

Collapse of the Atlantic Ocean Circulation



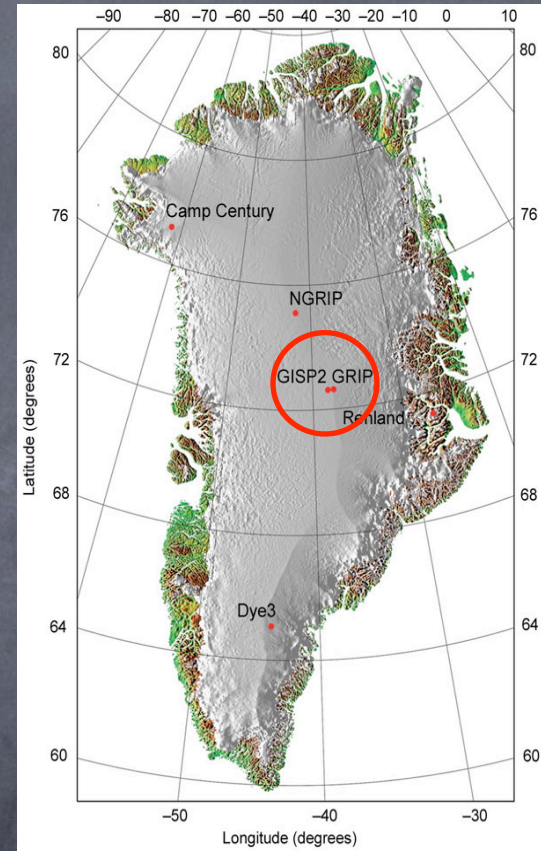
Henk Dijkstra

Institute for Marine and Atmospheric research Utrecht,
Department of Physics and Astronomy, Utrecht, The Netherlands

Work with

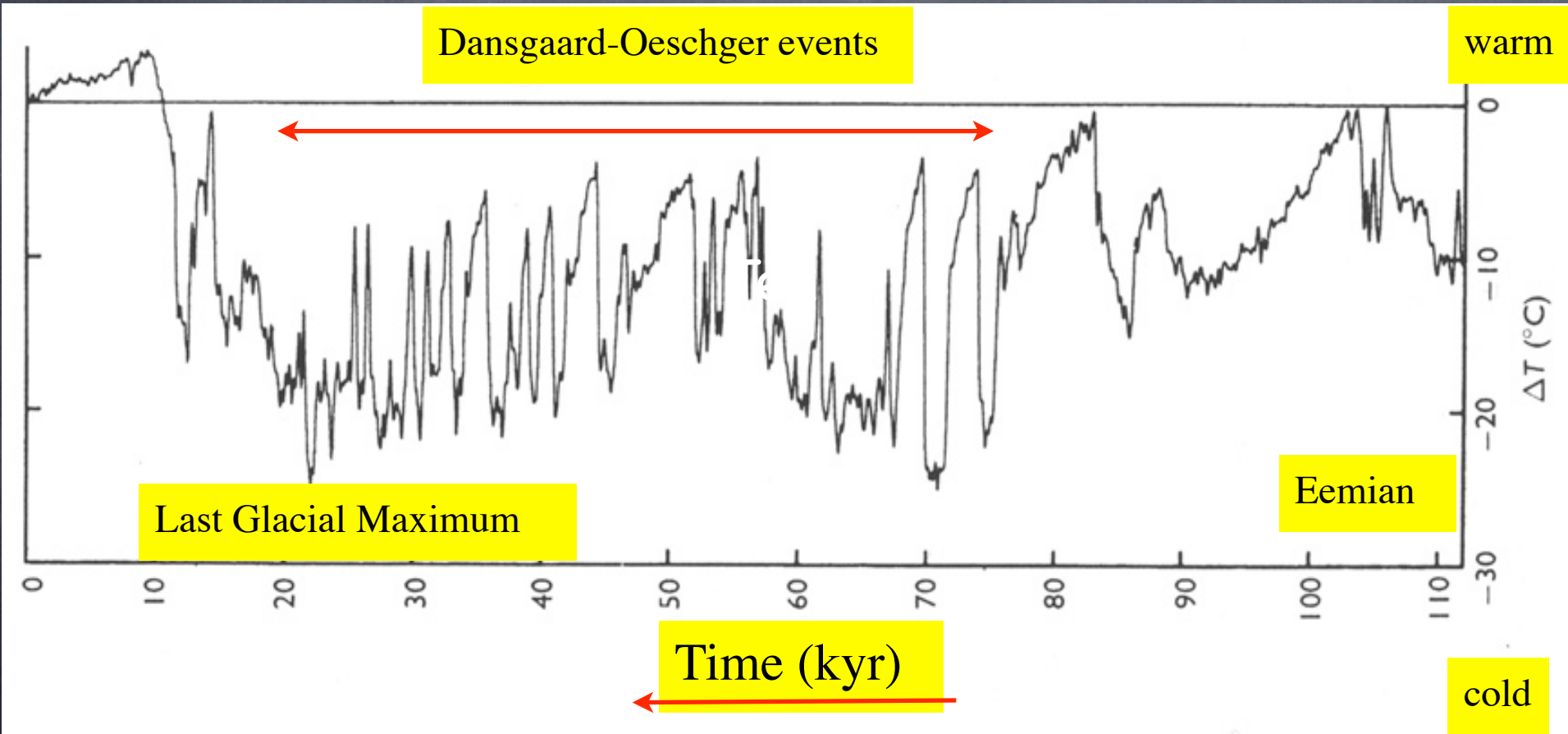
Fred Wubs (RUG, Netherlands) & Wilbert Weijer (LANL, USA)

Ice Core Data

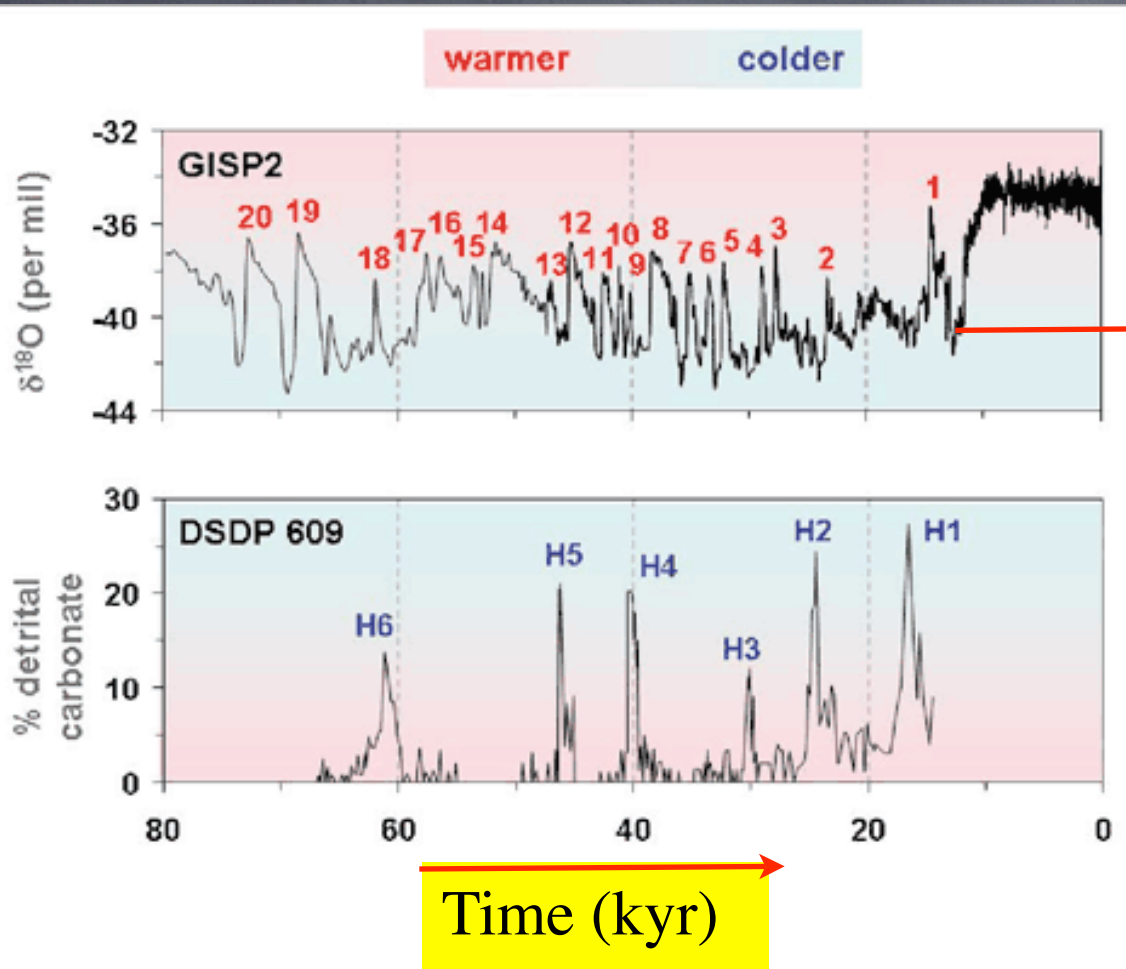


From the oxygen isotope ratio of water in an ice core the temperature (at the time of snow deposition) can be reconstructed

Climate variability on Greenland (GISP2) during the last 100,000 years



Dansgaard-Oeschger & Heinrich events



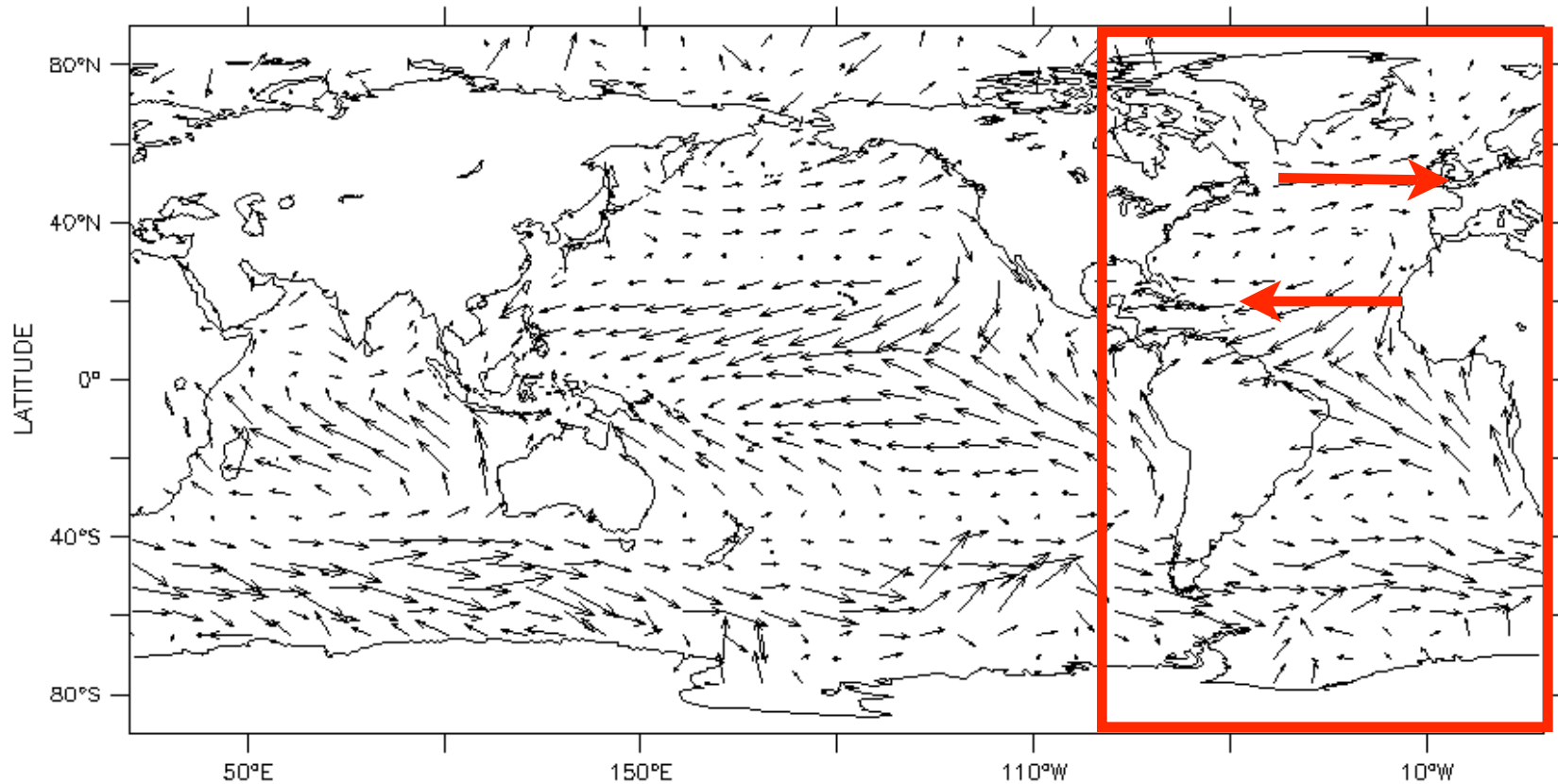
Younger Dryas



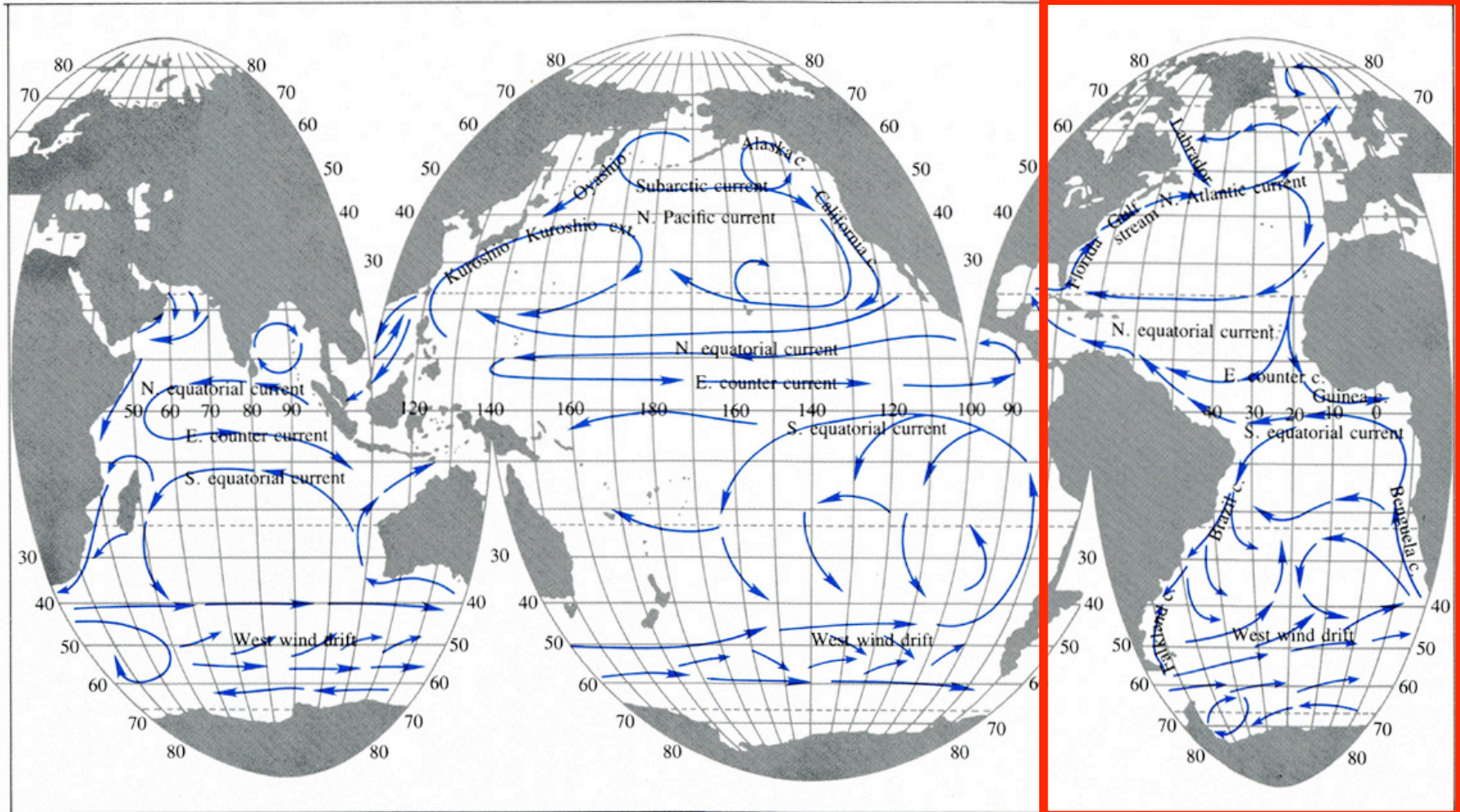
Strong indications of changes in ocean circulation during Heinrich events

Annual mean surface wind velocity

→ : 10 m/s



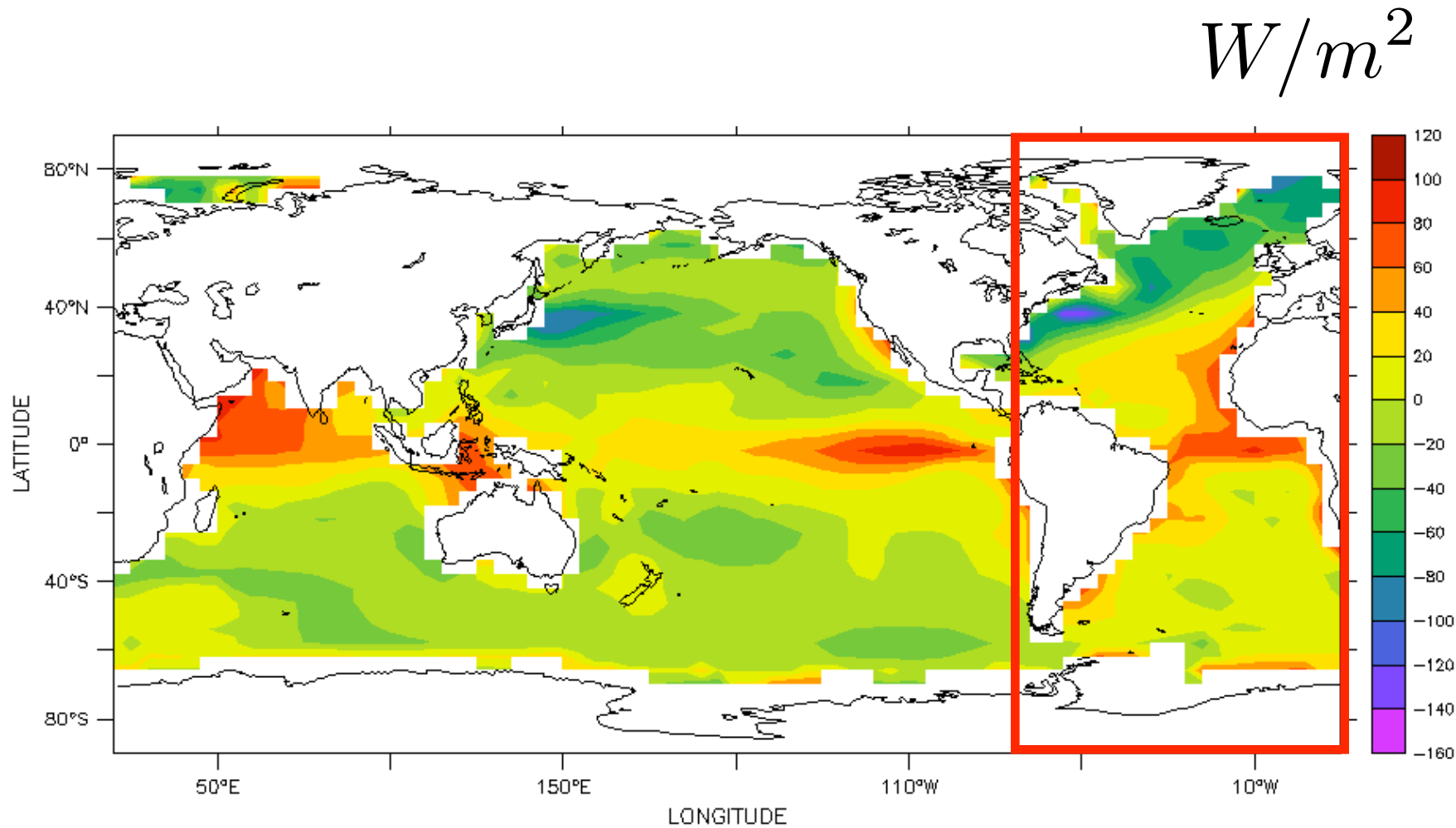
Surface Ocean Circulation



Wind-driven circulation: circulation associated with direct forcing of the wind

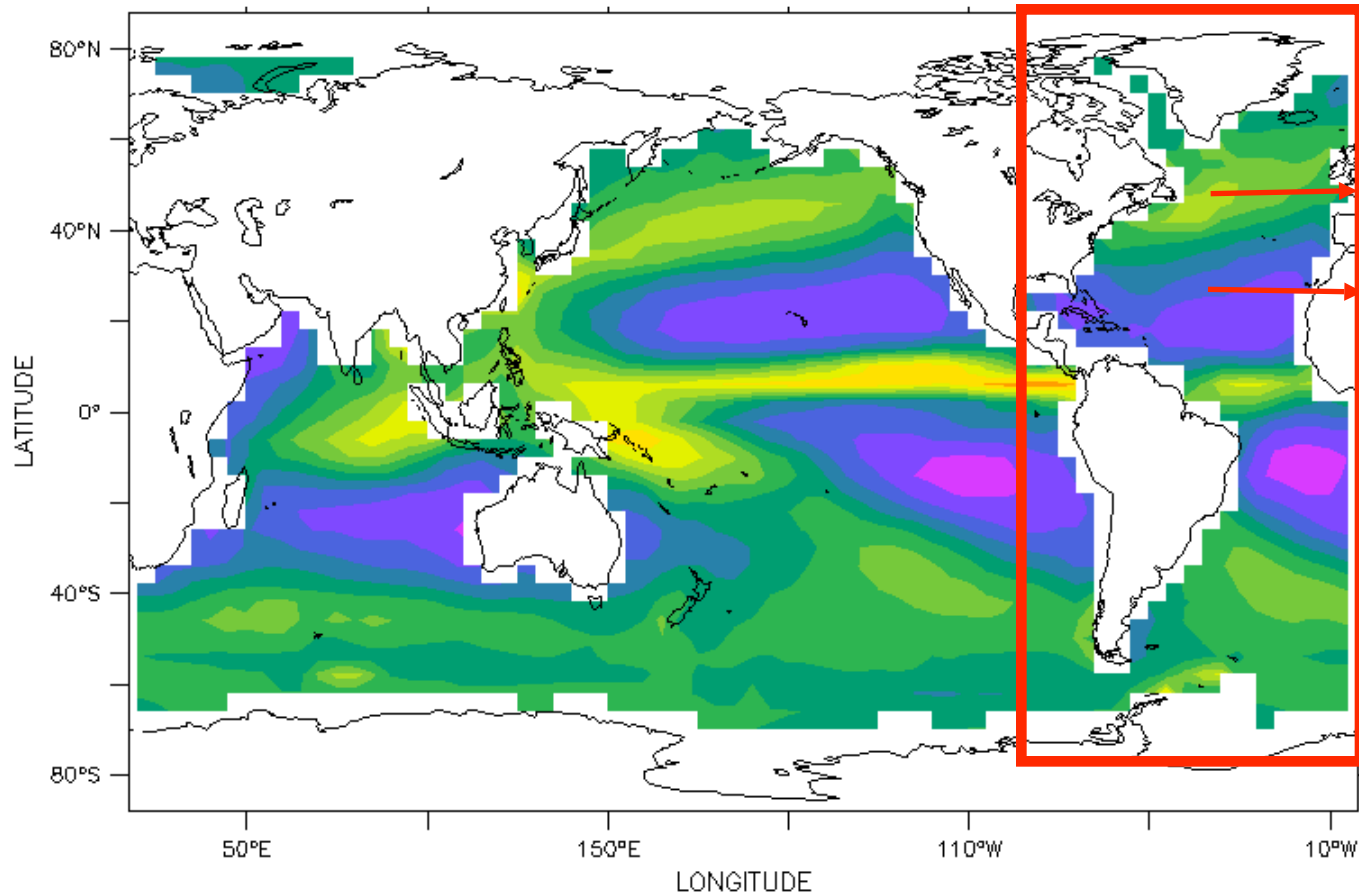
After: Sverdrup, H.U. et al. (1942)

Annual mean surface heat flux



Annual mean freshwater flux

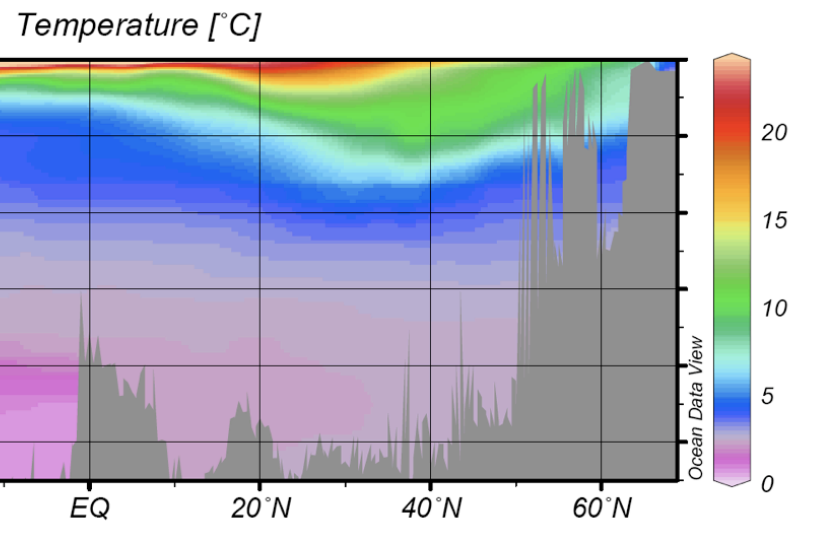
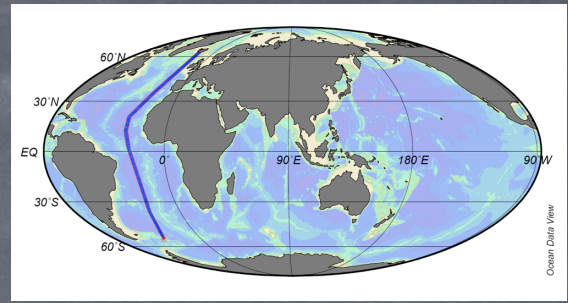
Precipitation - Evaporation



50 mm/month

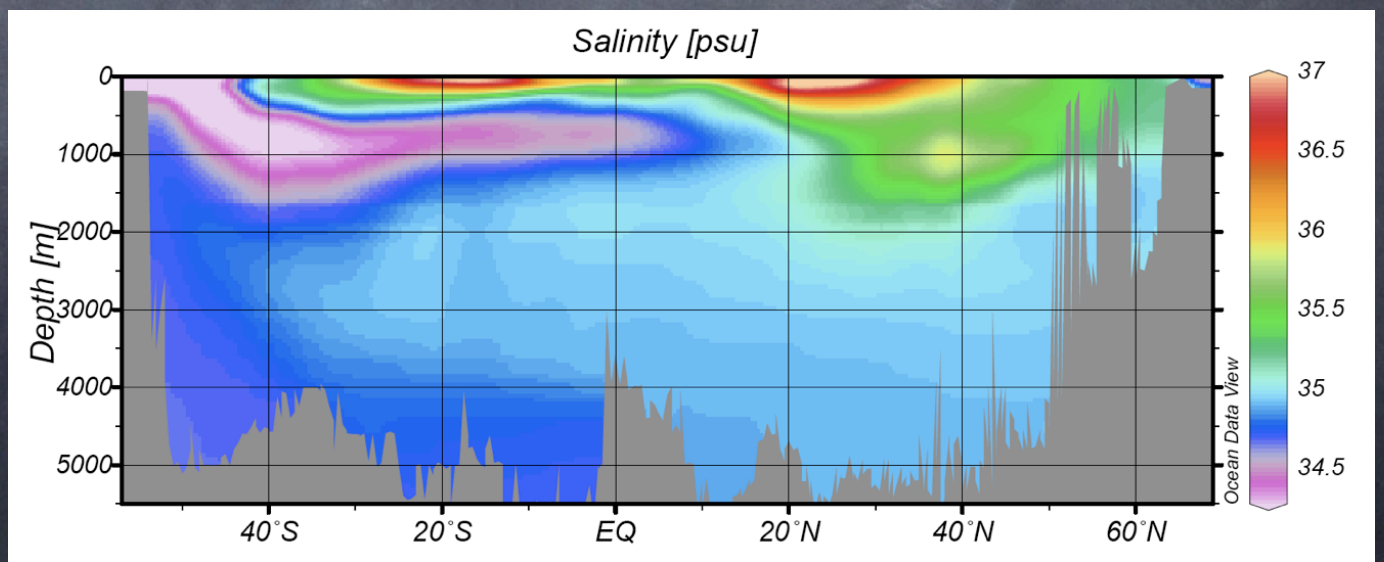
-100 mm/month

Along Atlantic N-S section:



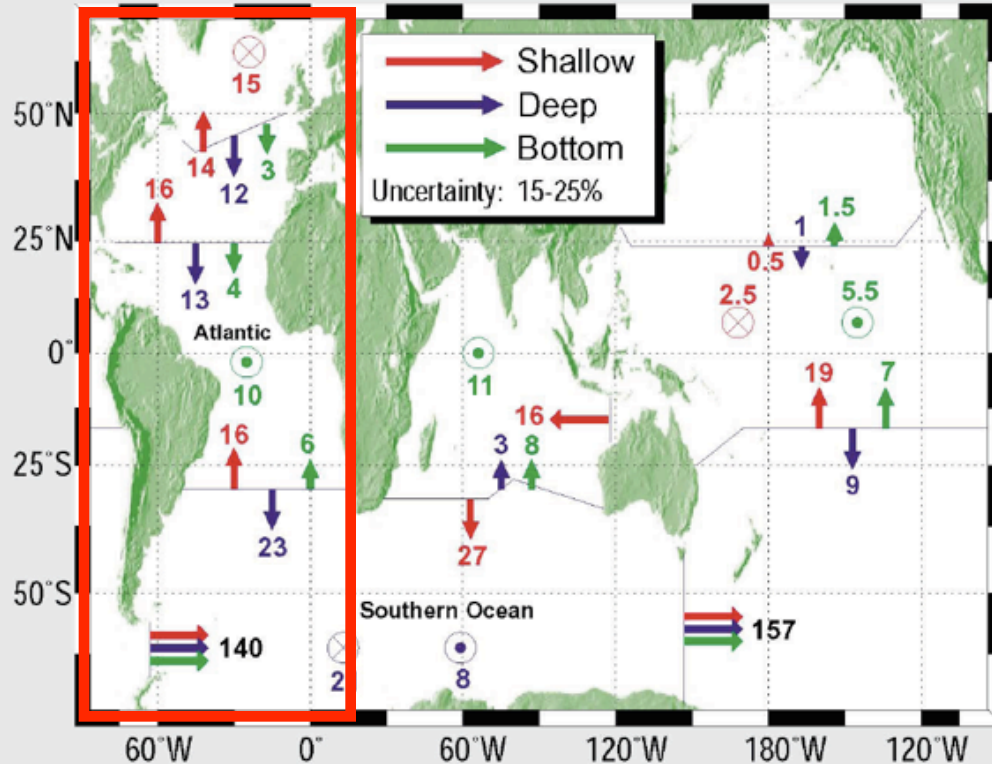
Temperature
(C)

Salinity
(ppt)



Three Dimensional Ocean Circulation

Global ocean circulation, based on Ganachaud and Wunsch (2000)



From NASA/JPL-Caltech

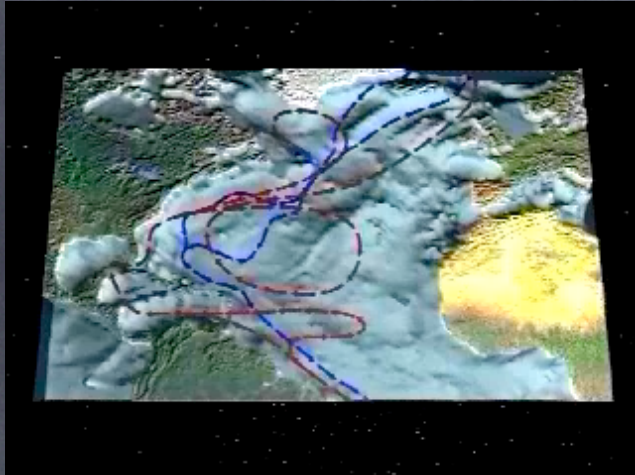
U.S. National Research Council (NRC, 2002)
Abrupt Climate Change – Inevitable Surprises

Ganachaud & Wunsch, Nature, 408, 453, (2000)

$$1 \text{ Sv} = 10^6 \text{ m}^3/\text{s}$$

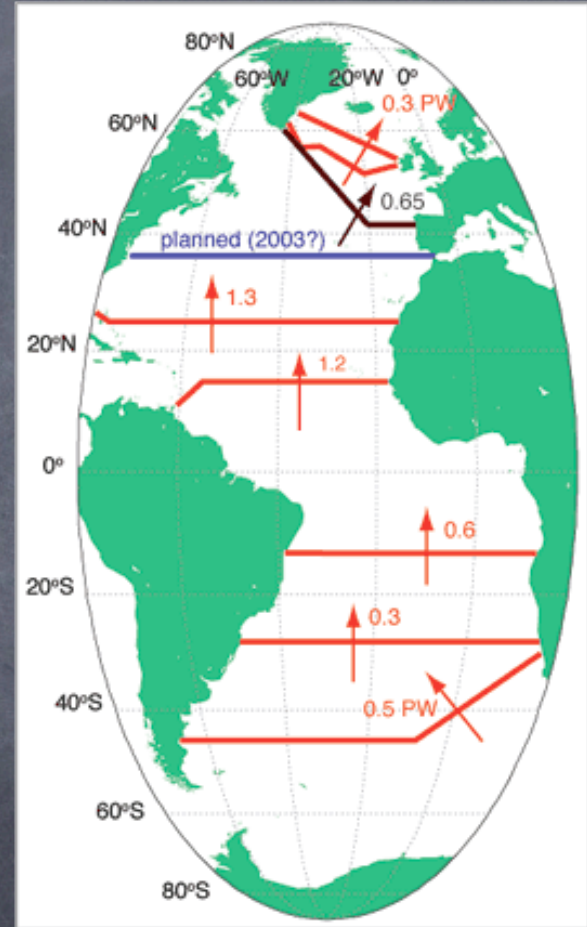
Thermohaline circulation: circulation associated with the transport of heat and salt

Meridional Overturning Circulation (MOC)

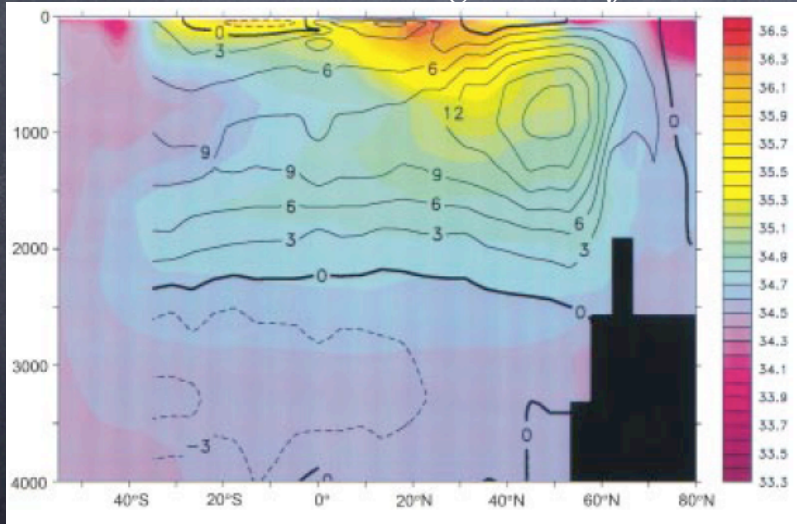


from WHOI

Heat Transport



Model determined
Meridional overturning streamfunction



40S

Contours in Sv

80N

$$1 \text{ PW} = 10^{15} \text{ W}$$

MOC: Volume transport in latitude/depth (is observable)

Ocean Models: Multi-scale & multi-parameter models

Local conservation of mass, momentum, heat and salt:

$$\mathcal{M}_\lambda \frac{\partial \mathbf{u}}{\partial t} + \mathcal{L}_\lambda \mathbf{u} + \mathcal{N}_\lambda(\mathbf{u})\mathbf{u} = \mathbf{F}_\lambda$$

$\mathcal{M}_\lambda, \mathcal{L}_\lambda, \mathcal{N}_\lambda$: Operators

λ : Parameter Vector

\mathbf{u} : State Vector

+ Boundary conditions & Initial conditions

Ocean Variables

$$\mathbf{u} = \begin{pmatrix} u \\ v \\ w \\ p \\ T \\ S \end{pmatrix}$$

Zonal velocity

Meridional velocity

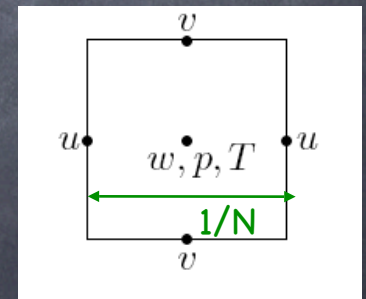
Vertical velocity

Pressure

Temperature

Salinity

Discretization on
grid: $N \times M \times L$

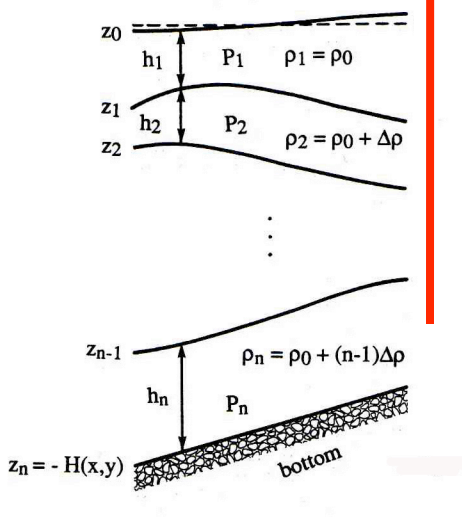
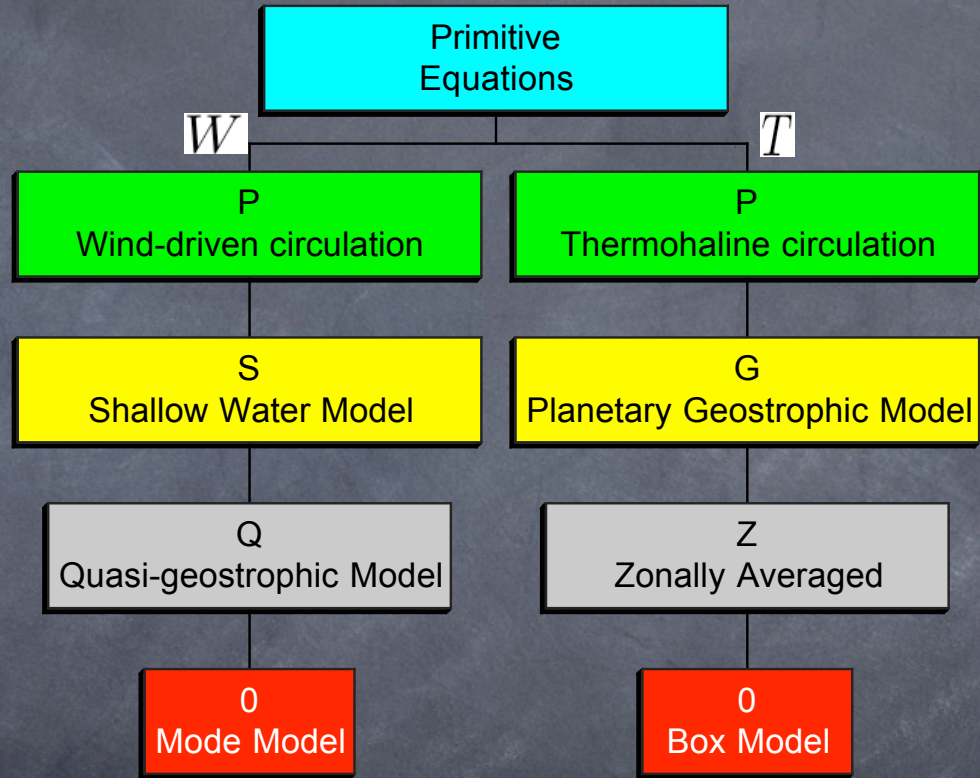


degrees of freedom: $d = N \times M \times L \times 6$

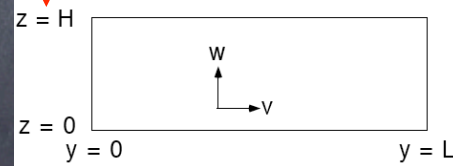
Ocean Models: Dynamical hierarchy

realism

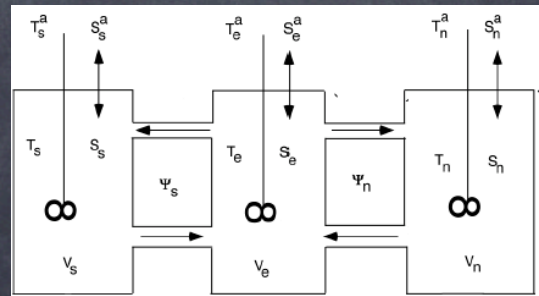
understanding



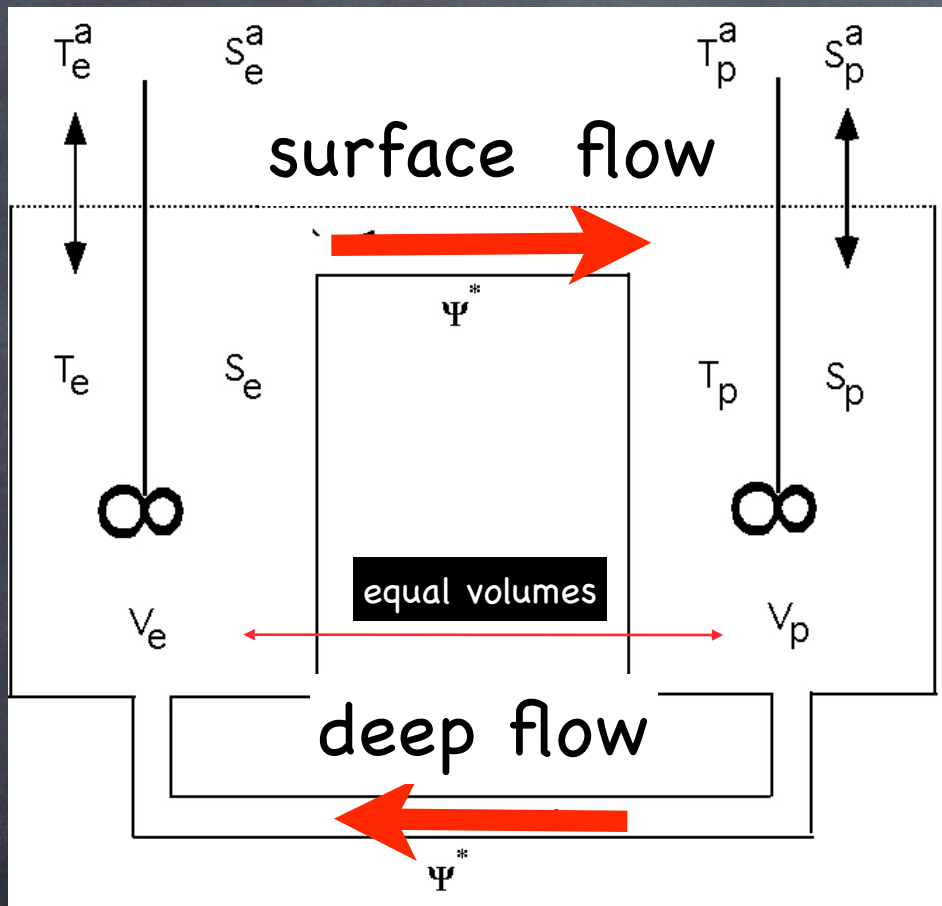
$W_S^{n,*}$



$T_Z^{R,*}$

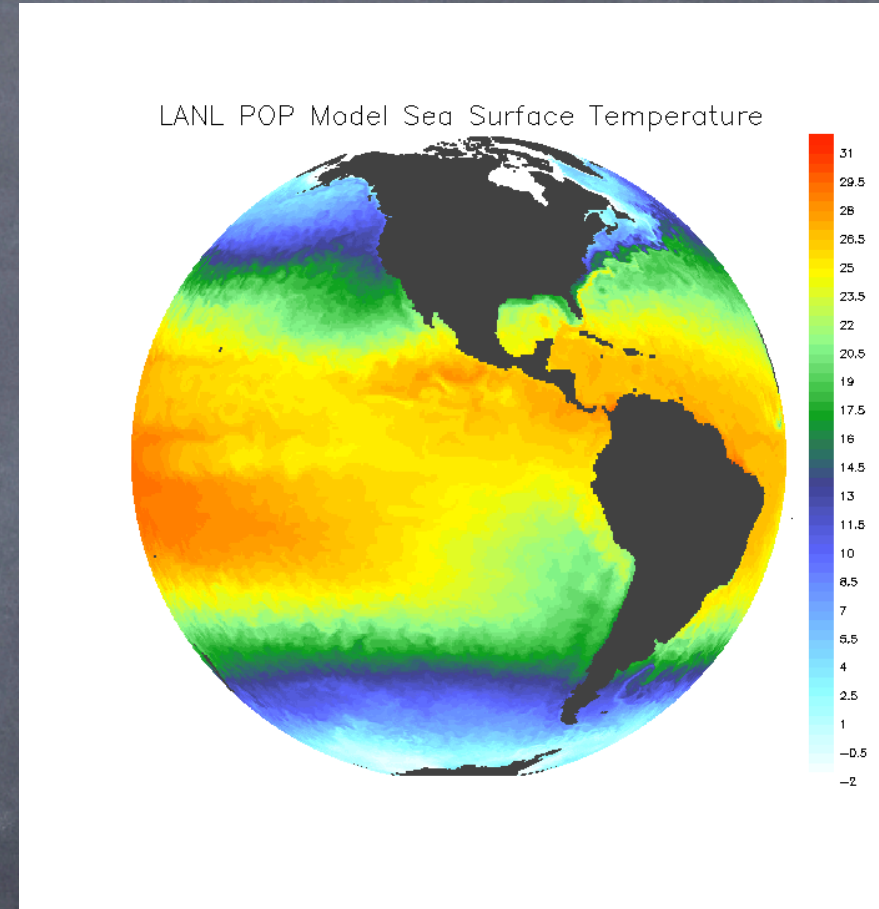


'Extremes' of the model hierarchy



$d = 2$

1 year model simulation \sim 1 day on 700 cores (IBM-p6)

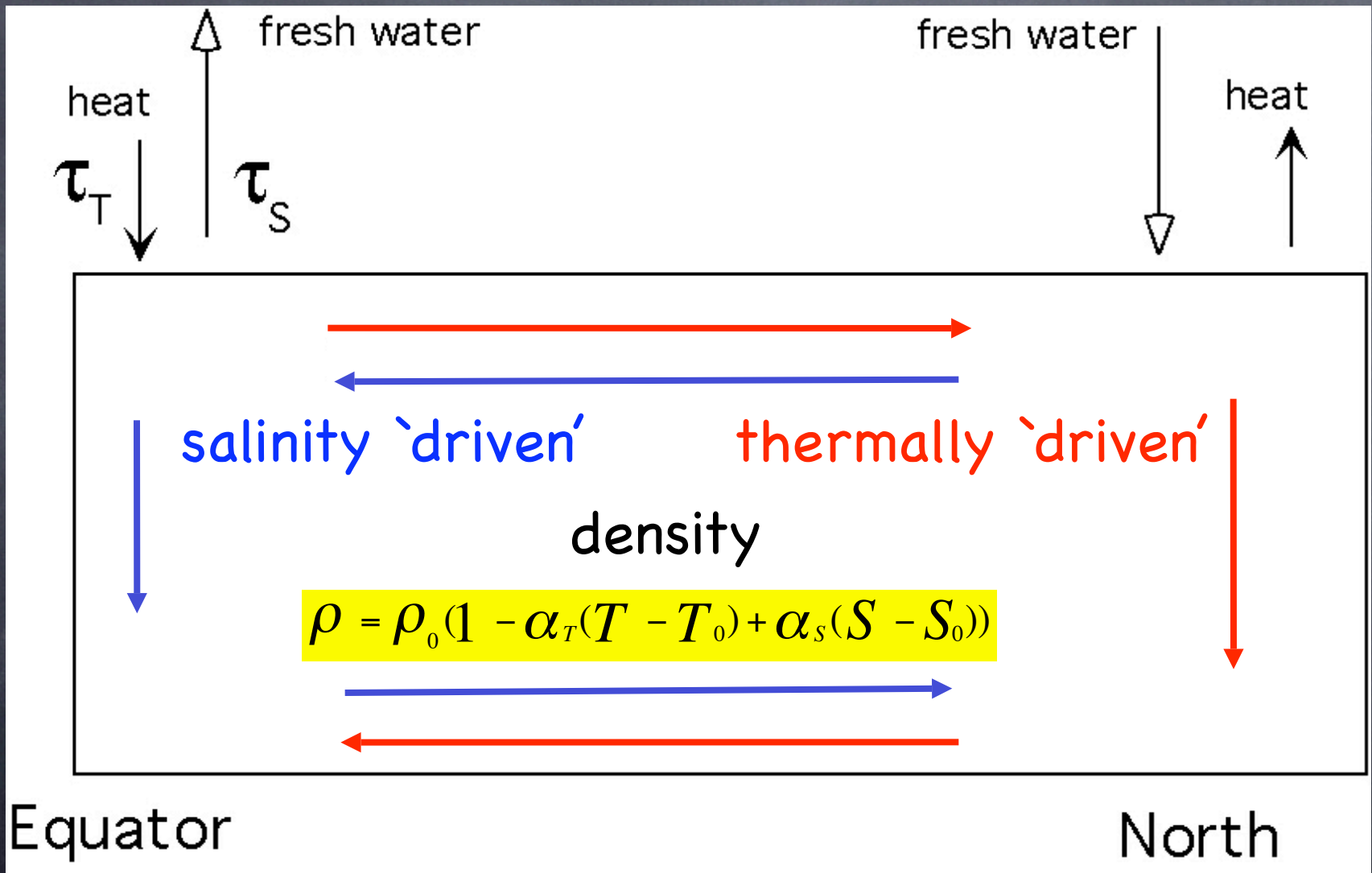


Sea surface temperature

Ocean model resolution: 10×10 km, L45

$d = 3600 \times 1800 \times 45 \sim 3 \times 10^8$

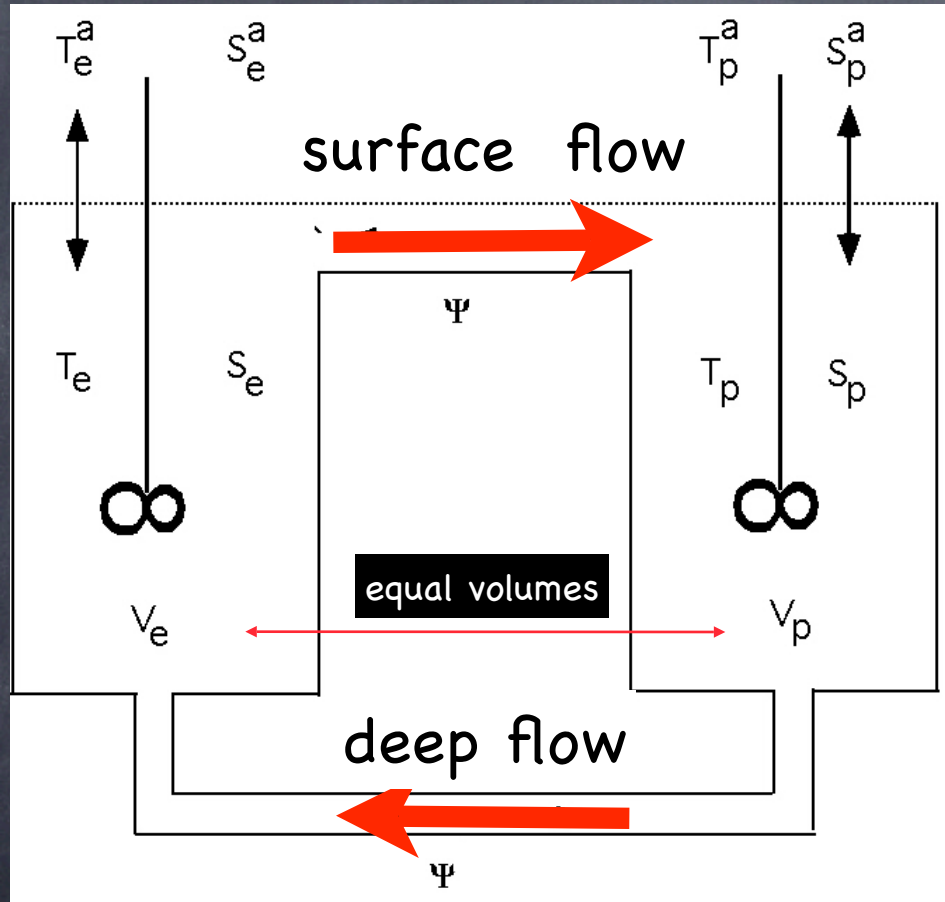
Possibility of rapid changes in the Atlantic MOC?



Equatorial Two-box model

Box

Polar Box



$$V \frac{dT_p}{dt} = C^T (T_p^a - T_p) + |\Psi| (T_e - T_p)$$

$$V \frac{dT_e}{dt} = C^T (T_e^a - T_e) + |\Psi| (T_p - T_e)$$

$$V \frac{dS_p}{dt} = C^S (S_p^a - S_p) + |\Psi| (S_e - S_p)$$

$$V \frac{dS_e}{dt} = C^S (S_e^a - S_e) + |\Psi| (S_p - S_e)$$

$$\Psi = \gamma (\rho_p - \rho_e)$$

$$\rho = \rho_0 (1 - \alpha_T (T - T_0) + \alpha_S (S - S_0))$$

Dimensionless two-box model

$$T = T(\text{equator}) - T(\text{pole})$$

$$S = S(\text{equator}) - S(\text{pole})$$

$$\frac{dT}{dt} = \eta_1 - (1 + |T - S|)T$$

$$\frac{dS}{dt} = \eta_2 - (\eta_3 + |T - S|)S$$

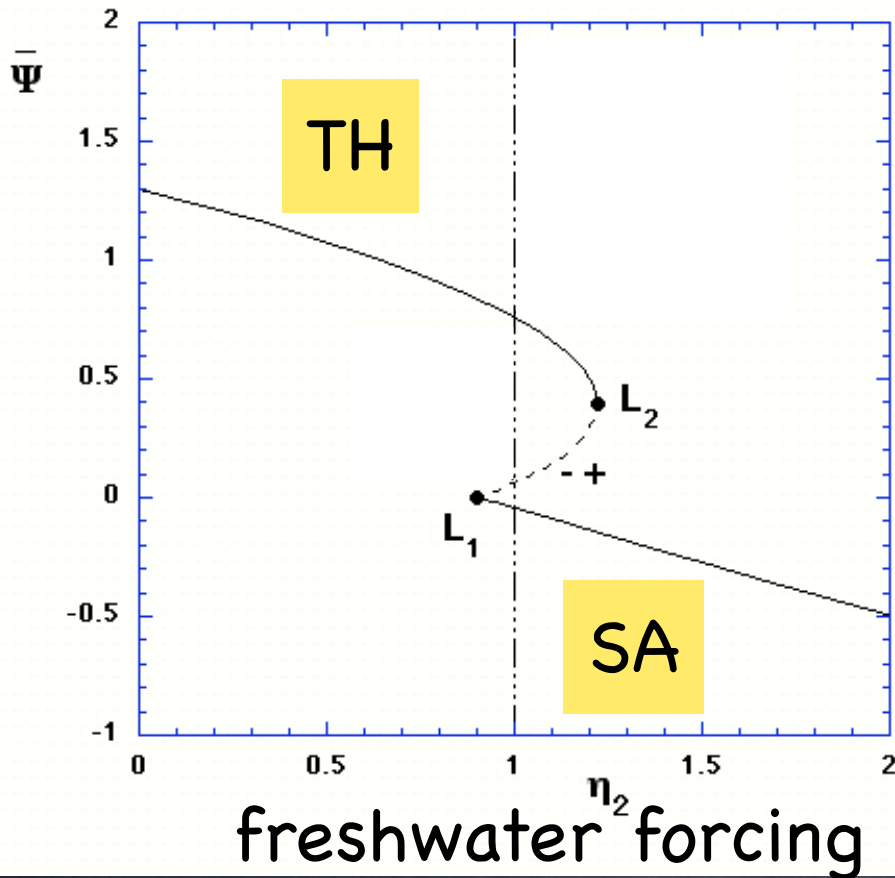
$$\Psi = T - S$$

$$\eta_3 = \frac{C^S}{C^T} = \frac{\tau^T}{\tau^S}$$

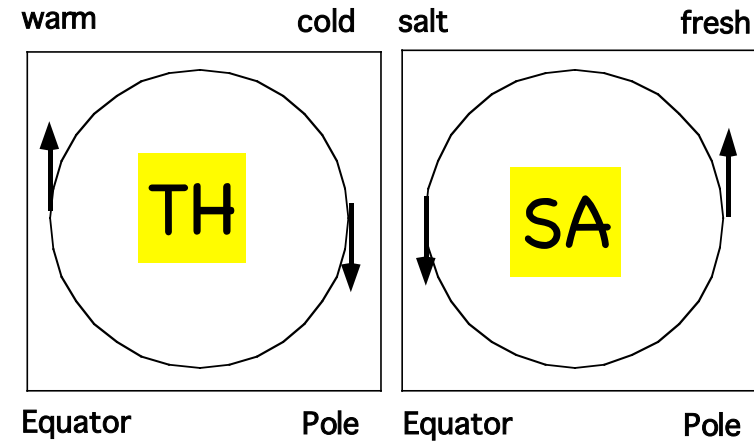
Ratio of adjustment time
to surface forcing

Bifurcation diagram

MOC strength

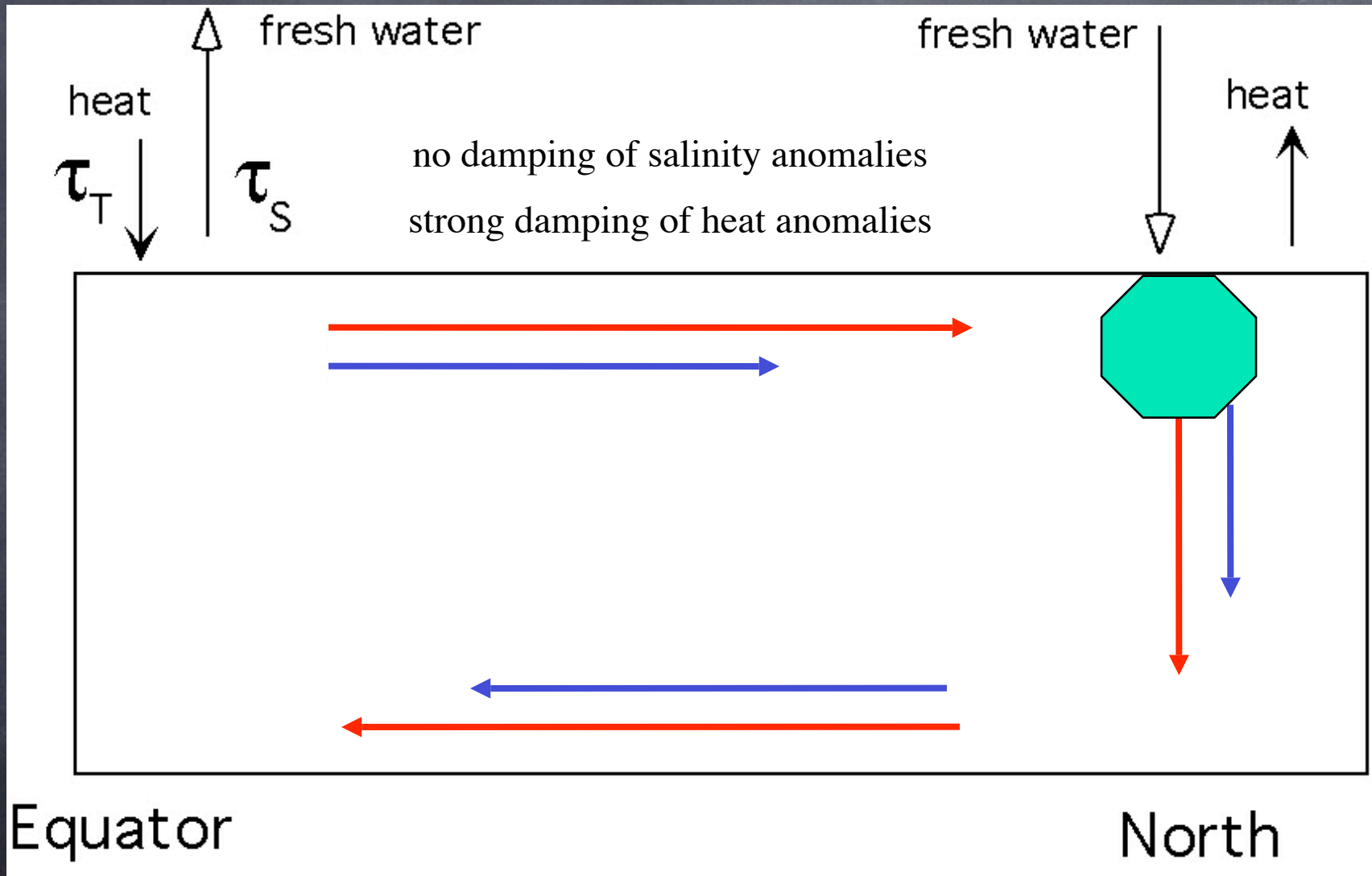


$$\Psi = T - S$$



L: saddle - node bifurcations

The salt-advection feedback



Robustness over the model hierarchy ?

Continuation Methods

$$M \frac{dx}{dt} + G(x, \lambda) = 0, x \in \mathbb{R}^d$$

d: # degrees of freedom

Numerics

Steady states:

$$G(x, \lambda) = 0 \Rightarrow$$

$$J(x^k, \lambda^k) \Delta x^{k+1} = -G(x^k, \lambda^k)$$

Norm

Newton-Raphson

Euler predictor

Pseudo-arclength method

s

instabilities

Linear stability

$$\sigma = \sigma_r + i\sigma_i$$

Complex growth factor

Control parameter

λ

$$Ax = b$$

$$A : d \times d$$

MRILU

GMRES

$$Ax = \sigma Bx$$

$$A, B : d \times d$$

JDQZ

Status UU/RUG/LANL group ~ 2009

- Full 3D primitive equations (ocean - only models)
- Solutions for ocean models with $d \sim 1,000,000$
- Tailored preconditioner for ocean model & (F)GMRES
- Implementation of state of the art turbulent mixing schemes

Basic
paper:

A tailored solver for bifurcation analysis
of ocean-climate models

Arie de Niet ^a, Fred Wubs ^{a,*}, Arjen Terwisscha van Scheltinga ^b,
Henk A. Dijkstra ^b

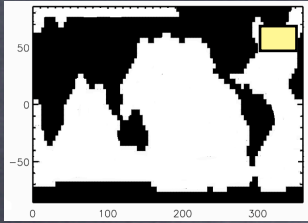
Journal of Computational Physics 227 (2007) 654–679

Recent developments:

Parallel implementation into TRILINOS/LOCA

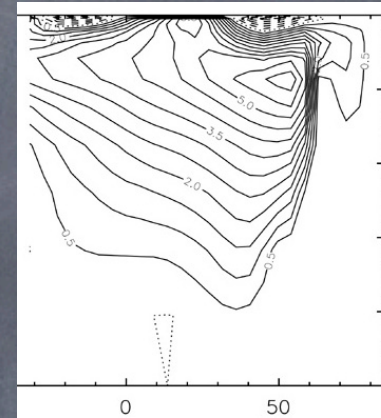
work with Sandia & LANL groups

Bifurcation diagram (global ocean model)



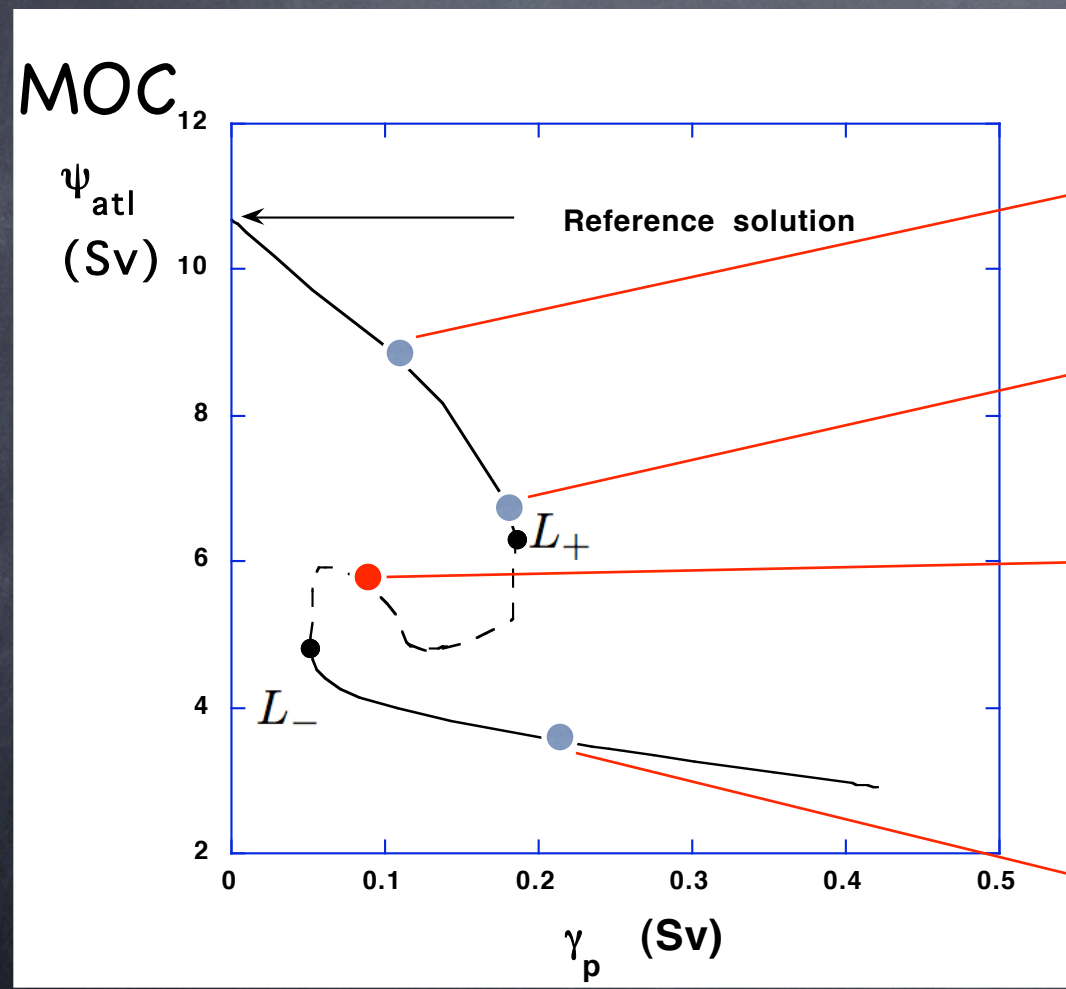
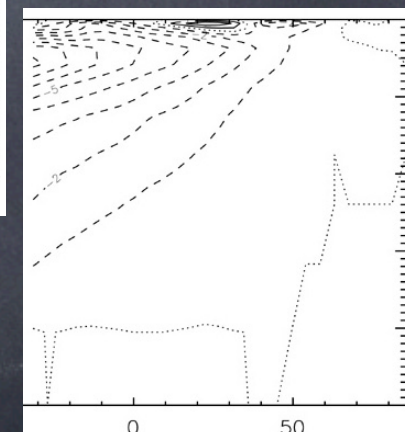
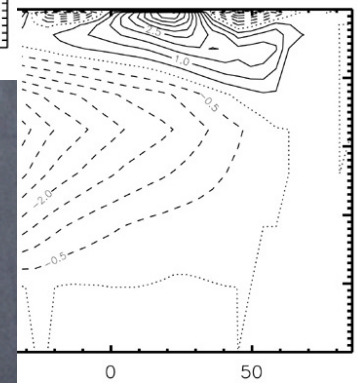
$d \sim 300,000$

depth

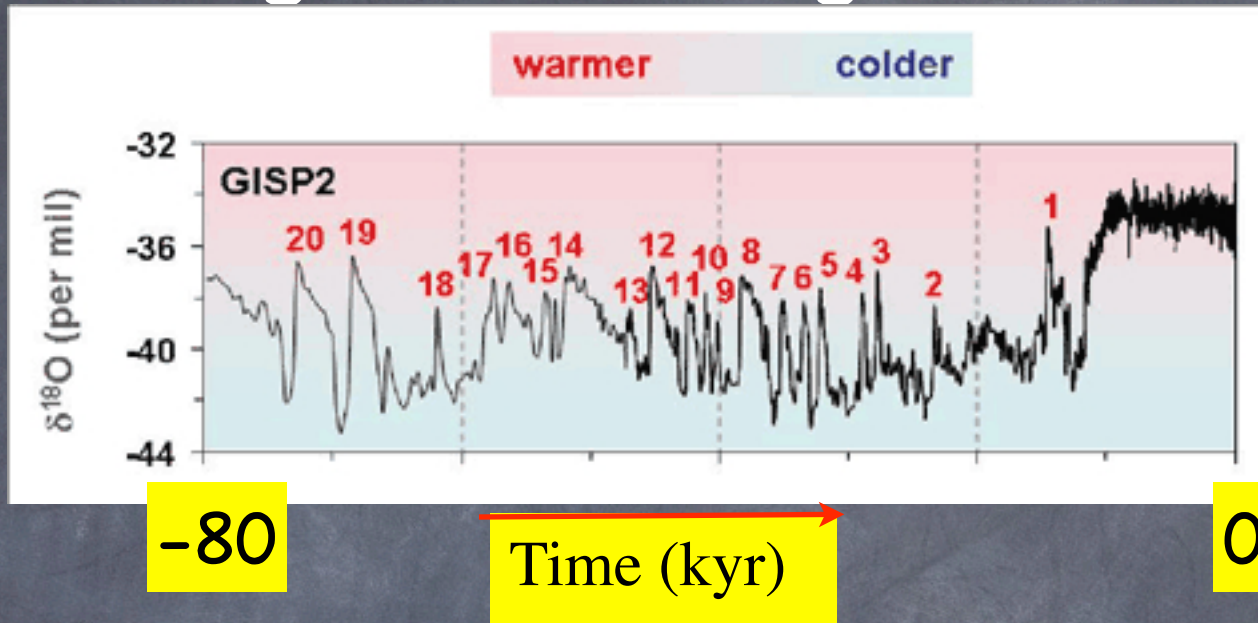


Atlantic MOC (Sv)

latitude



Dansgaard-Oeschger Events



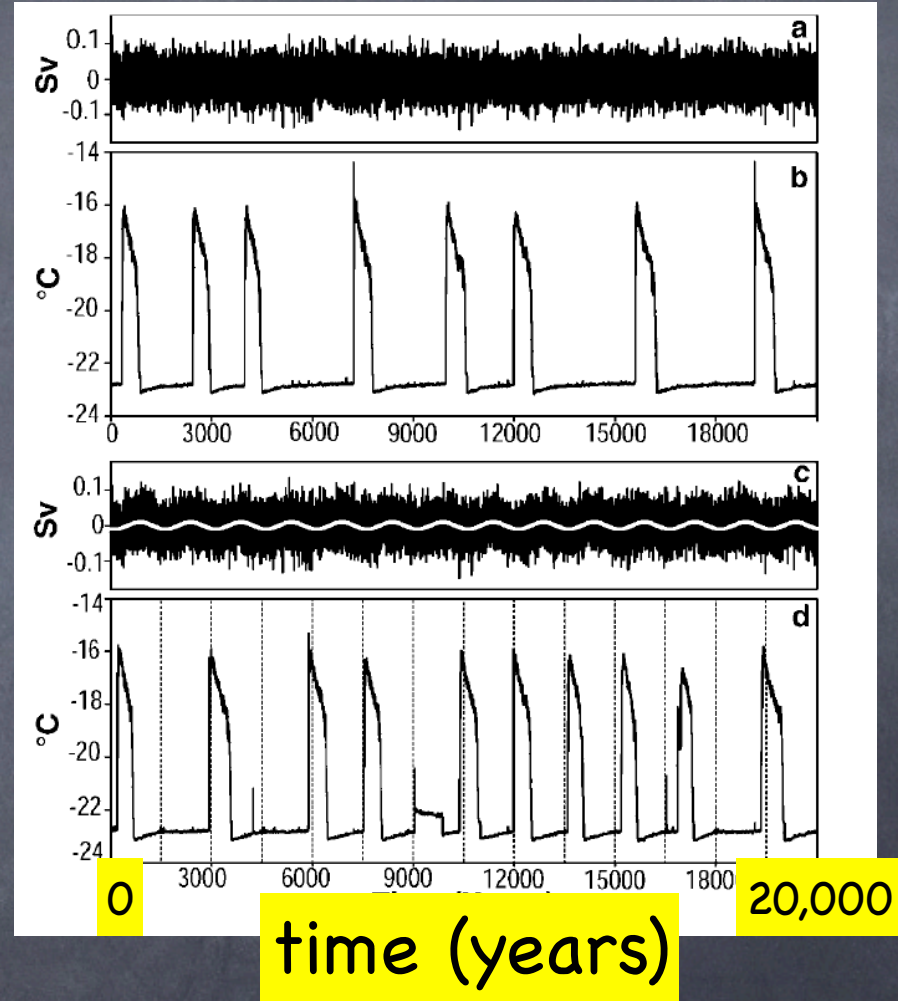
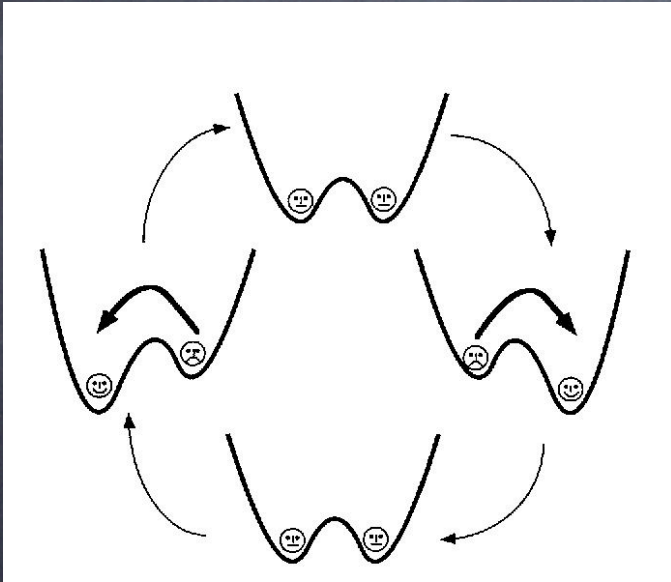
The Atlantic Meridional Overturning Circulation (MOC) is sensitive to freshwater perturbations and multiple equilibria may have existed in the past

Dynamical scenarios:

1. Stochastic Resonance
2. Coherence Resonance

1. Stochastic Resonance

freshwater
forcing
temperature



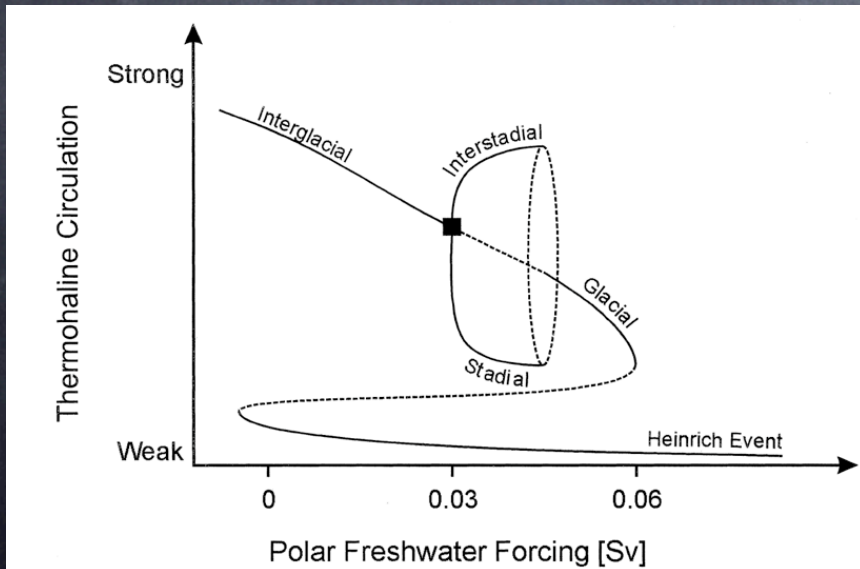
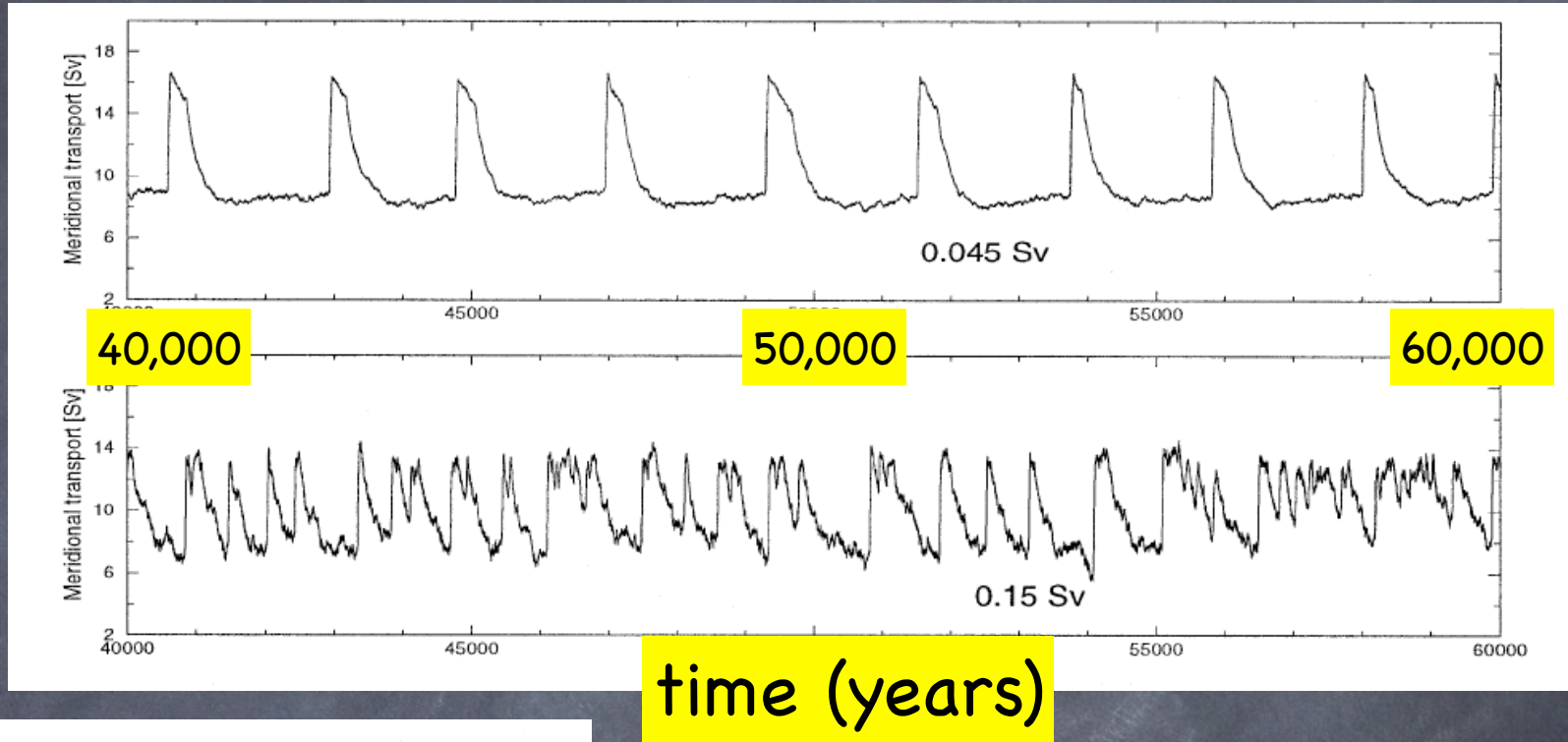
Ganopolski & Rahmstorf, PRL, (2002)

Problem: origin of the 1500 year period in the freshwater forcing???

2. Coherence Resonance

MOC strength

MOC strength

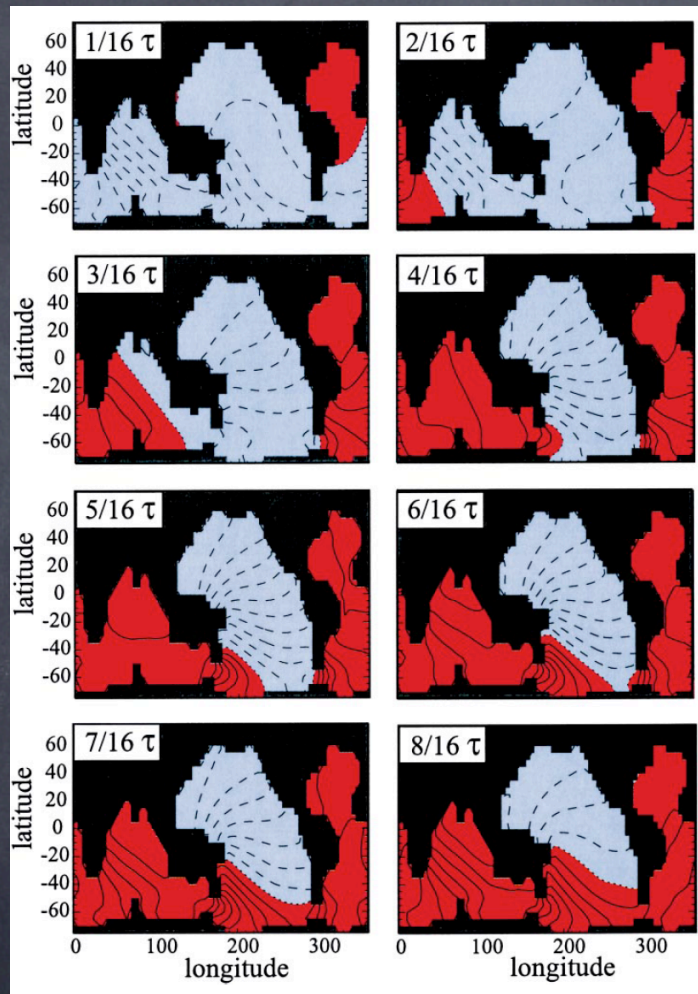


Box model results

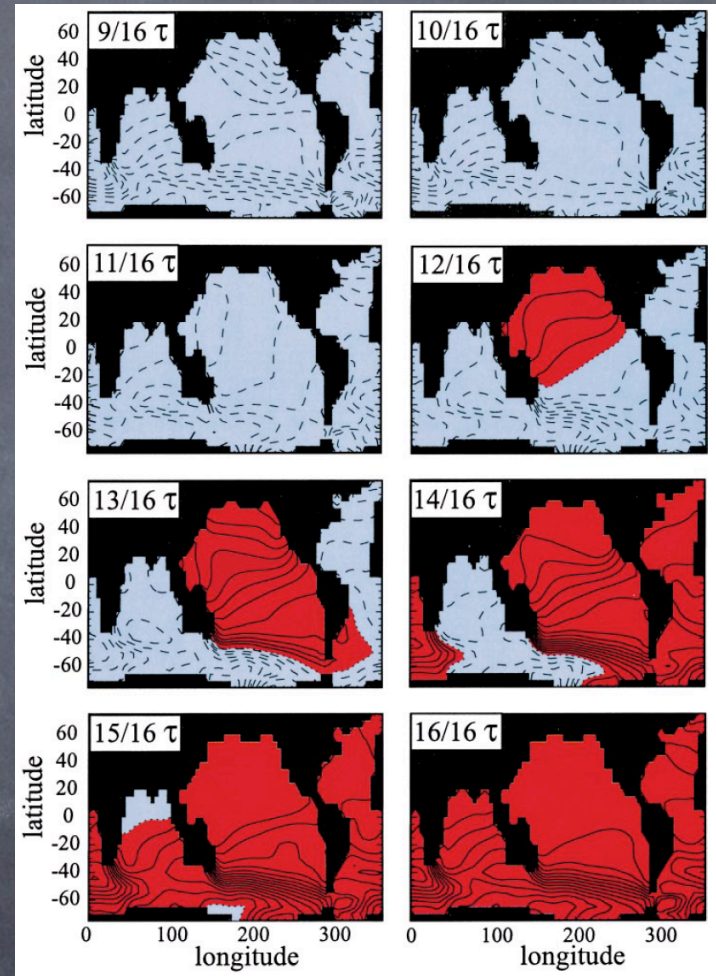
Timmermann et al., J. Clim., (2003)

Problem: robustness of the oscillatory modes???

Linear Stability of Steady States → Global Temperature Pattern of an Oscillatory Mode



3000 m depth



500 m depth

Period: 3800 yr

... but modes are strongly damped.

Consequences for the Present-Day climate?

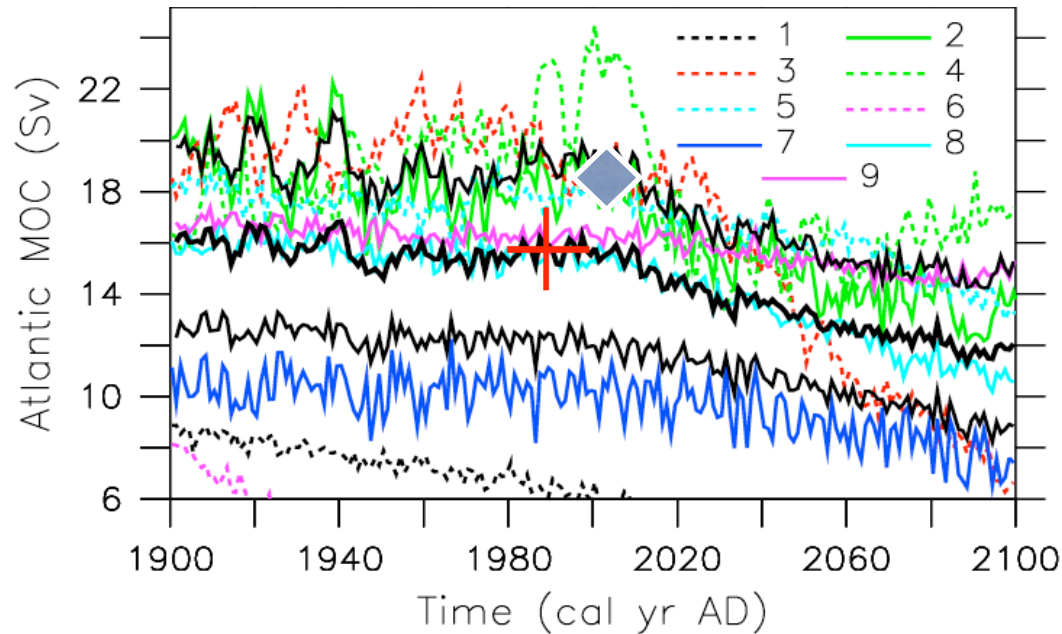
General notion:

Increasing precipitation in the northern North Atlantic (as well as increased melt water from Greenland) may destabilize the MOC!

Central problem:

Can the present Atlantic MOC collapse and if so, what is the probability that this occurs before 2100?

Intergovernmental Panel for Climate Change: 2007 model results



CO_2

up to 720 ppmv
by 2100

Measured (2004):

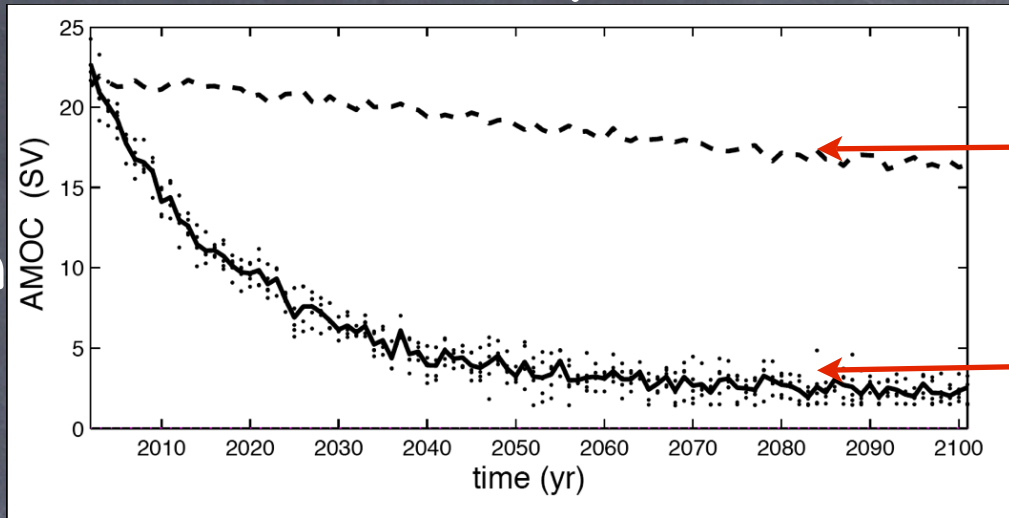
MOC at 26N:

19 ± 5 Sv

In the 'best' models, the MOC only decreases by a few Sv from 2000 to 2100

Artificial collapse (ECHAM5/OM1)

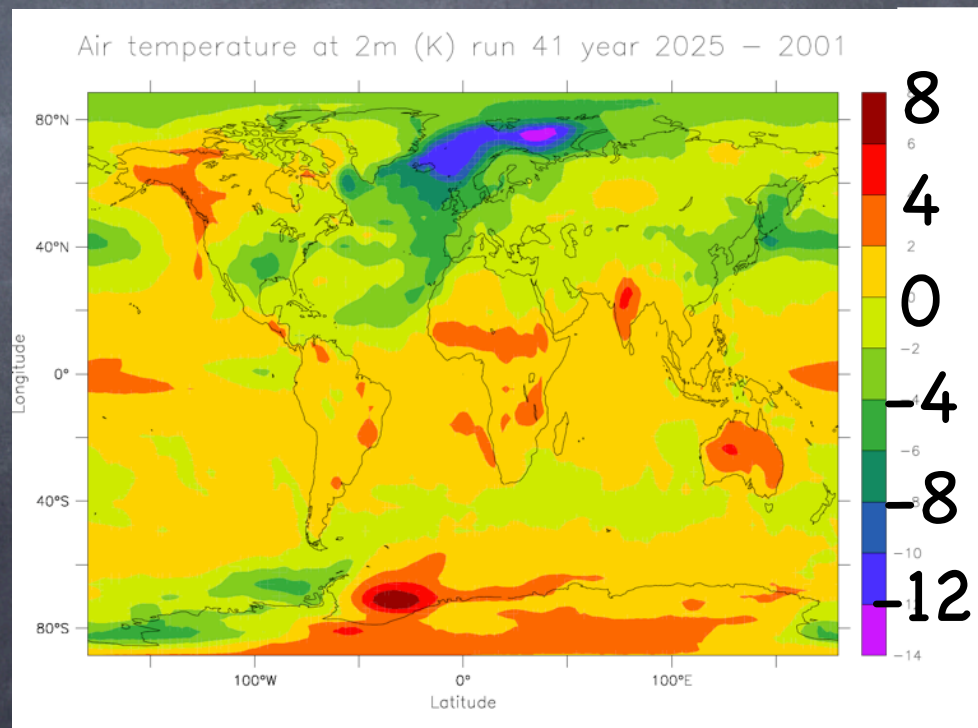
MOC strength (Sv)



ocean model resolution: 50 x 100 km, L24

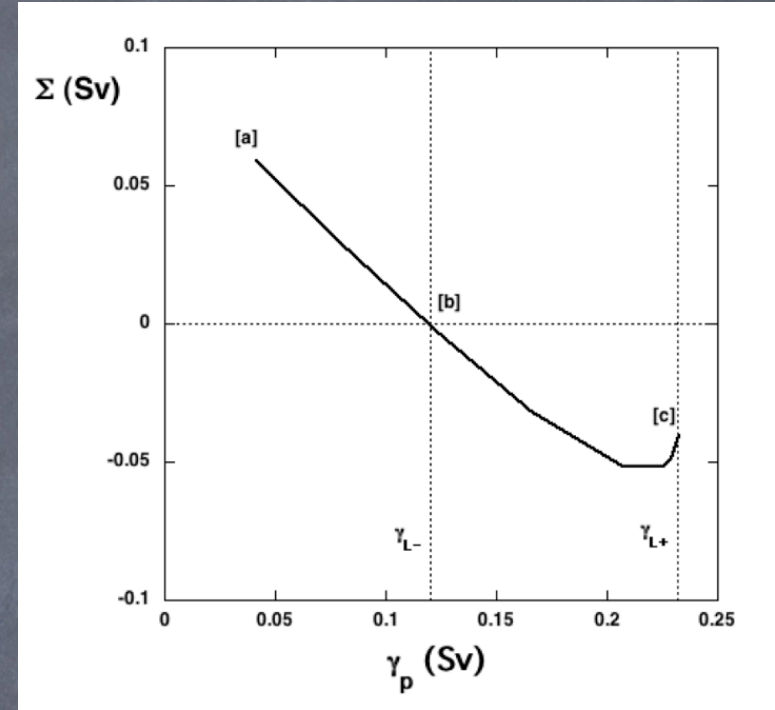
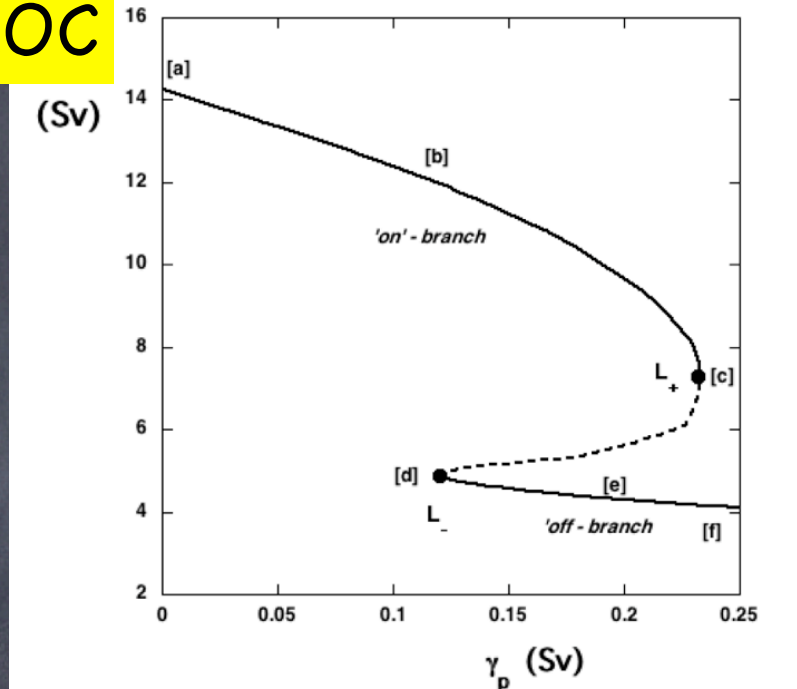
Surface Air Temperature difference 2025 - 2001

... but no multiple equilibria in these models so far. Why?

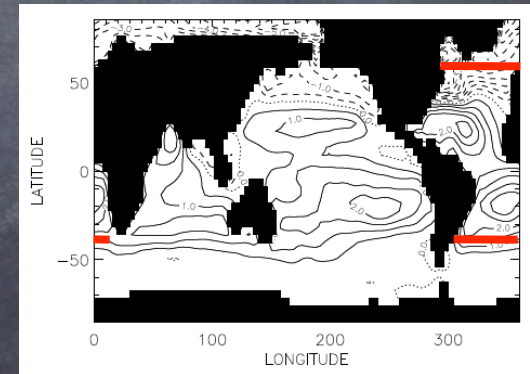


Freshwater budget over the Atlantic basin

MOC

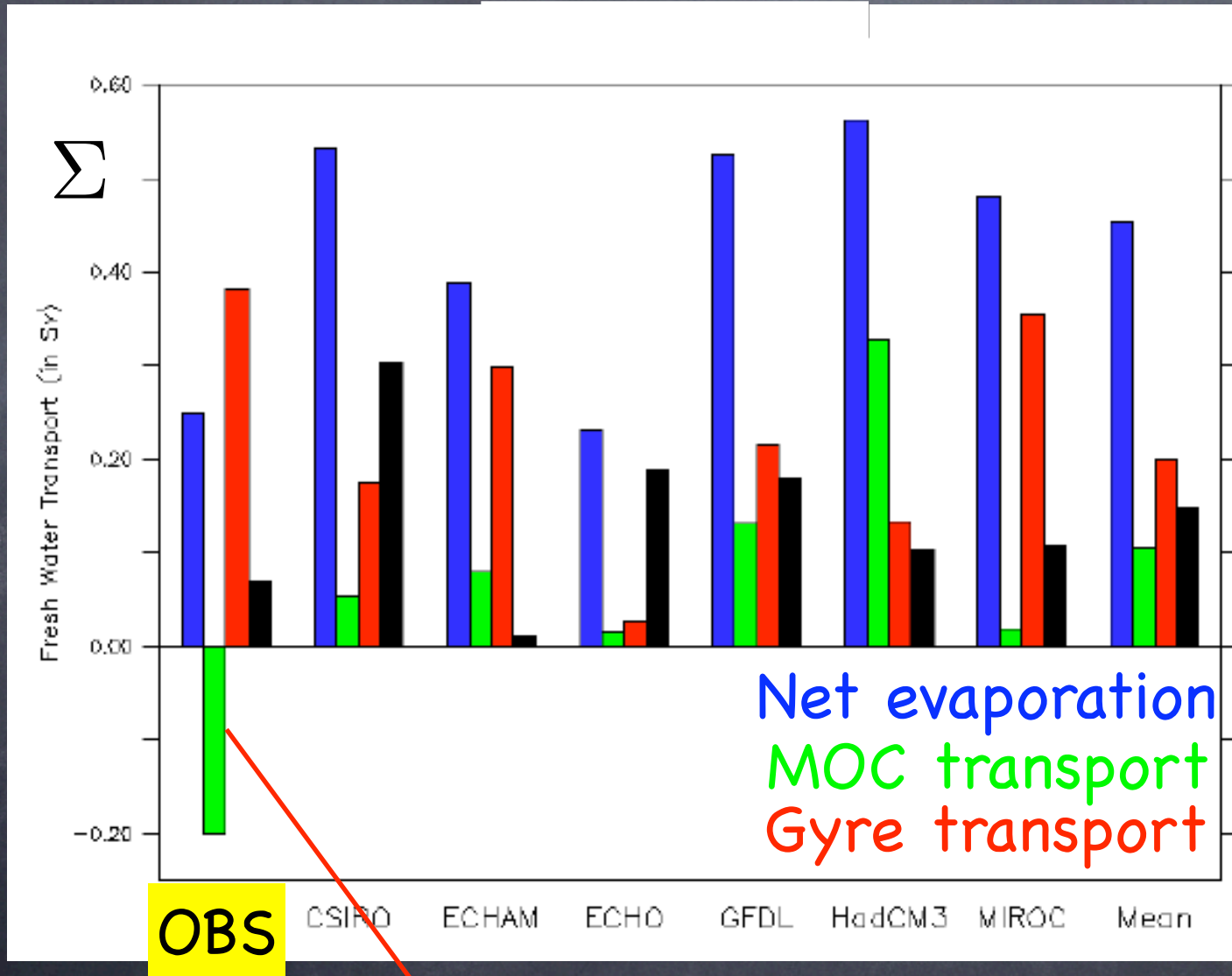


Net freshwater transport of Σ : the MOC in/out of the Atlantic basin



Transition is only possible when the MOC exports freshwater at 35 S in the Atlantic!!

Climate models likely have a large bias!



OBS

Weijer et al., JPO, (1999)

Drijfhout et al., in prep (2009)

Summary and Perspective

The Atlantic Meridional Overturning Circulation (MOC) is sensitive to freshwater perturbations and multiple equilibria may have existed in the past (and possibly at present)

In current dynamical theories of the Dansgaard-Oeschger events, transition behavior between different MOC equilibria is a central component

We are still far from a reasonable estimate of the probability that the MOC will collapse before 2100