General approaches to paleoclimates

Krakow 2014

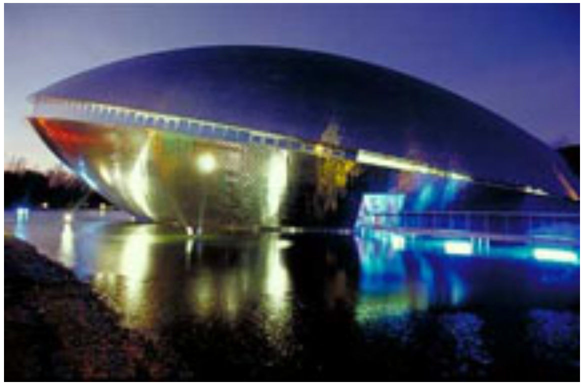
Gerrit Lohmann

AWI

Alfred Wegener Institute
Helmholtz Centre for Polar and Marine Research

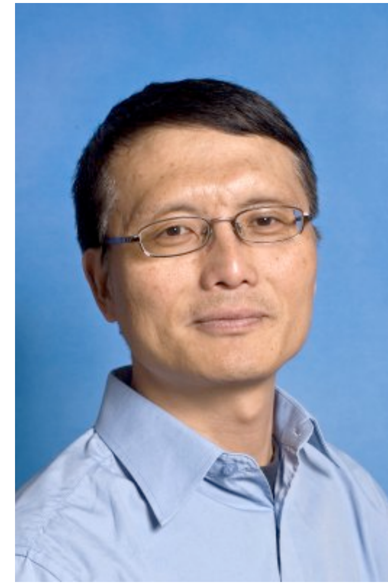
My Town

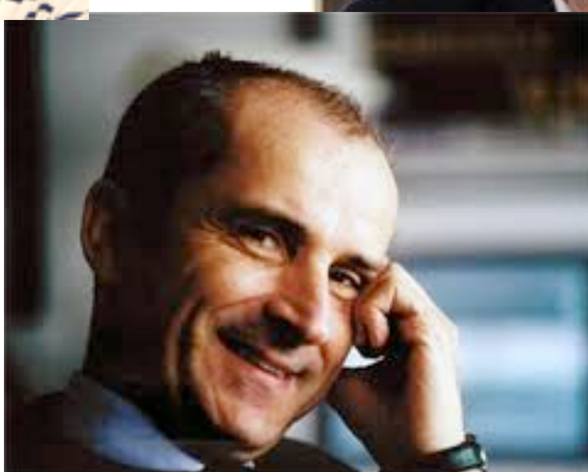
Bremen



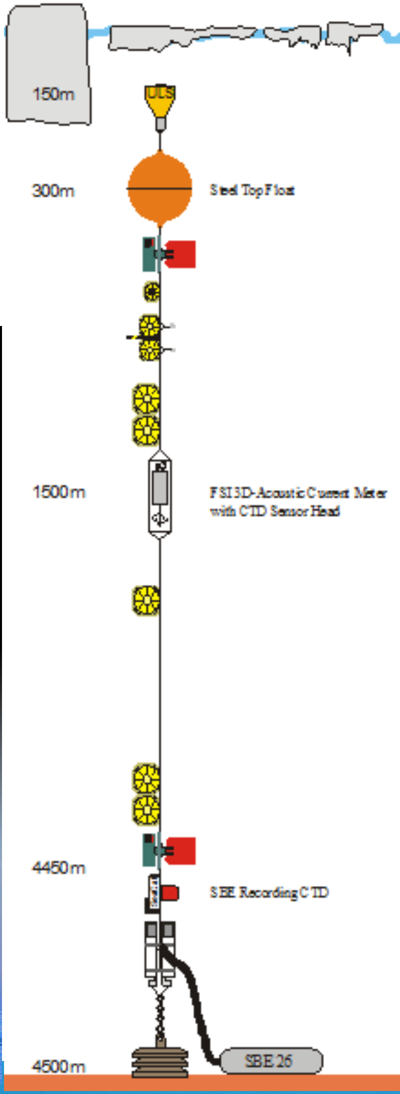
Bremerhaven (Harbor of Bremen)

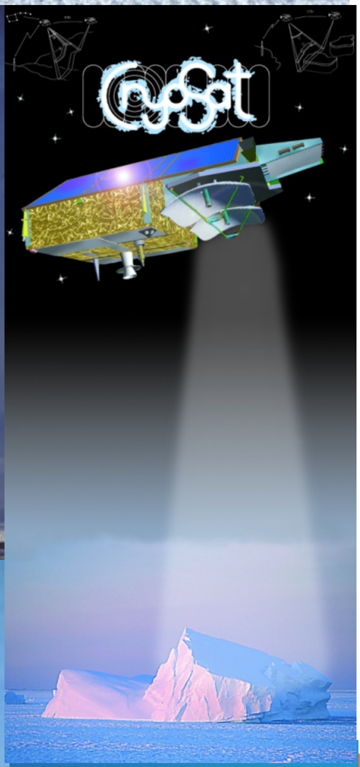
My teachers



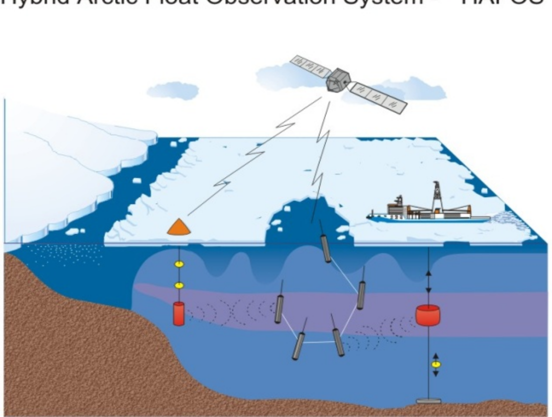


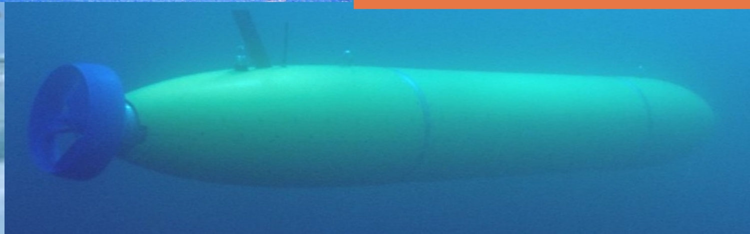
Tools @ AWI

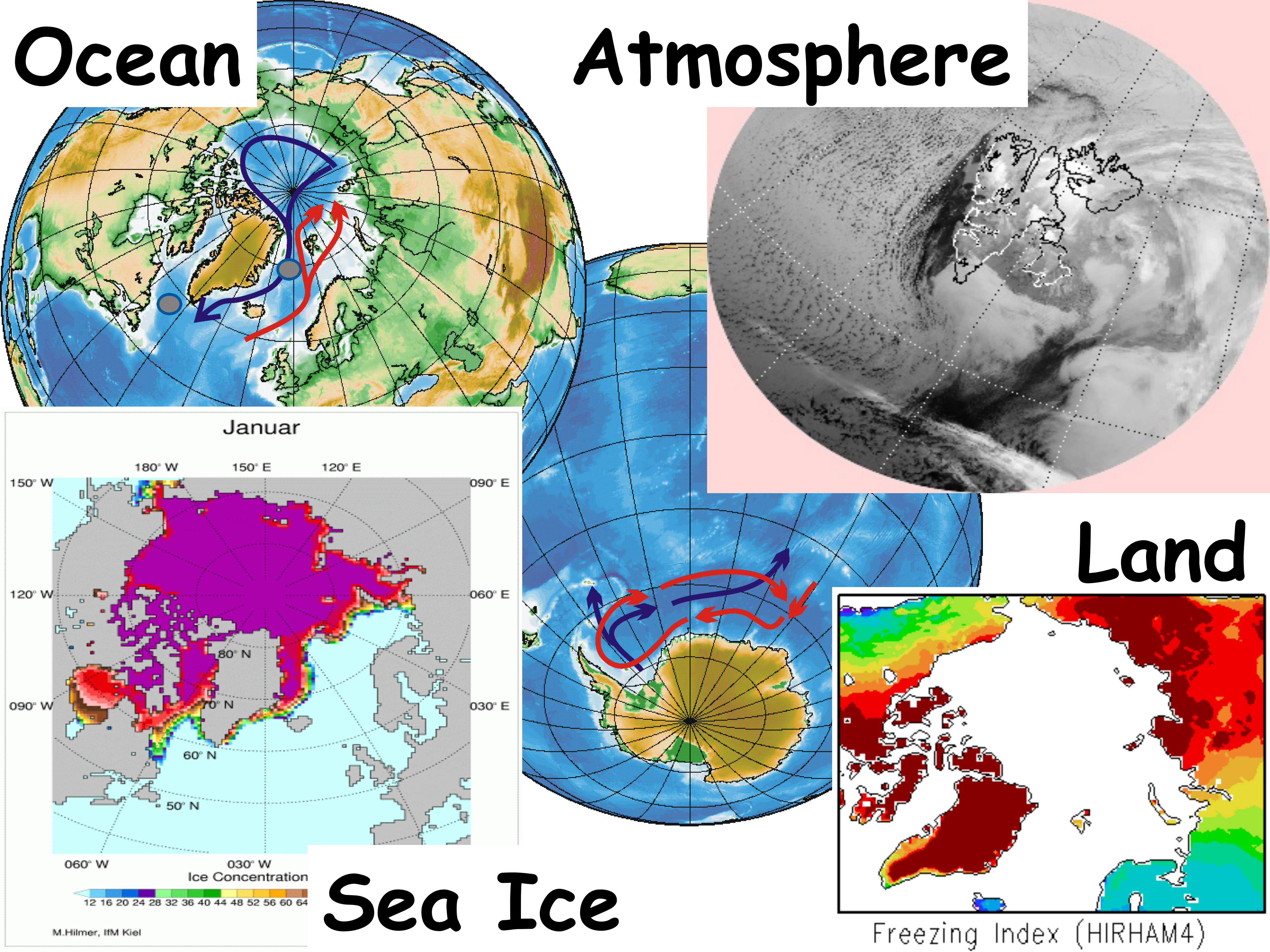




Hybrid Arctic Float Observation System - "HAFOS"






Ocean
Atmosphere
Land
Sea Ice
Januar
180° W
150° E
120° E
150° W
090° E
120° W
060° E
090° W
030° E
80° N
70° N
60° N
50° N
060° W
030° W
Ice Concentration
12 16 20 24 28 32 36 40 44 48 52 56 60 64
M.Hilmer, IfM Kiel
Freezing Index (HIRHAM4)

Climate Change

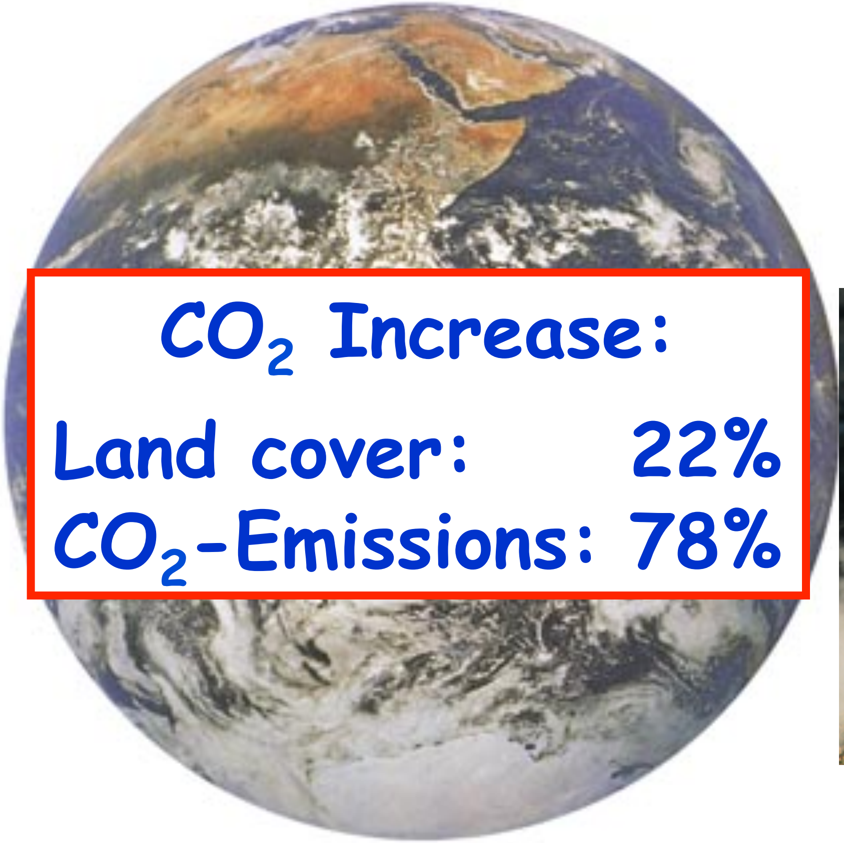
Natural Causes

- External: Sun-Earth Geometry
- Internal: Feedbacks, Noise

Anthropogene Causes

- Land cover changes
- CO_2-Emissions
- ...

CO_2



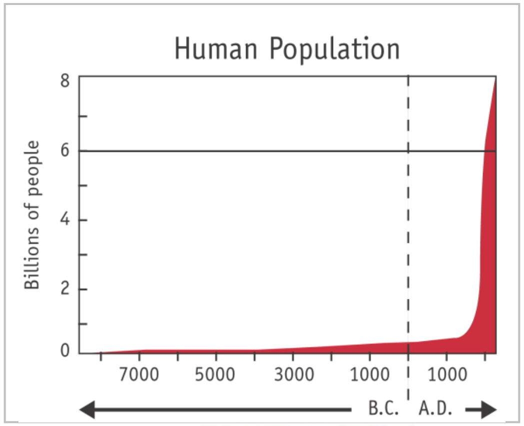
CO_2 Increase:

Land cover: 22%

CO_2-Emissions: 78%

The Challenge: Sustainable Energy

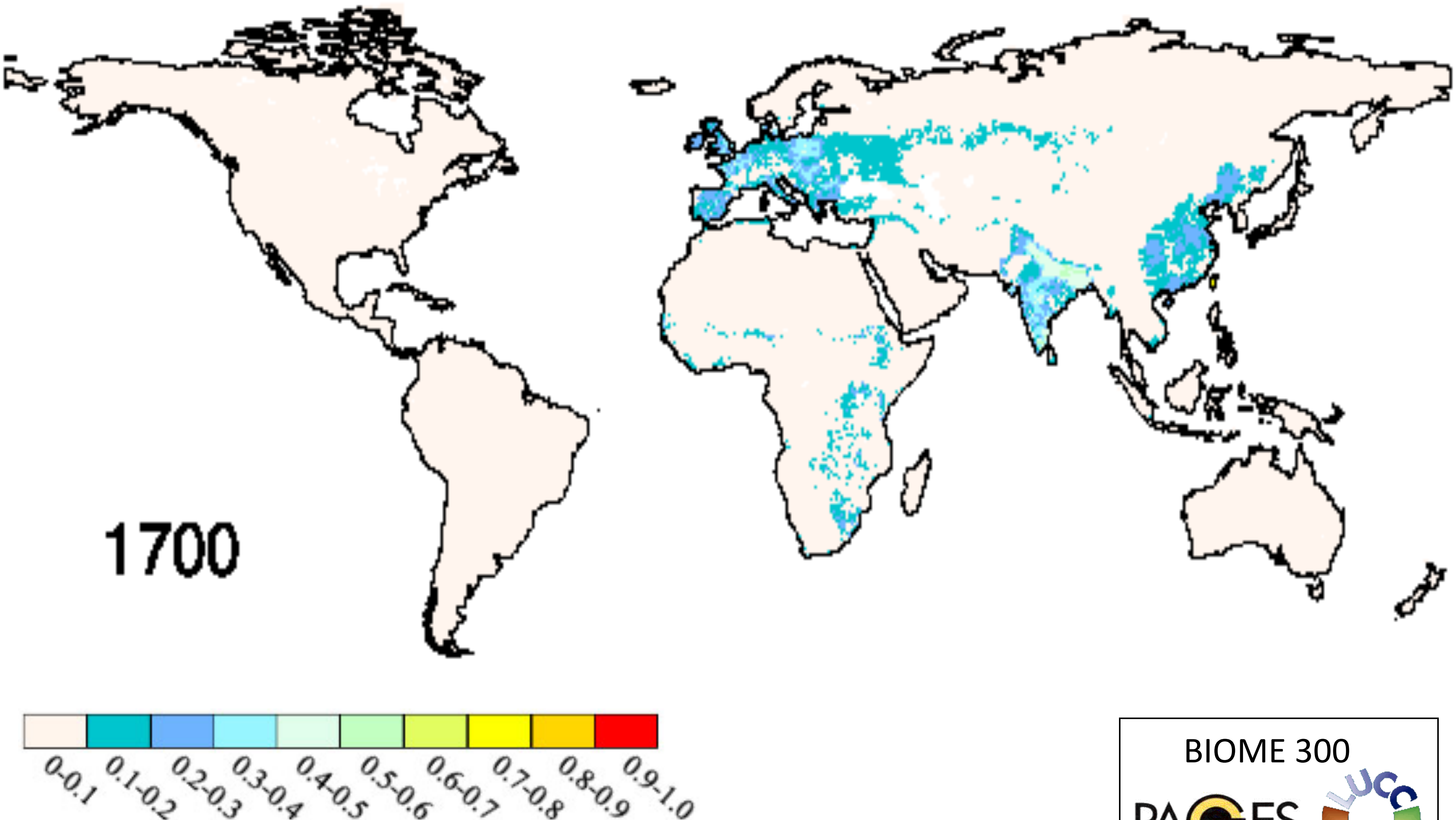
Human Population: 7.047 billion



The Challenge: Sustainable Management of an Ever-Changing Planet

Global Crop Cover Change
1700 to 1992

Center for Sustainability and the Global Environment
Institute for Environmental Studies
University of Wisconsin-Madison



Fraction of Grid Cell in Croplands

BIOME 300

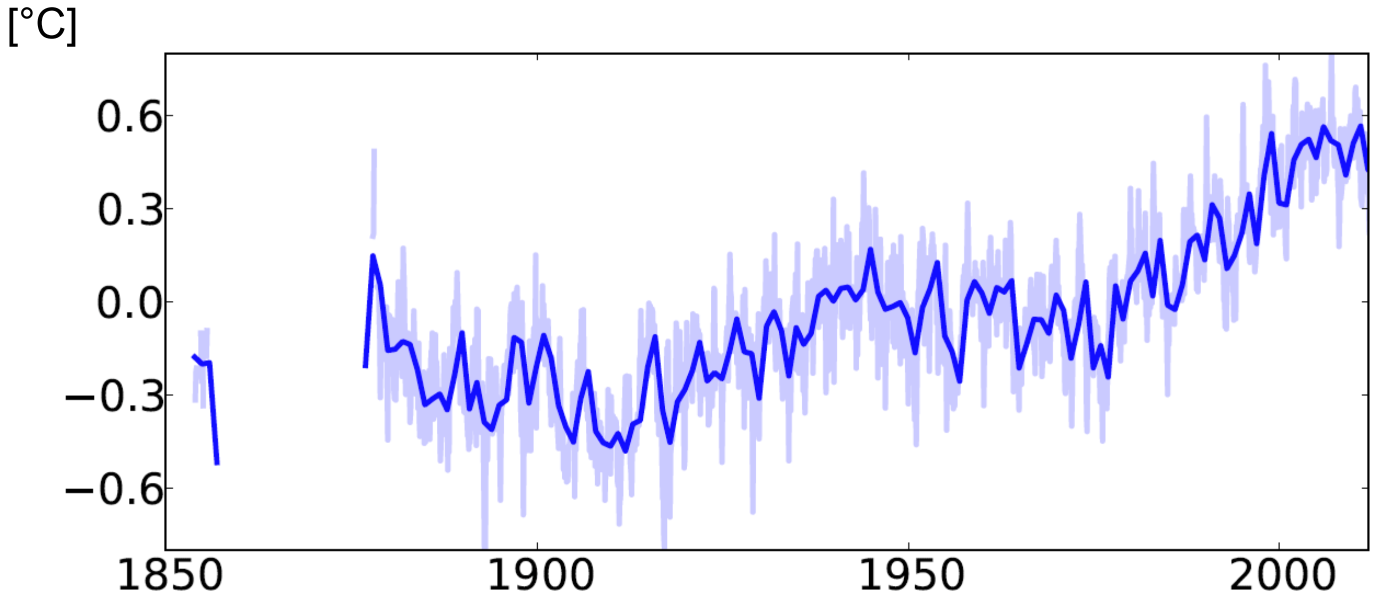
PAGES

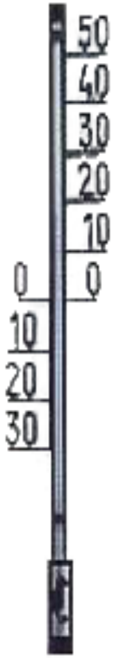
Climate Trends at different Timescales

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

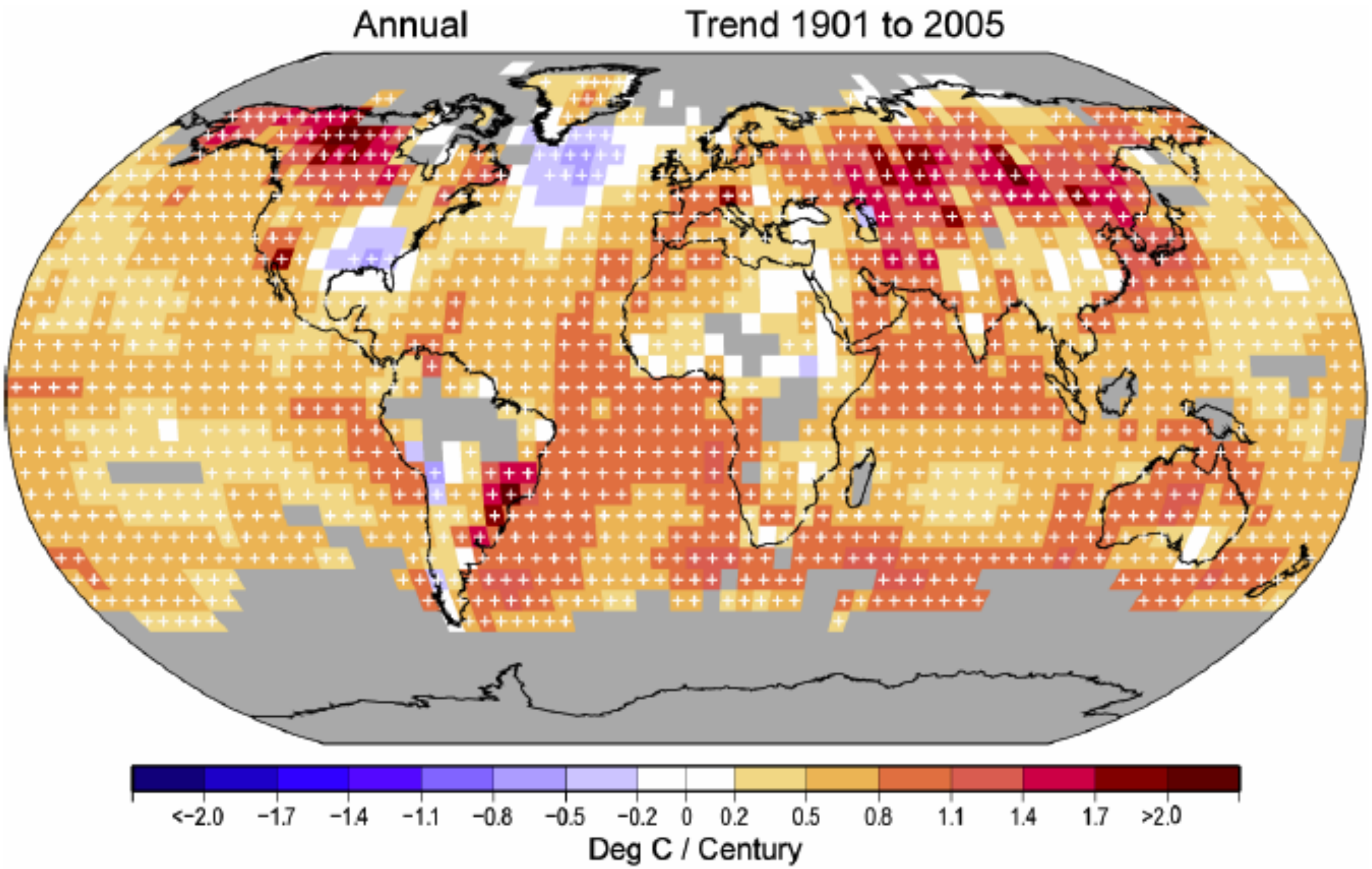
Northern Hemisphere Temp. anomaly

HadCRU





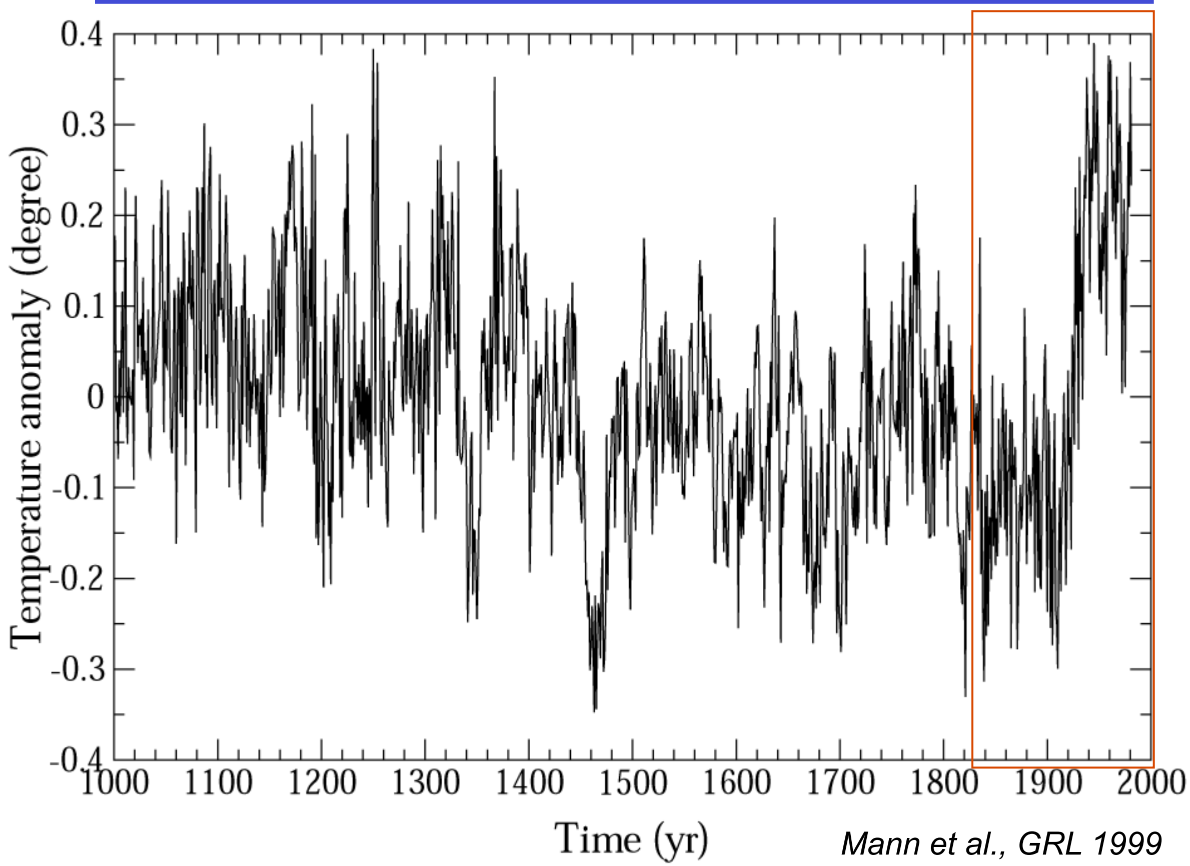
Observations: Temperature trend since 1901



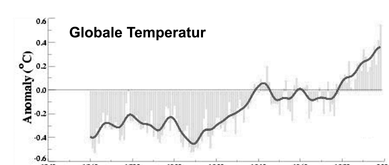
How is this related to past changes?

Climate Trends at different Timescales

Temperature of the last **1000 years**



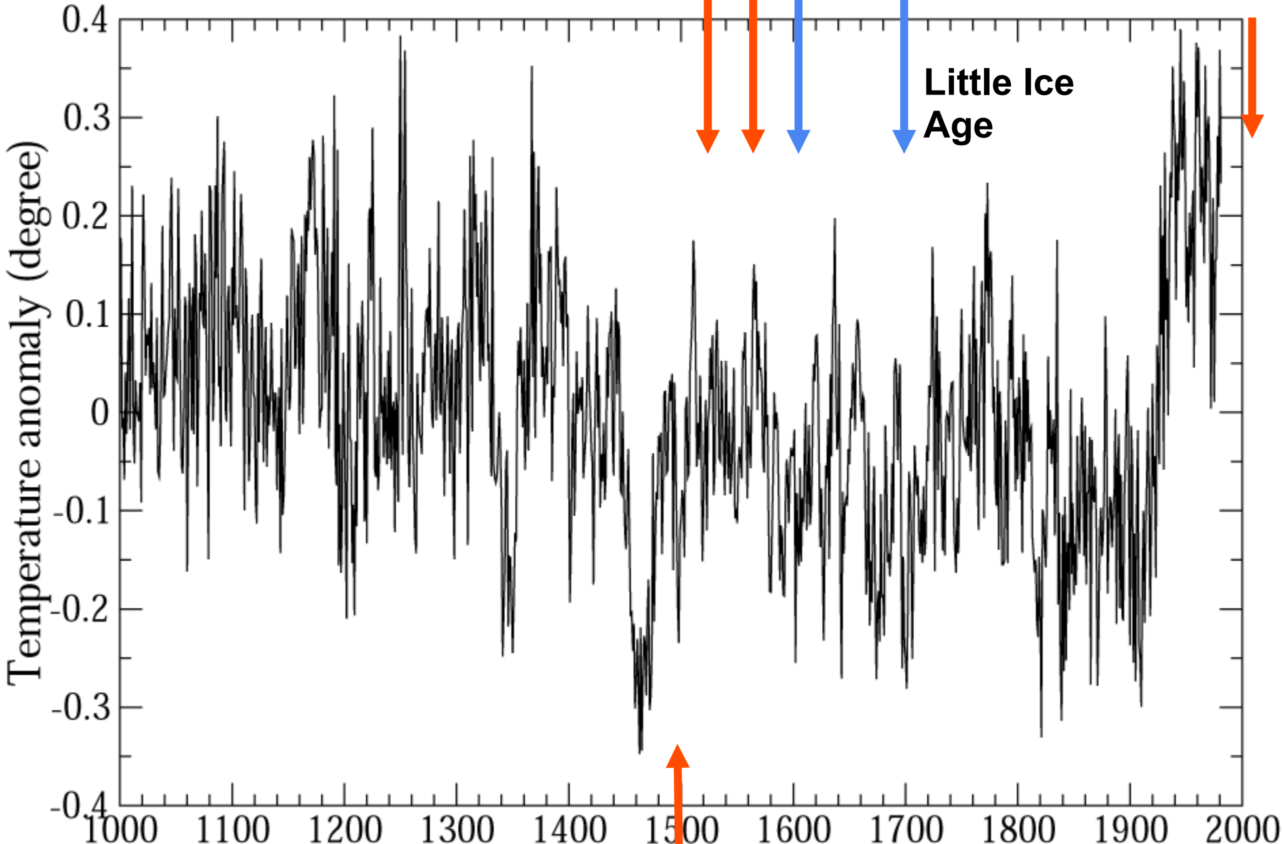
Mann et al., GRL 1999



History

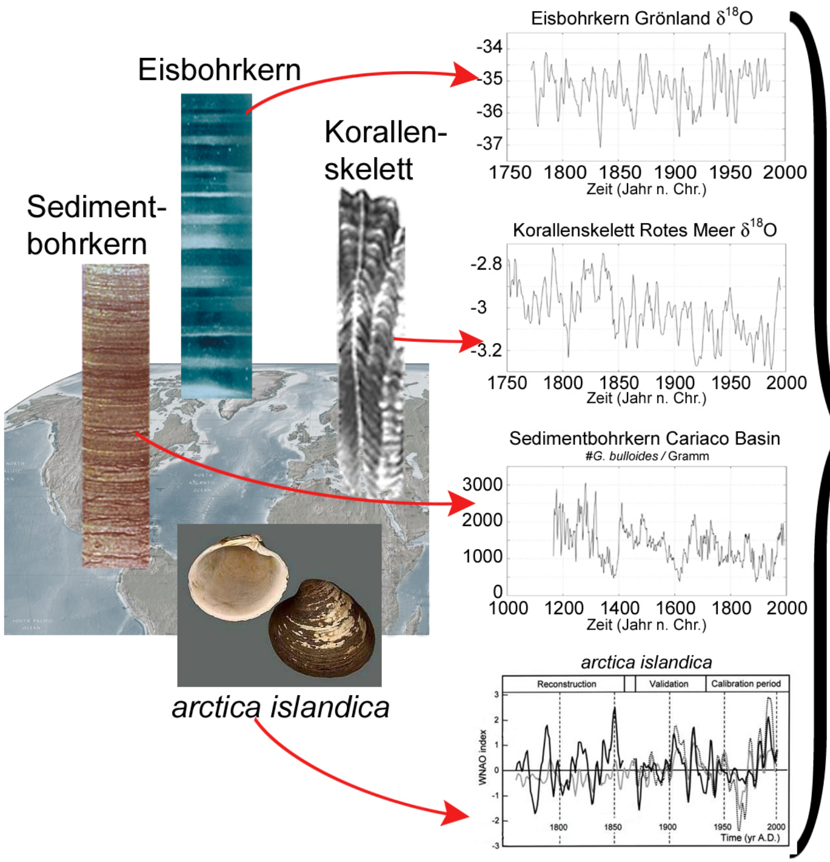
last **1000 Years**

Pieter Breughel d.Ä.

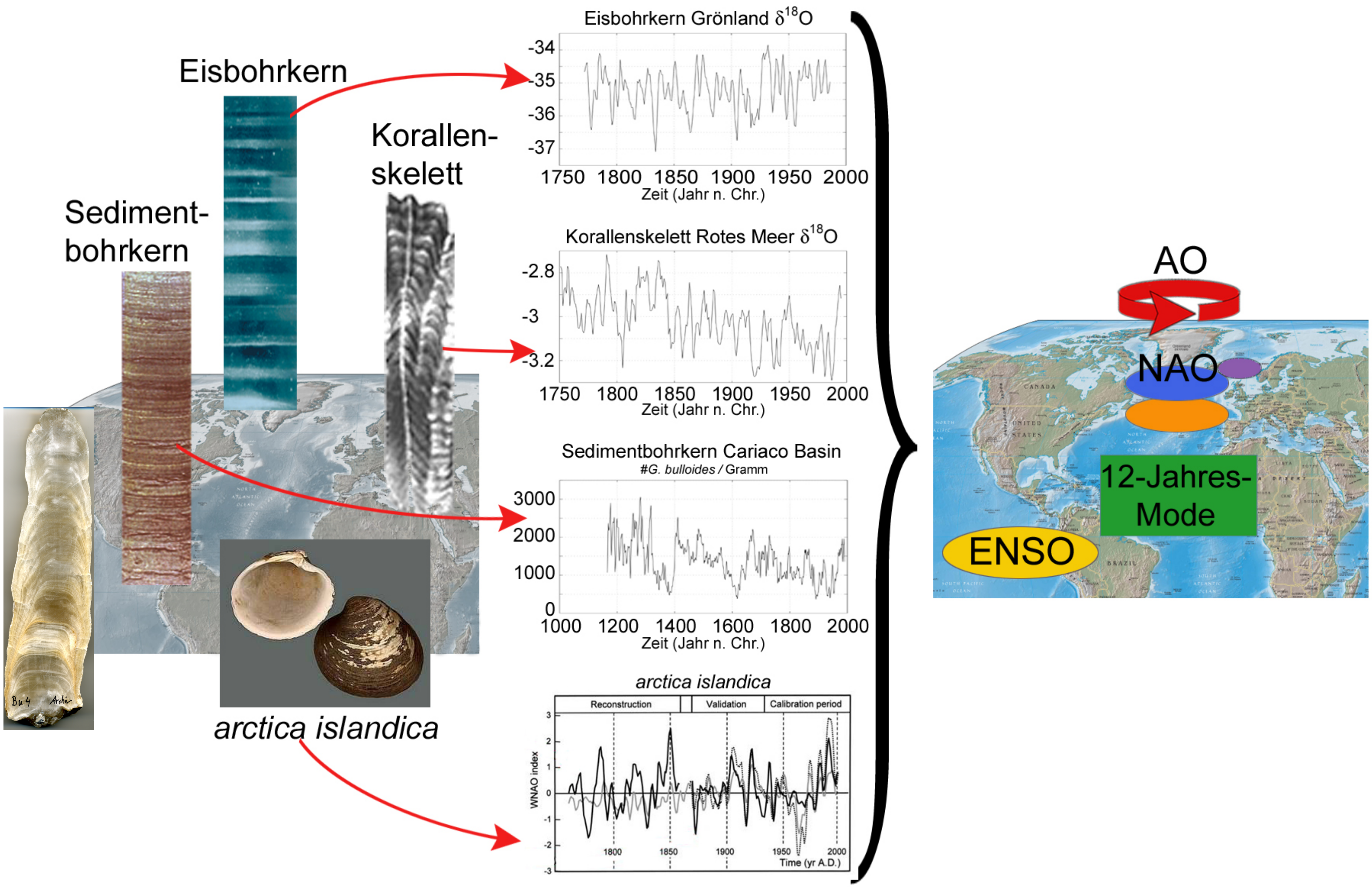


Proxy Data

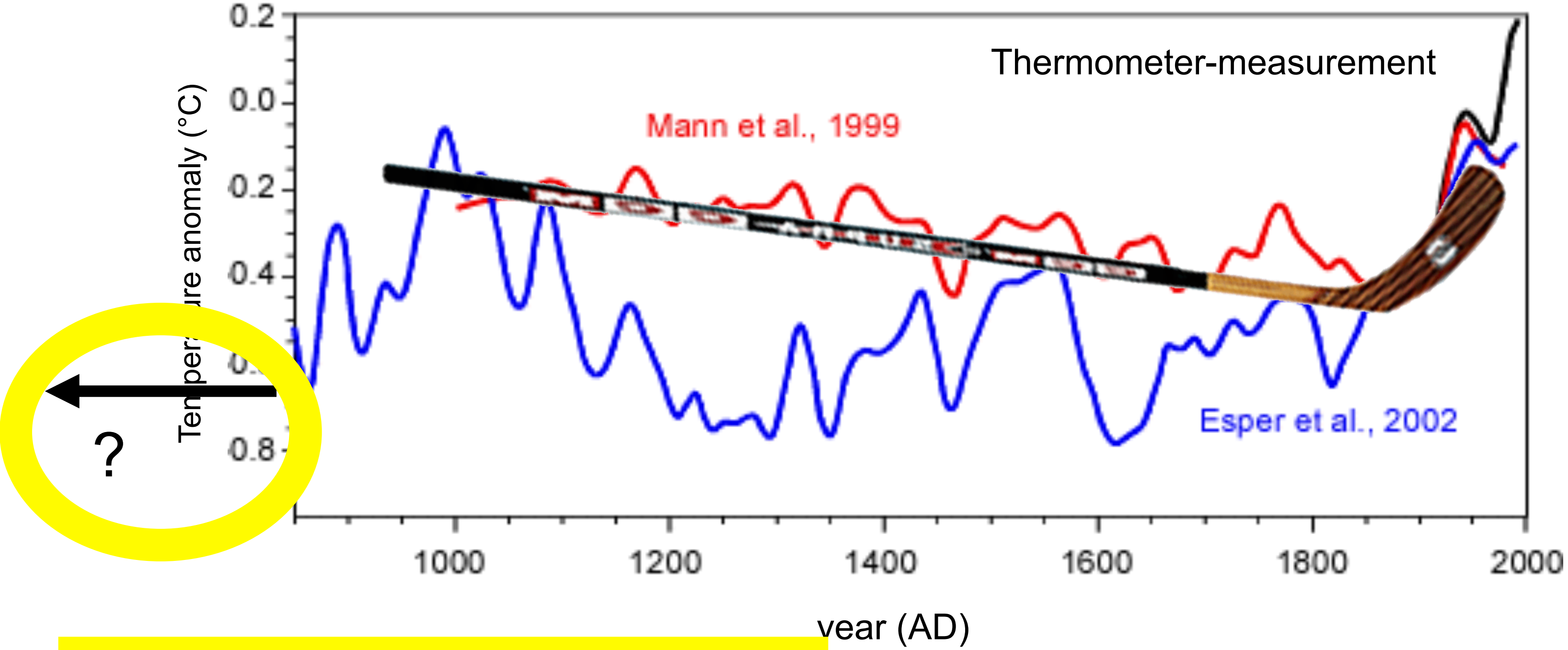
- Indirect data, often qualitative
- Long time series from archives
- Information beyond the instrumental record



Upscaling Konzept



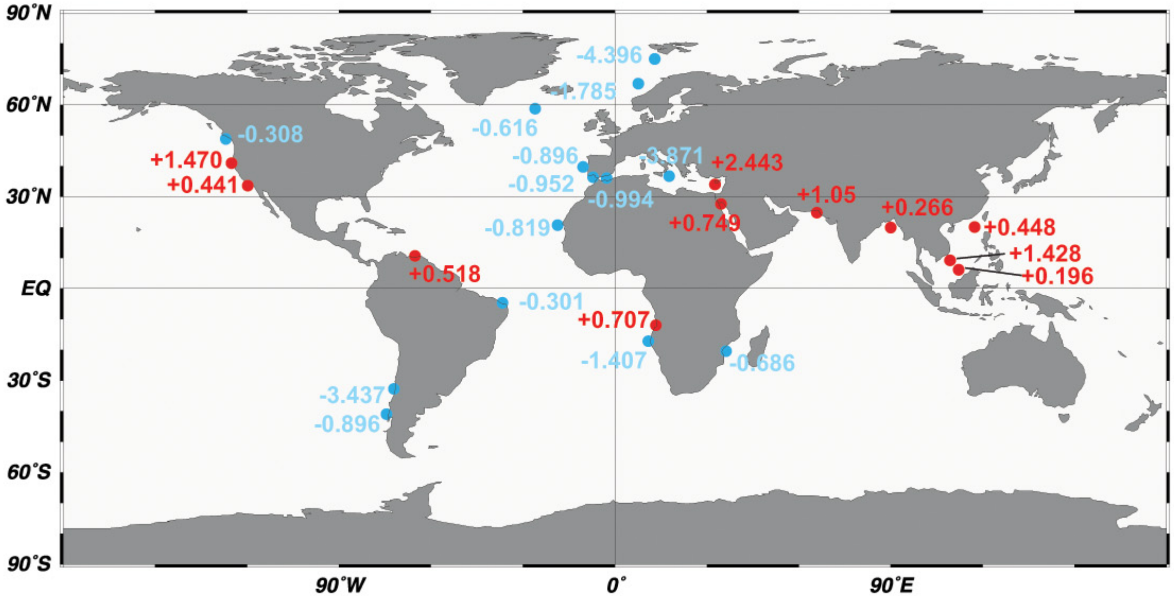
Climate archives **Climate variabiliy**



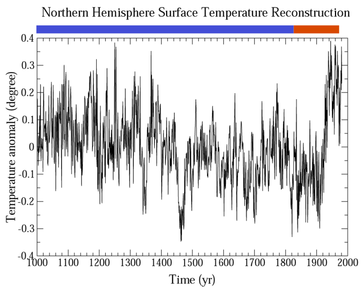
Further back in time?

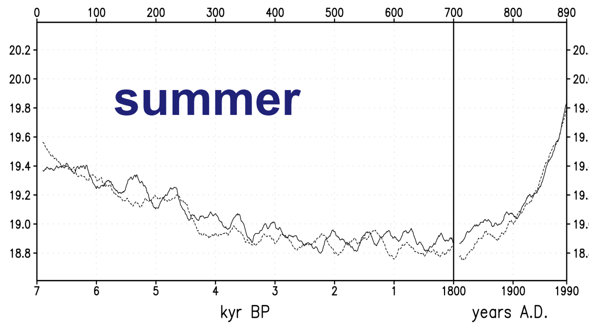
Climate Trends at different Timescales

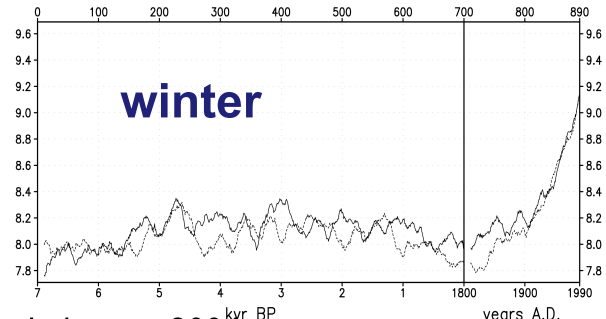
Holocene: Temperature proxy for the last 7000 years

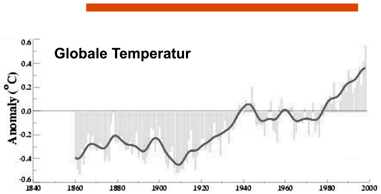


Lorenz, Kim, Rimbu, Schneider, Lohmann 2007





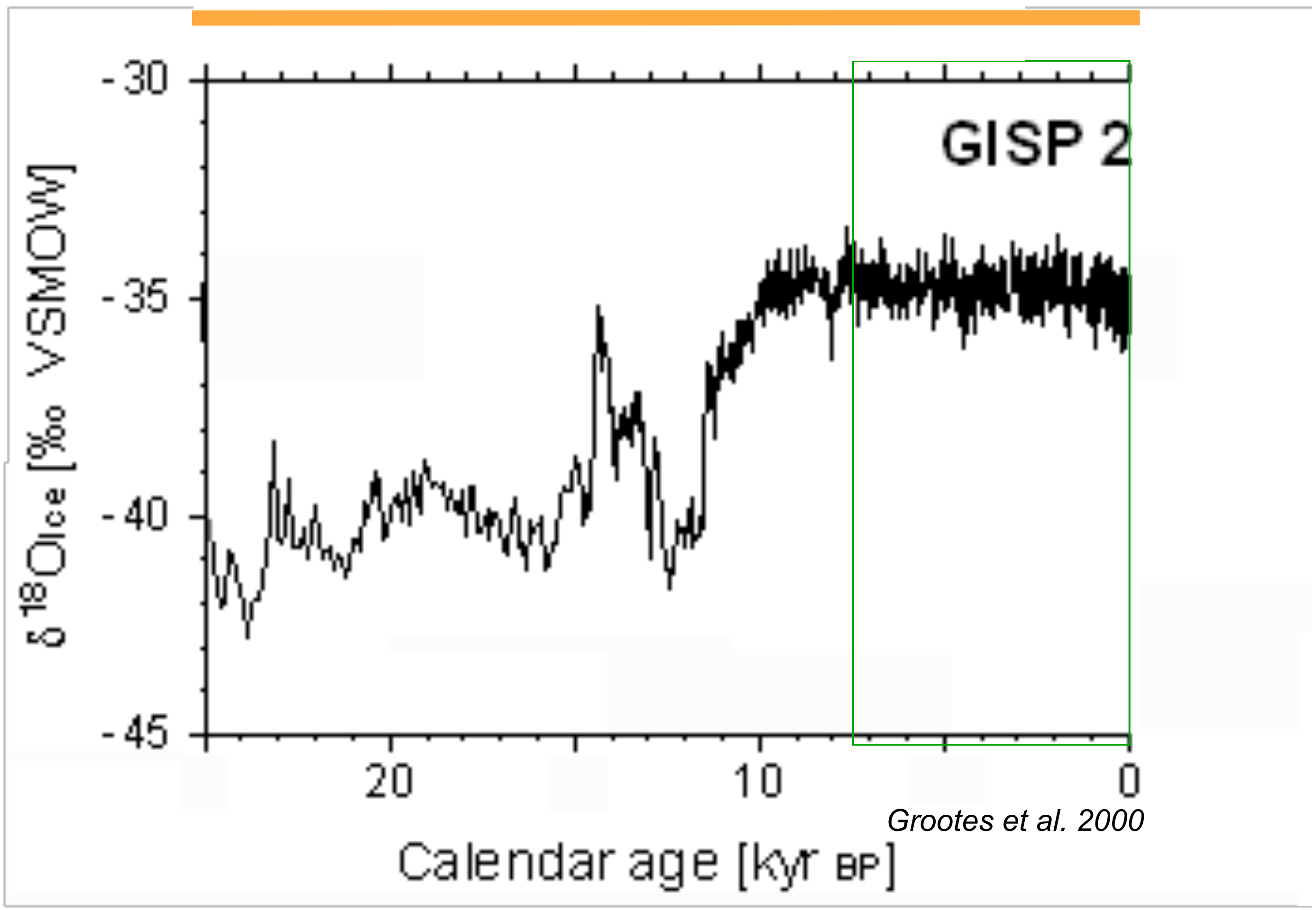




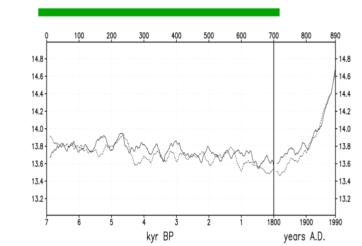
Lorenz, Lohmann 2004

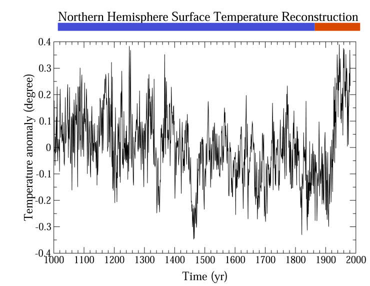
Climate Trends at different Timescales

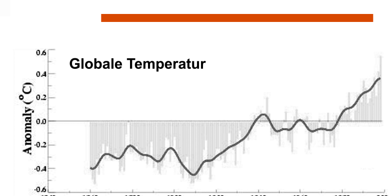
Deglaciation – Greenland ice core

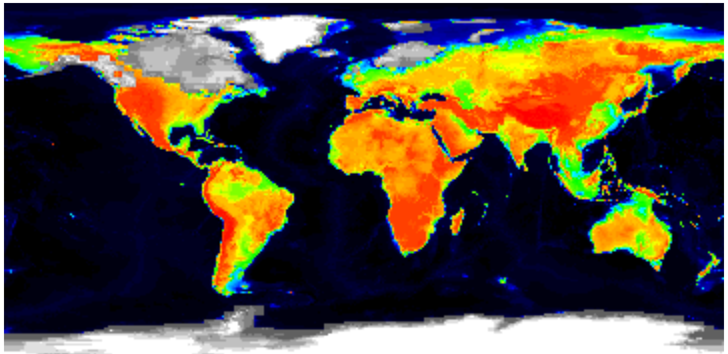


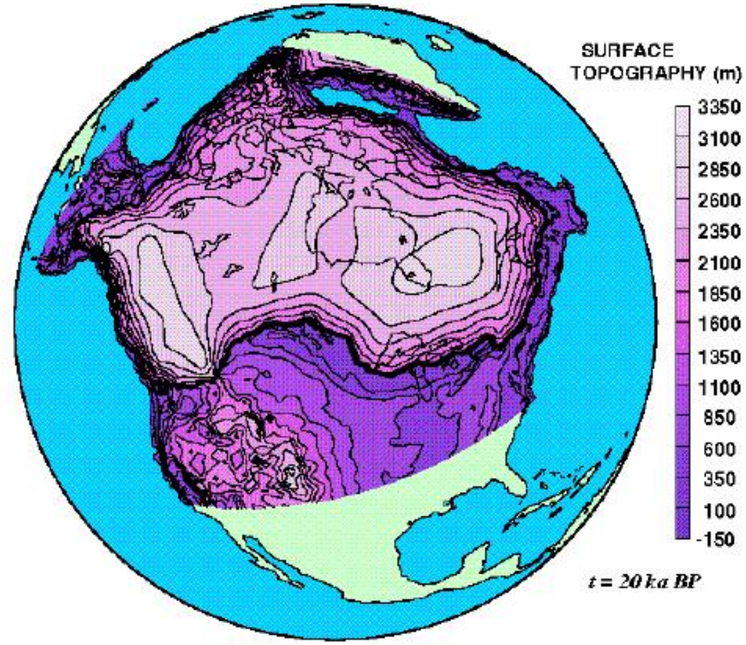
Grootes et al. 2000











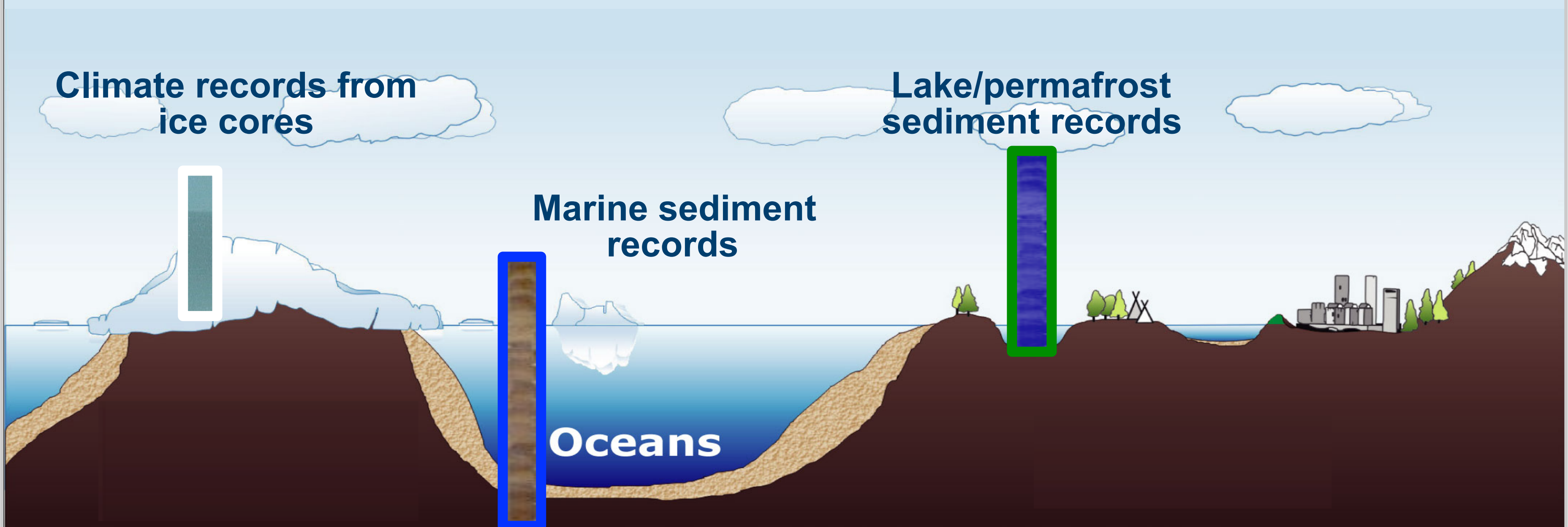
Deglaciation

Earth System: a polar perspective

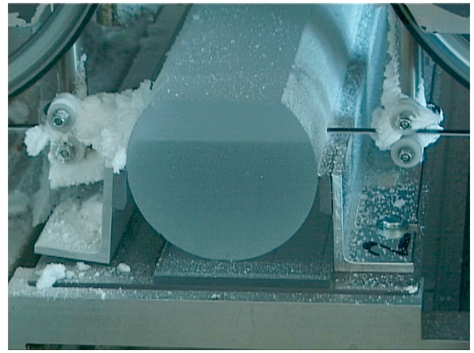
Ice drilling camp, 2009

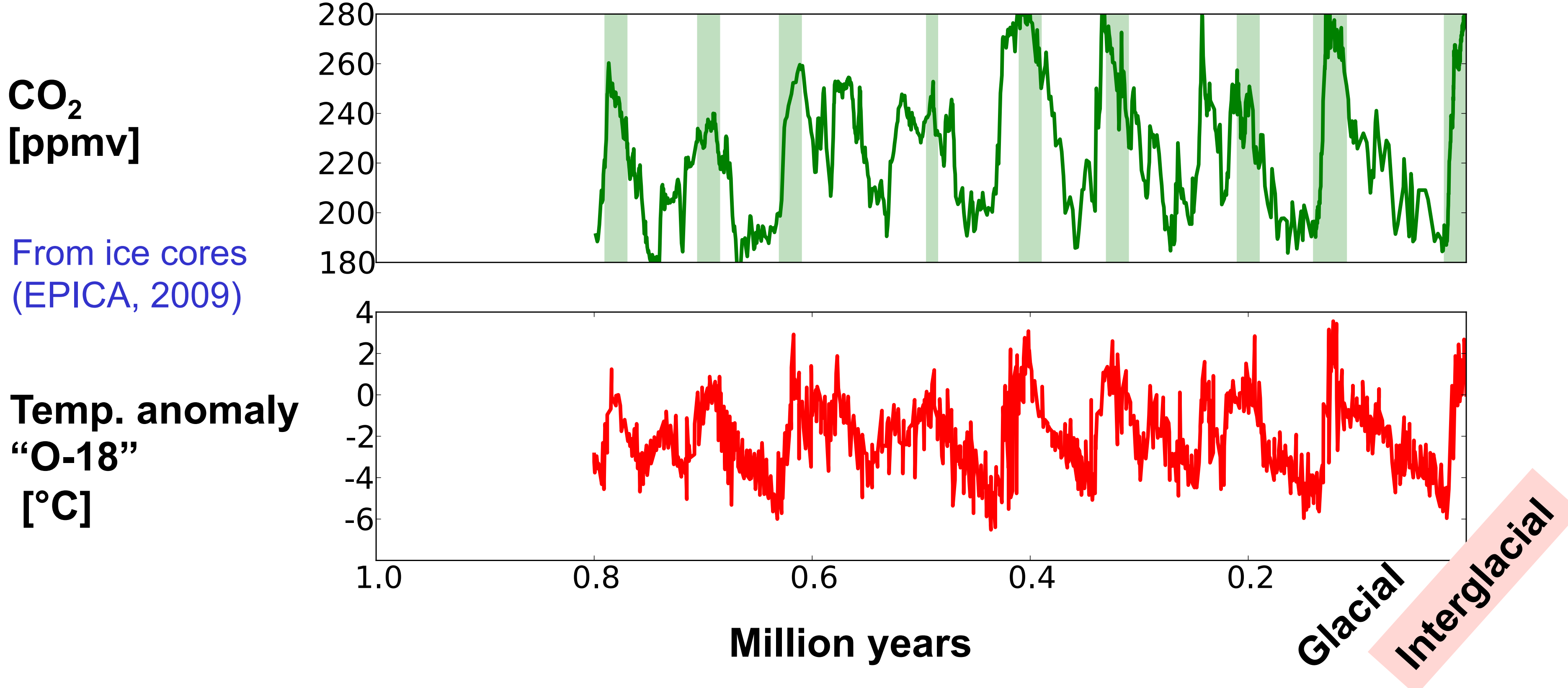
Polarstern, marine sediments

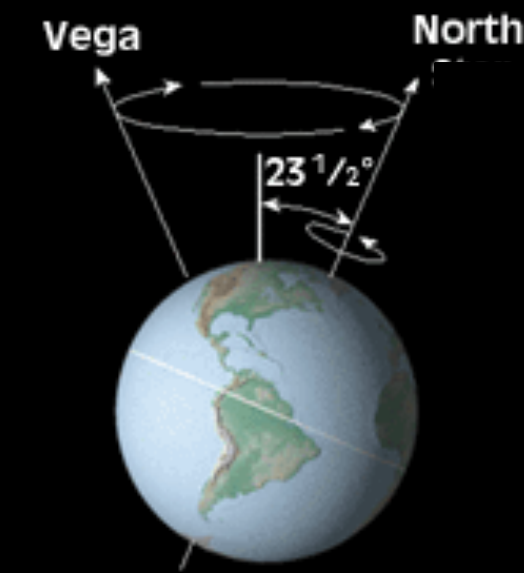
Lake/permafrost sediments



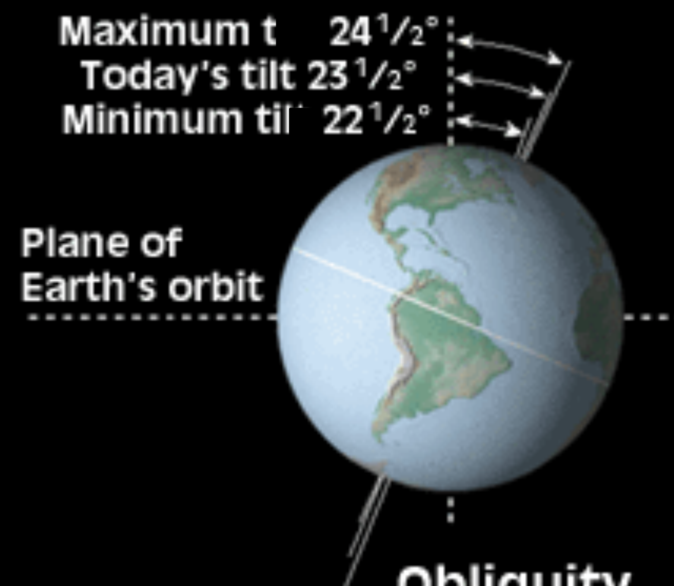
Information from ice cores







Precession

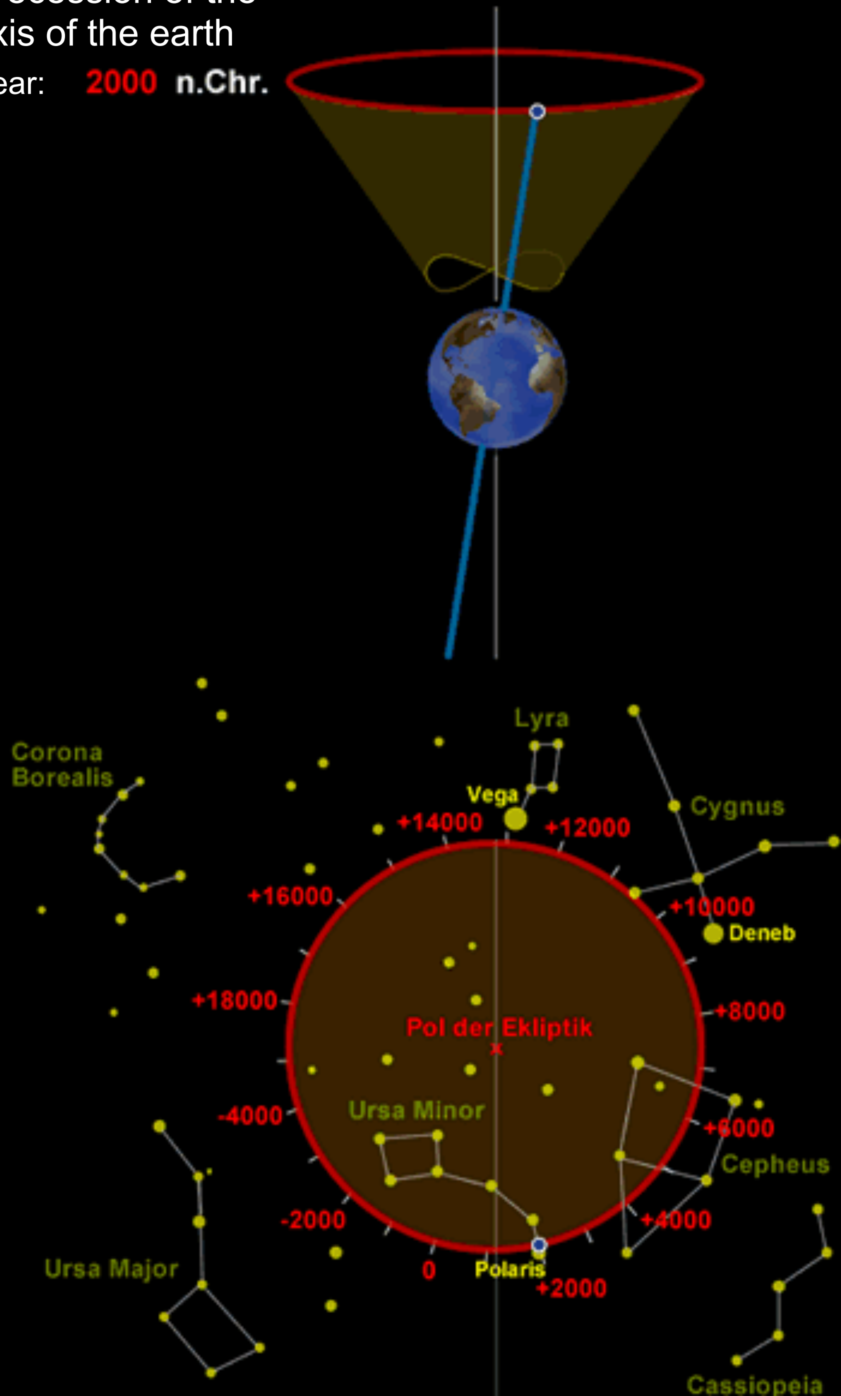


Obliquity

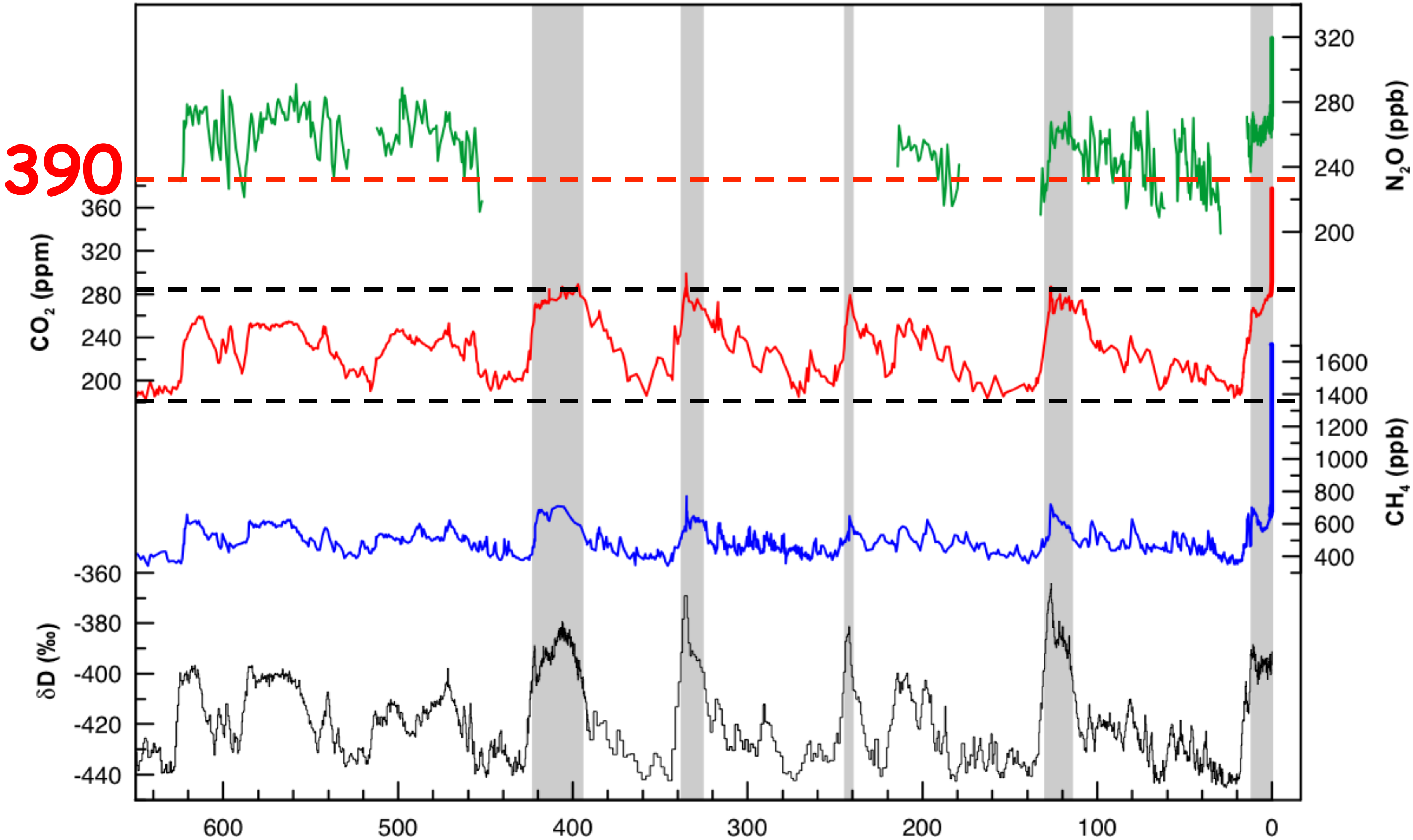
Eccentricity

Precession of the axis of the earth

Year: 2000 n.Chr.



Atmospheric Gas Concentrations from Ice Cores



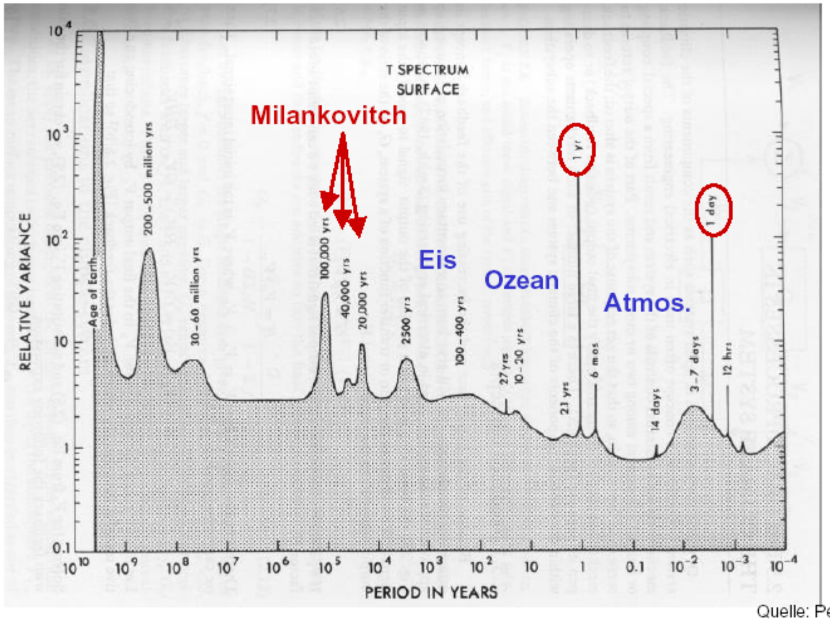
Time (Thousands of Years Before Present)

EPICA 2008

Orbital focing

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

- Geometry of the Sun-Earth configuration



Quelle: Peixoto & Oort

Sunspots   Photo: Nasa

Glacial-Interglacial variability

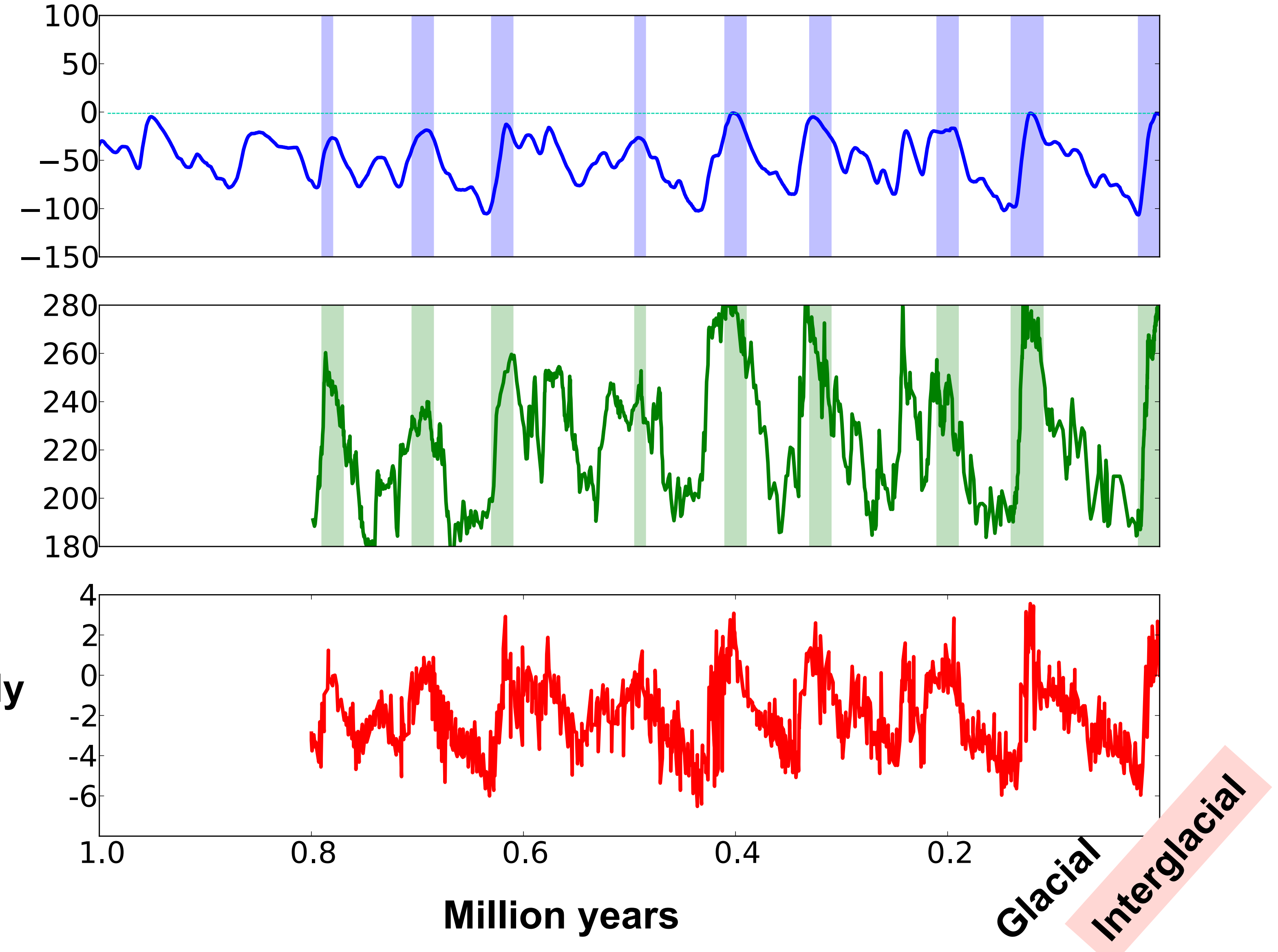
Global Sea Level [m]

(Bintanja et al., 2005)

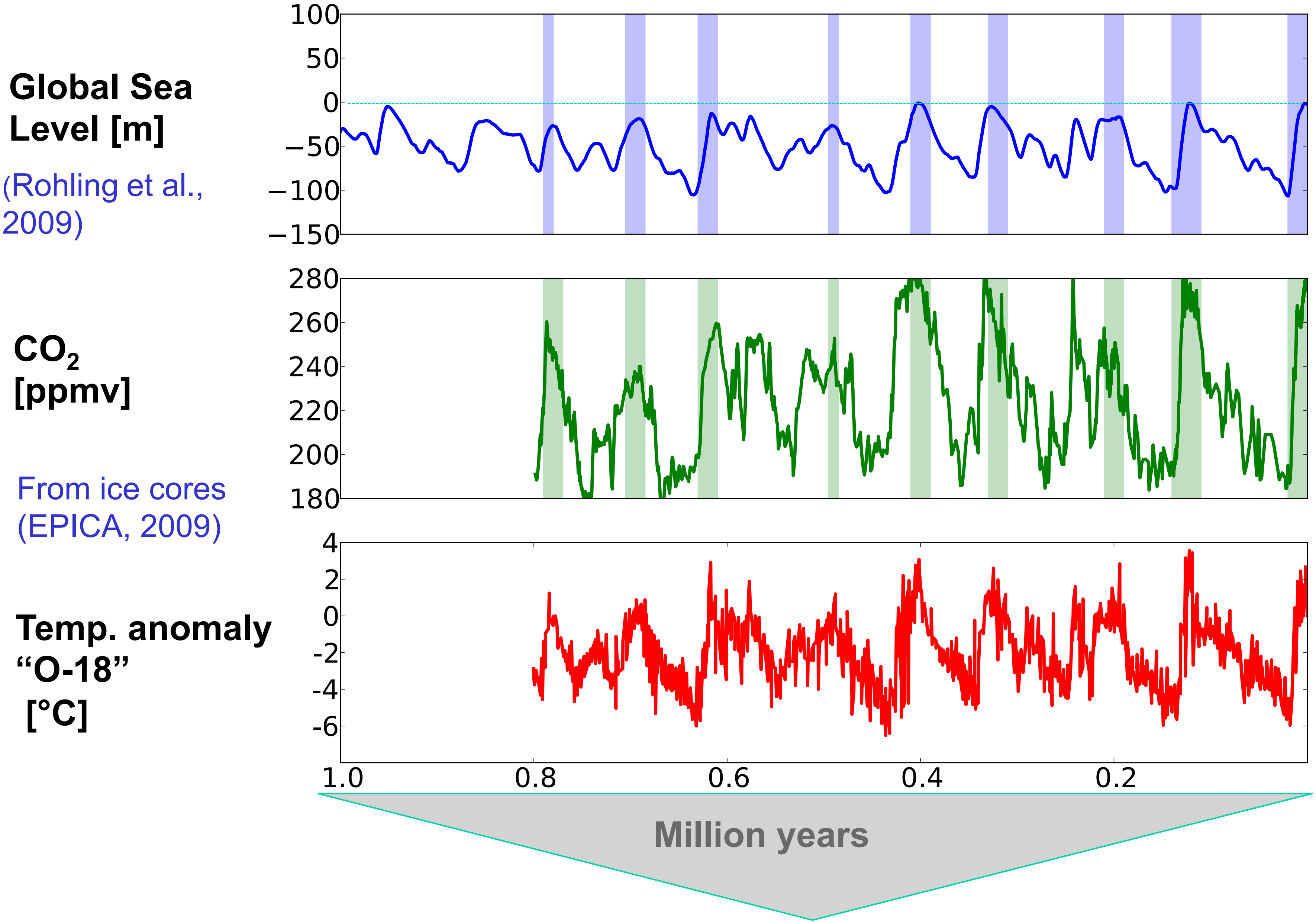
CO_2 [ppmv]

From ice cores (EPICA, 2009)

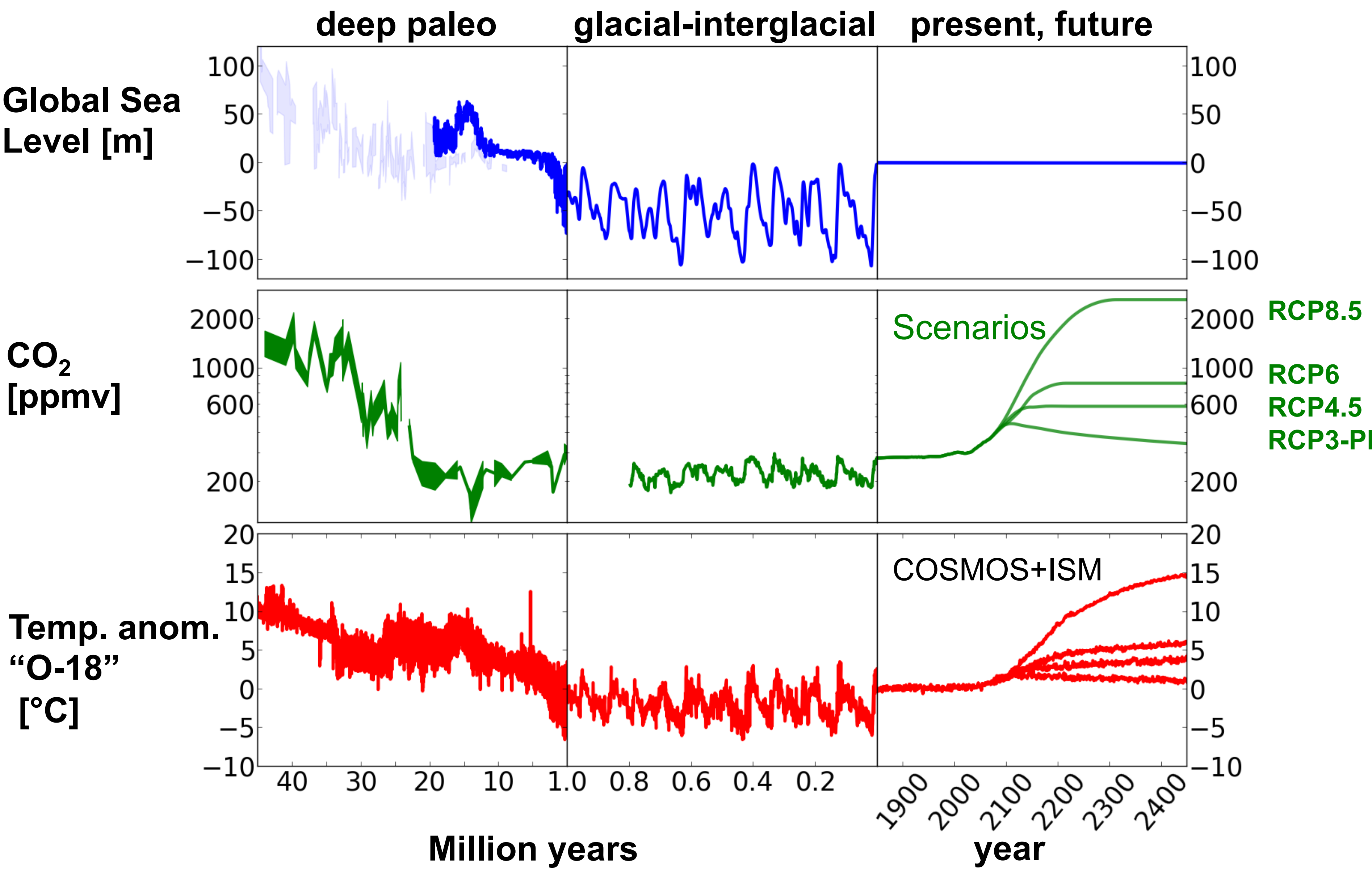
Temp. anomaly "O-18" [°C]



Glacial-Interglacial variability

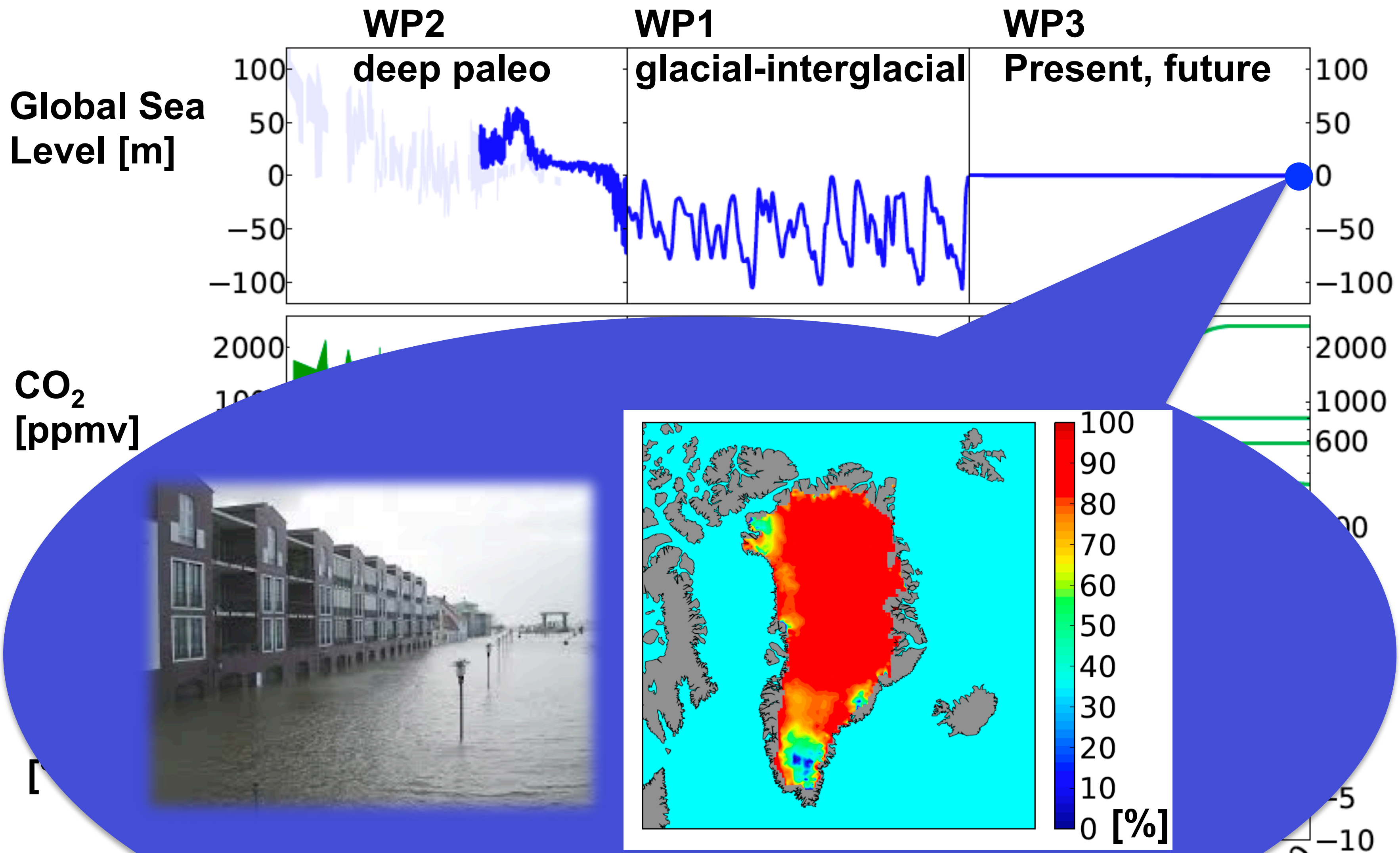


Natural variability and perturbed climate



(Kominz et al., 2008; Pagani et al., 2009; Kramer et al., 2011; Crowley & Kim 1995,Wei et al.,)

Greenland ice volume change



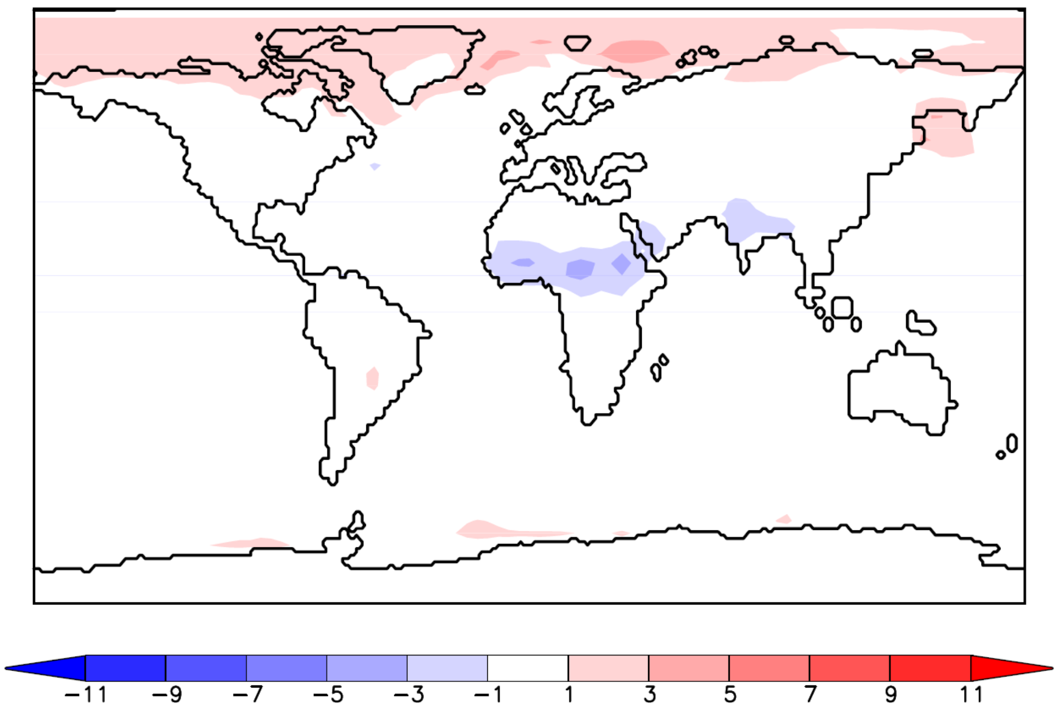
RCP6 scenario: Year 2400 relative to 1850

Greenland: 0.8 m sea level rise

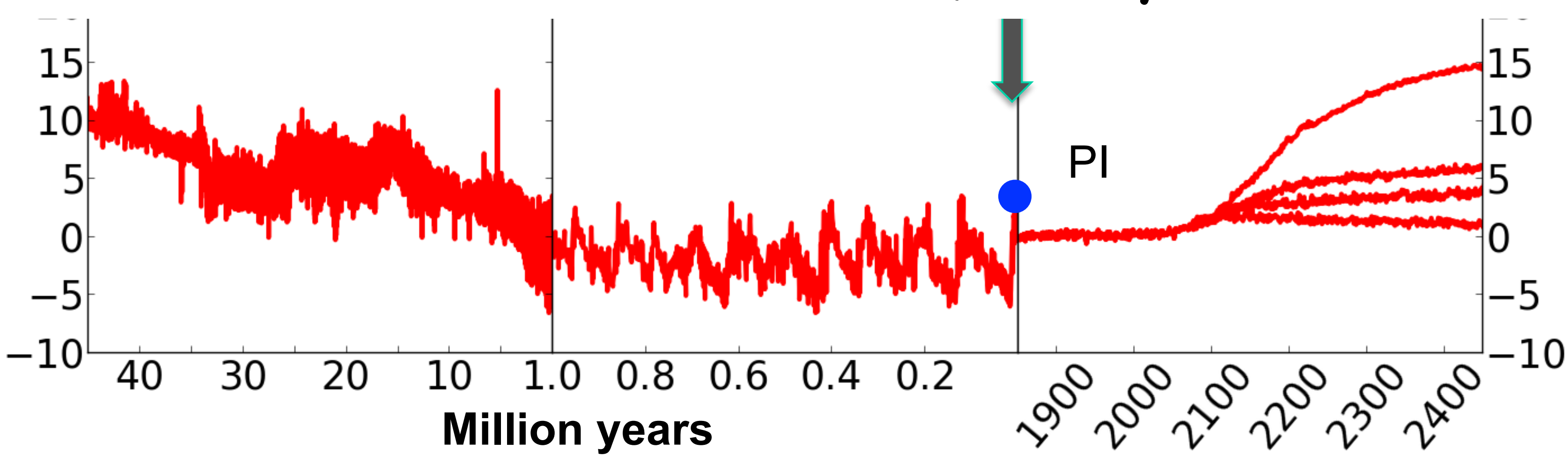
Time Journey: Range of Variability

Temp. anomaly to pre-industrial time
COSMOS
(Wei et al., 2012)

Validation of the models



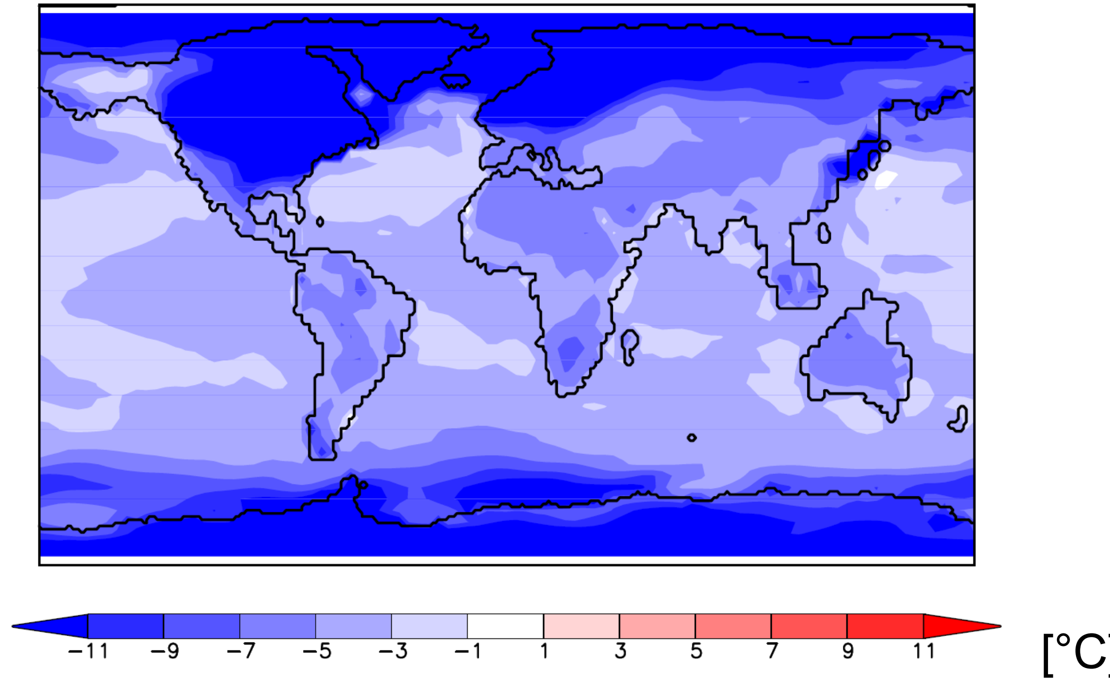
Mid-Holocene (6000 years Before Pres



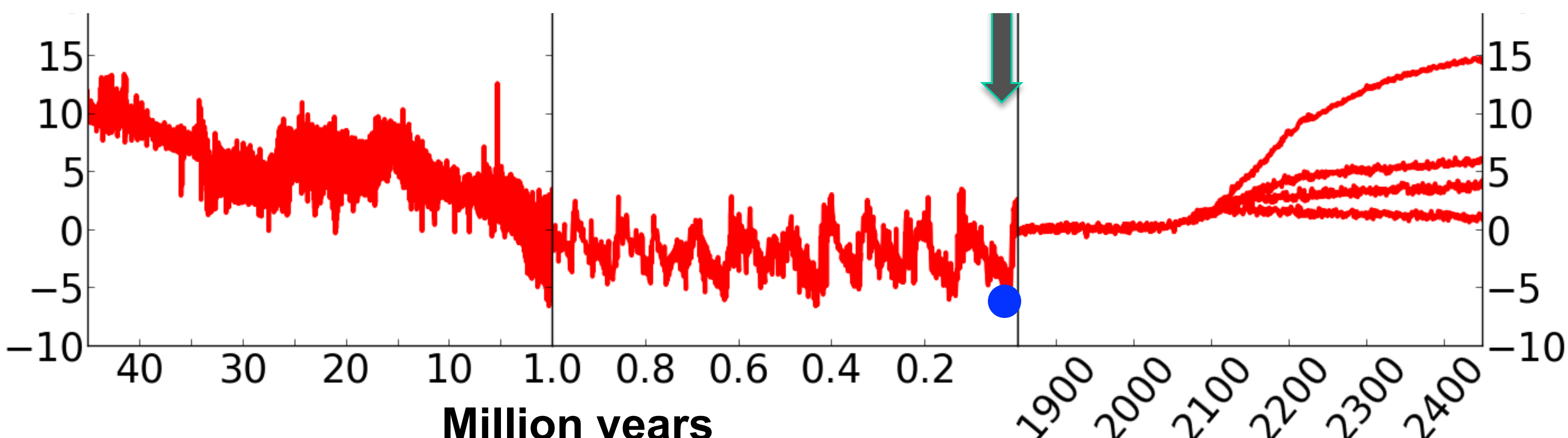
Earth System from a polar perspective

Temp. anomaly to to pre-industrial time
COSMOS
(Zhang et al., 2012)

Polar amplification

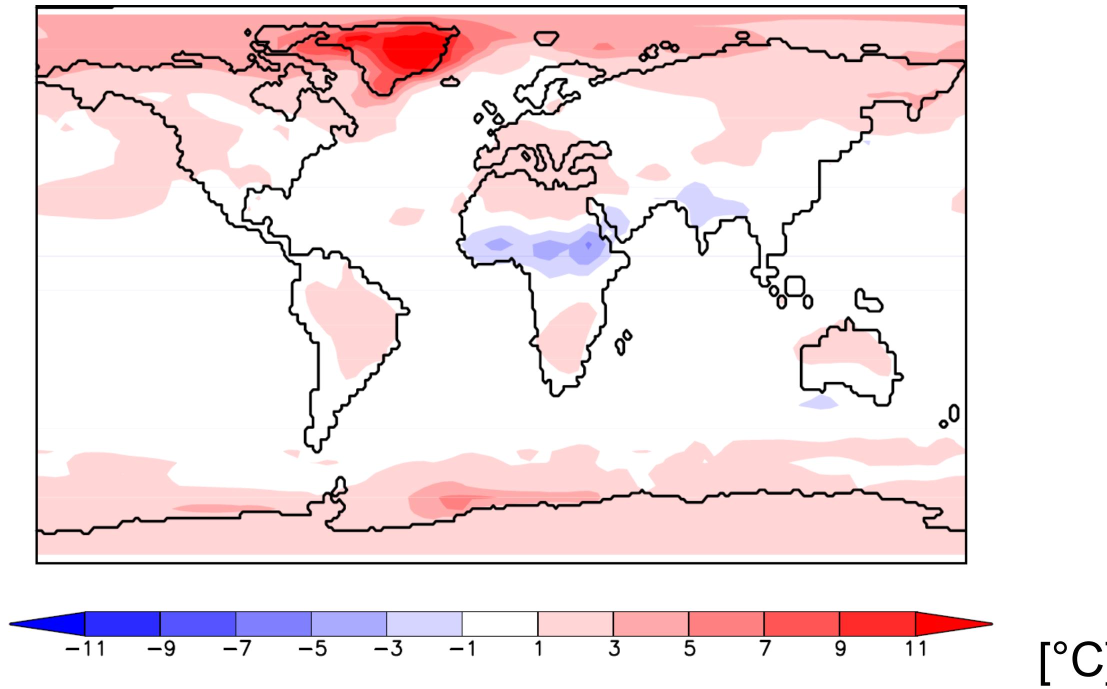


Last Glacial Maximum (21,000 years BP)



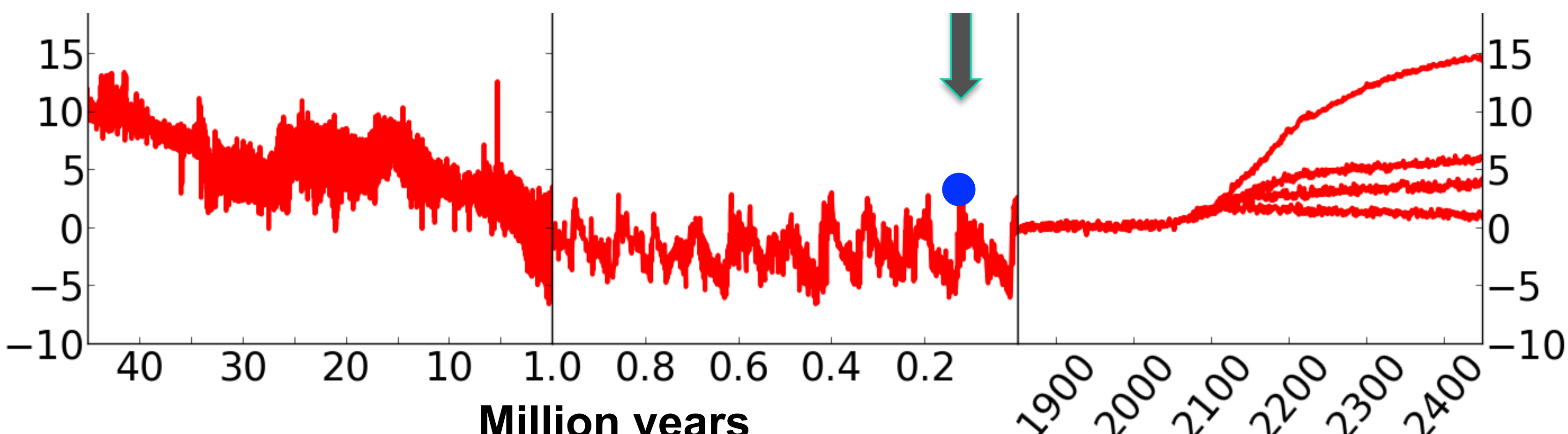
Earth System from a polar perspective

Temp. anomaly to to pre-industrial time
COSMOS
(Pfeiffer & L, 2013)

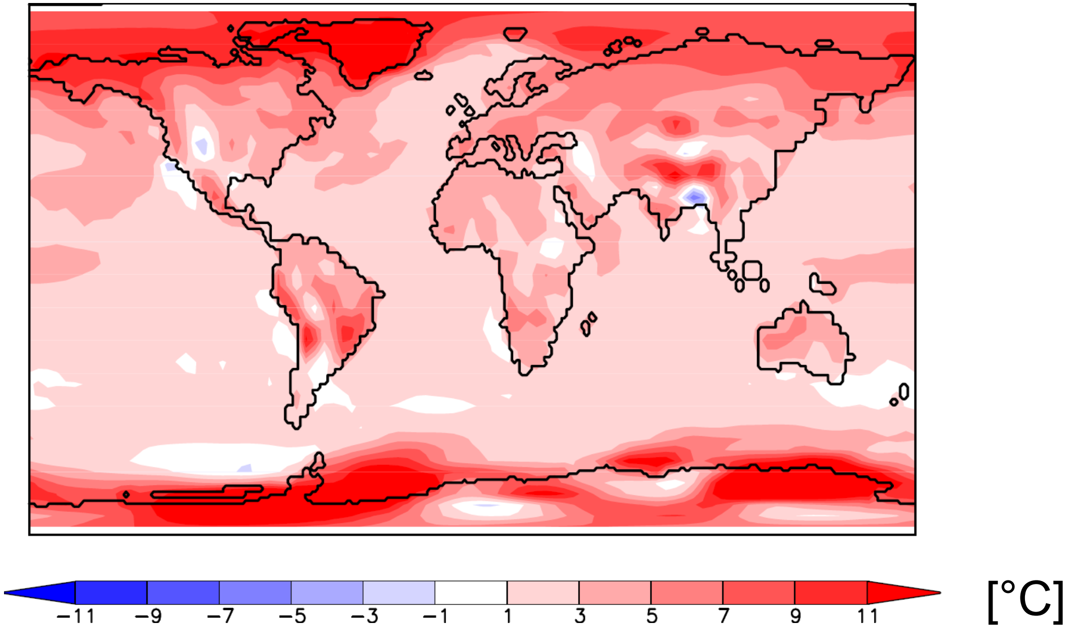


Warm climates
Polar amplification
Sea level

Last Interglacial MIS5.5 (124,000 years BP)



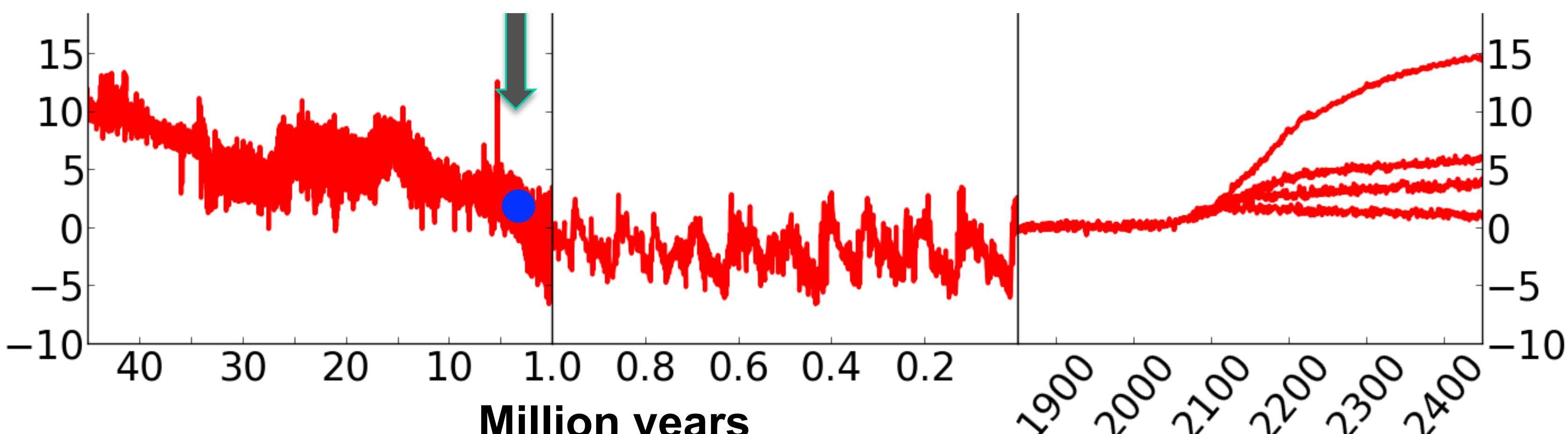
Earth System from a polar perspective



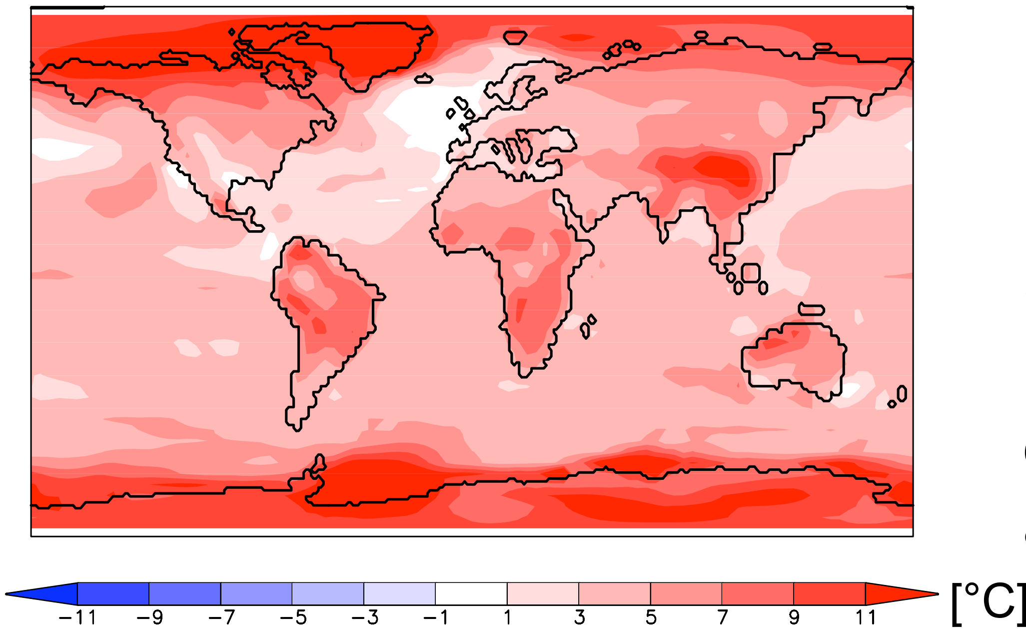
Temp. anomaly to to pre-industrial time
COSMOS
(Stepanek & L, 2012; Haywood et al., 2013)

Warm climates
Polar amplification

Pliocene (3 Million years BP)



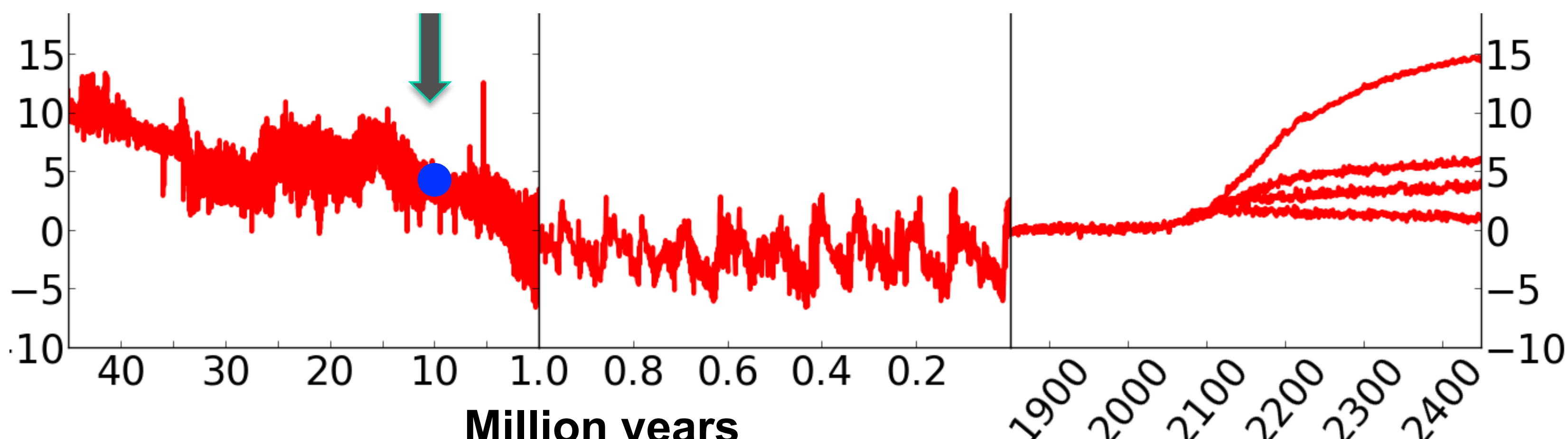
Earth System from a polar perspective



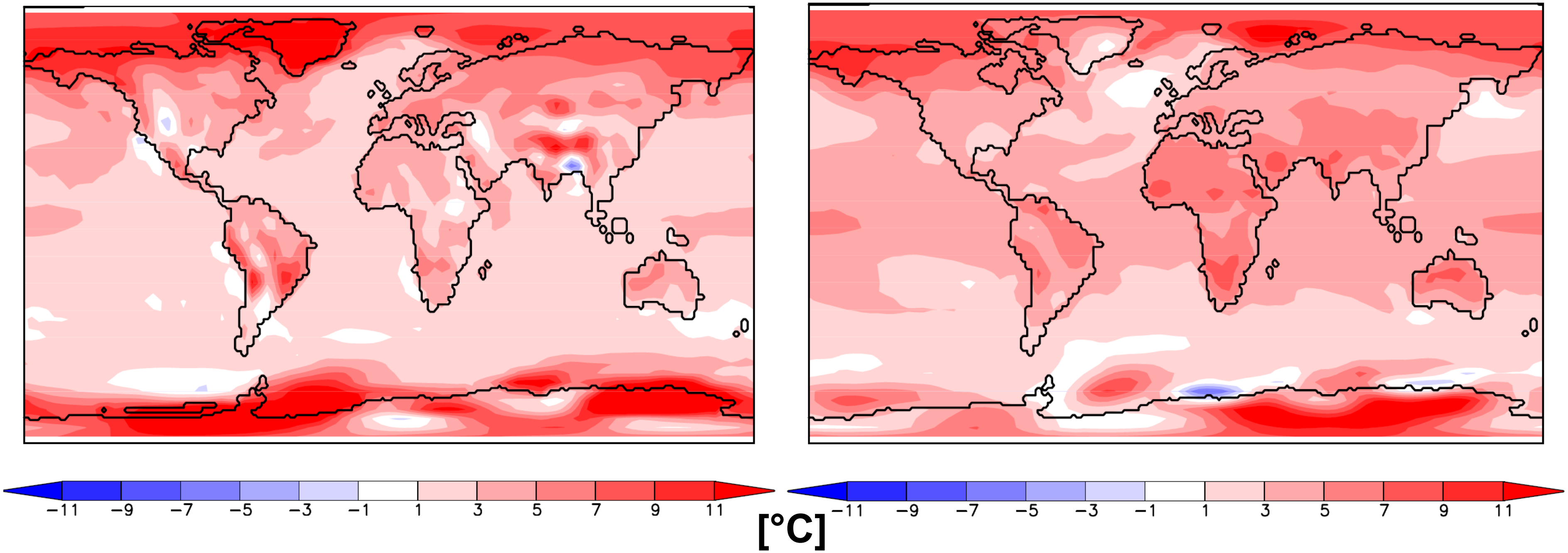
Temp. anomaly to to pre-industrial time
COSMOS
(Knorr et al., 2011)

Geodynamic-tectonic processes on paleo-environmental conditions and glacial evolution

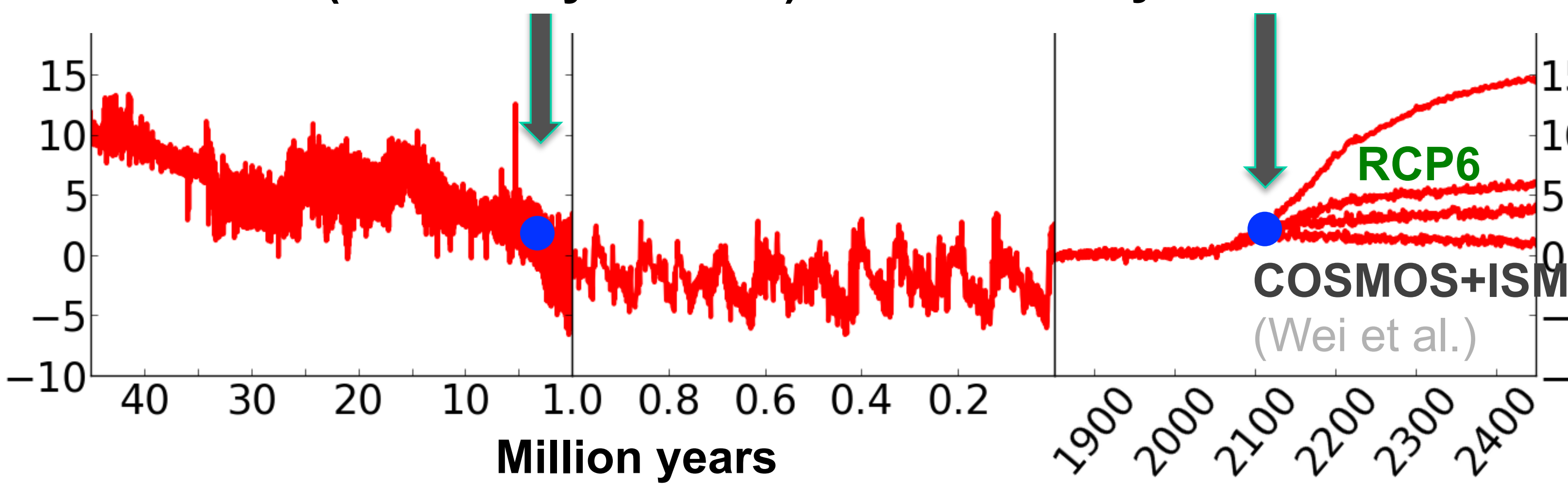
Miocene (10 Million years BP)



Earth System from a polar perspective



Pliocene (3 Million years BP) **Scenario: years 2083-2133**



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:

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

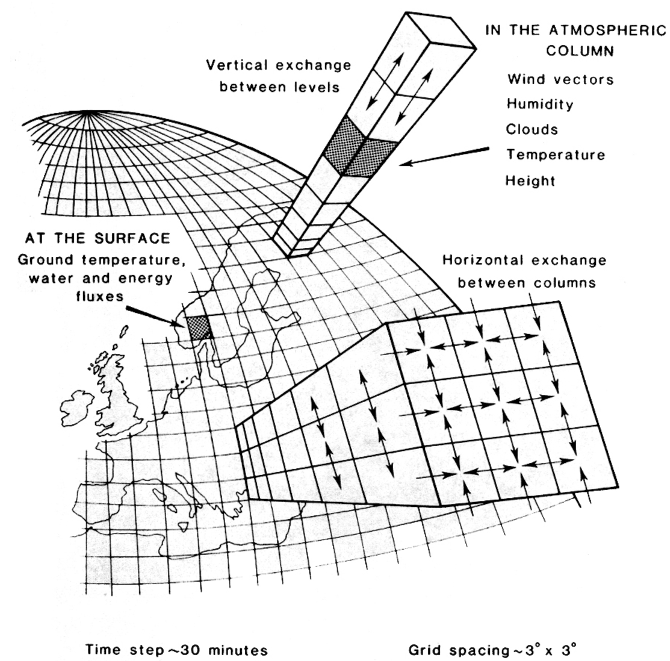
Equation of state:

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

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

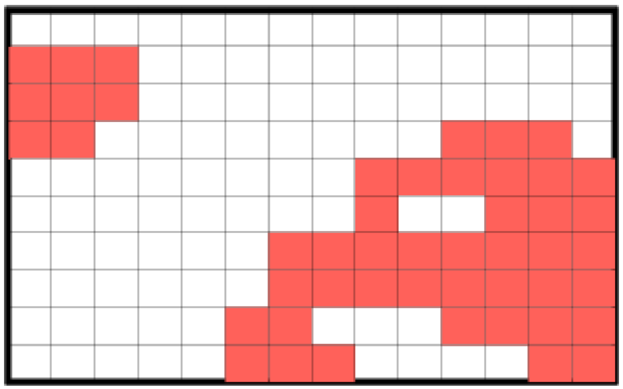
Subgrid scale processes are **parameterized** by diffusive mixing.

Cartesian Grid GCM



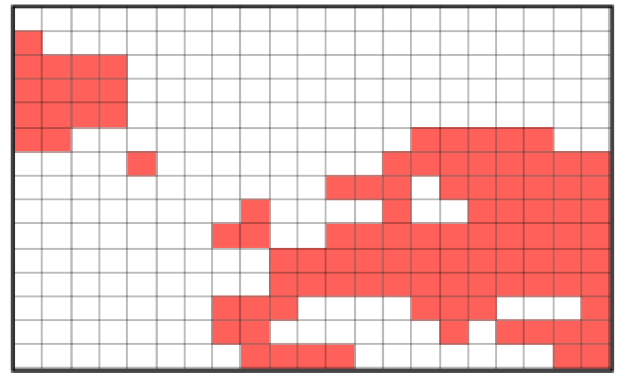
Grid resolution

T 21



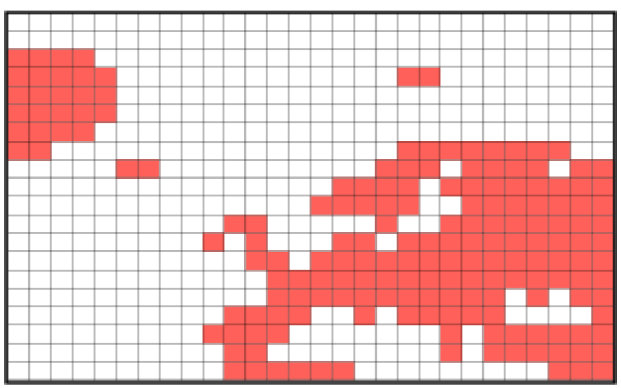
ca. 500 km Gitterabstand

T 42



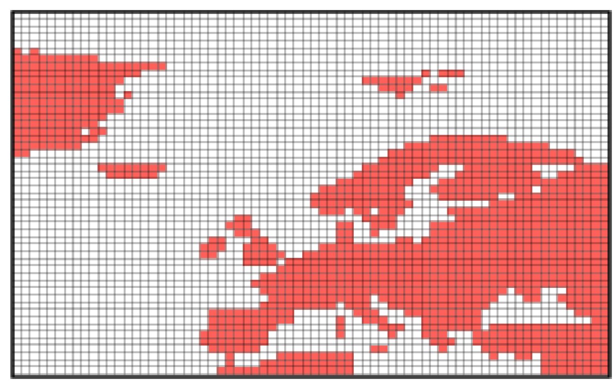
ca. 250 km Gitterabstand

T 63

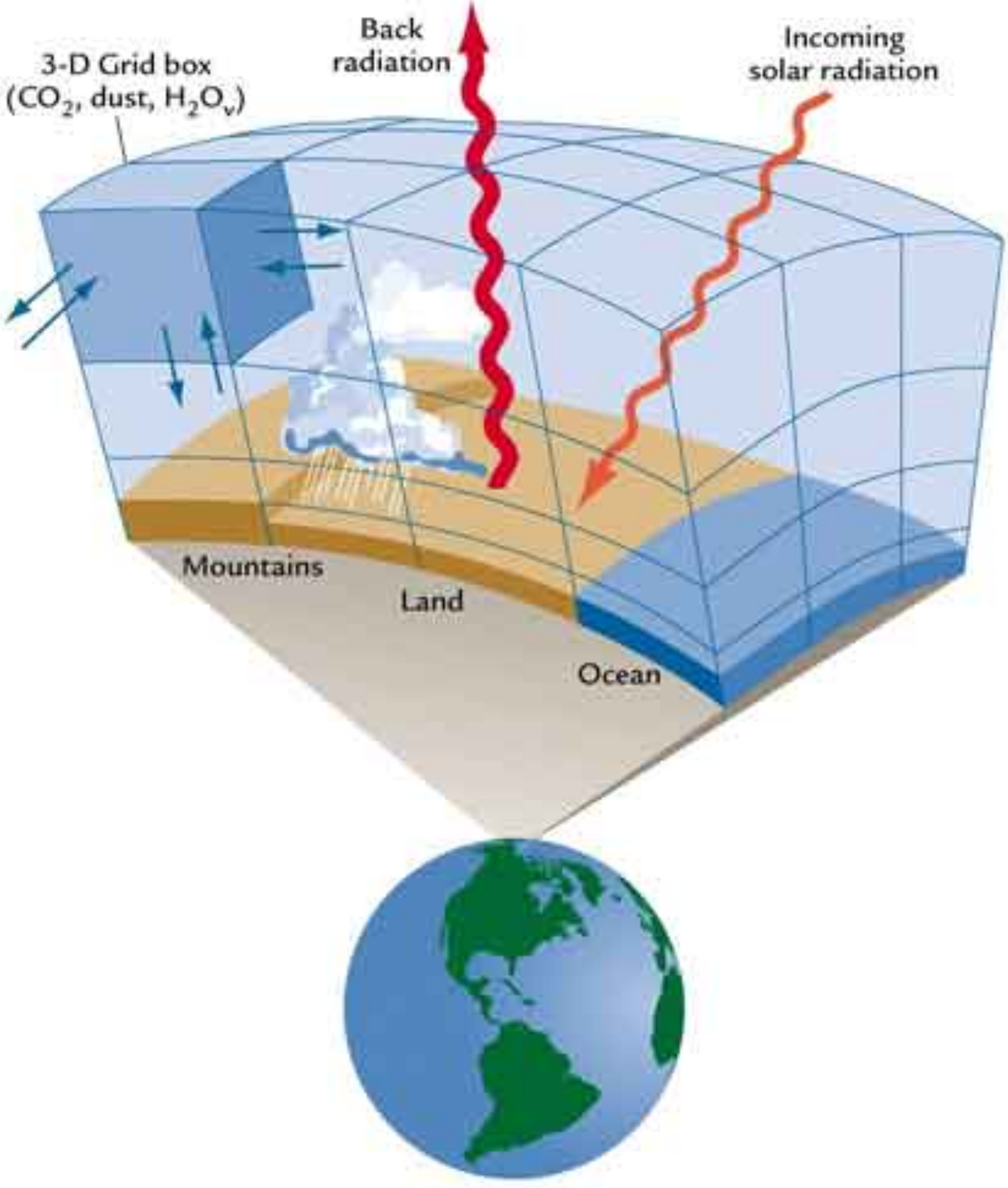


ca. 180 km Gitterabstand

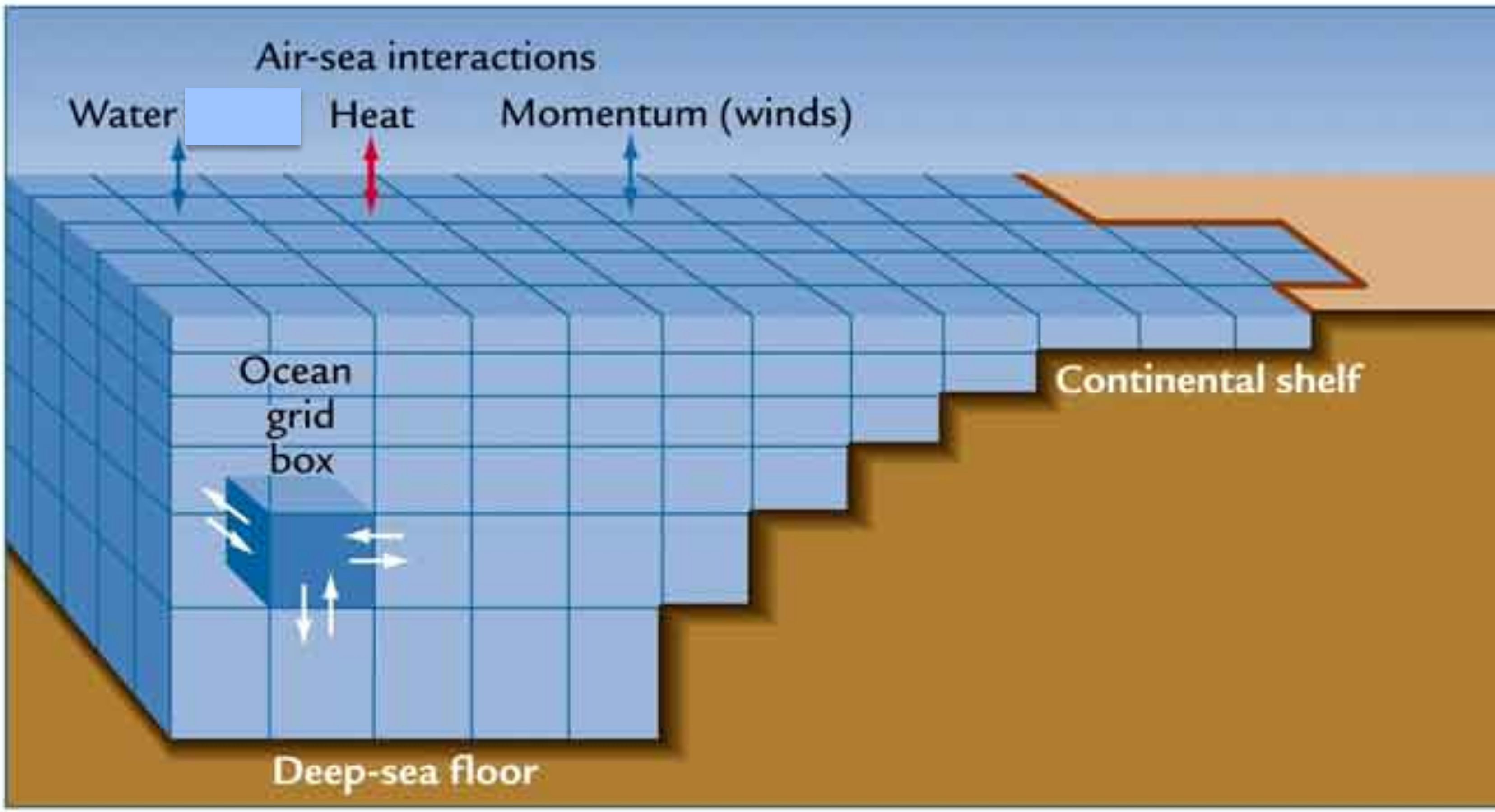
T 106



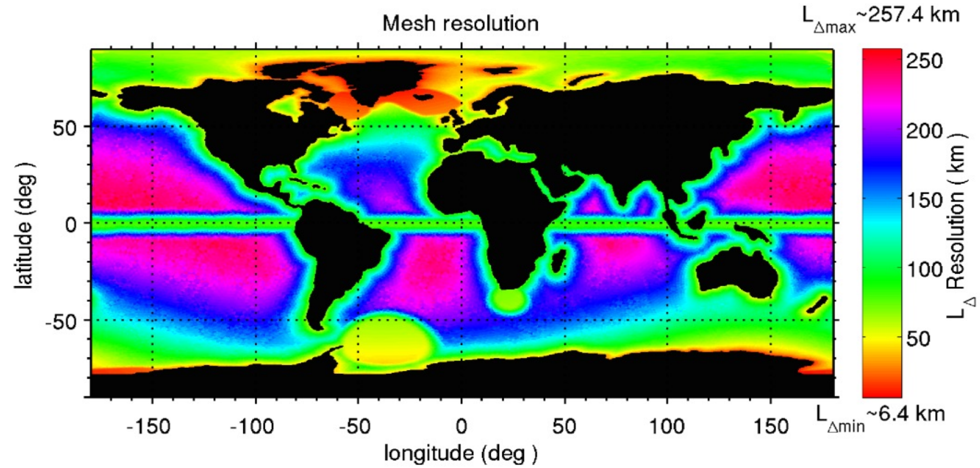
ca. 110 km Gitterabstand

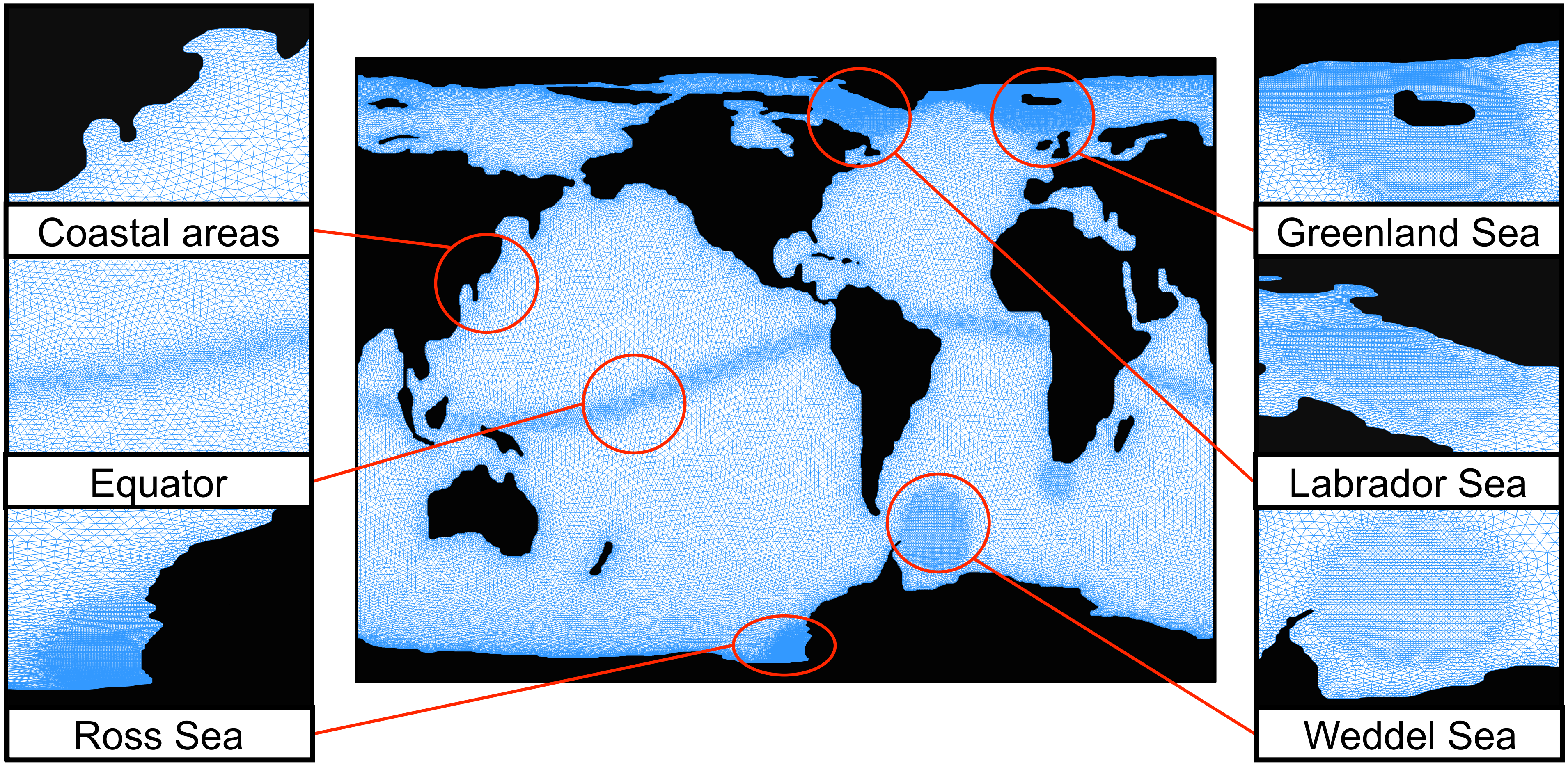

3-D Grid box
(CO_2, dust, H_2O_v)
Back
radiation
Incoming
solar radiation
Mountains
Land
Ocean

Ocean circulation models and boundary conditions



- **Model Setup:**
  - mesh with high resolution at deep water mass formation areas
  - min. resolution ~ 6.5 km
  - 41 depth level
  - ~ 6.000.000 3D tetrahedral elements, ~ 1.000.000 3D nodes





Dynamics of the Ocean System

Momentum equation

$$\overbrace{\rho\left(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\substack{\text{Unsteady}\\ \text{acceleration}}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{\substack{\text{Advective}\\ \text{acceleration}}}\right)}^{\text{Inertia (per volume)}} = \overbrace{\underbrace{-\nabla p}_{\substack{\text{Pressure}\\ \text{gradient}}} + \underbrace{\mu\nabla^2\mathbf{v}}_{\text{Viscosity}}}^{\text{Divergence of stress}} + \underbrace{\mathbf{f}}_{\substack{\text{Other}\\ \text{body}\\ \text{forces}}} .$$

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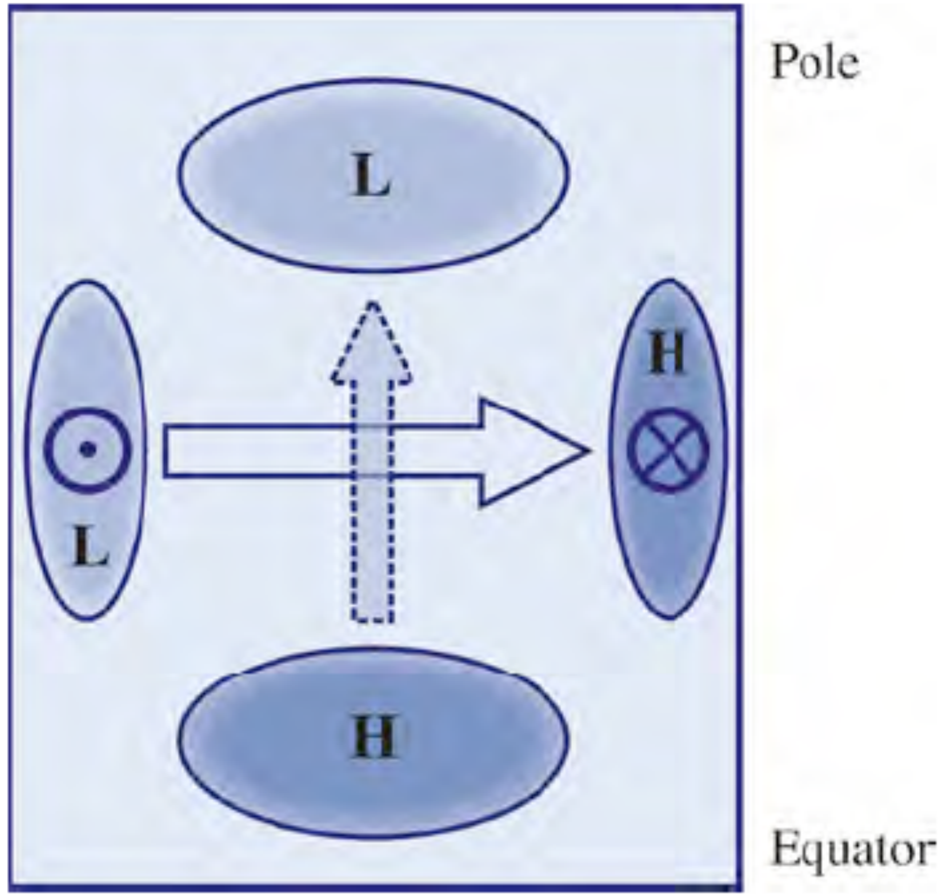
Scaling (non-dimensionalized)

$$\left(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{10^{-4}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{10^{-4}}\right) = \underbrace{-\frac{1}{\rho}\nabla p}_{10^{-3}} + \underbrace{\nu\nabla^2\mathbf{v}}_{10^{-12}} + \underbrace{2\mathbf{\Omega}\times\mathbf{v}}_{10^{-3}} .$$

Geostrophic balance: Pressure gradient Coriolis force



Schematic of the surface flow driven by a north-south density gradient in an ocean basin. The primary north-south gradient – as a result of the surface forcing – is in balance with an eastward geostrophic current which generates a secondary high and low pressure system.

Depth integrated flow

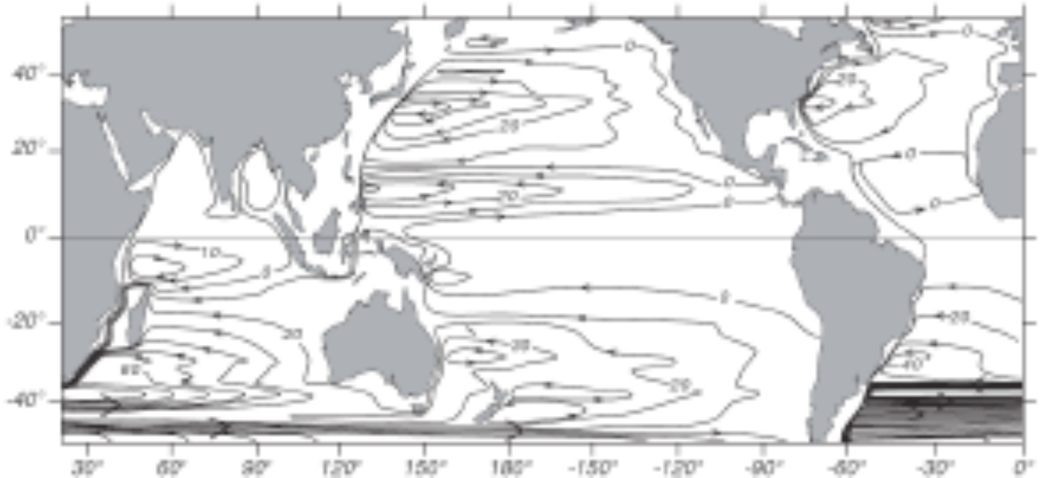
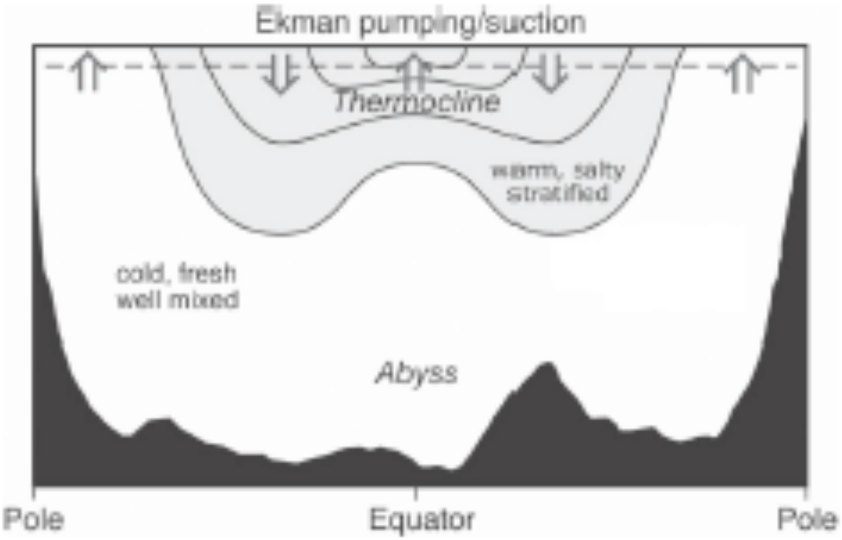


Figure 2.8: Depth-integrated Sverdrup transport applied globally using the wind stress from Hellerman and Rosenstein (1983). Contour interval is 10 Sverdrups. After Tomczak and Godfrey (1994: 46).

Deep water

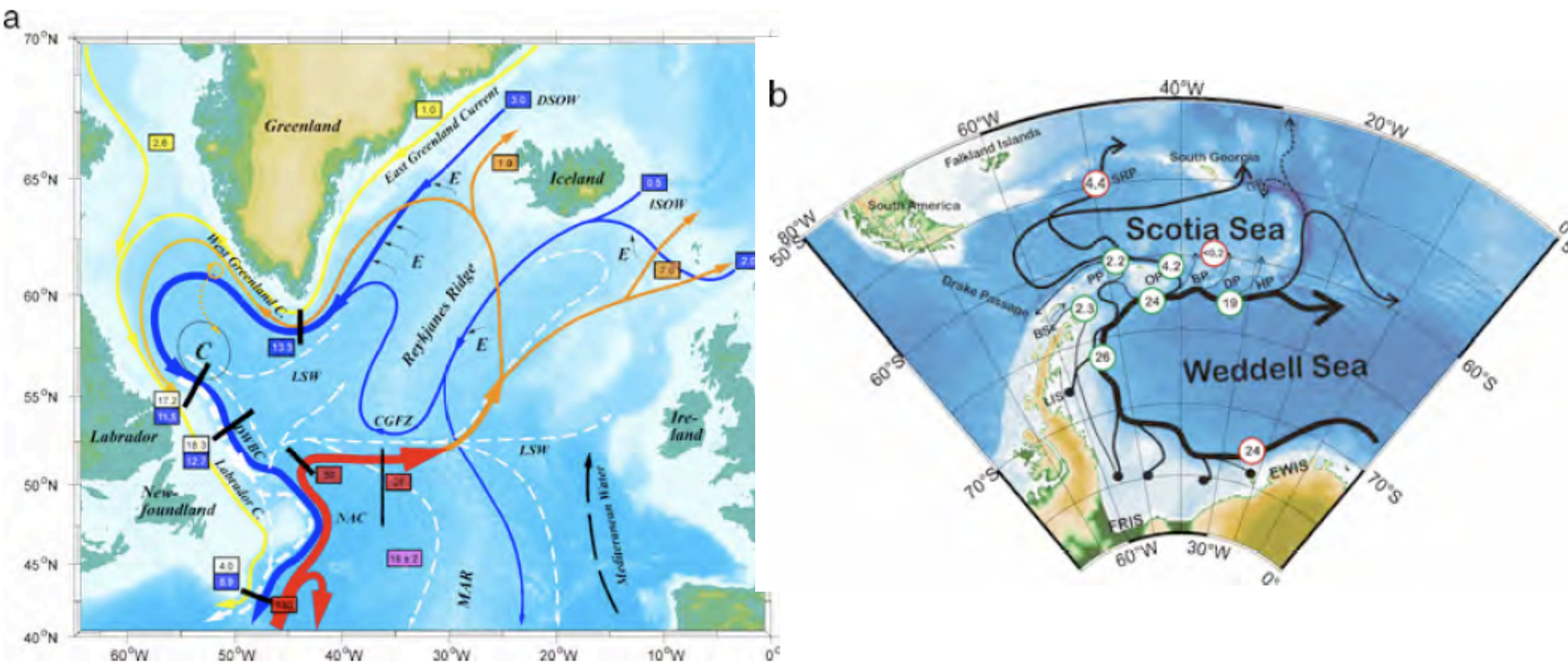
Vertical structure of the ocean

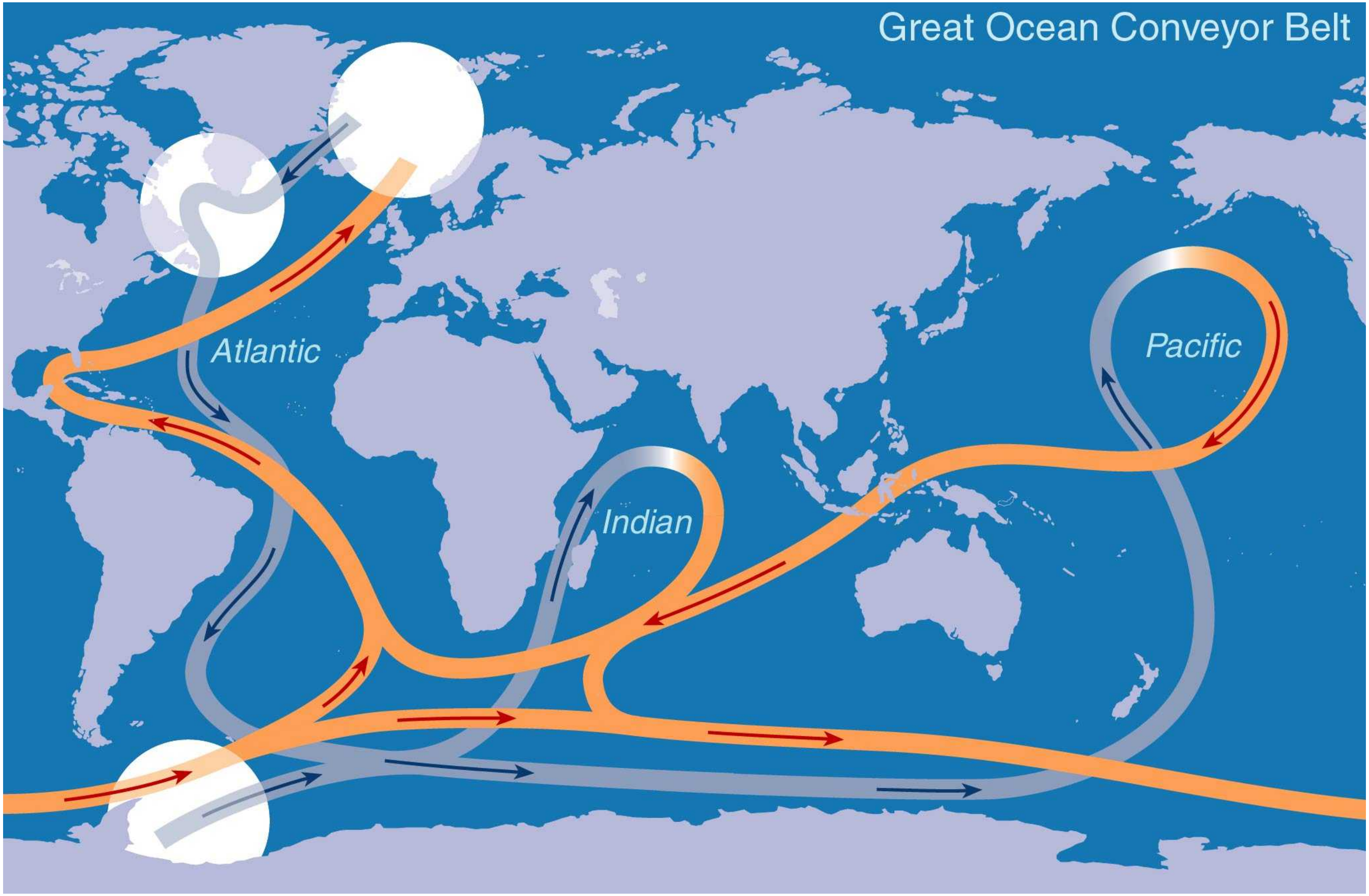


Warm, salty,
stratified

Cold, fresh,
well mixed

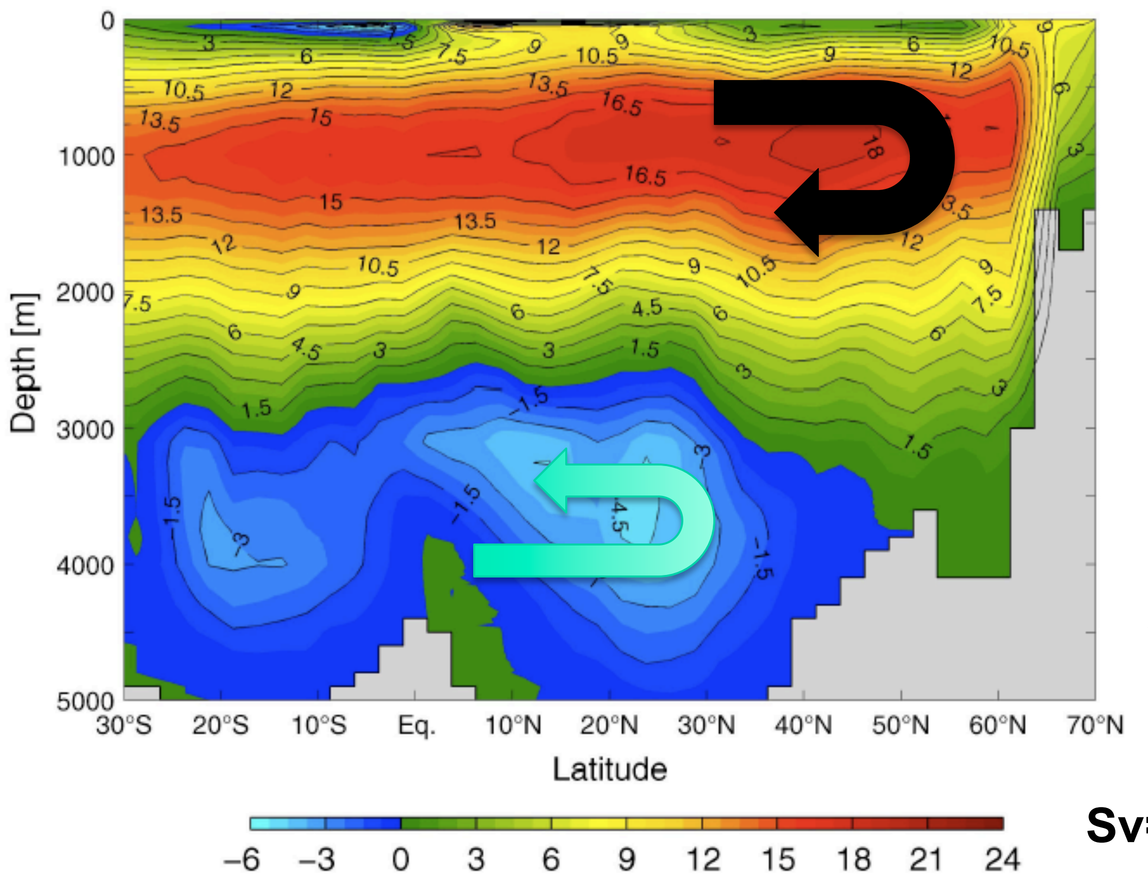
High latitudes: Schematic of the flow of important water masses




Great Ocean Conveyor Belt
Atlantic
Pacific
Indian

Meridional overturning circulation

Atlantic Ocean deep sea circulation



NADW: 18 Sv

AABW: 4 Sv

Sv=10^6 m^3/s

Symmetric solution

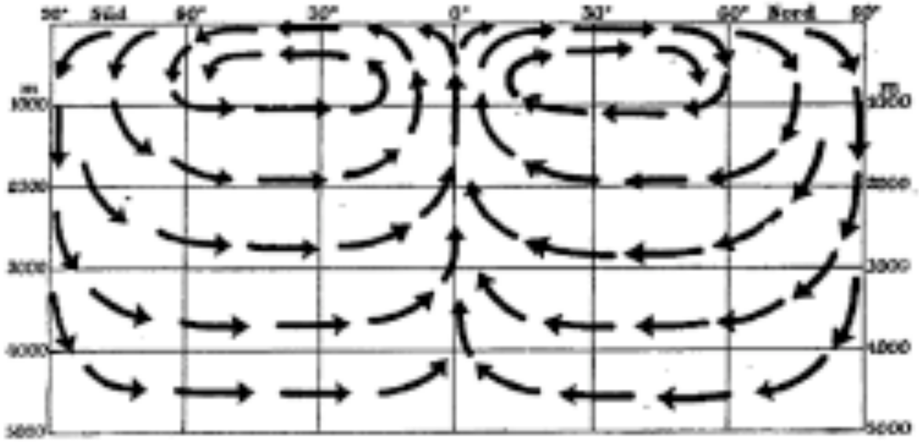
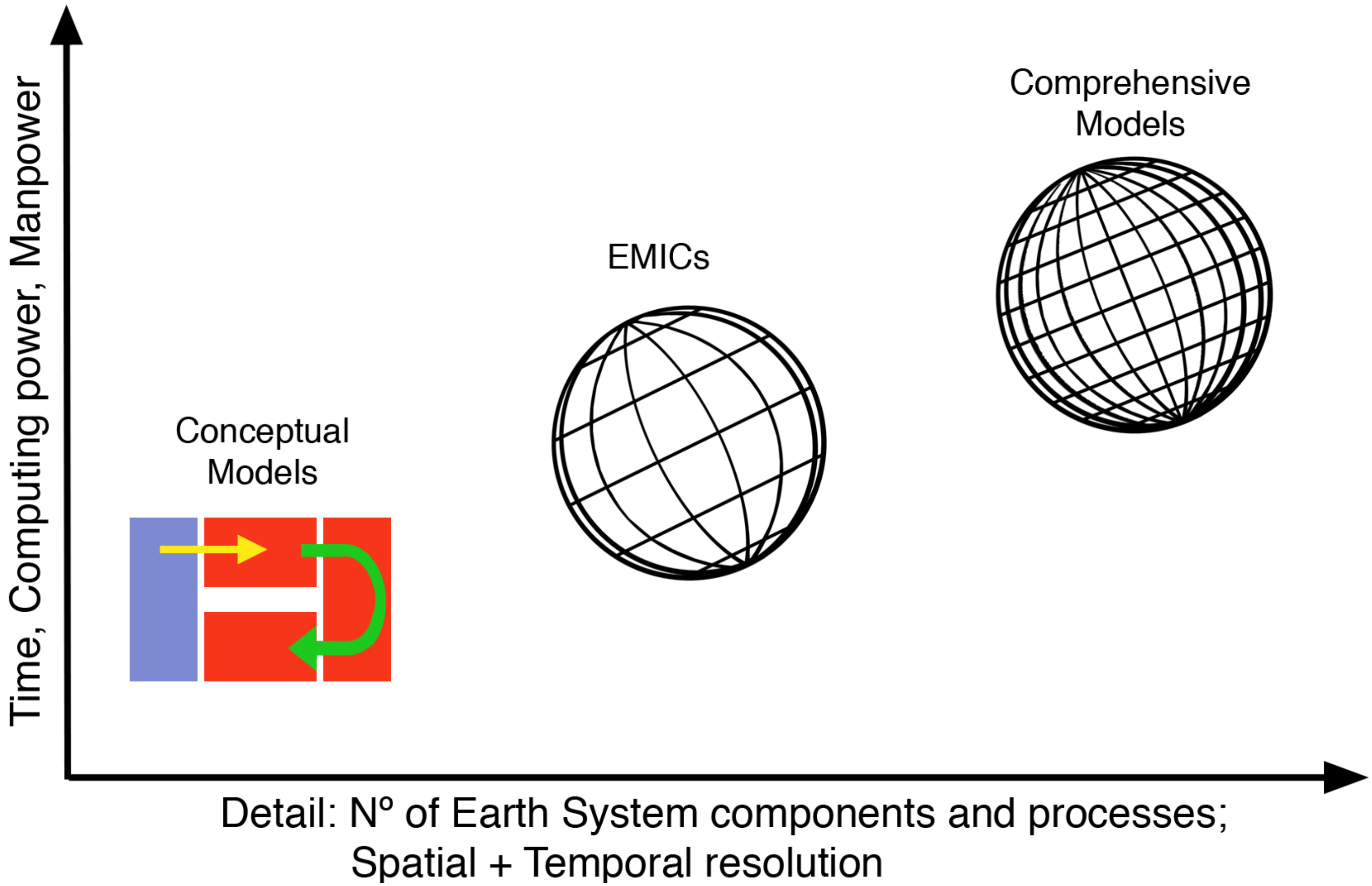


Figure 2.15: Atlantic circulation model according to (von Lenz, 1847a, b), figure after (Merz and Wüst, 1922)

Von Lenz, 1847

Types of models

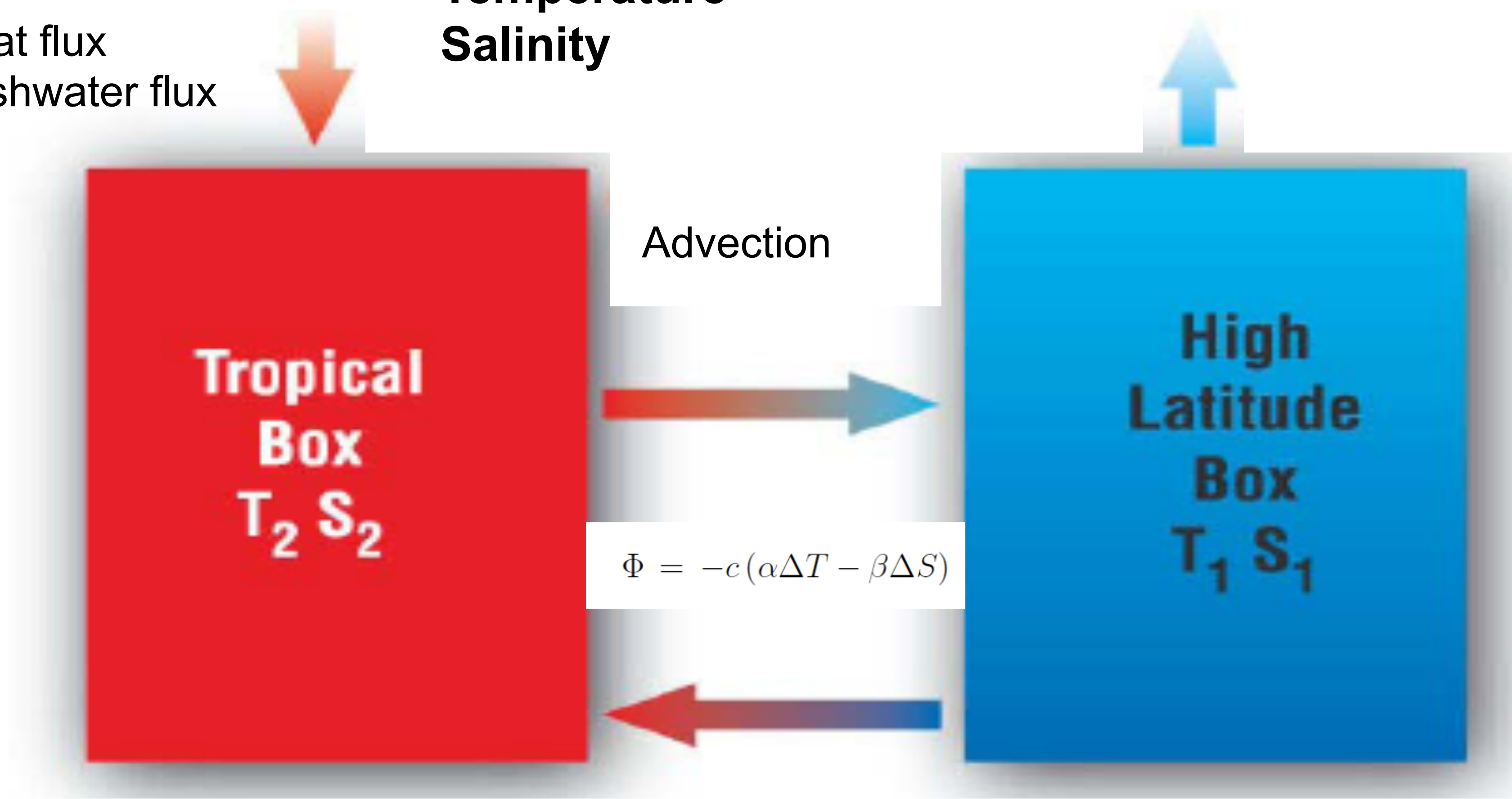


Modified from Claussen et al.

Idealized model of the ocean circulation

Variables:
Temperature
Salinity

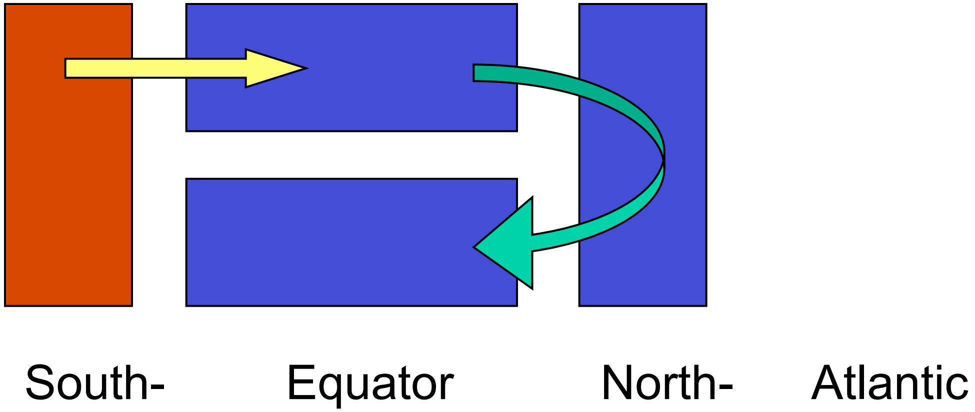
Heat flux
freshwater flux



<u>Different modes of operation: salinity matters</u>

Stommel (1961)

Conceptual Model of MOC



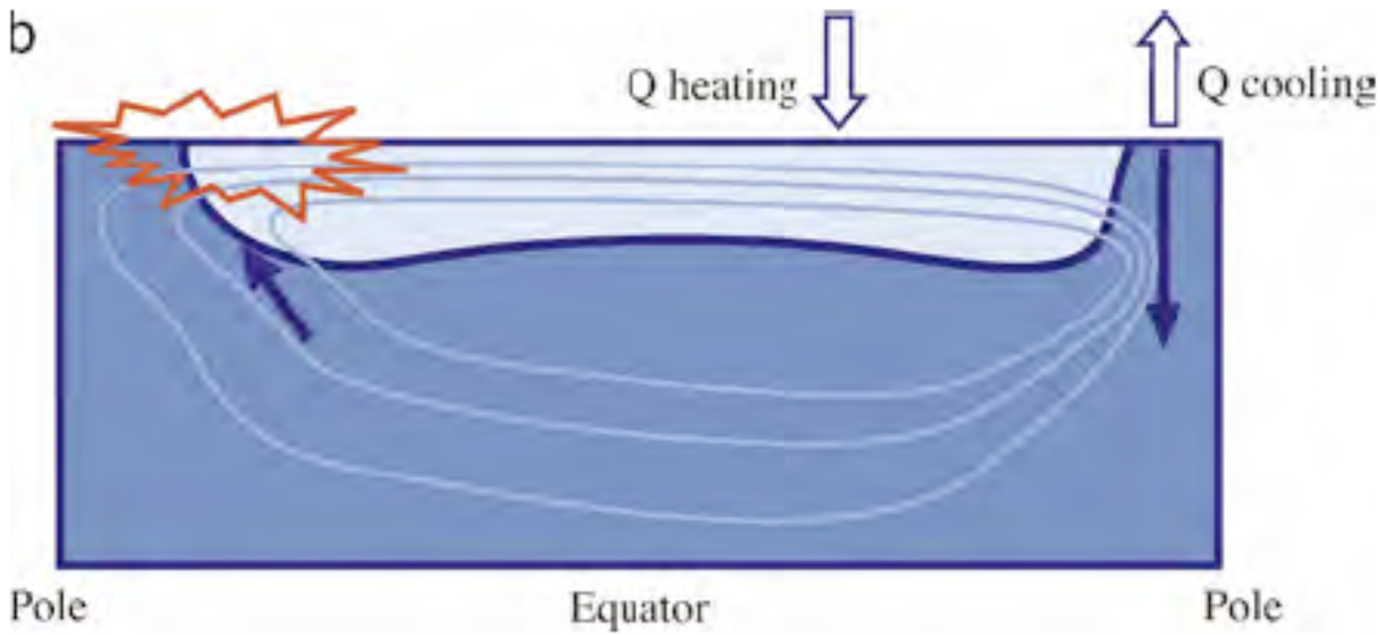
Box Models

- Stommel ‘s model almost completey ignored (25 years)
- Rooth, 1982: Two hemisphere counterpart,
- Unaware of Stommel (1961) model
- Rooth suggested to F. Bryan: test with a GCM

Mixing

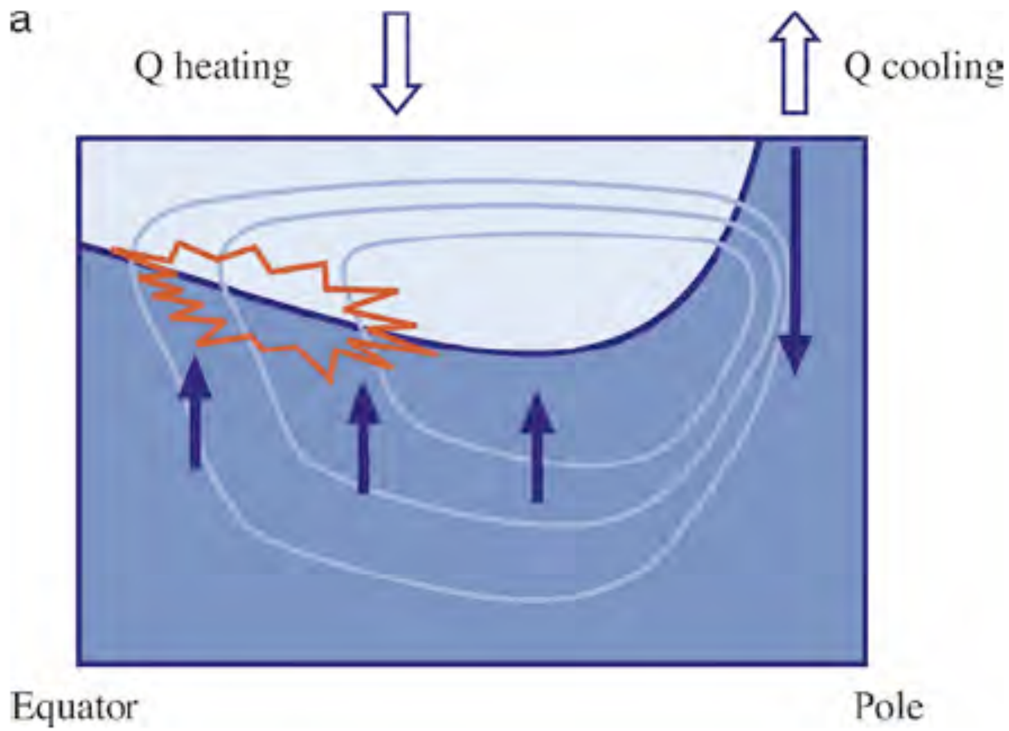
- without mixing heavy water with lighter water in rising areas or in the surface layers of MOC, the circulation system cannot be closed.
- Since mixing consumes turbulent mechanical energy generated by wind in the surface layer and/or by tides and breaking of internal waves in the interior, the overturning can only work on the basis of mechanical driving.

MOC and mixing

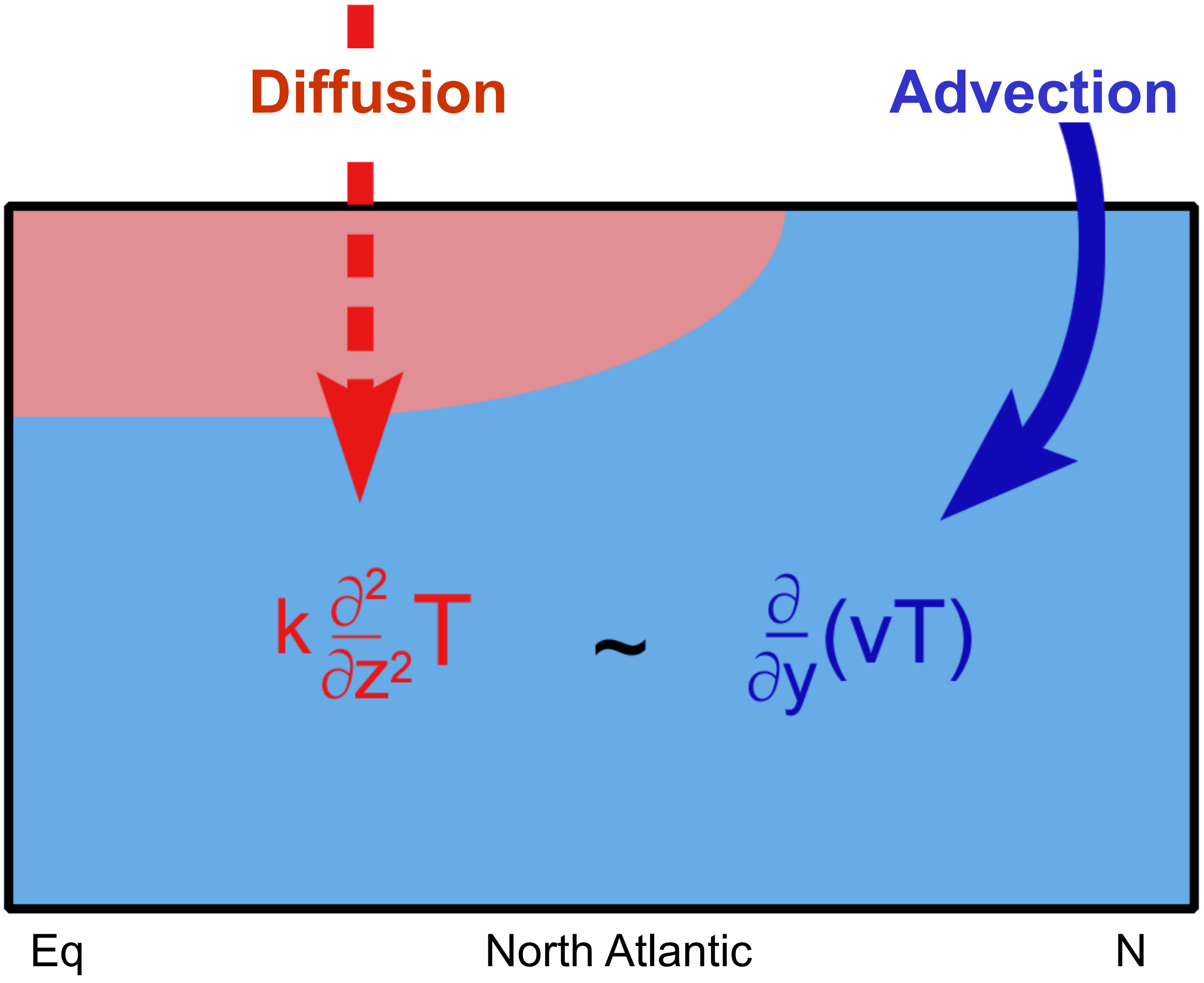


the upwelling can be wind-induced (Ekman pumping), isopycnals must outcrop at the surface as in the Southern Ocean.

What drives the AMOC?

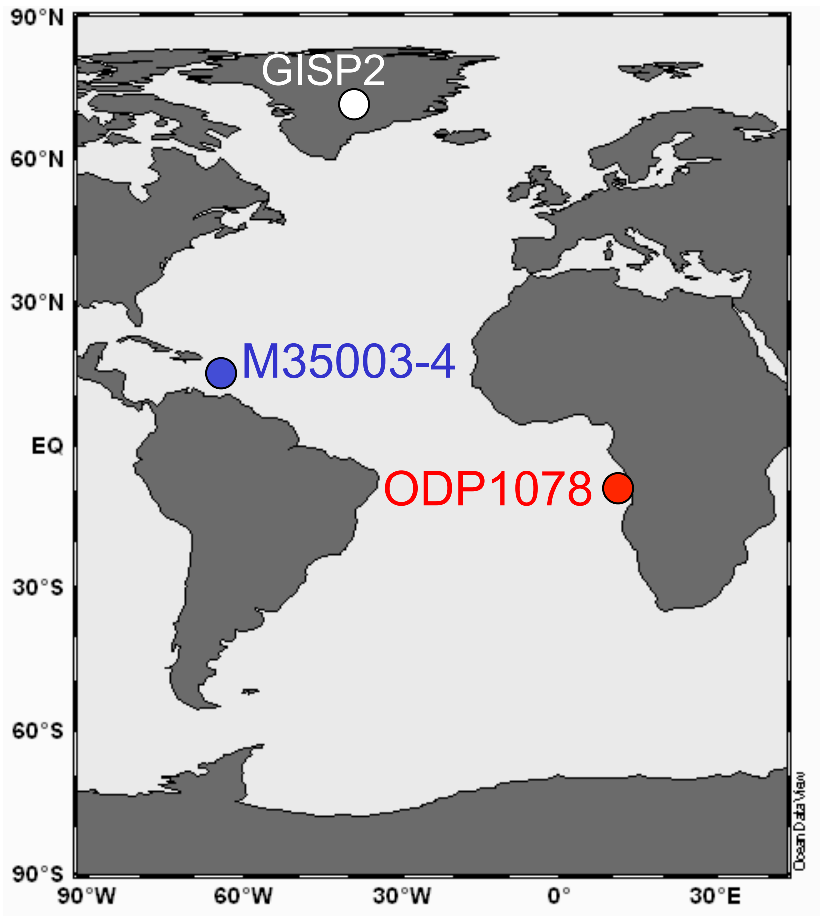


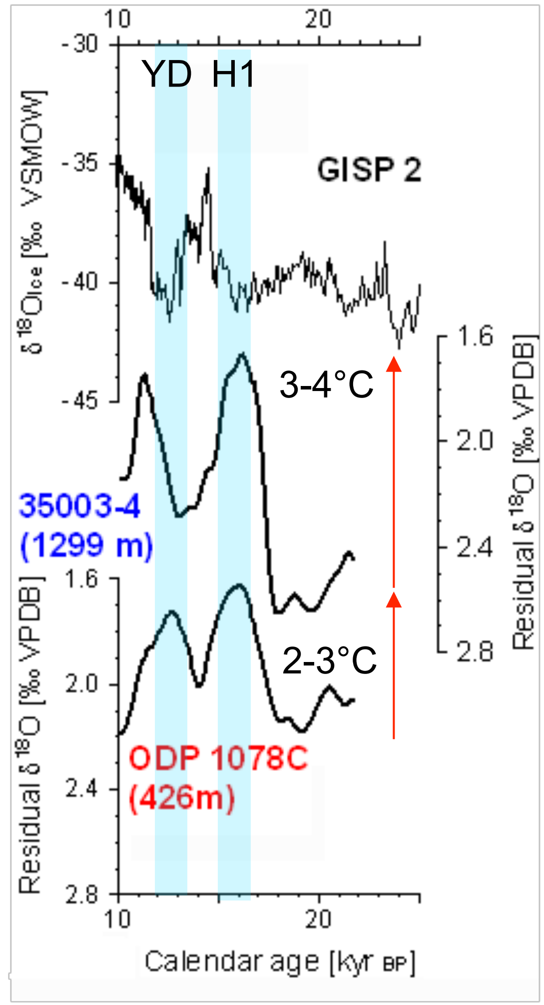
Windstress and breaking surface waves drive the MOC -> mixing



Diffusion
Advection
$k\frac{\partial^2}{\partial z^2}T \sim \frac{\partial}{\partial y}(vT)$
Eq
North Atlantic
N

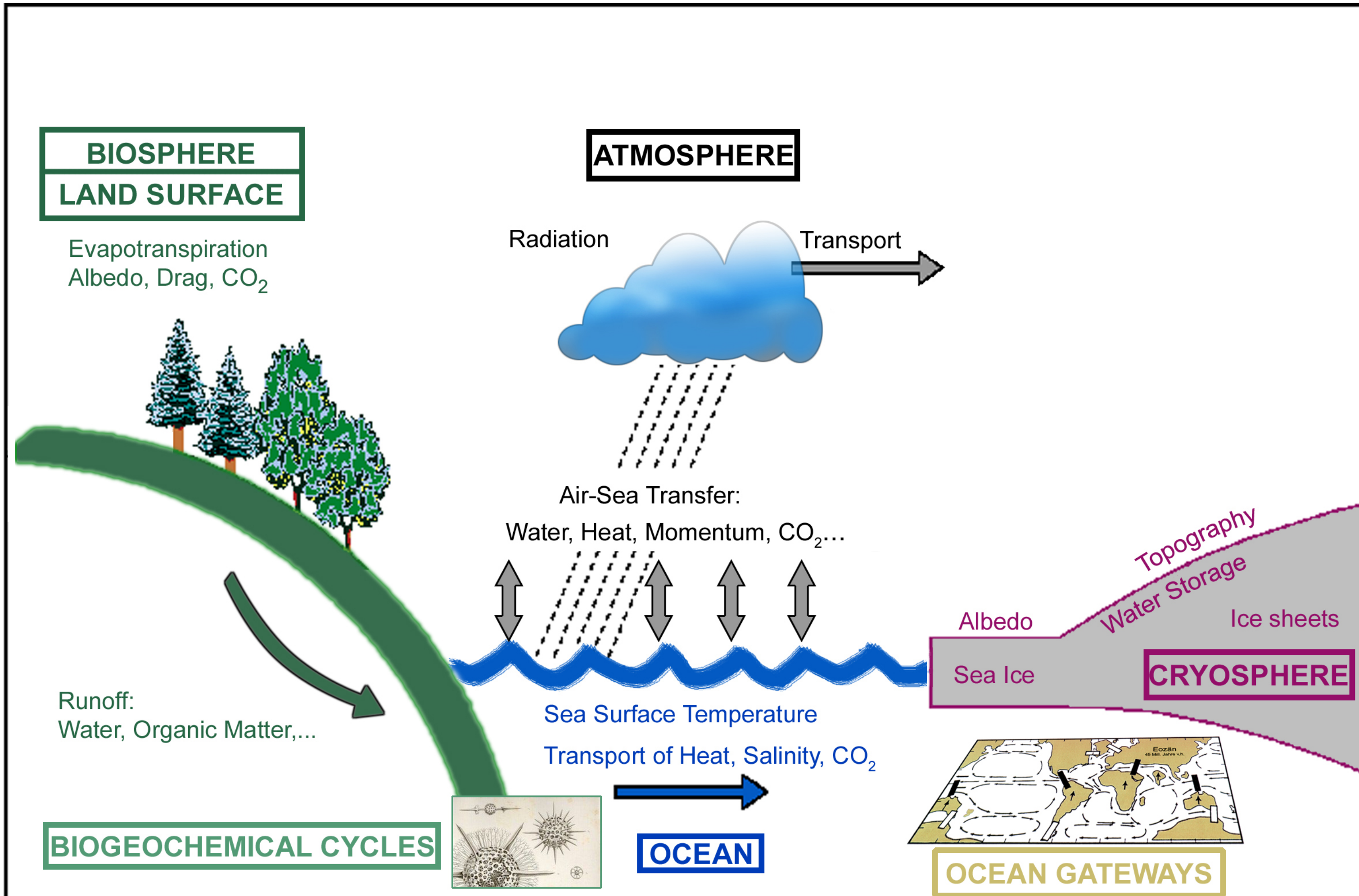
Lessons from Paleoclimate Data



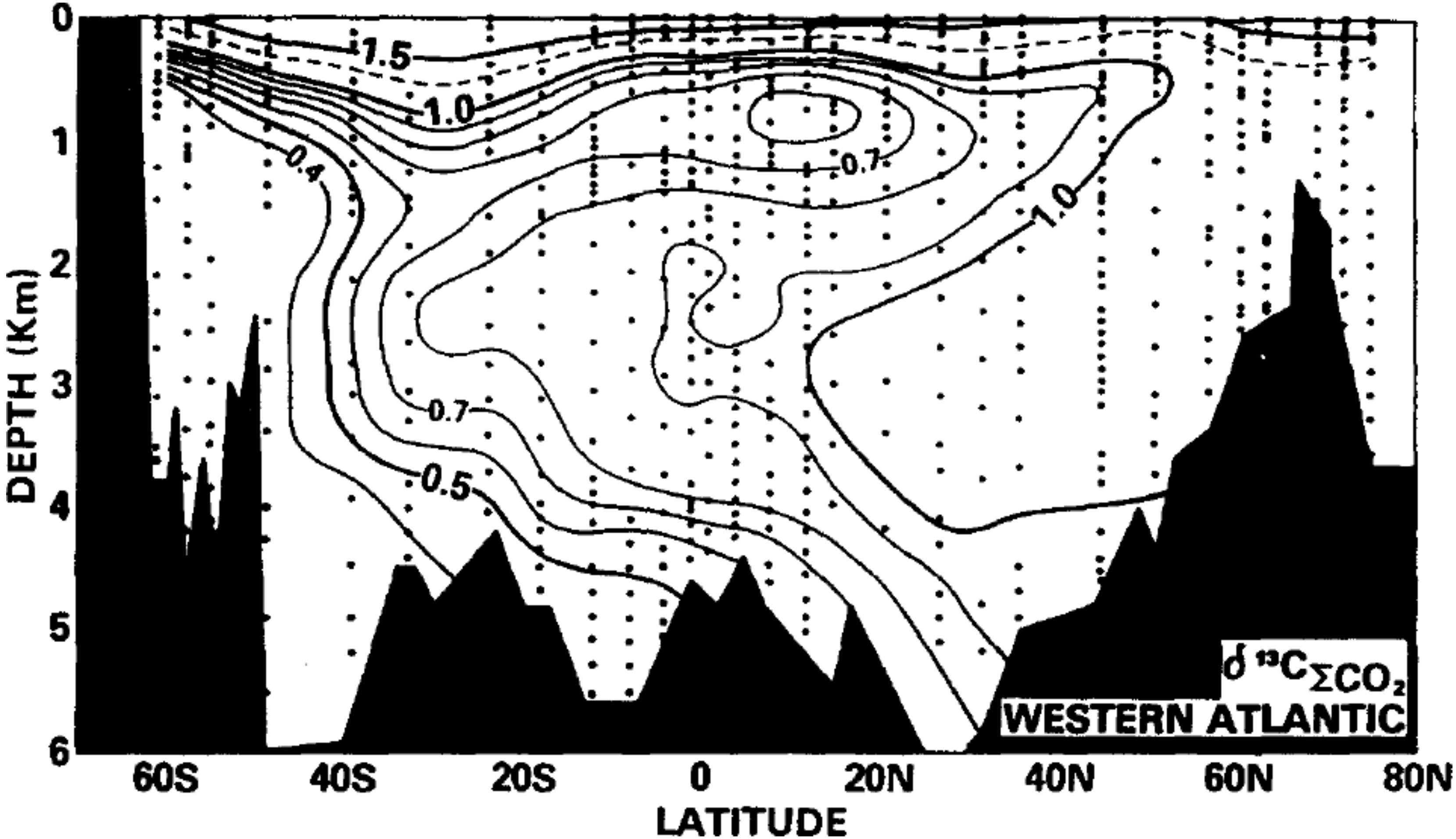


GISP2: Grootes et al. 2000
M35003-4: Hüls and Zahn 2000)

The complex Earth System requires a multi-disciplinary approach

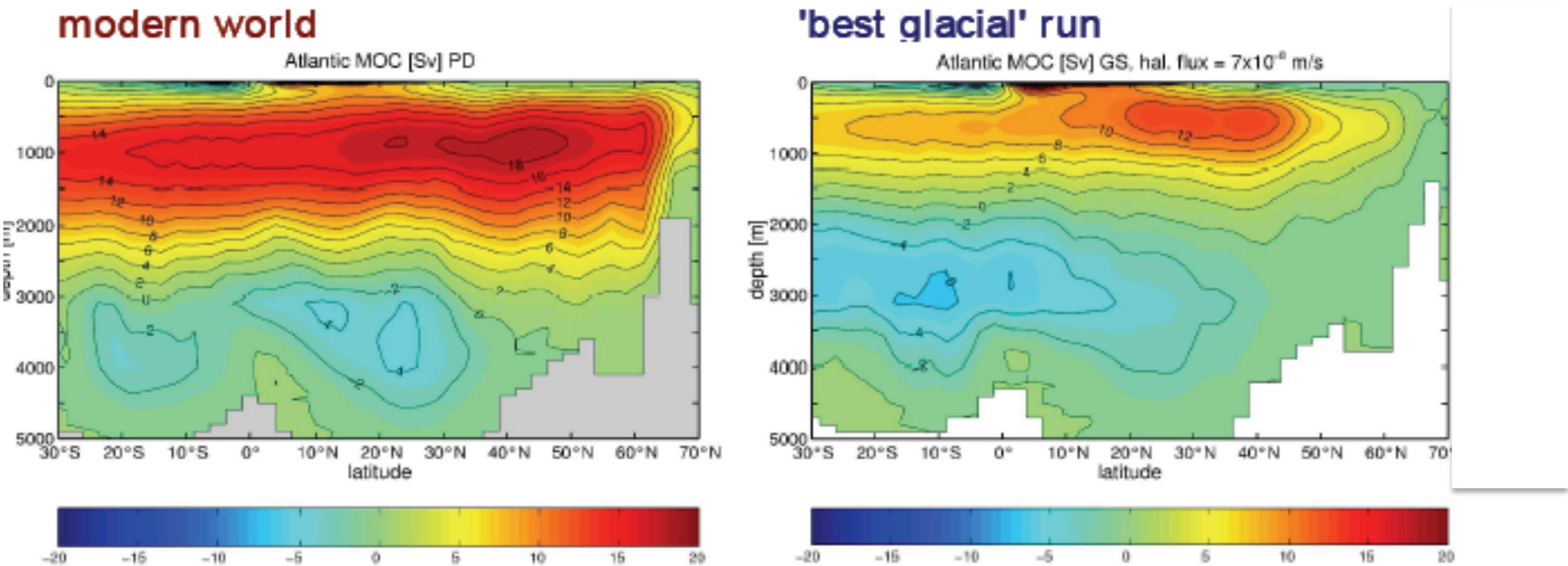


Water masses in the Atlantic Ocean



Kroopnick 1985

Glacial-Interglacial changes: Atlantic meridional overturning (AMOC)



<u>LGM:</u>

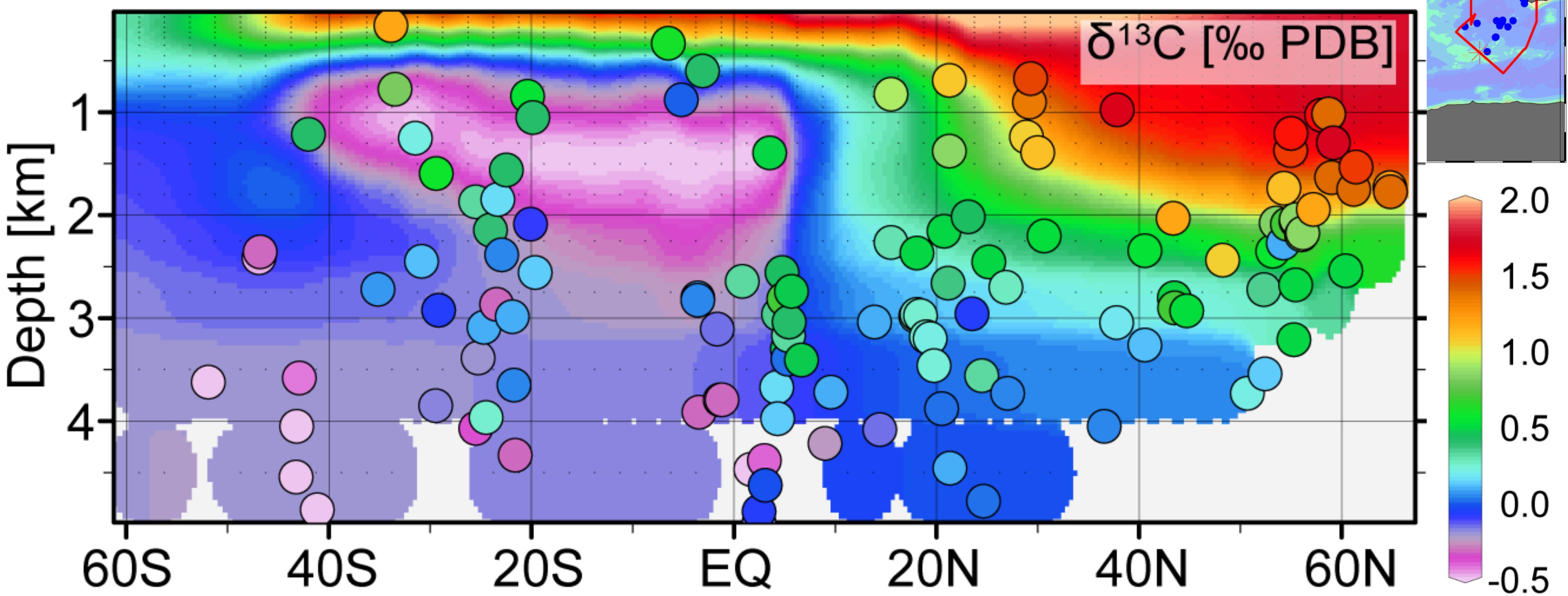
AMOC is shallower

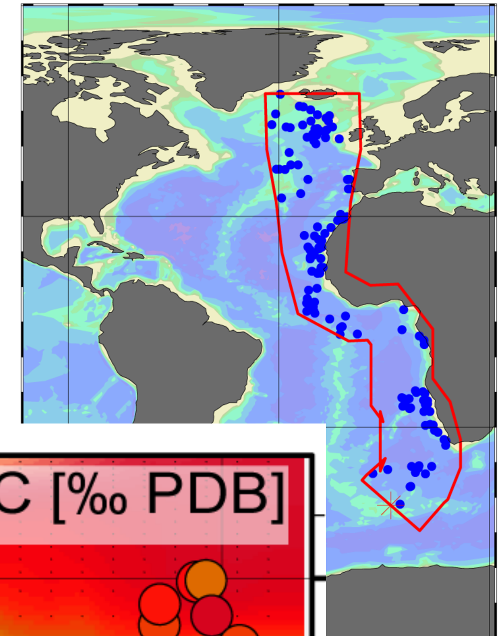
AMOC is slightly weaker

Hesse et al. 2011;
Butzin et al. 2005, 2012

Glacial-Interglacial changes:
δ13C as proxy for water mass structure

Data *(Wuellersdorfii)* **and Model** *(best glacial)*





Hesse et al. 2011

Goal of Paleo-modeling

- Past climate variations help us to understand the climate system as a whole
- To elaborate processes (first and second order)
- Test hypotheses by different model scenarios and comparing model results to data
- Models need to be validated by present and past variability

General approaches to paleoclimates