0
100
200
300
400
500
600
700
800
+
+
=
Warm ⟷ Cold

Sunspots Photo: Nasa

Precession

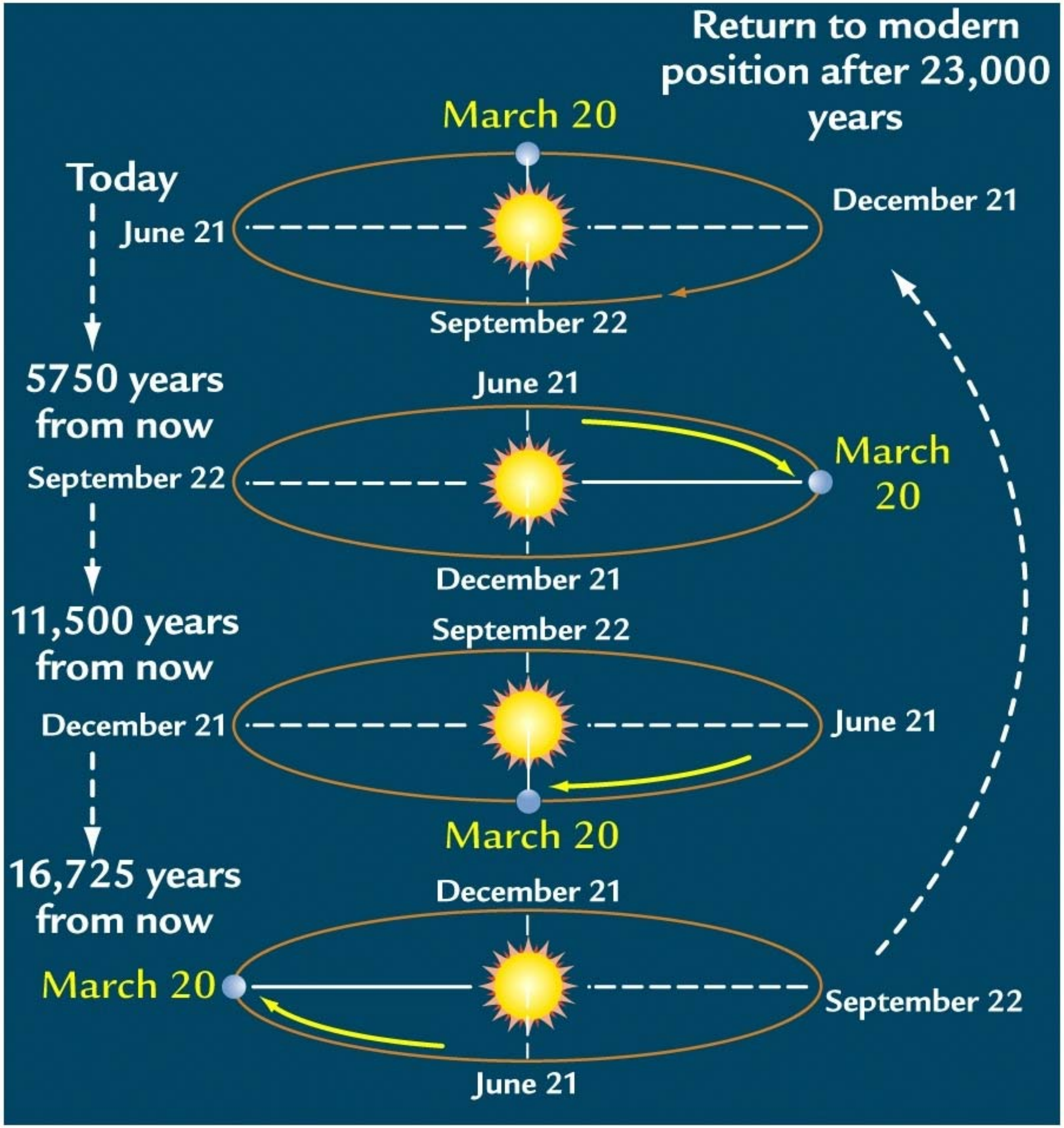


Circular motion (revolution)
Wobbling motion
(precession)
Angle
of tilt
Spinning motion
(rotation)



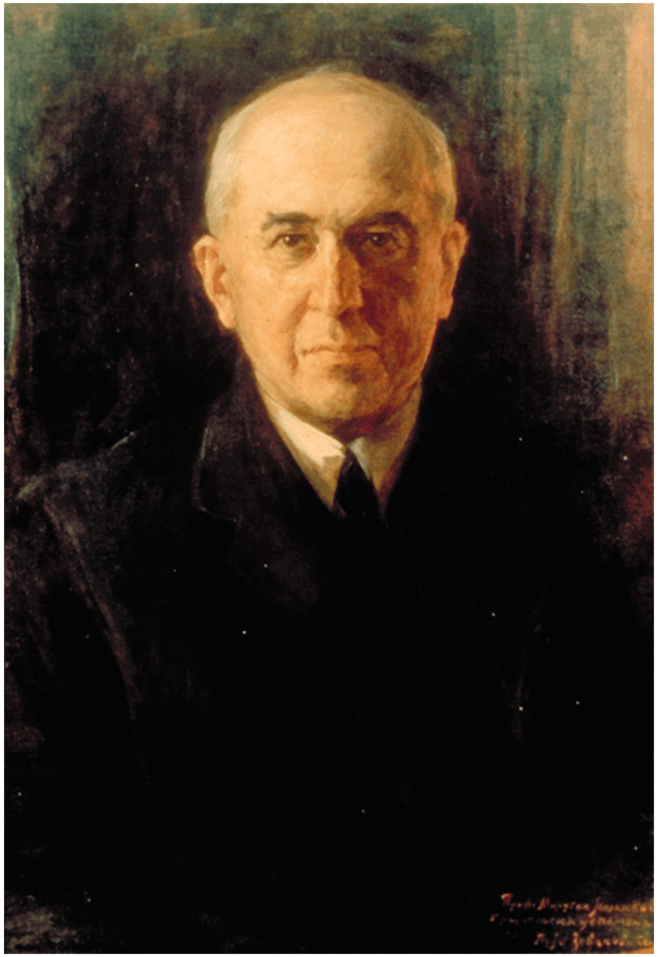
25,700
years
North Star
(Polaris)
Spin axis
today
N
Precession
of Earth's
spin axis
(wobble)
Equator
S

Precession



Return to modern position after 23,000 years
Today
March 20
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

Portrait of Milutin Milankovitch by Paja Jovanovic, 1943, courtesy of Vasko Milankovitch



Milutin Milankovitch (1879 - 1958)

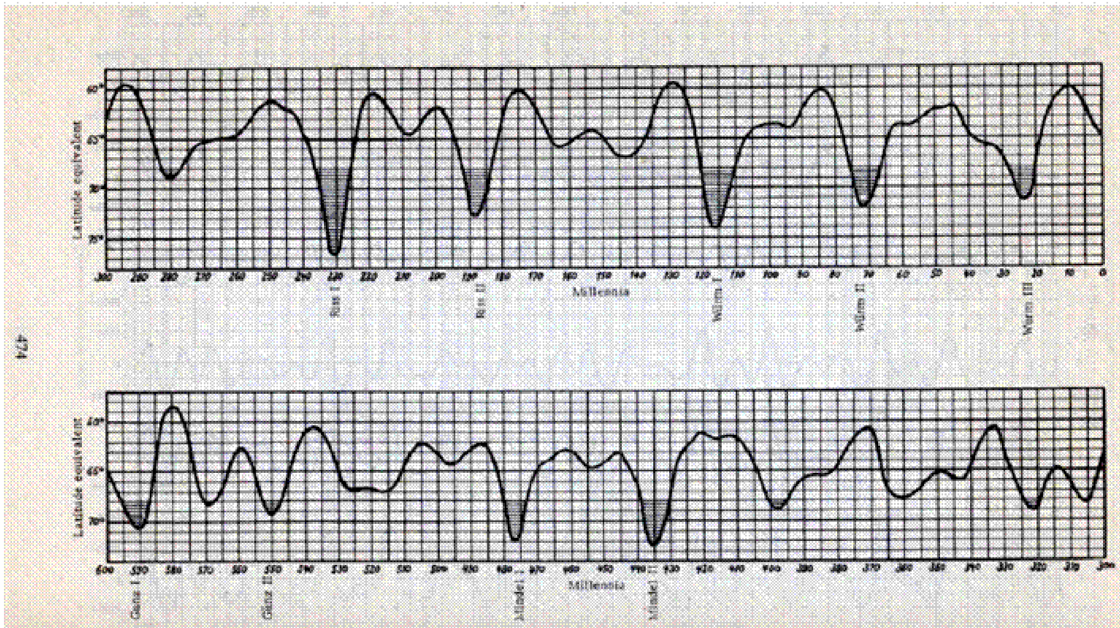


FIGURE 87. The secular march of the summer insolation for 65° North represented by latitudinal oscillations

(Milankovitch, 1941)

- Glaciations correspond to summer insolation minima…

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.

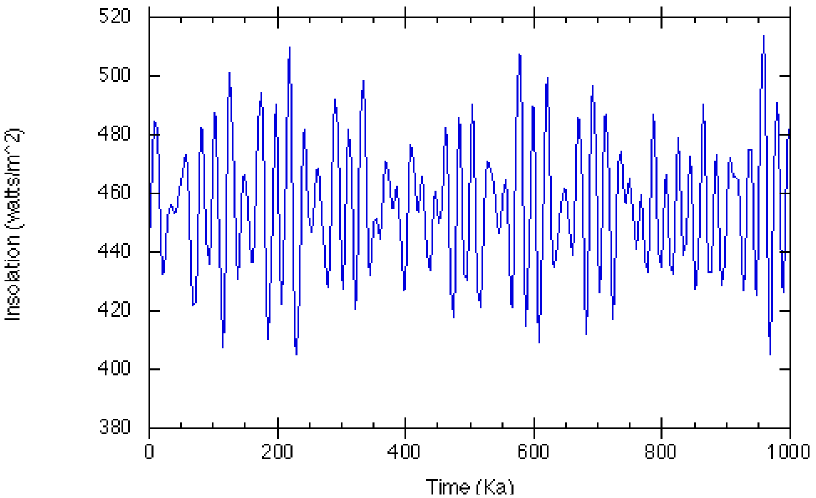
Despite these considerable advances, Milankovitch's theory was not widely accepted in his day. It's major limitation was the lack of a well dated, continuous climate curve to test the hypothesis.

The modern rebirth of the Milankovitch Hypothesis required several advances

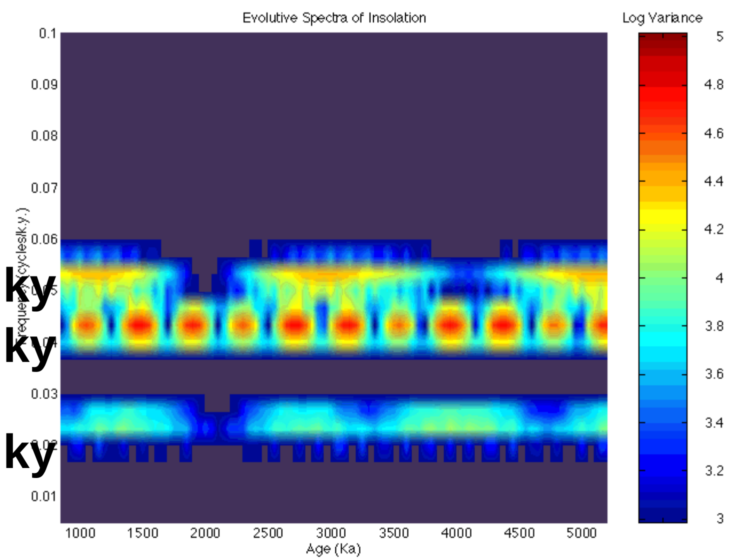
1. Continuous sedimentary sequences
2. A reliable means of extracting continuous climate information from these sediments
3. Improved dating methods (chronology)
4. Quantitative analysis methods

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.



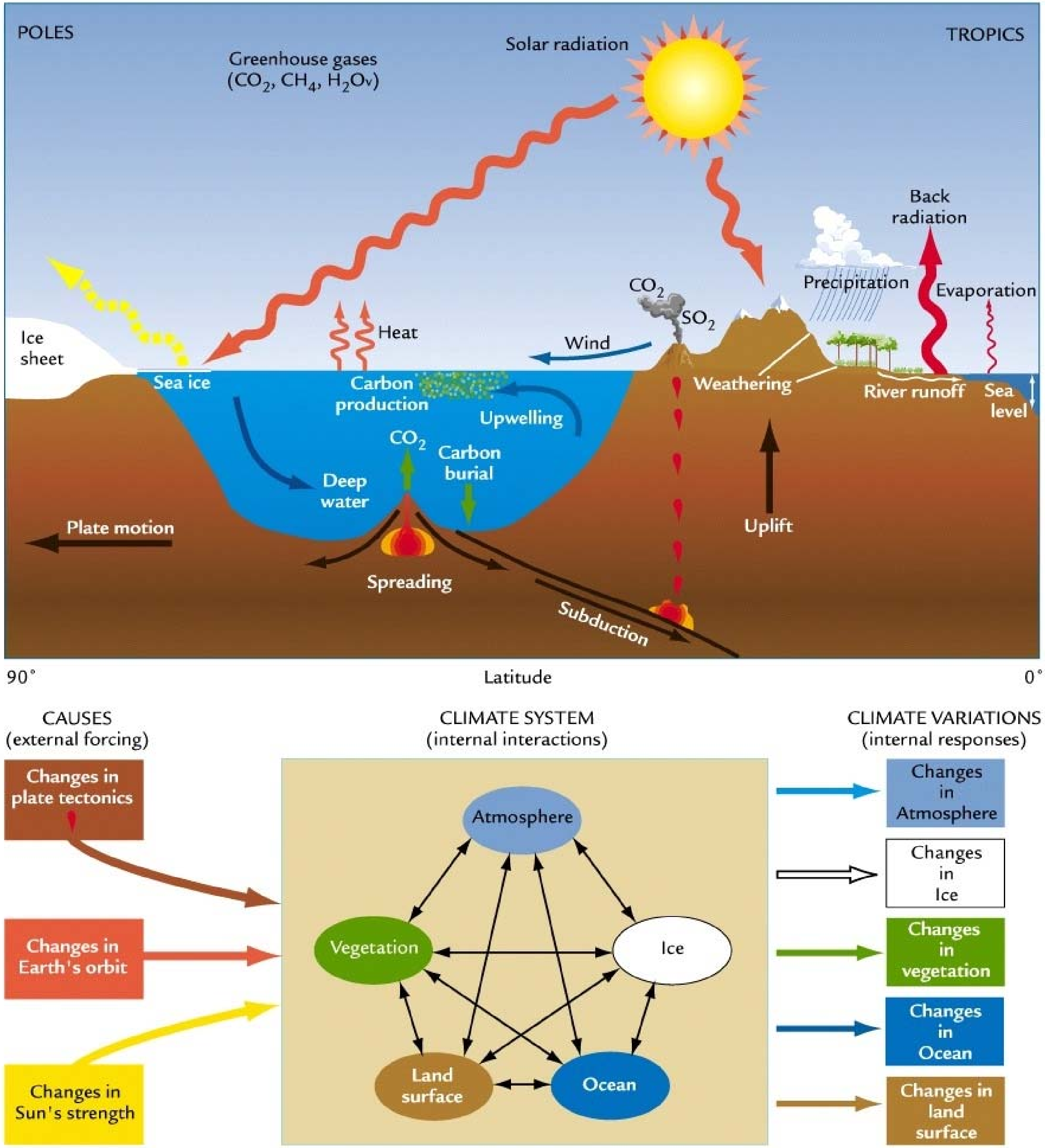
0.052 = 19 ky

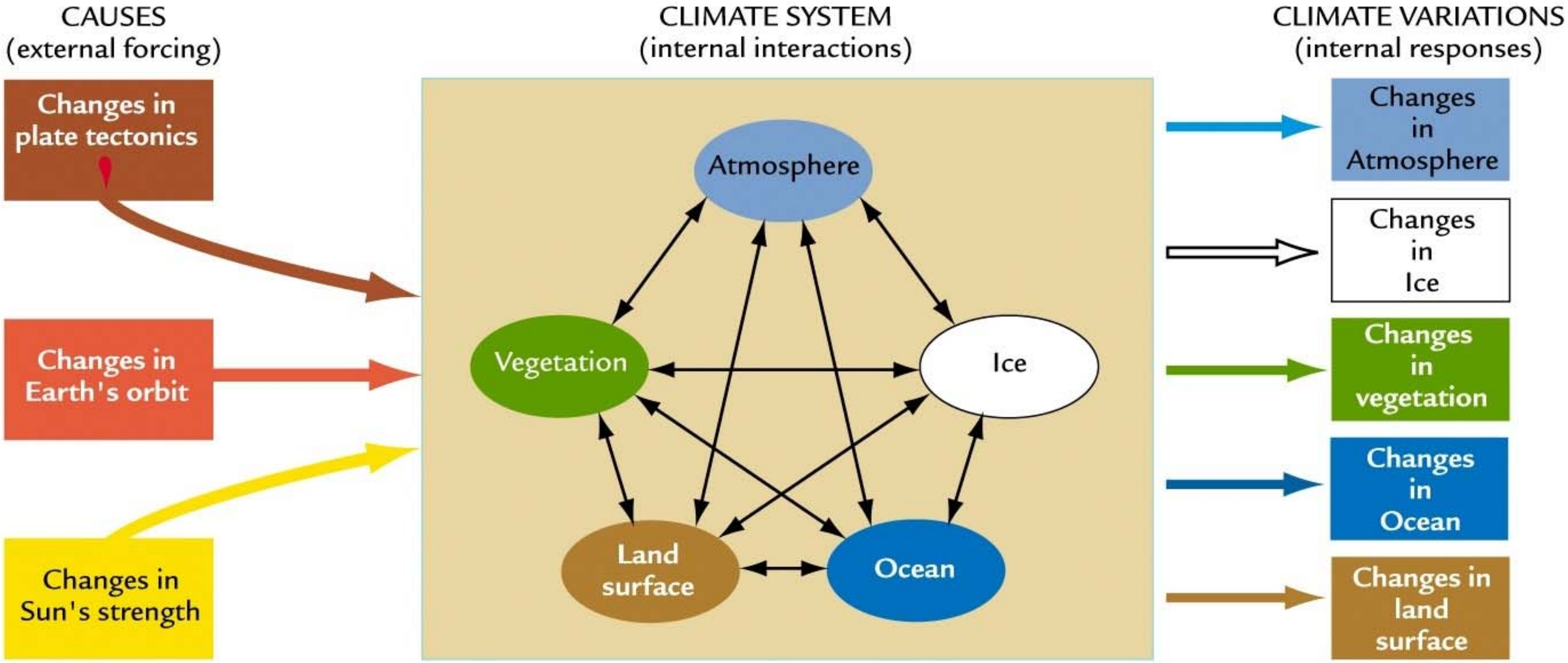
0.043 = 23 ky

0.024 = 41 ky

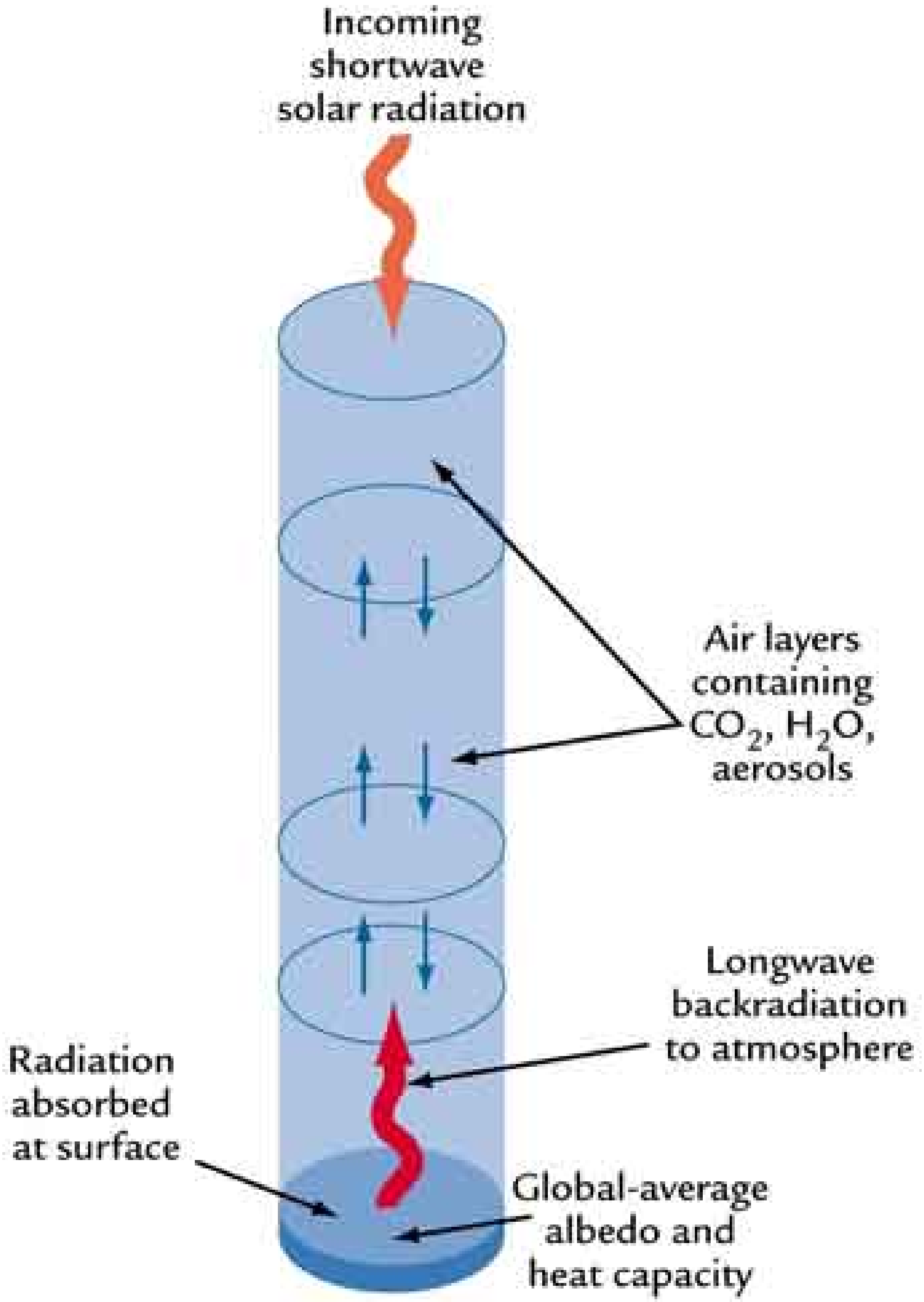
Reasons

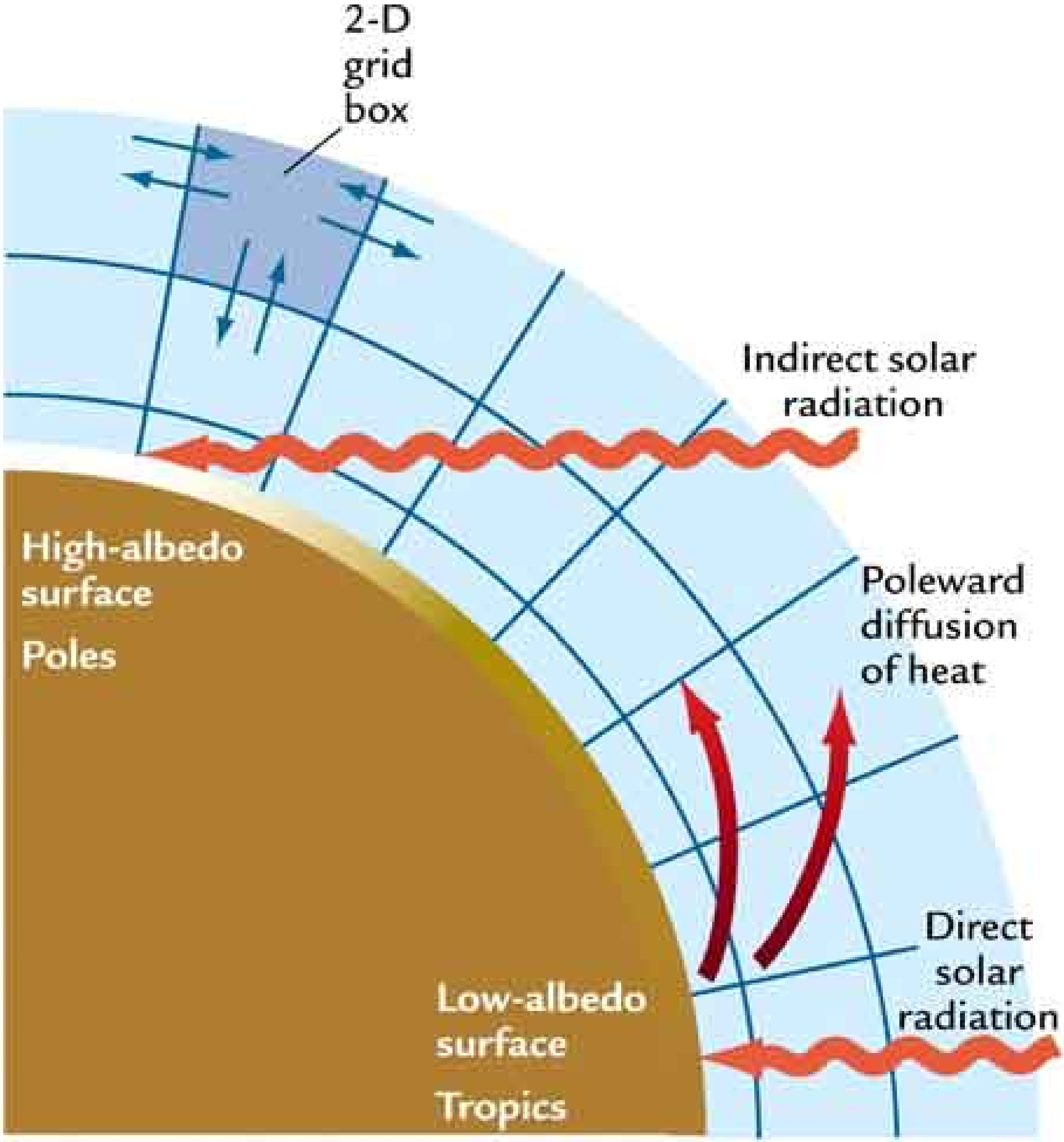
- **Obliquity:** caused by the gravitational pull of large planets, including Jupiter. Earth's obliquity varies cyclically with a period of 41,000 years.
- **Eccentricity** of the orbit ~100,000 years due mostly to the gravitation perturbations due to Venus.
- **Precession** (~20,000) due to the **equatorial 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.**

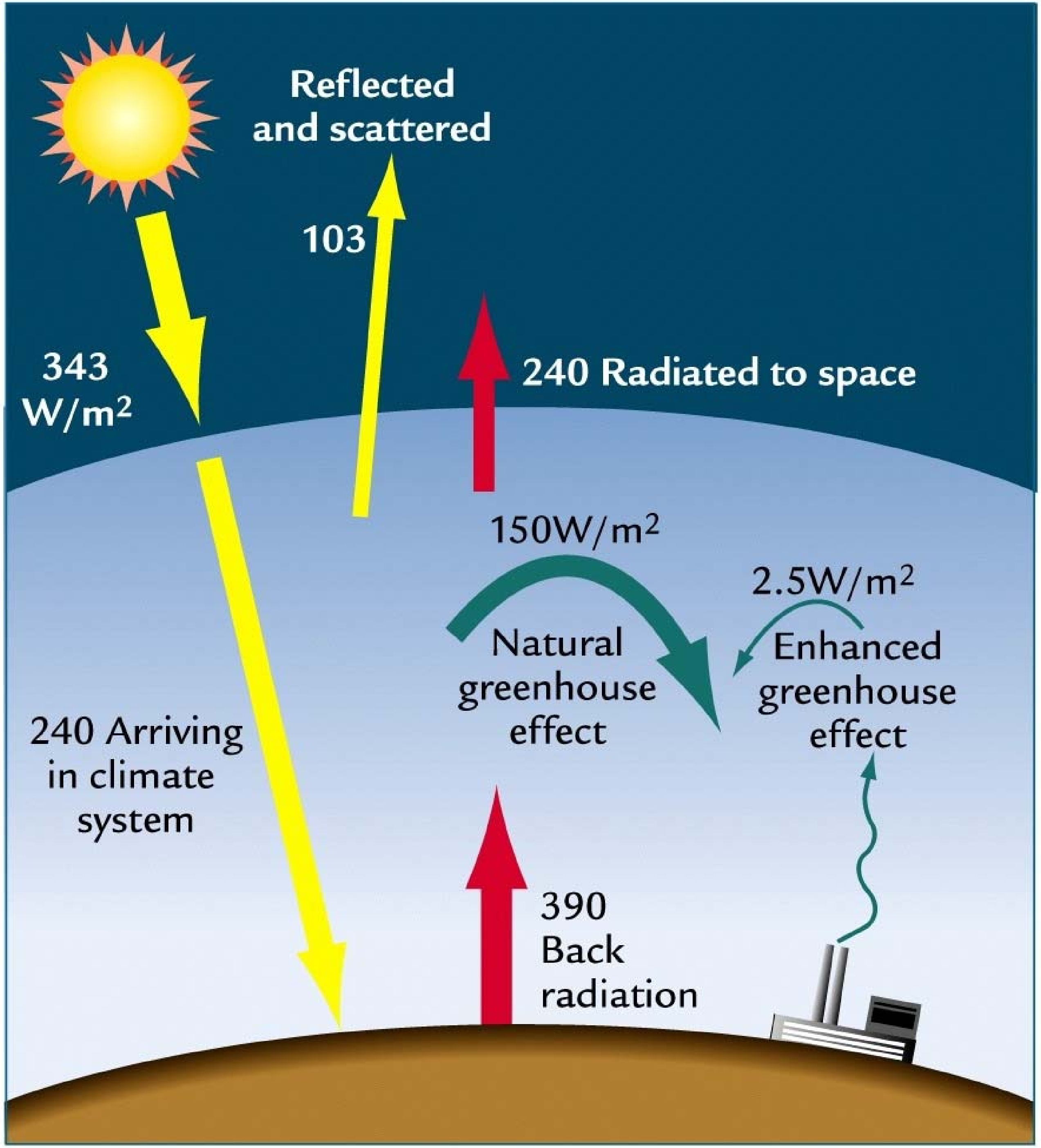

POLES
TROPICS
Greenhouse gases
(CO_2, CH_4, H_2Ov)
Solar radiation
Back
radiation
Precipitation
Evaporation
CO_2
SO_2
Ice
sheet
Heat
Wind
Sea ice
Carbon
production
Upwelling
Weathering
River runoff
Sea
level
CO_2
Carbon
burial
Deep
water
Plate motion
Uplift
Spreading
Subduction
90°
Latitude
0°
CAUSES
(external forcing)
CLIMATE SYSTEM
(internal interactions)
CLIMATE VARIATIONS
(internal responses)
Changes in
plate tectonics
Changes in
Earth's orbit
Changes in
Sun's strength
Atmosphere
Vegetation
Ice
Land
surface
Ocean
Changes
in
Atmosphere
Changes
in
Ice
Changes
in
vegetation
Changes
in
Ocean
Changes in
land
surface



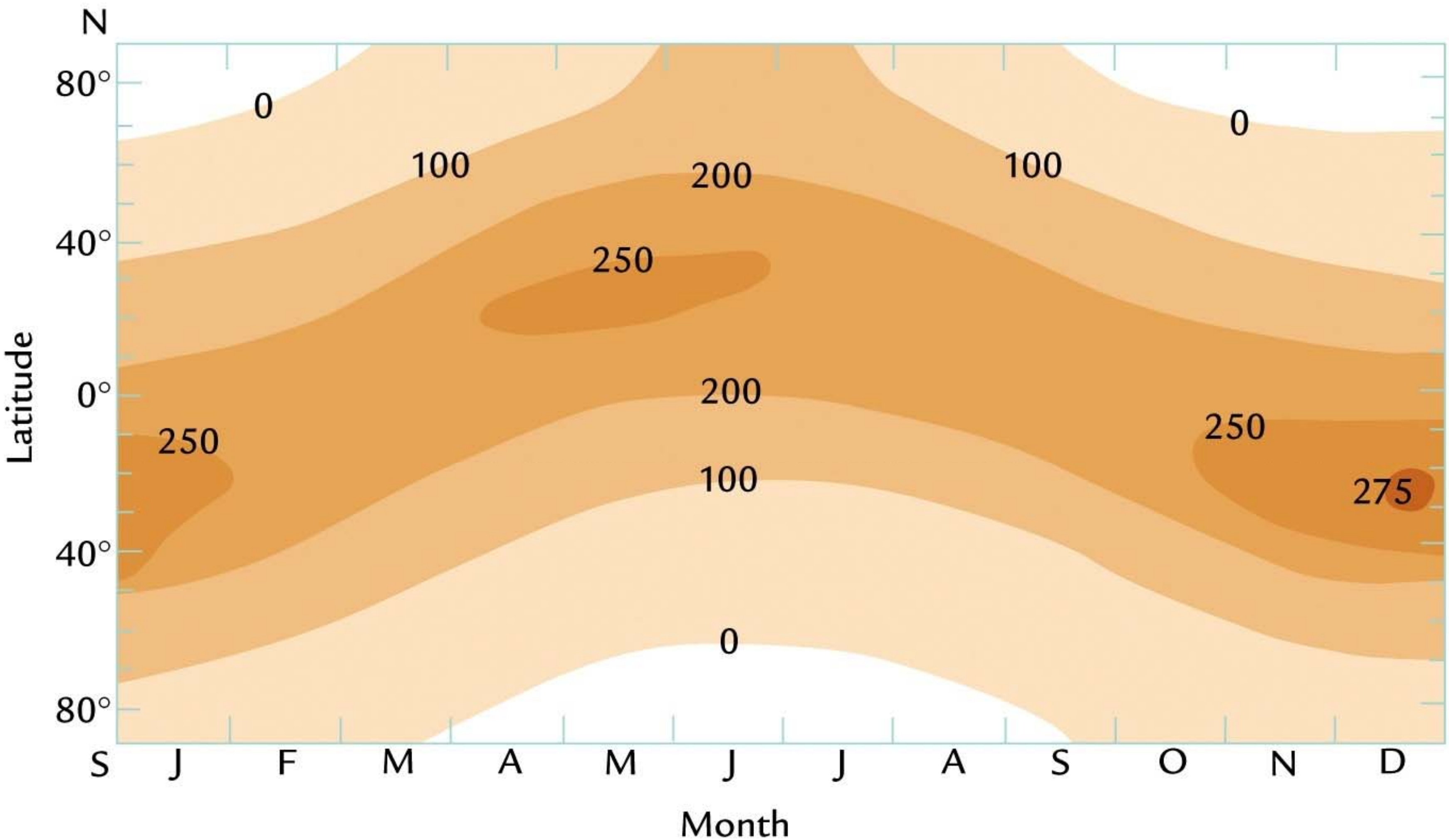
CAUSES
(external forcing)
CLIMATE SYSTEM
(internal interactions)
CLIMATE VARIATIONS
(internal responses)
Changes in plate tectonics
Changes in Earth's orbit
Changes in Sun's strength
Atmosphere
Vegetation
Ice
Land surface
Ocean
Changes in Atmosphere
Changes in Ice
Changes in vegetation
Changes in Ocean
Changes in land surface


Incoming shortwave solar radiation
Air layers containing CO_2, H_2O, aerosols
Longwave backradiation to atmosphere
Radiation absorbed at surface
Global-average albedo and heat capacity

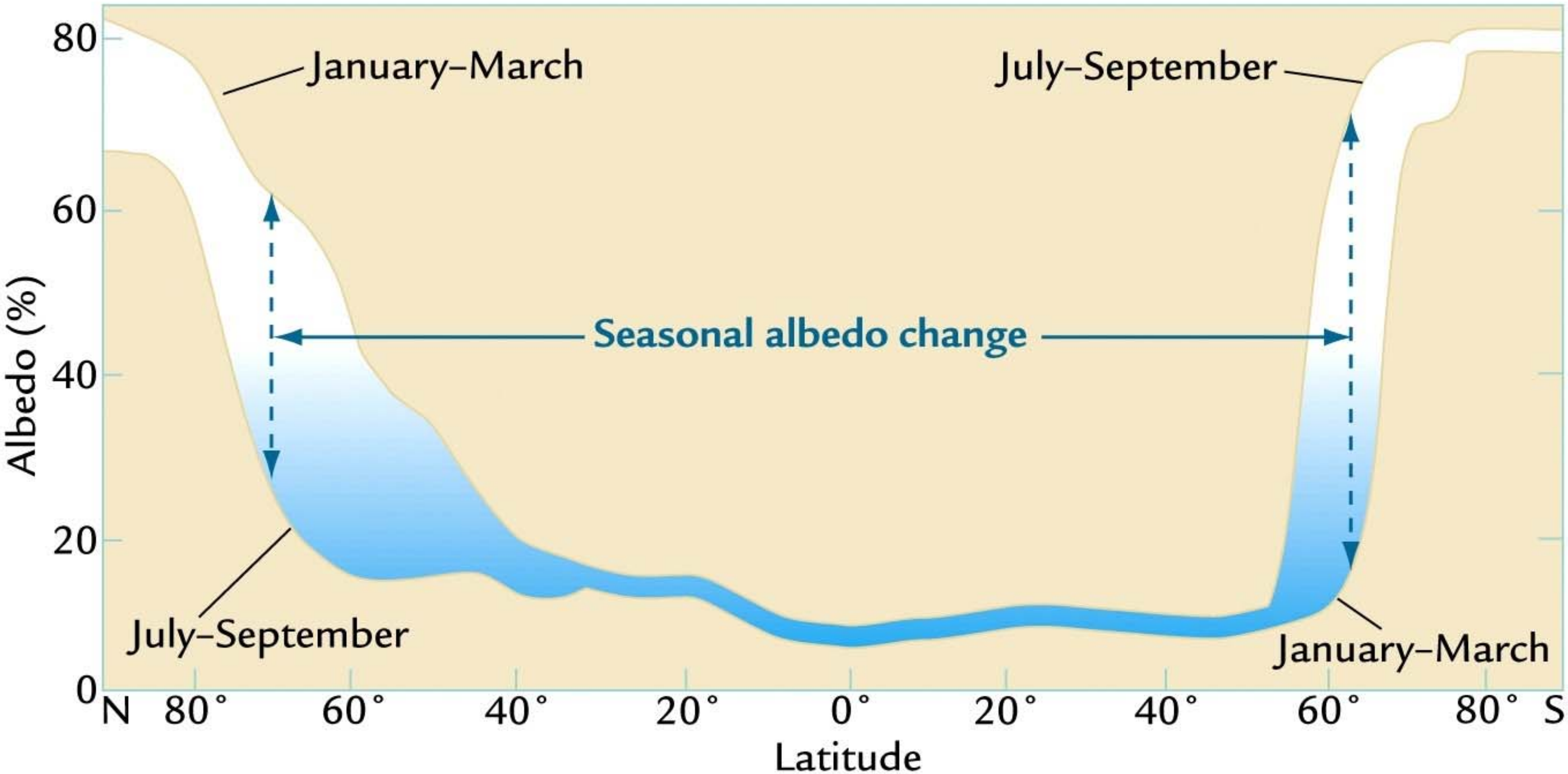

2-D grid box
Indirect solar radiation
High-albedo surface
Poles
Poleward diffusion of heat
Direct solar radiation
Low-albedo surface
Tropics



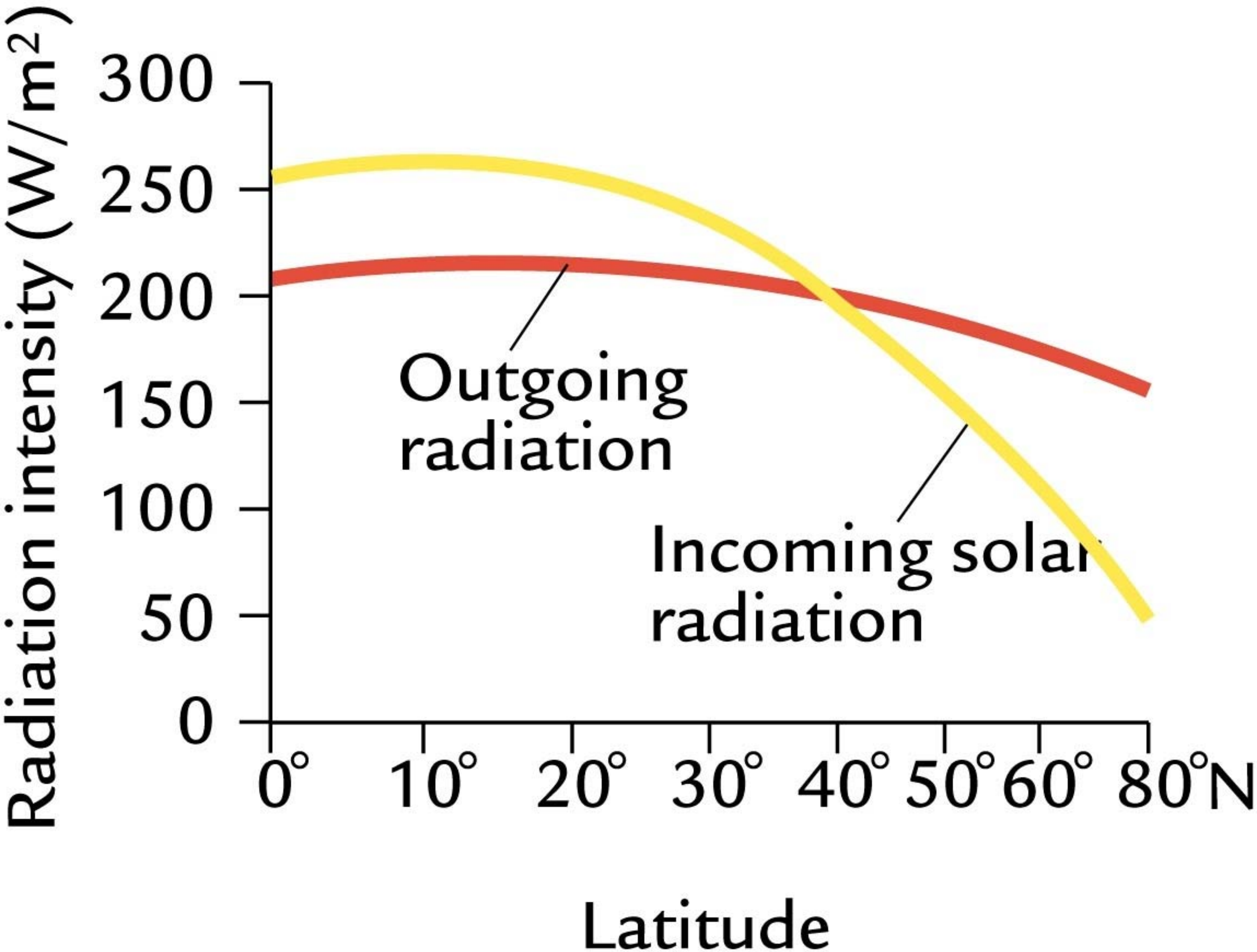
Reflected
and scattered
103
343
W/m2
240 Radiated to space
150W/m2
2.5W/m2
Natural
greenhouse
effect
Enhanced
greenhouse
effect
240 Arriving
in climate
system
390
Back
radiation



B Seasonal radiation (W/m²)

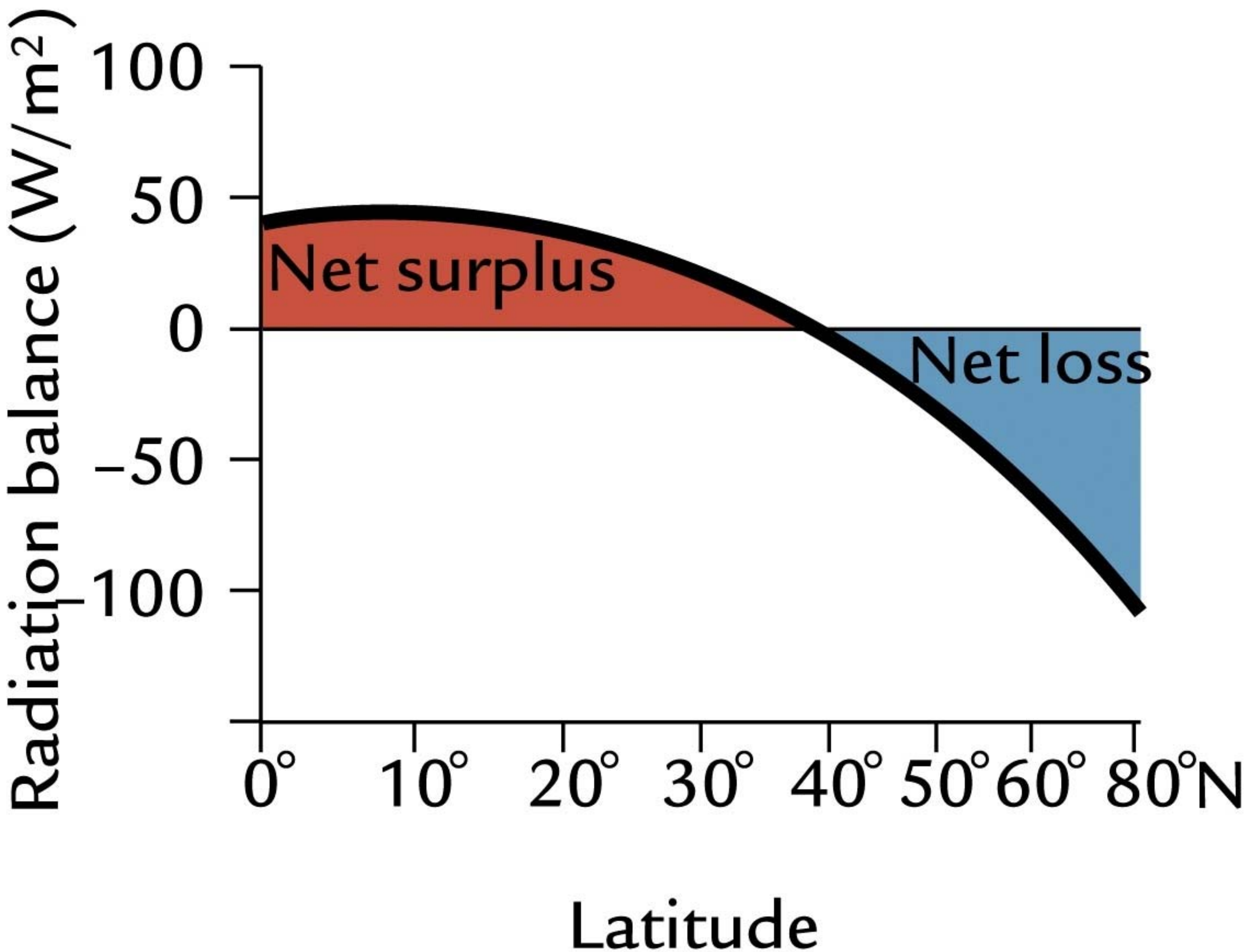


80
60
40
20
0
Albedo (%)
January–March
July–September
Seasonal albedo change
July–September
January–March
N
80°
60°
40°
20°
0°
20°
40°
60°
80°
S
Latitude



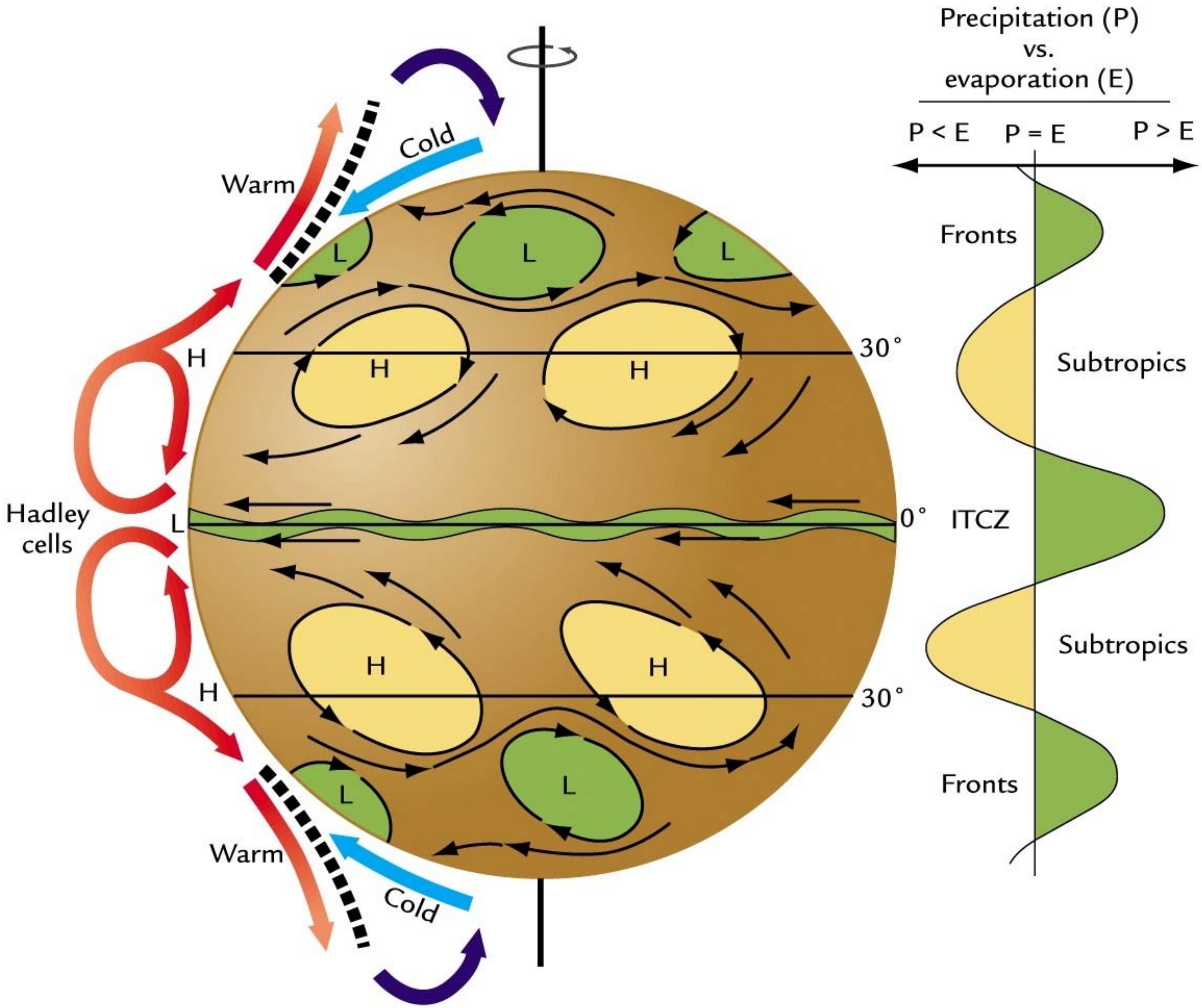
Radiation intensity (W/m²)
300
250
200
150
100
50
0
Outgoing radiation
Incoming solar radiation
0°
10°
20°
30°
40°
50°
60°
80°N
Latitude

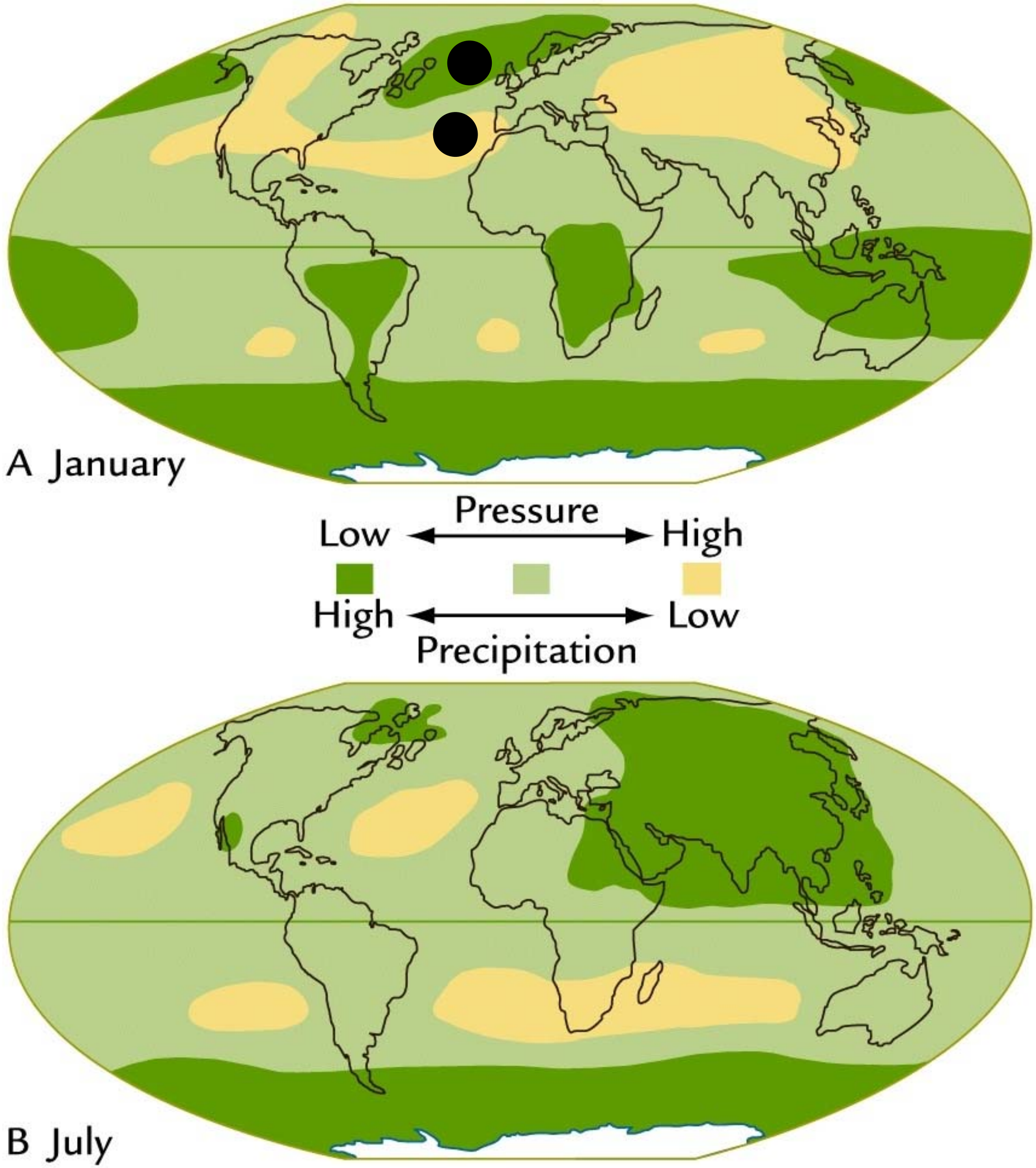
A

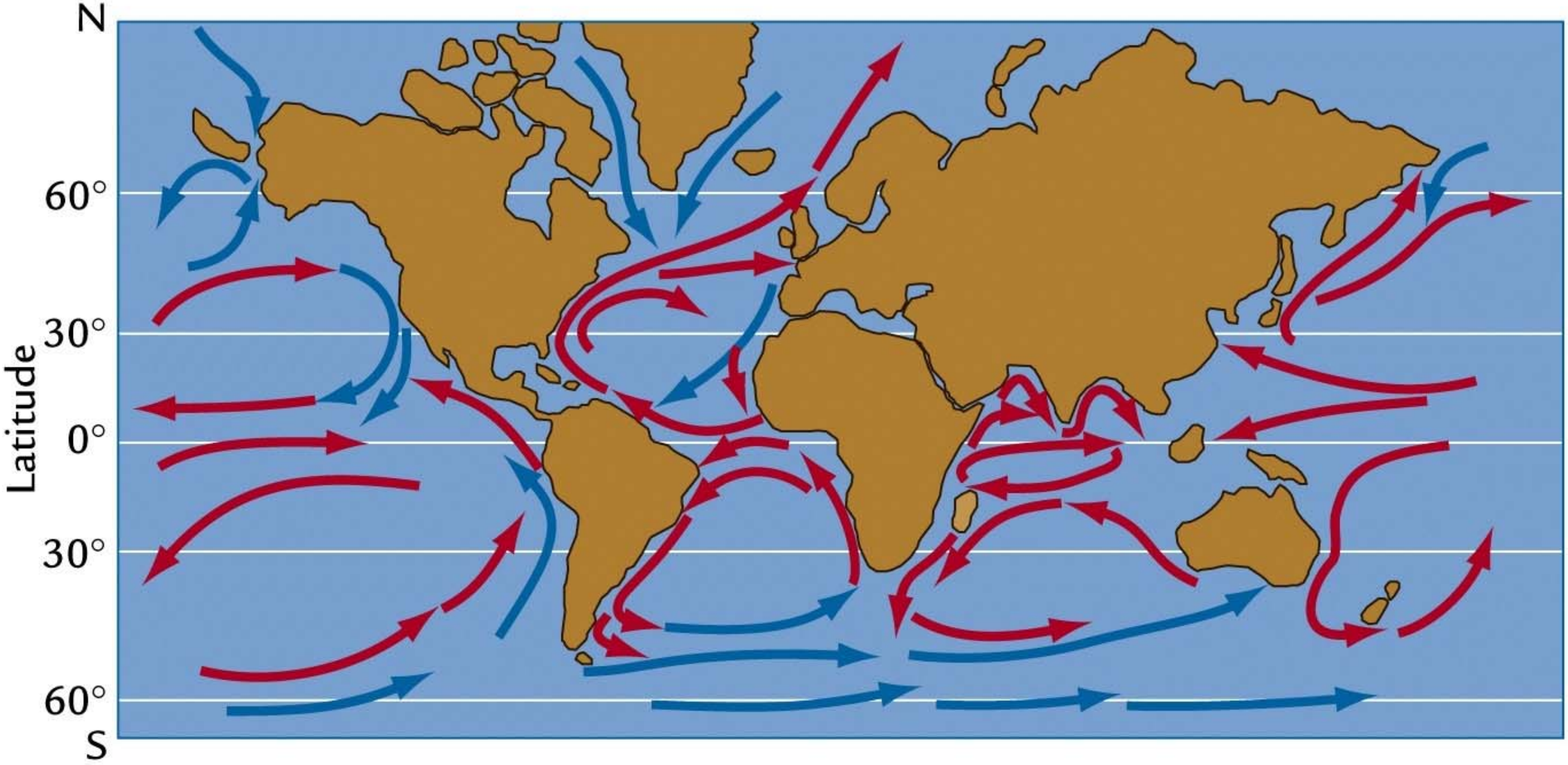


Radiation balance (W/m²)
100
50
0
−50
−100
Net surplus
Net loss
0°
10°
20°
30°
40°
50°
60°
80°N
Latitude

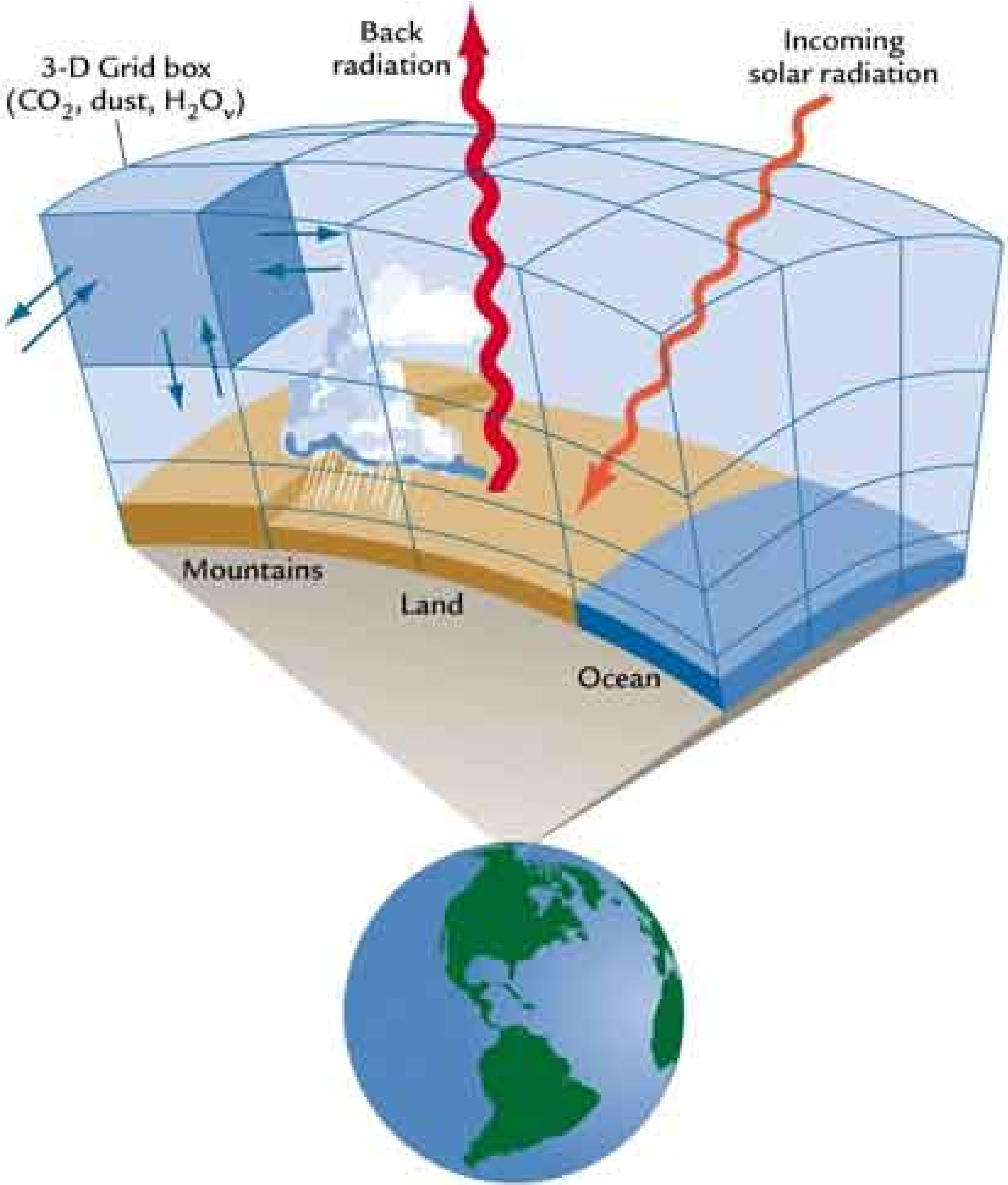
B


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


A January
Pressure
Low
High
High
Low
Precipitation
B July


N
60°
30°
0°
30°
60°
S
Latitude


Winter sea ice cover
Gulf Stream
North Atlantic
deep water


3-D Grid box
(CO_2, dust, H_2O_v)
Back
radiation
Incoming
solar radiation
Mountains
Land
Ocean

Modelling

Circulation Models

Fluid dynamical equations

Momentum equations:

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

Continuity equation:

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

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

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

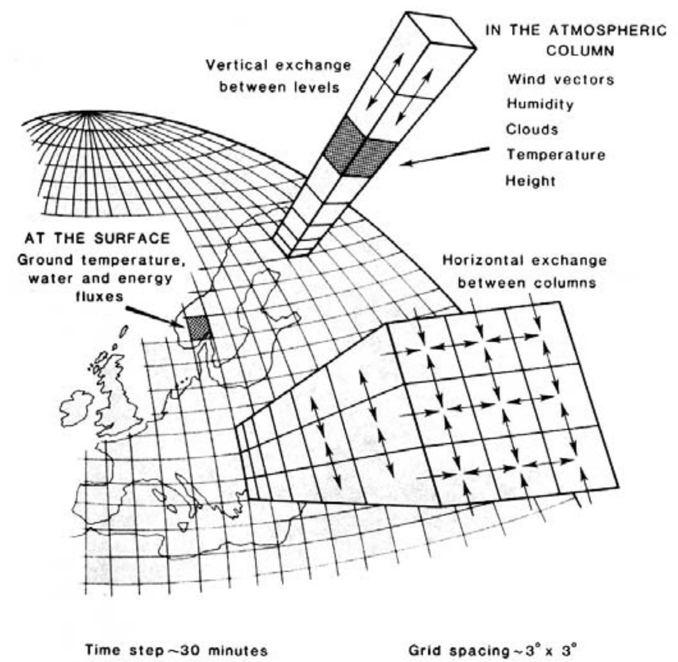
Equation of state:

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

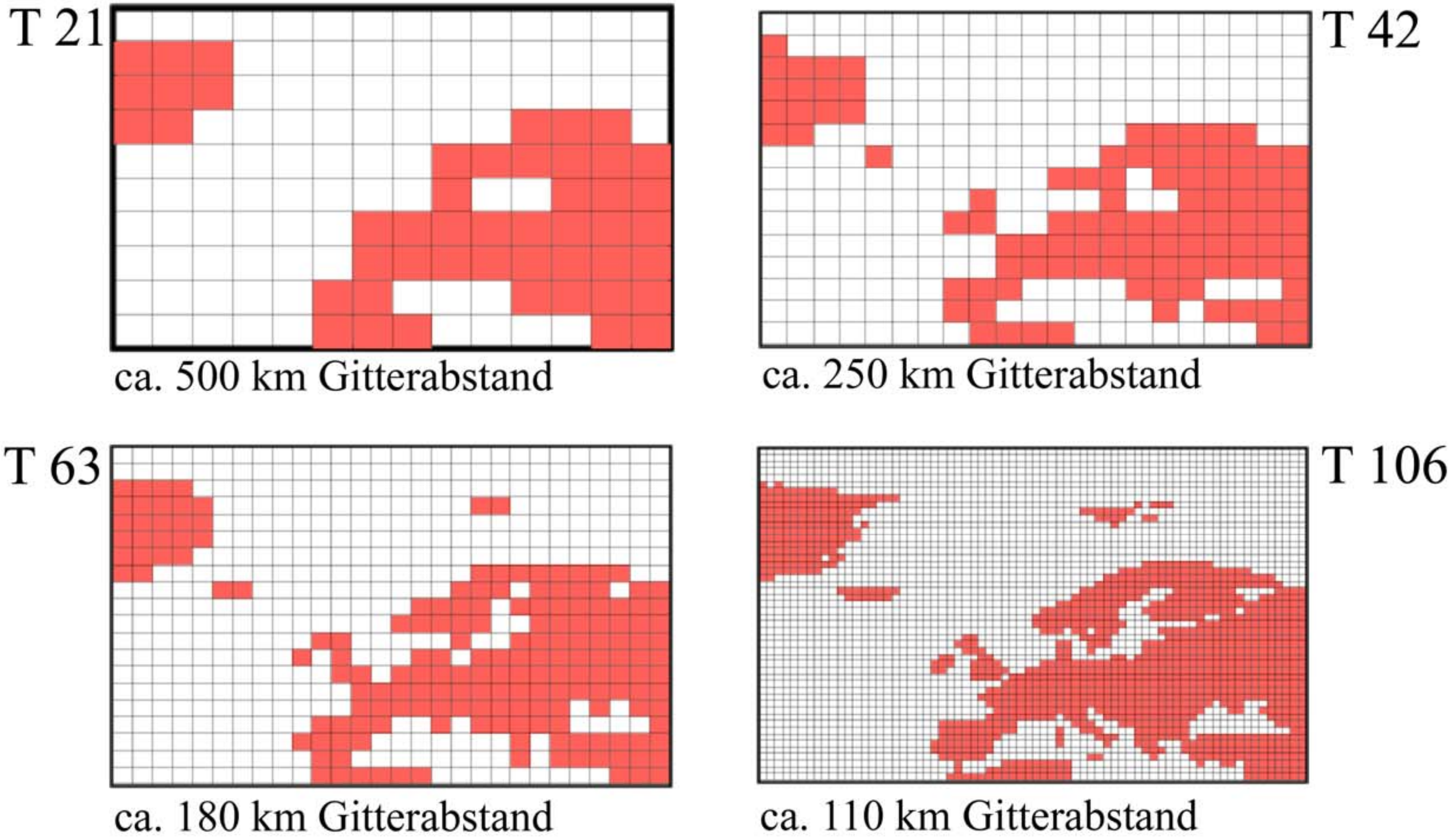
The equations are **"coarse grained"** in space and time.

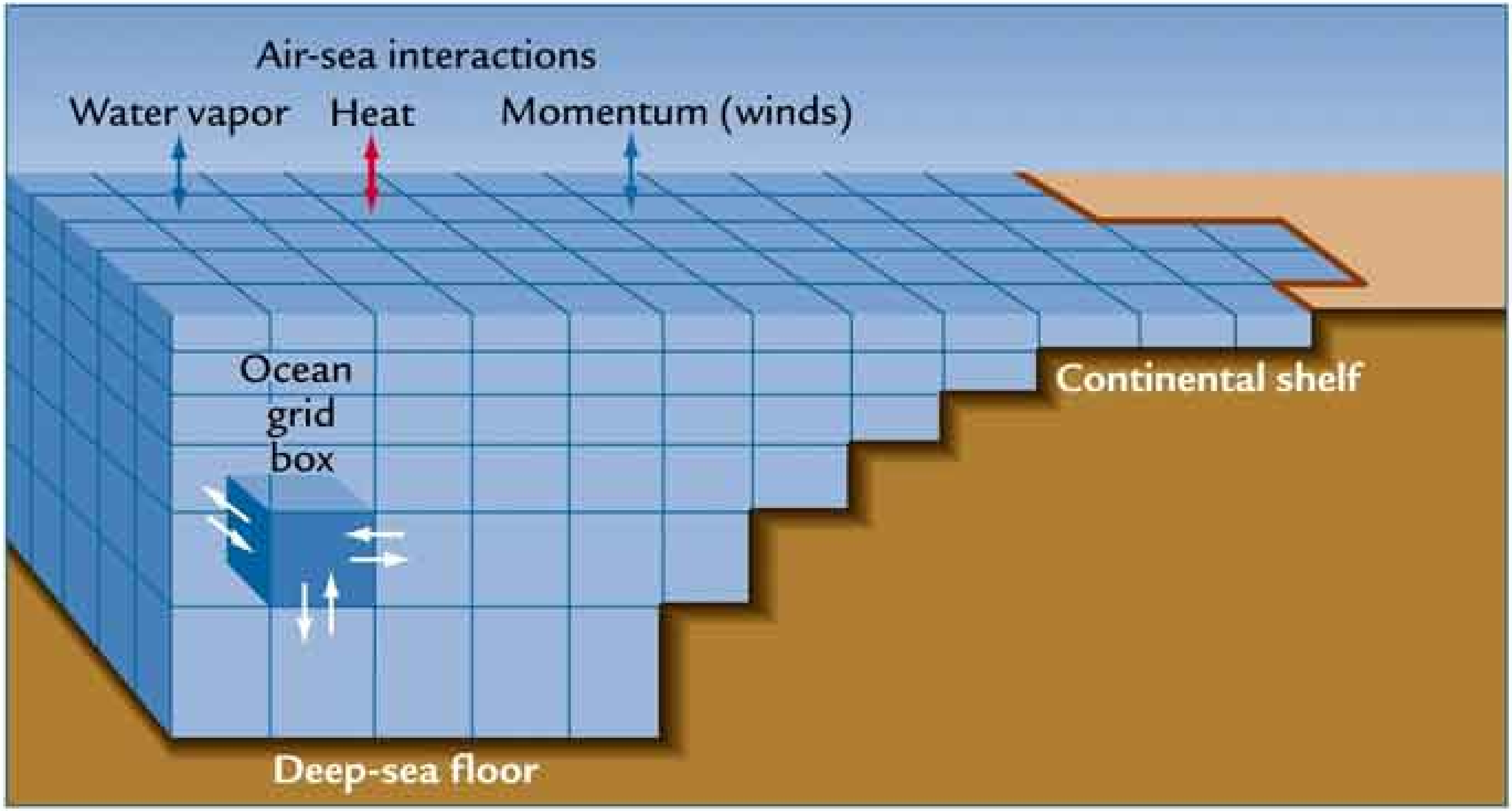
Subgrid scale processes are **parameterized** by diffusive mixing.

Cartesian Grid GCM

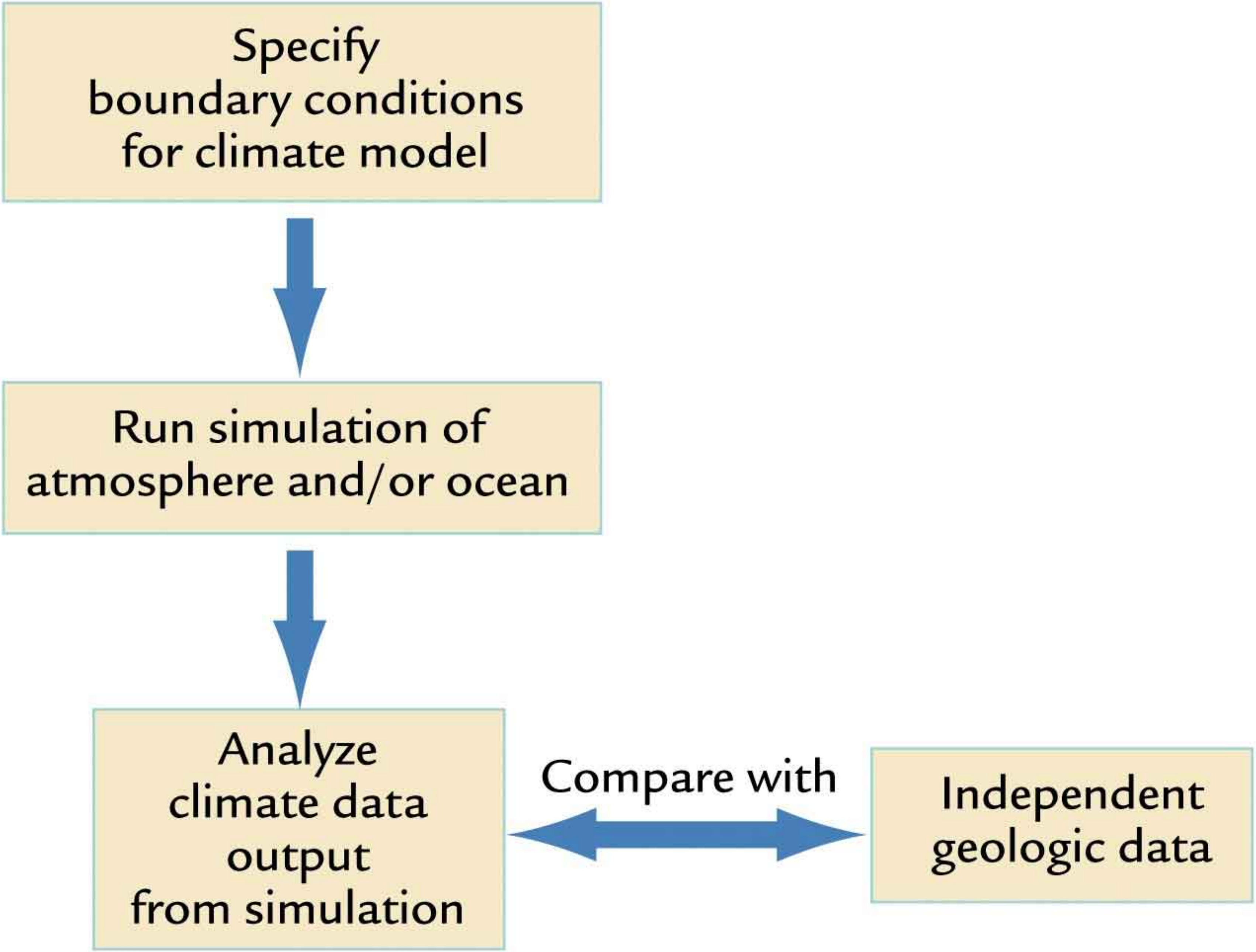


Grid resolution



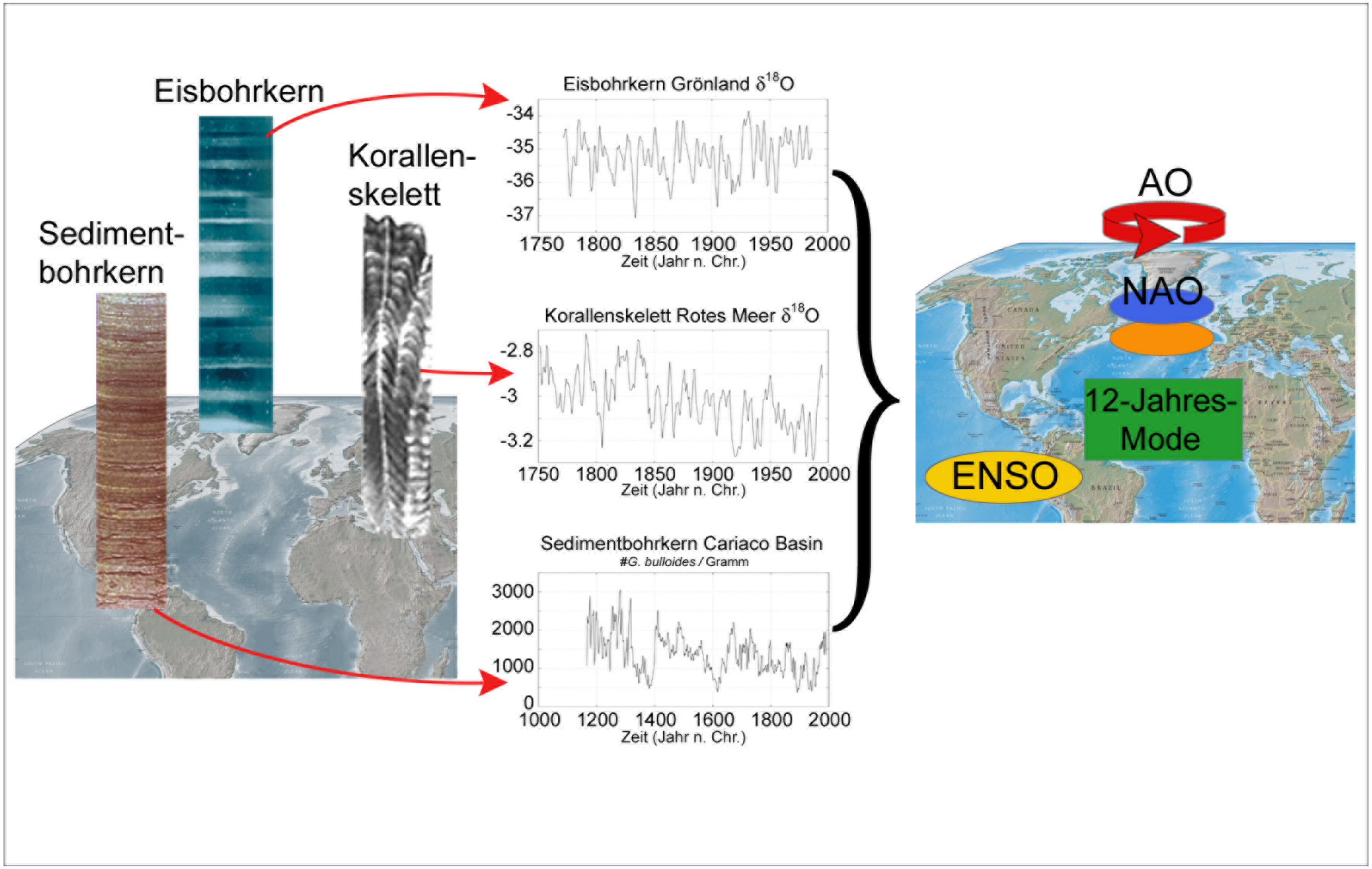


Air-sea interactions
Water vapor
Heat
Momentum (winds)
Ocean
grid
box
Continental shelf
Deep-sea floor


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

Upscaling

Interpretation of Proxy Data



Statistic

Covariance (cross, auto)

$$\gamma(\Delta) = E\left((x(t) - \overline{x}) \, (y(t + \Delta) - \overline{y}) \right)$$

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

Correlation (cross, auto)

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

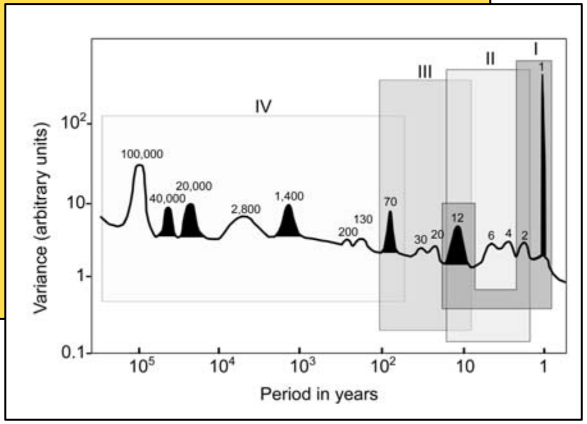
measures the tendency of x (t) and y (t) to covary

Spectrum (cross, auto)

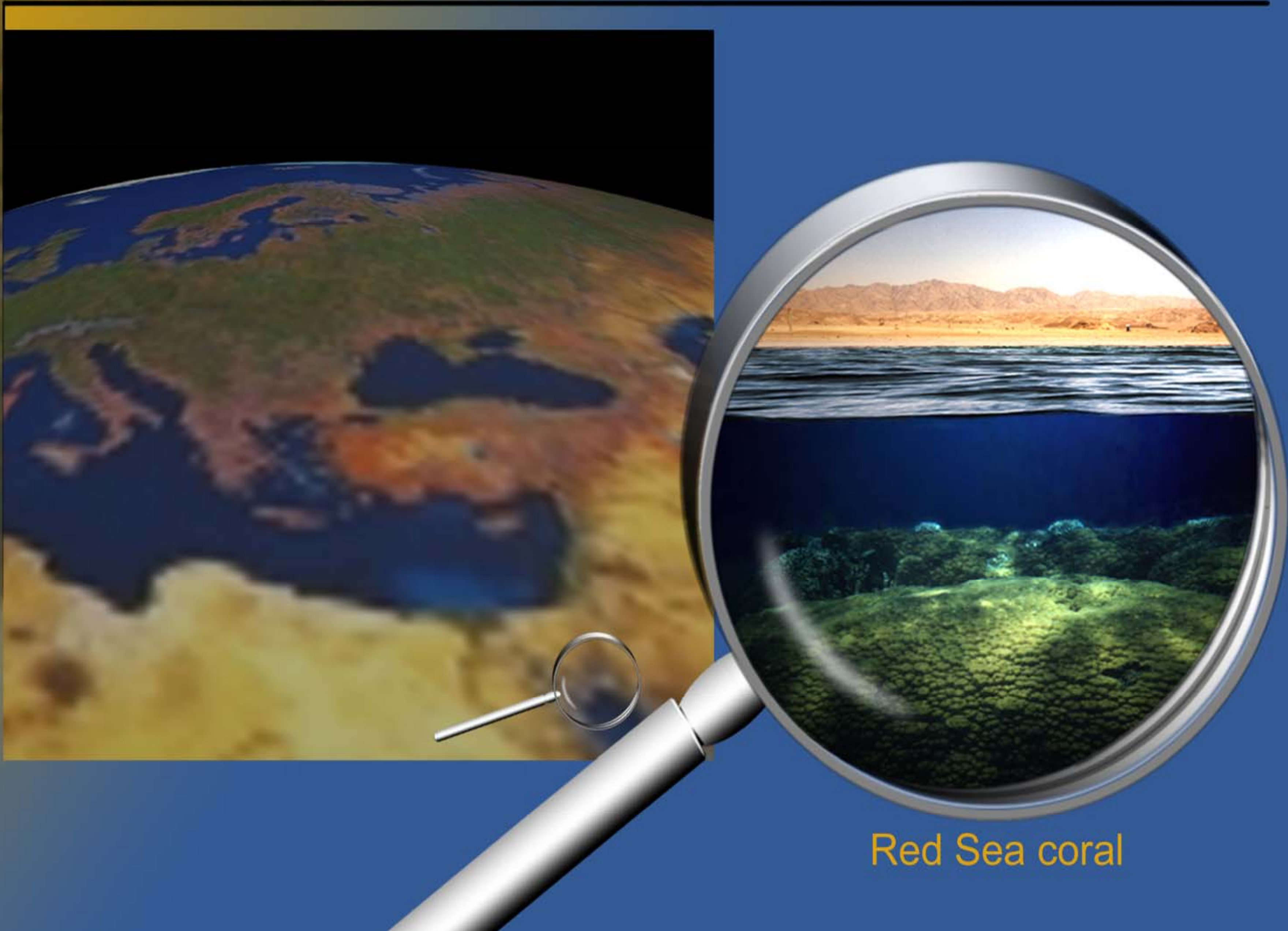
(spectral density)

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

measures variance

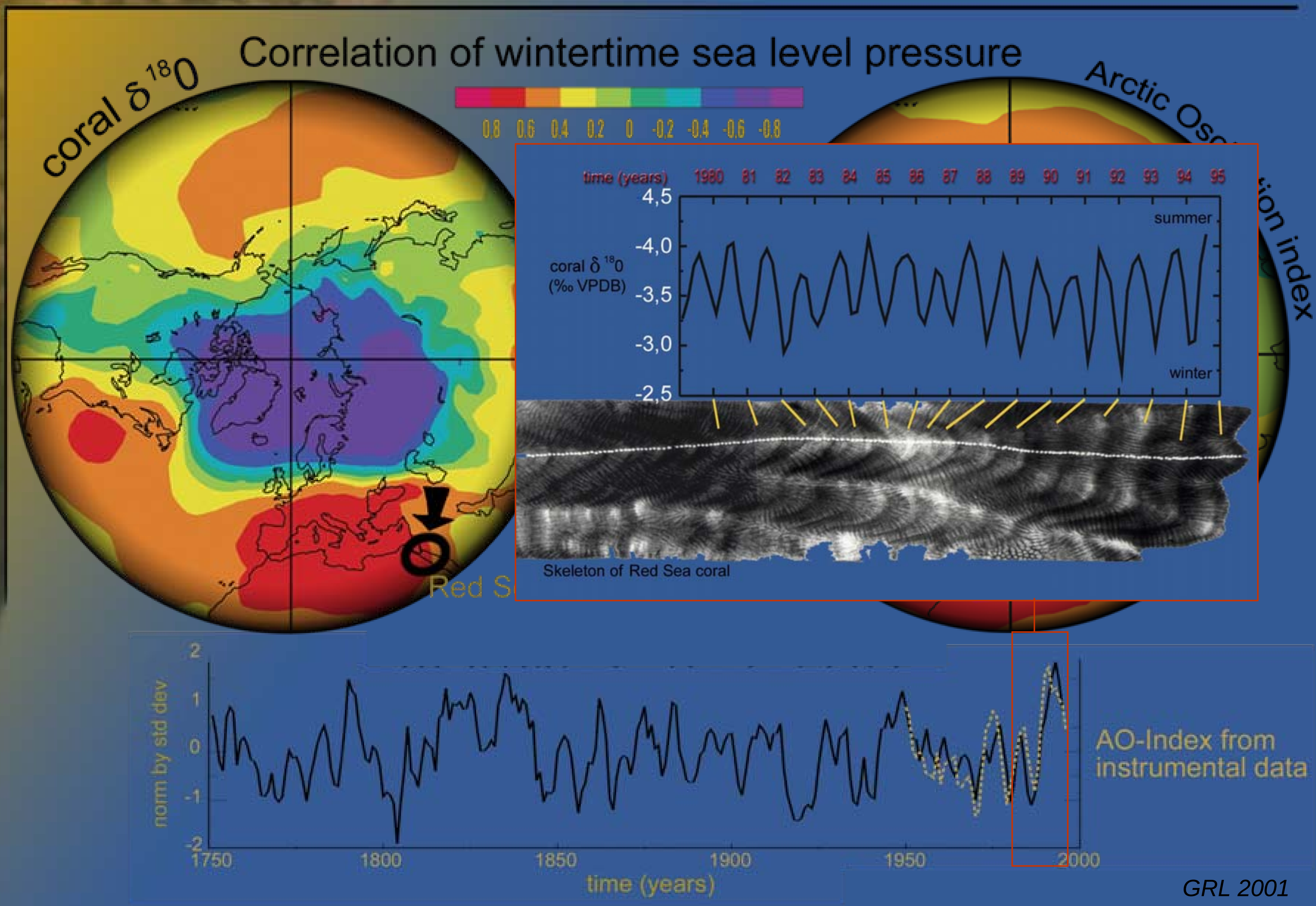


Climate Modes from Proxy Data



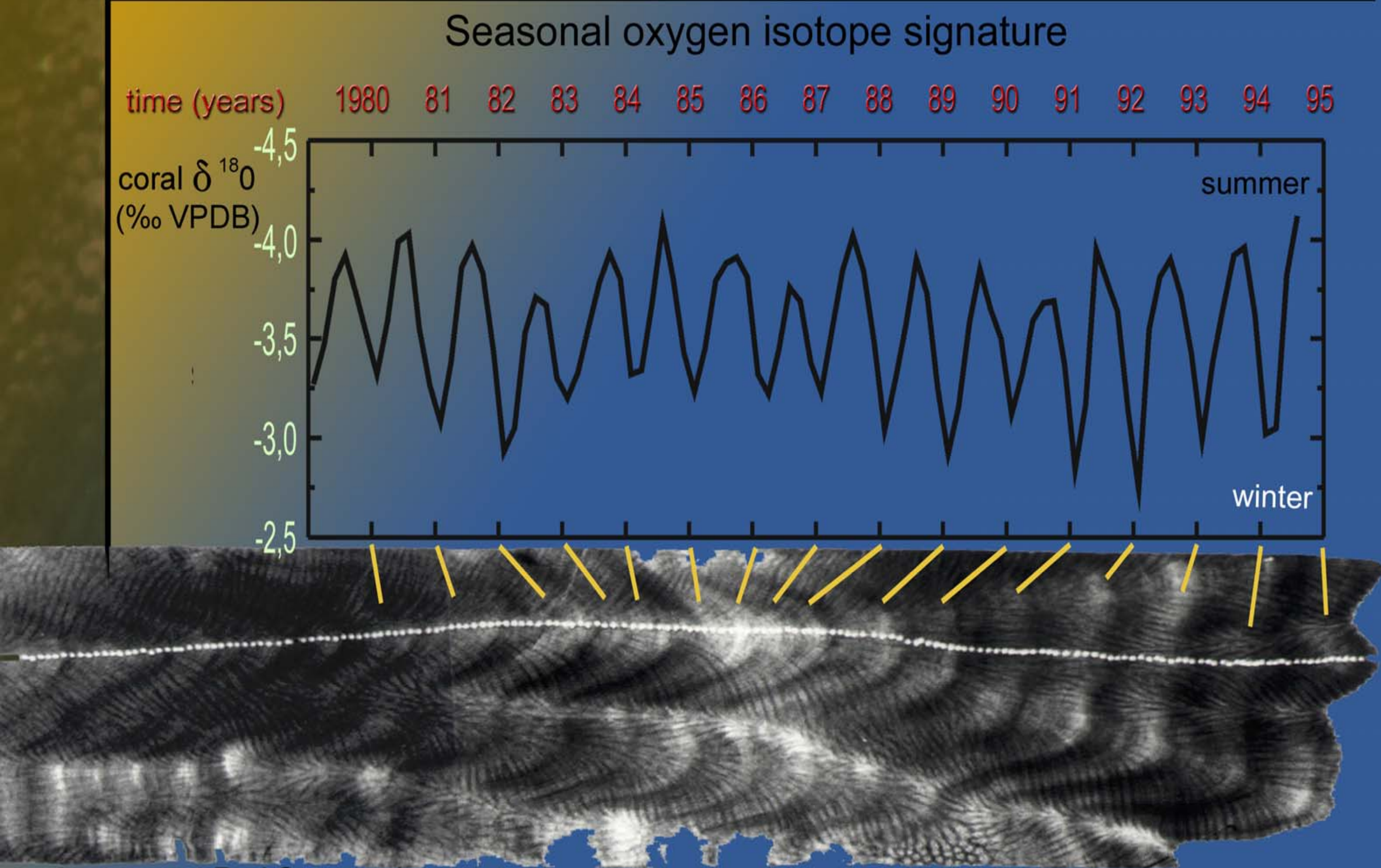
Red Sea coral

Climate Modes from Proxy Data



GRL 2001

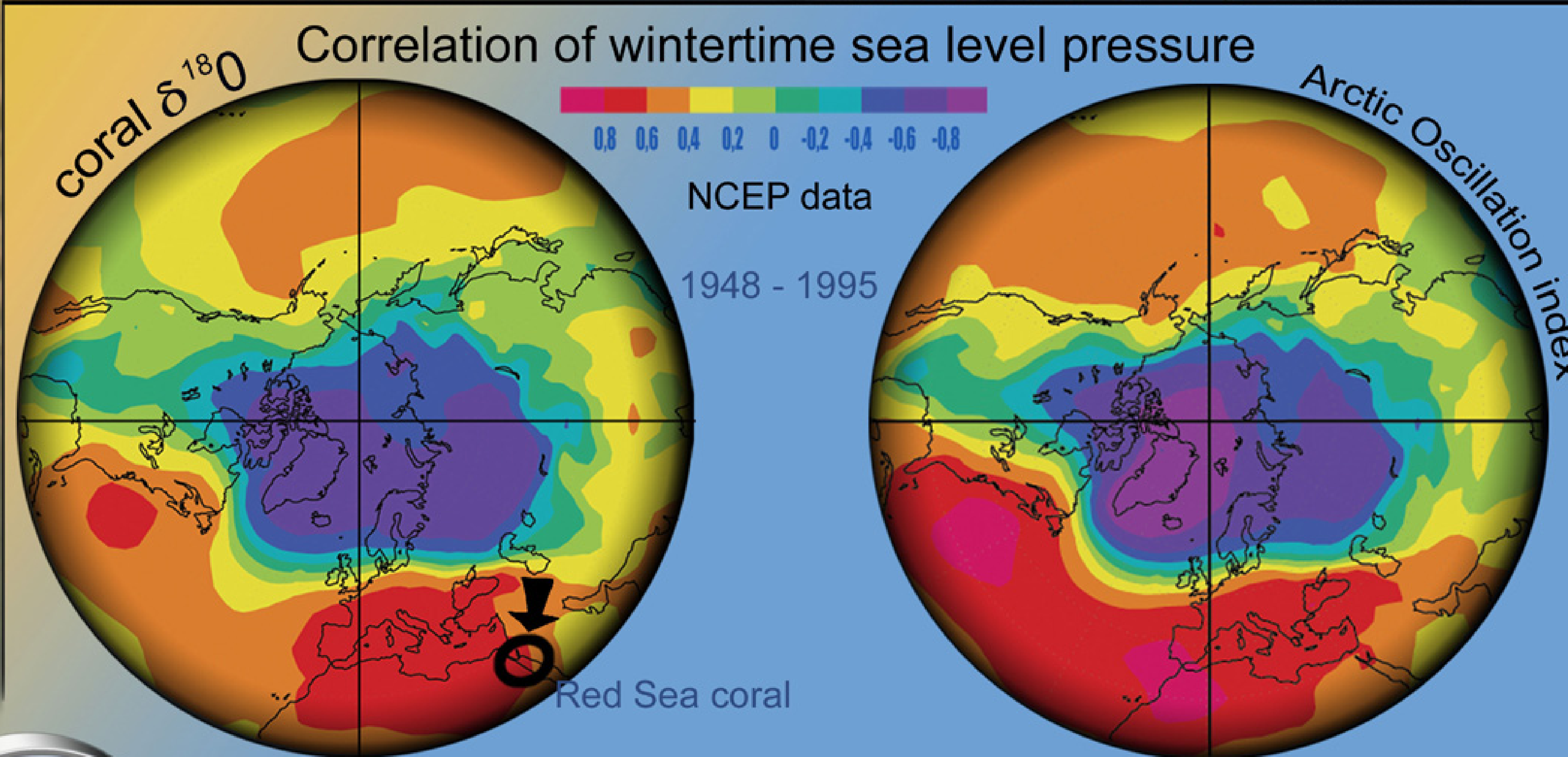
ARCTIC OSCILLATION SIGNATURE IN A RED SEA CORAL

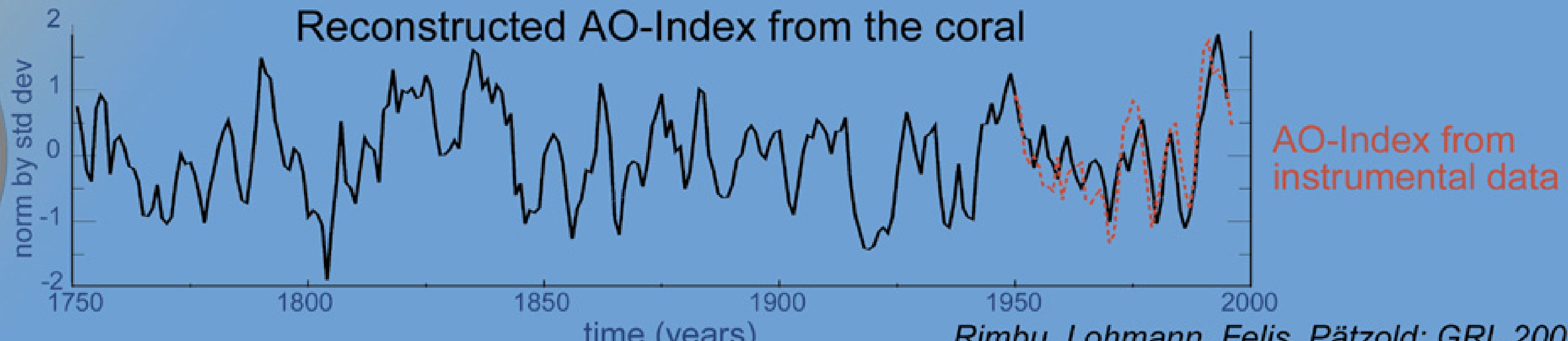


Skeleton of Red Sea coral

Felis et al. Paleoceanography 2000

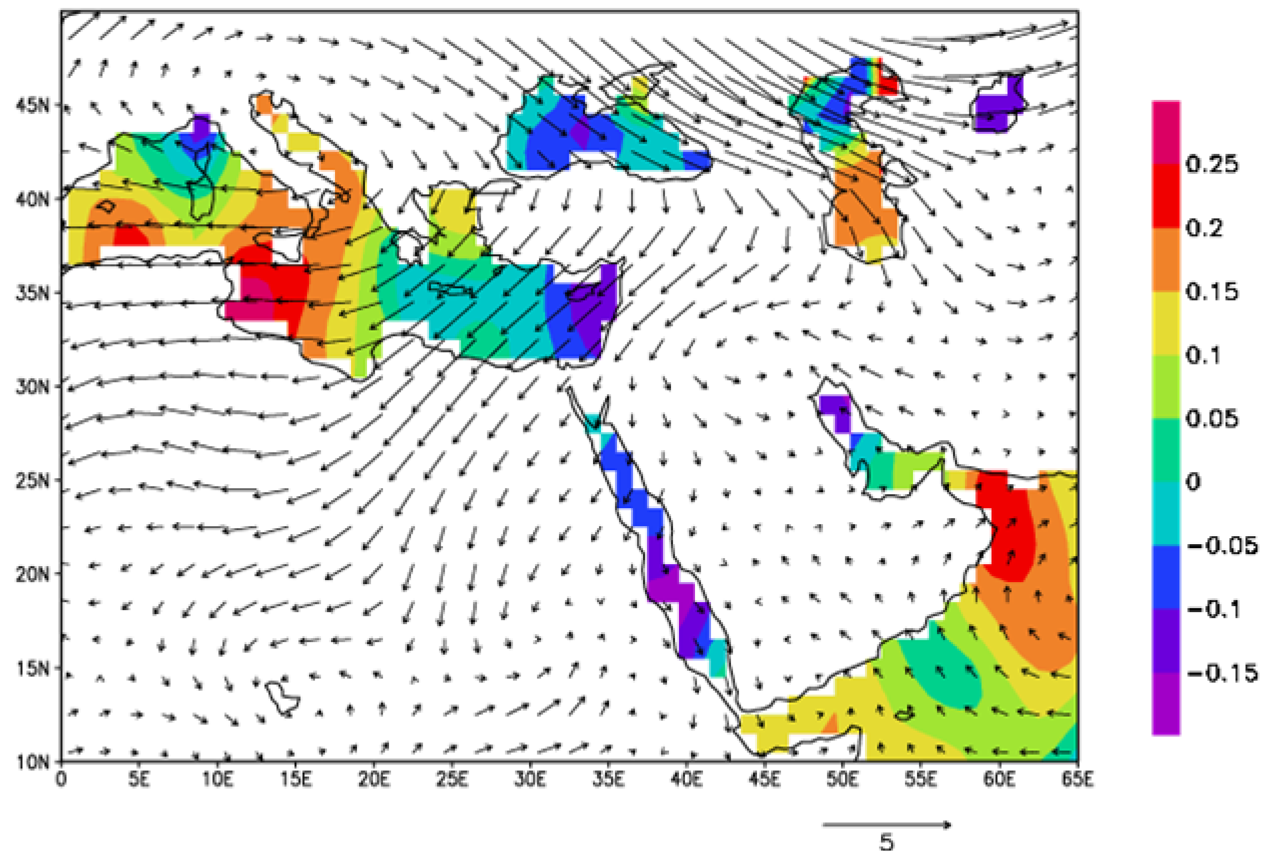
ARCTIC OSCILLATION SIGNATURE IN A RED SEA CORAL





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

ARCTIC OSCILLATION SIGNATURE IN A RED SEA CORAL