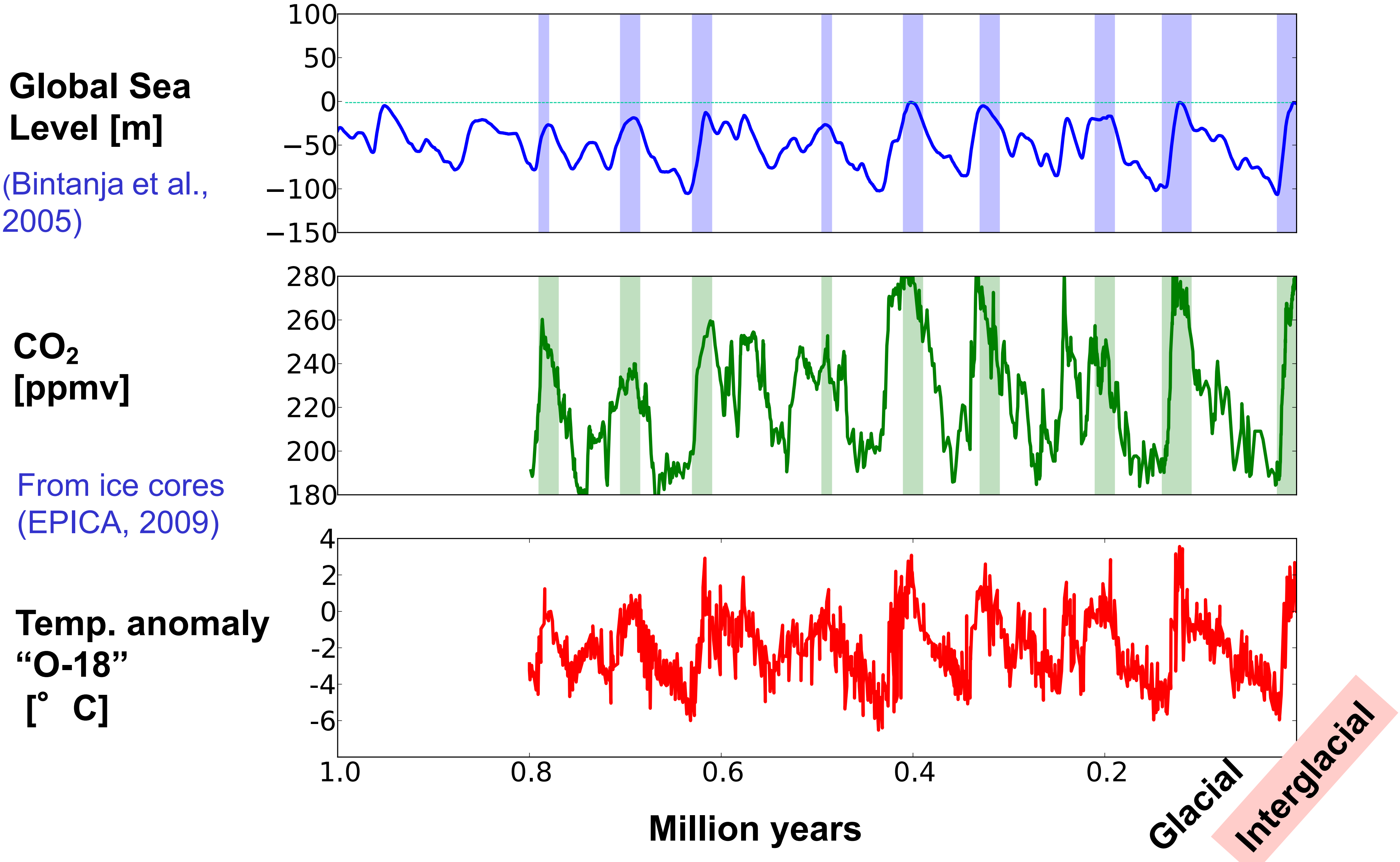
Climate warming `backward´

The last 100 Million years

Transitions from Greenhouse to Icehouse Climate

Glacial-Interglacial variability



Glacial-Interglacial variability

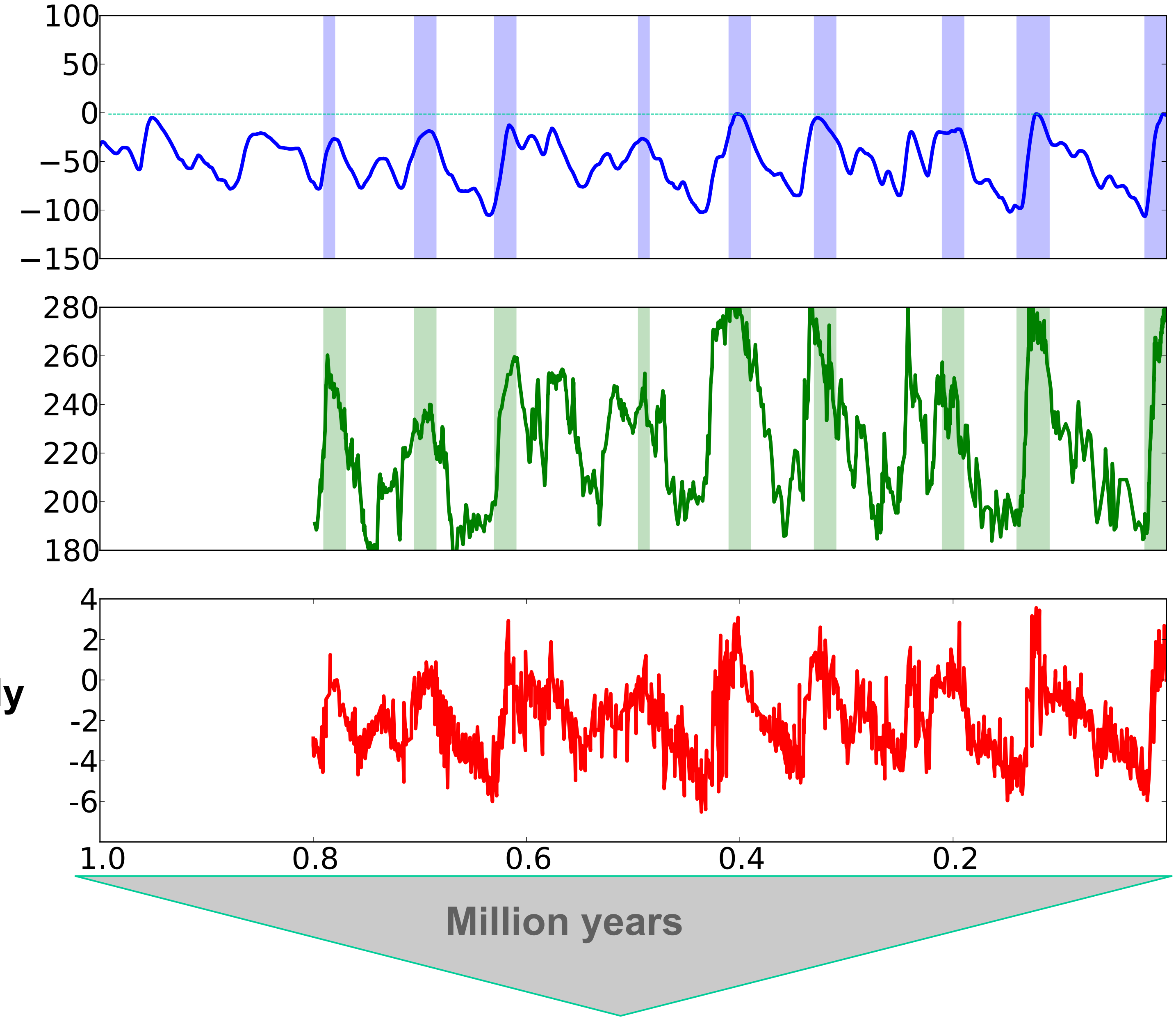
Global Sea Level [m]

(Rohling et al., 2009)

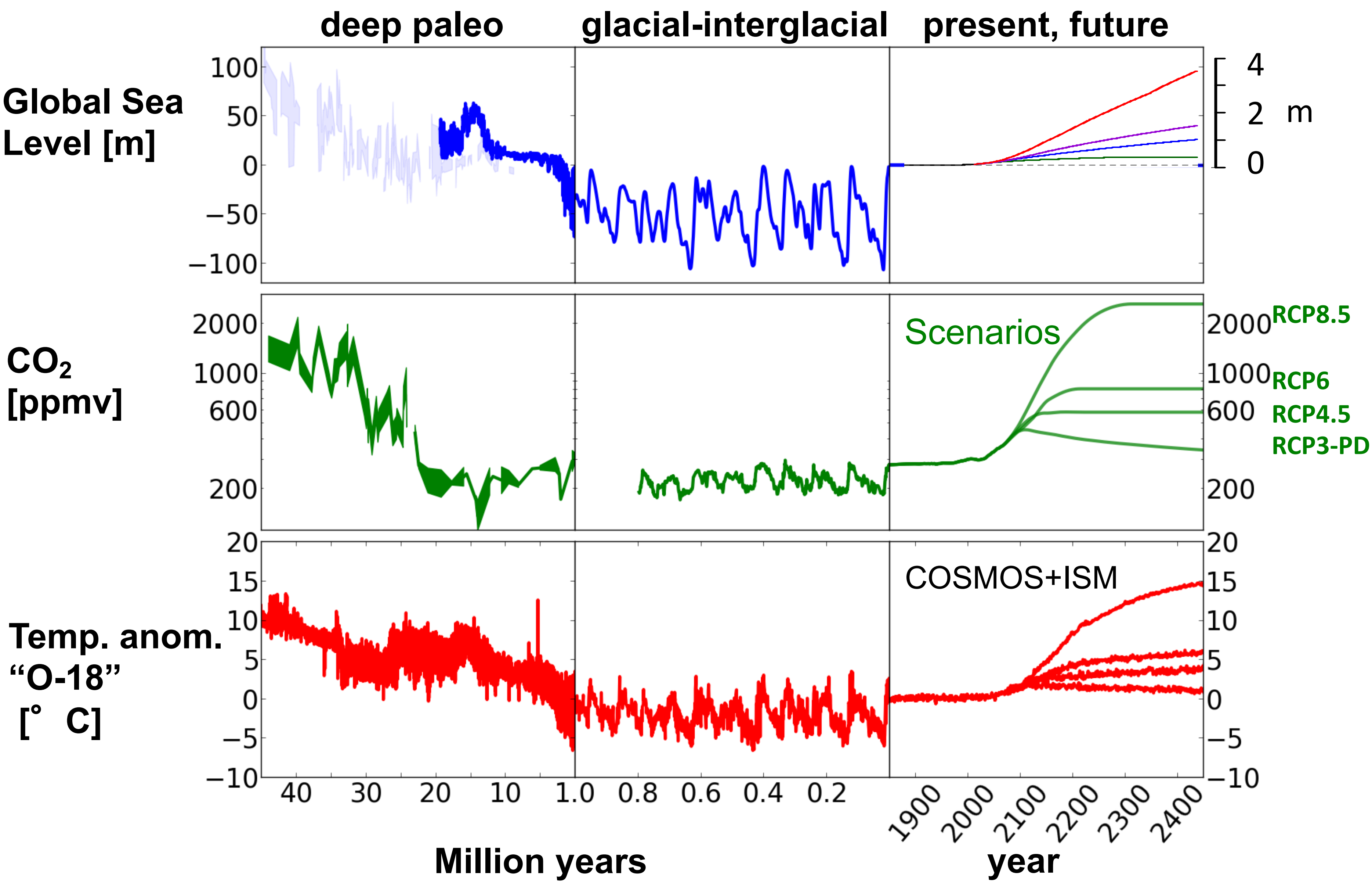
CO_2 [ppmv]

From ice cores (EPICA, 2009)

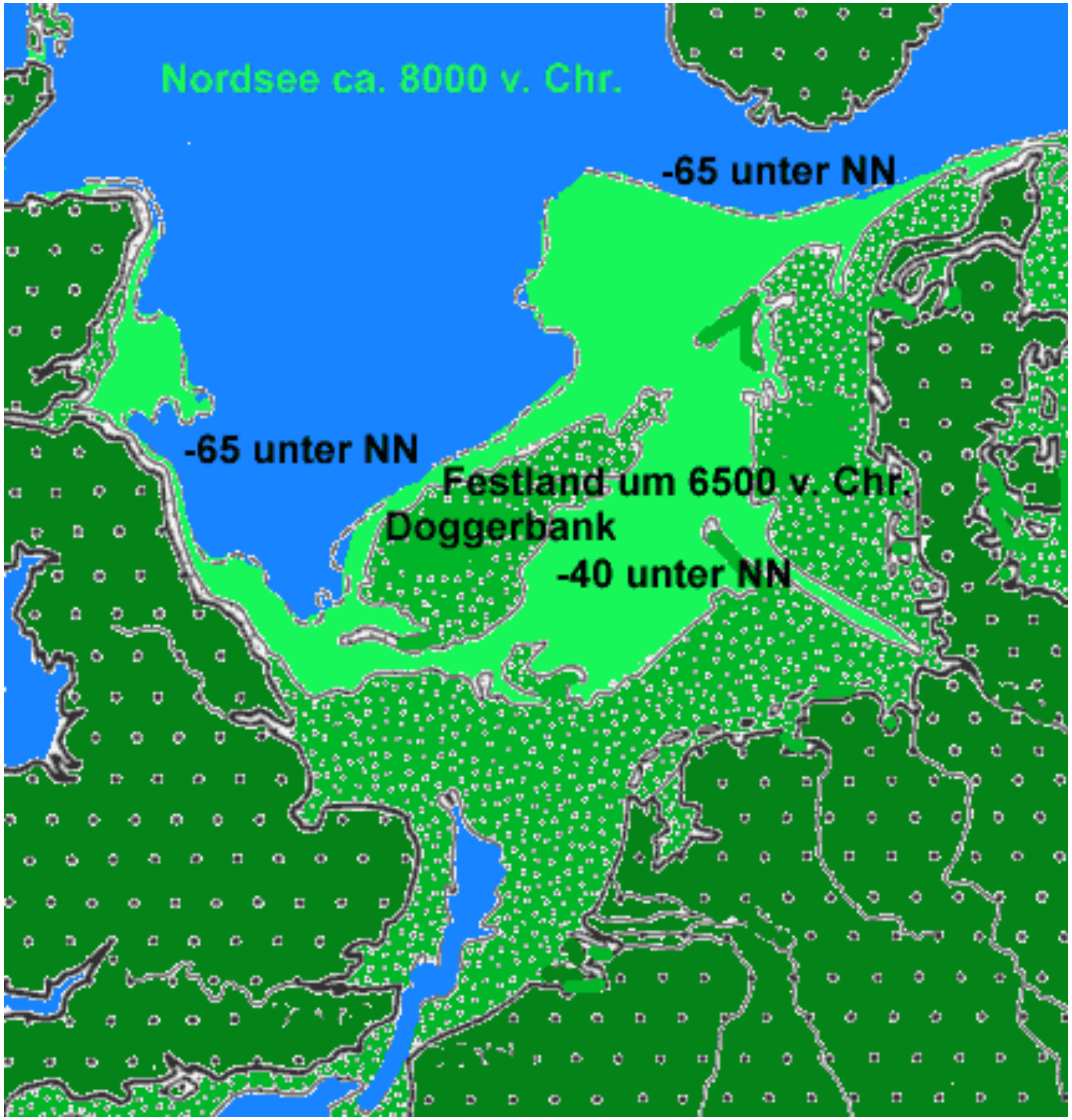
Temp. anomaly "O-18" [° C]



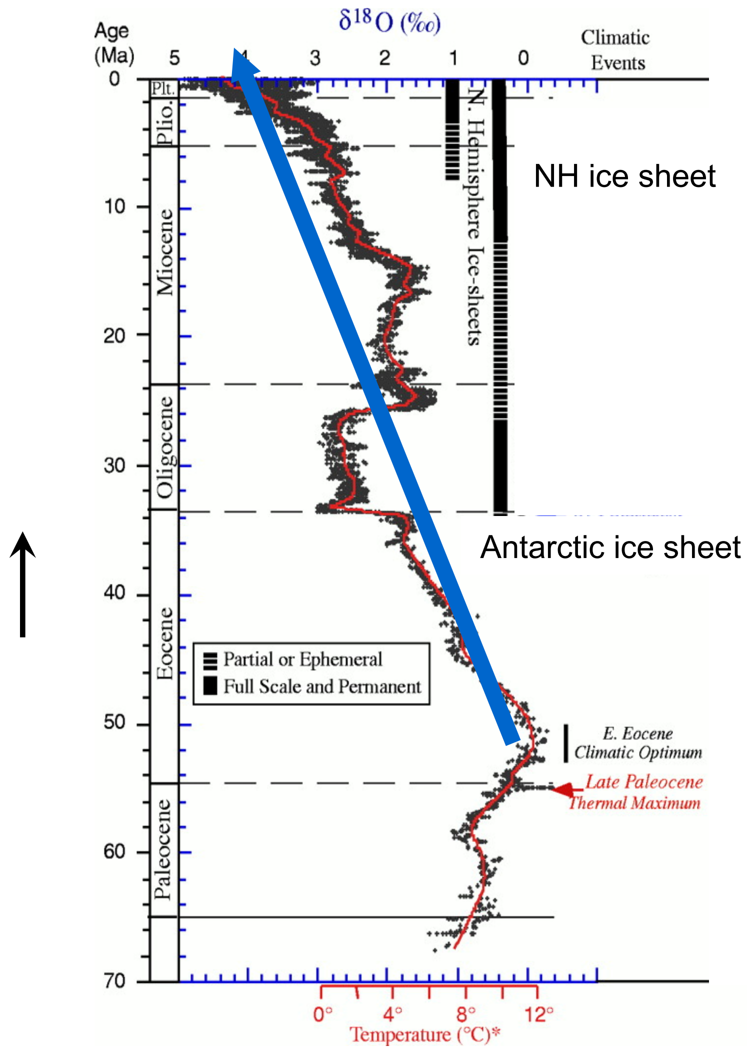
Natural variability and perturbed climate



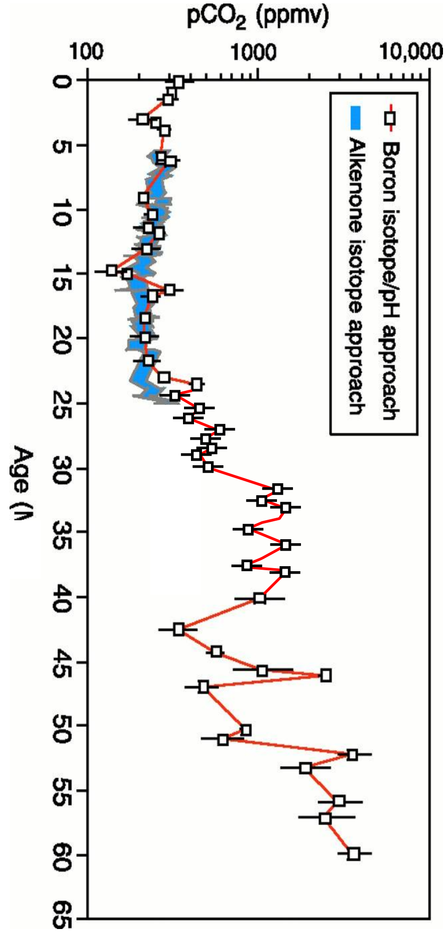
(Kominz et al., 2008; Pagani et al., 2009; Kramer et al., 2011; Crowley & Kim 1995, Wei & Lohmann,)


Nordsee ca. 8000 v. Chr.
-65 unter NN
-65 unter NN
Festland um 6500 v. Chr.
Doggerbank
-40 unter NN

Transitions from Greenhouse to Icehouse Climate: Evidence from Marine Sediments



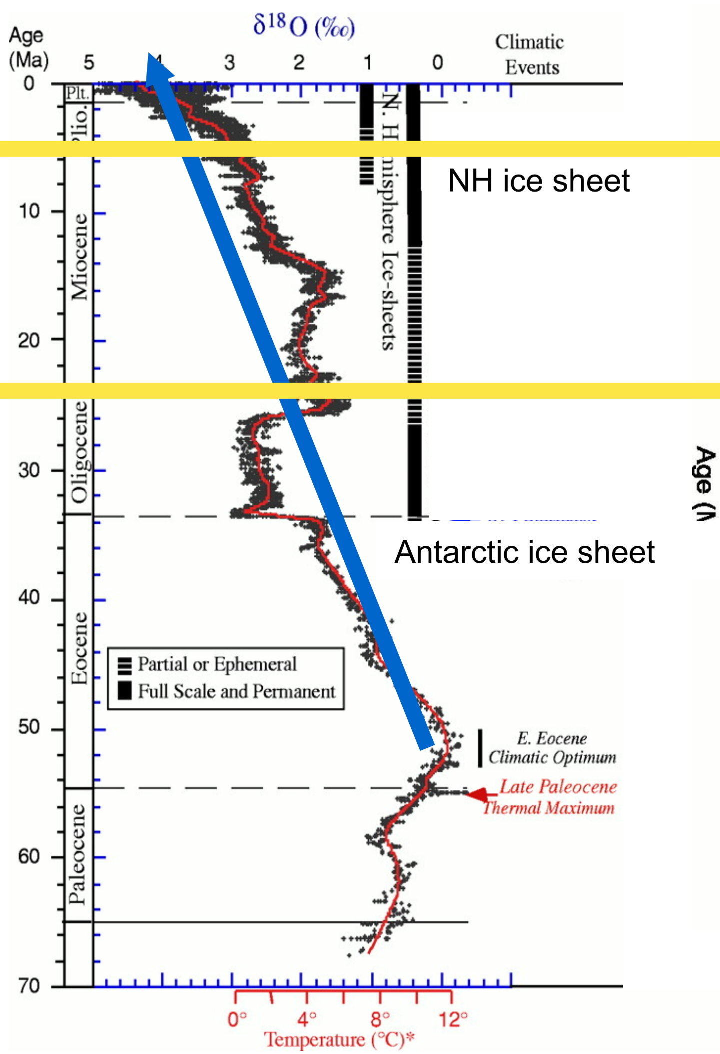
Global deep-sea O-18
(Zachos et al. 2001)



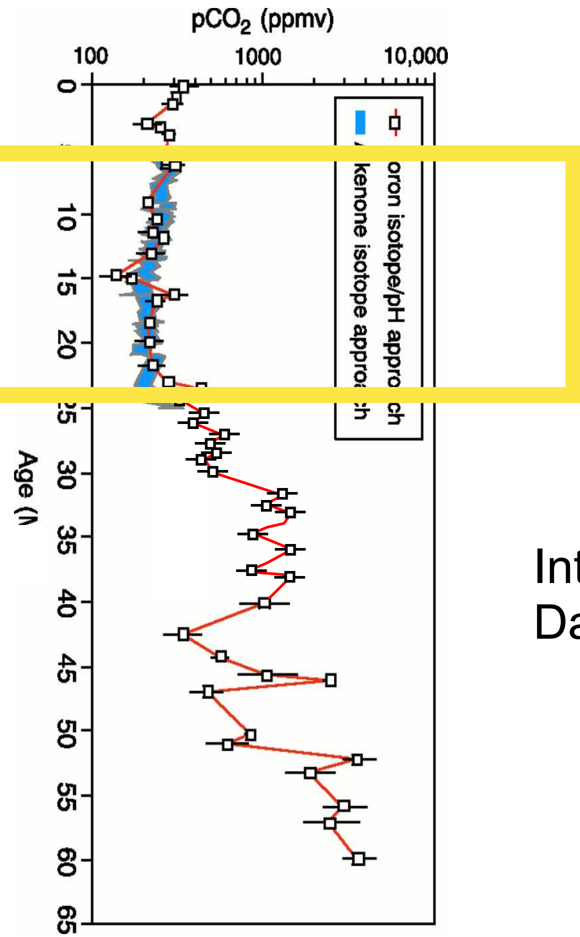
Proxy estimates of atmospheric pCO2 *(Pearson & Palmer 2000; Pagani et al. 1999, 2005)*

Integrative approach
Data-Modelling

Transitions from Greenhouse to Icehouse Climate: Evidence from Marine Sediments



Global deep-sea O-18
(Zachos et al. 2001)

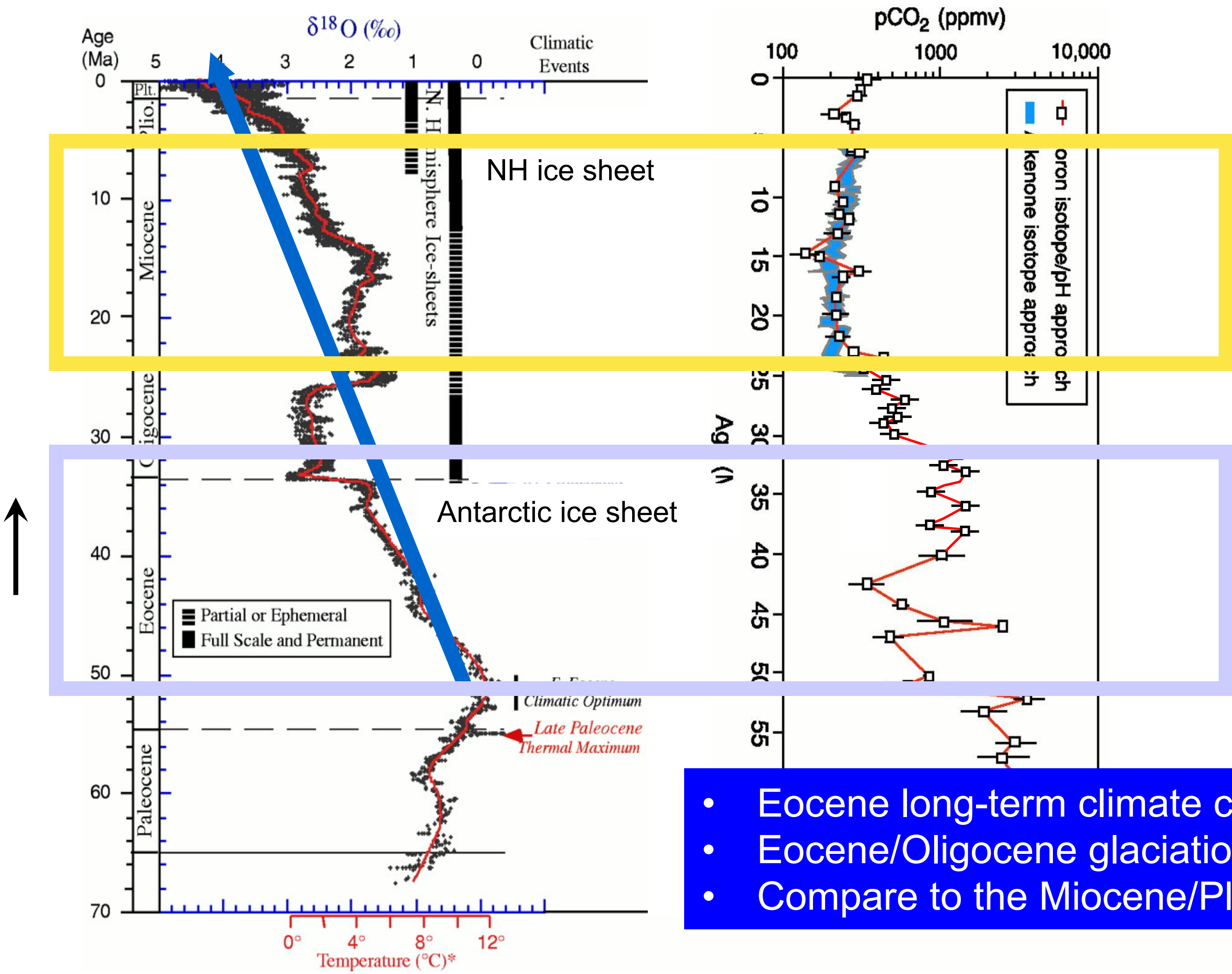


Miocene

Proxy estimates of atmospheric pCO2 *(Pearson & Palmer 2000; Pagani et al. 1999, 2005)*

Integrative approach
Data-Modelling

Transitions from Greenhouse to Icehouse Climate: Evidences from Marine Sediments



Miocene

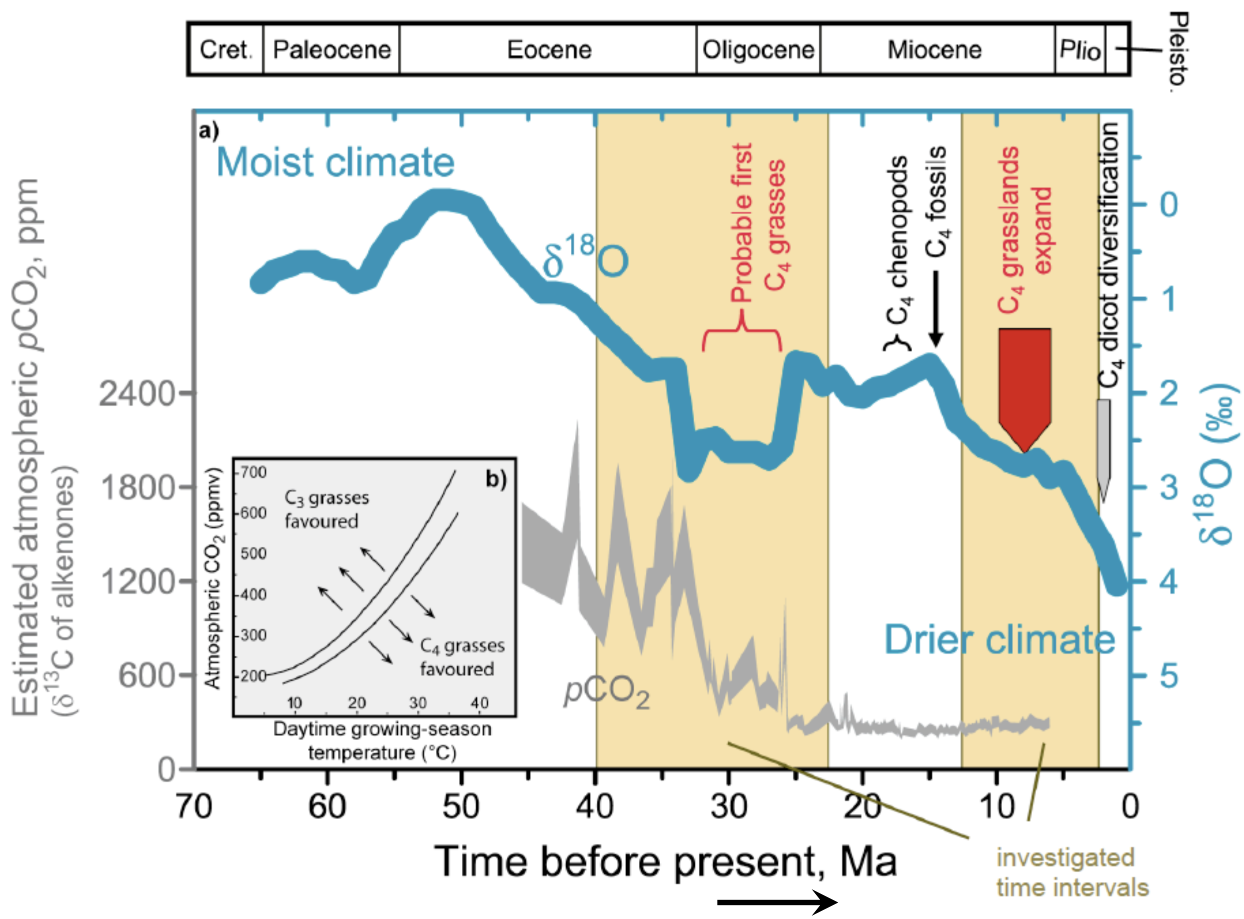
Eocene/Oligocene

- Eocene long-term climate cooling
- Eocene/Oligocene glaciation of Antarctica; drop in pCO2
- Compare to the Miocene/Pliocene cooling; low pCO2

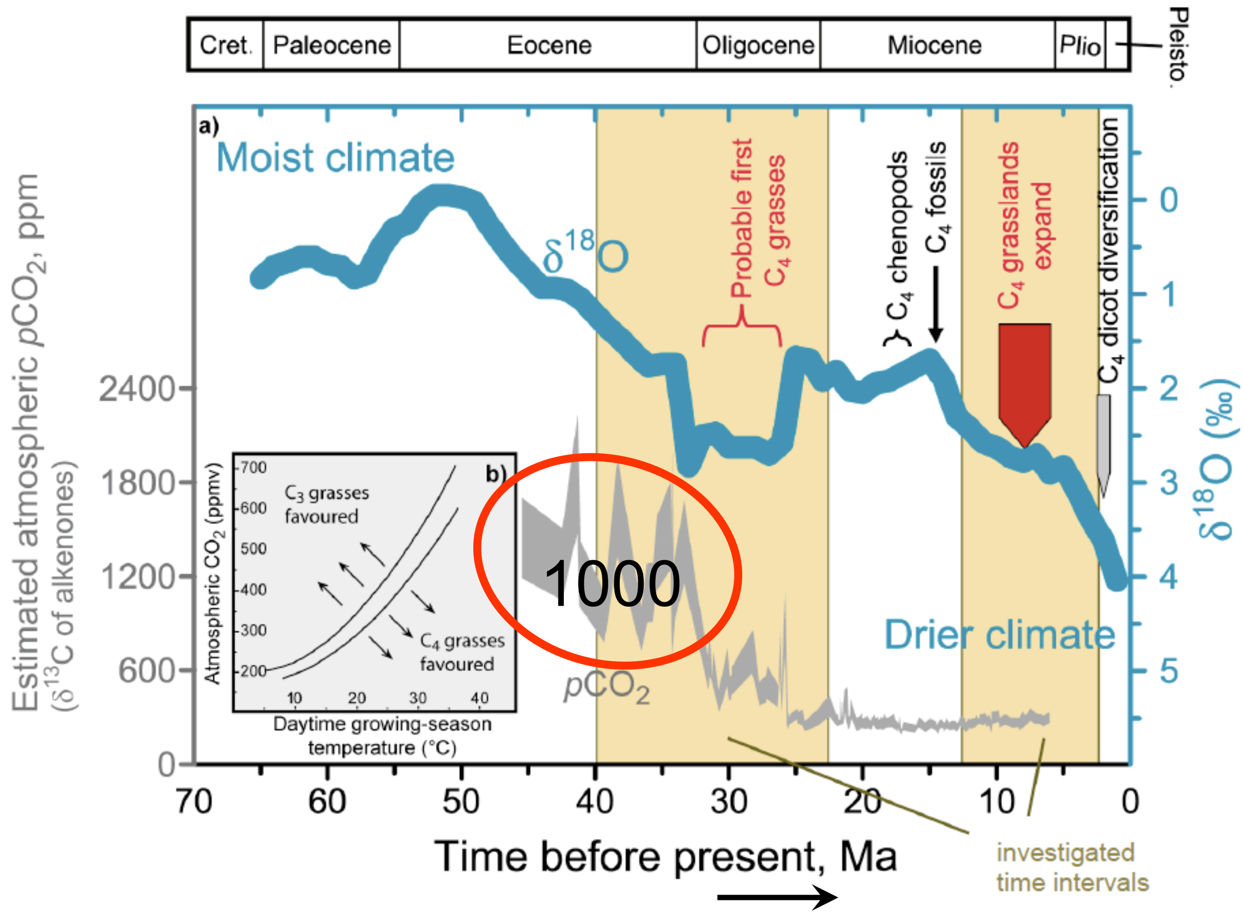
Global deep-sea O-18 *(Zachos et al. 2001)*

Proxy estimates of atmospheric pCO2 *(Pearson & Palmer 2000; Pagani et al. 1999, 2005)*

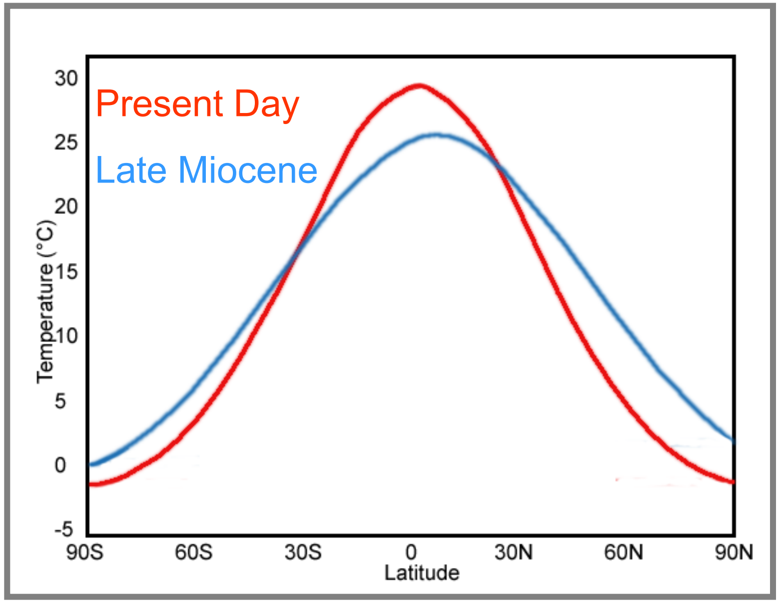
Climate warming `backward´



Climate warming `backward´



Flat Temperature Gradient



Crowley

Steppuhn et al., 2006

Many authors

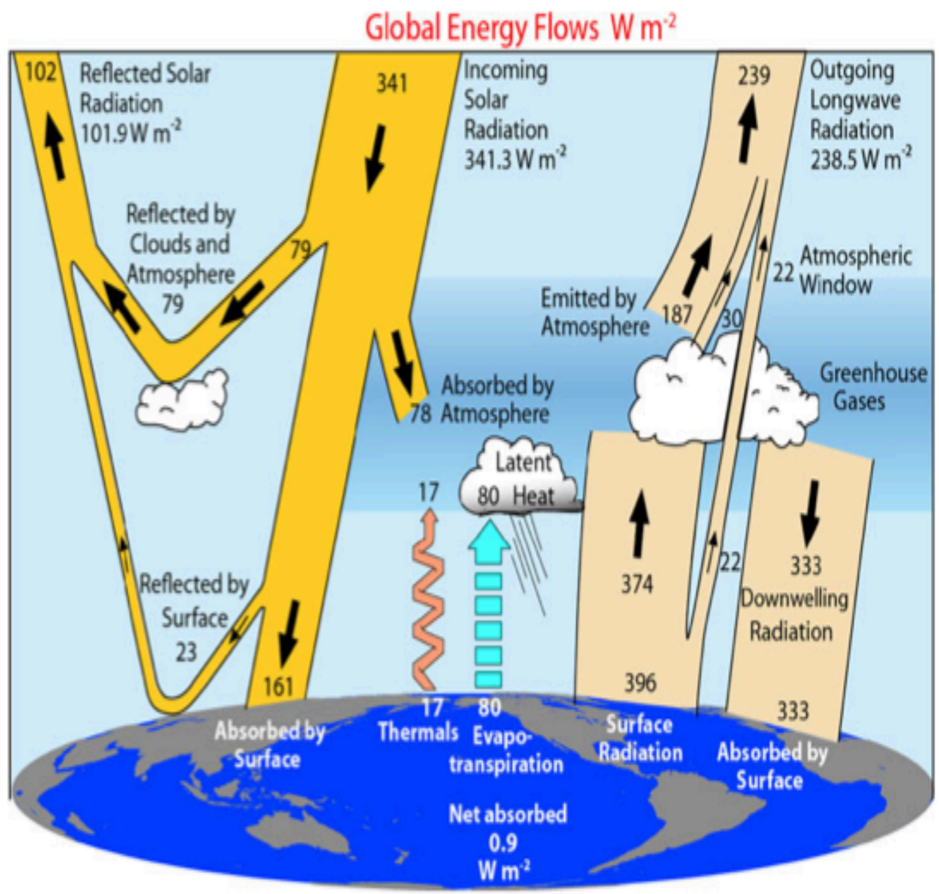
Reason?

Energy Budget

- In steady state, energy follows energy balance model:

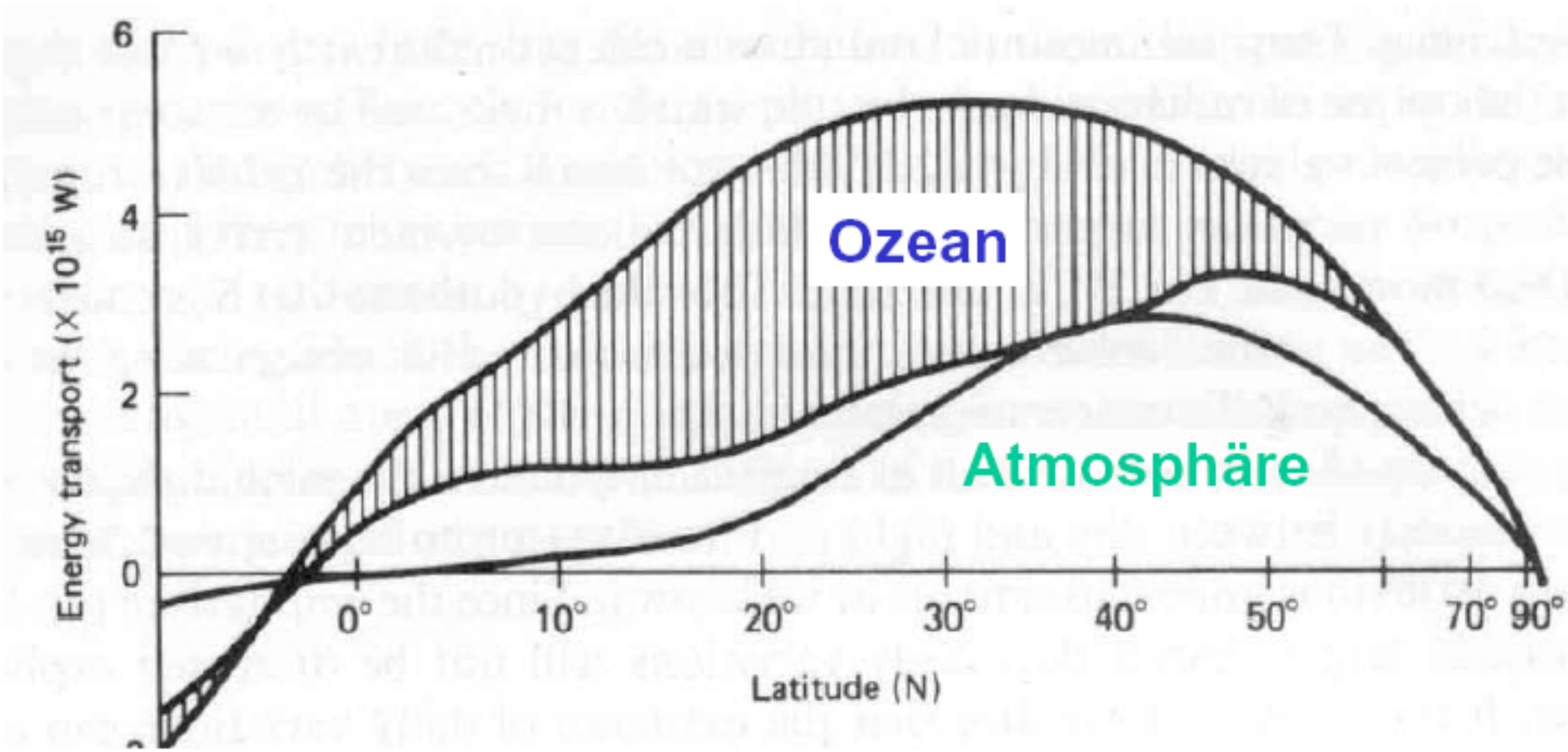
CHANGE IN STORAGE = IN – OUT

- many papers discuss an imbalance in this equation, which results in missing energy



(Trenberth & Fasullo, 2012)

Northward Heat Transport



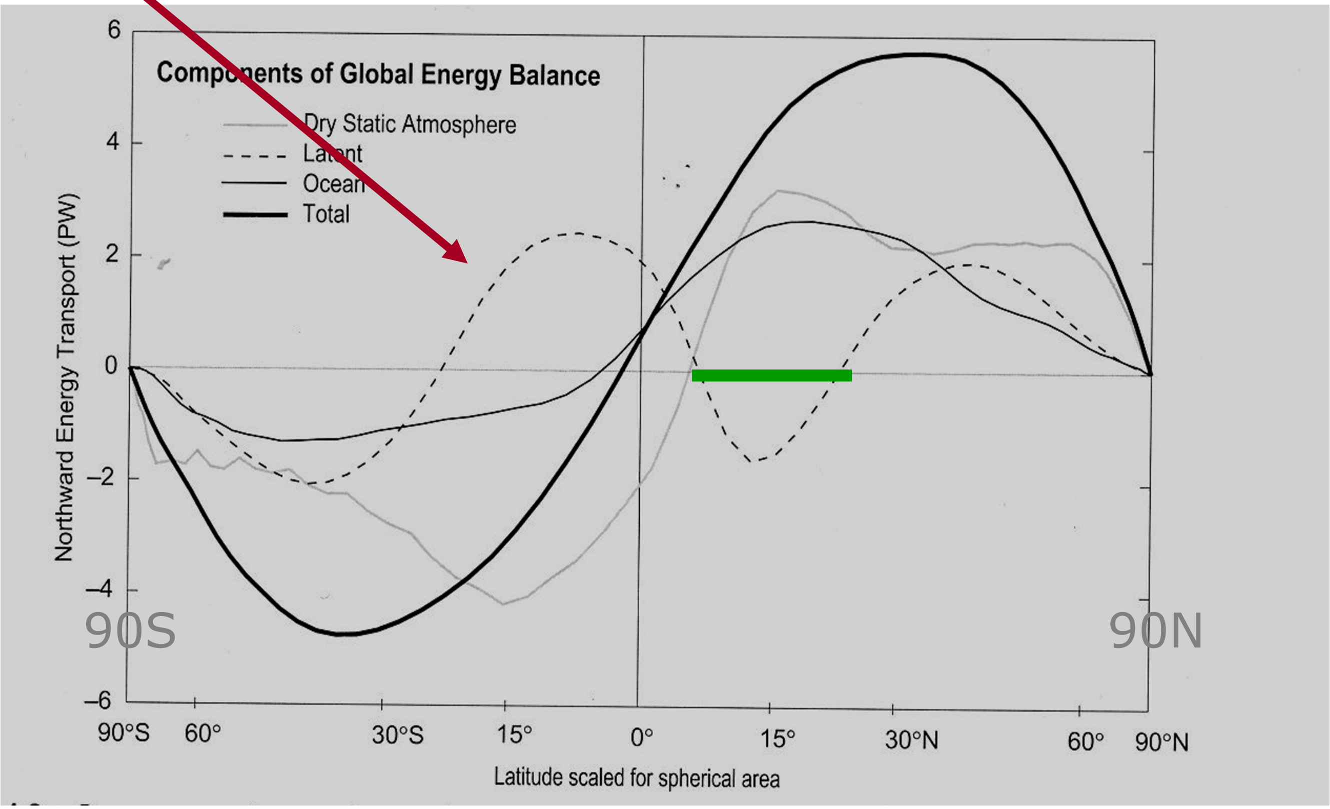
nach Von der Haar & Ort; Quelle: Gill

Global meridional heat transport divides roughly equally into 3 modes:

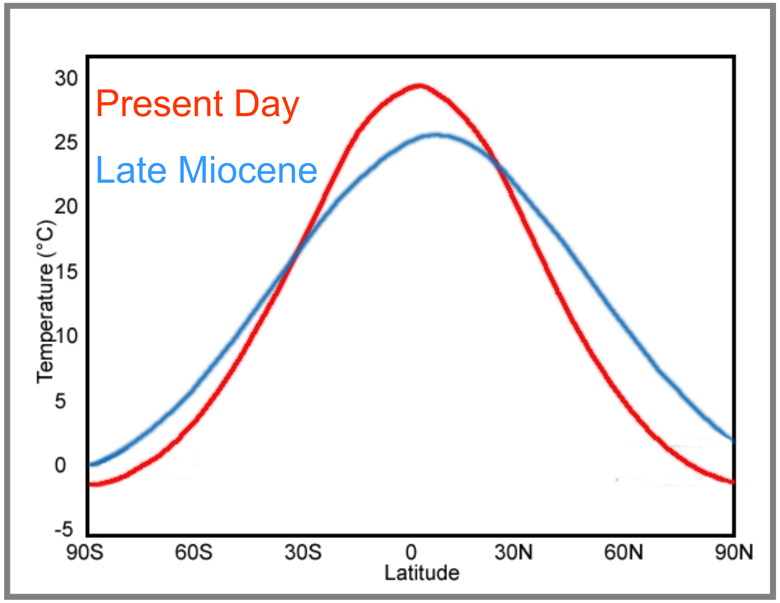
1. atmosphere (dry static energy)
2. ocean (sensible heat)
3. water vapor/latent heat transport

The three modes of poleward transport are comparable in amplitude, and distinct in character (sensible heat flux divergence focused in tropics, latent heat flux divergence focus in the subtropics)

(residual method, TOA radiation 1985-89 and ECMWF/NMC atmos obs)



Flat Temperature Gradient



Crowley

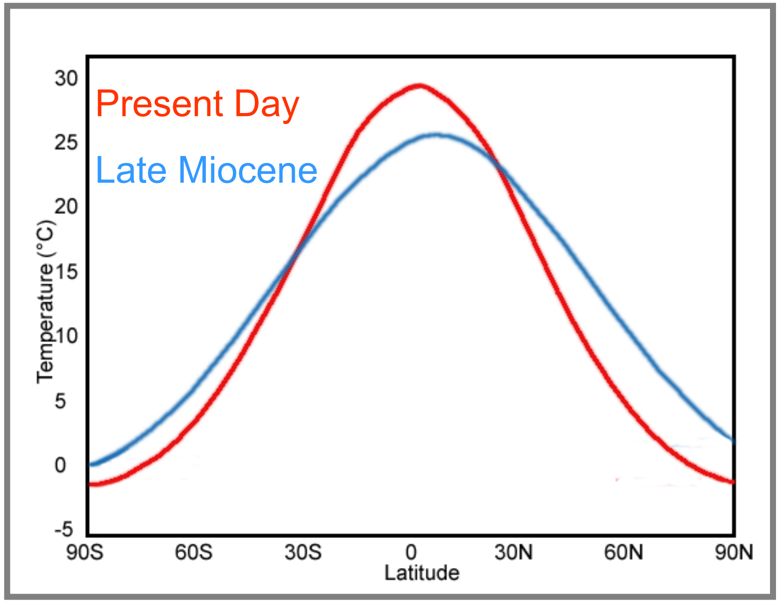
Steppuhn et al., 2006

Many authors

Reason?

- **Sensible heat transport**
- **Latent heat transport**
- **Ocean heat transport**
- **Orography** ⟶ **Greenland: high latitude warming**
- **Changes in the land surface cover**
- **Other effects?**

Flat Temperature Gradient



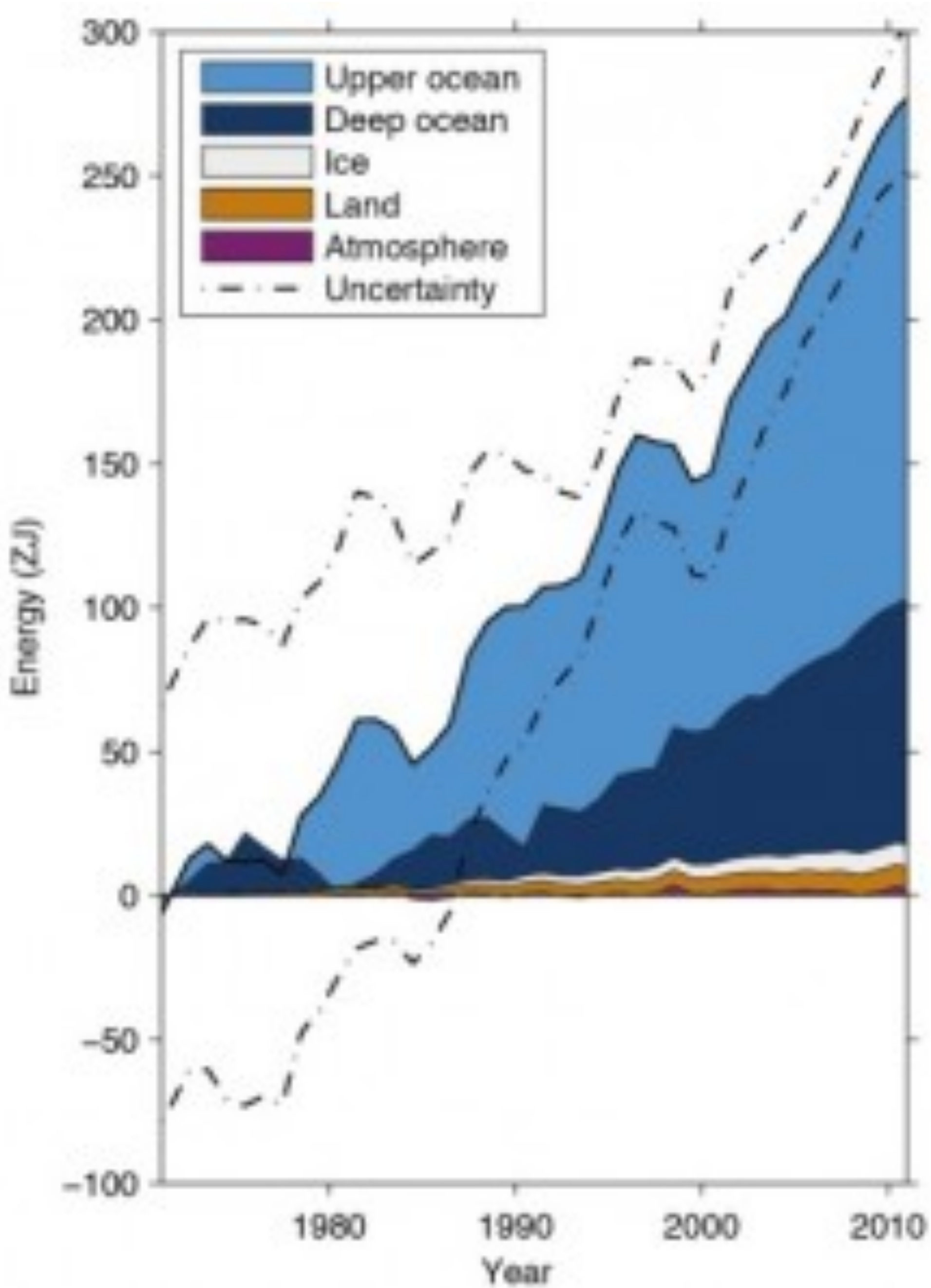
Crowley

Steppuhn et al., 2006

Many authors

Reason?

- **Sensible heat transport** ~ ΔT $\searrow$ EBMs, ……
- **Latent heat transport** ~ $\Delta T \frac{\partial q}{\partial T}$ $\rightarrow$ *Caballero & Langen*
- **Ocean heat transport** $\searrow$ Panama Gateway, Atlantic salinity reduction
- **Orography** $\longrightarrow$ **Greenland: high latitude warming**
- **Changes in the land surface cover**
- **Other effects?**

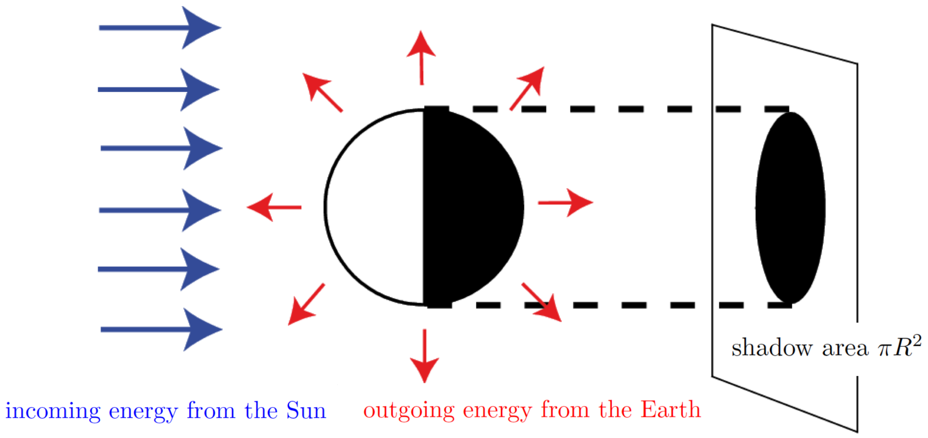


Our current warming

IPCC report 2013

Energy balance model

$$(1-\alpha)S\pi R^2 = 4\pi R^2 \epsilon\sigma T^4$$



$$T = \sqrt[4]{\frac{(1-\alpha)S}{4\epsilon\sigma}}$$

Figure 1. Schematic view of the energy absorbed and emitted by the Earth following (1). Modified after Goose (2015).

Heat capacity

The energy balance shall take the heat capacity into account:

$$C_p\,\partial_t T \;=\; (1-\alpha)S\cos\varphi\cos\Theta \quad \times 1_{[-\pi/2<\Theta<\pi/2]}(\Theta) \;-\; \epsilon\sigma T^4 \qquad (9)$$

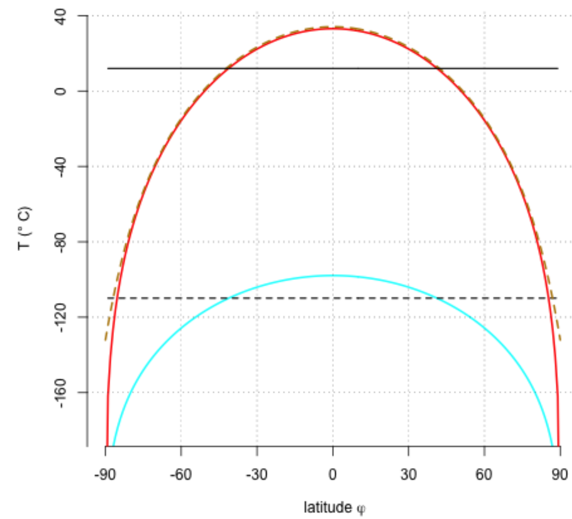


Figure 2. Latitudinal temperatures of the EBM with zero heat capacity (7) in cyan (its mean as a dashed line), the global approach (3) as solid black line, and the zonal and time averaging (11) in red. The dashed brownish curve shows the numerical solution by taking the zonal mean of (9).

and is a second order effect (not shown). The energy balance (9) is integrated over the longitude and over the day

$$\tilde{T}(\tilde{t}) = \frac{1}{2\pi}\int_0^{2\pi} T(t)\,d\Theta \qquad \text{with} \qquad \tilde{T}^4 \approx \frac{1}{2\pi}\int_0^{2\pi} T^4\,d\Theta$$

and therefore

$$C_p\,\partial_{\tilde{t}}\tilde{T} \;=\; (1-\alpha)S\cos\varphi\cdot\underbrace{\frac{1}{2\pi}\int_{-\pi/2}^{\pi/2}\cos\Theta\,d\Theta}_{2} - \epsilon\sigma\tilde{T}^4$$

$$= (1-\alpha)\frac{S}{\pi}\cos\varphi \;-\; \epsilon\sigma\tilde{T}^4 \qquad (10)$$

giving the equilibrium solution

$$\tilde{T}(\varphi) = \sqrt[4]{\frac{4}{\pi}}\cdot\sqrt[4]{\frac{(1-\alpha)S}{4\epsilon\sigma}}\quad(\cos\varphi)^{1/4} \qquad (11)$$

shown in Fig. 2 as the read line with the mean

$$\overline{\tilde{T}} = \sqrt[4]{\frac{4}{\pi}}\cdot\sqrt[4]{\frac{(1-\alpha)S}{4\epsilon\sigma}}\quad\underbrace{\frac{1}{2}\int_{-\pi/2}^{\pi/2}(\cos\varphi)^{5/4}d\varphi}_{1.862}$$

$$= \sqrt[4]{\frac{4}{\pi}\frac{1.862}{2}}\cdot\sqrt[4]{\frac{(1-\alpha)S}{4\epsilon\sigma}} = 0.989\,\sqrt[4]{\frac{(1-\alpha)S}{4\epsilon\sigma}} \qquad (12$$

Therefore, $\overline{\tilde{T}} = 285 \approx 288$ K, very similar as in (1). A numerical solution of (9) is shown as the brownish dashed line in Fig. 2 where the diurnal cycle has been taken into account and $C_p = C_p^a$ has been chosen as the atmospheric heat capacity

$$C_p^a = c_p p_s/g = 1004\,JK^{-1}kg^{-1}\cdot 10^5 Pa/(9.81ms^{-2}) = 1.02\cdot 10^7 JK^{-1}m^{-2}$$

which is the specific heat at constant pressure c_p times the total mass p_s/g. p_s is the surface pressure and g the gravity. The temperature $\overline{T}$ is 286 K, again close to 288 K.

The effect of heat capacity is systematically analyzed in Fig. 3. The temperatures are relative insensitive for a wide range of C_p. We find a severe drop in temperatures for heat capacities below 0.01 of the atmospheric heat capacity C_p^a. We find furthermore a pronounced temperature drop during night for low values of heat capacities and for long days (e.g. 240 h instead of 24 h) affecting the zonal temperatures (4.5 K colder at the equator). It is an interesting thought experiment what would happen if the length of the daylight/night would change. The analysis shows that the effective heat capacity is of great importance for the temperature, this depends on the atmospheric planetary boundary layer (how well-mixed with small gradients in the vertical) and the depth of the mixed layer in the ocean. To make a rough estimate of the involved mixed layer, one can see that the effective heat capacity of the ocean is time-scale dependent. A diffusive heat flux goes down the gradient of temperature and the convergence of this heat flux drives a ocean temperature tendency:

$$C_p^o \partial_t T = -\partial_z (k^o \partial_z T) \tag{13}$$

where $k_v = k^o / C_p^o$ is the oceanic vertical eddy diffusivity in $m^2\,s^{-1}$, and C_p^o the oceanic heat capacity relevant on the specific time scale. The vertical eddy diffusivity k_v can be estimated from climatological hydrographic data (Olbers et al., 1985; Munk and Wunsch, 1998) and varies roughly between 10^{-5} and $10^{-4}\,m^2\,s^{-1}$ depending on depth and region. A scale analysis of (13) yields a characteristic depth scale h_T through

$$\frac{\Delta T}{\Delta t} = k_v \frac{\Delta T}{h_T^2} \quad \longrightarrow h_T = \sqrt{k_v\ \Delta t} \tag{14}$$

For the diurnal cycle h_T is less that half a meter and the heat capacity generally less than that of the atmosphere. As pointed out by Schwartz (2007), the effective heat capacity that reflects only that portion of the global heat capacity that is coupled to the perturbation on the timescale of the perturbation. We discuss the sensitivity of the system with respect to k_v later in the context of a full circulation model.

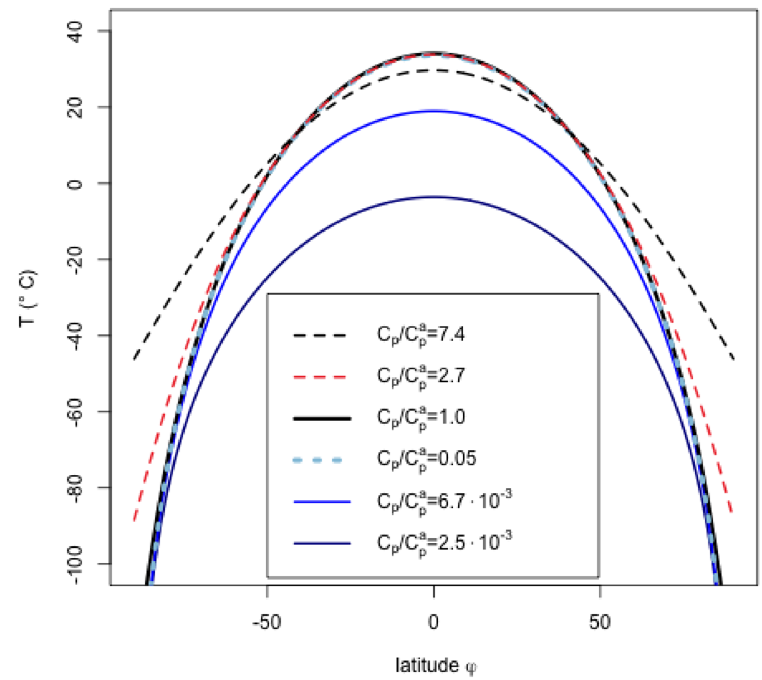


Figure 3. Temperature depending on C_p when solving (9) numerically. The reference heat capacity is the atmospheric heat capacity $C_p^a = 1.02 \cdot 10^7 JK^{-1}m^{-2}$. The climate is insensitive to changes in heat capacity $C_p \in [0.05 \cdot C_p^a, 2.0 \cdot C_p^a]$.

Vertical mixing

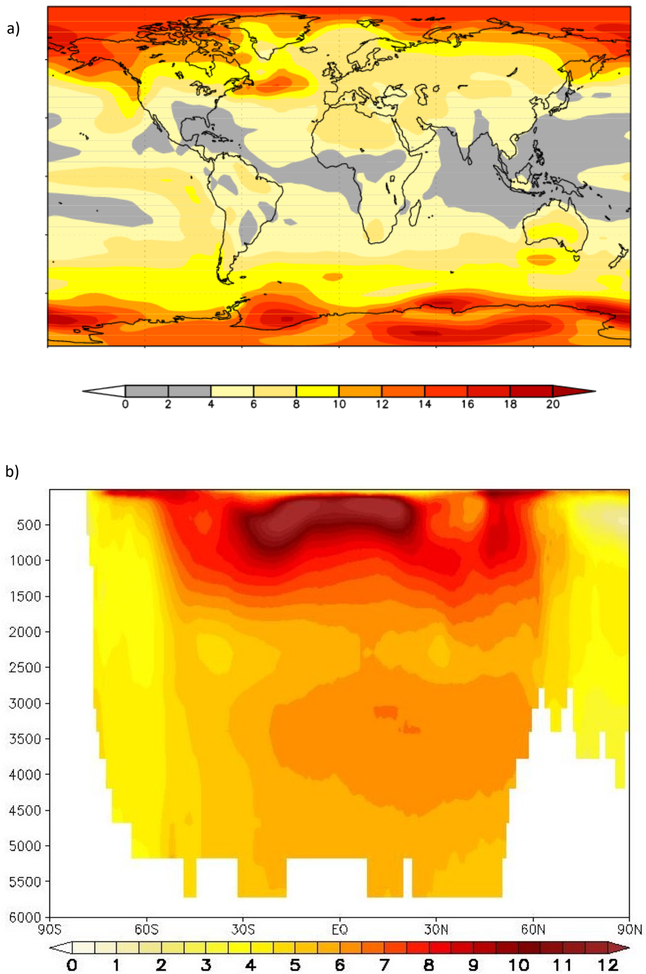


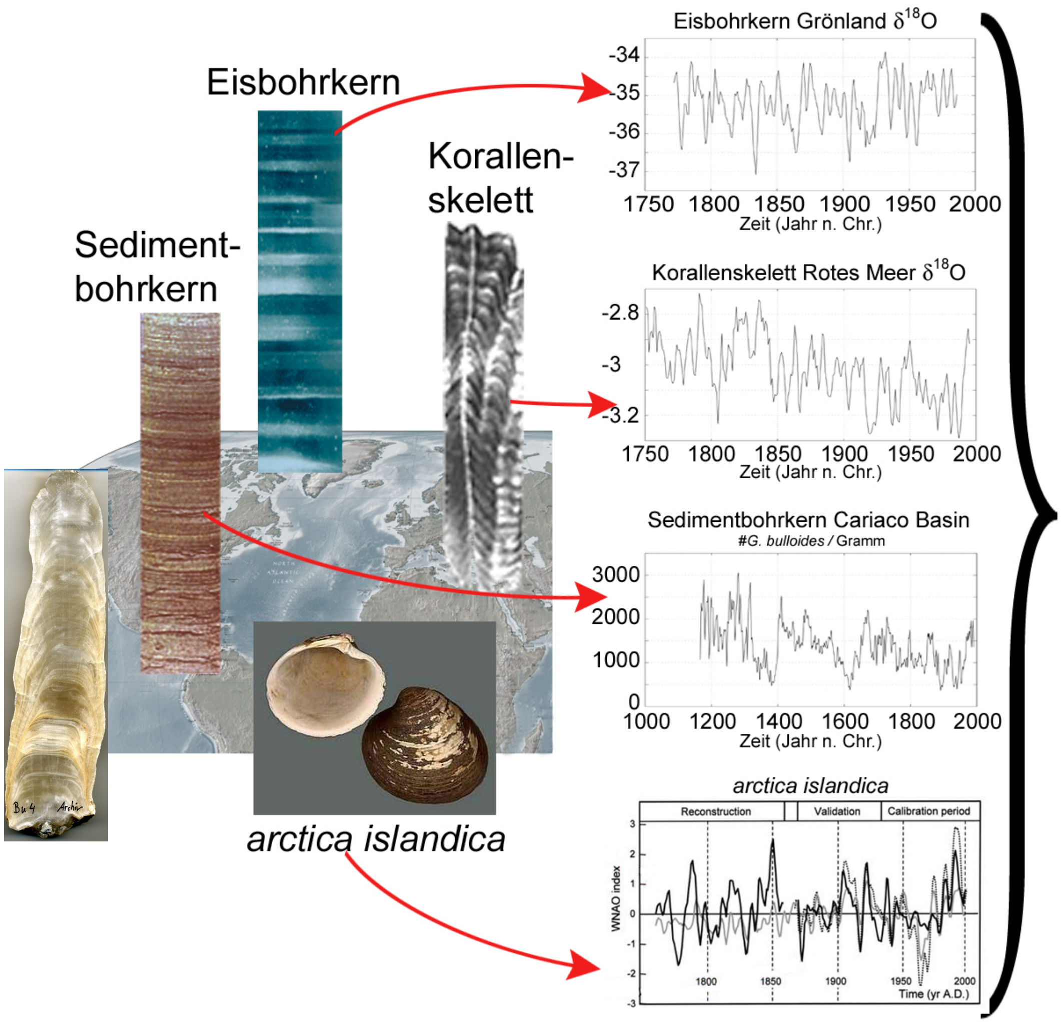
Figure 5. a) Anomalous near surface temperature for the vertical mixing experiment relative to the control climate. b) Vertical temperature anomaly (zonal mean). Shown is the annual mean of a 100 year mean after 900 years of integration using the Earth system model COSMOS. Units are °C. Note the different scales.

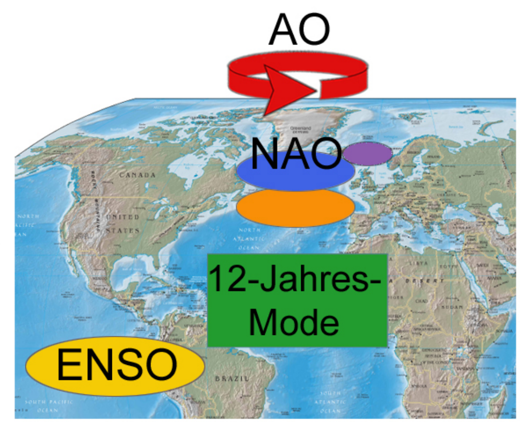
In deeper levels of the ocean, the increased vertical mixing leads to a smearing of water properties at different vertical layers and pronounced warming at the thermocline and mid-latitudes. Heat gained at the surface is diffused down the water column, and, compared to the control simulation, the wind-induced Ekman cells in the upper part of the oceans intensified and deepened.

kv largely determines the intensity of the diabatic processes and thus influence the meridional mass transport affecting the large-scale ocean circulation and its sensitivity

Upscaling concept

Examples: corals, ice cores



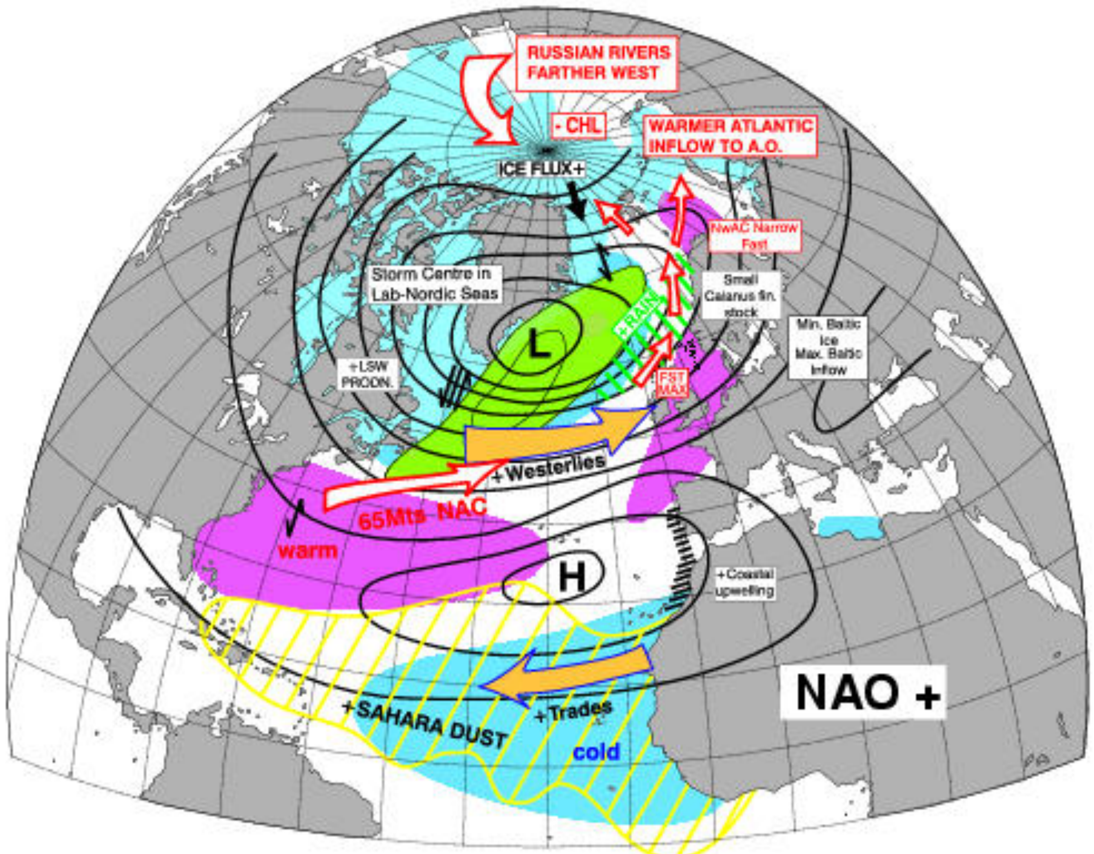


Climate archives

Climate variabiliy

Lohmann, 2007

The Phases of the North Atlantic Oscillation



During the high phase of the NAO westerlies in the North Atlantic are enhanced, resulting in mild and wet winter conditions over Northern Europe. (Courtesy of CEFAS, UK)

AV/D1/99-1

Statistics

covariance is a measure of how much two random variables change together

Covariance (cross, auto)

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

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

$$\operatorname{cov}(X,Y) = \frac{1}{n}\sum_{i=1}^{n}(x_i - E(X))(y_i - E(Y)).$$

Correlation (cross, auto)

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

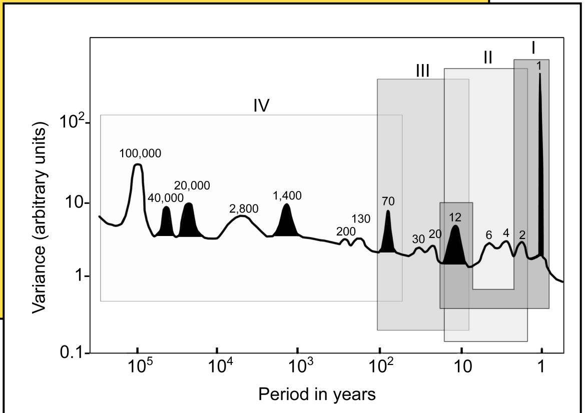
measures the tendency of x (t) and y (t) to covary, between -1 and 1

Spectrum (cross, auto)

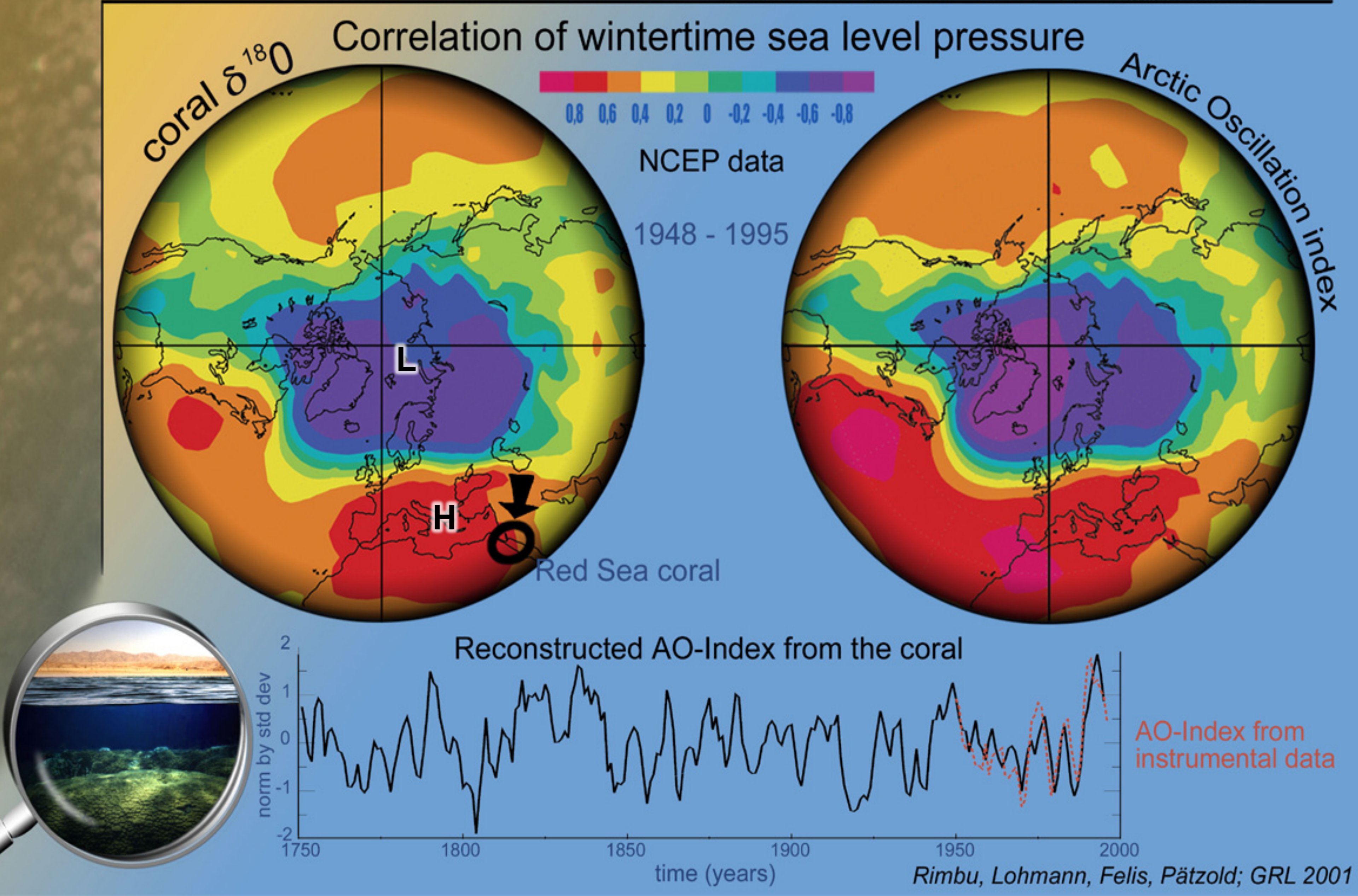
(spectral density)

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

measures variance



ARCTIC OSCILLATION SIGNATURE IN A RED SEA CORAL



http://climexp.knmi.nl

1) Monthly climate indices (temp, precip, ...)

Calculate different regions on the world
(home town, Bremen 53° N, 8° E)

2) Correlation with temperature, precipiation, SLP

3) Explain the teleconnections for different seasons

---

4) Modes of climate variability (global temperature)

Field correlations

HadCRUT4.5 SST/T2m anom 8-9E 53-54N mean with Trenberth SLP

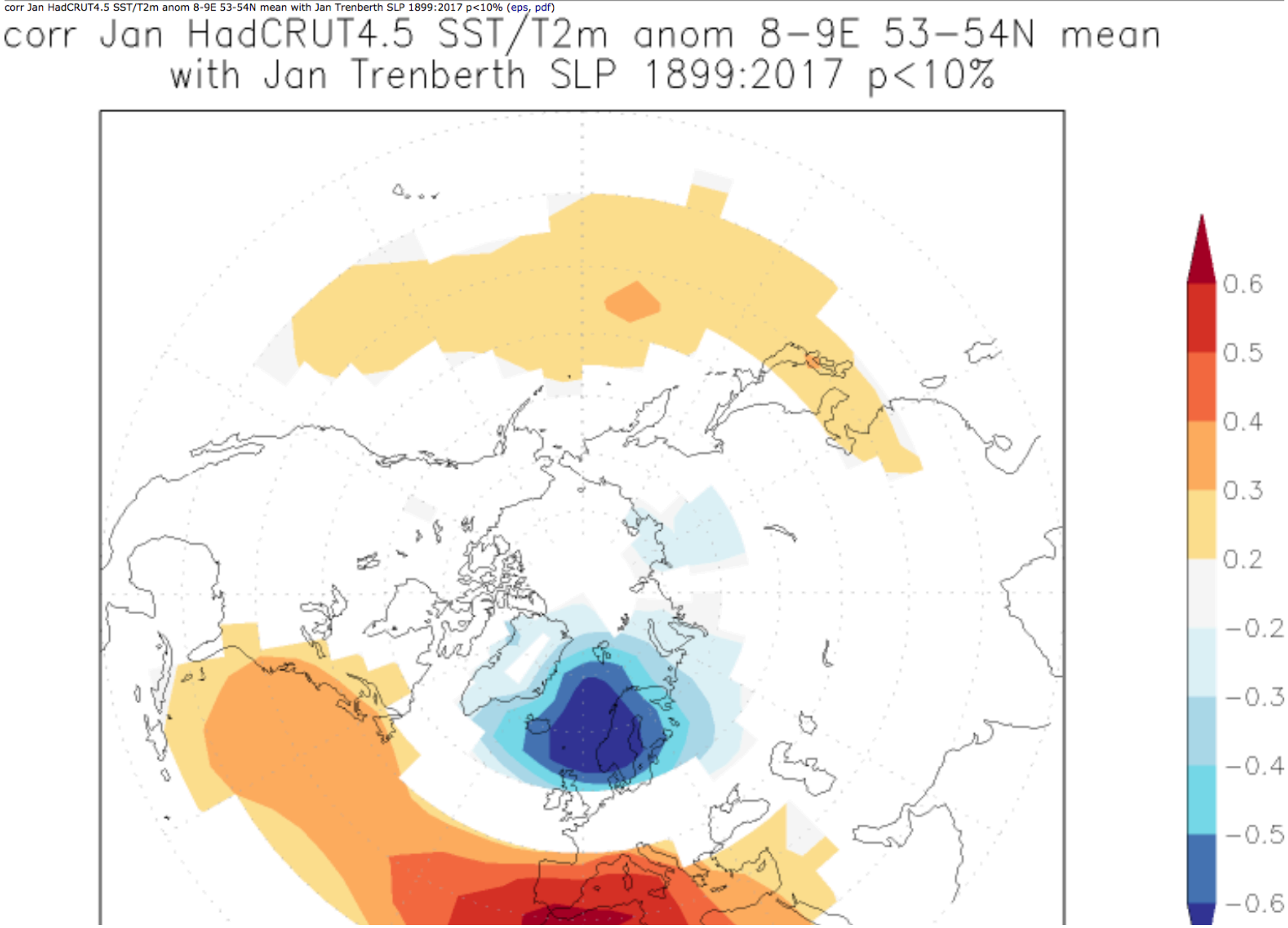
Computing correlations... (this may take a minute or so)

If it takes too long you can abort the job here (using the [back] button of the browser does not kill the correlation job)

Requiring at least 50% valid points

Plotting with GrADS 2.0...

corr Jan HadCRUT4.5 SST/T2m anom 8-9E 53-54N mean with Jan Trenberth SLP 1899:2017 p<10% (eps, pdf)



Select a time series
- Daily station data
- Daily climate indices
- Monthly station data
- Monthly climate indices
- Annual climate indices
- View, upload your time series

Select a field
- Daily fields
- Monthly observations
- Monthly reanalysis fields
- Monthly and seasonal historical reconstructions
- Monthly seasonal hindcasts
- Monthly decadal hindcasts
- Monthly CMIP3+ scenario runs
- Monthly CMIP5 scenario runs
- Annual CMIP5 extremes
- Monthly CORDEX scenario runs
- Attribution runs
- External data (ensembles, ncep, enact, soda, ecmwf, ...)
- View, upload your field

Investigate this time series
- View per month, season, half year or full year (Jan-Dec or Jul-Jun)
- View last 1, 5, 10, N years
- Correlate with other time series
- Correlate with a field (correlation, regression, composite)
  - only observations
  - only reanalyses
  - only seasonal forecasts
  - only scenario runs
  - only user-defined fields
- Verify against another time series
- Spectrum, autocorrelation function
- Wavelet
- Running mean/s.d./skew/curtosis
- Trends in return times of extremes
- Plot and fit distribution

Investigate this field
- Plot this field
- Plot difference with a field
- Compute mean, s.d. or extremes
- Trends in extremes
- Make EOFs
- Correlate with a time series
- Pointwise correlations with a field
  - only observations
  - only reanalyses
  - only seasonal hindcasts
  - only decadal hindcasts
  - only CMIP5 scenario runs
  - only user-defined fields
- Spatial correlations with a field
  - only observations
  - only reanalyses
  - only seasonal hindcasts
  - only decadal hindcasts
  - only CMIP5 scenario runs
  - only user-defined fields
- SVD
  - only observations
  - only reanalyses
  - only seasonal hindcasts
  - only CMIP5 scenario runs
  - only user-defined fields
- Verify field against observations