Paleoclimate dynamics- identifying driving mechanisms of climate change

POLMAR course 2023

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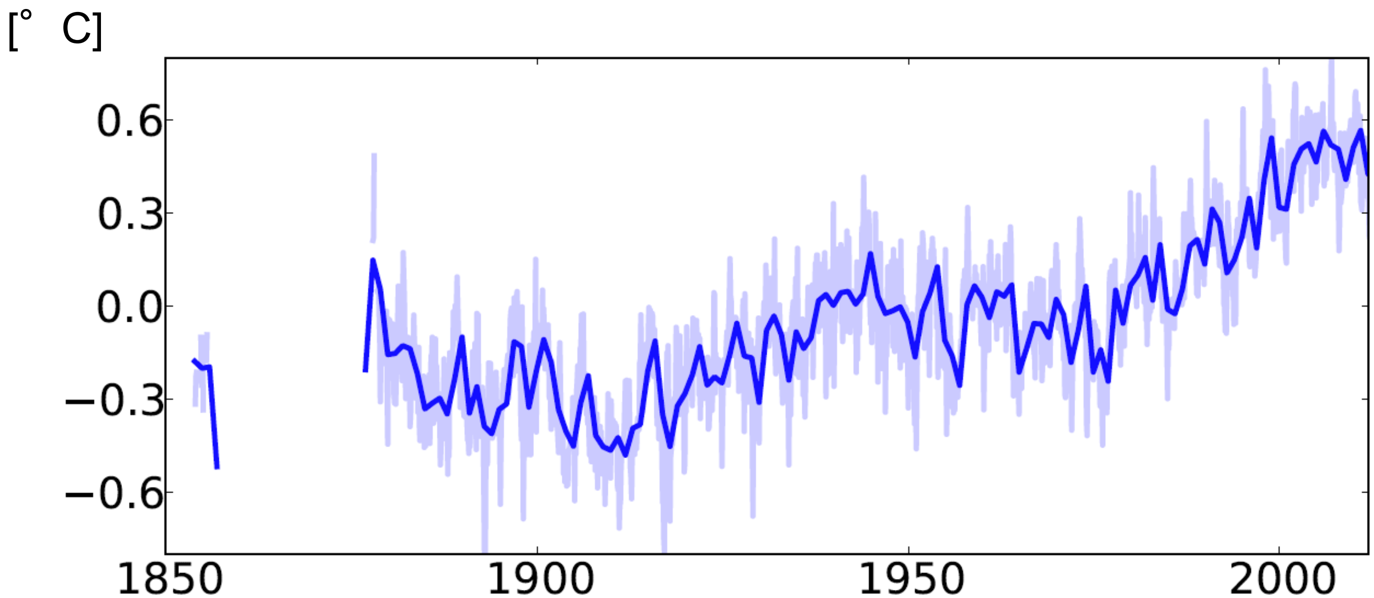
Helmholtz Centre for Polar and Marine Research

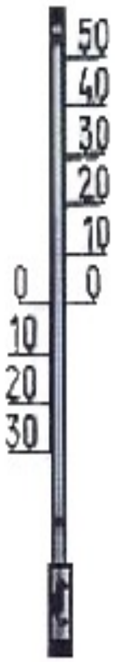
Climate Trends at different Timescales

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

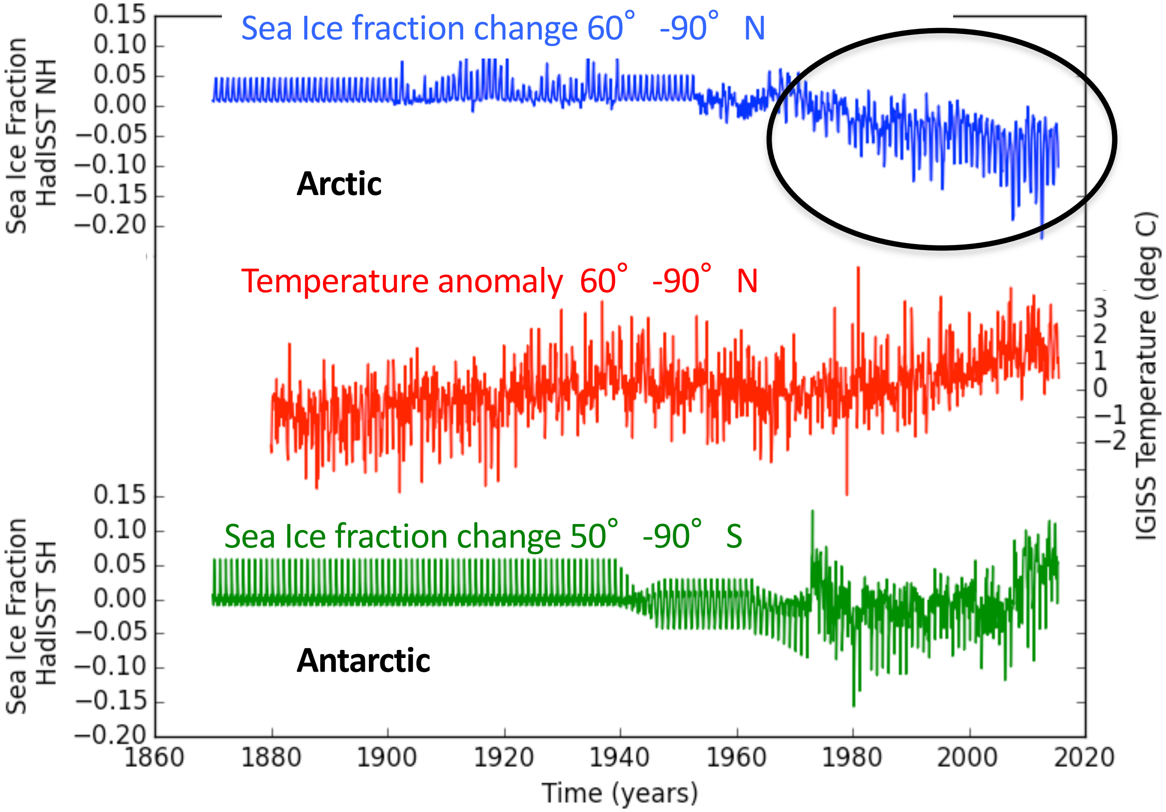
Northern Hemisphere Temp. anomaly

HadCRU



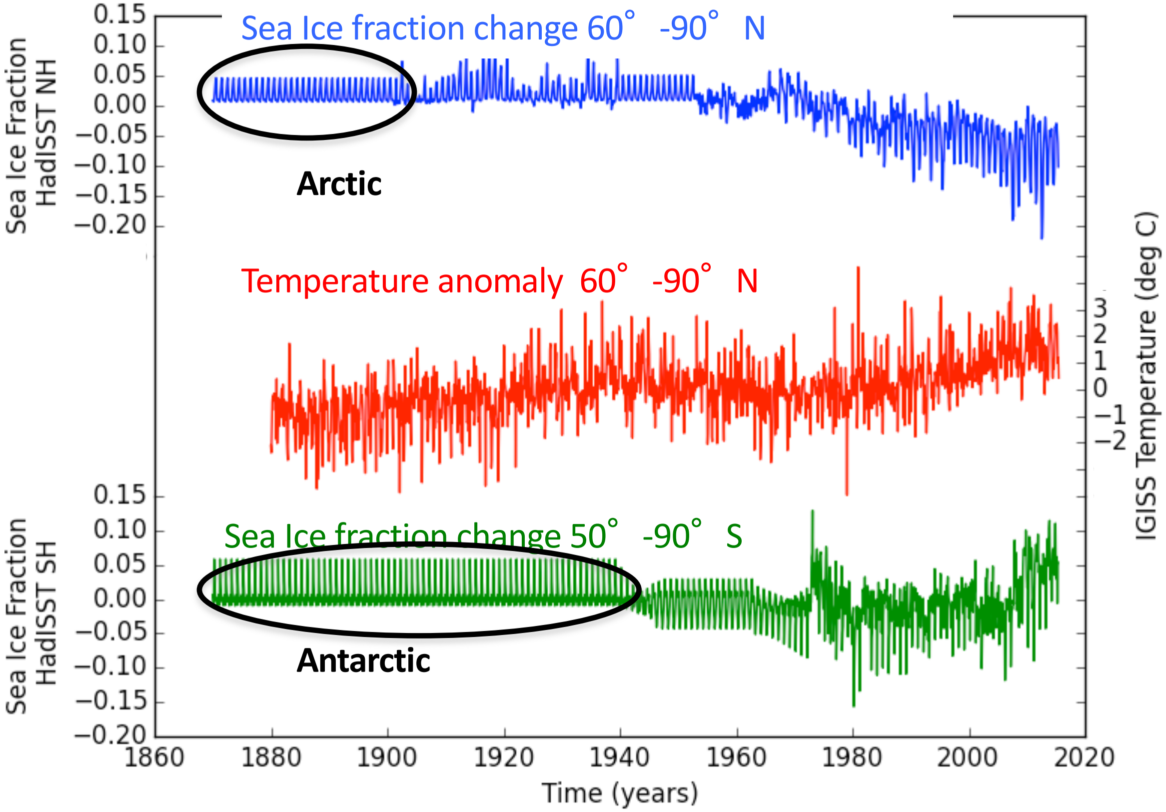


Arctic Sea Ice retreat



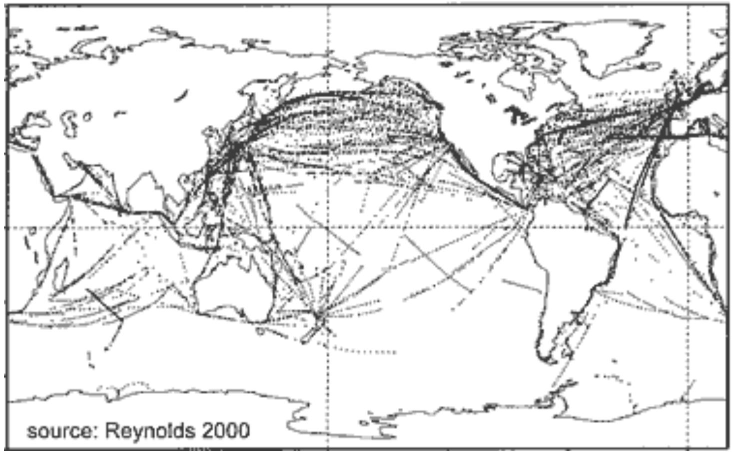
Arctic Sea Ice retreat

Missing Information about Sea Ice



The “Climate dilemma“

- Instrumental data are **sparce**



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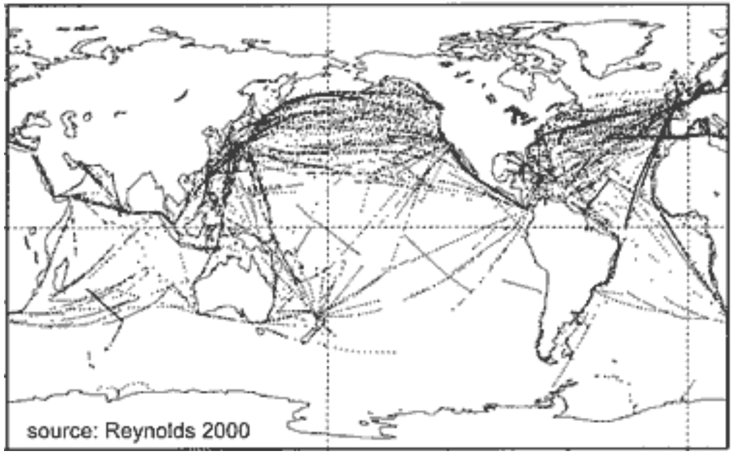

- The records of direct temperature measurements are **short** and already fall in the phase of strong **human influence**.

The "Climate dilemma"

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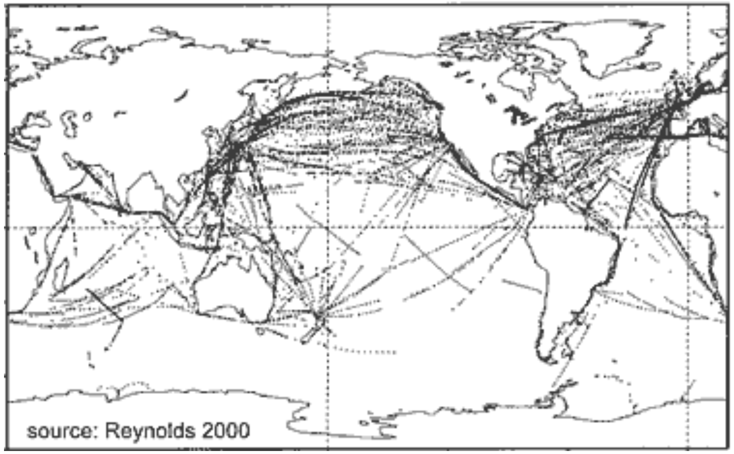
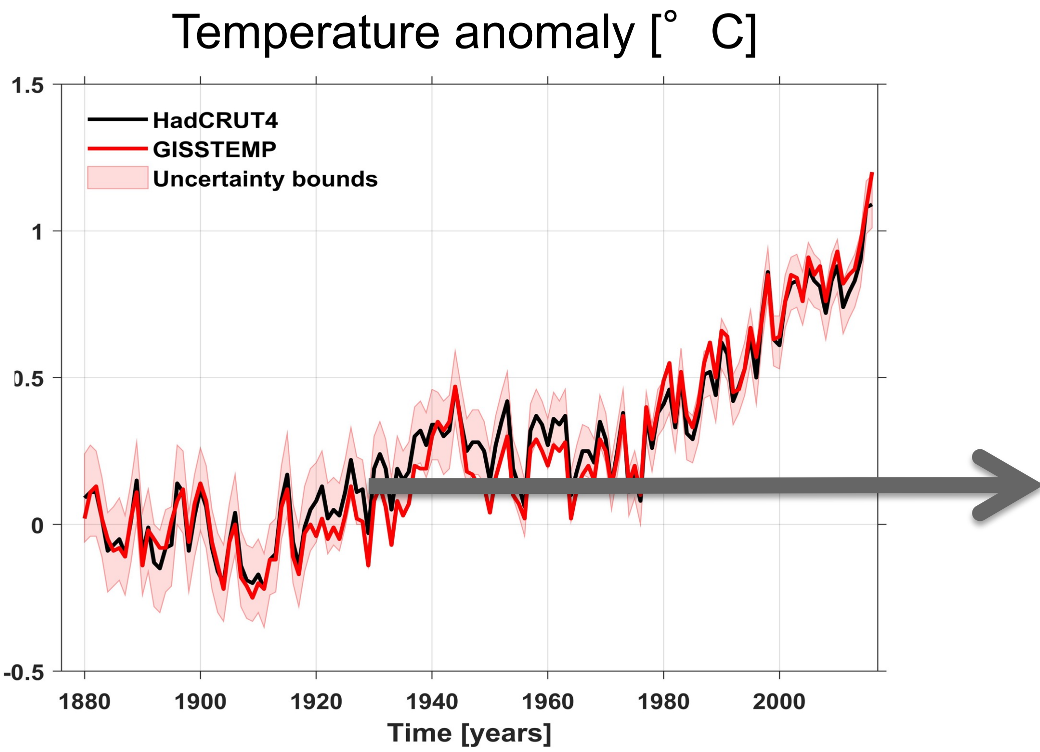


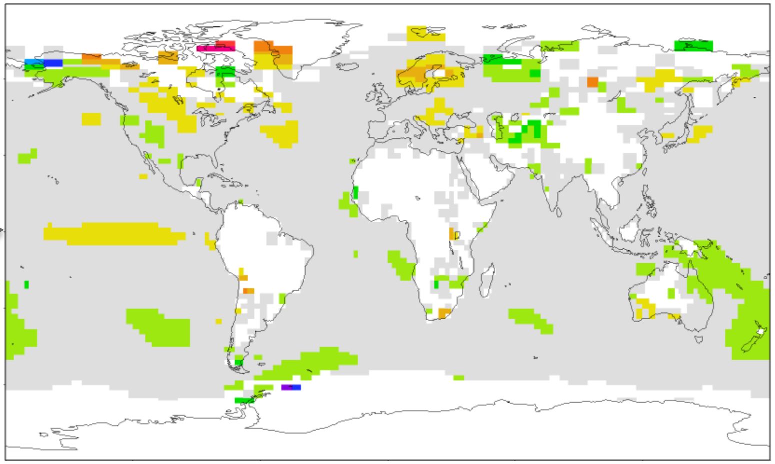
- The records of direct temperature measurements are **short** and already fall in the phase of strong **human influence**.

- **For the time before instrumental records, one has to rely on information from proxy data and modeling.**

Motivation: Observational Record

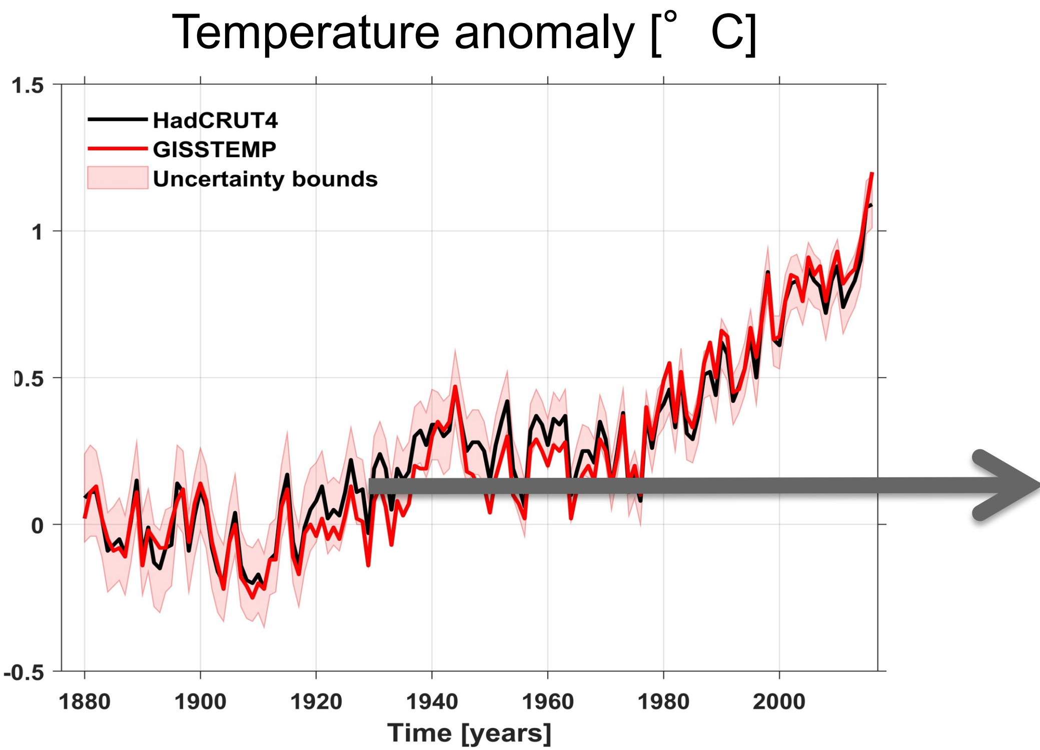


Uncertainty largely due to missing information at high latitudes



Temperature Anomaly 1930
White areas: not enough data

Motivation: Observational Record



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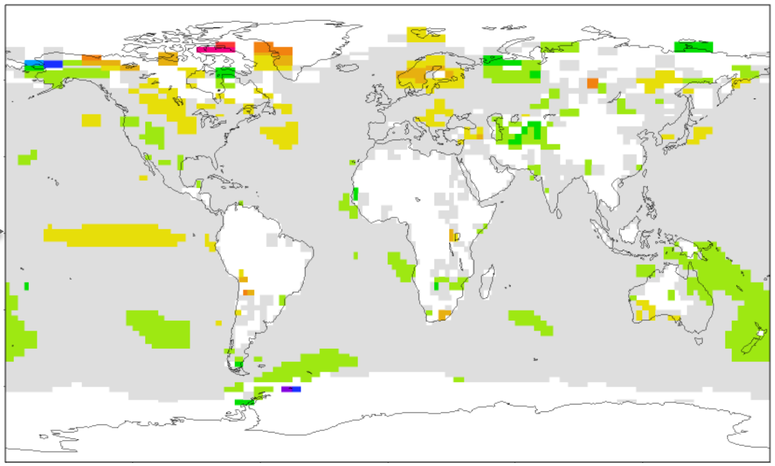
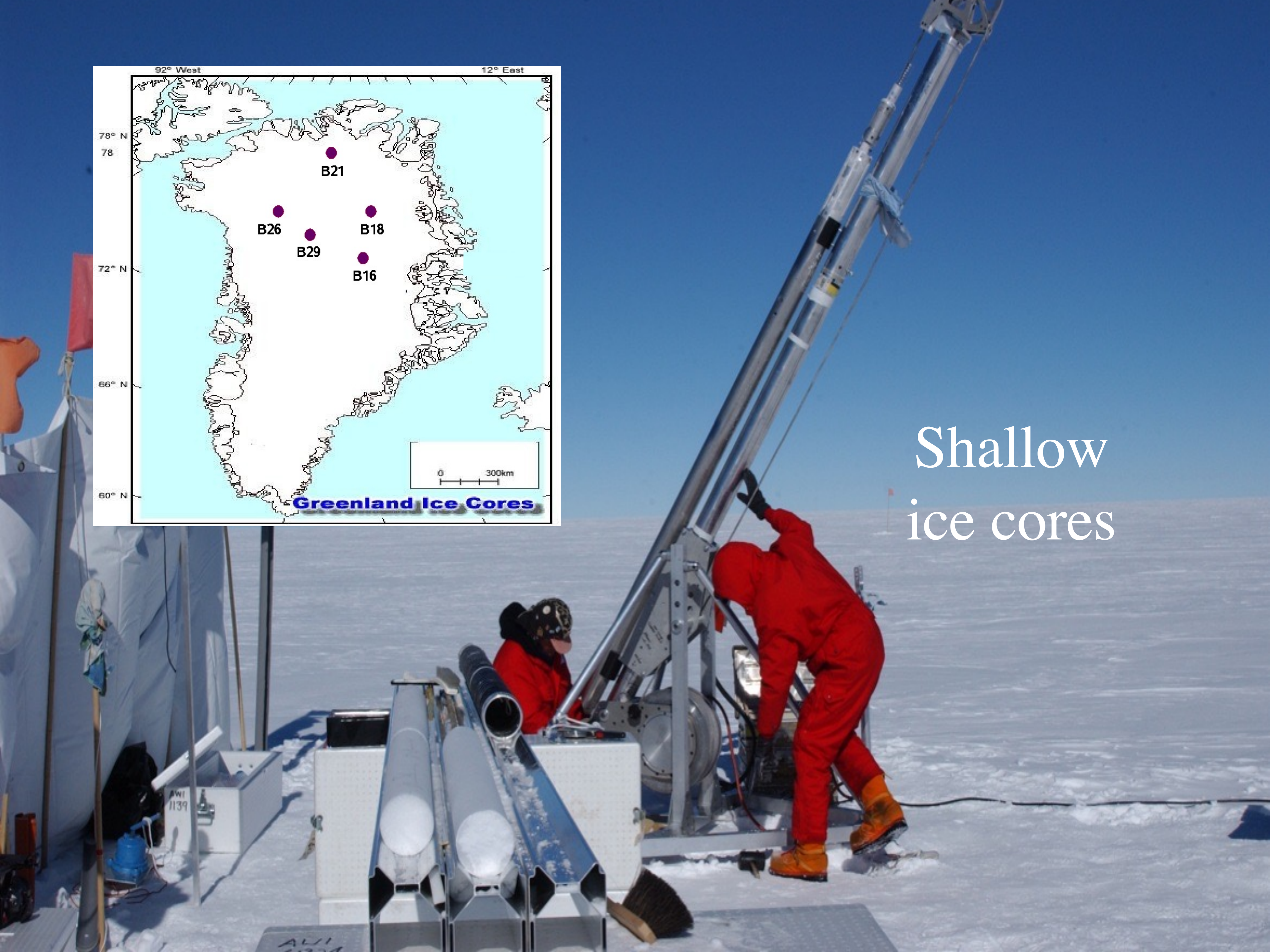


Temperature Anomaly 1930
White areas: not enough data

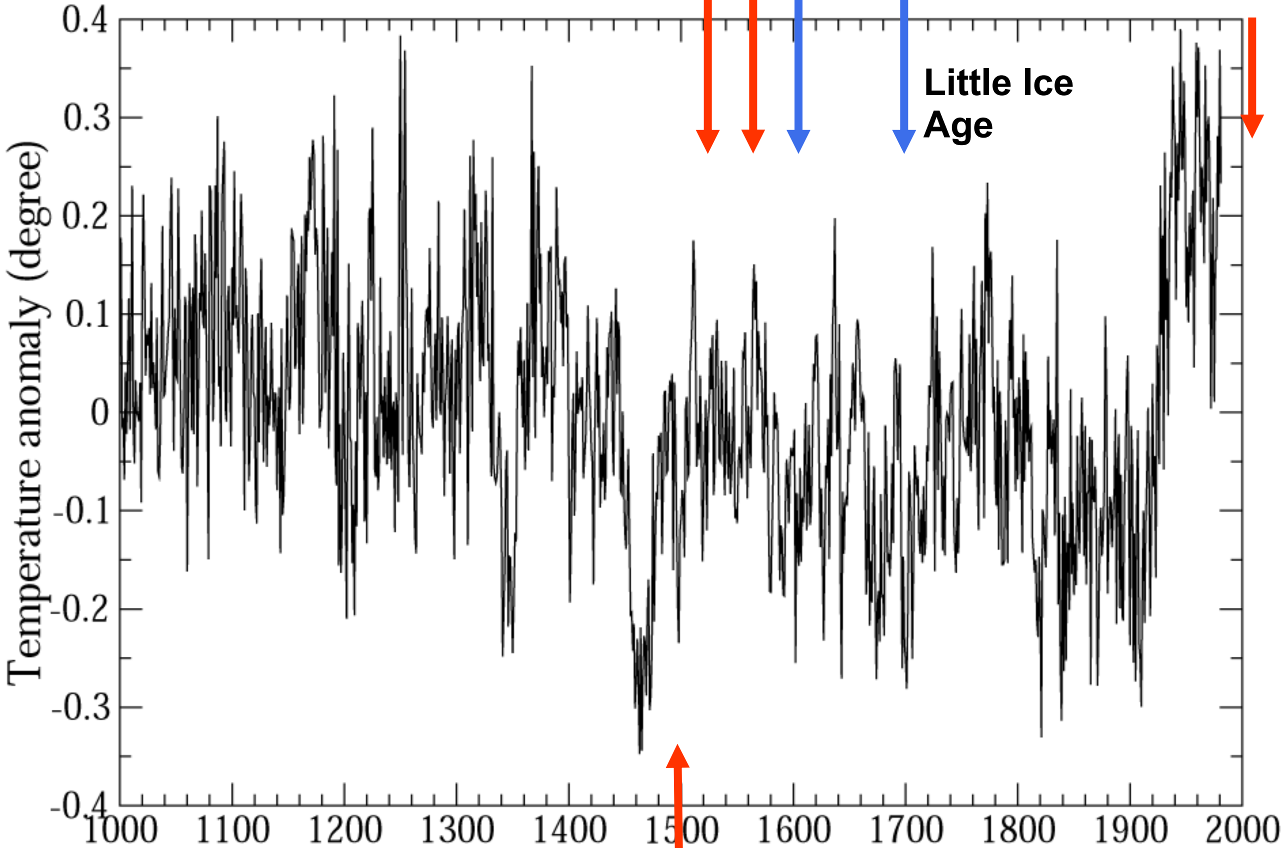
Climate variability beyond the instrumental record: Decadal, centennial, millennial

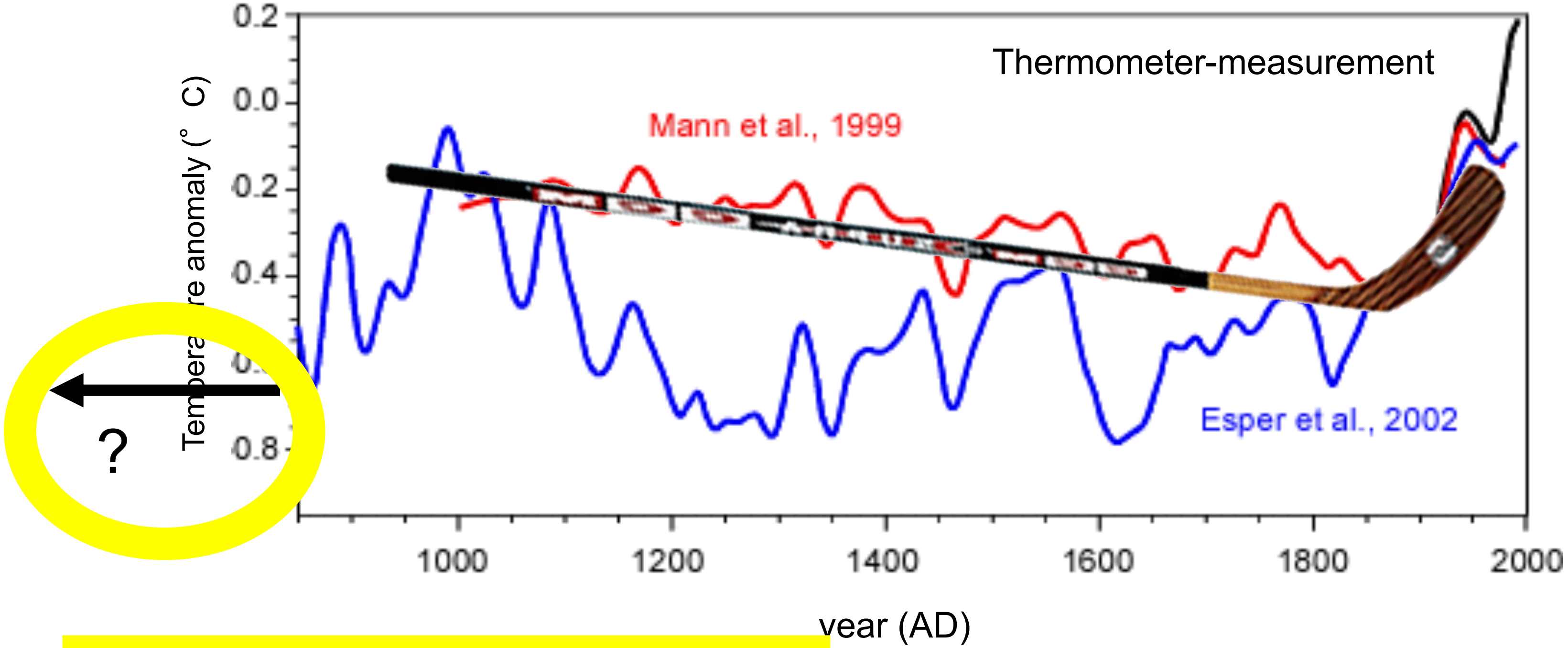


Shallow ice cores

History

last **1000 Years**





Further back in time?

Proxy Data

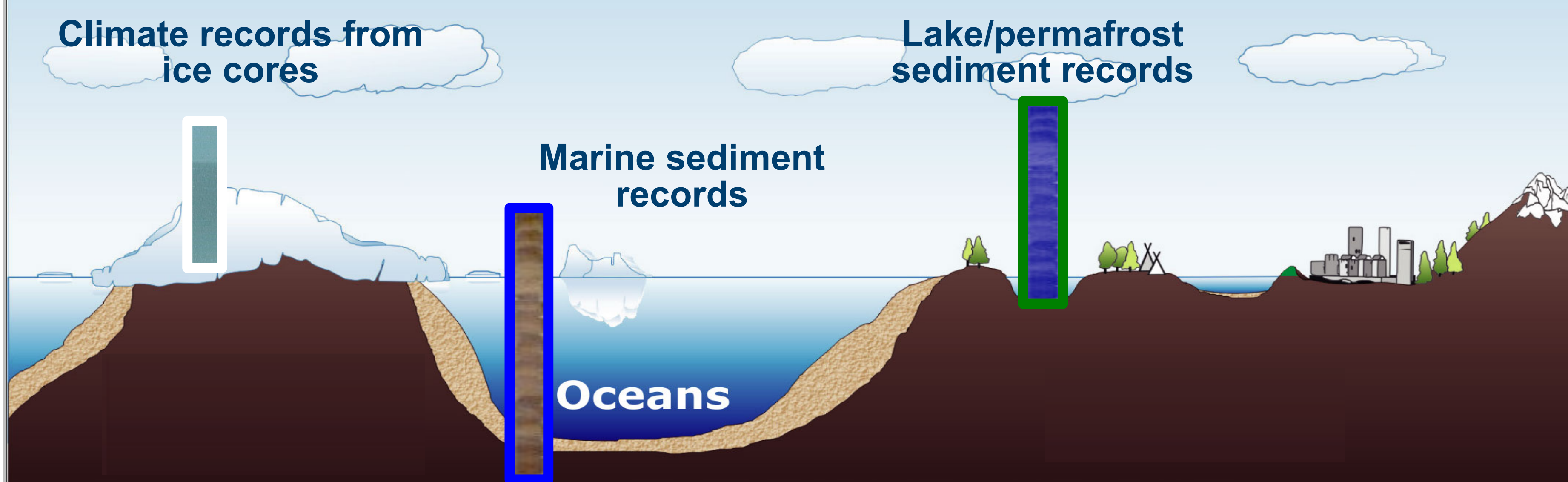
- Indirect data, often qualitative
- Long time series from archives
- Information beyond the instrumental record

Earth System: a polar perspective

Ice drilling camp, 2009

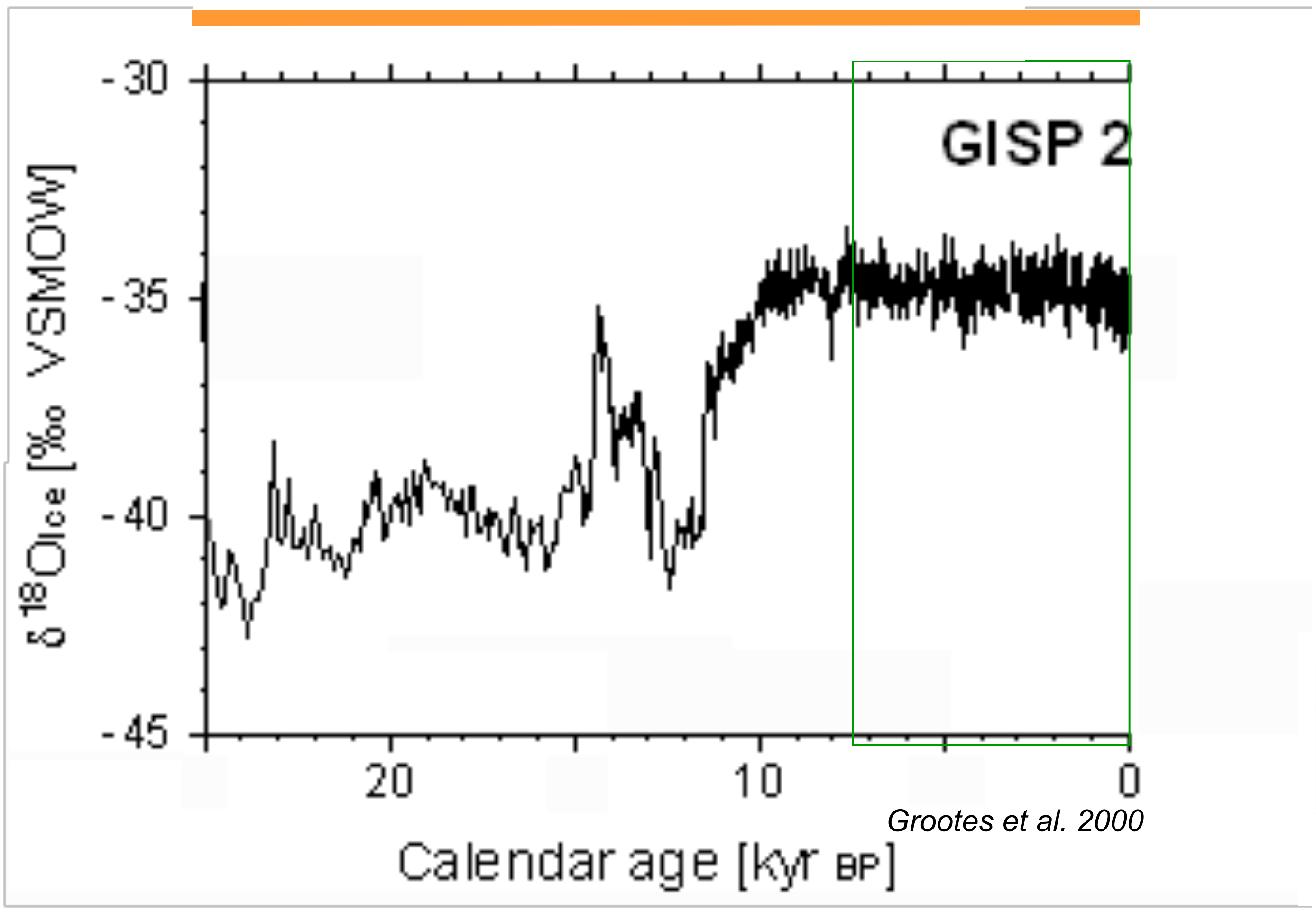
Polarstern, marine sediments

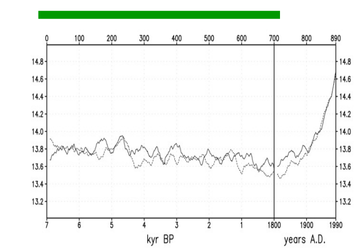
Lake/permafrost sediments

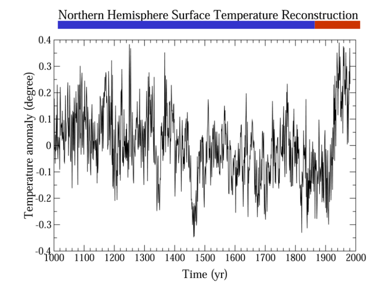


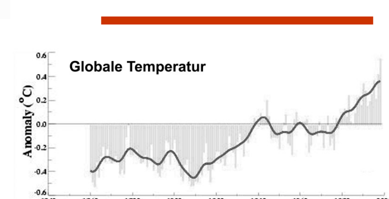
Climate Trends at different Timescales

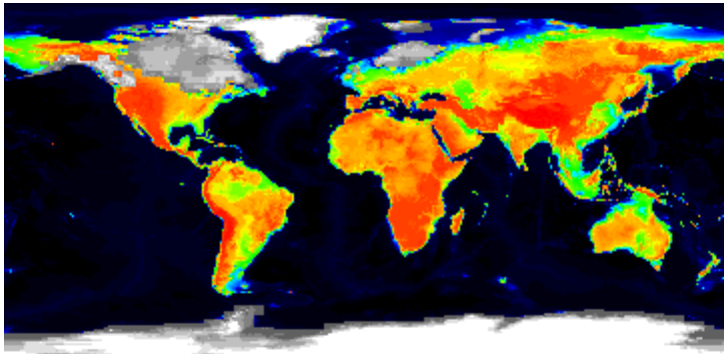
Deglaciation – Greenland ice core

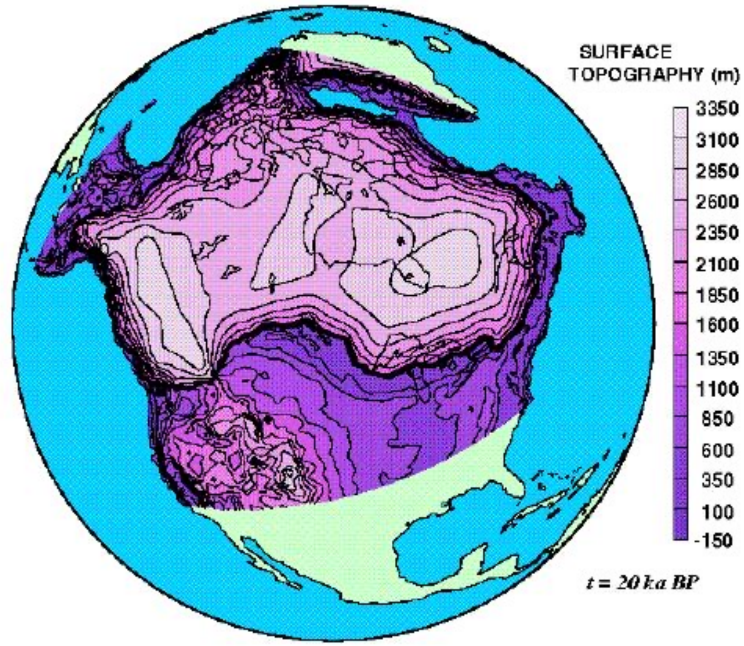






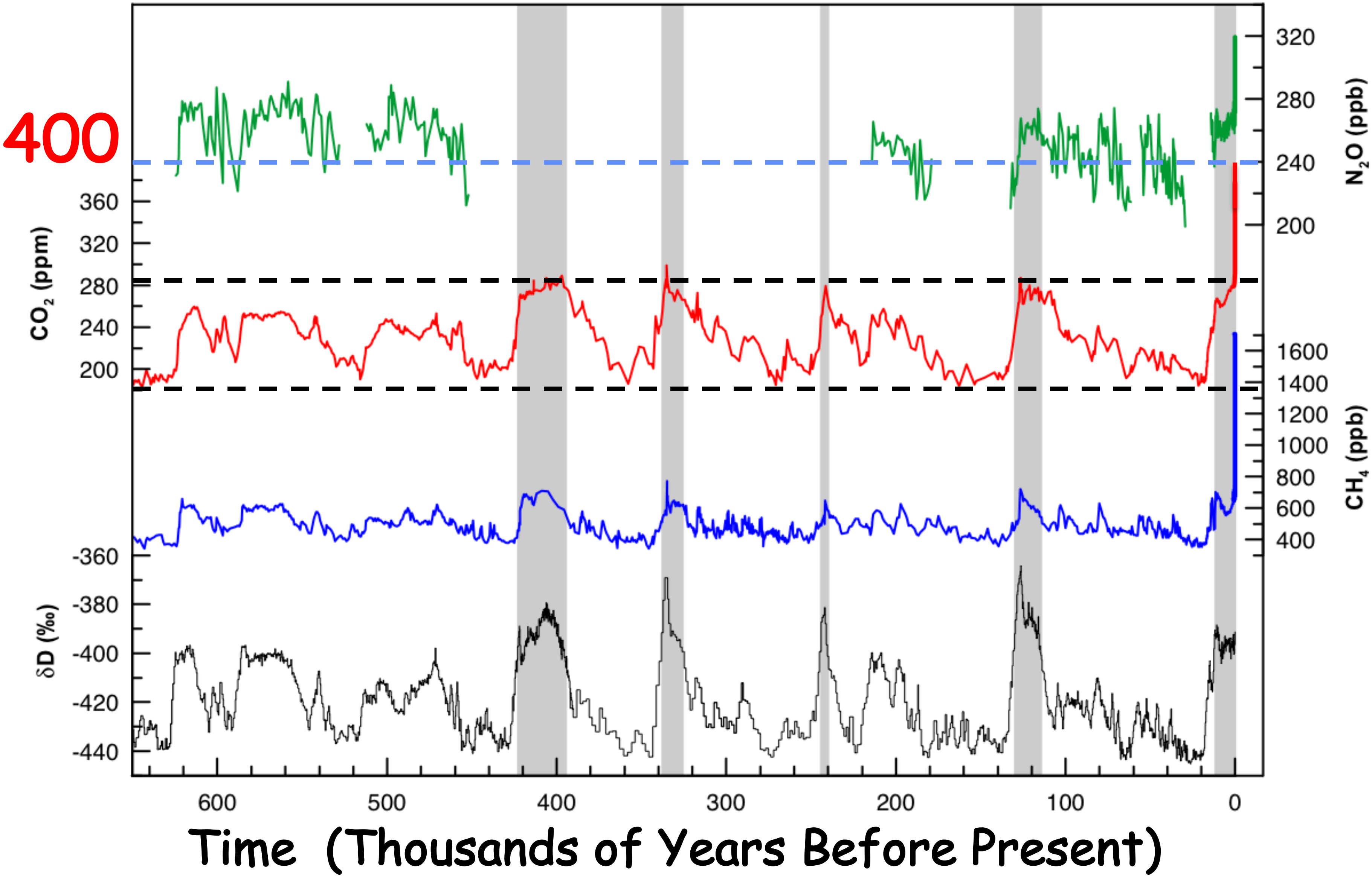




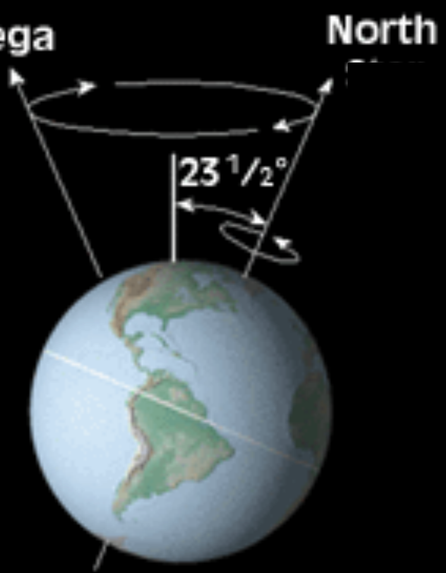


Deglaciation

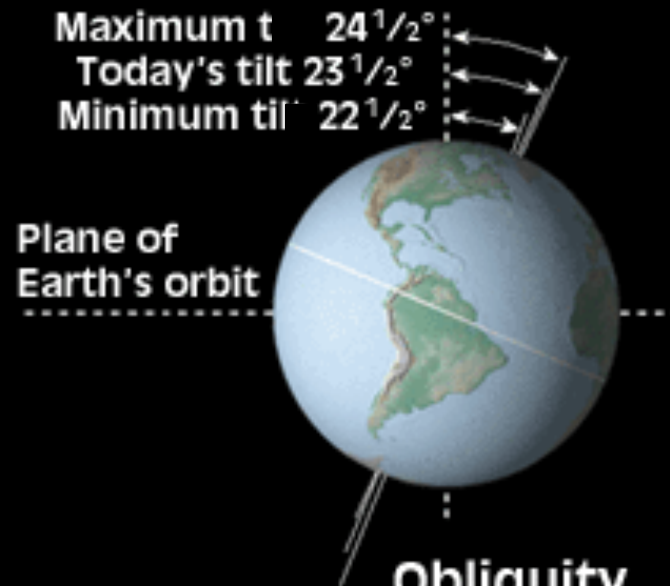
Atmospheric Gas Concentrations from Ice Cores



EPICA 2008



Precession

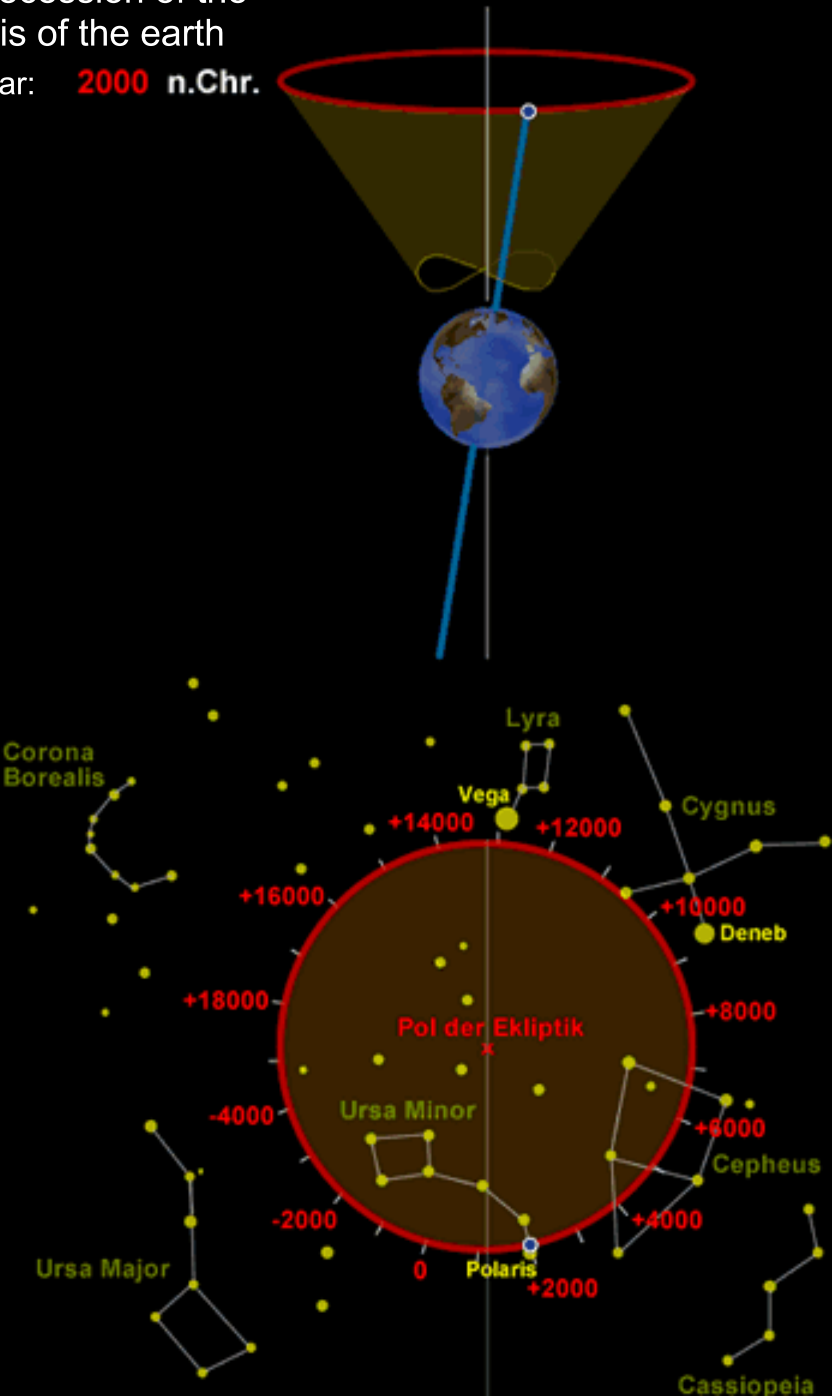


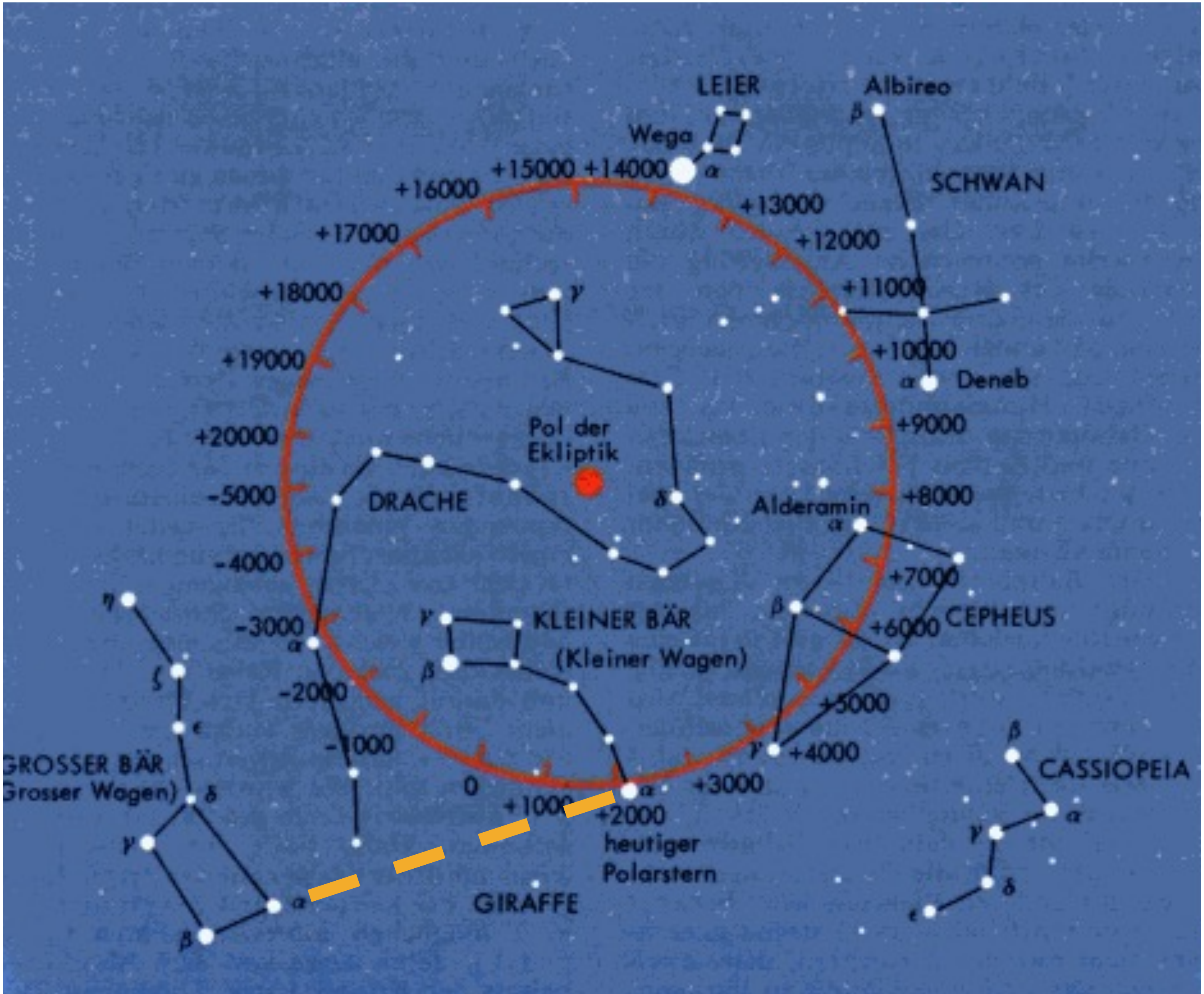
Obliquity

Eccentricity

Precession of the axis of the earth

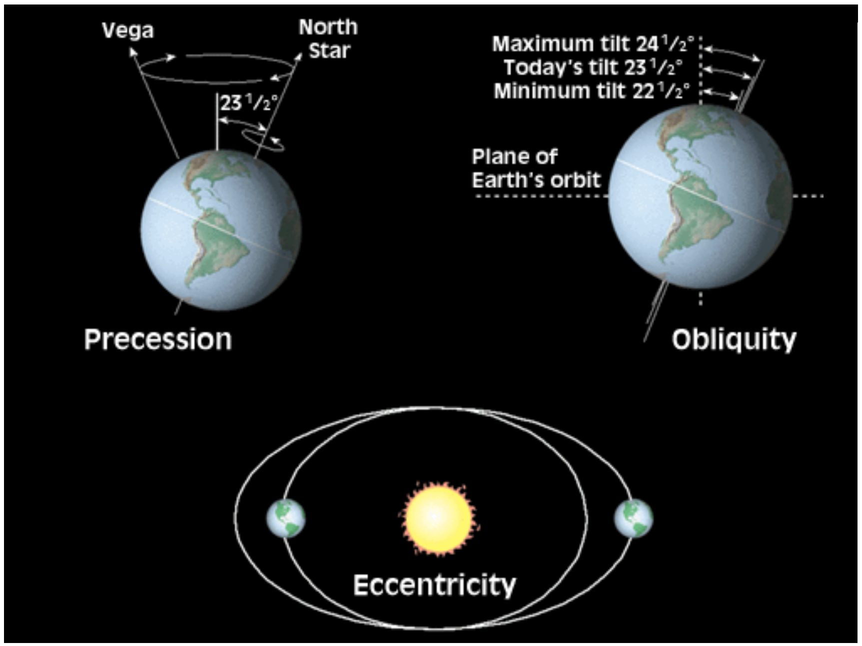
Year: 2000 n.Chr.

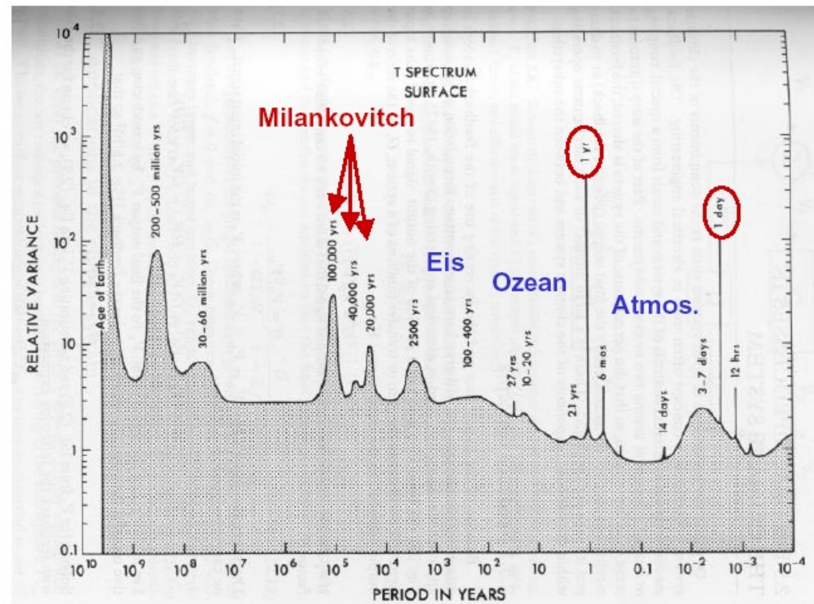




LEIER
Albireo
Wega
SCHWAN
+15000 +14000
+16000
+13000
+17000
+12000
+11000
+18000
+10000
+19000
Deneb
Pol der Ekliptik
+9000
+20000
DRACHE
-5000
+8000
Alderamin
-4000
+7000
CEPHEUS
-3000
KLEINER BÄR
(Kleiner Wagen)
+6000
-2000
+5000
-1000
+4000
GROSSER BÄR
Grosser Wagen)
0
+1000
+2000
+3000
CASSIOPEIA
heutiger Polarstern
GIRAFFE

Orbital forcing

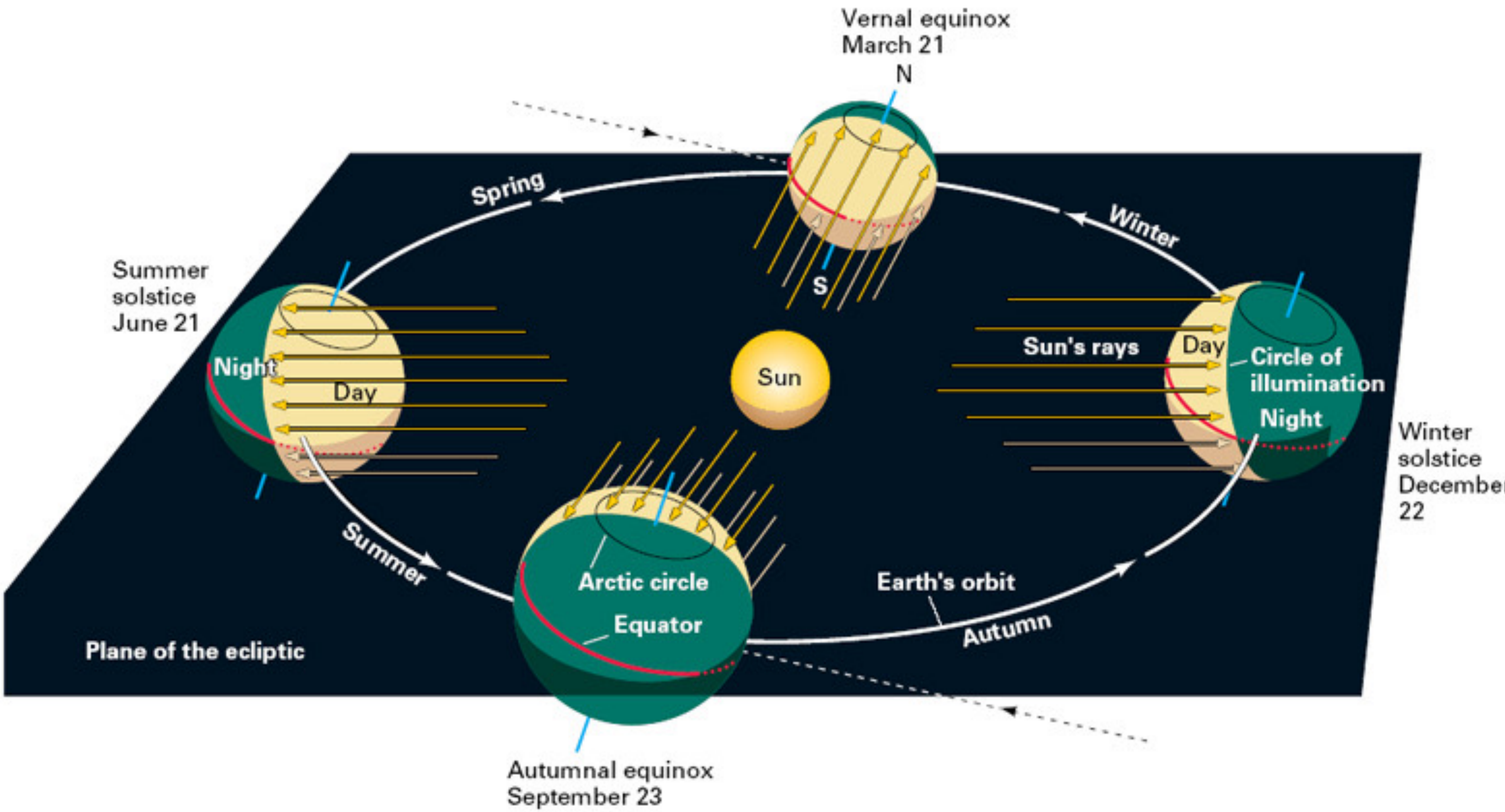




Quelle: Peixoto & Oort

- ~20,000, ~40,000, ~100,000 years
- 0.5, 1 year
- Tides
- **Geometry of the Sun-Earth configuration (& Moon)**

The seasons



Strahler, 2002

The Earth's orbit

Keppler

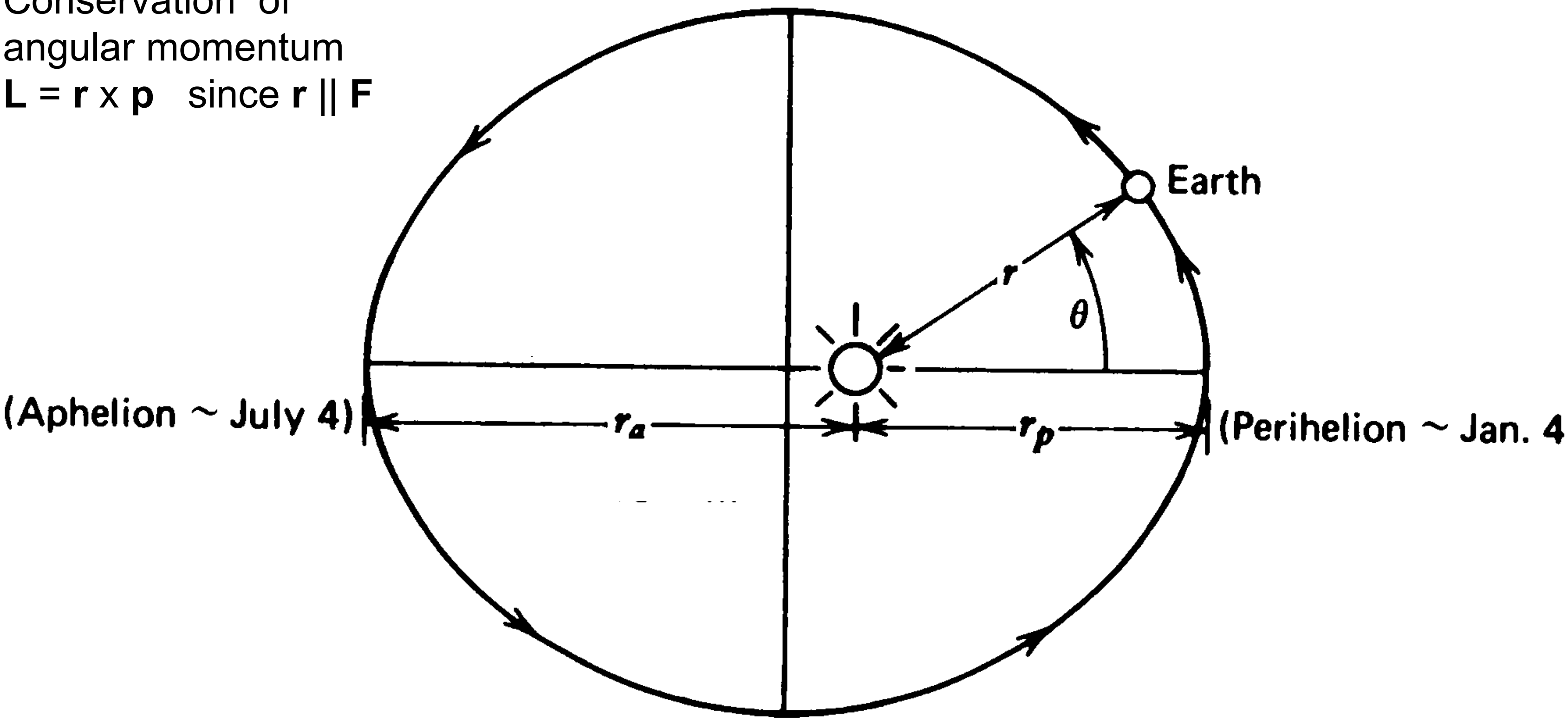
$$r = \frac{a(1-\epsilon^2)}{1+\epsilon\cos\theta}$$

r = a +/- 2%

mean orbital distance	**a = 150 Mio km**
eccentricity	**ε = 0.0167** (shown exaggerated)

Conservation of angular momentum

L = **r** x **p** since **r** || **F**

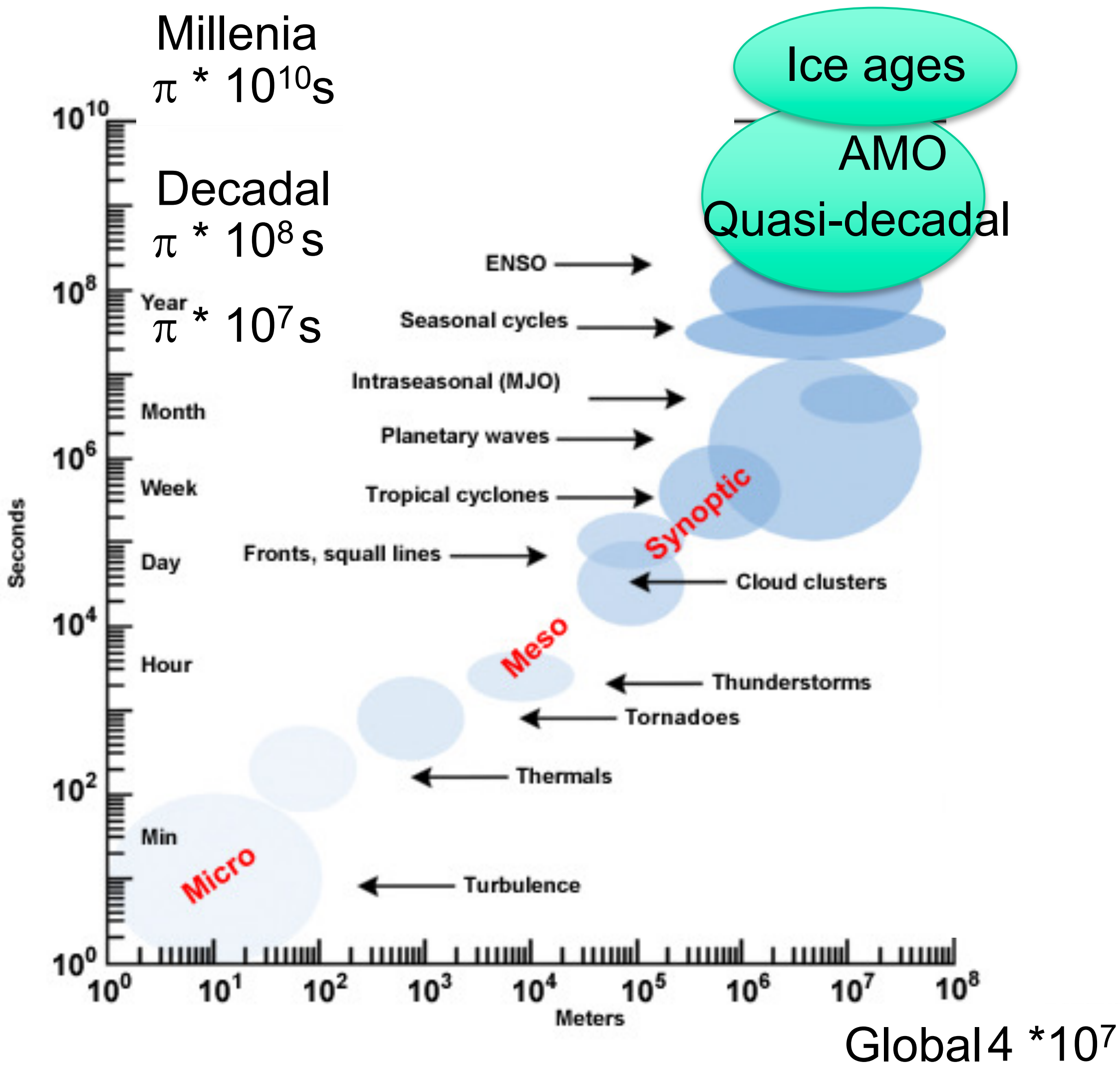


Wieder, 1982

Sunspots Photo: Nasa

Spatio-Temporal Scales

Dissipative Systems (as atmosphere & ocean) cannot maintain large gradients on long time scales



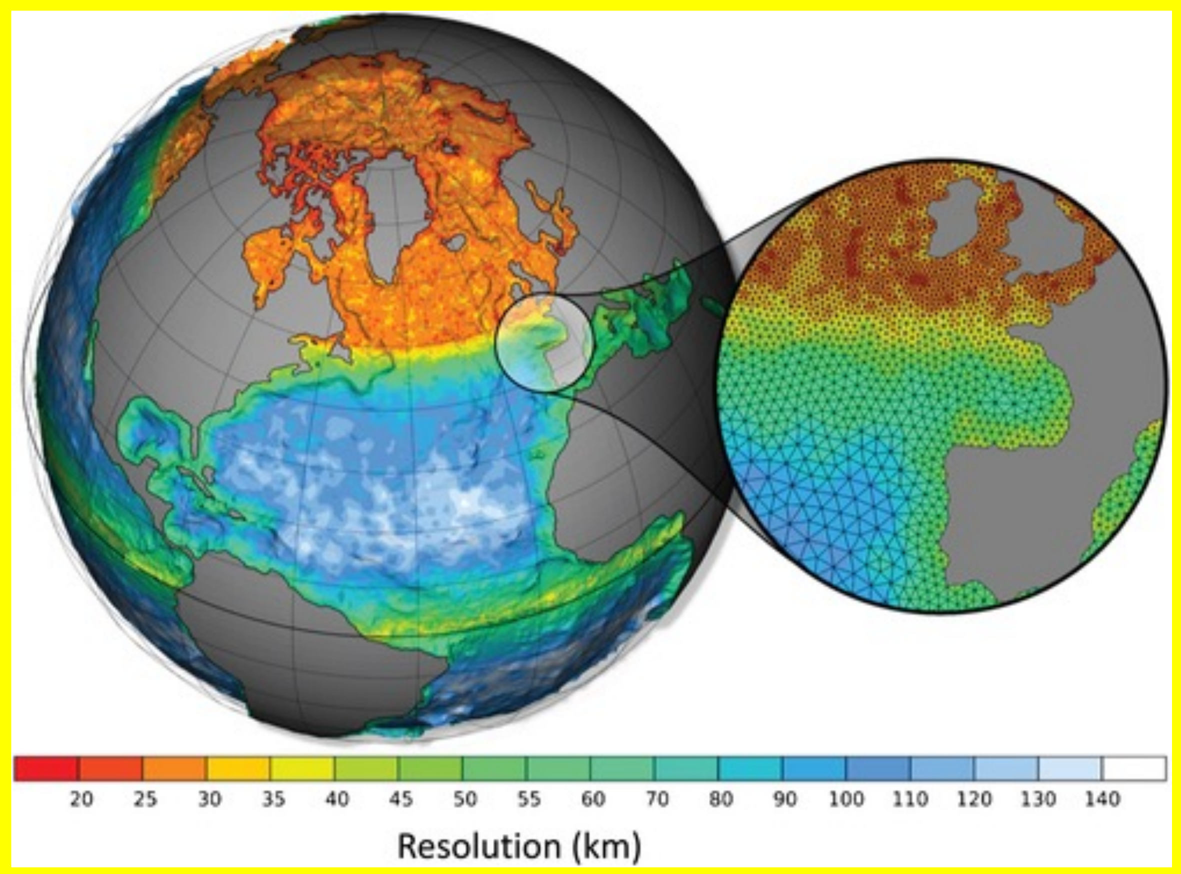
Spatial || temporal Scales

Earth System Analysis: Models

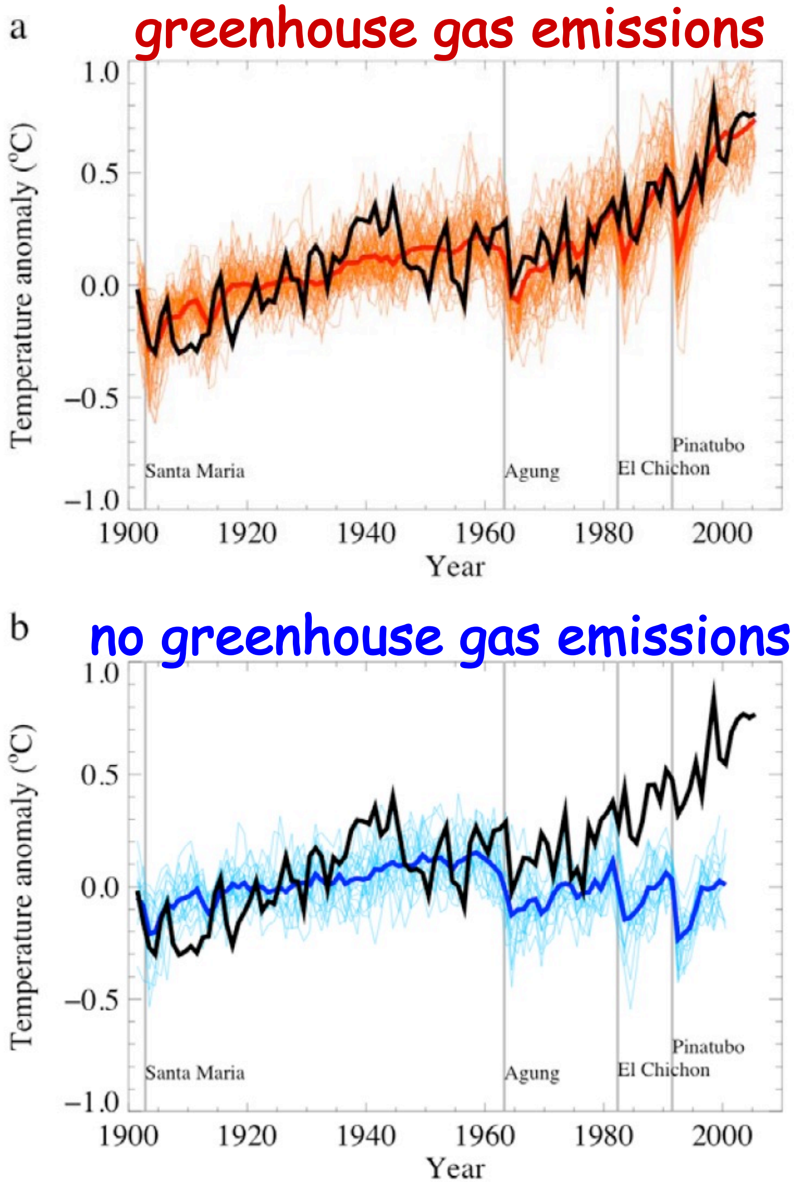
$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -2\Omega \times \mathbf{v} - \frac{1}{\rho}\nabla p + \mathbf{g} + \mathbf{F}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0$$

$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T - \frac{p}{\rho^2}\frac{d\rho}{dt} = Q$$



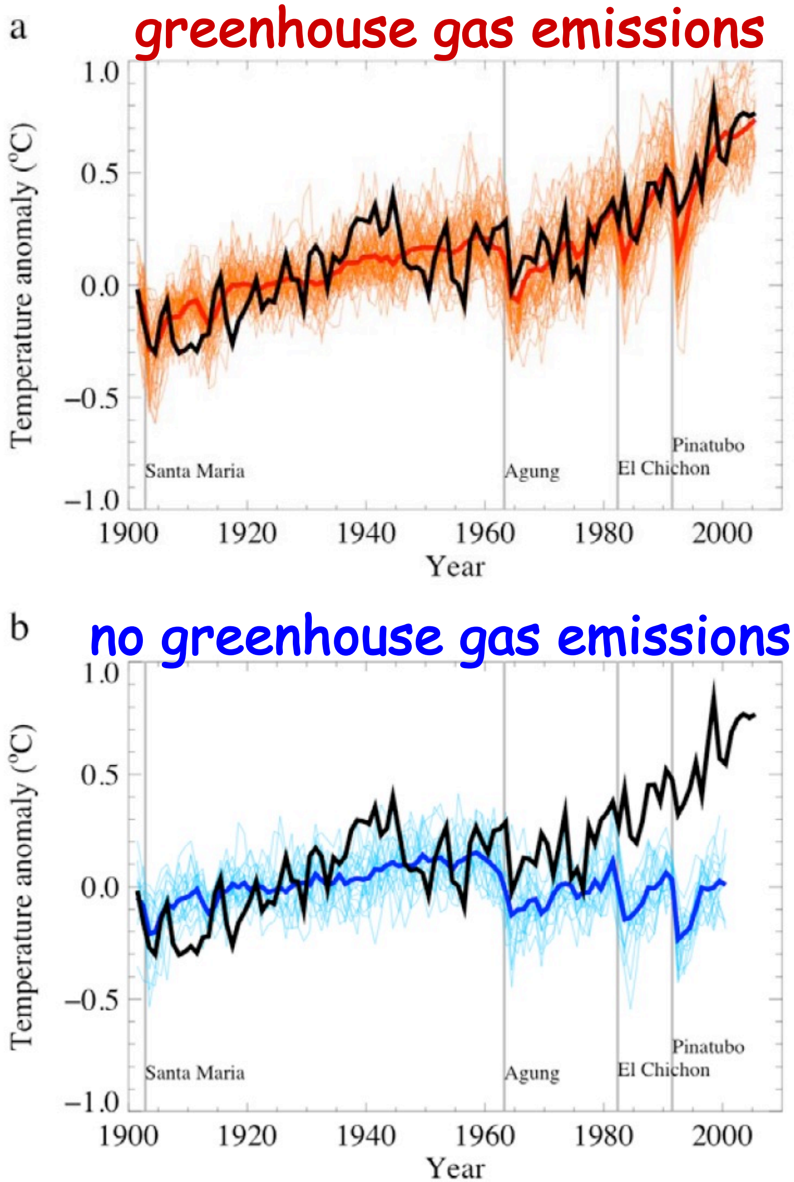
Attribution (model world)



observed changes are consistent with modeled response to external forcing, inconsistent with alternative explanations

Nobel Price, 2021

Attribution (model world)



observed changes are consistent with modeled response to external forcing, inconsistent with alternative explanations

Critics:

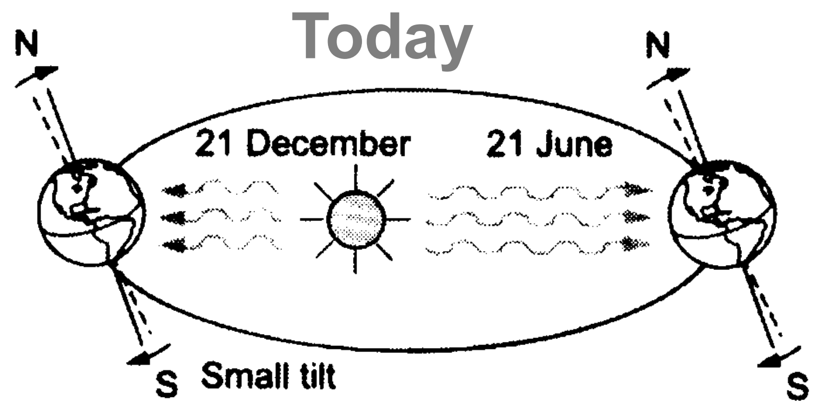
- **Time series too short**
- **Estimates of natural variability based only on models**

Configuration of the Earth's orbit: Examples

Perihelion (closest point)

in January

Tilt of the earth's axis: **23.5°**



Kutzbach (1992)

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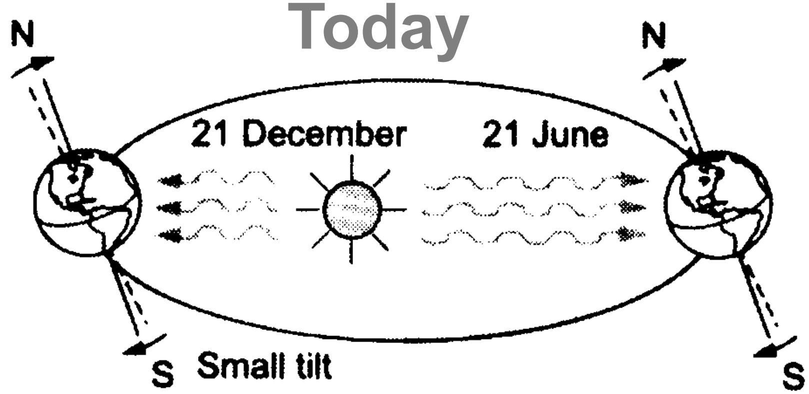
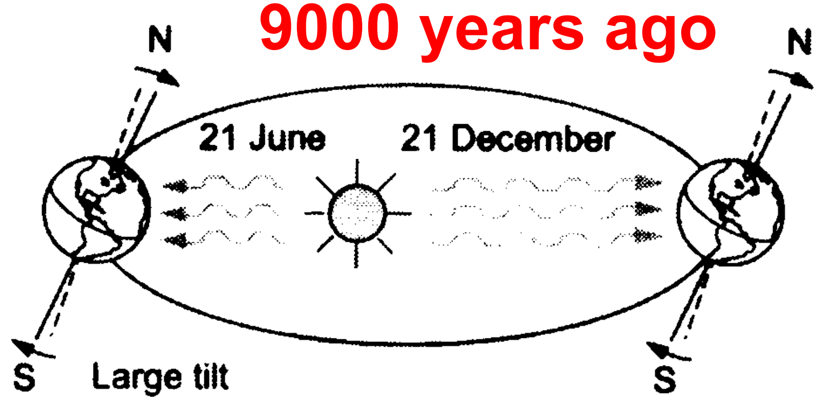
Today



Perihelion in July

Tilt of the earth's axis: **24.0°**

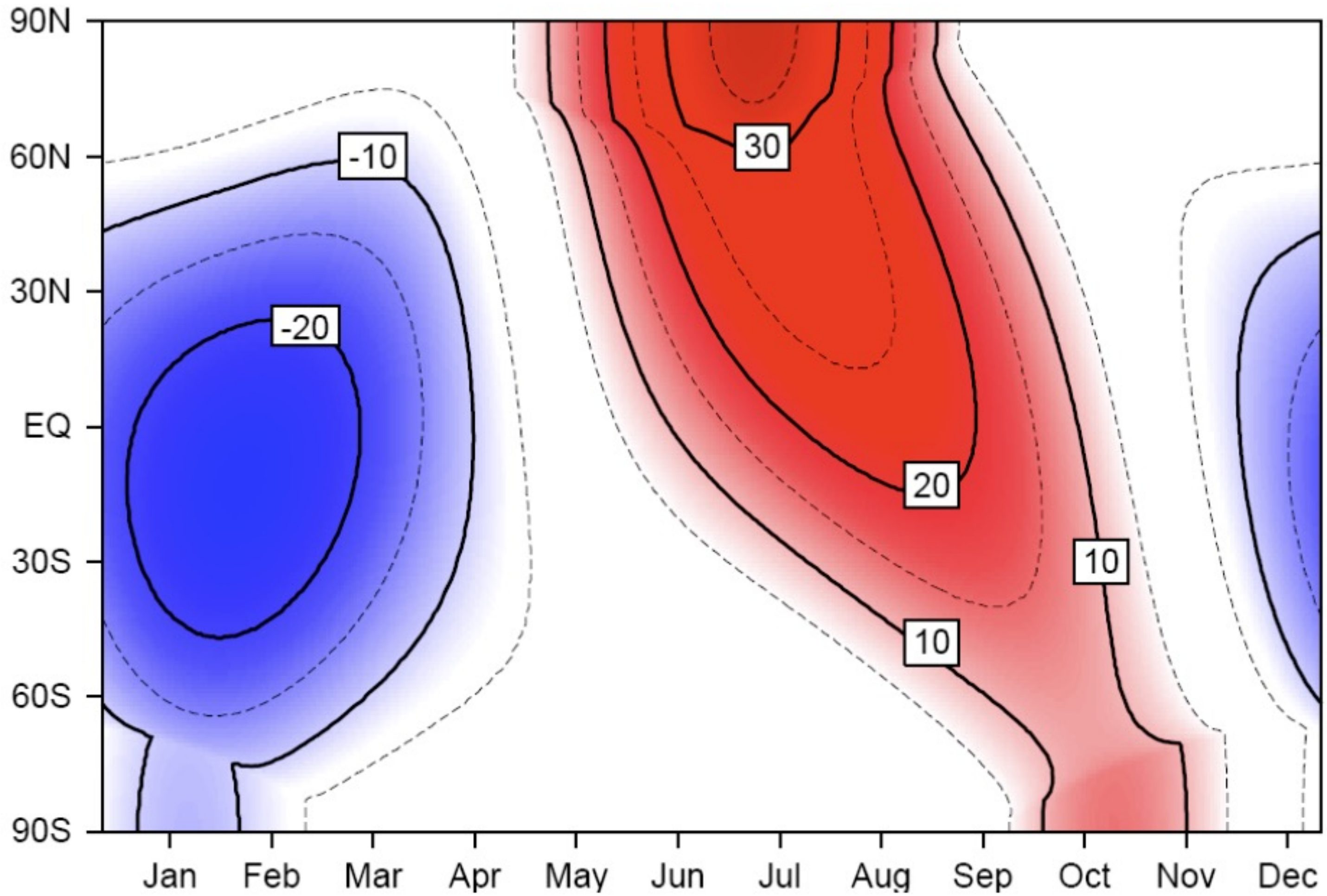
9000 years ago



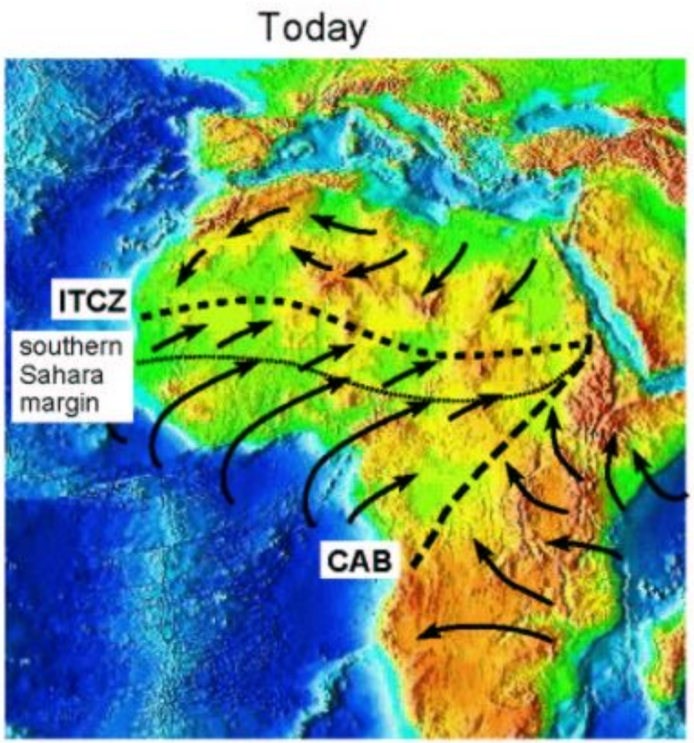
The incoming solar energy in the northern hemisphere 7 % greater in July and correspondingly less in January.

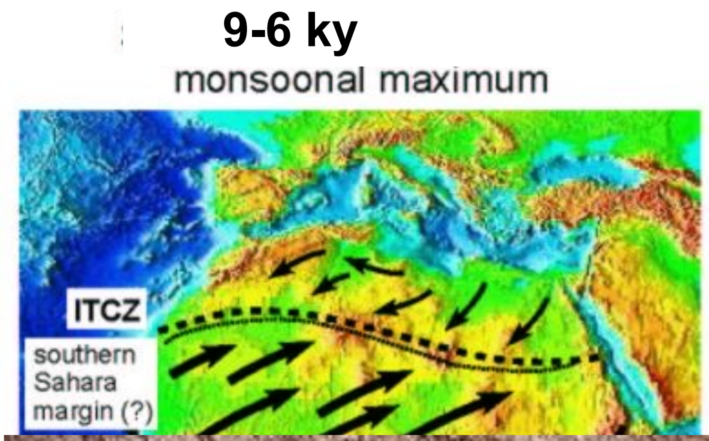
Kutzbach (1992)

Insolation (6k minus present)



Insolation effect on African climate

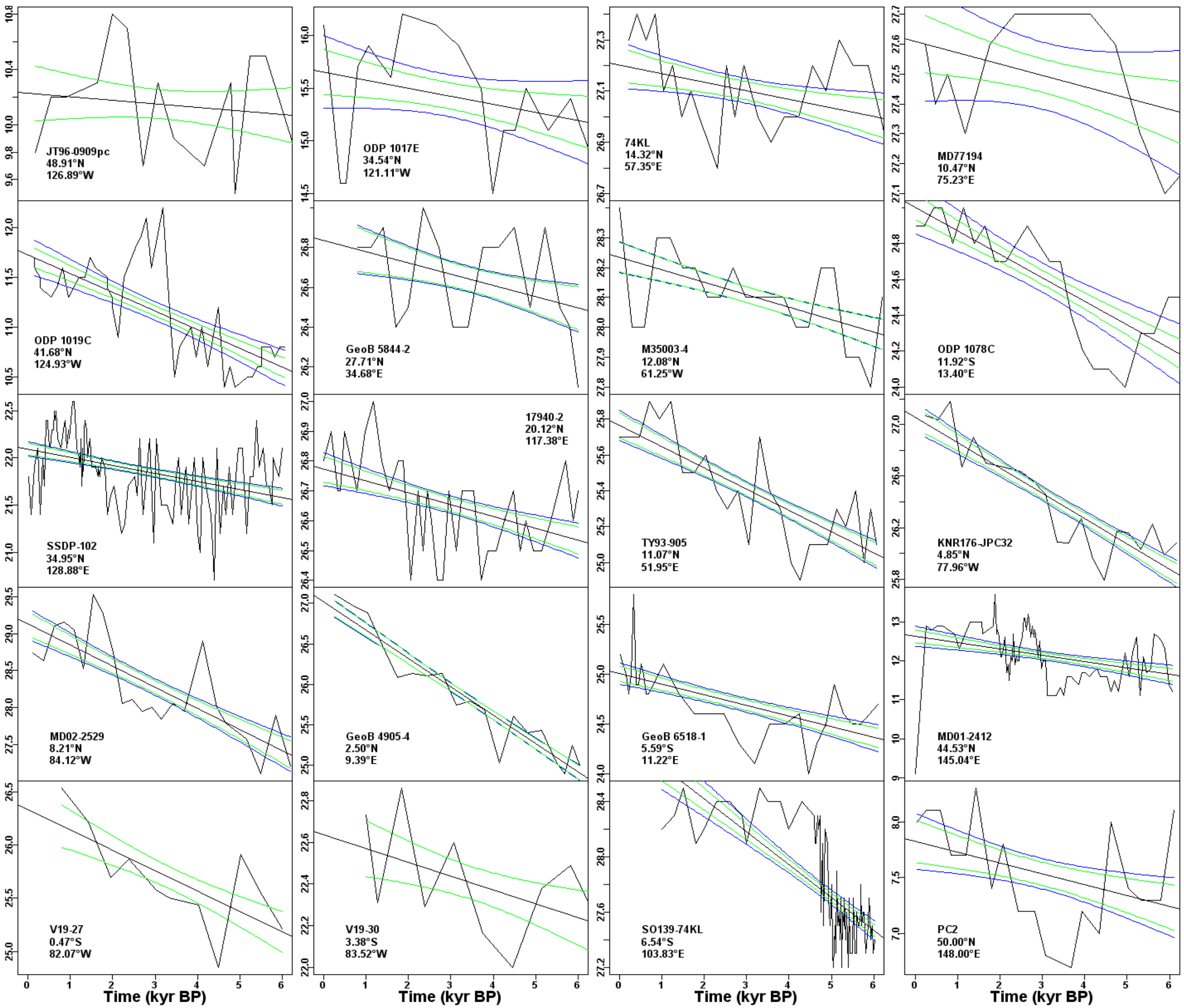




Movement of Intertropical Convergence Zone (ITCZ)

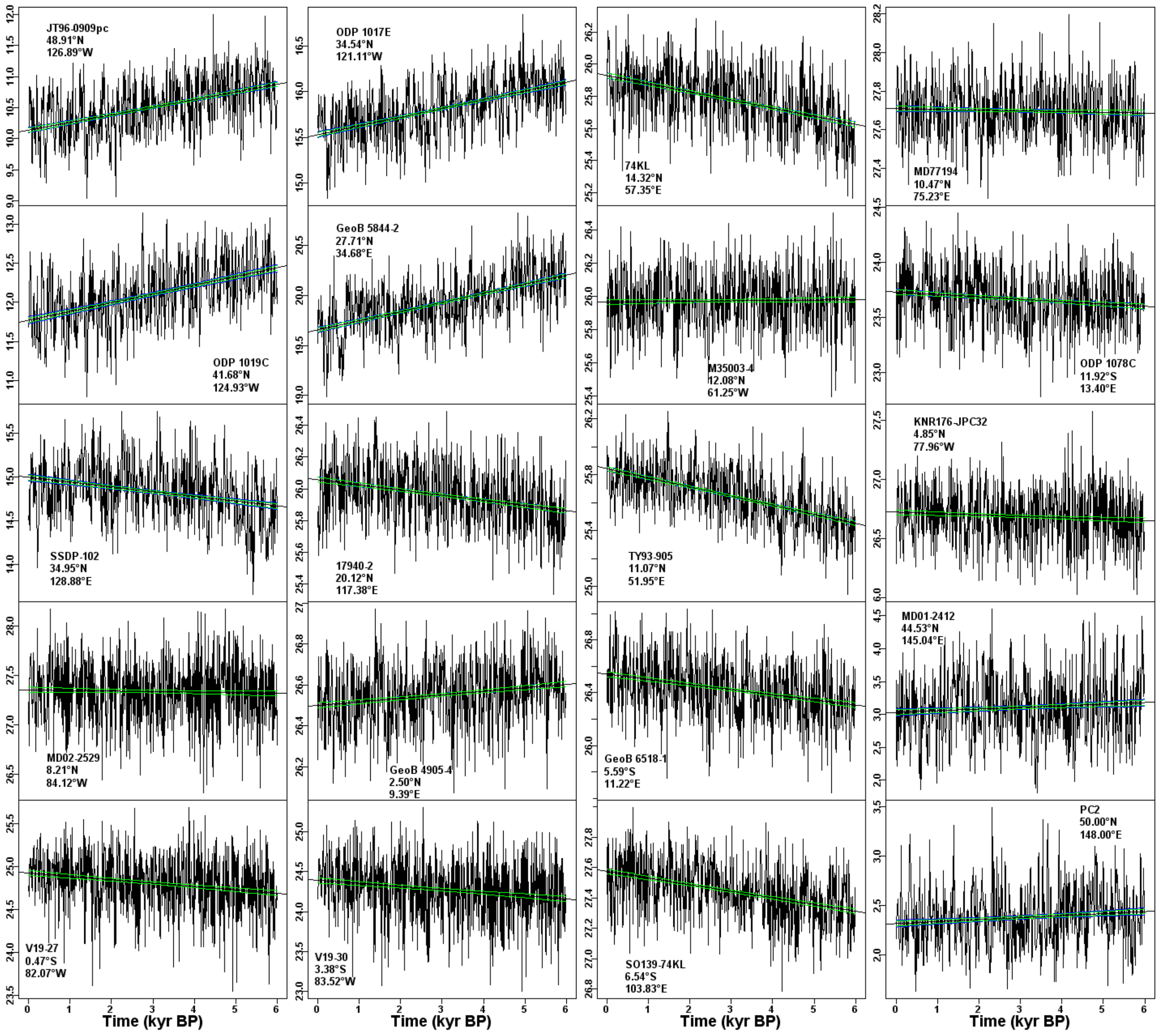
Monsoon

Alkenone Records + Trends



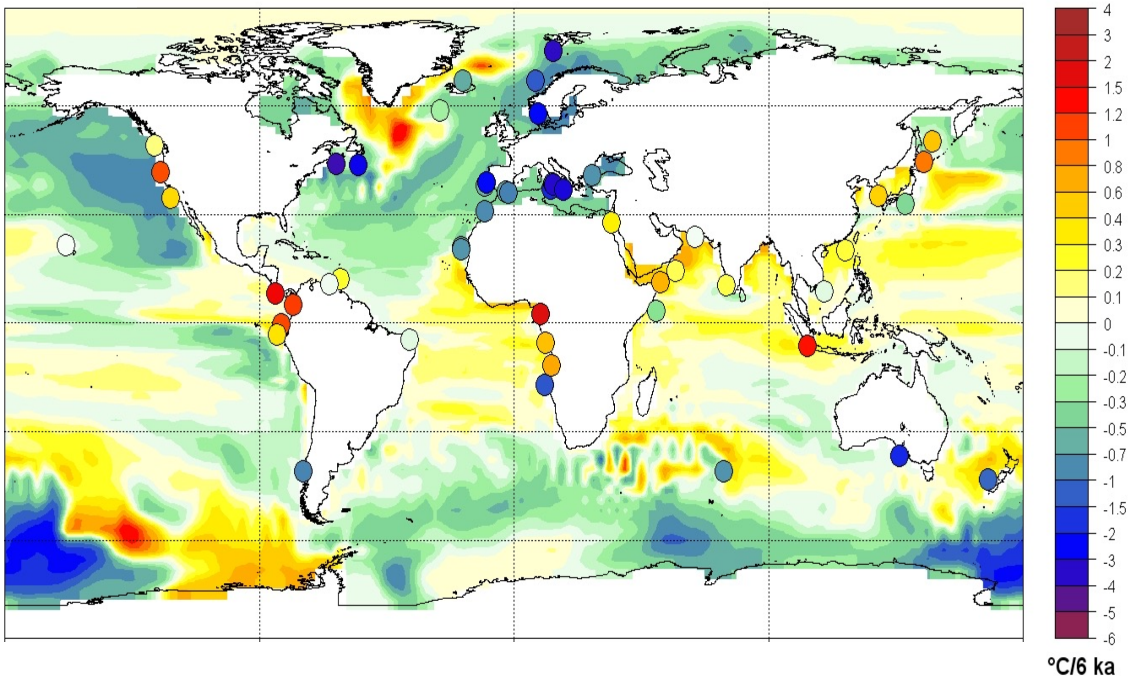
Lohmann et al., 2013

Model SST at core locations



Marine temperature trends (last 6000 years)

Annual mean sea surface temperature trends



Alkenone-based temperature trends

Lohmann et al., 2013, CP

Marine temperature trends (last 6000 years)

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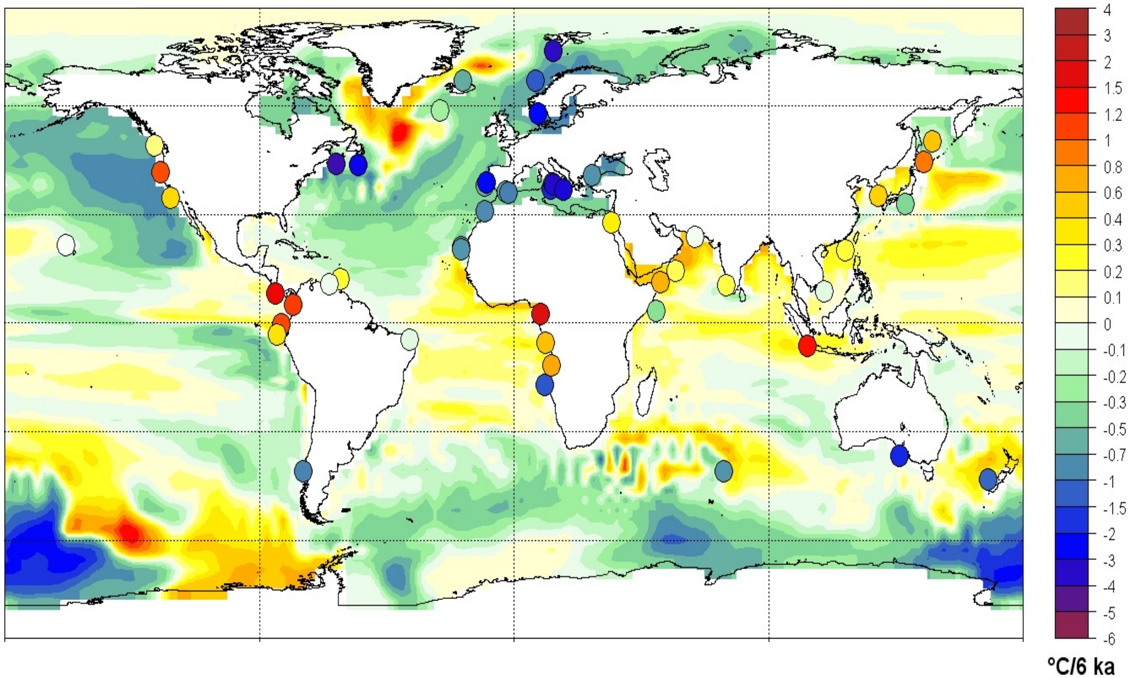
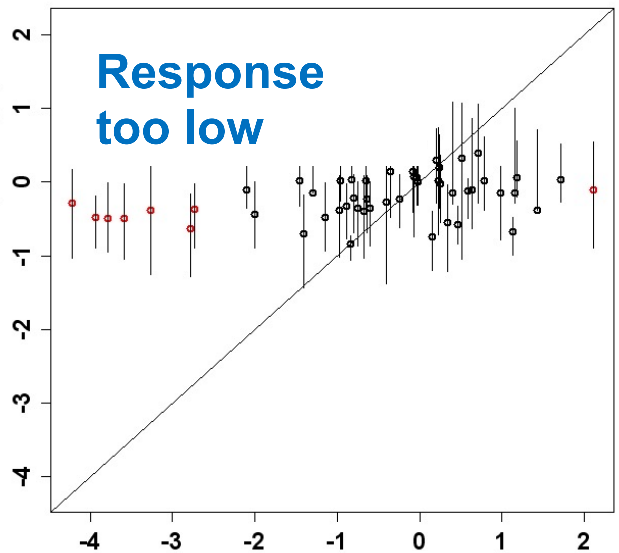


Alkenone-based temperature trends

ΔT



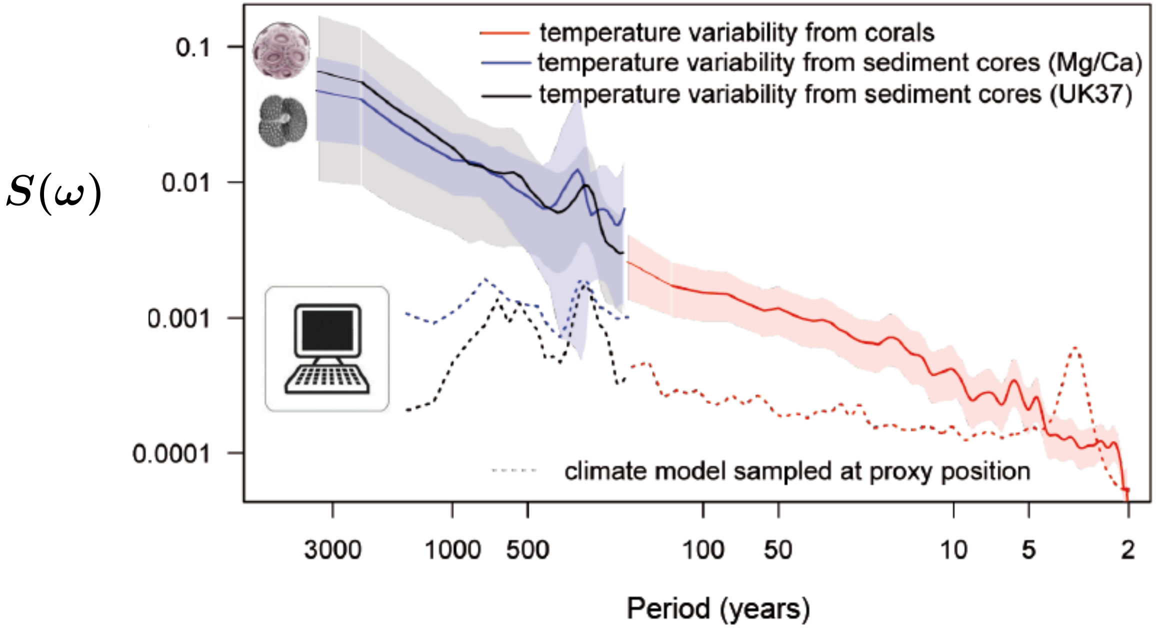
ΔT

Lohmann et al., 2013, CP

Marine temperature variability

(annual to millennial time scales)

Power spectrum



Current climate models seem to underestimate long-term variability

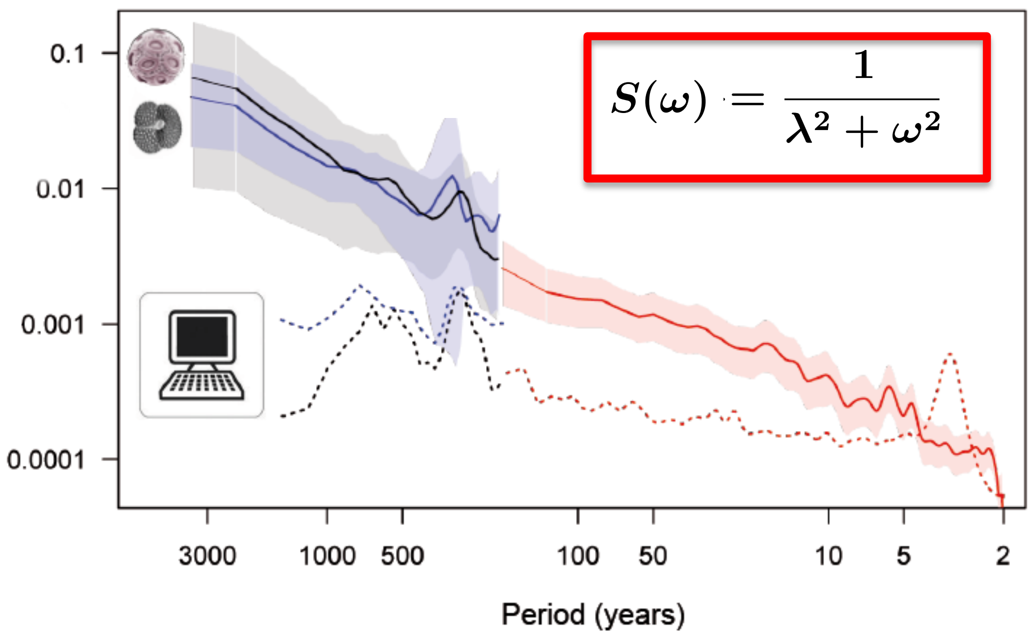
Laepple and Huybers, 2014; GRL, PNAS

Stochastic climate model (Hasselmann, 1976)

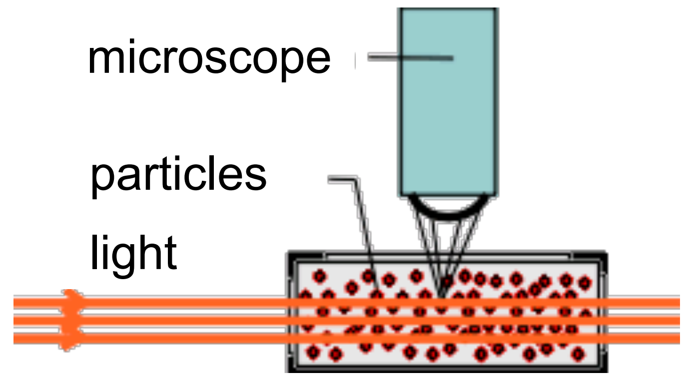
$$\frac{dT}{dt} = -\lambda T + \text{Noise} + \text{Forcing}$$

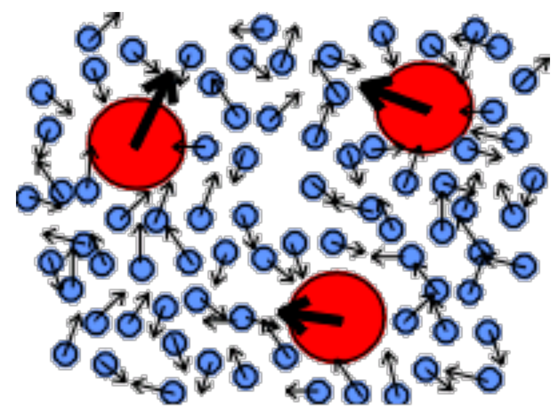
Relaxation, Rubber band

Power spectrum



$$S(\omega) = \frac{1}{\lambda^2 + \omega^2}$$





Disorderly, random motion
collision with molecules

Climate variability and sensitivity are related

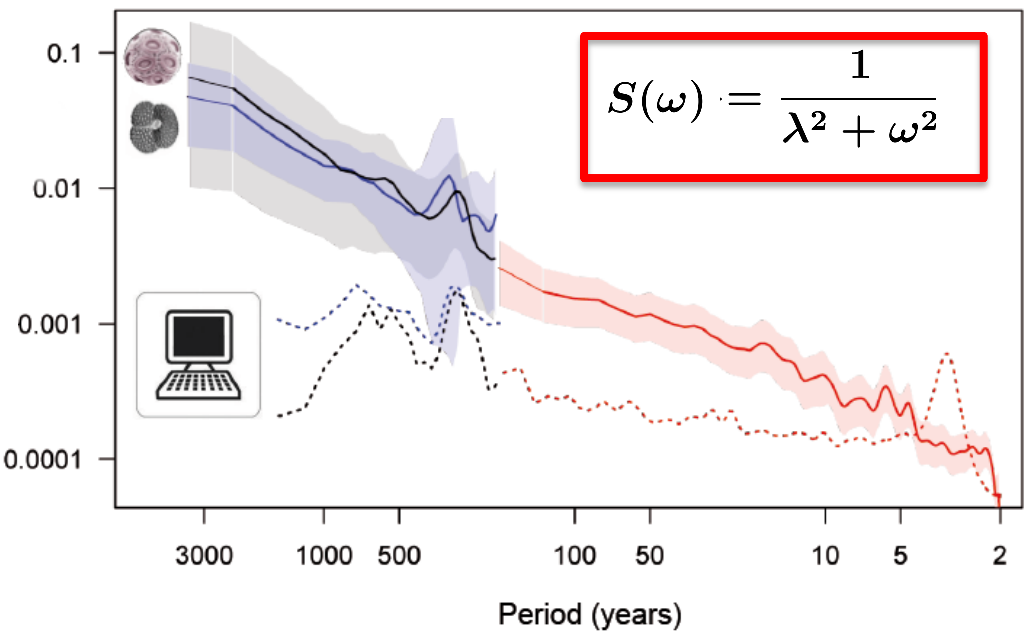
Stochastic climate model

$$\frac{dT}{dt} = -\lambda T + \text{Noise} + \text{Forcing}$$

$$\Delta T = \frac{\text{Forcing}}{\lambda}$$

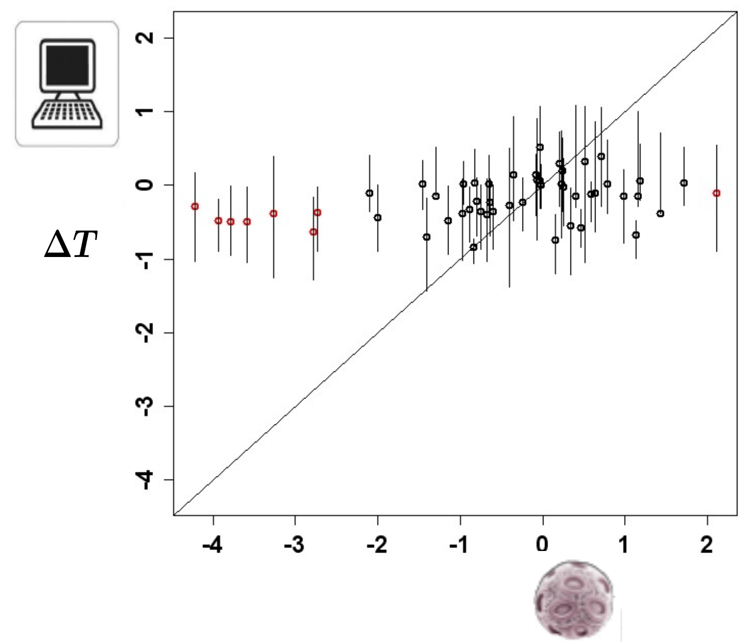
Power spectrum

$$S(\omega) = \frac{1}{\lambda^2 + \omega^2}$$



Variance too low

Response too low



Damping λ too high

(Fluctuation Dissipation Theorem)

under review

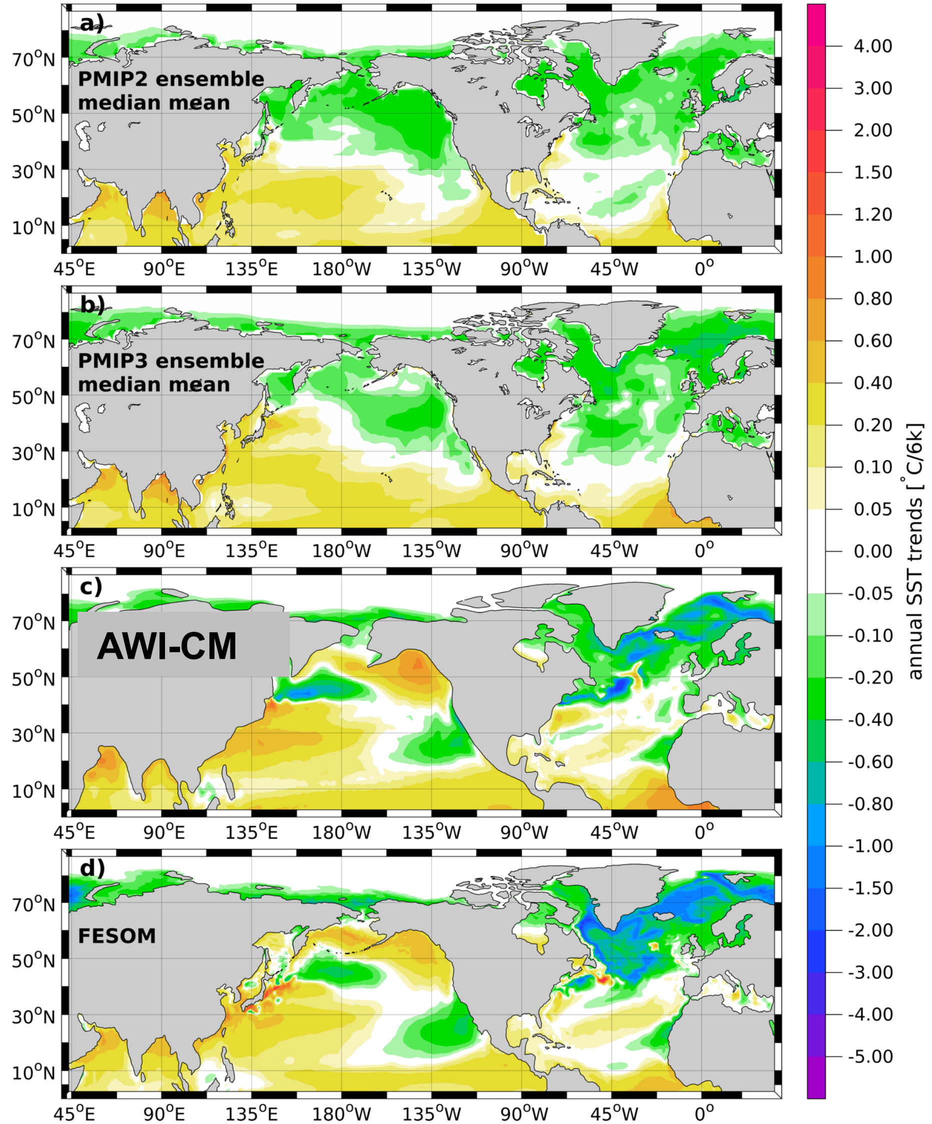
Holocene SST -Trends 6000 years: high resolution

PMIP2, ~3° resol

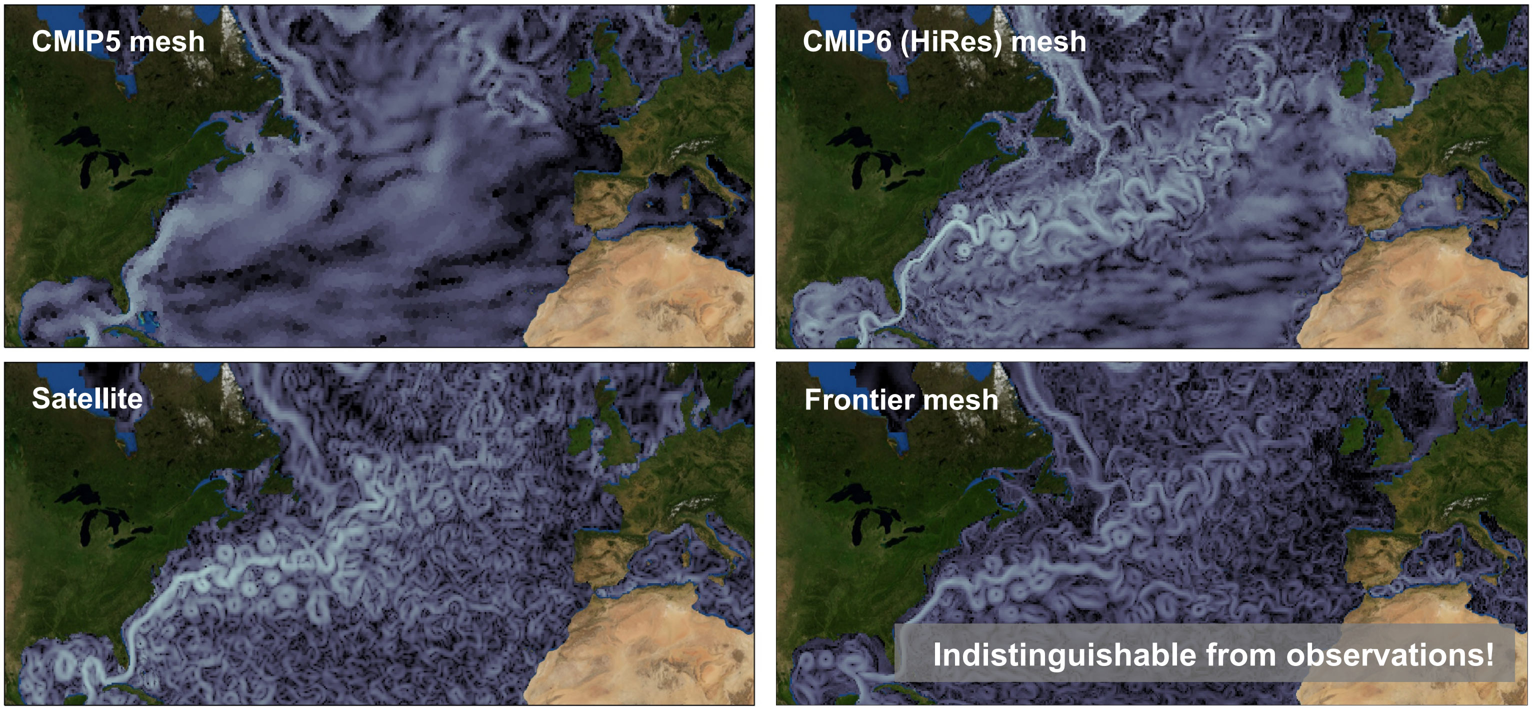
PMIP3, ~2° resol

Climate model ECHAM6-FESOM

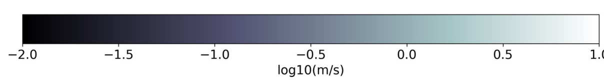
Downscaling Ocean



How realistic is the model?

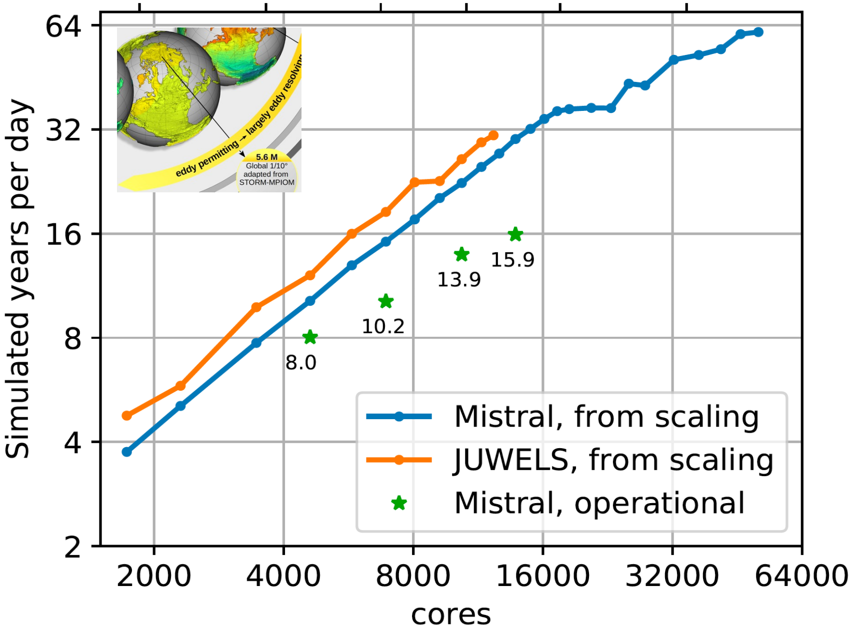


Displayed on a common 1/4° mesh



Ocean velocity

Scalability

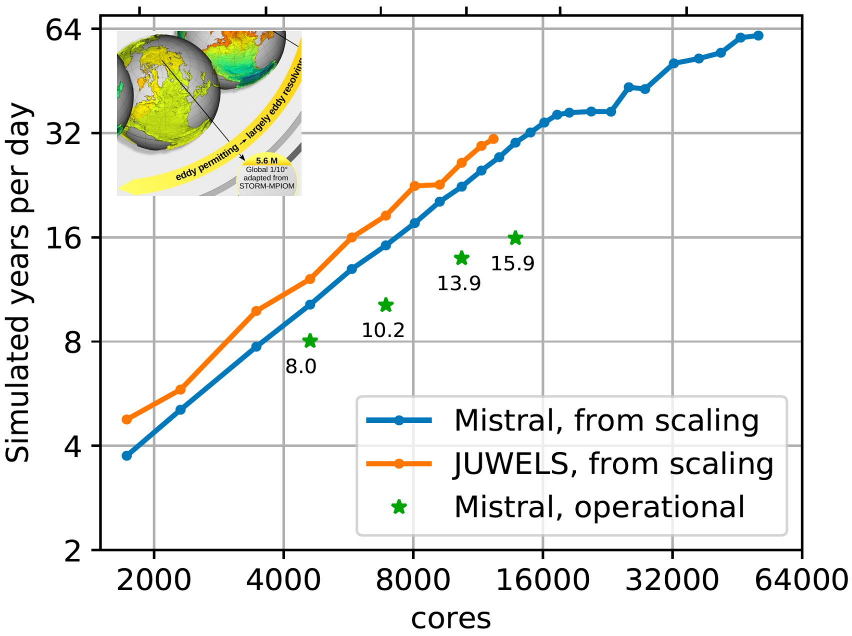


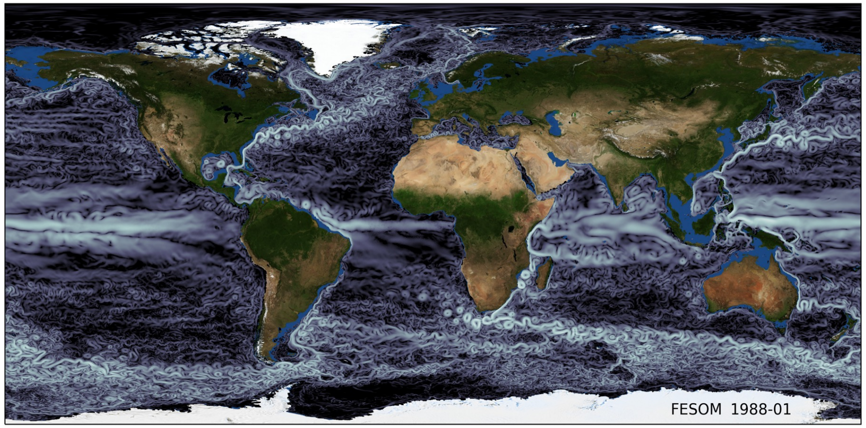
Koldunov et al (2019)

Limited by available HPC capabilities (today)

Limited by our ability to use future HPC systems (tomorrow)

Scalability





Koldunov et al (2019)

Limited by available HPC capabilities (today)

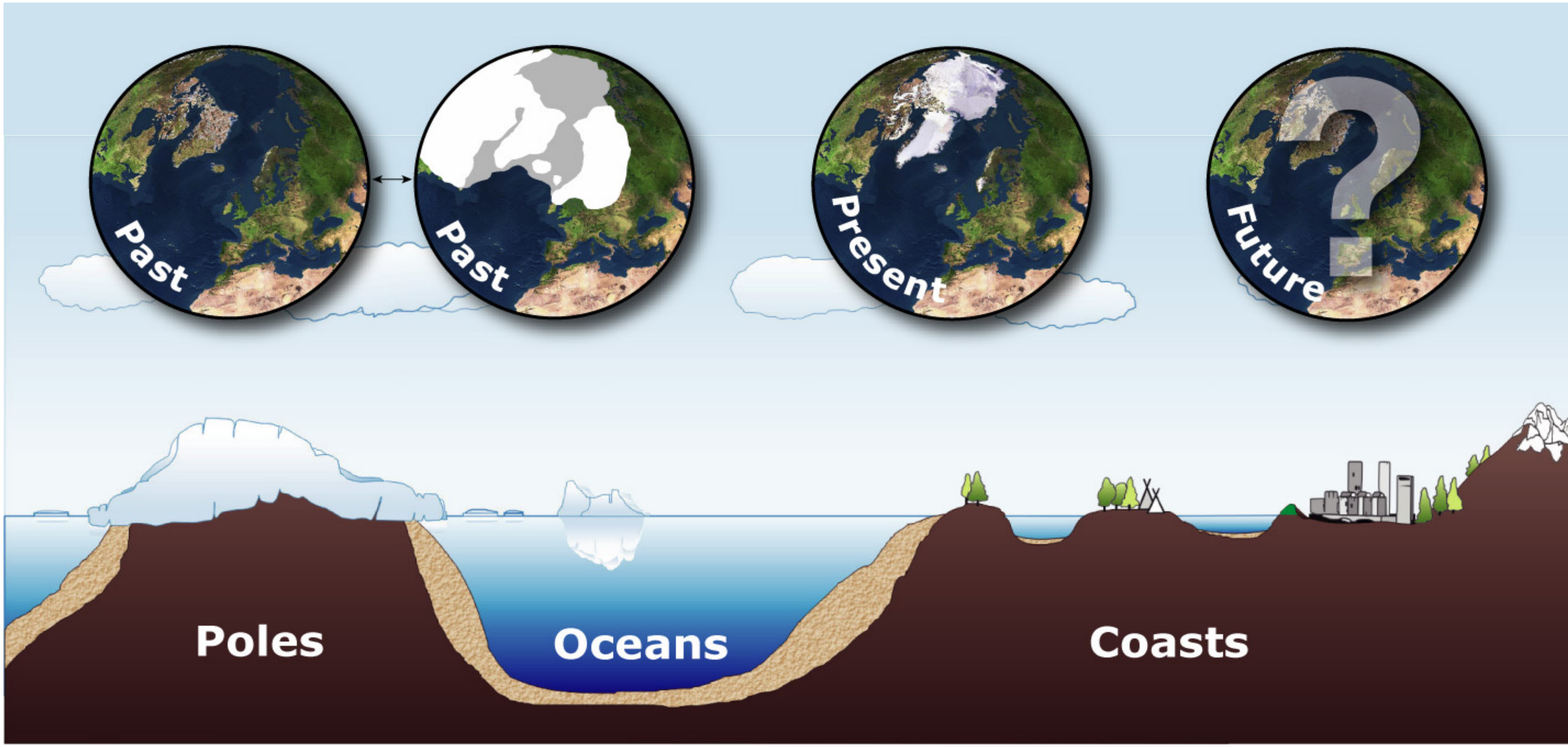
Limited by our ability to use future HPC systems (tomorrow)

Parameterizations

Some critical small-scale processes are *not* represented by the laws of physics, but by physically motivated rules of thumb (parametrizations)

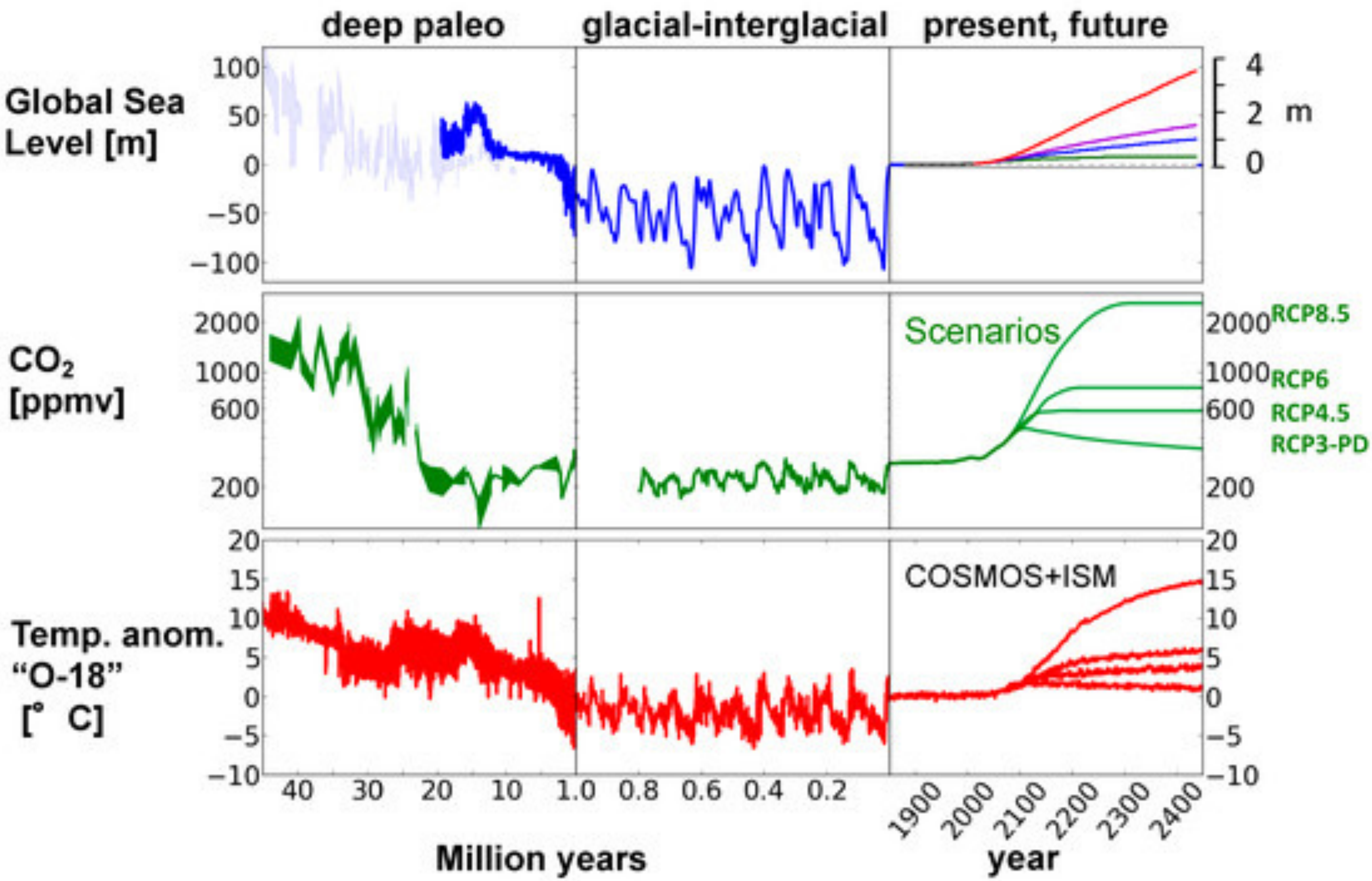
➔ Large uncertainties in regional (global) climate change projections

➔ Limitations in predicting extreme events

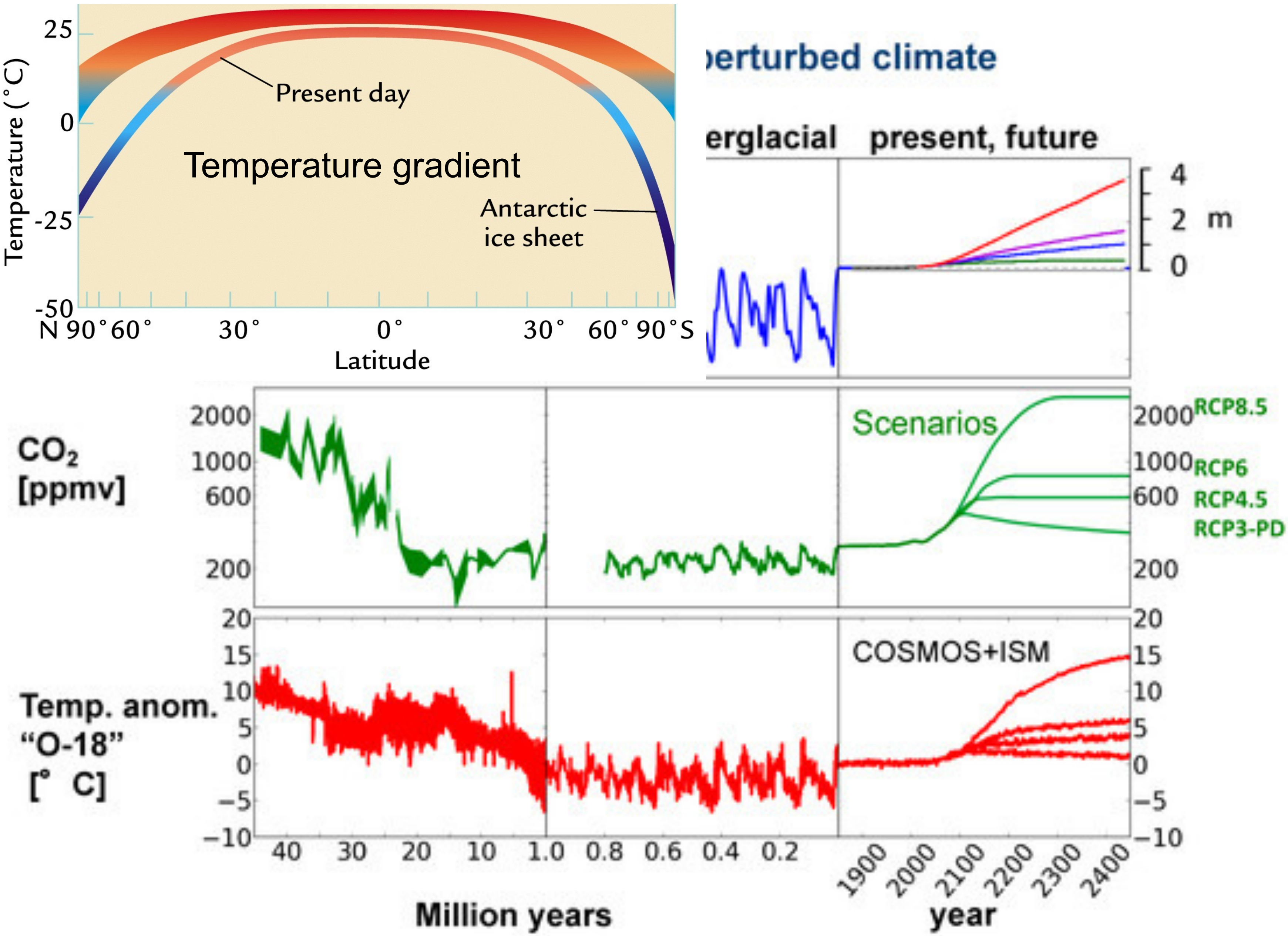


Is the warming and CO_2 rise unprecedented in the geologic record?

Natural variability and perturbed climate



Lohmann et al., 2020b

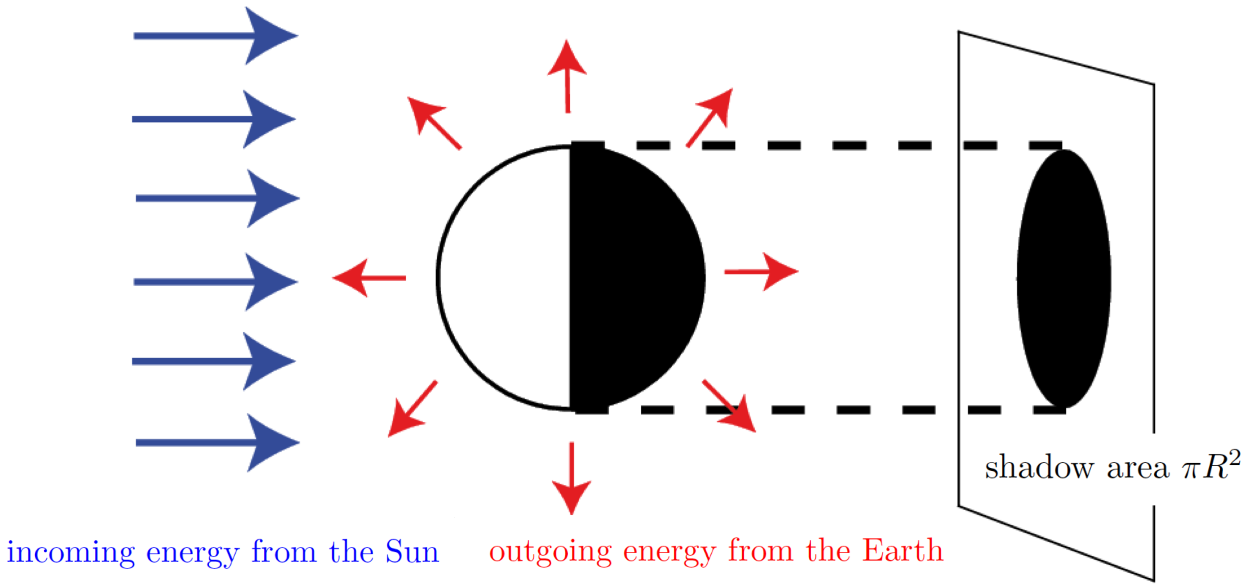


Lohmann et al., 2020b

Energy balance model: Concepts of climate

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

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

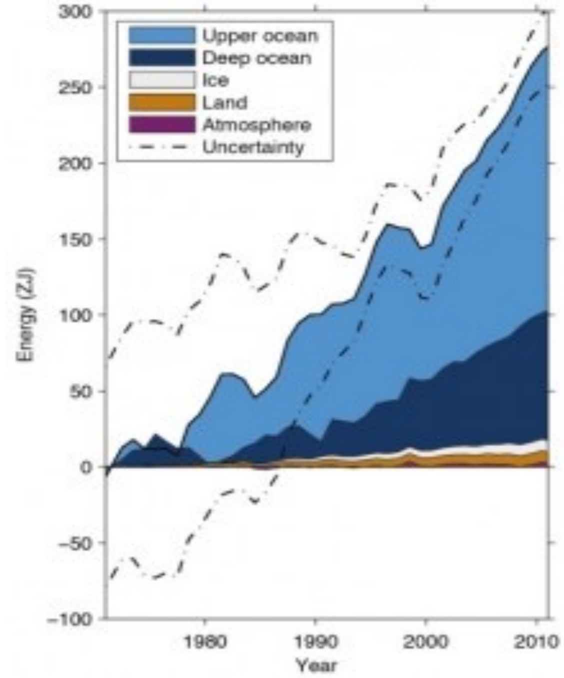


Heat capacity of the climate system

Fast rotation

Lohmann, 2020

Our current warming: mainly in the ocean

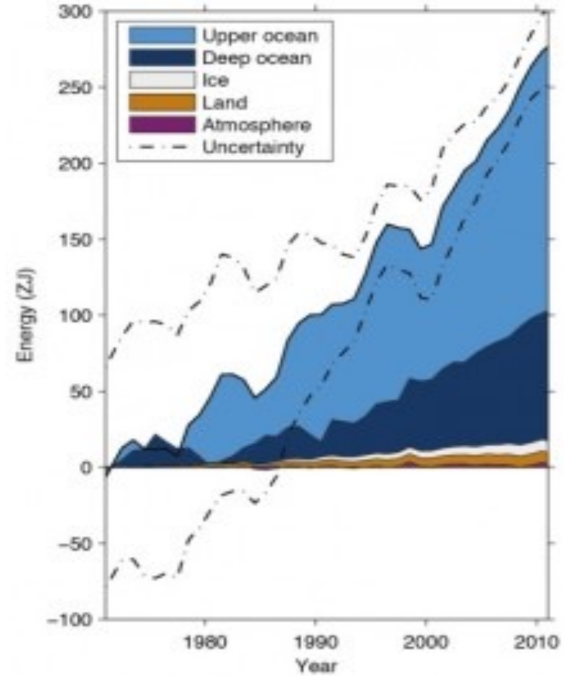


Effective heat capacity/heat uptake

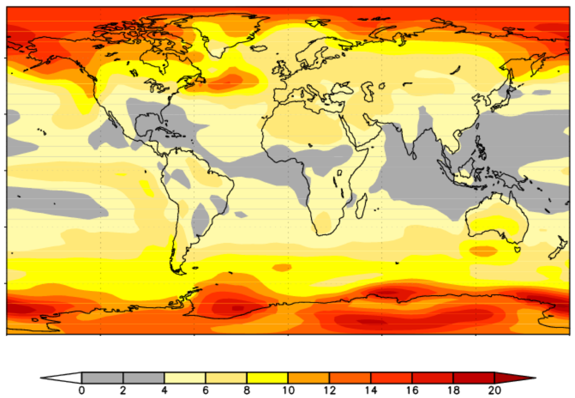
$$C_p^o \partial_t T = \partial_z (k^o \partial_z T)$$

Our current warming is

mainly a warming of the ocean



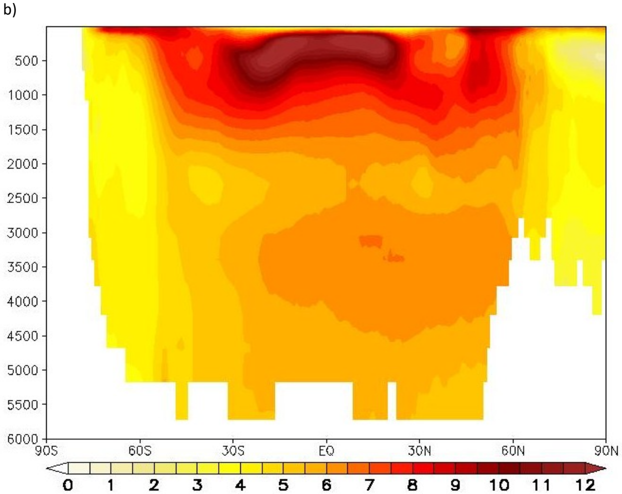
a)



Effective heat capacity/heat uptake

$$C_p^o \partial_t T = \partial_z (k^o \partial_z T)$$

b)



Increased k leads to high latitude warming

& pronounced warming at the thermocline.

Potential solution for the Cenozoic temperature conundrum

Lohmann, 2020

Lohmann, accepted 2021

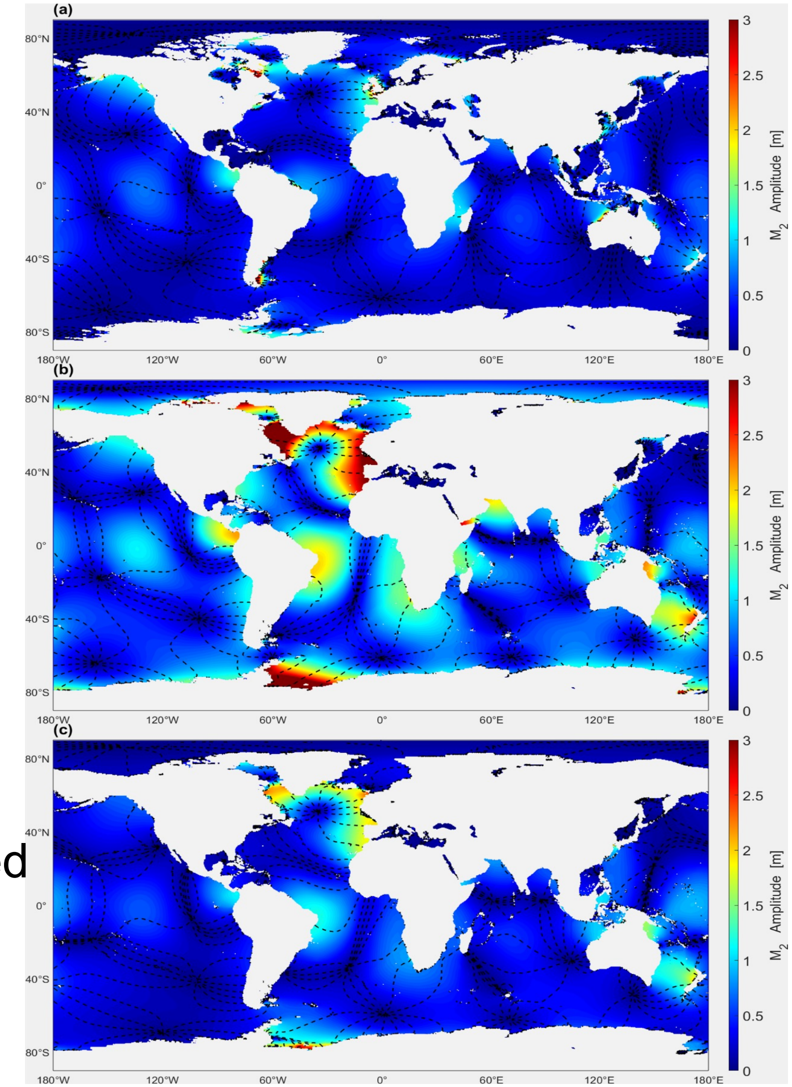
Tidal-induced mixing

M2-mode

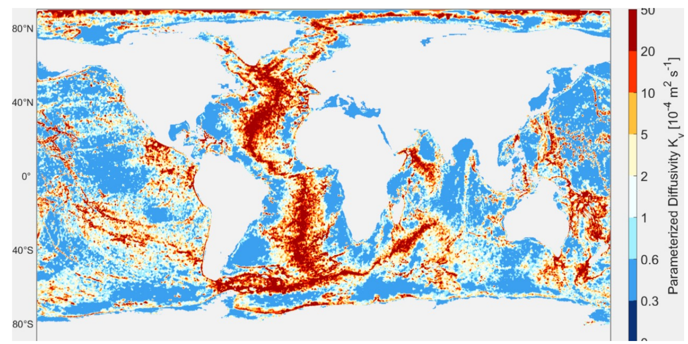
PI

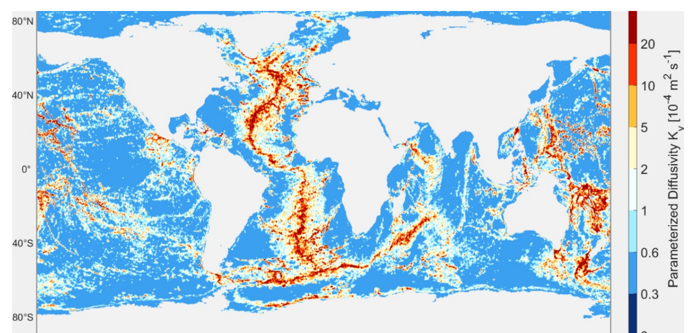
LGM

LGM modified

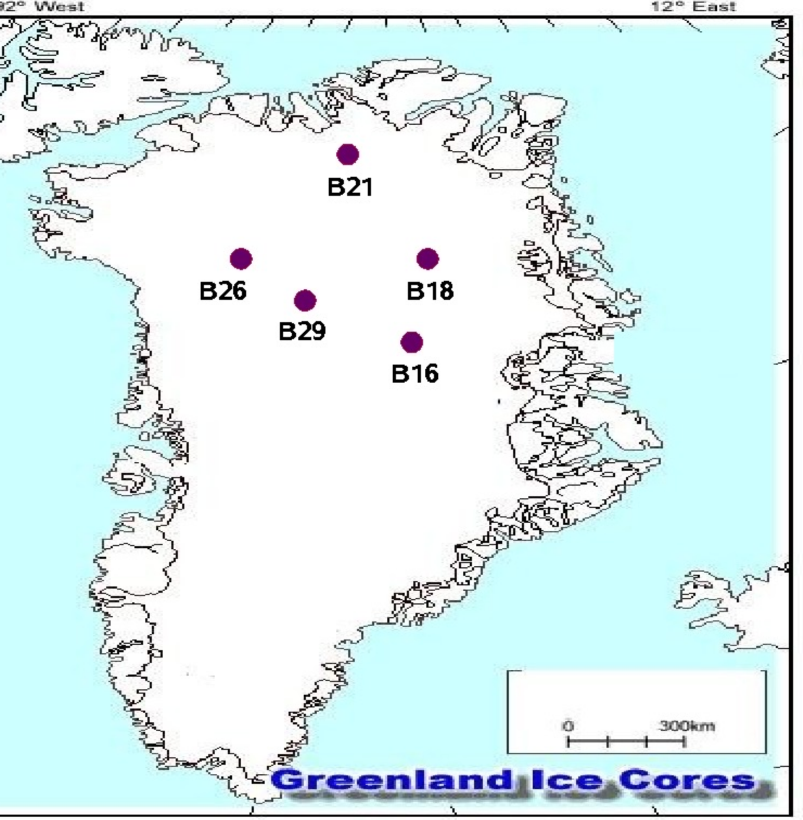


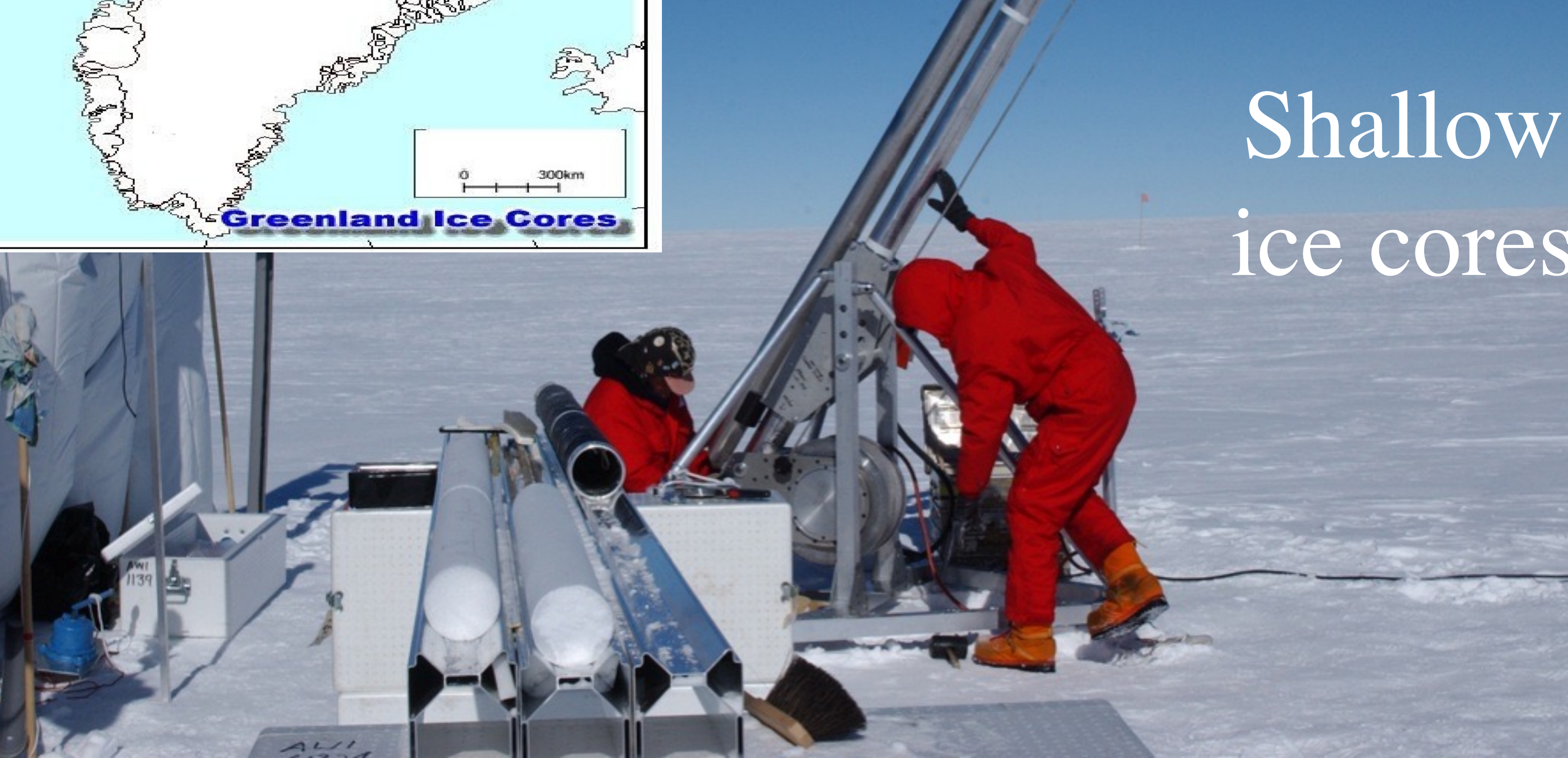
After considering ice shelves, the strength of tide will decrease significantly during the LGM: k_v



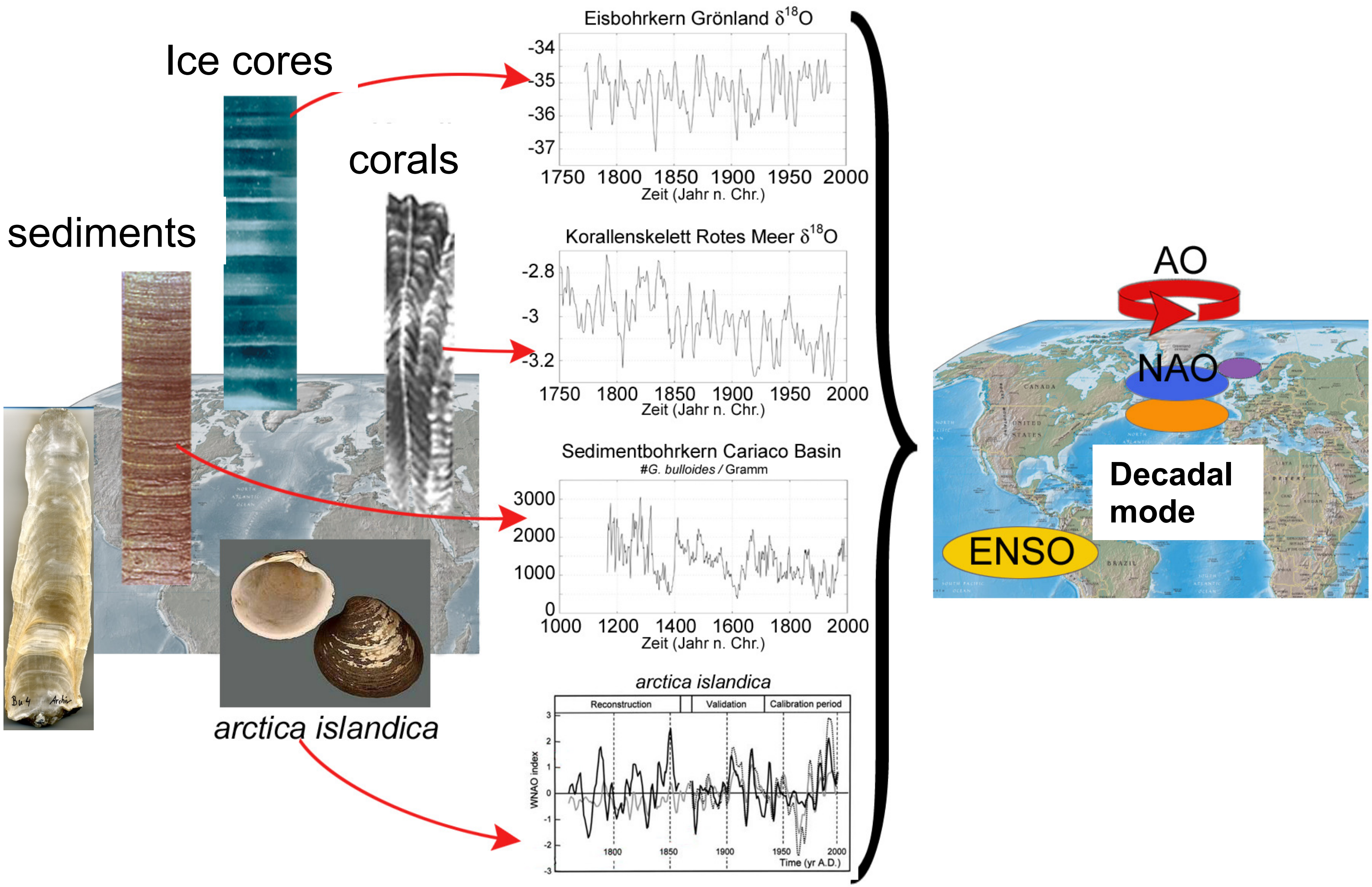


Shallow ice cores





Upscaling concept

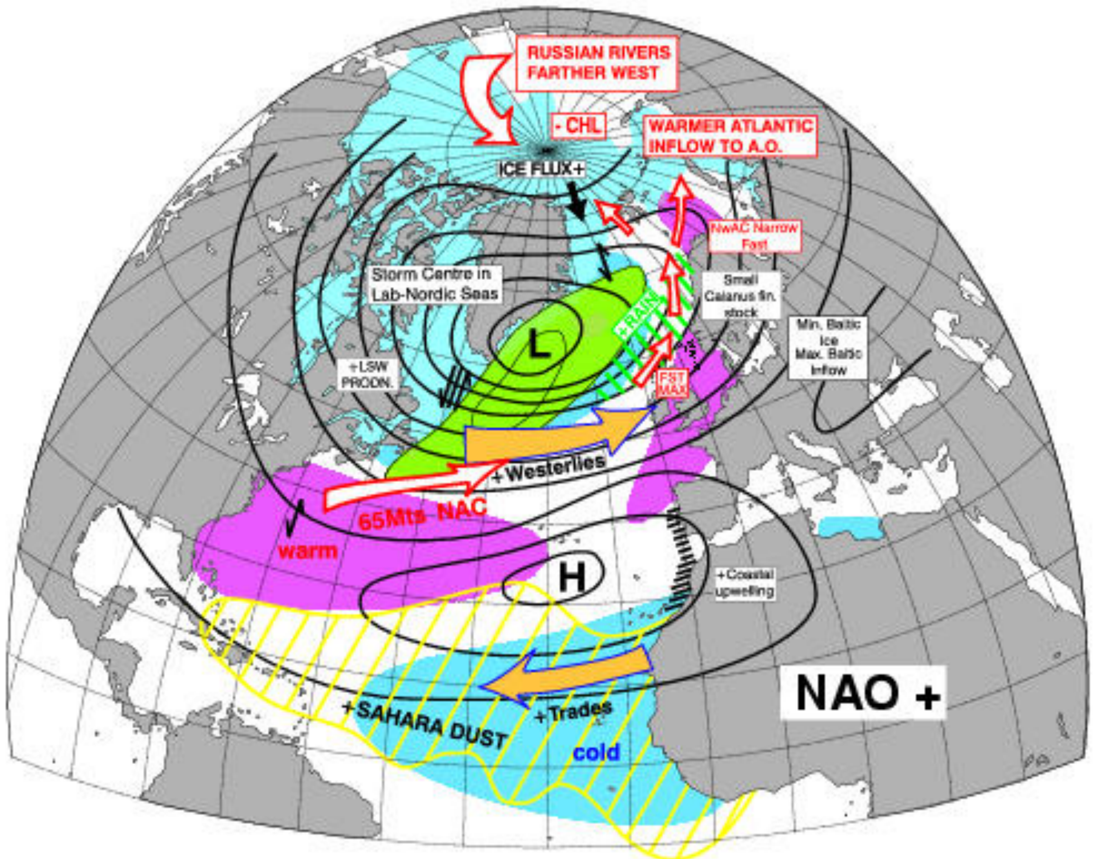


Climate archives

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

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

Correlation (cross, auto)

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

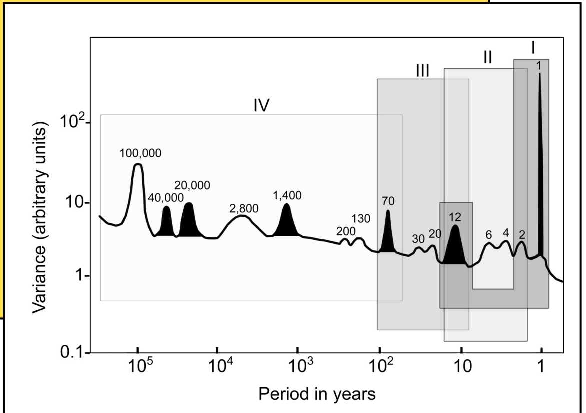
measures the tendency of x (t) and y (t) to covary, between -1 and 1

Spectrum (cross, auto)

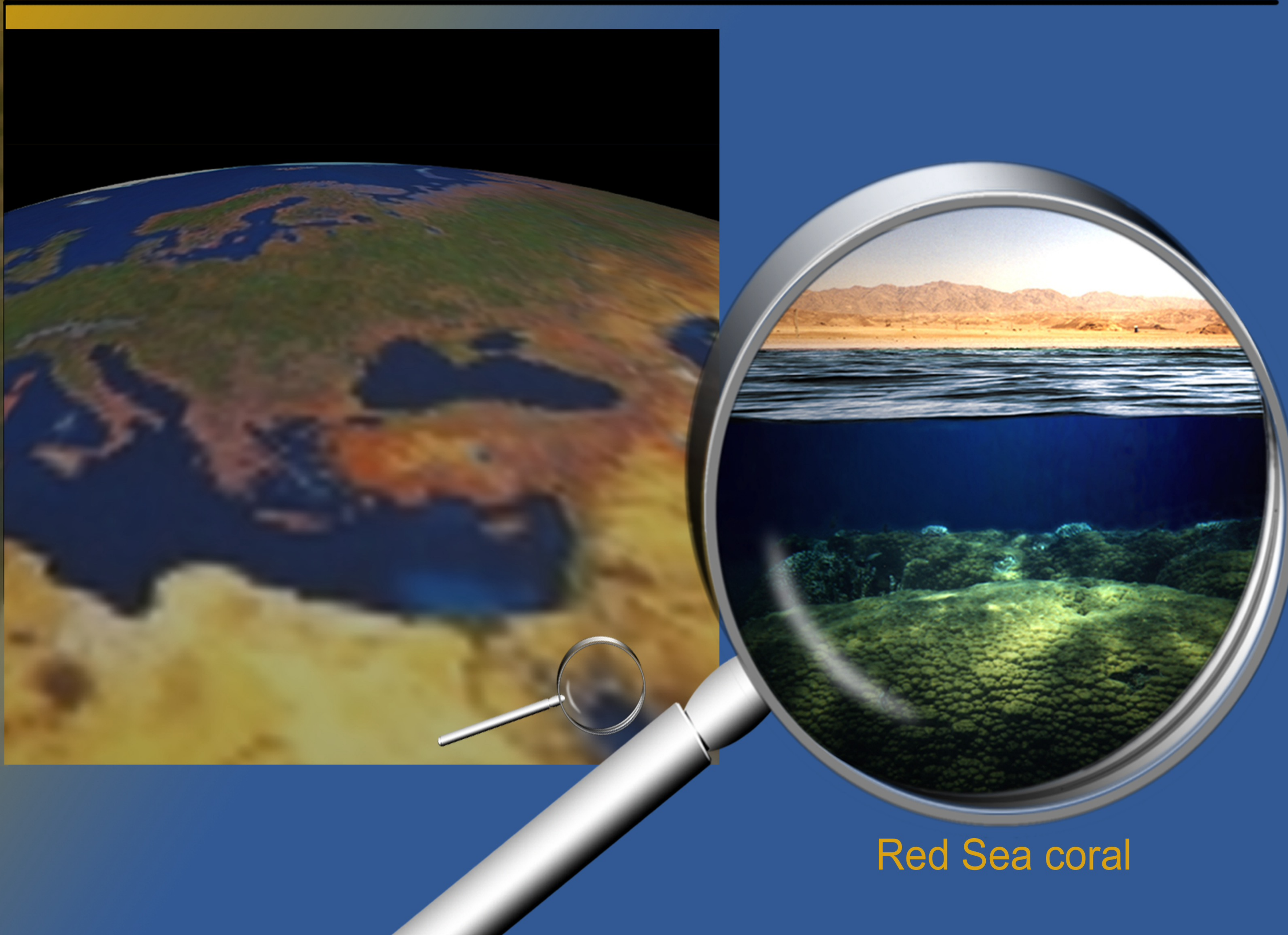
(spectral density)

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

measures variance

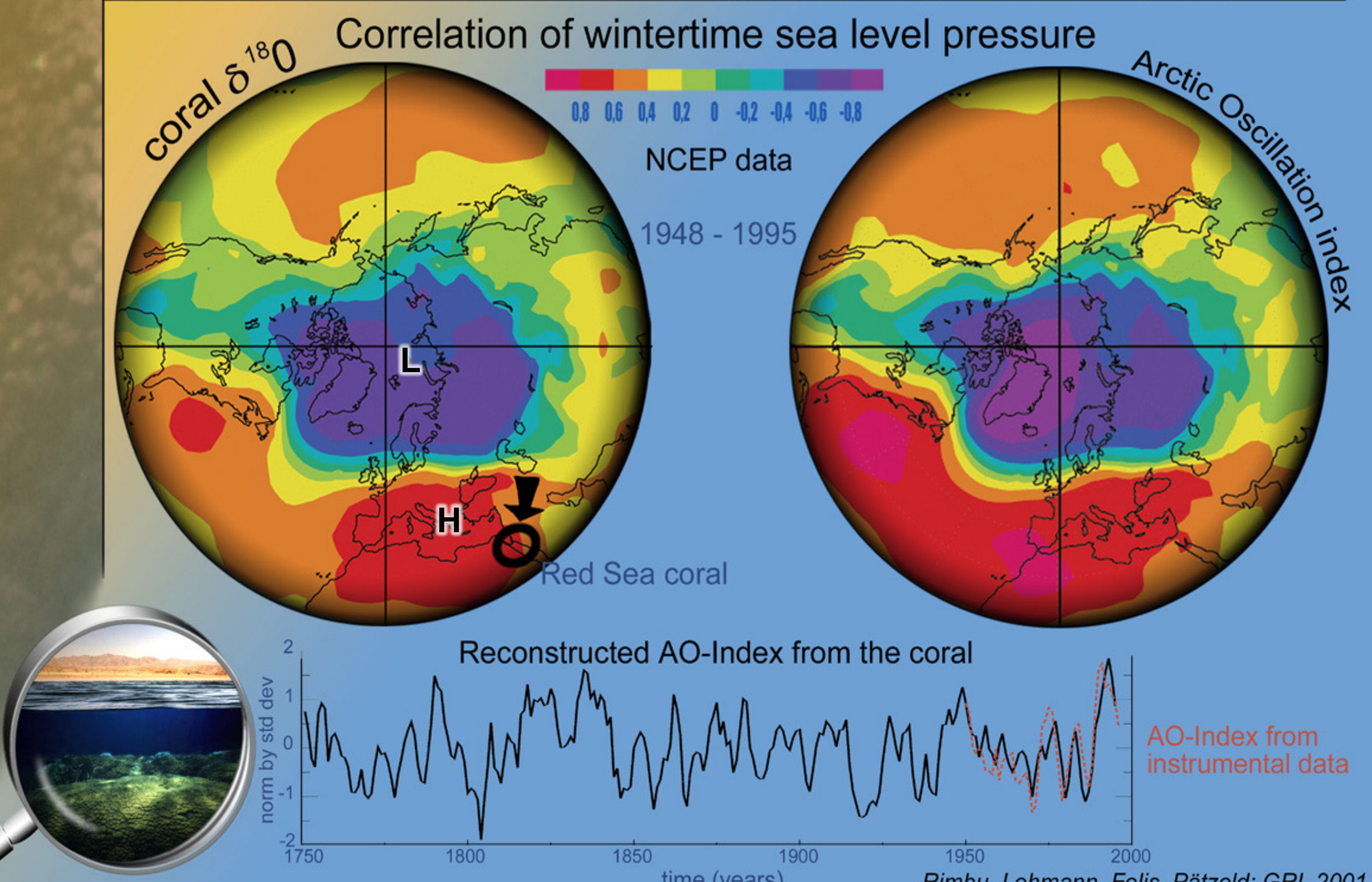


Climate Modes from Proxy Data



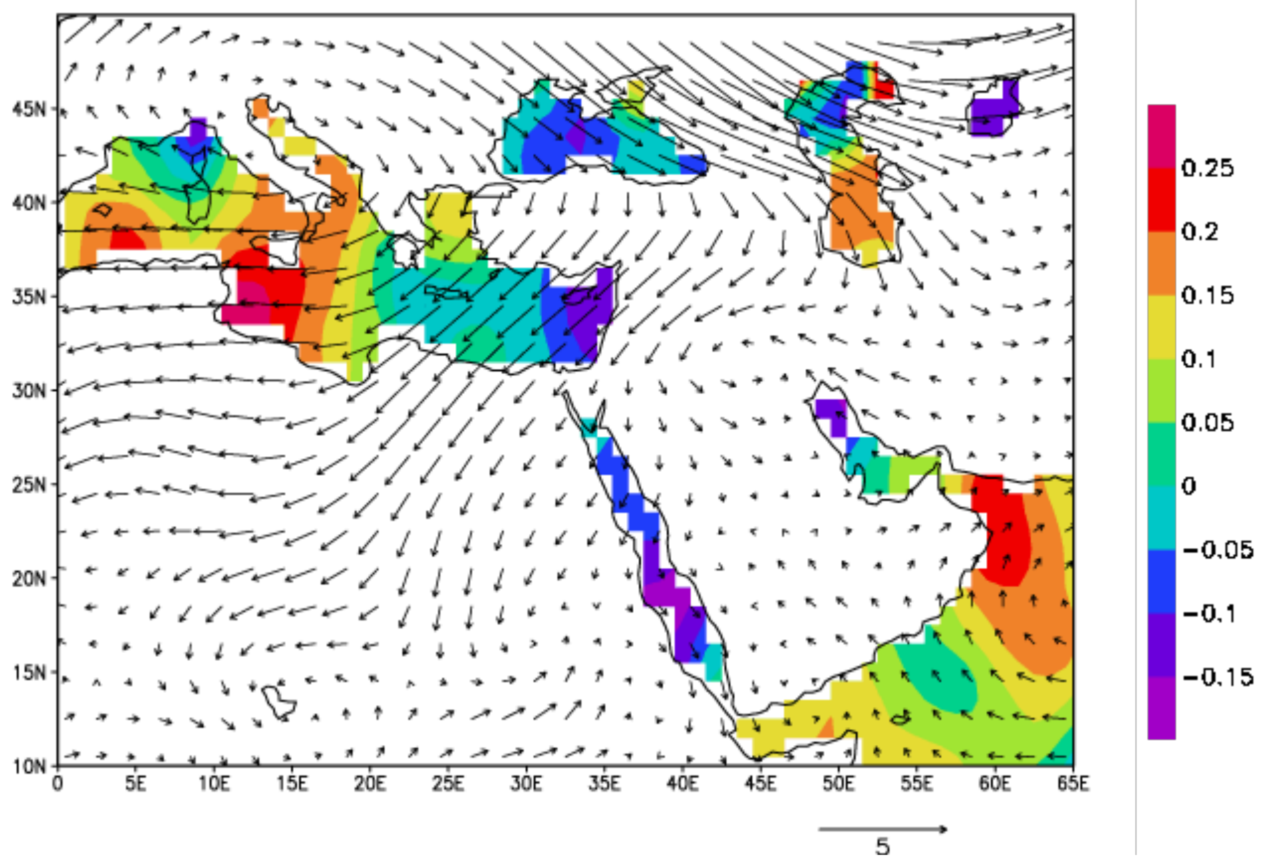
Red Sea coral

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

Exercise teleconnections
using http://climexp.knmi.nl

1) **Monthly climate indices** (temp, precip, ...)
a) Select one pre-defined index
b) Correlation with temperature, precipiation, SLP
c) Explain the teleconnections for different seasons

2) Home town climate
a) Calculate different regions on the world
(home town, Bremerhaven has 53° N, 8° E)
b) Correlation with temperature, precipiation, SLP
c) Explain the teleconnections for different seasons
d) Exlain related modes of climate variability
(ENSO, PDO, NAO, Monsoon)

Help News About Contact World weather Effects of El Niño Seasonal forecasts Climate Change Atlas

Select a monthly time series

Climate indices

Select a time series by clicking on the name		
ENSO	absolute NINO12, NINO3, NINO3.4, NINO4, relative NINO12, NINO3, NINO3.4, NINO4 (1880-now, ERSST v4, relative is relative to 20S-20N, i.e., without global warming, recommended)	i
	NINO12, NINO3, NINO3.4, NINO4 (1870-now, HadISST1)	i
	NINO12, NINO3, NINO3.4, NINO4 (1856-1981 Kaplan, 1982-now NCEP OISSTv2)	i
	SOI (1866-now, Jones)	

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

KNMI Climate Explorer

Climate Explorer European Climate Assessment & Data KNMI search in the Climate Explorer

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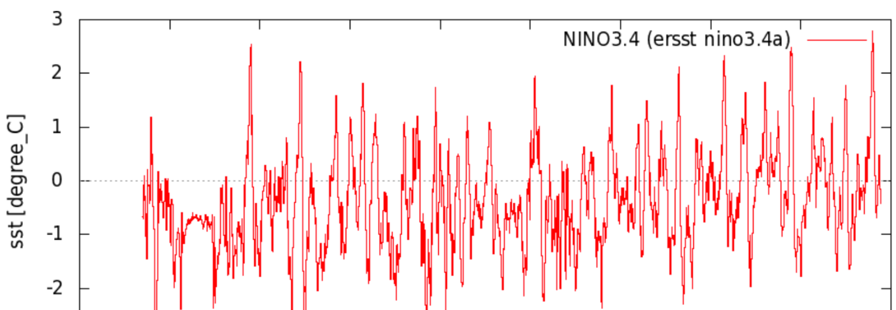
Time series

monthly NINO3.4

cutting out region defined by mask ersstv5 nino3.4 mask.nc, sst [degree C] from NOAA ERSSTAv5 (in situ only), SSTA normalized to 1981-2010, plotdat anomal 1981 2010 ersst nino3.4.dat, cutting out region defined by mask ersstv5 nino3.4 mask.nc, sst [degree C] from NOAA ERSSTv5 (in situ only), (eps, pdf, raw data, netcdf)



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

KNMI Climate Explorer

Climate Explorer European Climate Assessment & Data KNMI search in the Climate Explorer

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Correlate time series with an observation field

NINO3.4

Observations		
Temperature	1850-now anomalies: ◯ HadCRUT4 median,	i
	1880-now anomalies: GISS ◯ 250km, ◯ 1200km	i
	1880-now anomalies: ◯ NCDC v3.2.1	i
	1850-now anomalies: ◯ HadCRUT4 filled-in by Cowtan and Way	i
Land	1850-2010 anomalies: ◯ CRUTEM4	i
	1880-now anomalies: GISS ◯ 250km, ◯ 1200km	i
	1880-now anomalies: ◯ NCDC v3.2.1	i

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

Field

HadCRUT4.5 SST/T2m anom

.... Or select a position

HadCRUT4 near-surface temperature ensemble data - ensemble
X axis: whole world in 72 5.00° steps, first point at 177.50° W, last point at 177.50° E
Y axis: regular grid with 36 5.00° steps, first point at 87.50° S, last point at 87.50° N

Monthly data available from Jan1850 to Jul2017 (2011 months)
Variable temperature_anomaly (near_surface_temperature_anomaly) in K
The associated land/sea mask is available for some operations

Get grid points, average area or generate subset

Mask:	no mask add a mask to the list
Latitude:	53 °N - 54 °N
Longitude:	8 °E - 9 °E
Boundaries:	halfway grid points
Make:	average max min set of grid points subset of the field

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
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- Monthly seasonal hindcasts
- Monthly decadal hindcasts
- Monthly CMIP3+ scenario runs
- Monthly CMIP5 scenario runs
- Annual CMIP5 extremes
- Monthly CORDEX scenario runs
- Attribution runs

KNMI Climate Explorer

Climate Explorer | European Climate Assessment & Data | KNMI

search in the Climate Explorer

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Field correlations

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

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

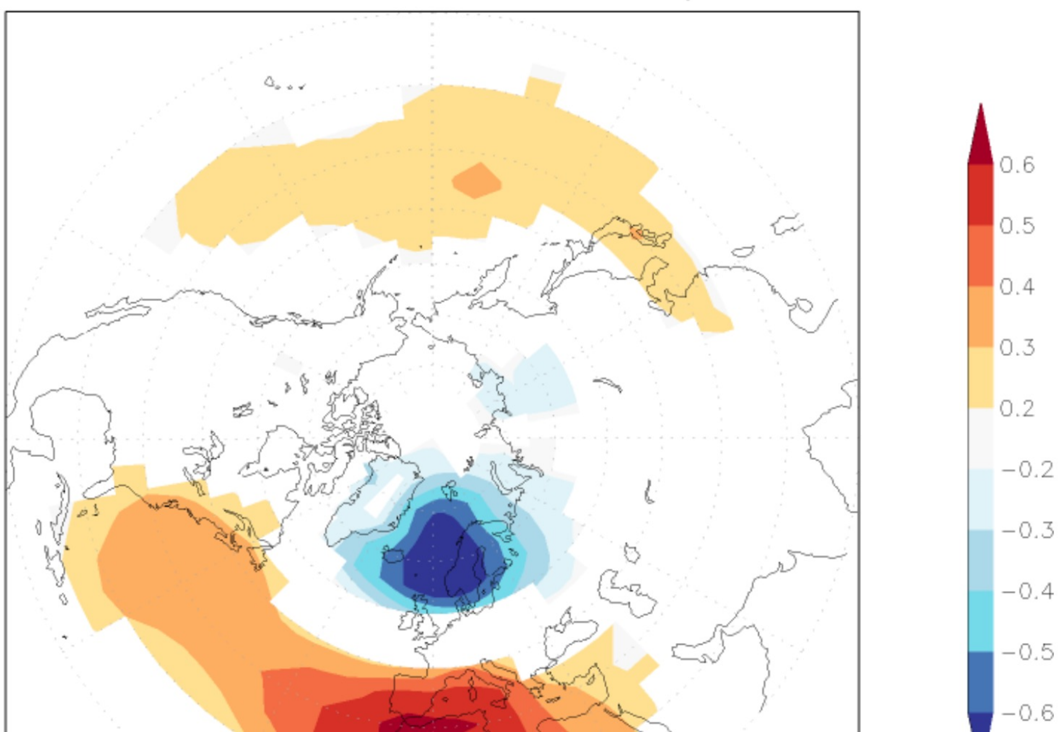
If it takes too long you can abort the job here (using the [back] button of the browser does not kill the correlation job)

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)

corr Jan HadCRUT4.5 SST/T2m anom 8–9E 53–54N mean with Jan Trenberth SLP 1899:2017 p<10%



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
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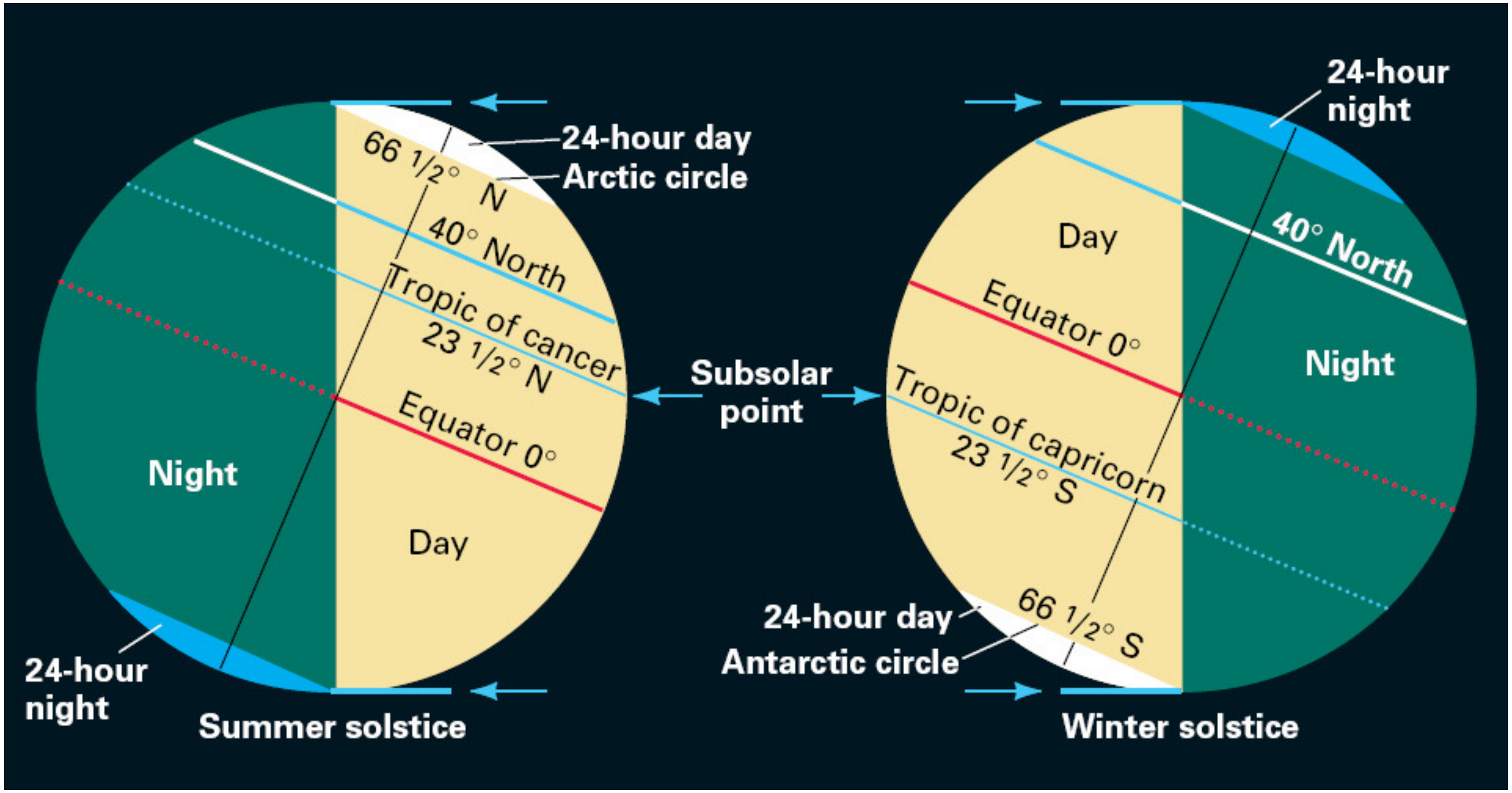
- Monthly decadal hindcasts
- Monthly CMIP3+ scenario runs
- Monthly CMIP5 scenario runs
- Annual CMIP5 extremes
- Monthly CORDEX scenario runs
- Attribution runs
- External data (ensembles, ncep, enact, soda, ecmwf, ...)
- View, upload your field

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

Solstice

Solstice ("sun stands still")
On June 22, the subsolar point is 23½° N (Tropic of Cancer)
On Dec. 22, the subsolar point is 23½° S (Tropic of Capricorn)



Strahler, 2002

Effect of **obliquity** on the **position Tropic of Cancer**

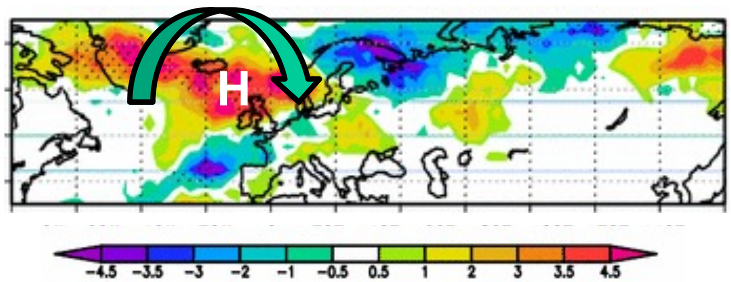
Highway in Mexico

How many meters per year?

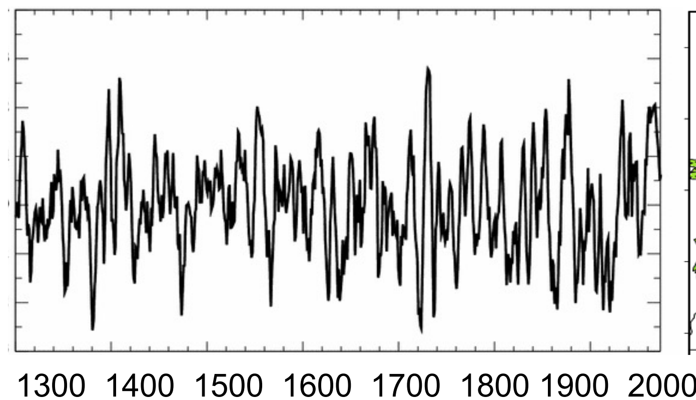
Earth's obliquity oscillates between 22.1° and 24.5° on a 41,000-year cycle.
The Earth radius a=6371

High-resolution modelling of the jet stream and associated extreme events in Europe

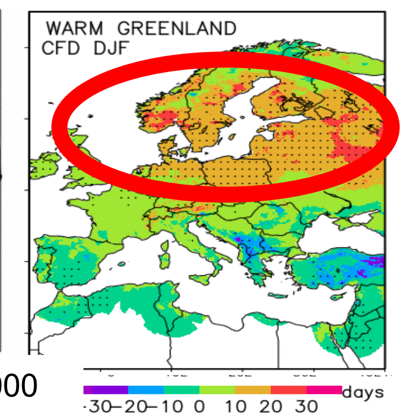
Assessment of resolution impact on the jet stream in the Euro-Atlantic region



Blocking frequency
Greenland Ice cores



Decadal-centennial variability



Continous Frost days

Rimbu and Lohmann, 2011

Climate variability across time scales: challenges from limited instrumental, paleoclimate data and modeling

Past climates help us to understand the climate system as a whole

To elaborate processes (first and second order)

Test hypotheses by scenarios and comparing model results to data

Holocene: High latitude cooling, low-latitude warming
Models and data disagree in amplitude, variability underestimated (fdt)

Dynamics: Heterogeneities in temperature,
large gradients can persist on long time scales

Interpretation of proxy data: Seasonal to syonptic signatures
Bring the current climate into a long-term context, extremes