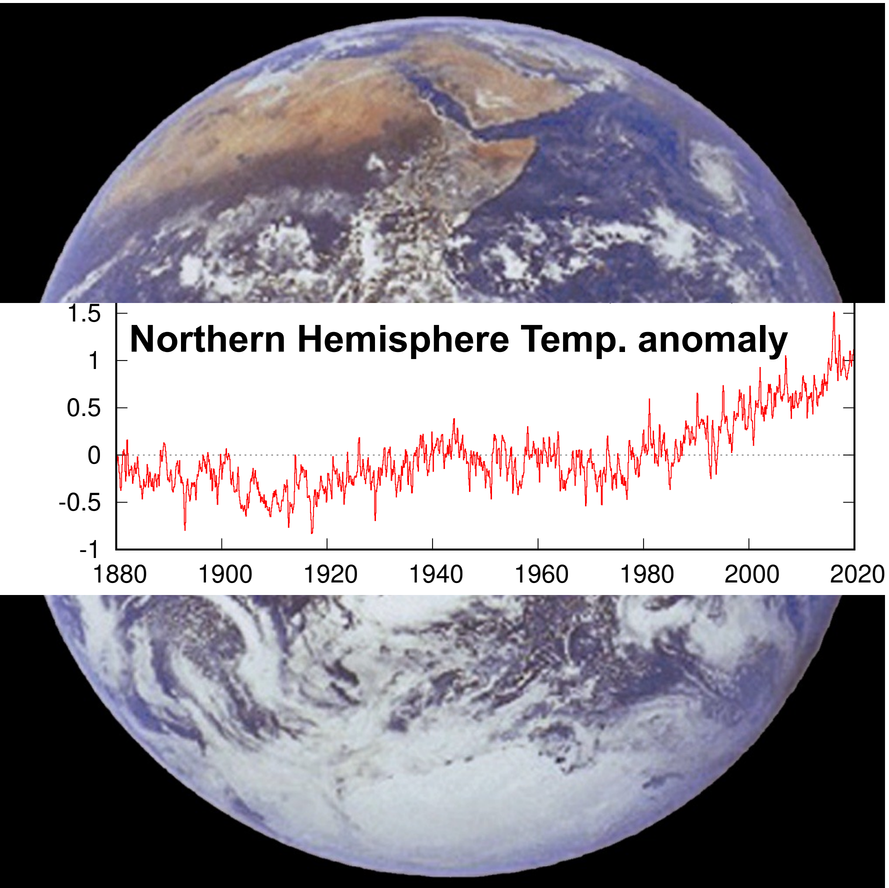
Nobel Price Physics 2021: Hasselmann and Manabe



Gerrit Lohmann

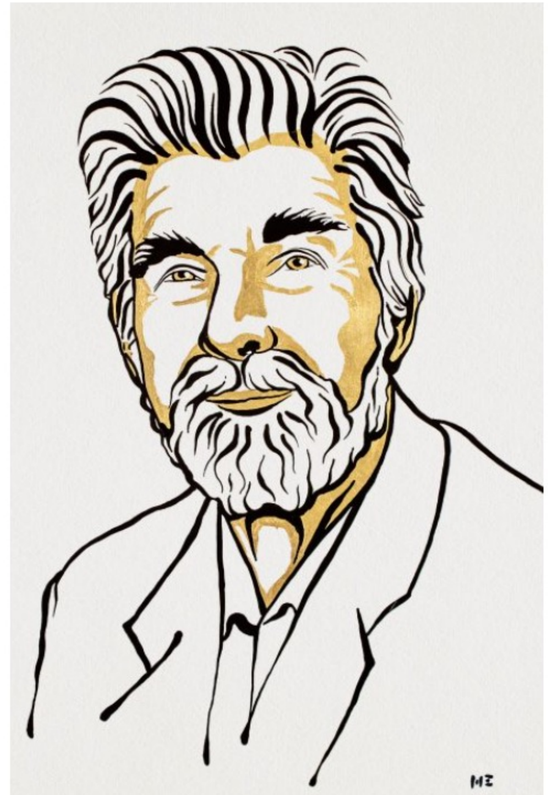
Uni Bremen & AWI

jDPG, Oldenburg
09.12.2021

"for groundbreaking contributions to our understanding of complex systems"

Ill. Niklas Elmehed © Nobel Prize Outreach

Syukuro Manabe

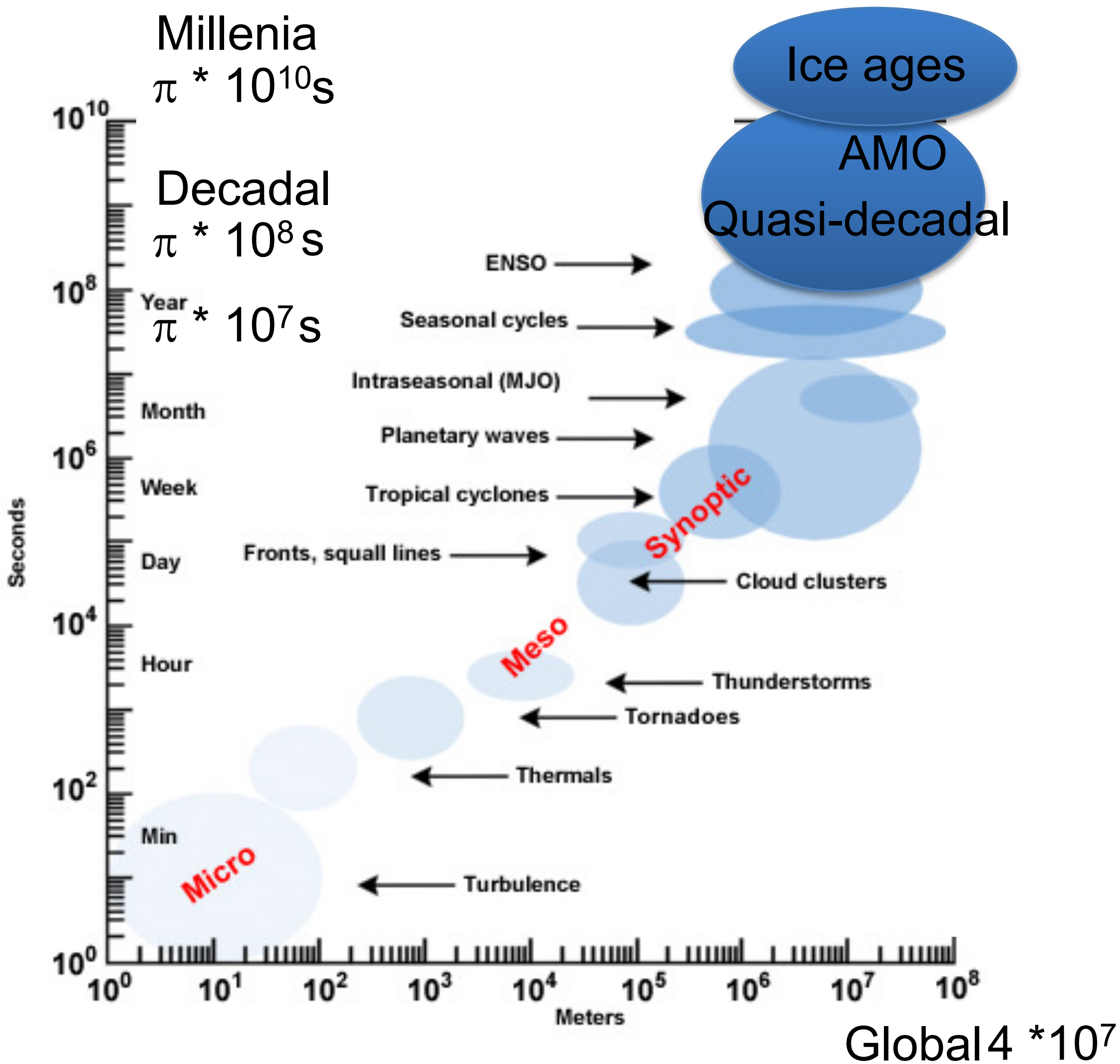


Ill. Niklas Elmehed © Nobel Prize Outreach

Klaus Hasselmann

"for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming"

Spatio-Temporal Scales



Spatial || temporal Scales

Climate Calculations with a Combined Ocean-Atmosphere Model

SYUKURO MANABE AND KIRK BRYAN

Geophysical Fluid Dynamics Laboratory, ESSA, Princeton University, Princeton, N. J.

13 March 1969 and 6 May 1969

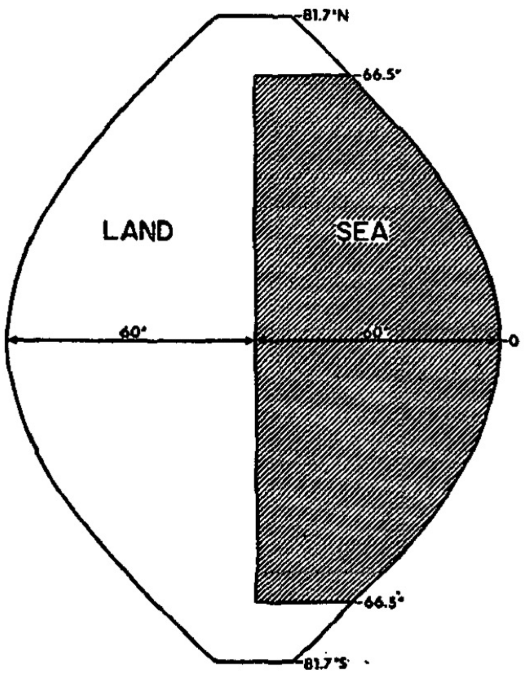


FIG. 1. Ocean-continent configuration of the model.

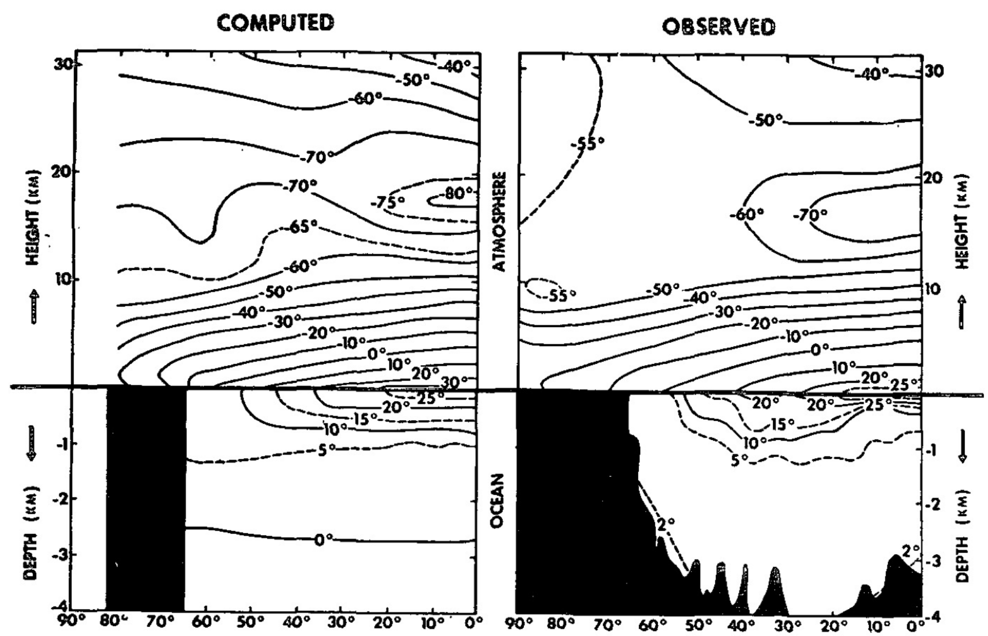
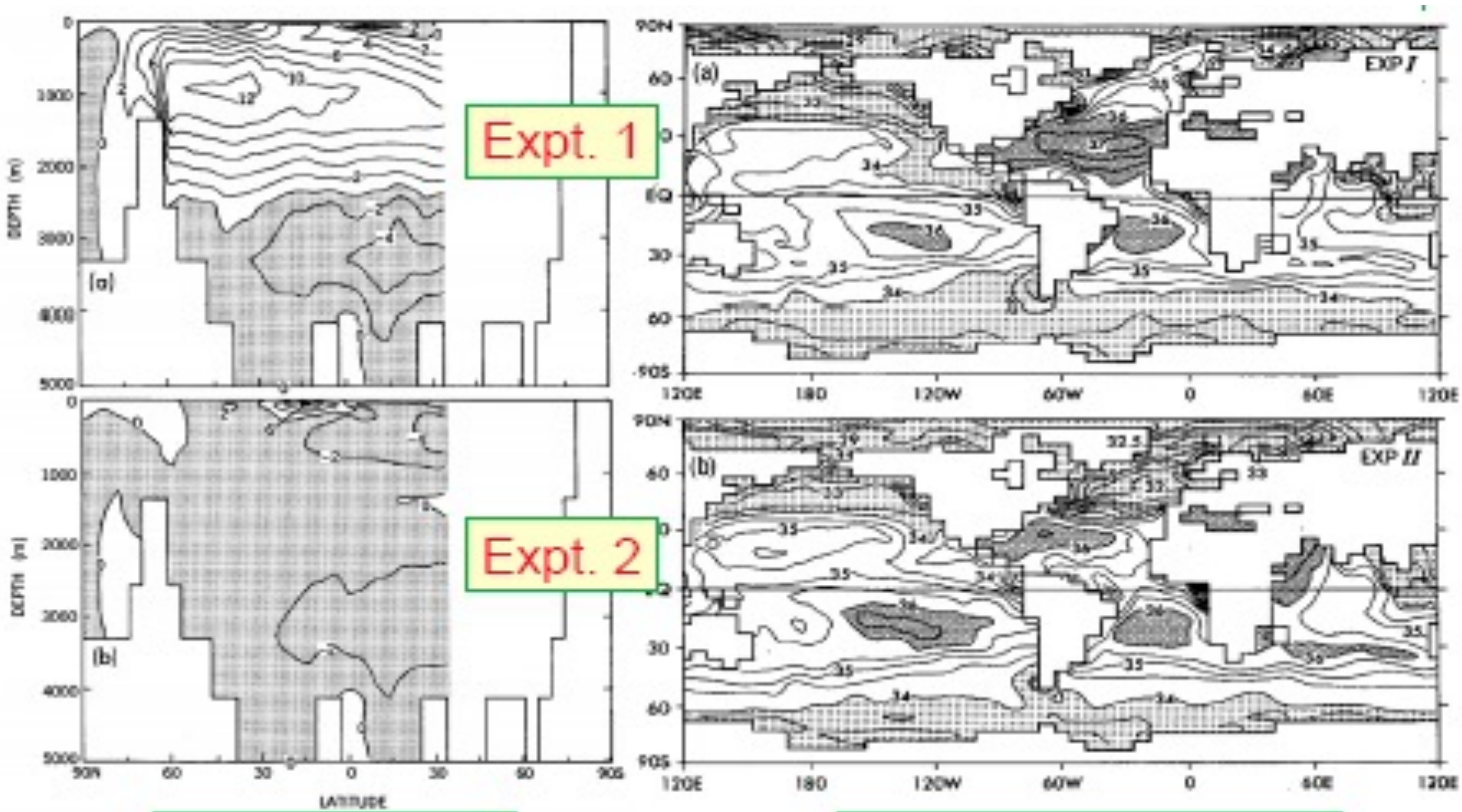


FIG. 2. Zonal mean temperature of the joint ocean-atmosphere system, left-hand side. This distribution, which is the average of two hemispheres, represents the time mean over two-sevenths of the period of the final stage of the time integration. The right-hand side shows the observed distribution in the Northern Hemisphere. The atmospheric part represents the zonally averaged, annual mean temperature. The oceanic part is based on a cross section for the western North Atlantic from Sverdrup *et al.* (1942).

Coupled model. Manabe & Stouffer (1988)

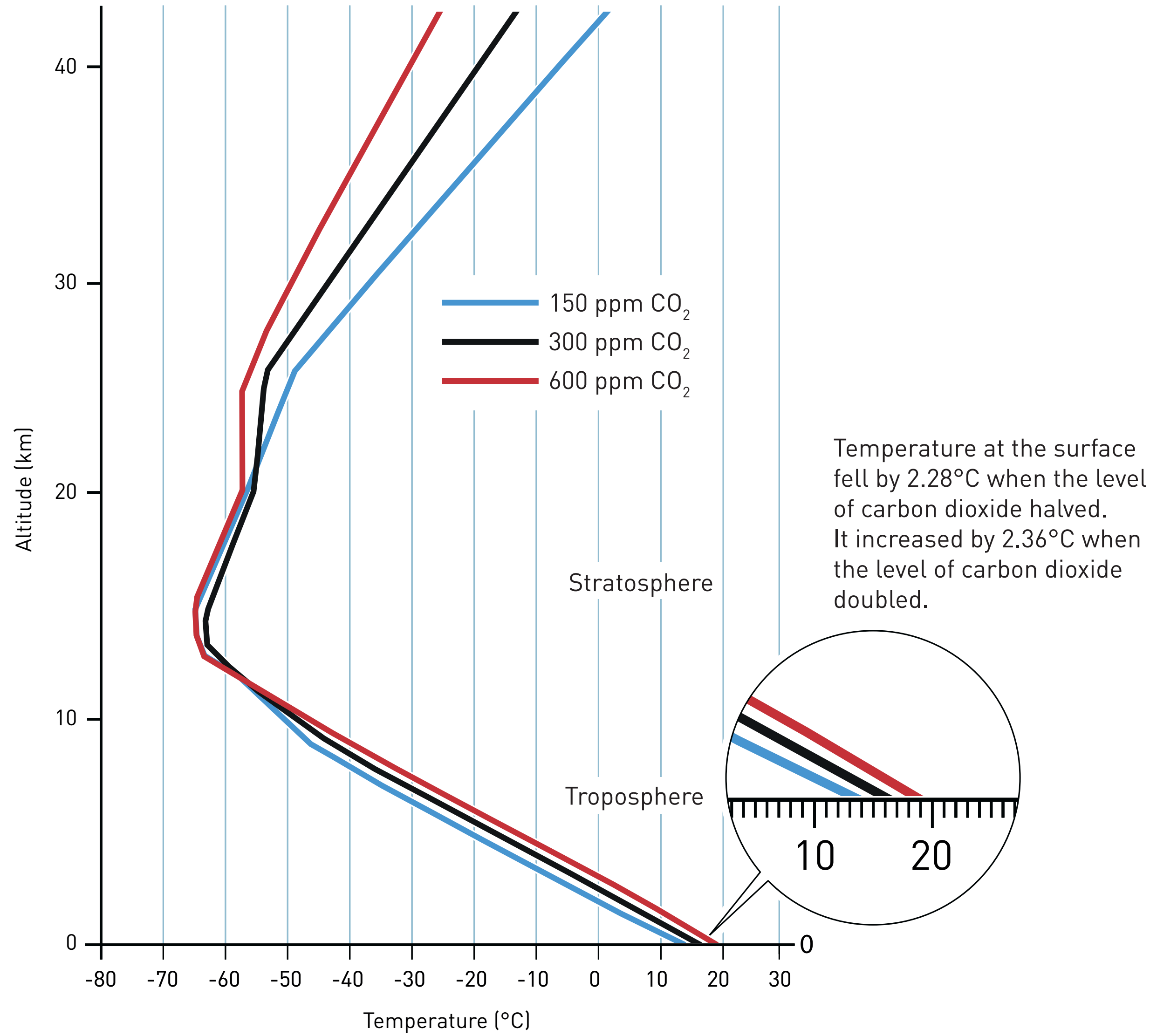
Overtunrning **Sea surface salinity**



Mehrfachgleichgewichte im Ozean

Carbon dioxide heats the atmosphere

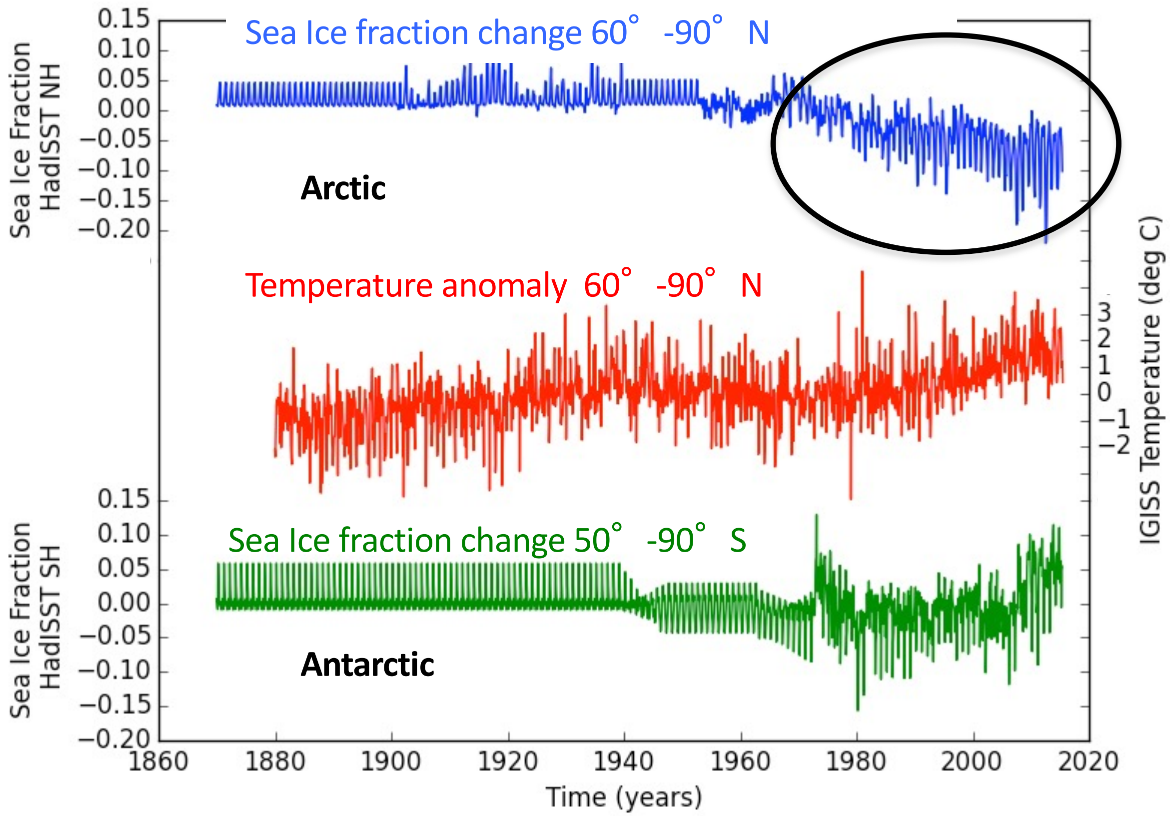
Increased levels of carbon dioxide lead to higher temperatures in the lower atmosphere, while the upper atmosphere gets colder. Manabe thus confirmed that the variation in temperature is due to increased levels of carbon dioxide; if it was caused by increased solar radiation, the entire atmosphere should have warmed up.



Source: Manabe and Wetherald (1967) Thermal equilibrium of the atmosphere with a given distribution of relative humidity, *Journal of the atmospheric sciences*, Vol. 24, Nr 3, May.

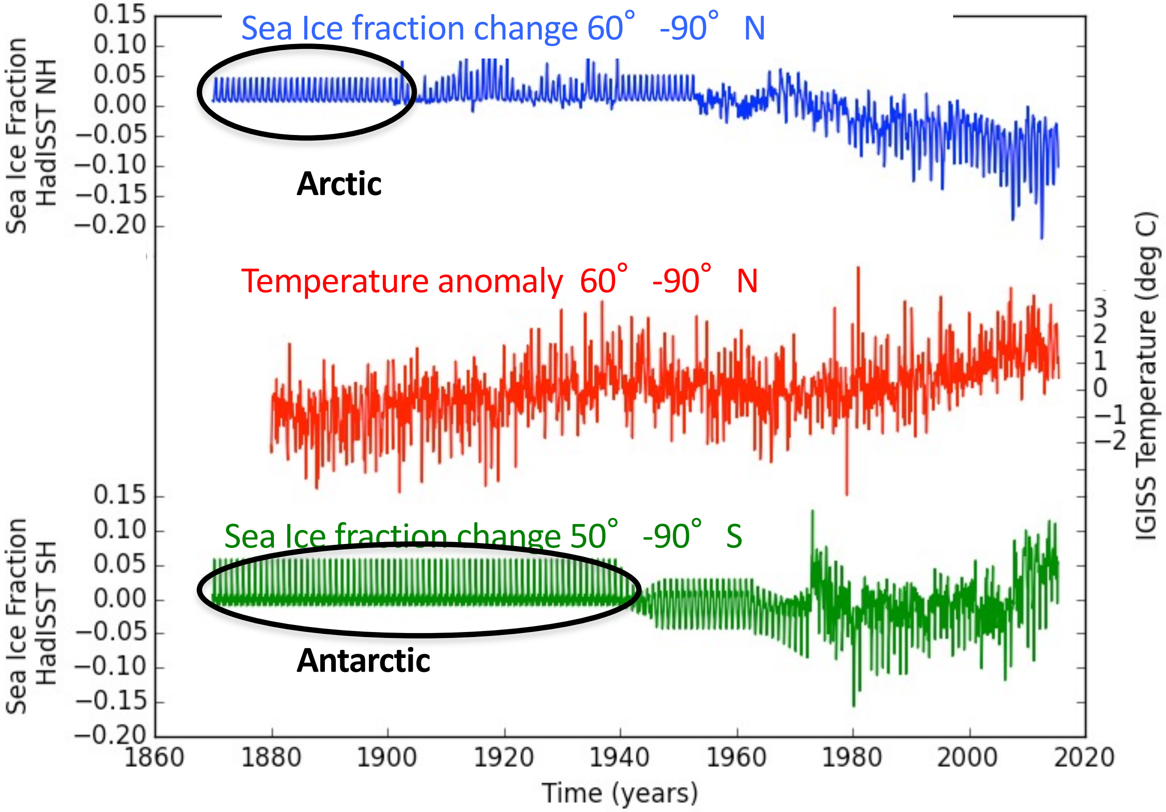
Manabe and Wetherald, 1967

Arctic Sea Ice retreat



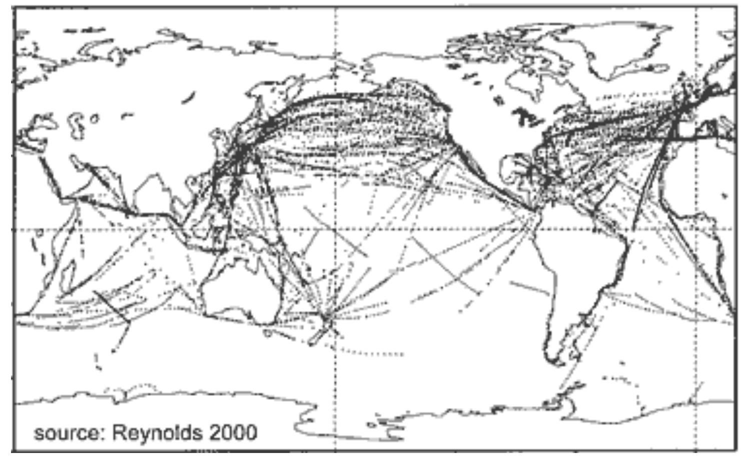
Arctic Sea Ice retreat

Missing Information about Sea Ice



The “Climate dilemma“

- Instrumental data are **sparce**



The “Climate dilemma“

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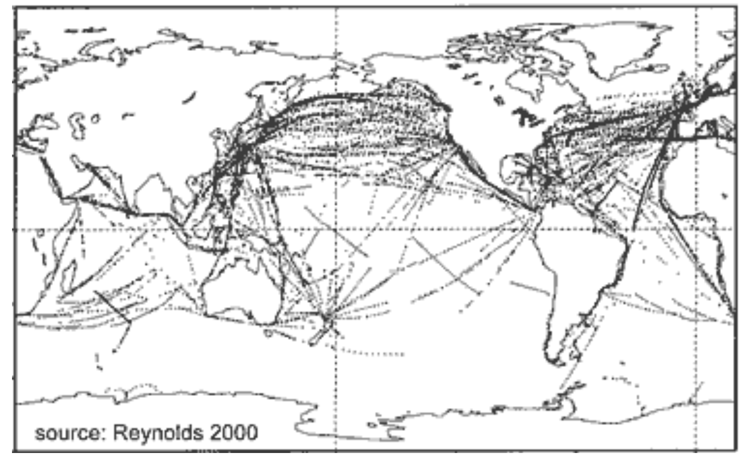
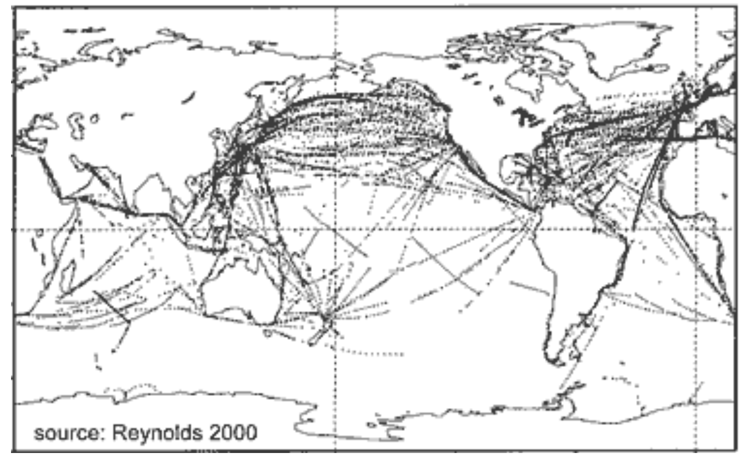


- The records of direct temperature measurements are **short** and already fall in the phase of strong **human influence**.

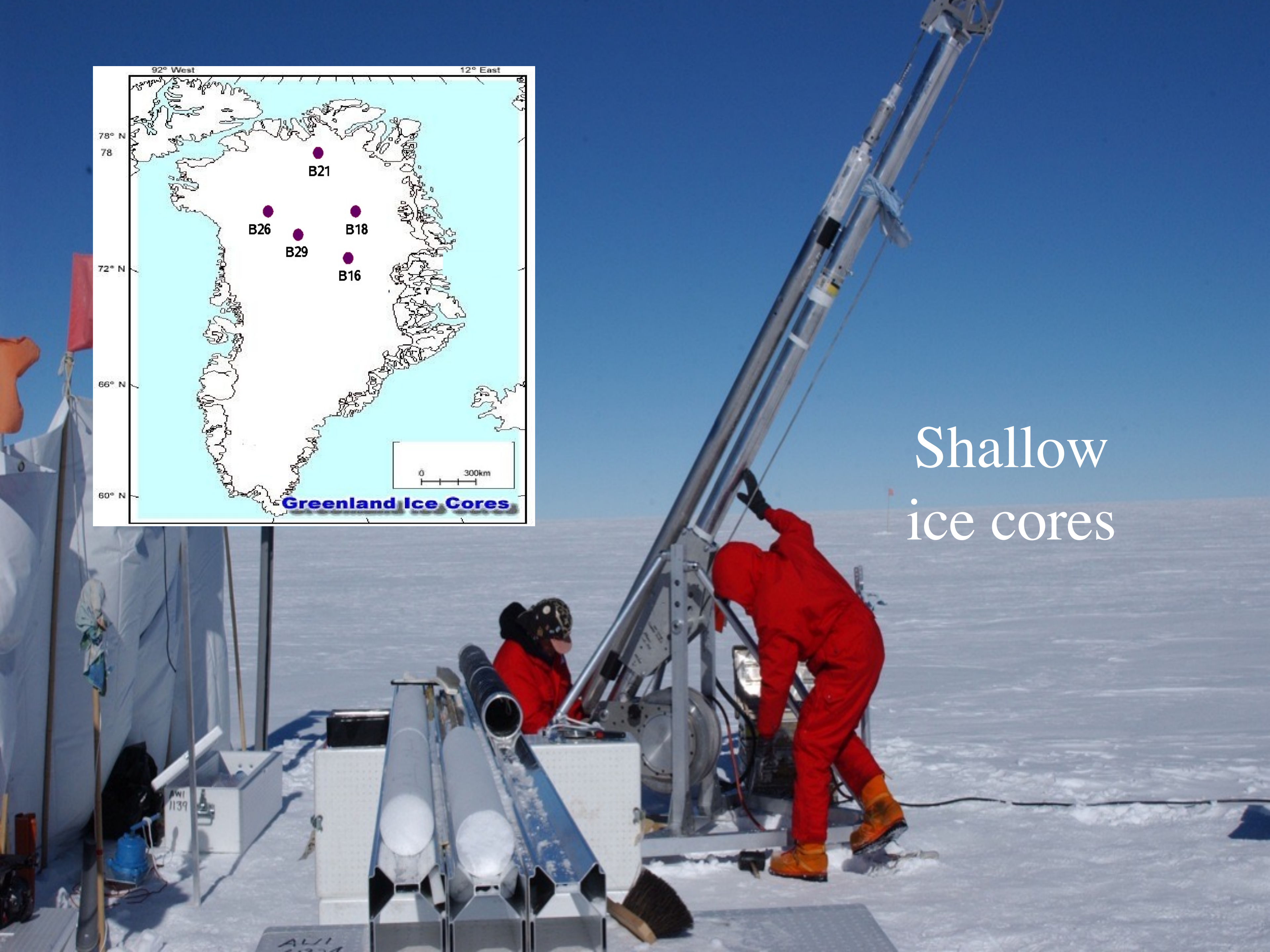
The “Climate dilemma“

- Instrumental data are **sparce**

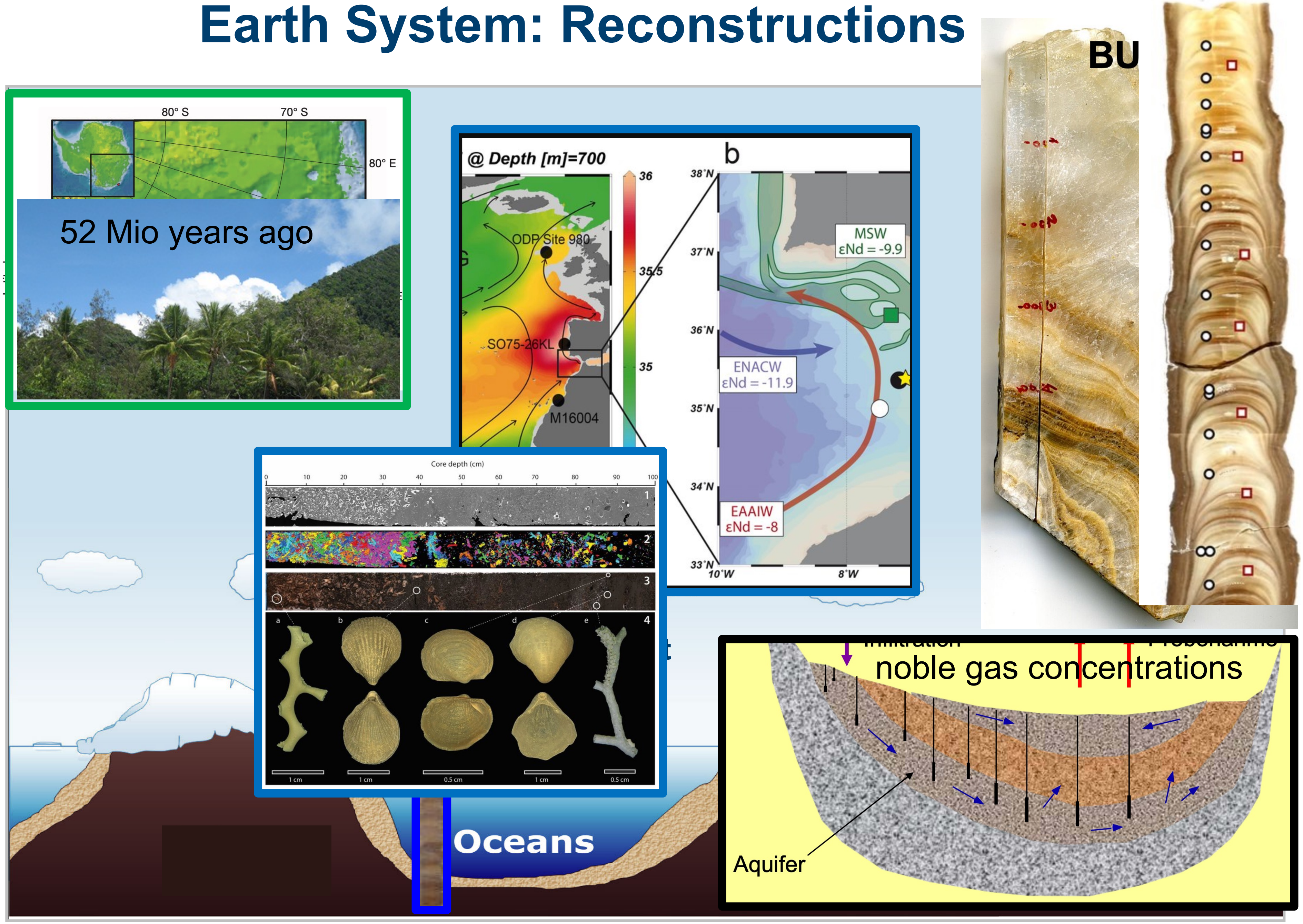


- The records of direct temperature measurements are **short** and already fall in the phase of strong **human influence**.

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


92° West
12° East
78° N
78
72° N
66° N
60° N
B21
B26
B18
B29
B16
0
300km
Greenland Ice Cores
Shallow
ice cores

Earth System: Reconstructions

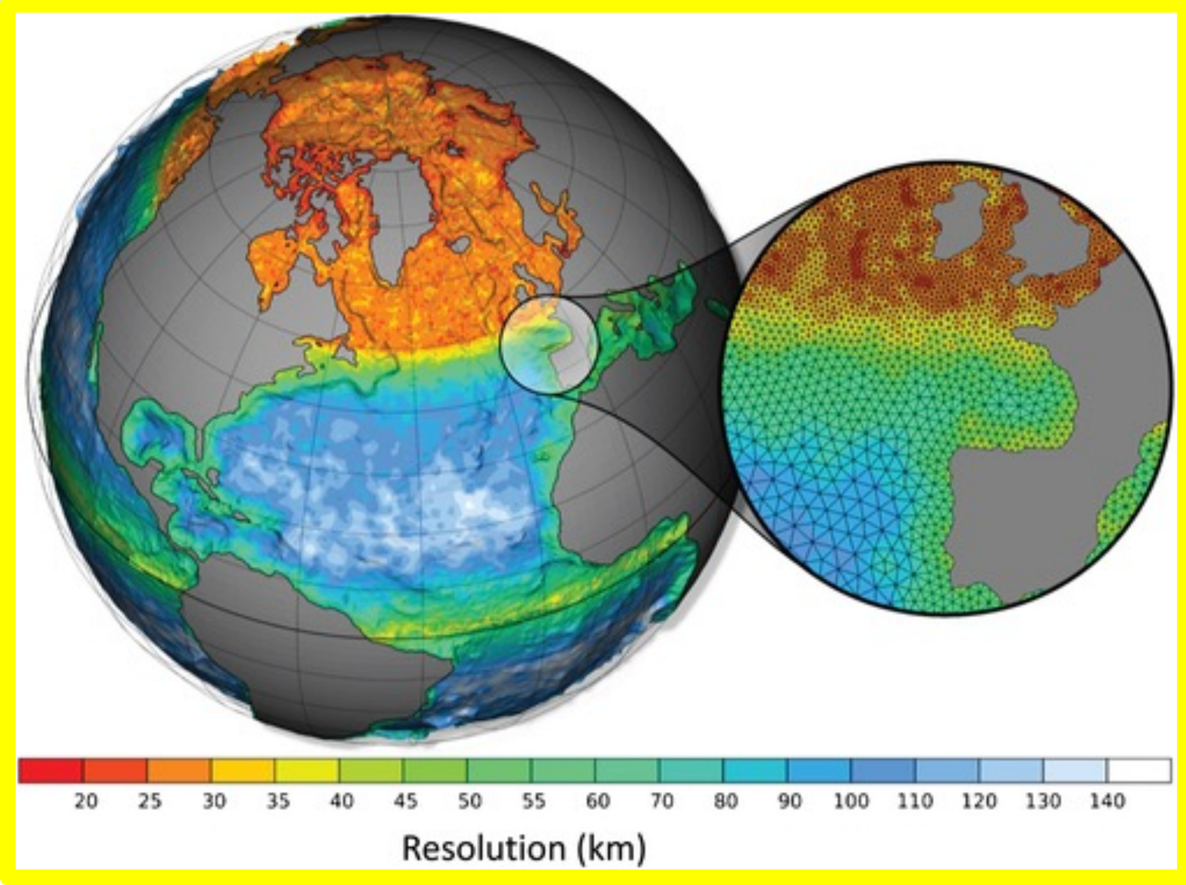


Earth System Analysis: Models

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

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

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



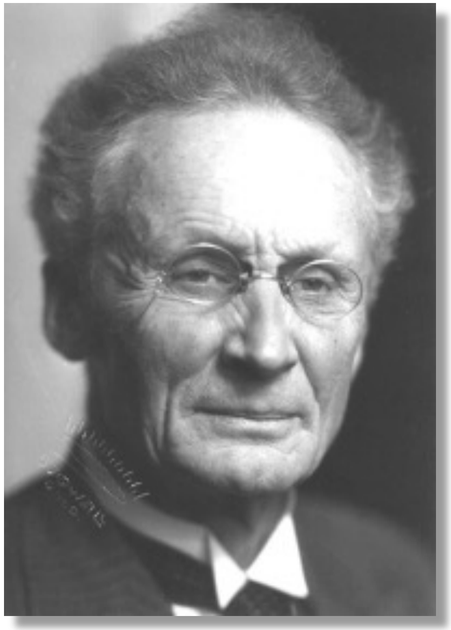
We know the governing equations

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

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

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

$$p = \rho R T$$

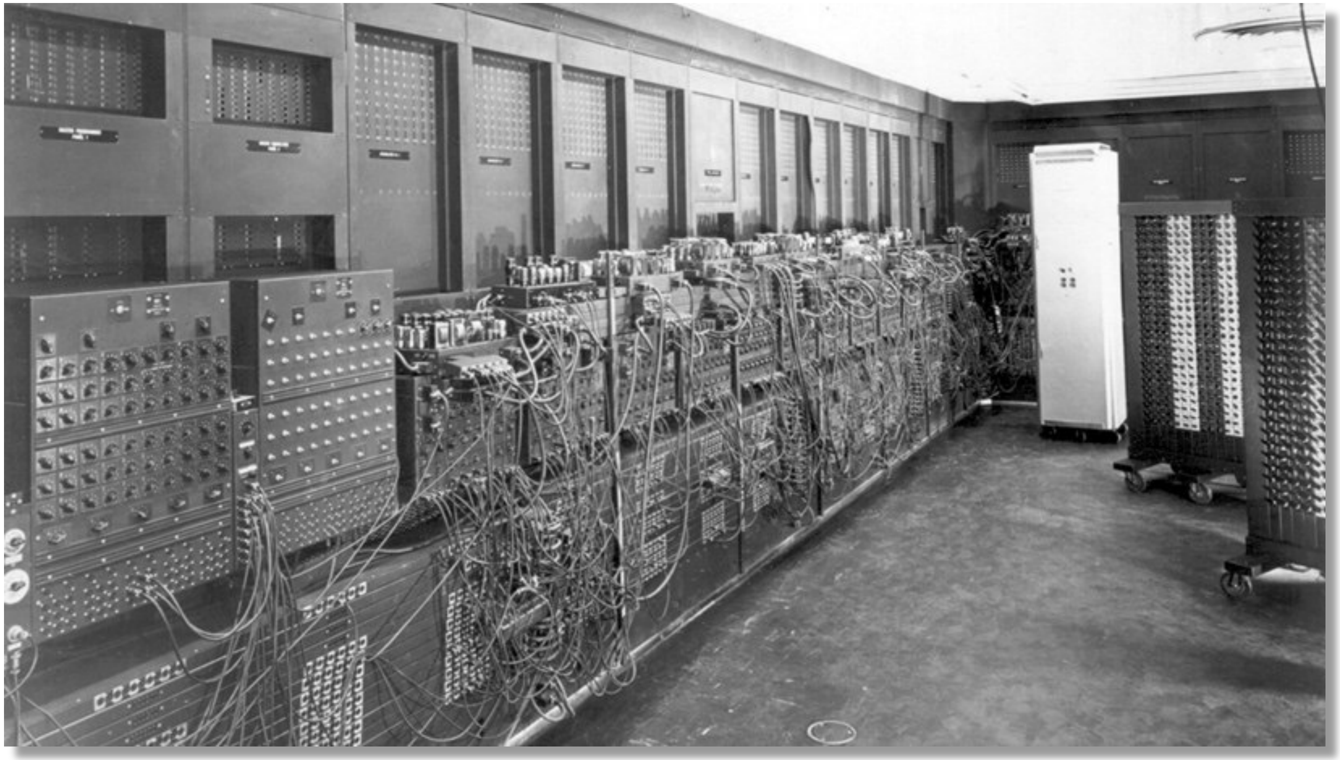


Vilhelm Bjerknes

BJERKNES, V., 1904: Das Problem der Wettervorhersage, betrachtet vom Standpunkte der Mechanik und der Physik. – Meteorol. Z. **21**, 1–7.

We know how to solve them numerically!

John von Neumann



ENIAC

The first multipurpose electronic computer (1946)

Optimal Fingerprints for the Detection of Time-dependent Climate Change

K. HASSELMANN

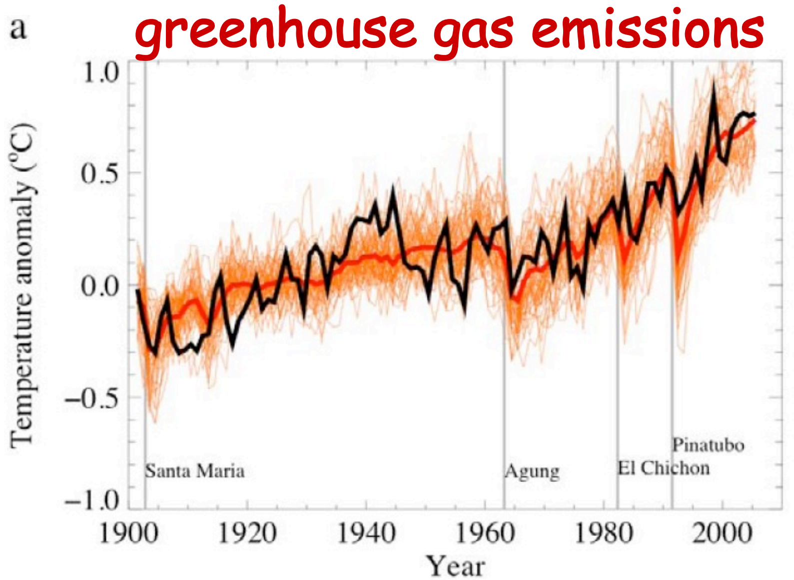
Max-Planck-Institut für Meteorologie, Hamburg, Germany

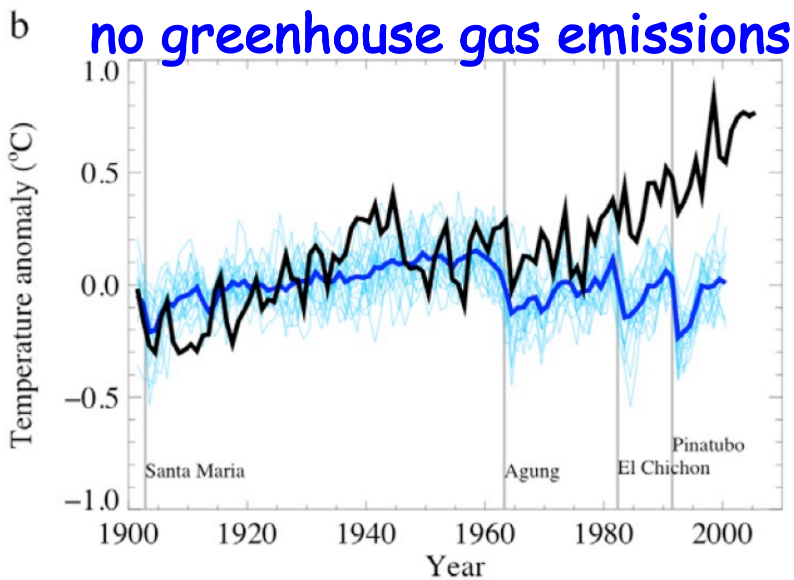
(Manuscript received 24 August 1992, in final form 17 March 1993)

$$f'_a = g'_a \sigma_a^{-2}. \tag{14}$$

The multiplication of the signal with the inverse of the covariance matrix is seen to weight the fingerprint components f'_a in the EOF frame relative to the signal components g'_a by the inverse σ_a^{-2} of the EOF variances, thereby slewing the fingerprint vector away from the EOF directions with high noise levels toward the low-noise directions.

Attribution (model world)

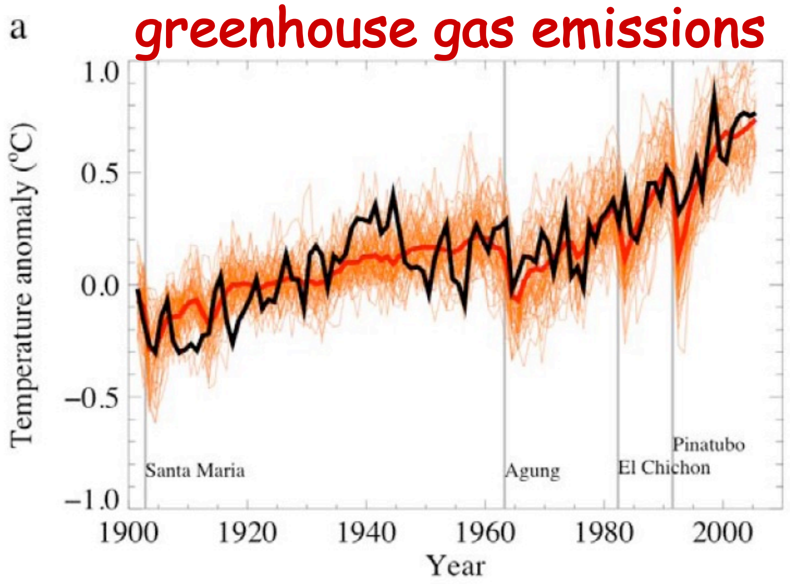




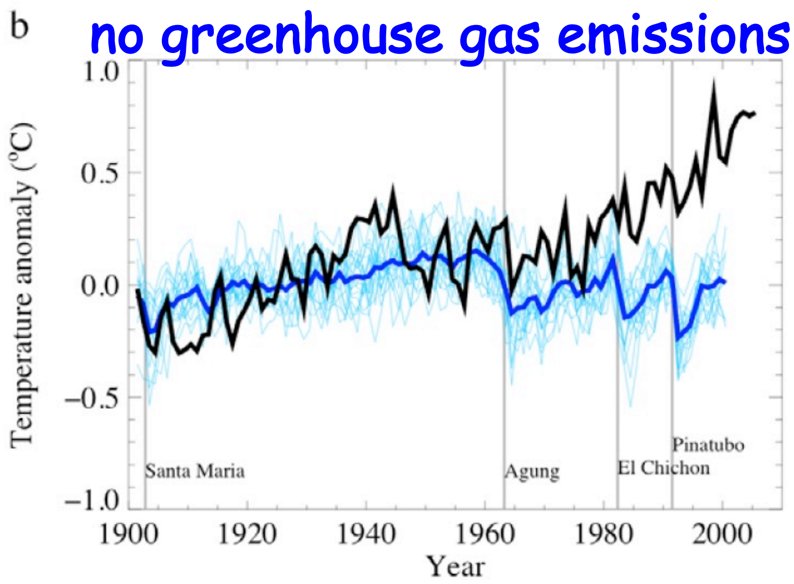
observed changes are consistent with
modeled response to external forcing,
inconsistent with alternative explanations

Nobel Price, 2021
Hasselmann

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**

Stochastic climate model (Hasselmann, 1976)

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

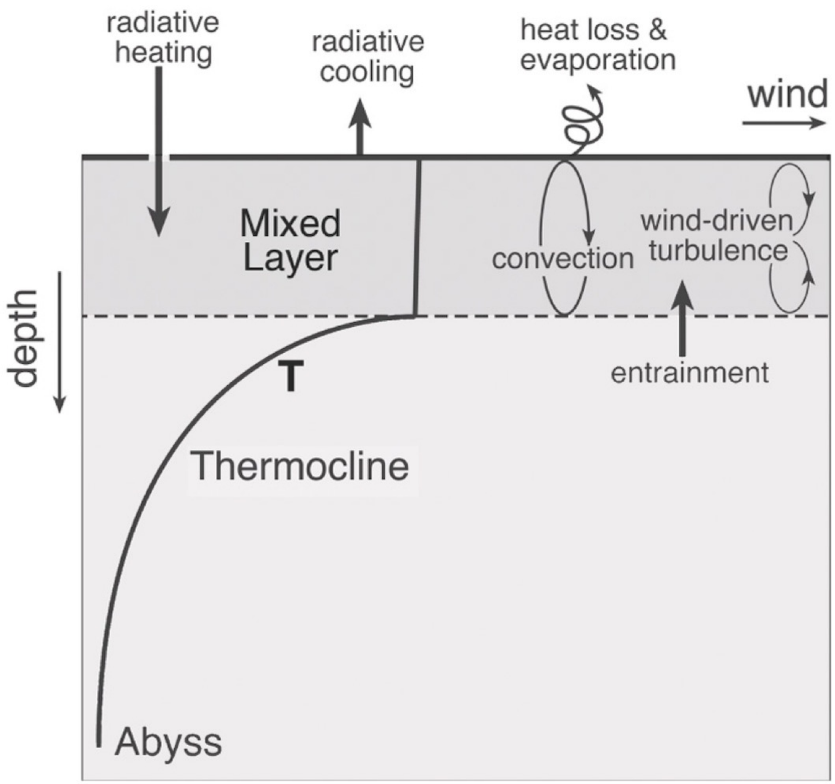
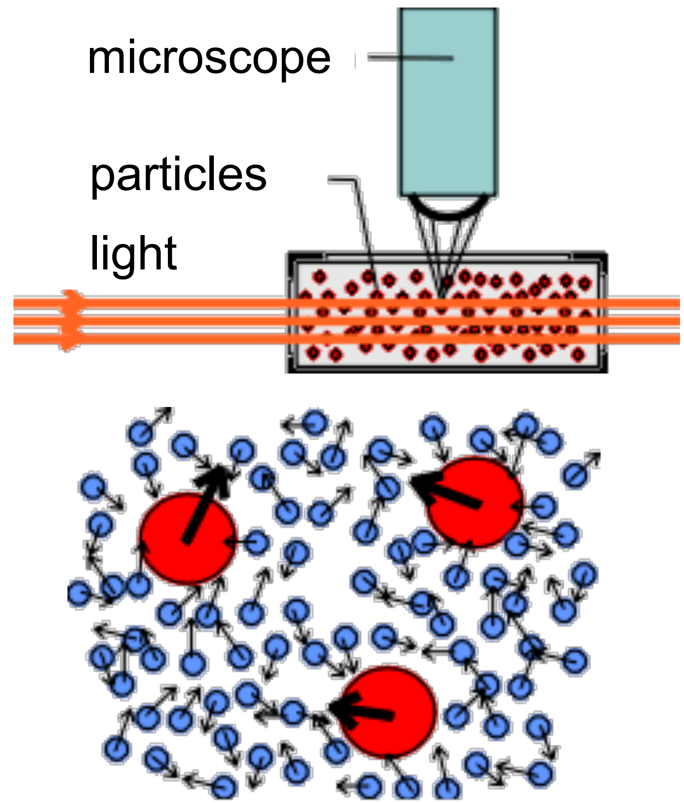


Figure 8.4: Schematic picture of mixed layer in the ocean.



Disorderly, random motion
collision with molecules

Exercise 59 – Spectrum of Stochastic Climate Model

Imagine that the temperature of the ocean mixed layer of depth h is governed by

$$\frac{dT}{dt} = -\lambda T + \frac{Q_{net}}{\gamma_O}, \tag{8.17}$$

where coefficient γ_O is given by the heat capacity $c_p \rho h$, and λ is the typical damping rate of a temperature anomaly. The air-sea fluxes due to weather systems are represented by a white-noise process $Q_{net} = \hat{Q}_\omega e^{i\omega t}$ where $\hat{Q}_\omega$ is the amplitude of the random forcing at frequency ω and $\hat{Q}^*$ is the complex conjugate. Remember that Q_{net} can be described through its distribution and its correlation properties: a Gaussian distribution of zero average $< Q_{net} >= 0$ and δ-correlated in time $< Q_{net}(t) Q_{net}(t+\tau) >= \delta(\tau)$ The brackets indicate an average over realizations of the random force. The spectrum of a process x is defined as

$$S(\omega) \;\; := \;\; \langle \hat{x}\hat{x}^* \rangle = \widehat{Cov_x(\tau)} \quad = \int_R \exp(i\omega\tau) Cov_x(\tau) d\tau \tag{8.18}$$

1. Calculate $S_Q(\omega)$ and describe why Q_{net} is called a white noise process.
2. Solve Eq. 8.17 for the temperature response $T = \hat{T}_\omega e^{i\omega t}$ and hence show that:

$$\hat{T}_\omega = \frac{\hat{Q}_\omega}{\gamma_O\left(\lambda + i\omega\right)} \tag{8.19}$$

3. Show that it has a spectral density $\hat{T}_\omega \hat{T}^*_\omega$ is given by:

$$\hat{T}\hat{T}^* = \frac{\hat{Q}\hat{Q}^*}{\gamma_O^2\left(\lambda^2 + \omega^2\right)} \tag{8.20}$$

and the spectrum

$$S(\omega) = <\hat{T}\hat{T}^*> = \frac{1}{\gamma_O^2\left(\lambda^2 + \omega^2\right)}. \tag{8.21}$$

The brackets $< \cdots >$ denote the ensemble mean. Make a sketch of the spectrum using a log-log plot and show that fluctuations with a frequency greater than λ are damped.
4. Calculate the spectrum of a regular oszillation with noise. How does the spectrum changes when you rectify the signal?

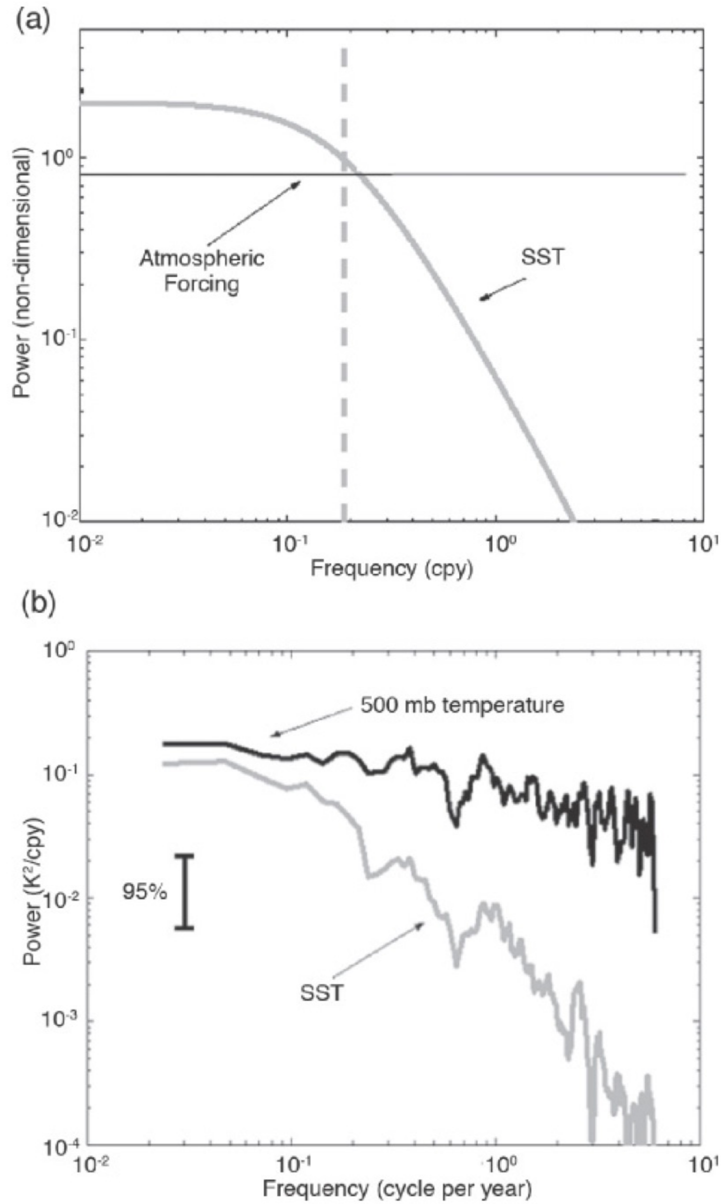
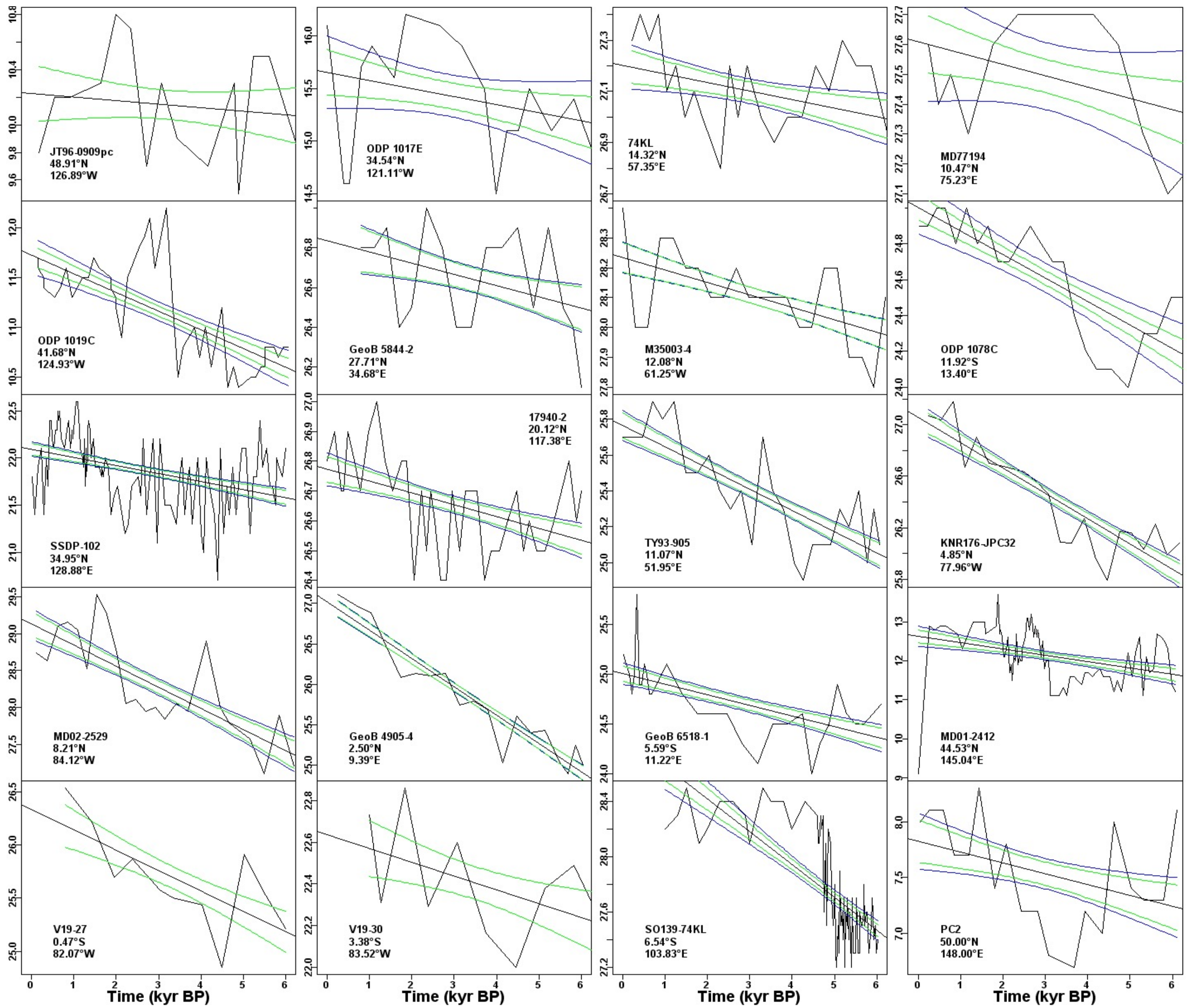


Figure 8.9: Powerspectrum of atmospheric temperature and sea surface temperature. Here $\mathbf{1/\lambda = 300}$ days from equation (8.43).

Sea Surface Temperatures

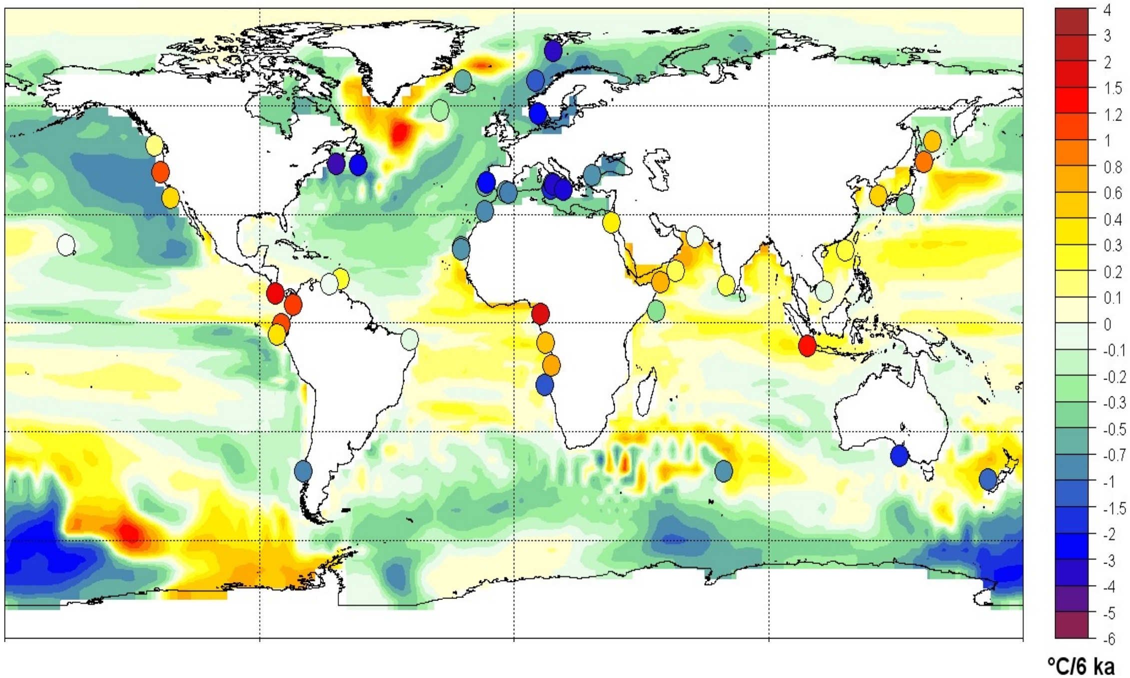
Alkenone Records



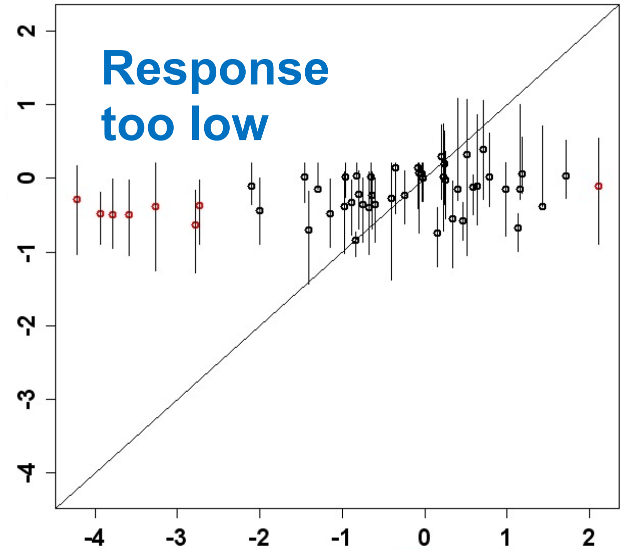
Lohmann et al., 2013, CP

Marine temperature trends (last 6000 years)

Annual mean sea surface temperature trends



ΔT



ΔT

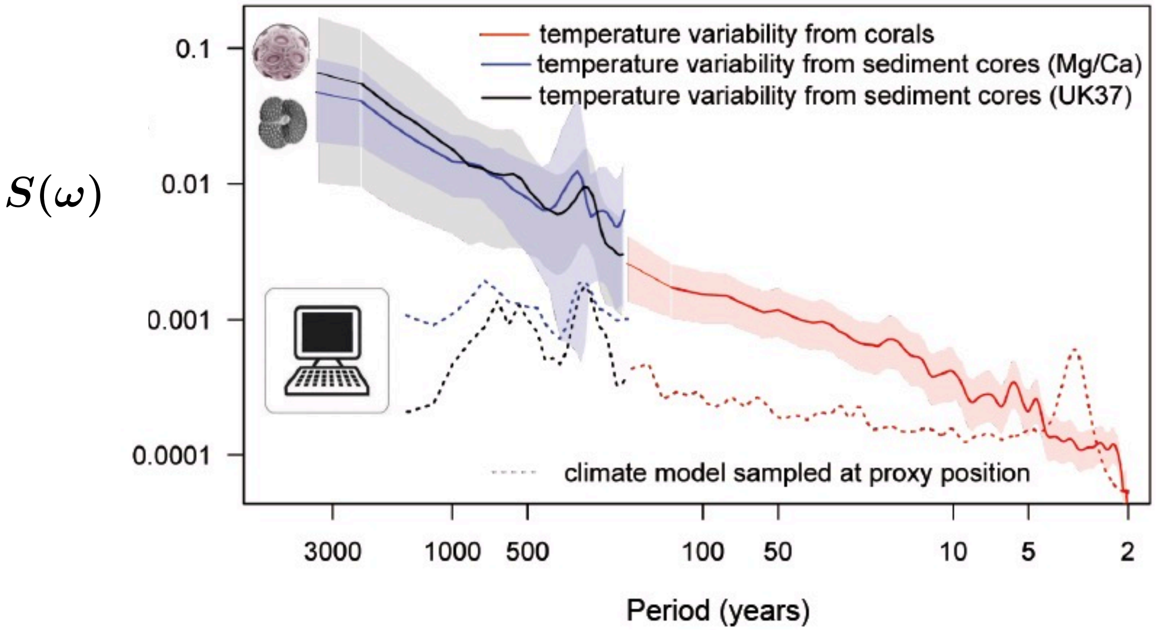
Alkenone-based temperature trends

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

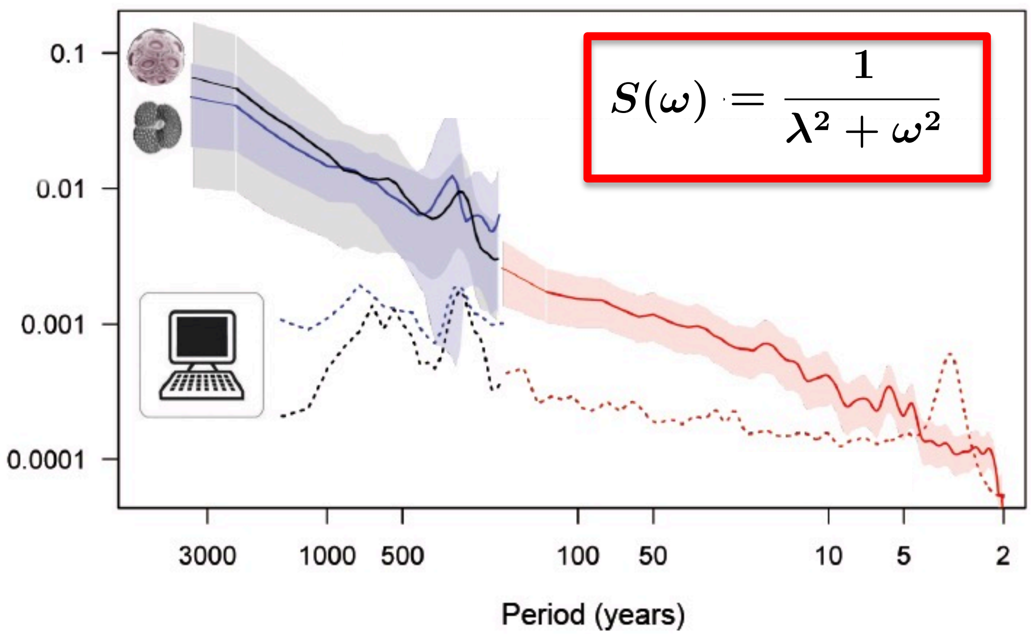
Climate variability and sensitivity are related

Stochastic climate model

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

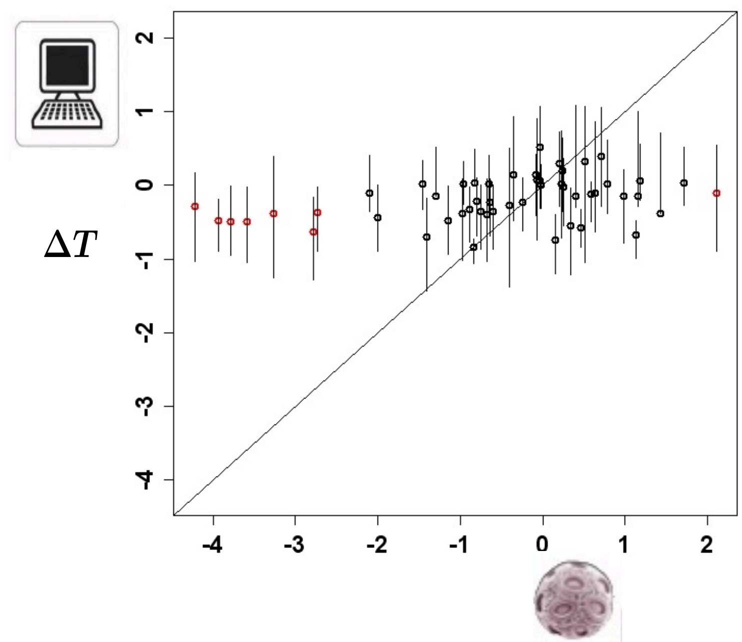
$$\Delta T = \frac{\text{Forcing}}{\lambda}$$

Power spectrum



Variance too low

Response too low

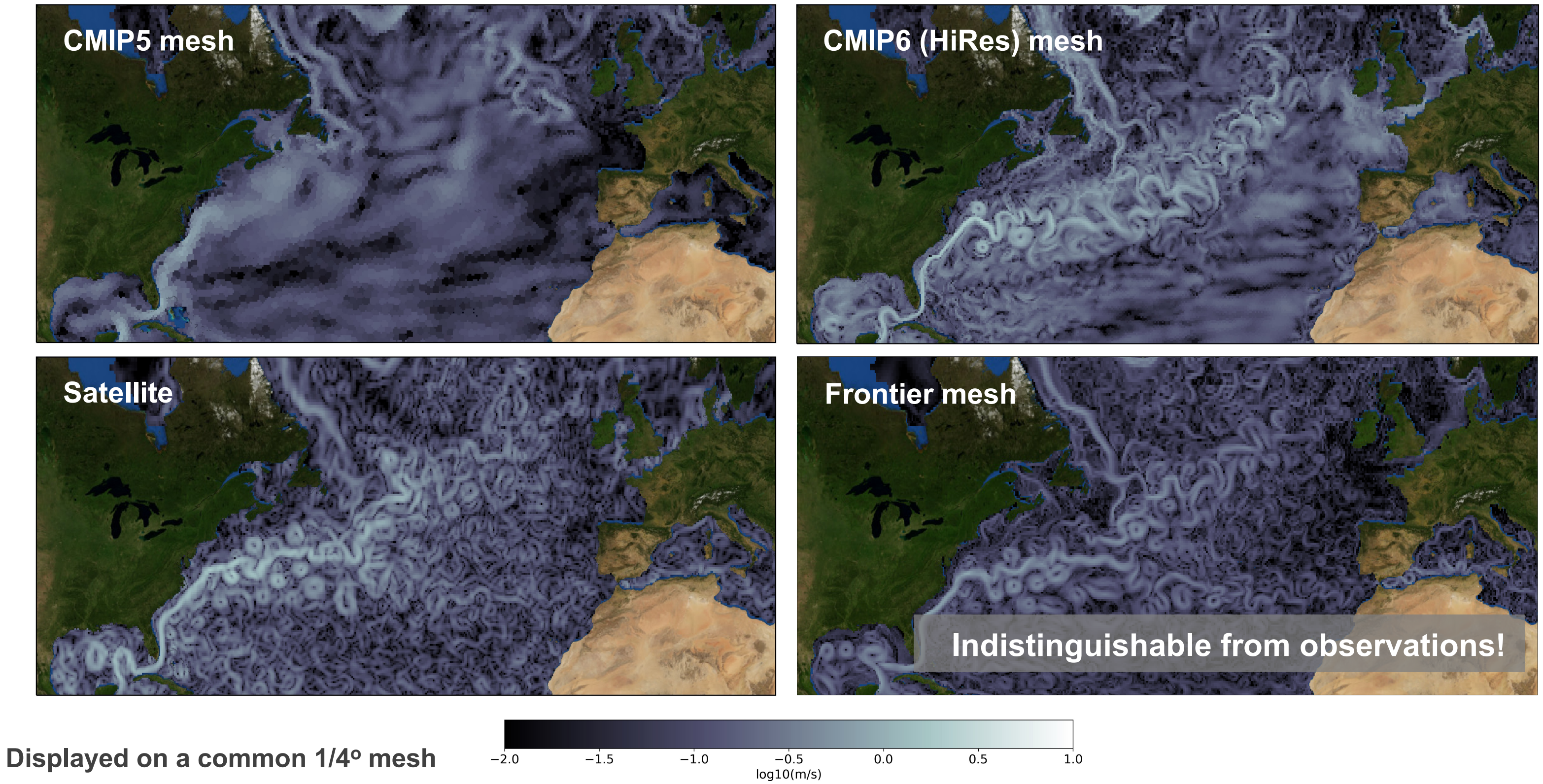


Damping λ too high

(Fluctuation Dissipation Theorem)

Lohmann 2018

How realistic is the model?

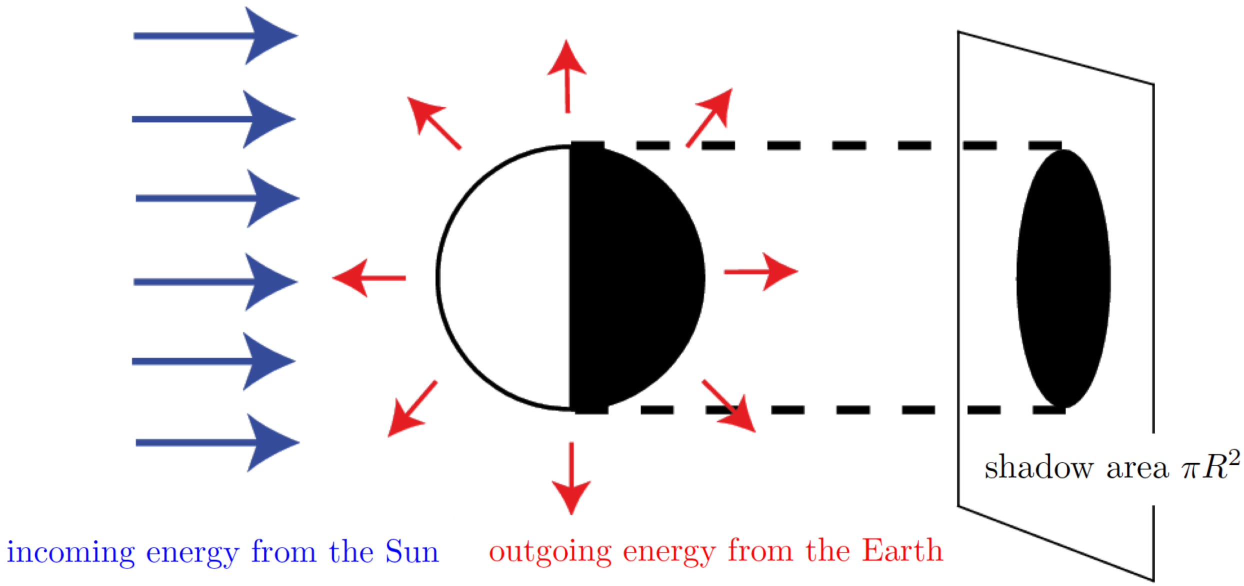


Ocean velocity

Energy balance model: Concepts of climate

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

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

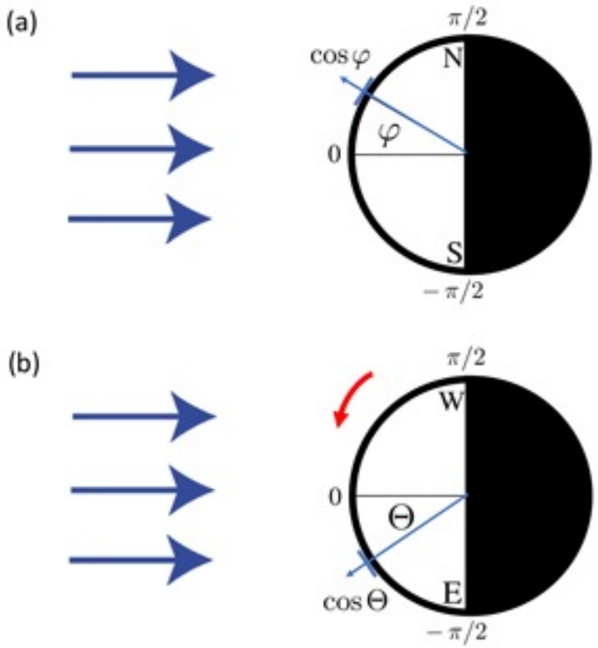


Heat capacity of the climate system

Fast rotation

Lohmann, 2020

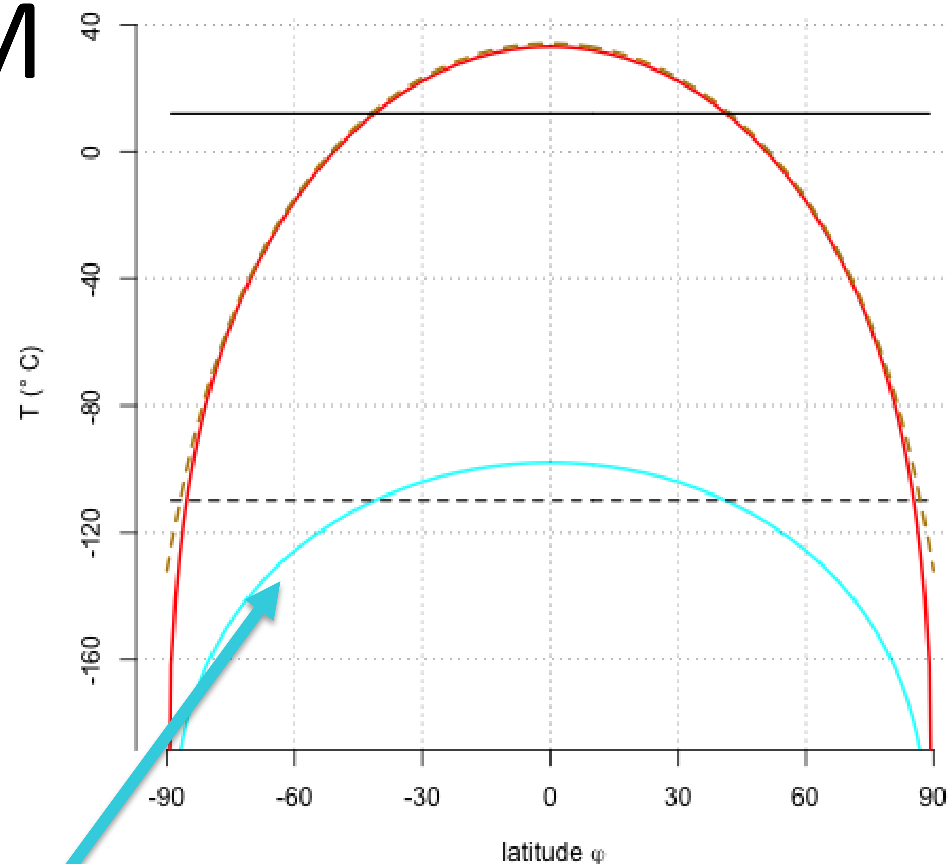
EBM



$$\overline{T} = \frac{1}{2}\int_{-\pi/2}^{\pi/2} T(\varphi)\cos\varphi \, d\varphi$$

$$= \frac{1}{2}\frac{\Gamma(5/8)}{\sqrt{2\pi}\,\Gamma(9/8)} \cdot \sqrt[4]{\frac{(1-\alpha)S}{4\epsilon\sigma}} \underbrace{\int_{-\pi/2}^{\pi/2} (\cos\varphi)^{5/4} d\varphi}_{\sqrt{\pi}\,\Gamma(9/8)/\Gamma(13/8)}$$

$$= \underbrace{\frac{1}{2}\frac{1}{\sqrt{2}}\frac{\Gamma(5/8)}{\Gamma(13/8)}}_{\frac{\sqrt{2}}{4}\frac{8}{5} = 0.4\sqrt{2}} \cdot \sqrt[4]{\frac{(1-\alpha)S}{4\epsilon\sigma}}.$$

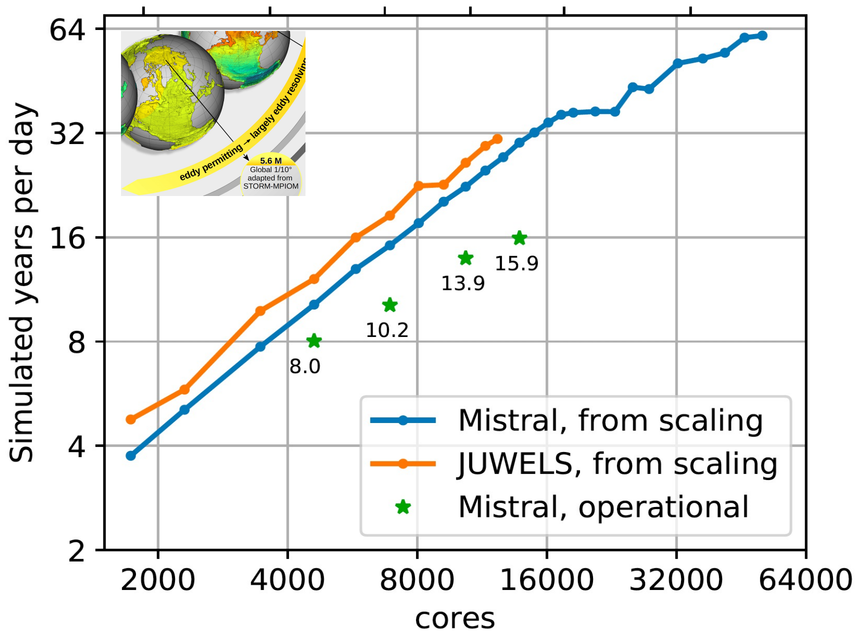


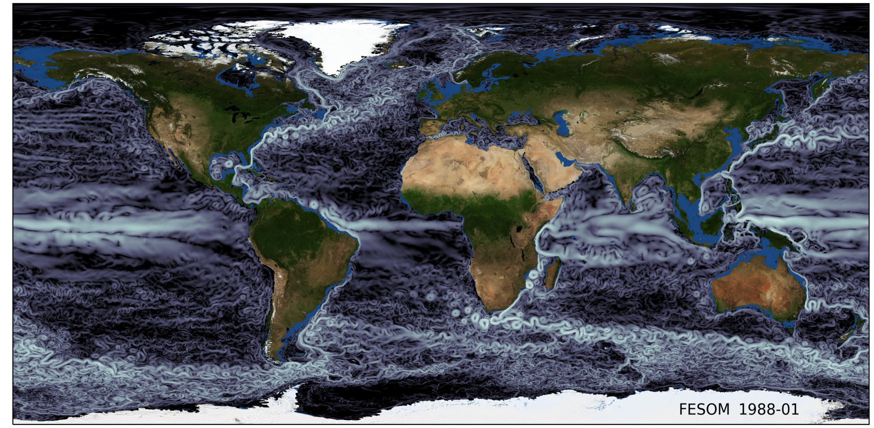
Heat capacity of the climate system

Fast rotation

Lohmann, 2020

Scalability





Koldunov et al (2019)

Limited by available HPC capabilities (today)

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

Parameterizations

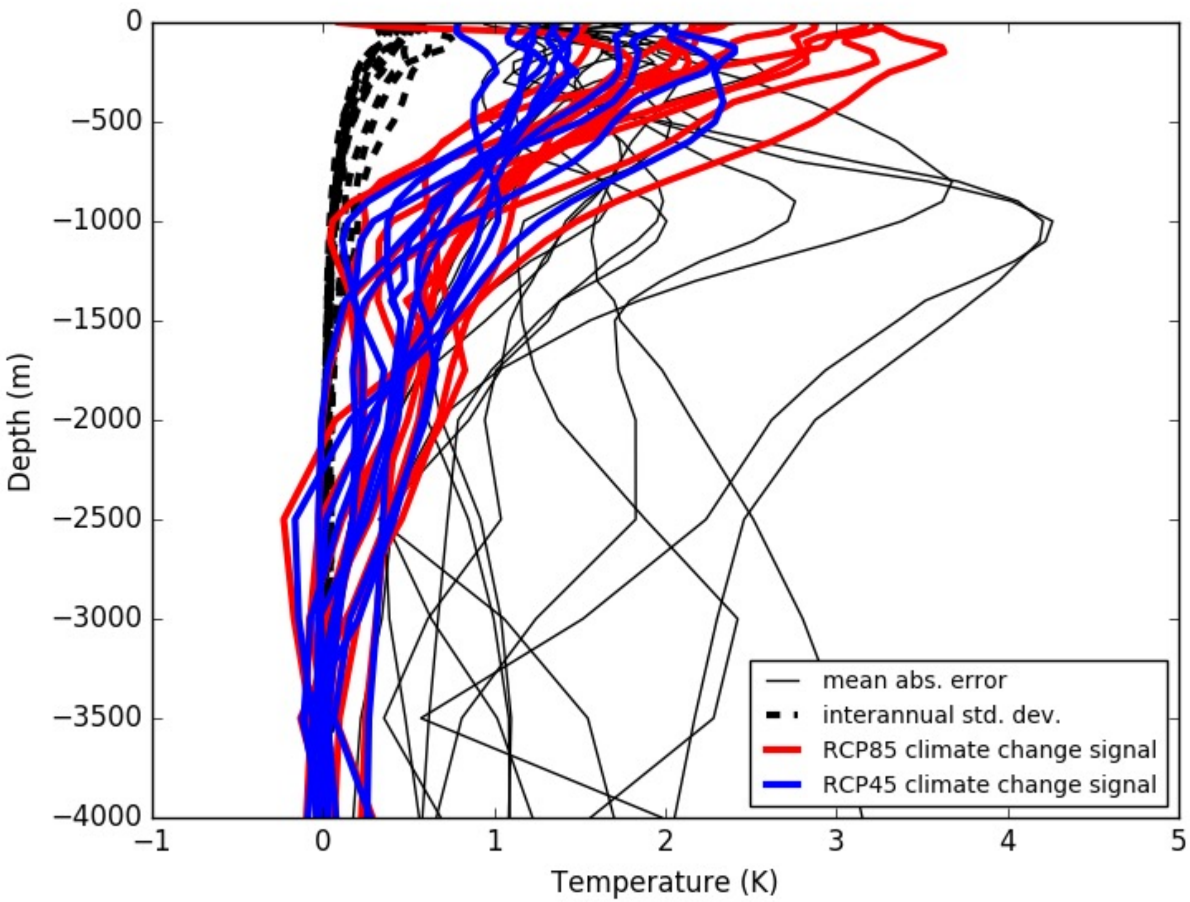
Some critical small-scale processes are *not* represented by the laws of physics, but by physically motivated rules of thumb (parametrizations)

➔ Large uncertainties in regional (global) climate change projections

➔ Limitations in predicting extreme events

So what's the issue then?

North Atlantic Ocean temperature biases



Rackow et al. (2019)

Based on 13 CMIP5 models

F = m · a
Research Conference on
MIR IST NOCH IMMER ALLES UNKLAR – ABER AUF EINEM VIEL HÖHEREN NIVEAU!
OH