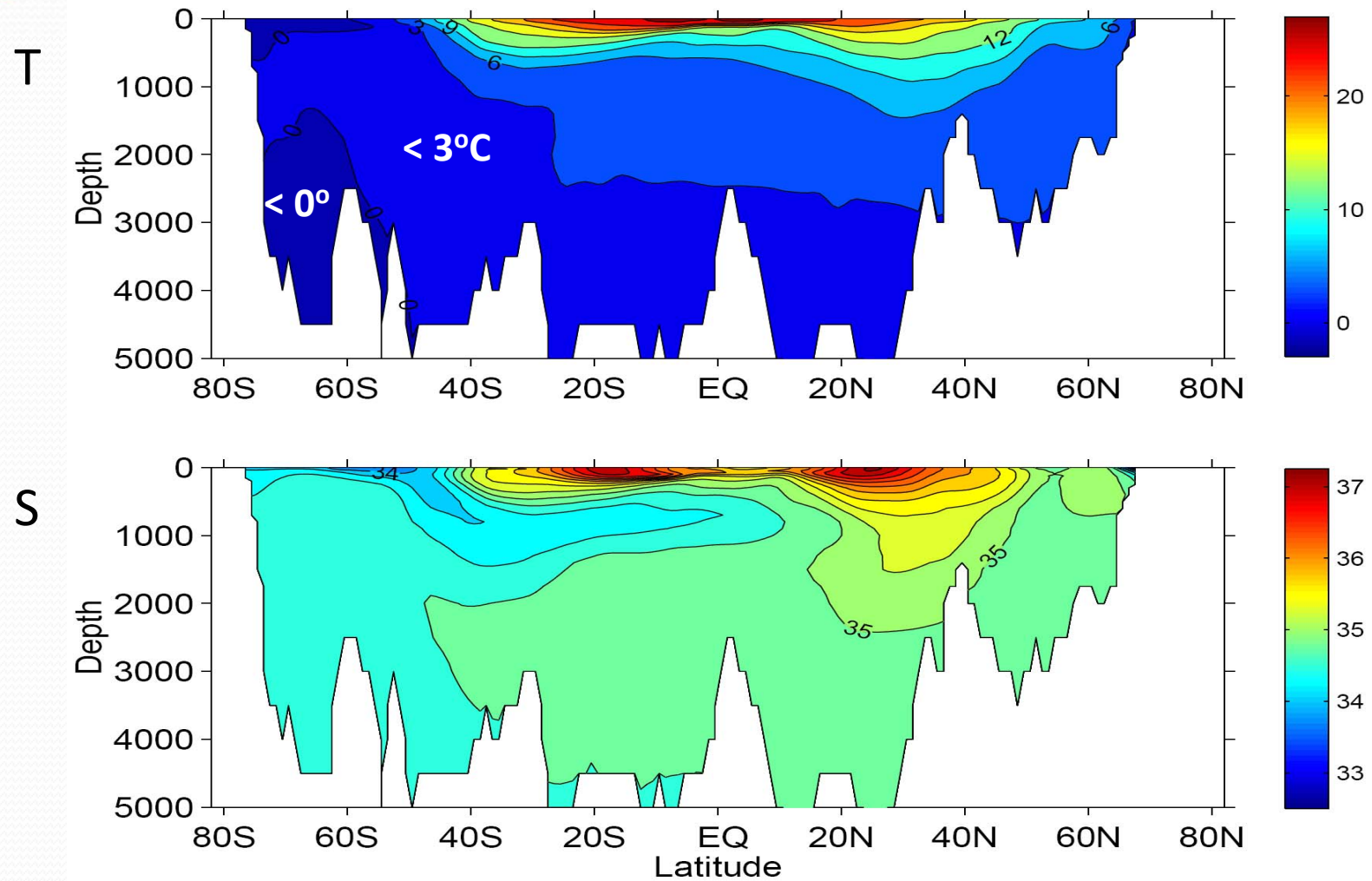




Lecture 18

Thermohaline circulation (THC) and ocean meridional overturning

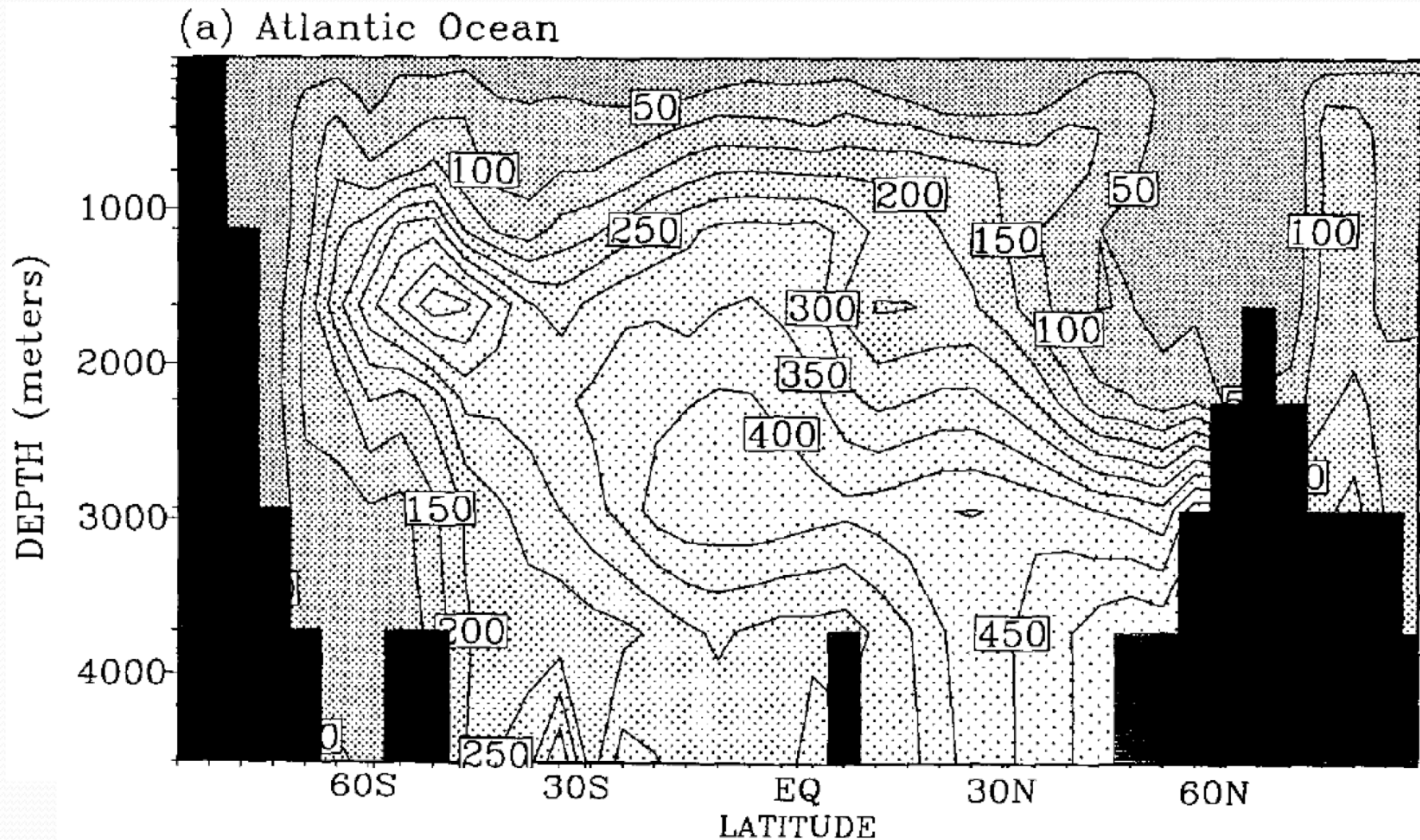
Atlantic Ocean



*What controls the ocean meridional stratification
and its meridional overturning circulation?*

Ocean ventilation age (years)

the time that would take for a hypothetical water parcel to reach certain depth from the surface.



From an ocean GCM, after Mat England 1995



Water Masses (Water types)

*A **watermass** is a body of water that can be distinguished by its physical characteristics (distinct range of T and S). The characteristics of a watermass often reflect the characteristics of the source region.*

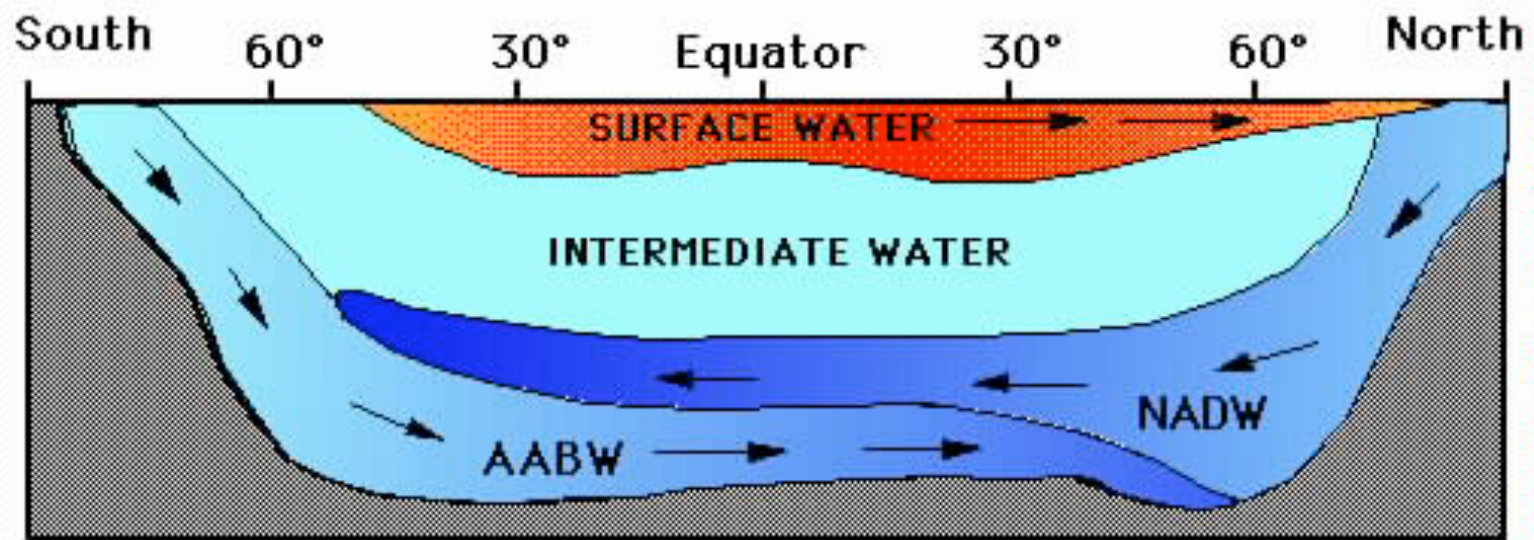
Several water masses in the Atlantic:

AABW = AntArctic Bottom Water

NADW = North Atlantic Deep Water

AAIW = AntArctic Intermediate Water

Atlantic Ocean Thermohaline Circulation



Increased nutrients & dissolved CO₂

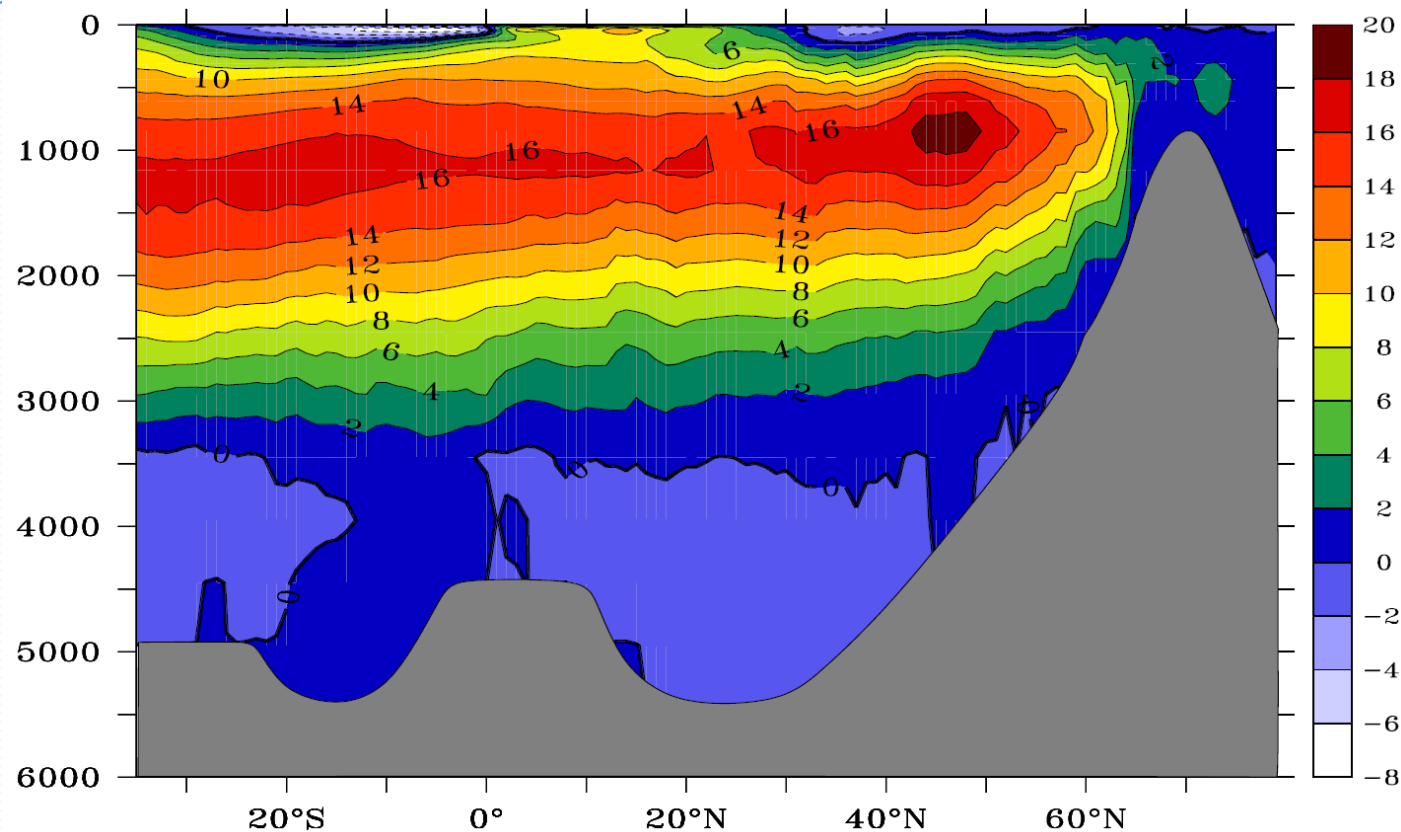


Warm, low nutrients, & oxygenated



A schematic picture of the main water masses in the Atlantic

The stream function (Ψ) of meridional overturning in the Atlantic (in Sv, m^3/s),

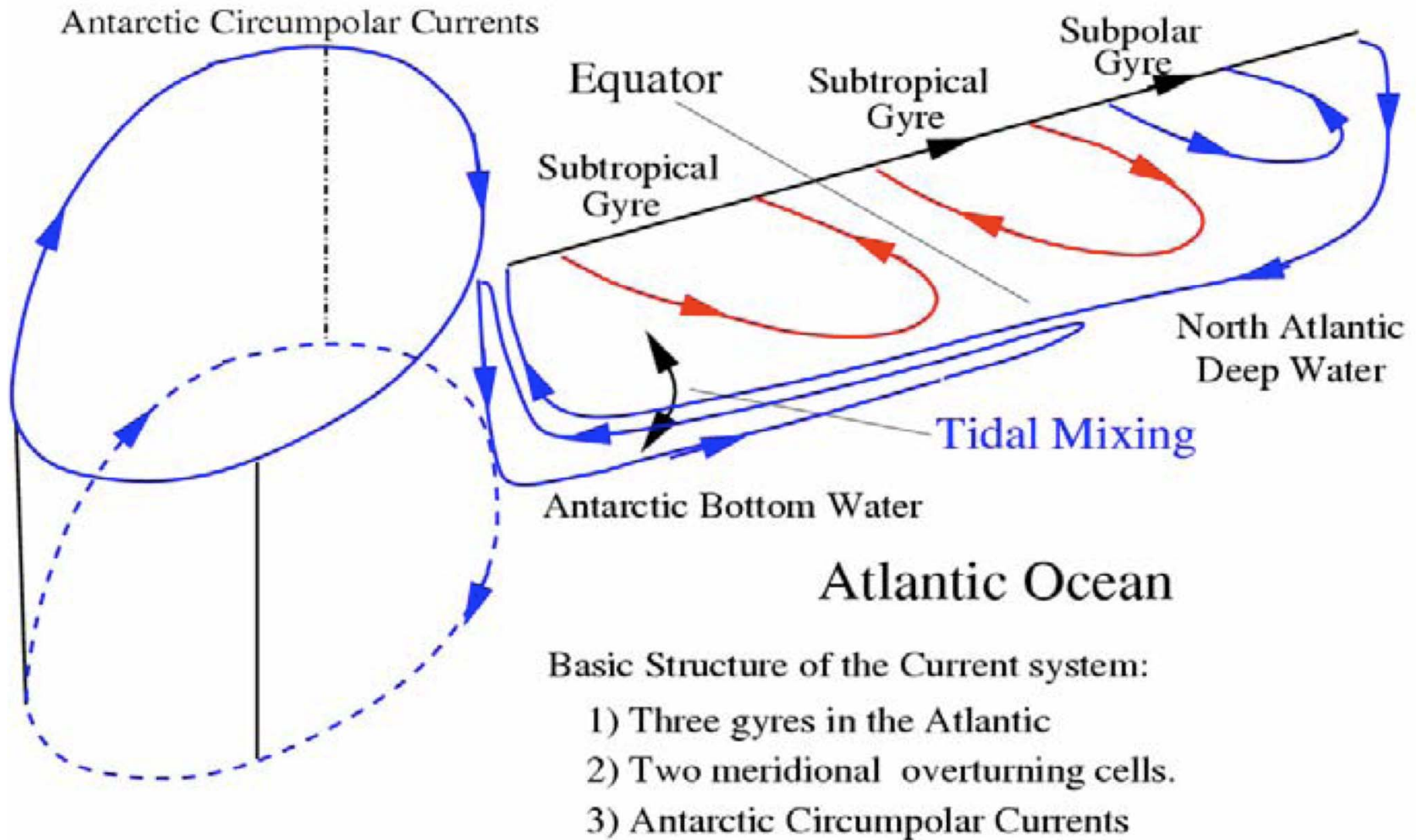


$$V = \int v(x, y, z) dx; W = \int w(x, y, z) dy; \quad V = \frac{\partial \Psi}{\partial z}; W = -\frac{\partial \Psi}{\partial y}$$

The streamlines (lines of $\Psi = \text{const}$) are shown. Note the Ekman (wind-driven) cells in the upper 500 m, the NADW cell down to 3500 m, and the AABW cell near the bottom (Köhl et al 2006), based on a GCM.

based on a model constrained by observational data (Köhl, et al 2006).

GENERAL OCEAN CIRCULATION



(Huang lecture, WHOI/MIT)

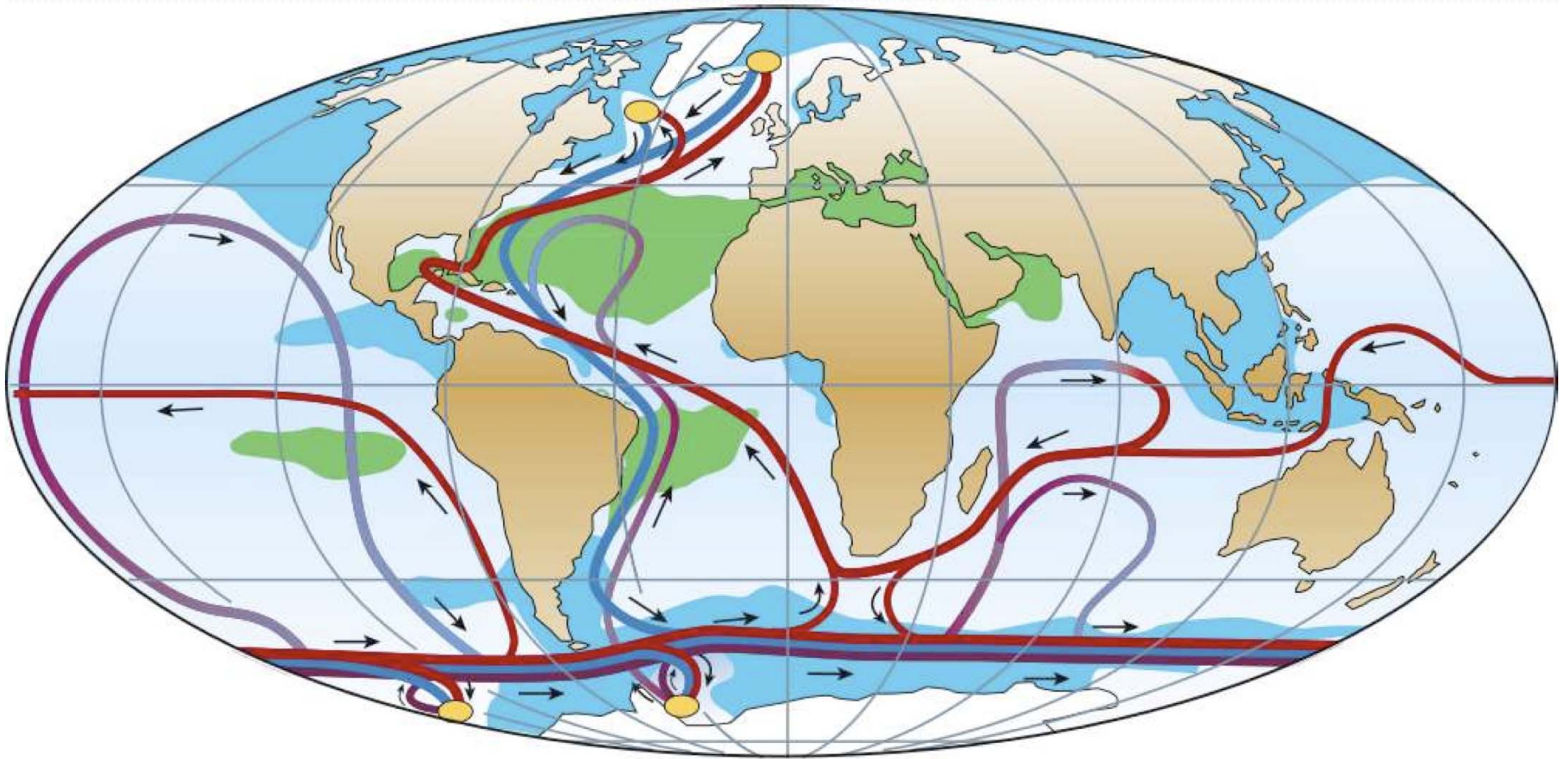
Conceptually, the ocean circulation can be separated into two components: the thermohaline (THC) and wind-driven; both contribute to the ocean overturning:

1. The wind-driven circulation is shallow (a few hundred meters) and includes western boundary currents such as the Gulf Stream and the Kuroshio (the last few lectures).

2. The thermohaline circulation (THC) is deep and governed by large scale surface density and hence temperature and salinity gradients. (Other names used for the THC: MOC – meridional overturning circulation, the ocean conveyor belt). The Gulf Stream also a part of the THC.

The THC controls the properties of the deep ocean, including its stratification, temperature, and the storage of CO₂ in the ocean.

LARGE SCALE OCEAN CIRCULATION



(Rahmstorf, 2002)



CONTENT:

- Forcing
- Theory
- Stability & Variability

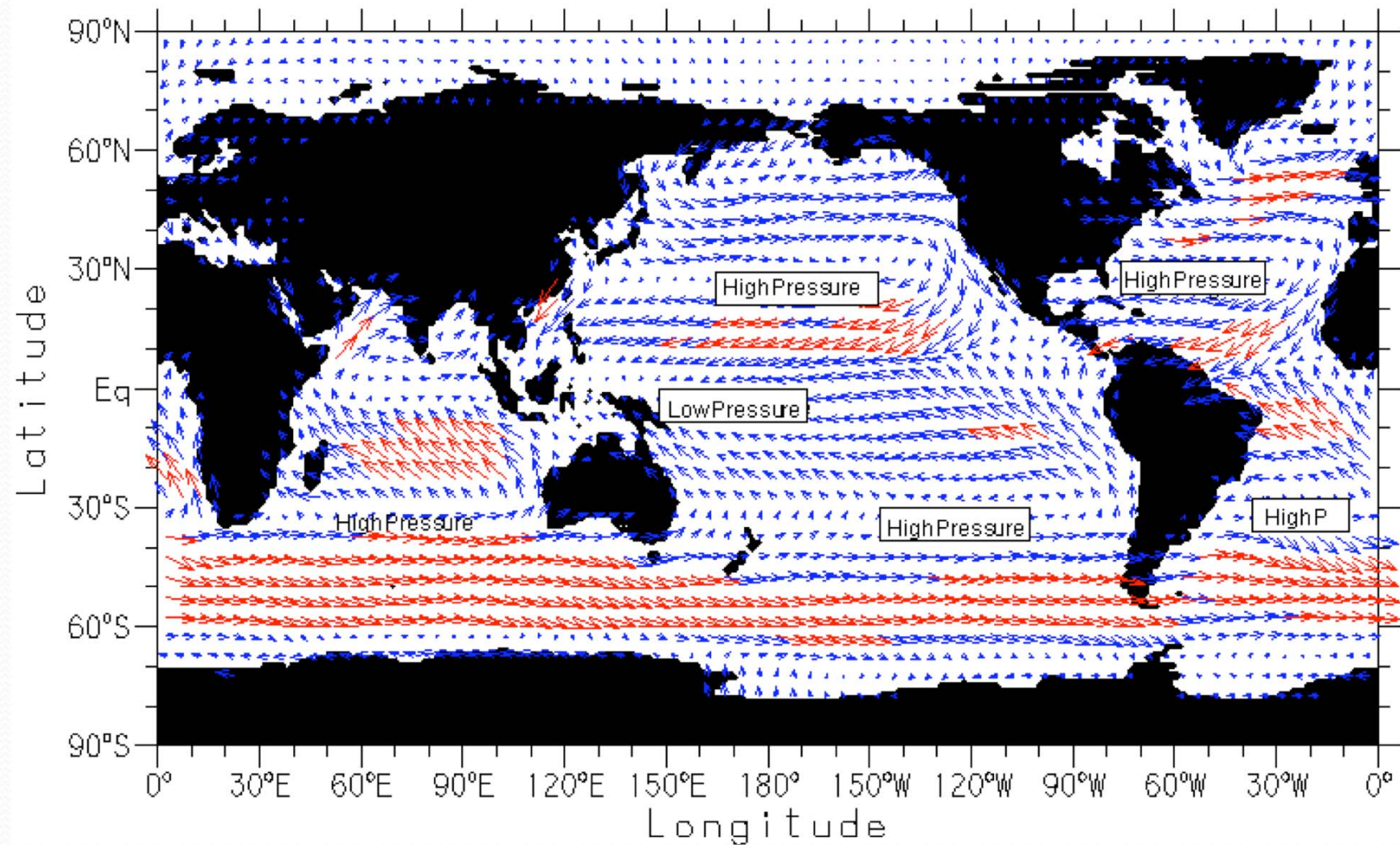


OCEAN CIRCULATION FORCING:

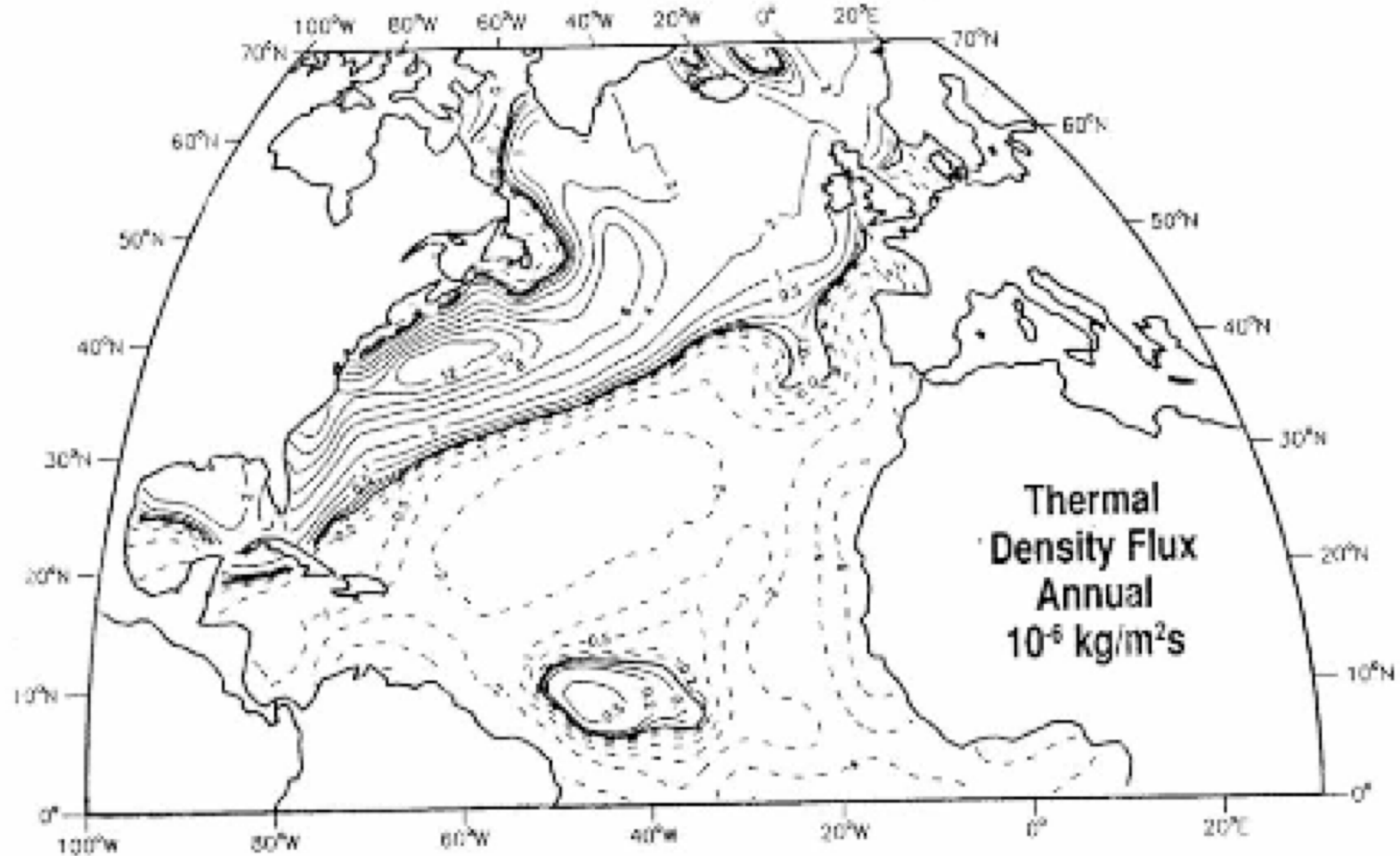
- 1) Wind stress
- 2) Heat flux
- 3) Freshwater flux
- 4) Tidal force

WIND STRESS

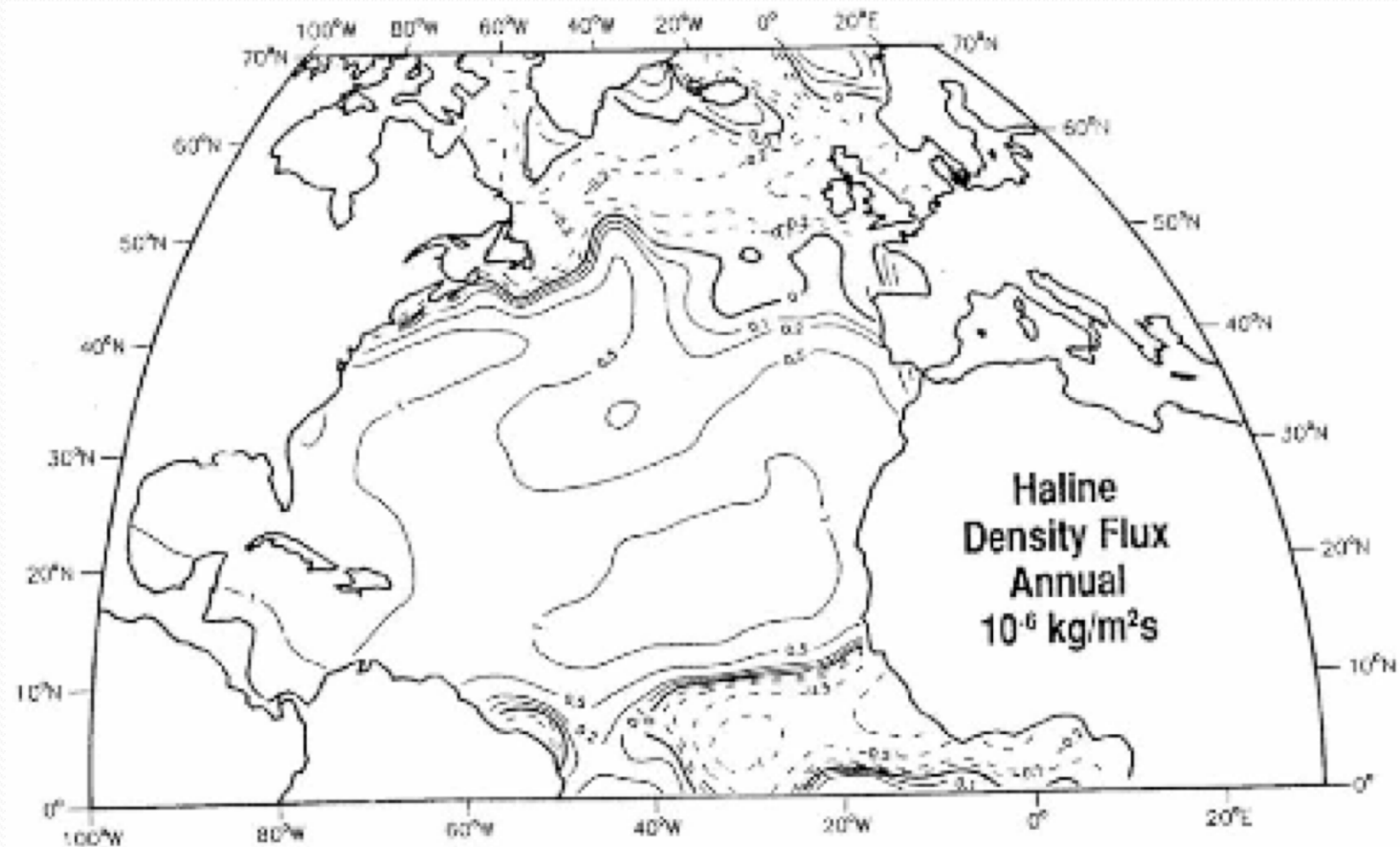
$\rightarrow = 0.50 \text{ dyne cm}^{-2}$
 $\rightarrow = 1.00$
 $\rightarrow > 1.00$ annual wind stress vector



HEAT FLUX

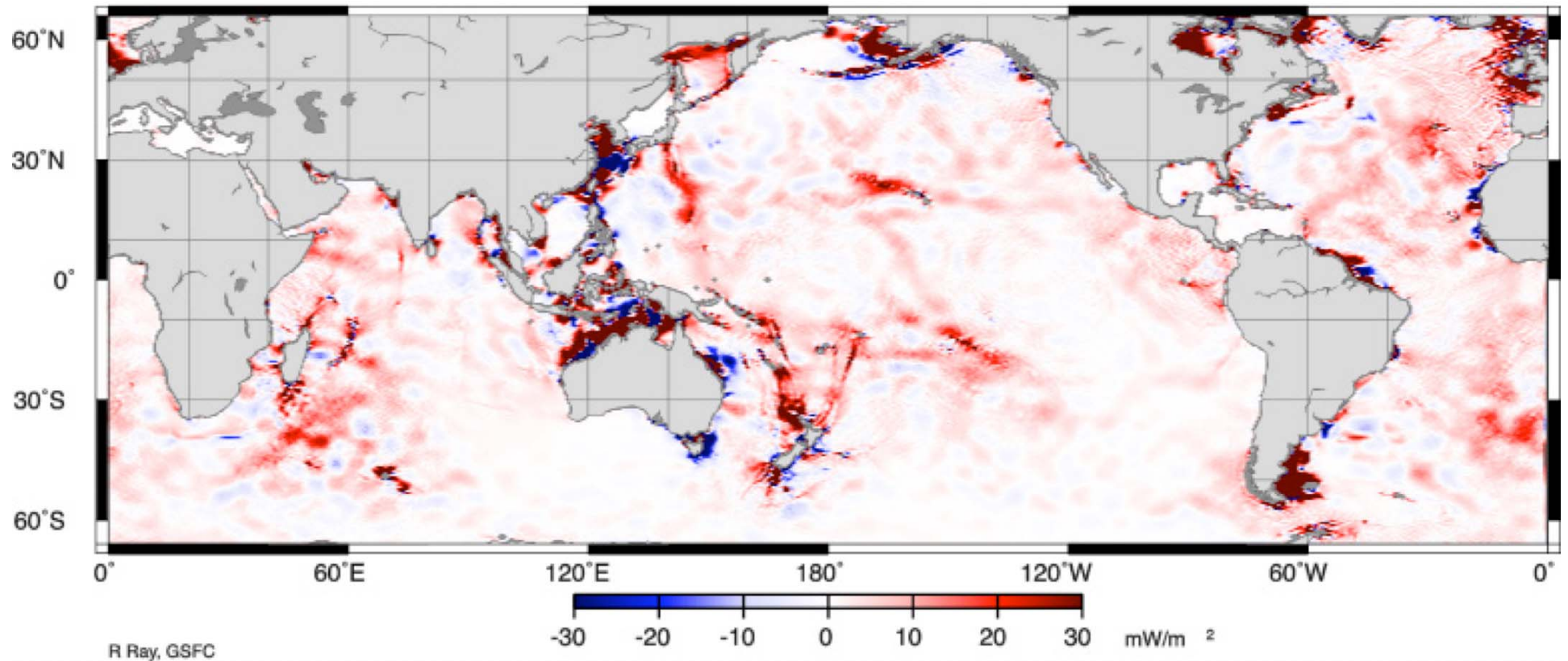


FRESHWATER FLUX



TIDAL FORCE

M2 Tidal Energy Dissipation
From balance of working and flux divergence

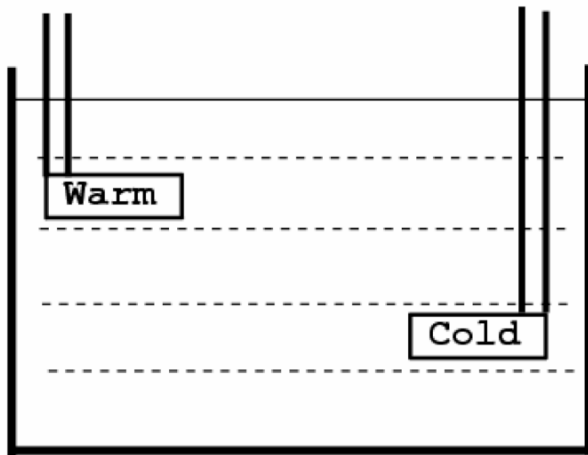


Sandstrom Theorem:

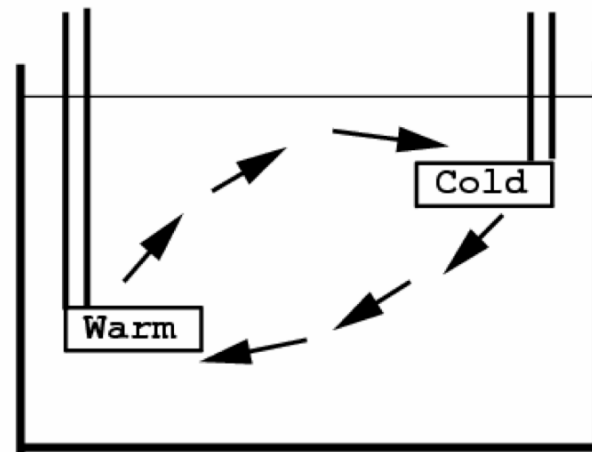
Sandstrom's original papers (1908, 1916) are in German, not easily accessible, but the citation from Defant's book is very concise and accurate:

A closed steady circulation can only be maintained in the ocean if the heat sources are situated at a lower level than the cold sources
(Defant, 1961, page 491).

Sandstrom (1916) considered the mechanical energy balance of the steady circulation in the oceans. In order to overcome friction, there should be a net input of mechanical energy over each closed streamline

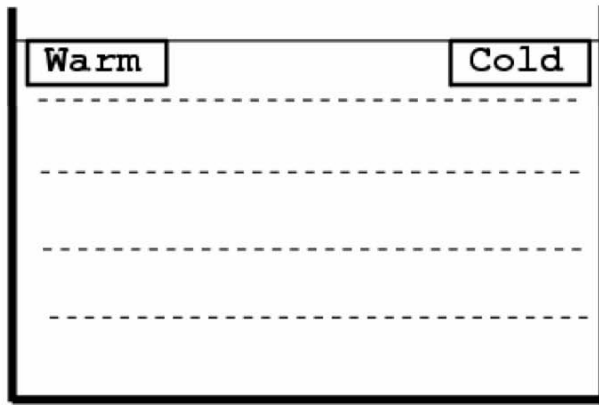


a) Heat source higher than cold source:
No circulation.

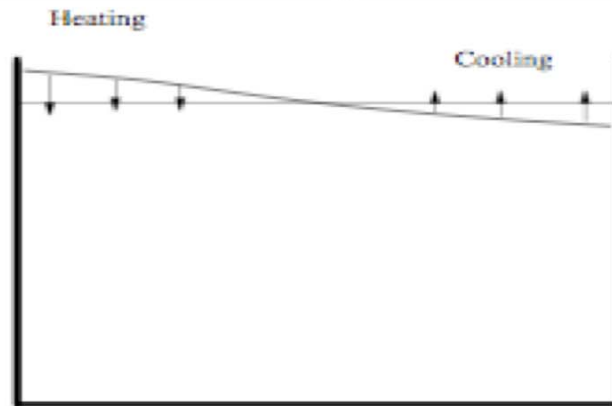


b) Cold source higher than heat source:
There is a circulation.

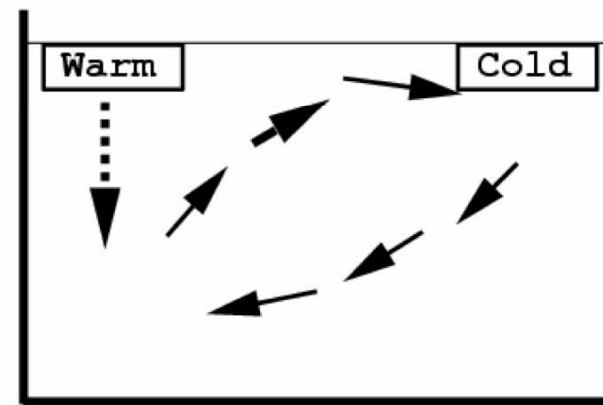
Application of the Sandstrom' Theorem to the world oceans



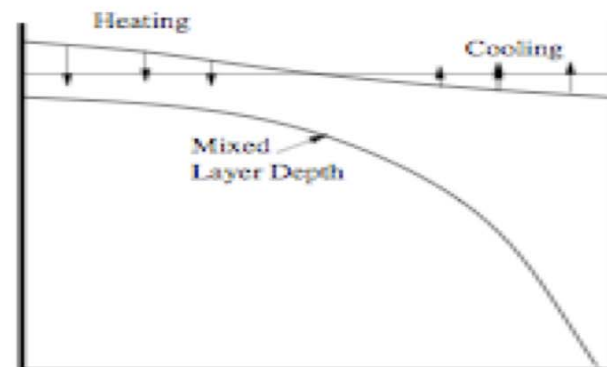
- a) Circulation driven by molecular mixing is extremely weak.



- a) Heating/cooling an infinitely thin layer do not generate much GPE.



- b) Effective depth of heat source moved downward by tidal and wind mixing: circulation is very strong.



- b) Convective adjustment induced by cooling is a sink of GPE.

Necessity of a net input of Energy to sustain the actual ocean circulation:

➤ The vertical mixing (wind or tides)

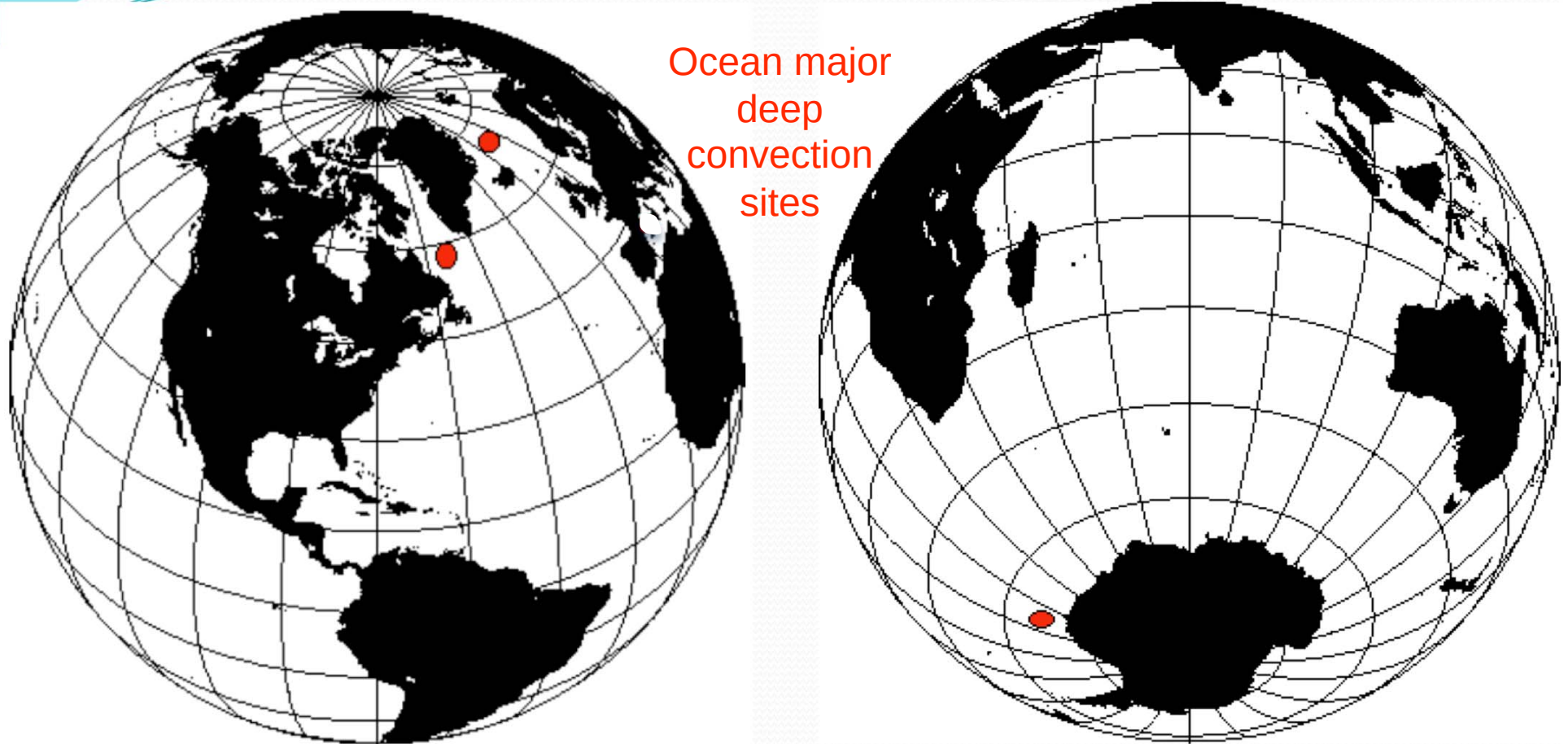


THERMOHALINE CIRCULATION STRUCTURE

To induce deep ocean circulation we need to interconnected mechanisms:

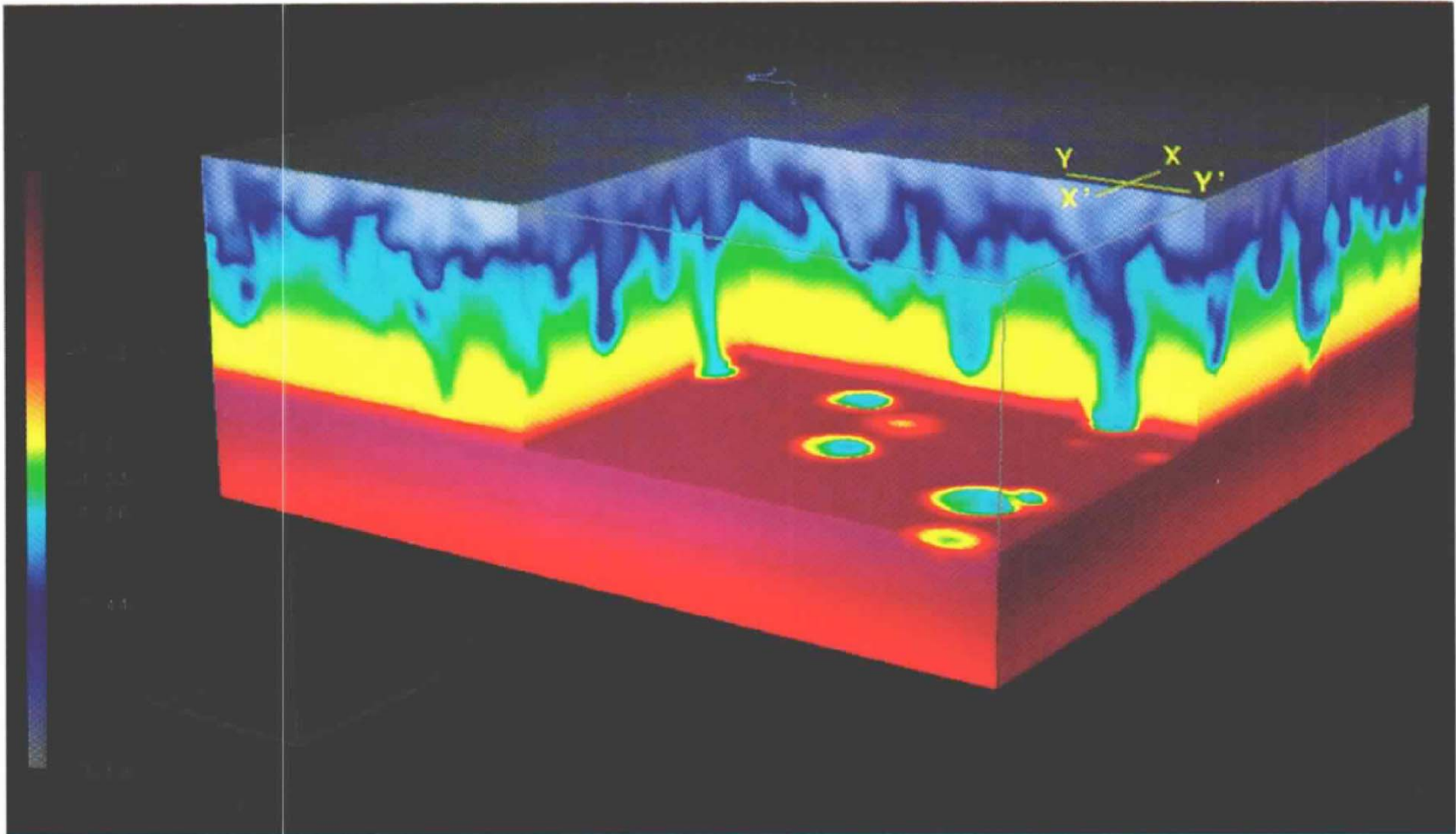
- 1. Deep convection (sinking of cold water in localized regions of high latitudes)*
- 2. Upwelling through the rest of the ocean (it is necessary to bring cold water back to the surface, otherwise the ocean will be filled completely with cold water and the circulation stops)*

CONVECTION:

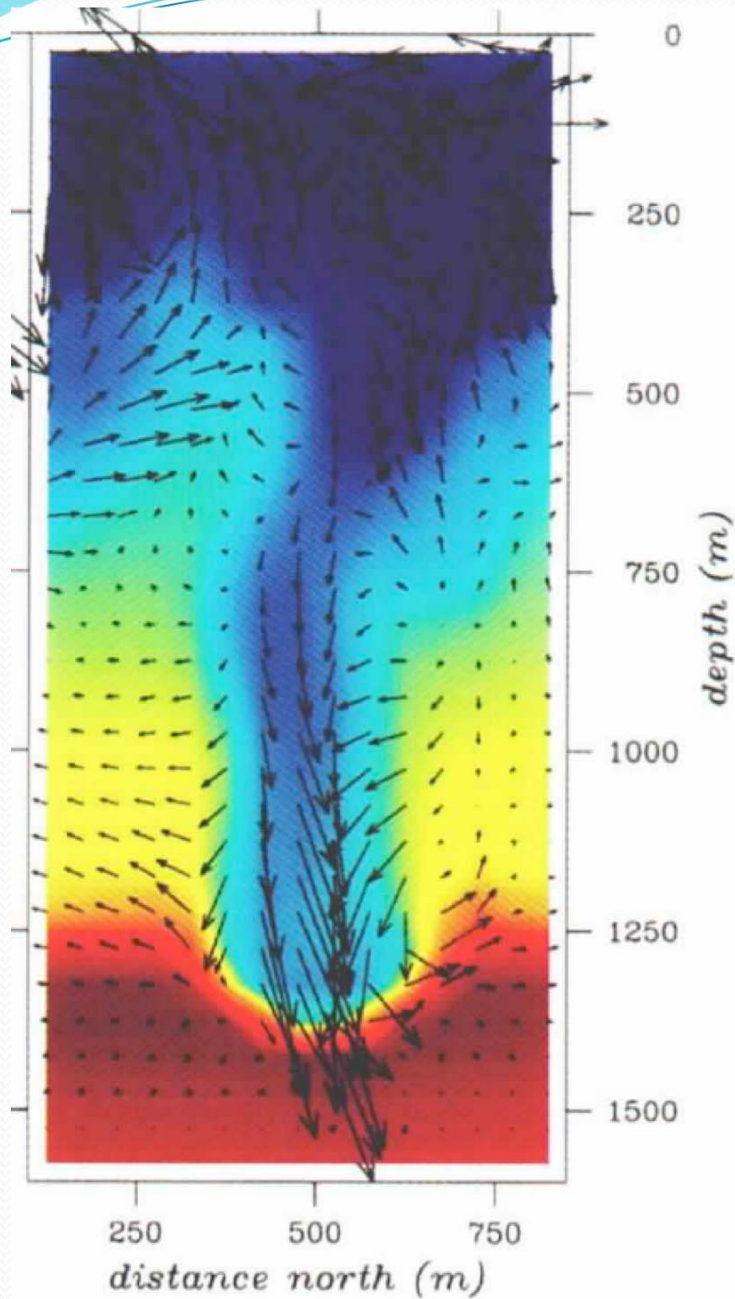


*Locations of **offshore** deep-water formation sites: in the southern hemisphere in **the Weddell and Ross Seas** off the Antarctic coast (where Antarctic Bottom Water is formed) and in the northern hemisphere in **the Labrador and Greenland Seas** (where North Atlantic Deep Water is formed).*

CONVECTIVE PLUME:

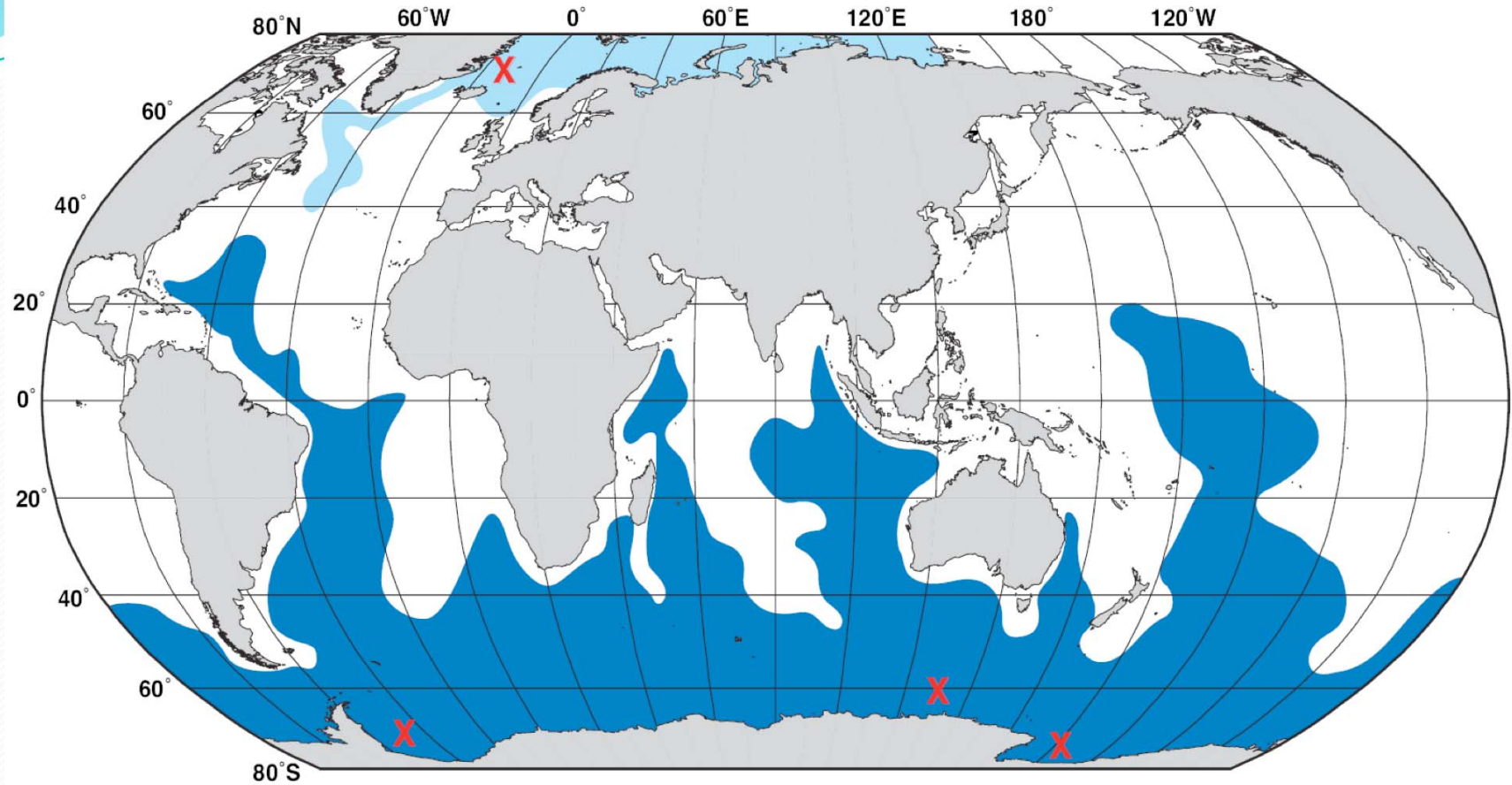


the plume's horizontal scale in the ocean $< 1\text{km}$



Note high vertical velocities
~4cm/s, plume's diameter
~200-300m, depth of
penetrations ~1000-1500m

However, convection is
highly episodic

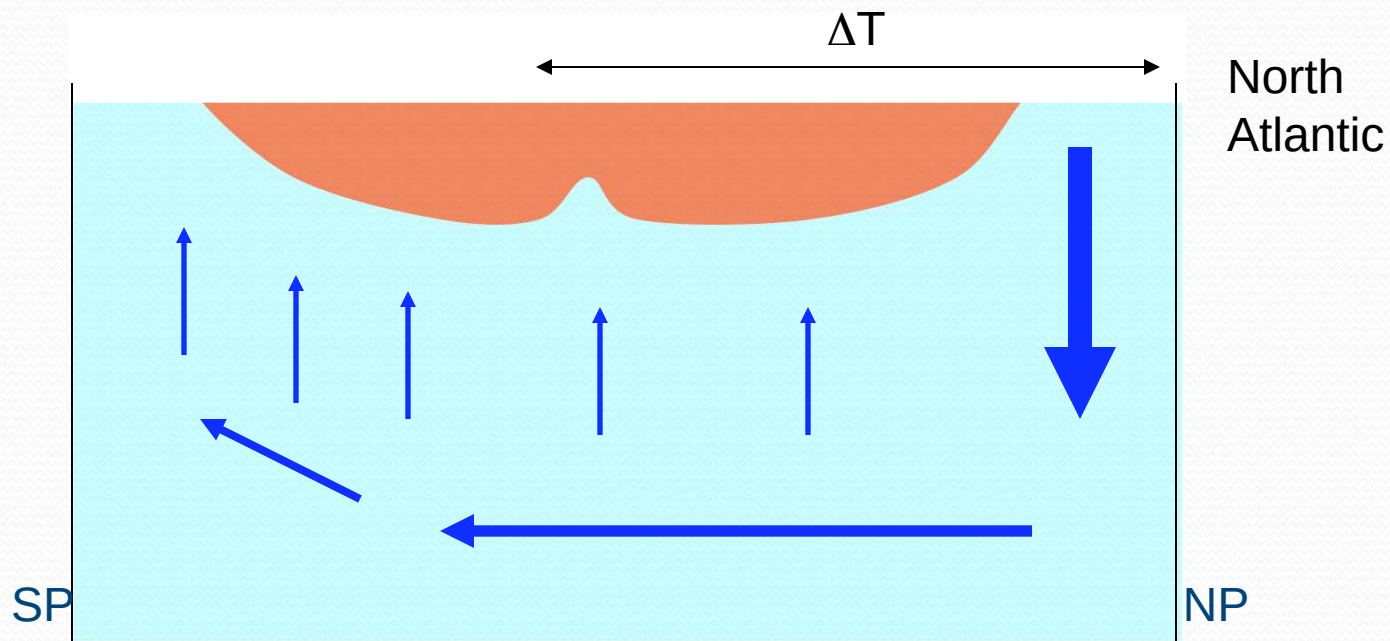


A representation of the spread of Antarctic Bottom Water (AABW, dark blue, based on the $\sigma_4=45.92$ kg/m³ density surface). From [Talley,1999]



What about upwelling?

A SCHEMATIC “TRADITIONAL” PICTURE OF THE THC:



THC in the Atlantic with only one region of sinking – in the Northern Hemisphere.

- 1. Sinking occurs in small confined regions*
- 2. Upwelling is broad and controlled by deep ocean mixing*
- 3. The gradient is largely thermally controlled $\sim \Delta T$.*
- 4. Salinity is important since it can inhibit or facilitate sinking*
- 5. Neglects wind-driven upwelling in the ACC region*

Main balances involved in the THC:

Assume: 1) Geostrophic flow:

$$f u_0 = -\frac{1}{\rho} \frac{\partial}{\partial y} P, \quad f v_0 = \frac{1}{\rho} \frac{\partial}{\partial x} P$$

2) Hydrostatic balance

$$\frac{\partial}{\partial z} p = -\rho g$$

3) Vertical advective-diffusive balance

$$w \frac{\partial}{\partial z} \rho = \kappa \frac{\partial^2}{\partial z^2} \rho$$

$\underline{u}=(u,v,w)$ –
velocity

k – the
coefficient of
vertical
turbulent
diffusion

$p=p(x,y,z)$ –
pressure

$\rho=\rho(x,y,z)$ –
density

Scaling theory

Assume: 1) Geostrophic flow:

$$fu_0 = -\frac{1}{\rho} \frac{\partial}{\partial y} P, \quad fv_0 = \frac{1}{\rho} \frac{\partial}{\partial x} P$$

2) Hydrostatic balance

$$\frac{\partial}{\partial z} p = -\rho g$$

3) Vertical advective-diffusive balance

$$w \frac{\partial}{\partial z} \rho = \kappa_v \frac{\partial^2}{\partial z^2} \rho$$

$$h \propto \kappa_v^{1/3} \Delta \rho^{-1/3}$$

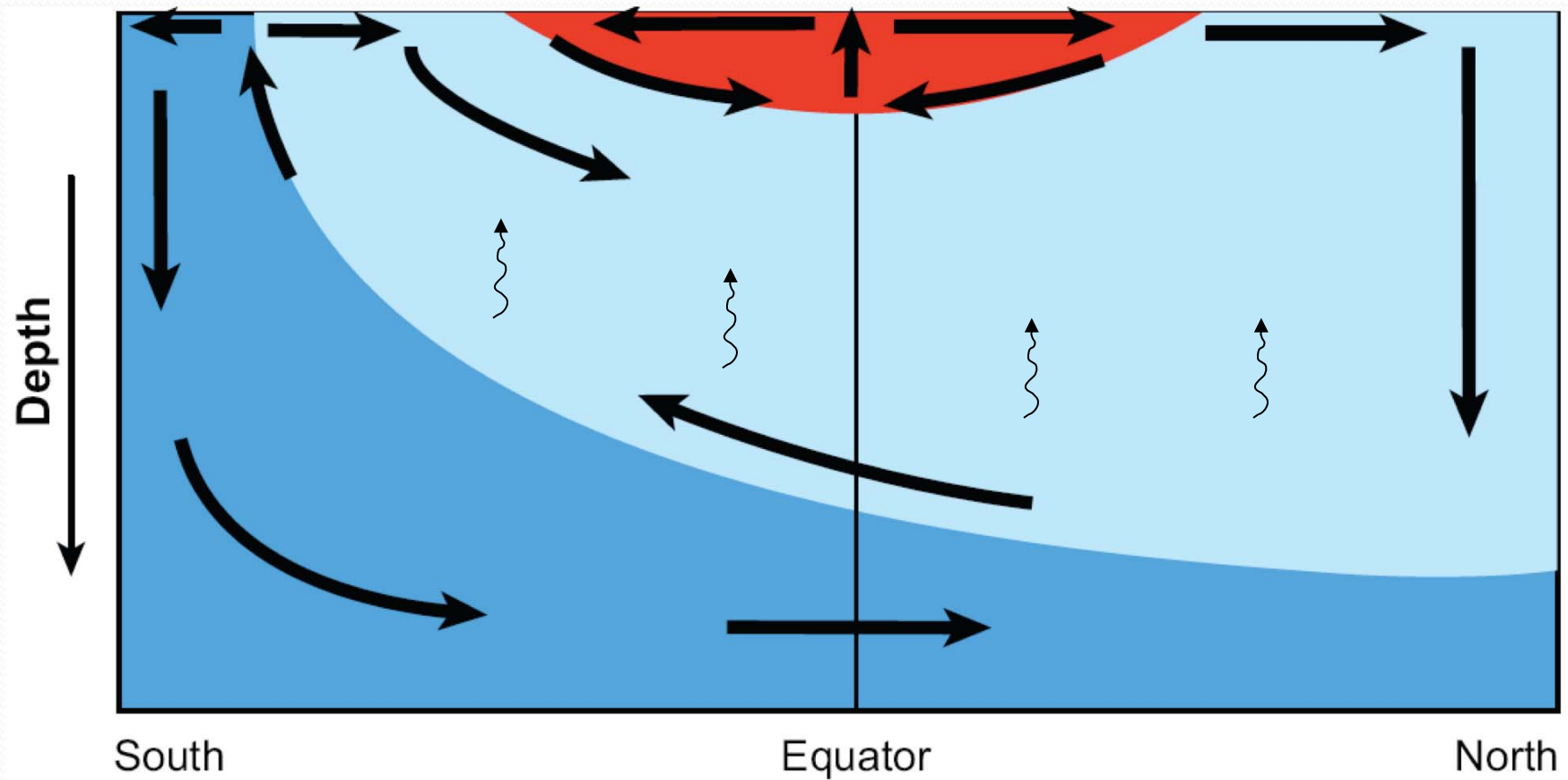
$$hUL \propto \kappa_v^{2/3} \Delta \rho^{1/3}$$



Comments:

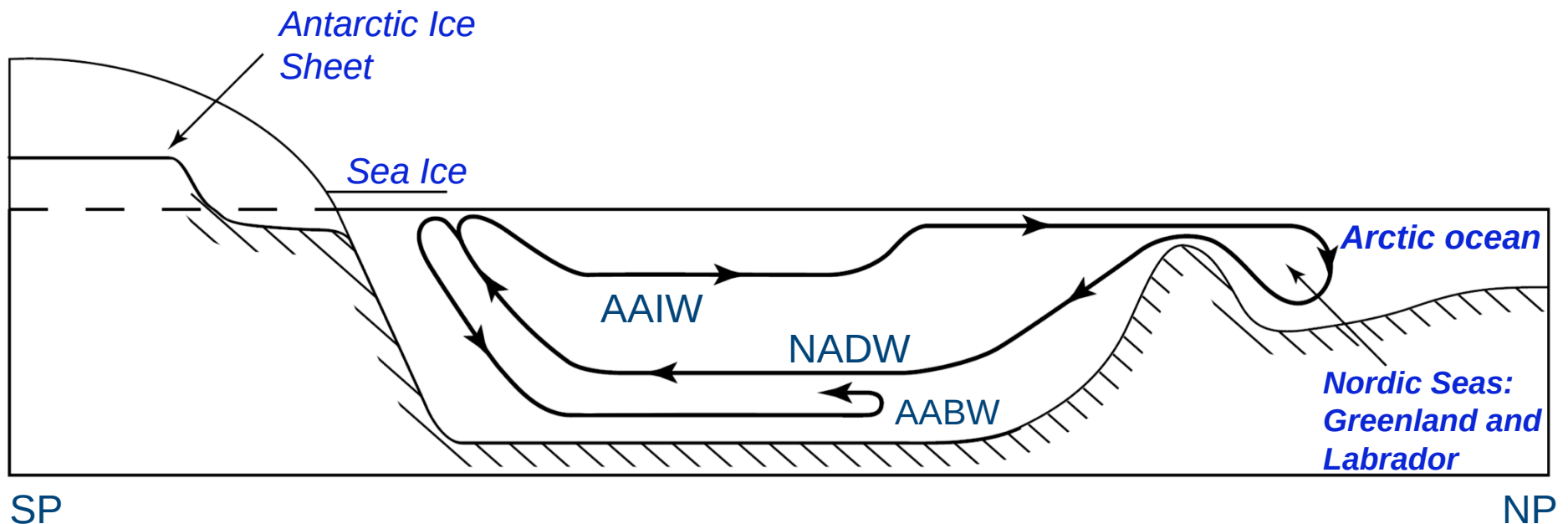
- 1) *The horizontal flow is predominantly meridional – hence there should be an East-West pressure gradient to maintain this flow.*
- 2) *The values of k_v are relatively small, but not too small. Too small values of k_v would imply no stratification in the deep ocean (k_v of the order of cm^2s^{-1} , measure are from 2 to 4 cm^2s^{-1} in Brazil basin or 0.1 cm^2s^{-1} in the NA)*
- 3) *The flow from the source region occurs largely as part of deep western boundary currents (opposite direction to surface western boundary currents)*

Ocean meridional overturning

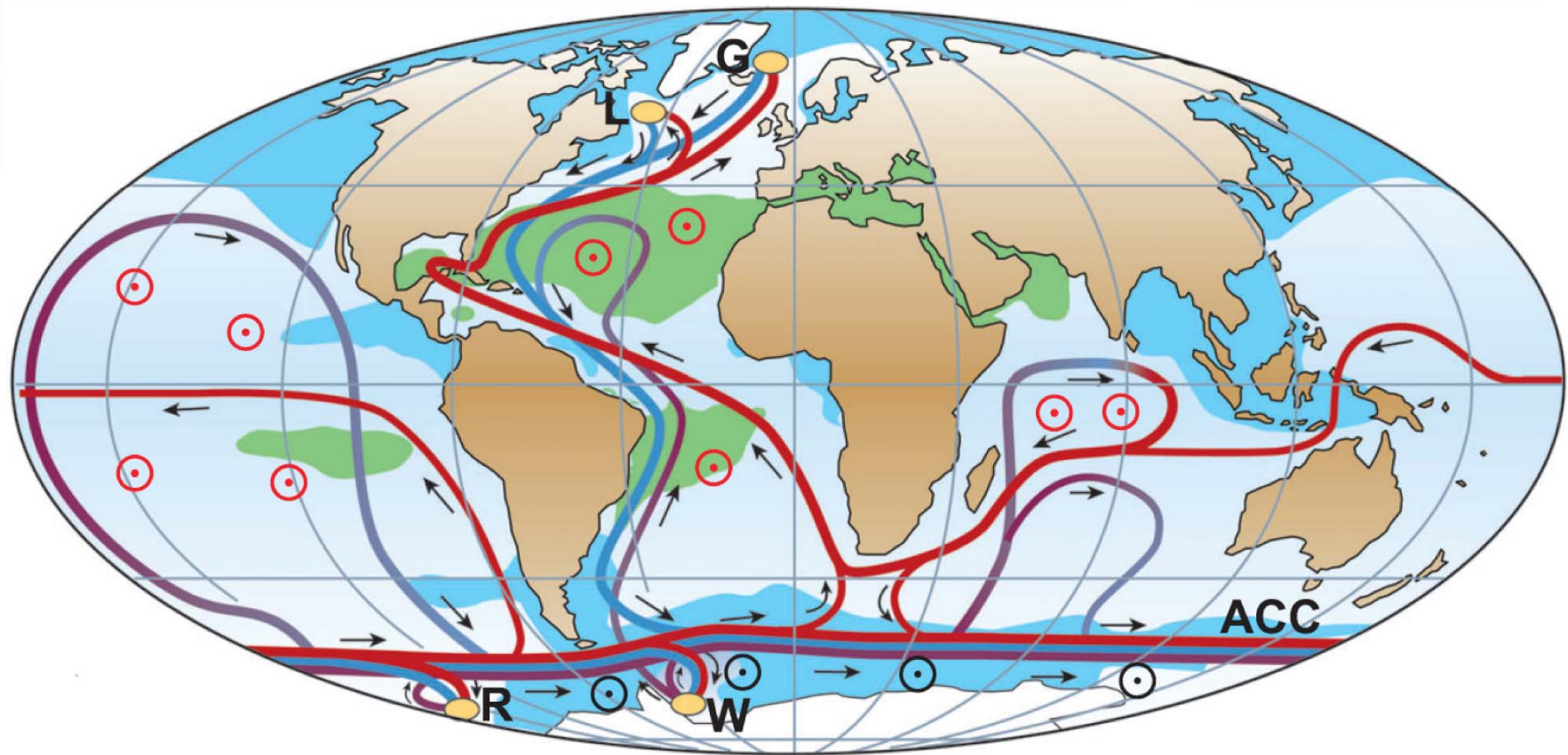


Barreiro, Fedorov and co-authors 2007

The circulation is more complicated: the sinking also occurs around Antarctica as well!



**Schematic diagram of the Atlantic Ocean's thermohaline circulation
(after Ghil et al 1987)**



- Surface flow
- Deep flow
- Bottom flow
- Deep Water Formation

- ⊙ Wind-driven upwelling
- ⊙ Mixing-driven upwelling
- Salinity > 36 ‰
- Salinity < 34 ‰

- L** Labrador Sea
- G** Greenland Sea
- W** Weddell Sea
- R** Ross Sea

Schematic representation of the global thermohaline circulation. Surface currents are shown in red, deep waters in light blue and bottom waters in dark blue. The main deep water formation sites are shown in orange. Kuhlbrodt et al 2006.

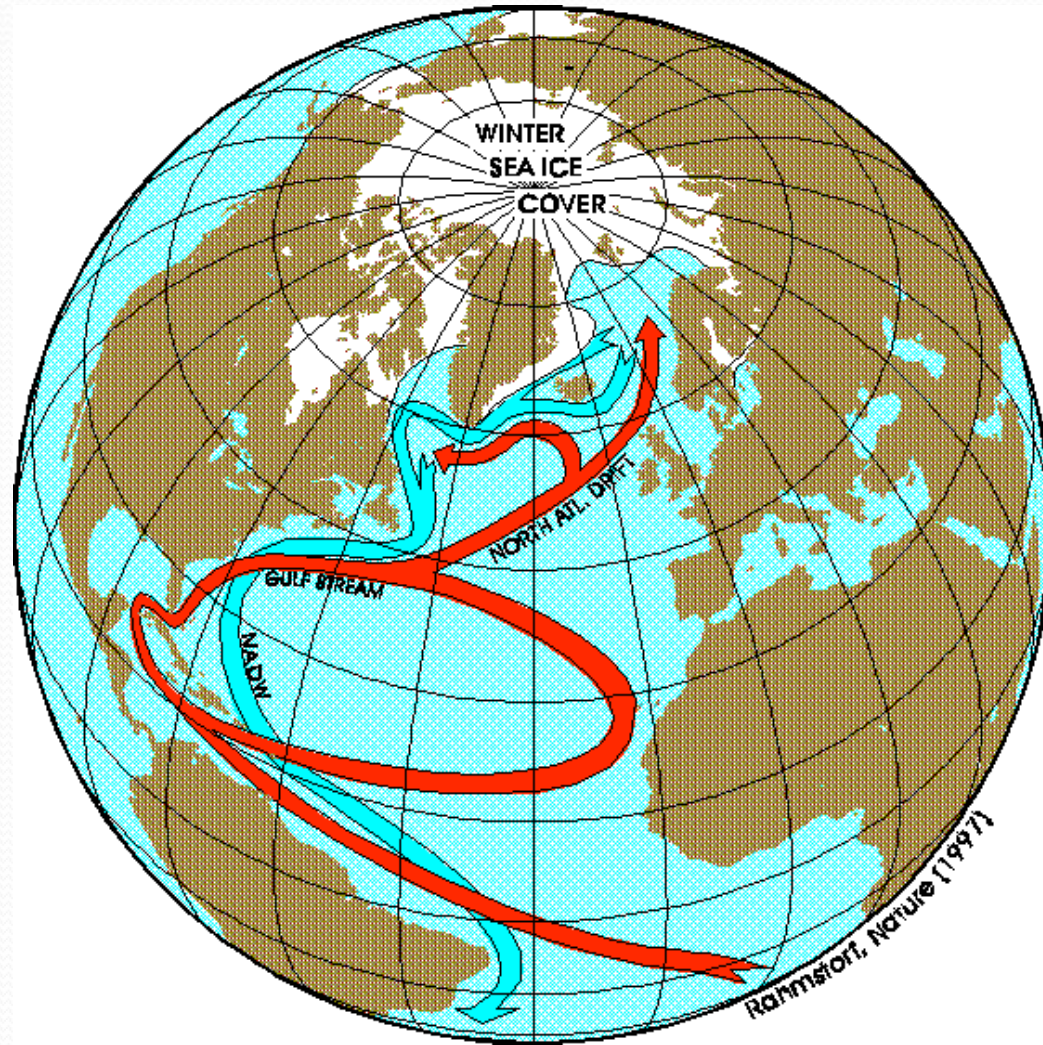
Key features of the thermohaline circulation are:

- *Deep water formation: the sinking of water masses, closely associated with convection, which is a vertical mixing process. Deep water formation takes place in a few localized areas: the Greenland-Norwegian Sea, the Labrador Sea, the Mediterranean Sea, the Weddell Sea, the Ross Sea.*
- *Spreading of deep waters (e.g., North Atlantic Deep Water, NADW, and Antarctic Bottom Water, AABW), mainly as deep western boundary currents (DWBC).*
- *Upwelling of deep waters: this is not as localized as convection and difficult to observe. It is thought to take place mainly in the Antarctic Circumpolar Current region, possibly aided by the wind (Ekman divergence).*
- *Near-surface currents: these are required to close the flow. In the Atlantic, the surface currents compensating the outflow of NADW range from the Benguela Current off South Africa via the Gulf Stream and the North Atlantic Current into the Nordic Seas off Scandinavia.*

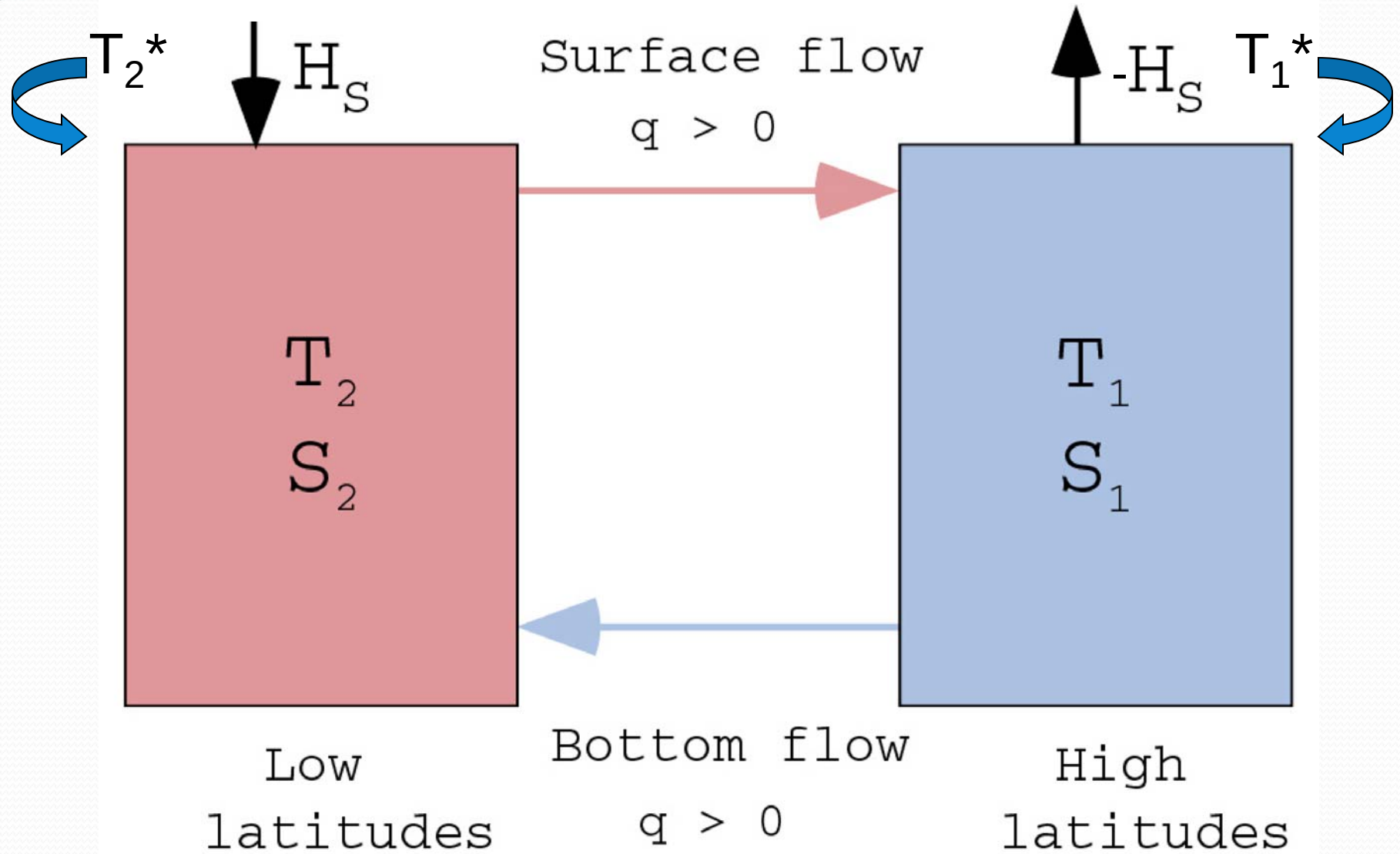


STABILITY AND VARIABILITY OF THE THC

- Abrupt climate changes
- Millennium-scale climate variability



Stommel's box model for the THC




$$q = \frac{k}{\rho_0} [\rho_1 - \rho_2]$$

$$\rho_i = \rho_0 (1 - \alpha T_i + \beta S_i); \quad i = 1, 2,$$

H_s – salt flux

T^* – restoring temperature (the temperature that the atmosphere tries to impose over the ocean)

Stommel's model for the THC

$$\dot{T}_1 = \lambda_T (T_1^* - T_1) + |q|(T_2 - T_1)$$

$$\dot{T}_2 = \lambda_T (T_2^* - T_2) - |q|(T_2 - T_1)$$

$$\dot{S}_1 = -H_S + |q|(S_2 - S_1)$$

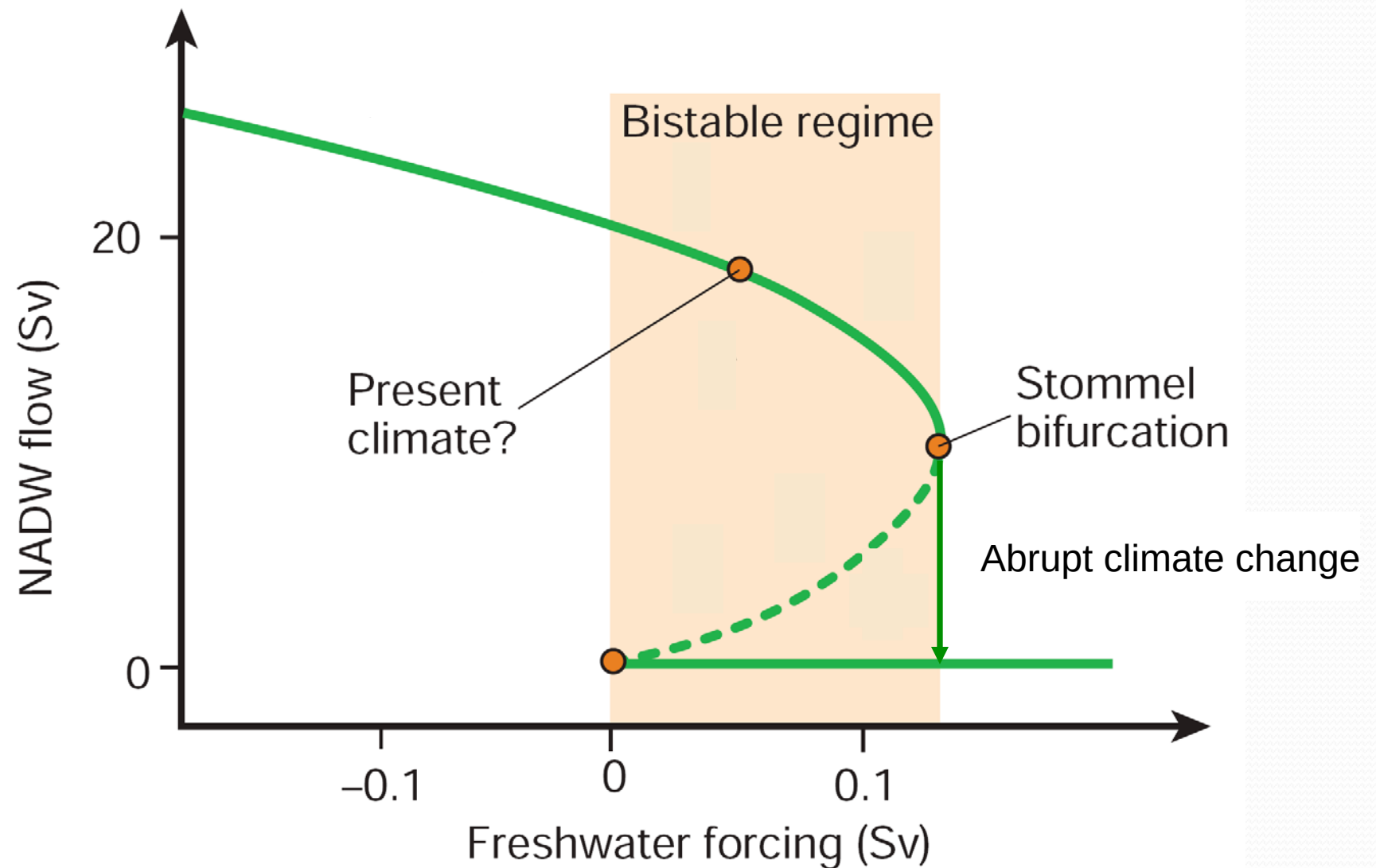
$$\dot{S}_2 = H_S - |q|(S_2 - S_1)$$



Multiple steady states

- 1) A stable state which is thermally-controlled, with a relatively fast circulation.
- 2) A stable state which is salinity-controlled, with a quite slow circulation.
- 3) An unstable state which is thermally controlled.

Steady states and hysteresis of the THC



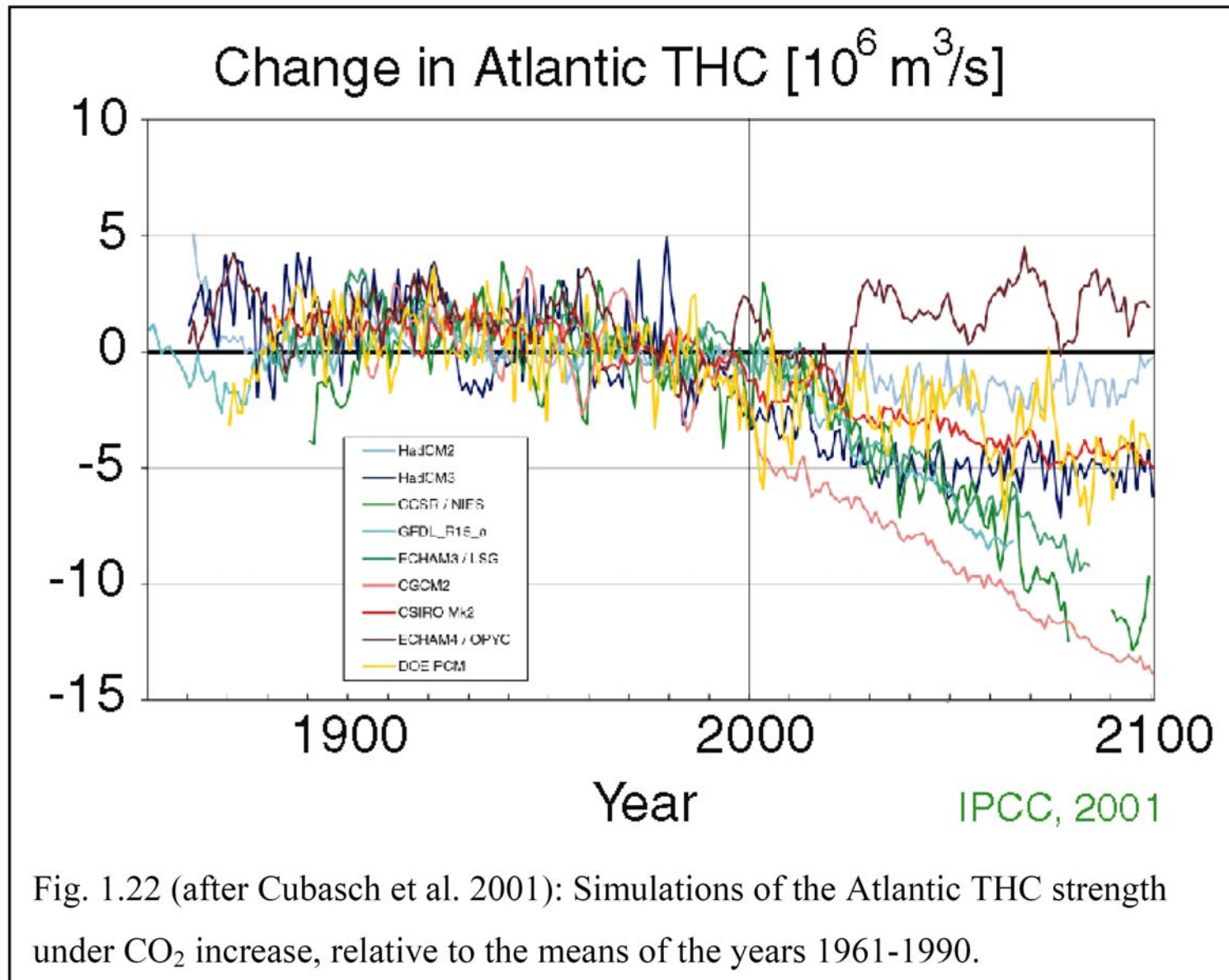
Proportional to $-H_s$



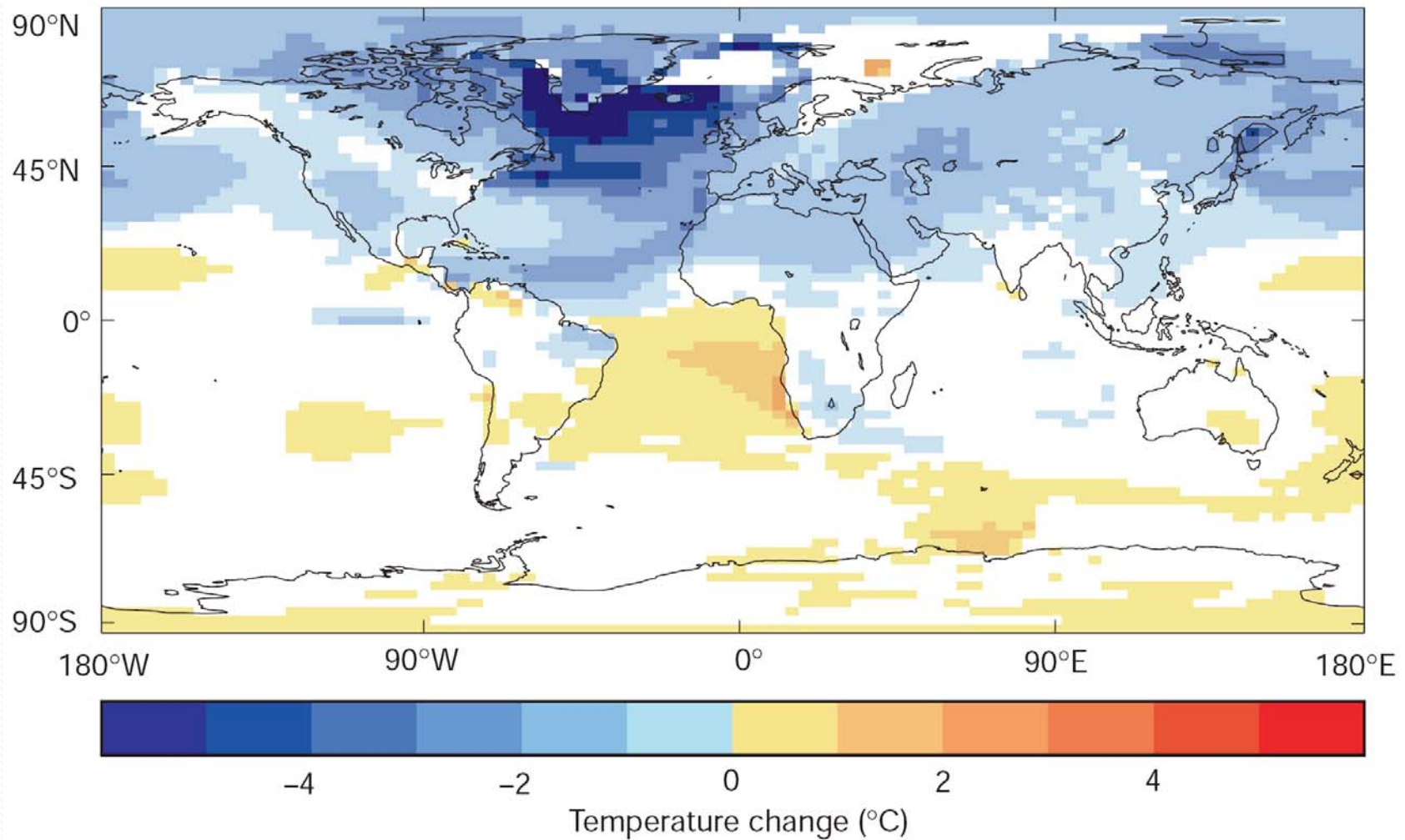
Hysteresis is important because:

- It allows the system to stay in the shut-down state even when the original freshwater forcing is removed!
- It shows the importance of the initial condition

Global Warming

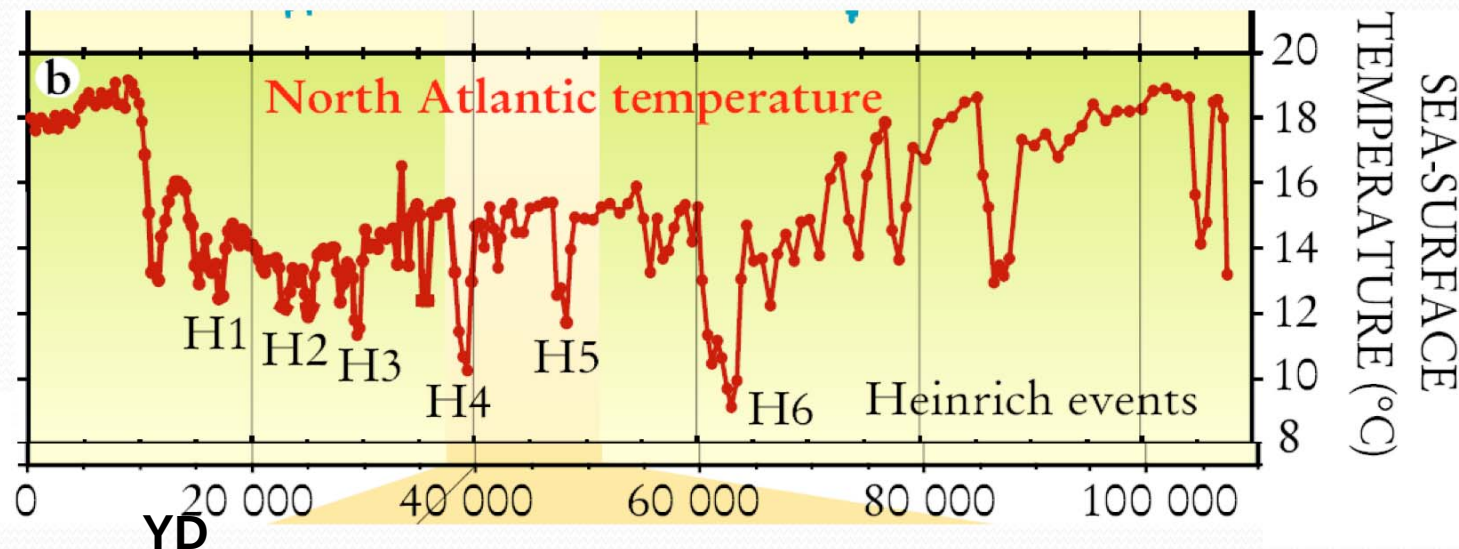


SST response to the shut-down of the THC (in a coupled AOGCM)



PAST CLIMATE

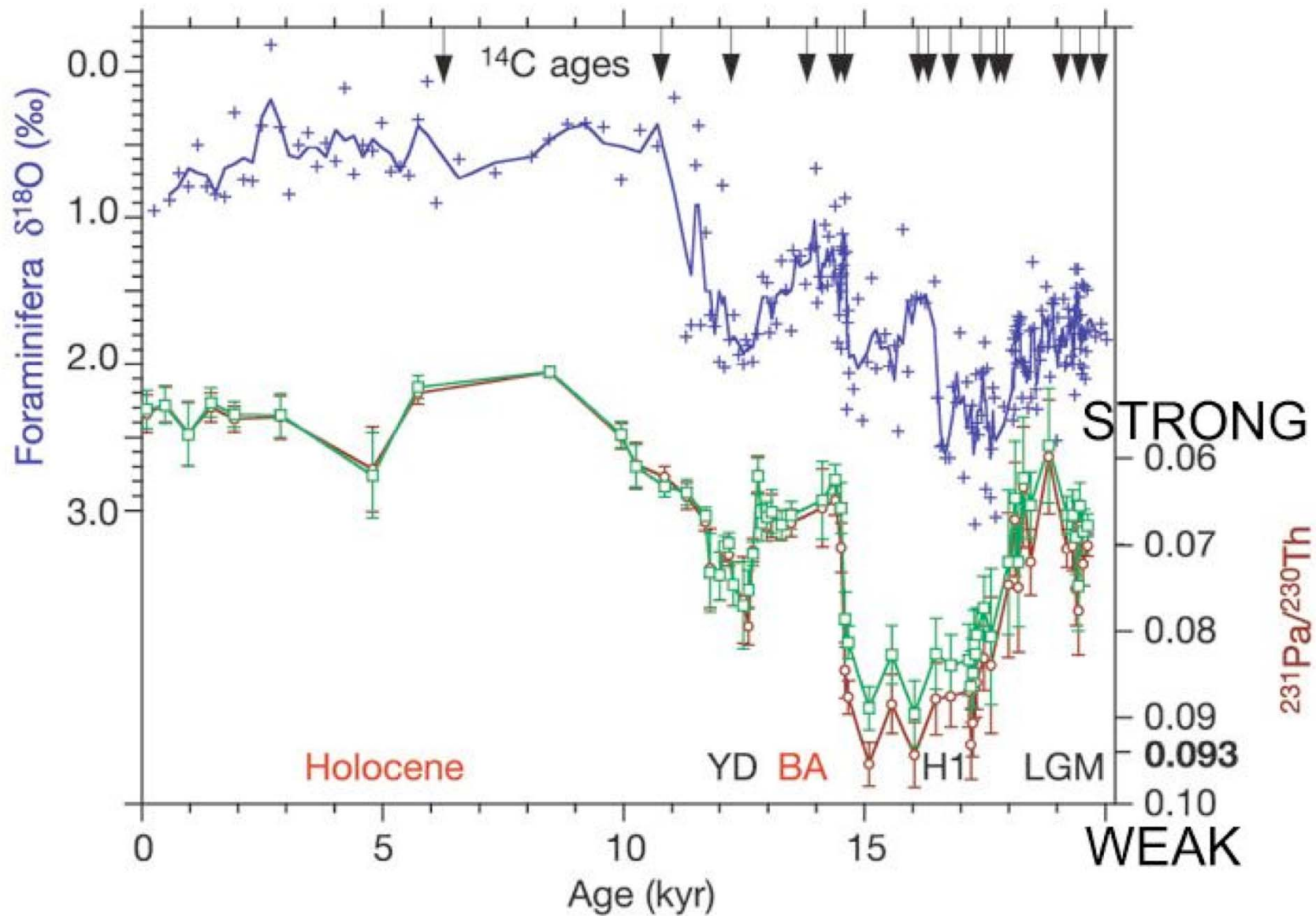
Climate variability (the North Atlantic) within the last glacial cycle: abrupt climate changes



The Younger Dryas (**YD**) event: A rapid dramatic cooling preceding the Holocene.

Heinrich events (H1, H2,...): Cooling; periodicity: 6 -10,000 years

MOC VARIABILITY:

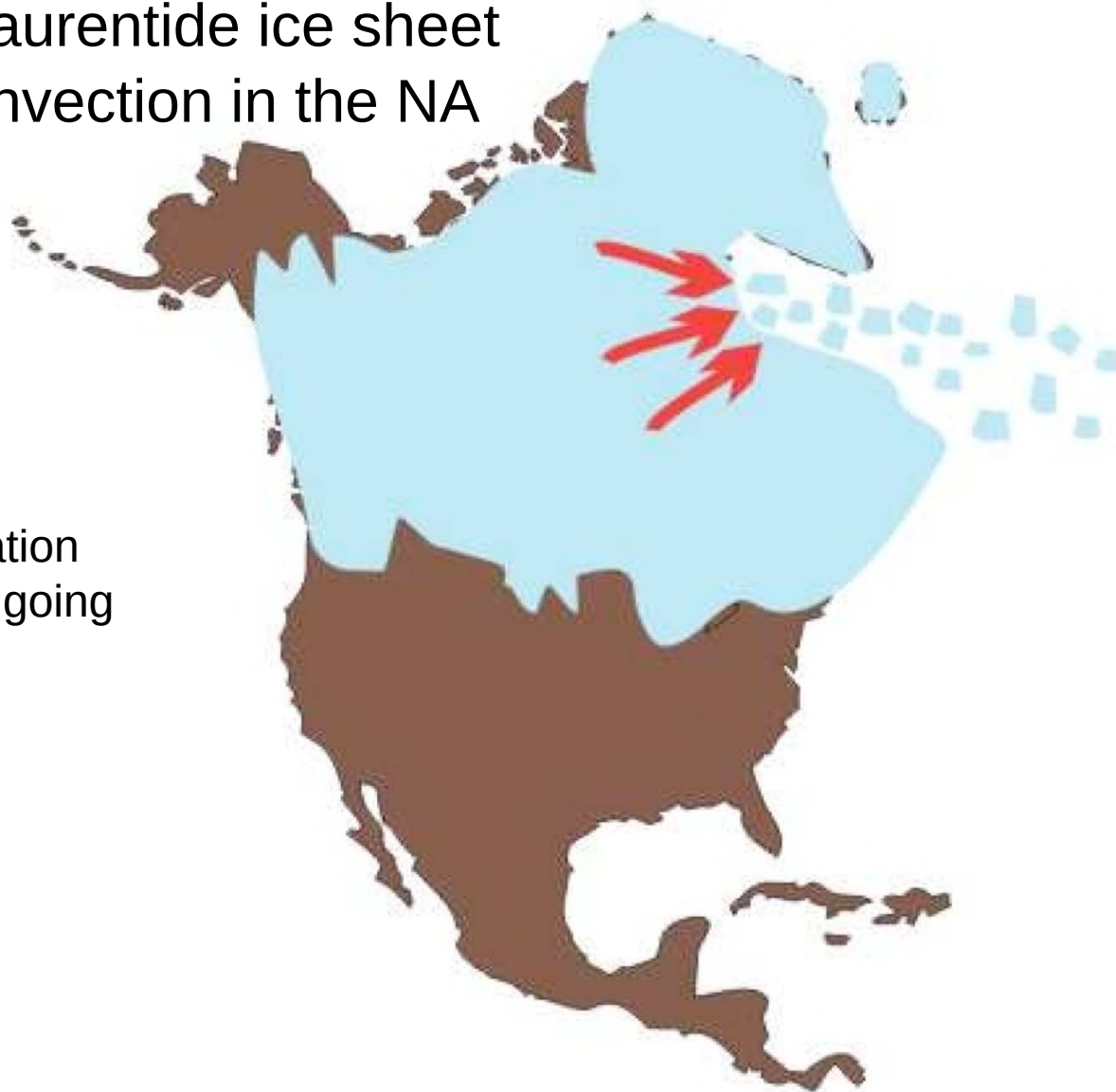


(McManus et al., 2004)

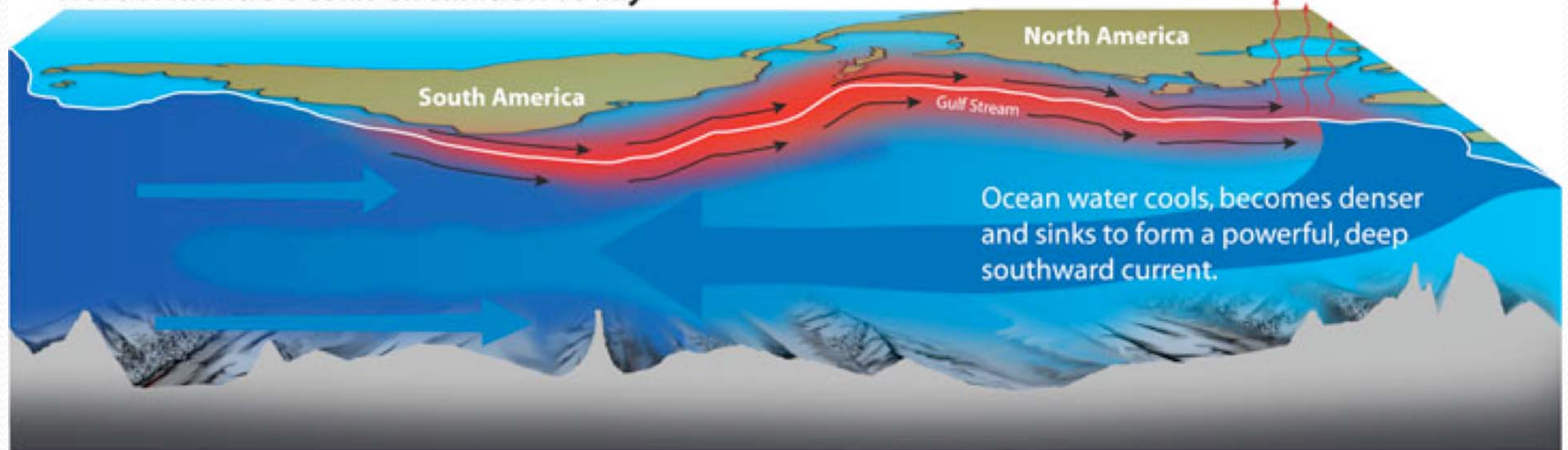
HEINRICH EVENT

Instability of the Laurentide ice sheet
Could stop the convection in the NA

Possible destabilization
of the thermal THC going
to the haline THC



North Atlantic Ocean Circulation Today



North Atlantic Ocean Circulation ~20,000 Years Ago (Peak of Last Ice Age)

