

Lecture On Ocean Circulation

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Climate Modeling

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Lecture On The Ocean Circulation

- *Ocean & Climate*

Why does the Ocean is important?

- *Ocean measurement:*

How do we know the Ocean?

- *Ocean Circulation*

- *Structure and Water Masses*
- *Forcing at the ocean-atmosphere interface*
(heat fluxes, evaporation-precipitation, wind stress)
- *Circulation:*
 - *The Gyres circulation*
 - *The Meridional Overturning Circulation*

- *Modeling the Ocean*

- *The varying Ocean and its impact on Climate*

Climate System:

Def: Climate is the atmospheric condition in a particular region averaged over 30 yr.

It is controlled by a complex dynamical system of 5 spheres:

- Atmosphere
- Ocean
- Cryosphere
- Biosphere
- Land

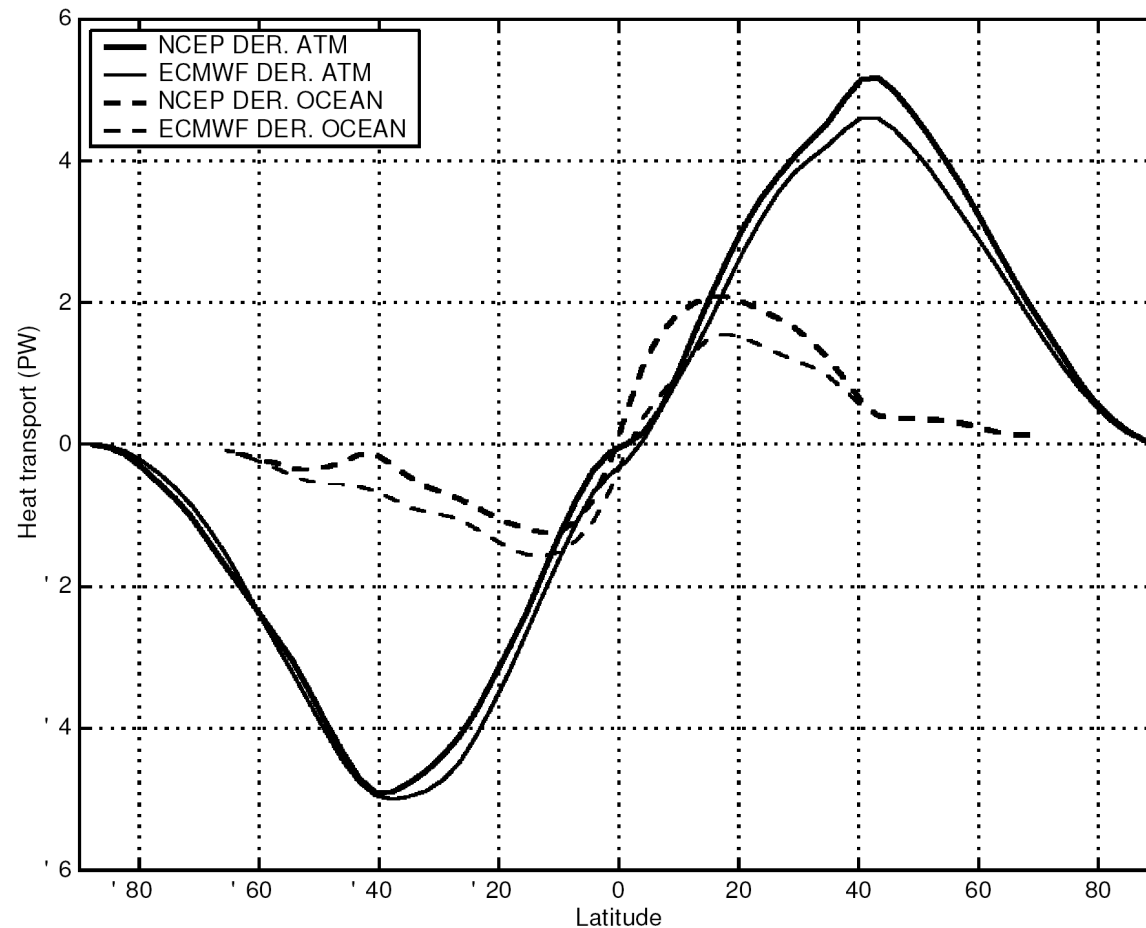


Why the Ocean?

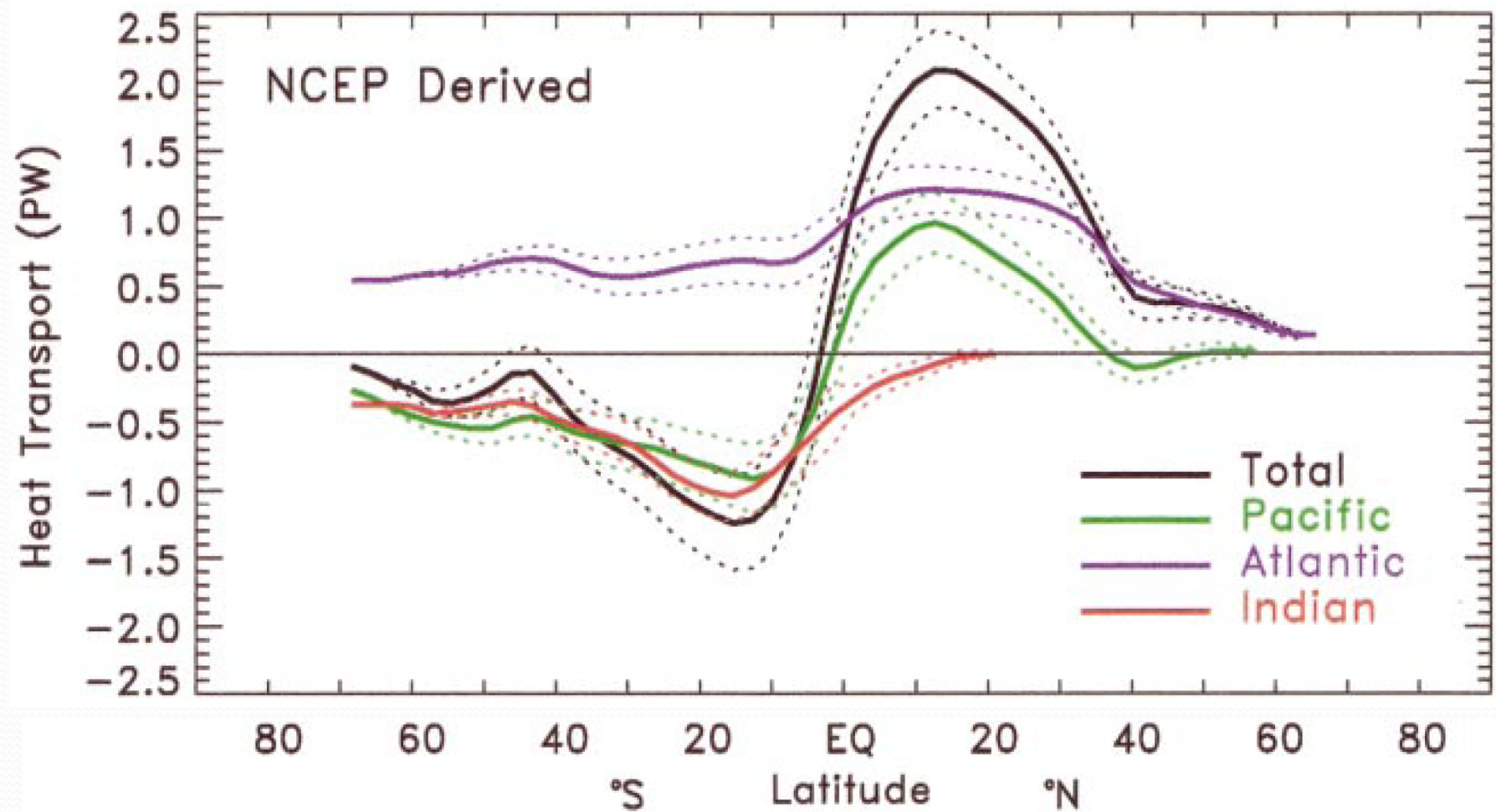


Why are we interested in the ocean in relationship to climate?

- Ocean SSTs are critical for the atmospheric circulation, clouds and precipitation
- Ocean transports heat poleward
- Ocean has a high heat capacity (provides thermal inertia to the system)
- Ocean provides longer timescales to the climate system (as compared to atmospheric timescales) via slow ocean adjustment to surface forcing -> possibility of coupled modes (e.g. El Niño)



Zonally averaged atmospheric (solid lines) and oceanic (dashed lines) northward heat transports as computed from NCEP (thick lines) and ECMWF (thin lines) reanalyses (Trenberth *et al.* 2001); in petawatts (10^{15}). Man's global energy consumption is about 0.016 pW





Ocean vs. Atmosphere

- The ocean is exposed to $\frac{2}{3}$ of the incoming solar radiation
- The heat capacity of the ocean is higher than the one of the atmosphere:
 - 3 m of the ocean has the same heat content than the entire atmosphere

Seasonal heat storage over 1m² area of ocean and land

$$C_p \approx 4.0 \times 10^3 \text{ J} \cdot \text{kg}^{-1} \cdot ^\circ\text{C}^{-1}$$

(specific heat for water and rock)

$$C_{p(\text{rock})} = 800 \text{ J} \cdot \text{kg}^{-1} \cdot ^\circ\text{C}^{-1}$$

$$\text{Density of water: } 1000 \text{ kg/m}^3$$

$$\text{Density of rock: } 3,000 \text{ kg/m}^3$$

Depth: Ocean upper (mixed) layer -100m

Depth: Rock – 1m

Area: 1m²

$$\begin{aligned}\Delta E_{\text{ocean}} &= C_{p(\text{water})} m_{\text{water}} \Delta t \\ &= (4000)(10^5)(10^\circ) \text{ Joules} \\ &= 4.0 \times 10^9 \text{ Joules}\end{aligned}$$

$$\Delta t = 10^\circ\text{C}$$

(seasonal variations in temperature)

$$\begin{aligned}\Delta E_{\text{land}} &= C_{p(\text{rock})} m_{\text{rock}} \Delta t \\ &= (800)(3000)(20^\circ) \text{ Joules} \\ &= 4.8 \times 10^7 \text{ Joules}\end{aligned}$$

$$\Delta t = 20^\circ\text{C}$$

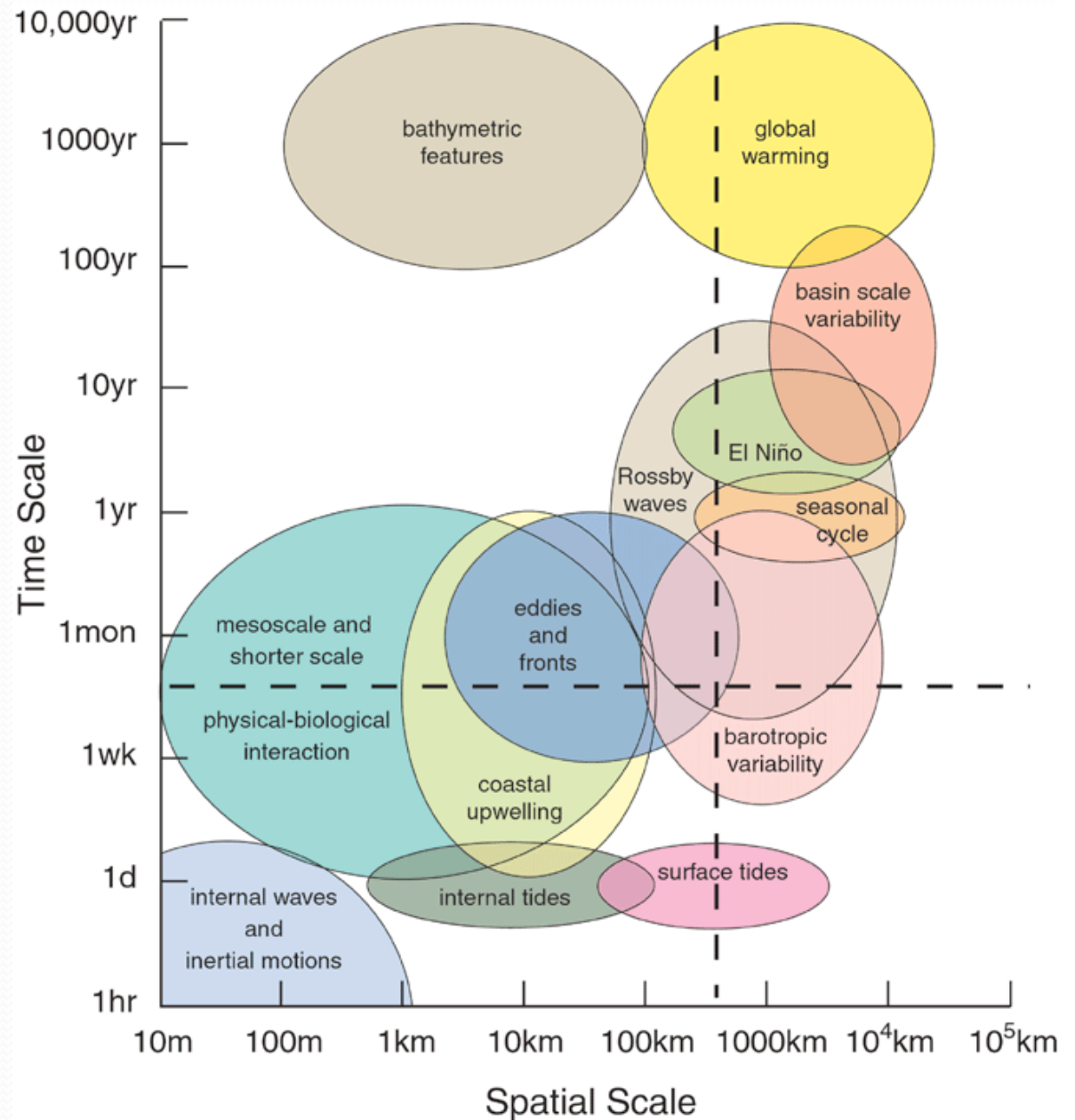
$$\frac{\Delta E_{\text{ocean}}}{\Delta E_{\text{land}}} = 100$$

Heat storage over land is two orders of magnitude smaller than that in the ocean!

Different processes:

Ocean processes are the most relevant for climate (10 yr and longer)

This does not mean that the other process does not contribute (through scale interaction)



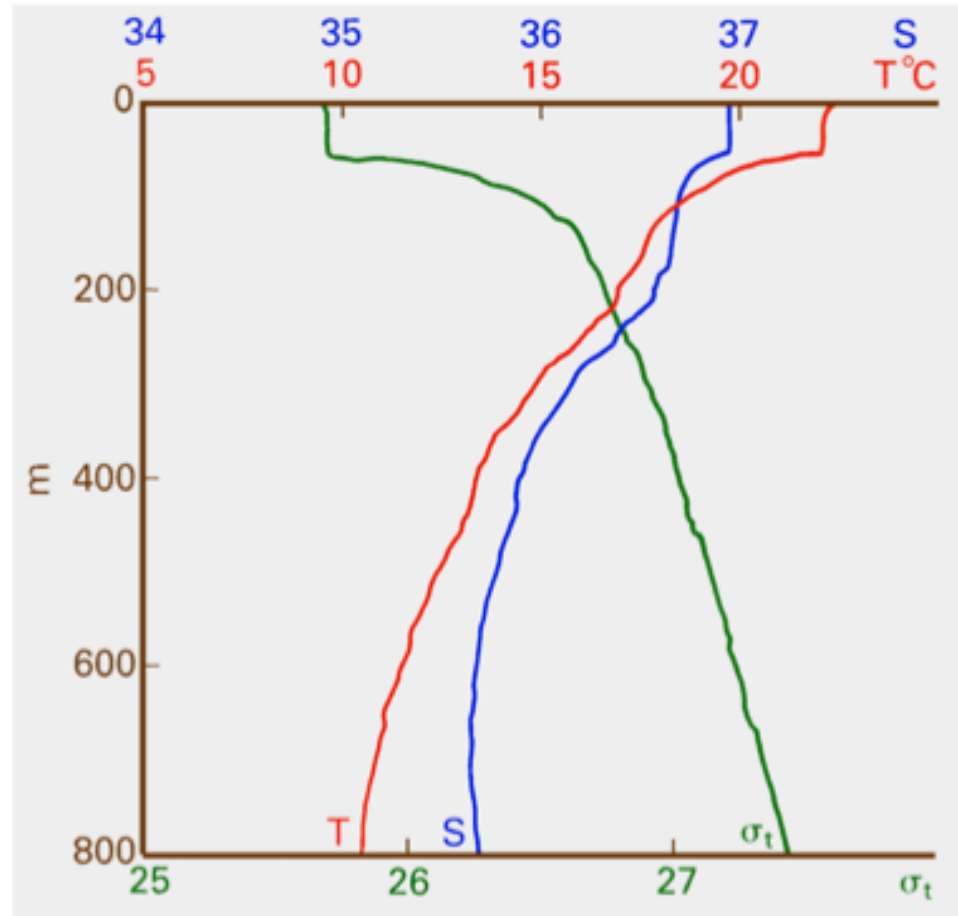


How do we know the Ocean?

- In situ measurement:
 - Scientific cruise (CTD & XBT)
 - Subsurface & surface floats and drifters
 - Moored station array
- Remote measurement:
 - Satellite

In situ measurement

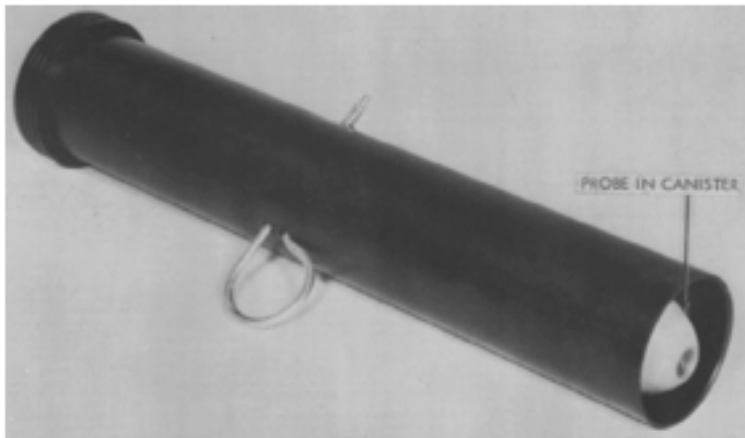
- CTD: Conductivity, Temperature, and Depth recorder



- The bottle calibrates the CTD results (especially for salinity)

In situ measurement

- XBT: eXpendable BathyThermometer



Easier to use:

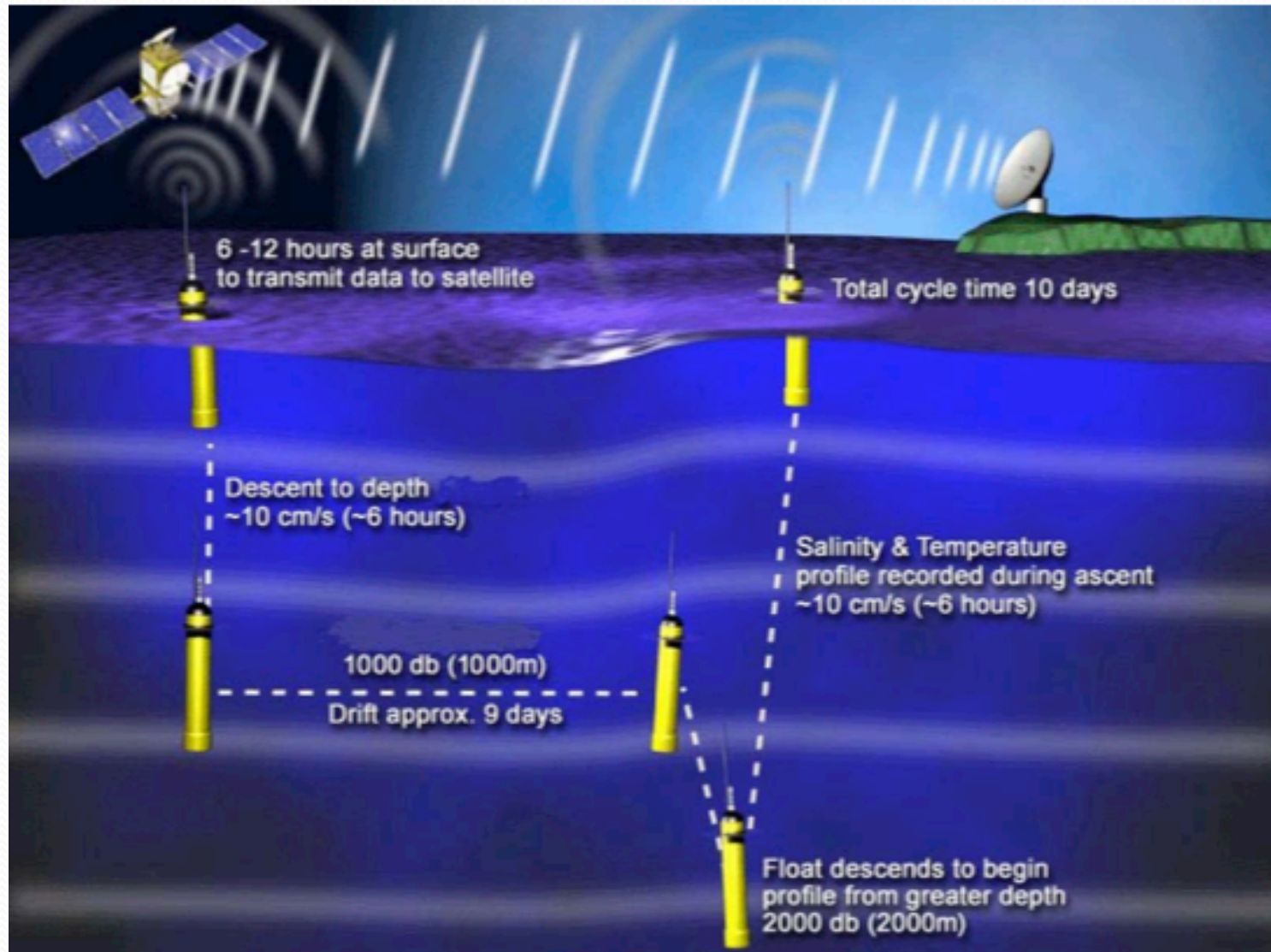
- No station: The boat don't need to stop

Less accurate:

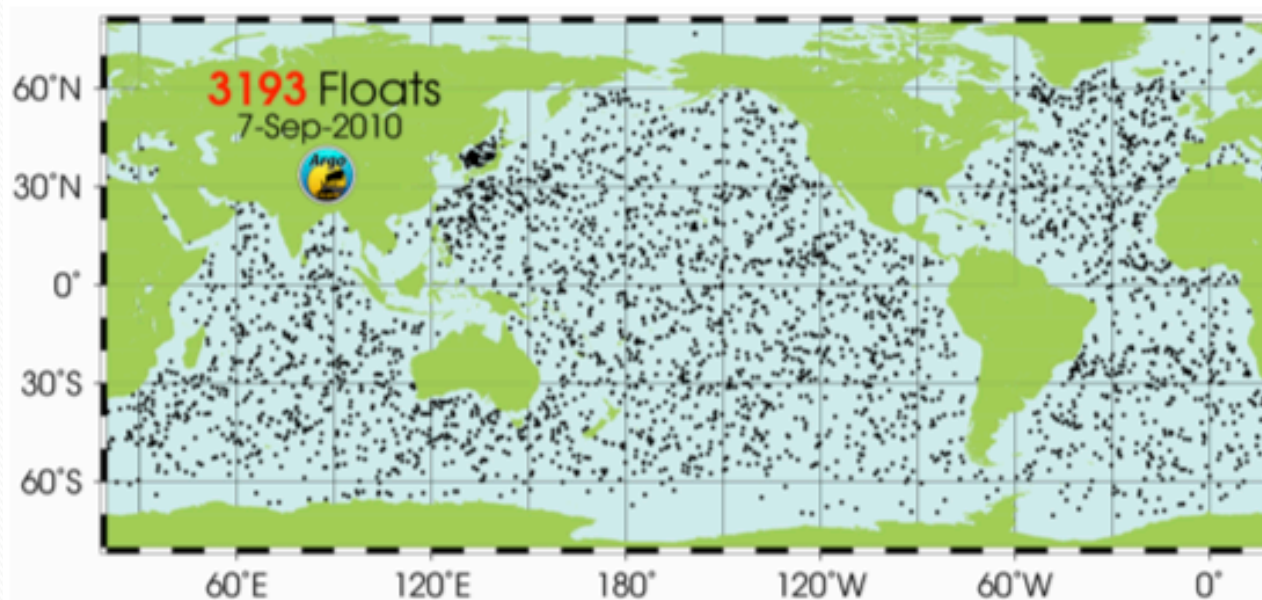
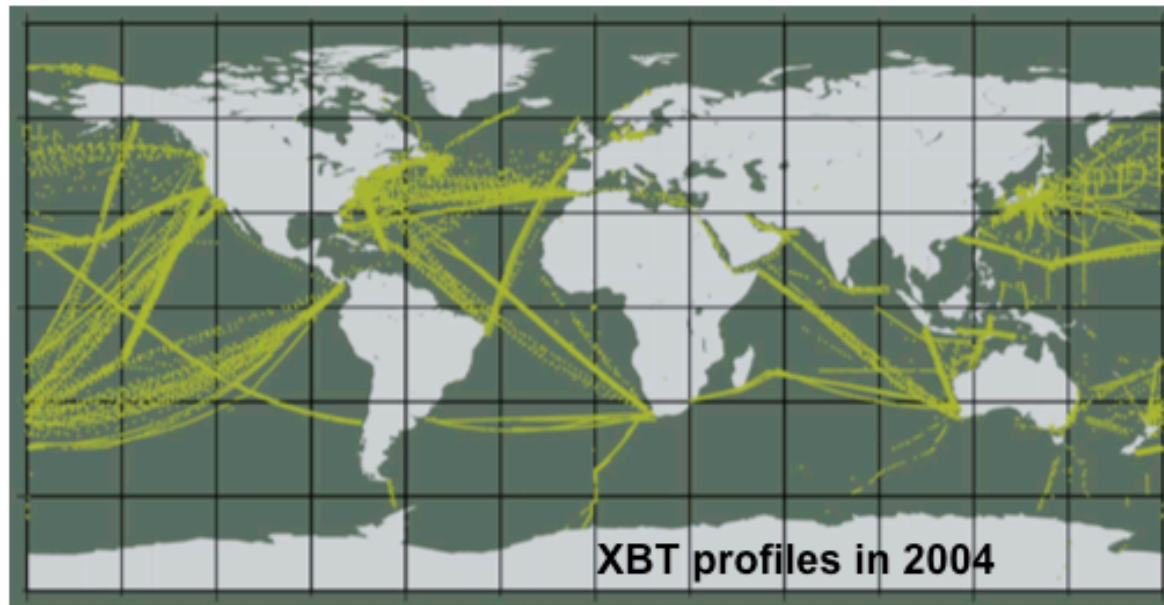
- No calibration: no bottle to compare
- No salinity measurement



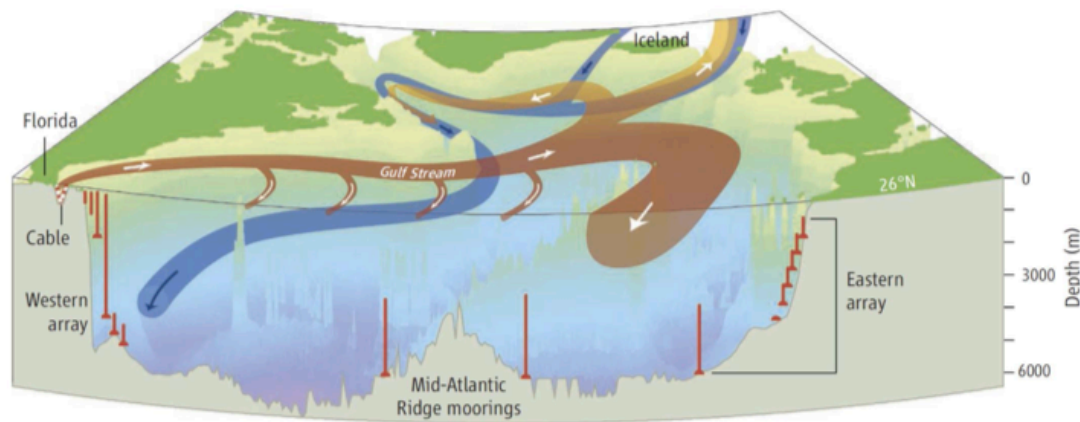
ARGO FLOATS



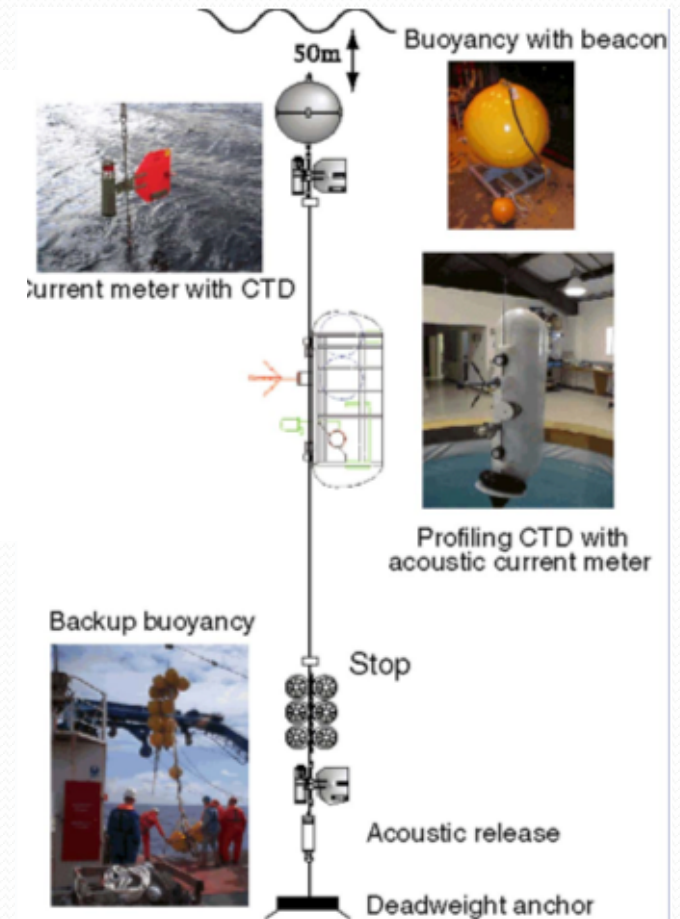
Global Coverage:



Rapid Array



Since April 2004 an observing system for the meridional overturning circulation have been developed and maintained at 26.5°N in the Atlantic.



What can we measure from Satellite?

- Sea Surface Temperature
- Sea Surface Height
- Sea Surface Salinity (not yet, 2012)
- Ocean Color (chlorophyll)

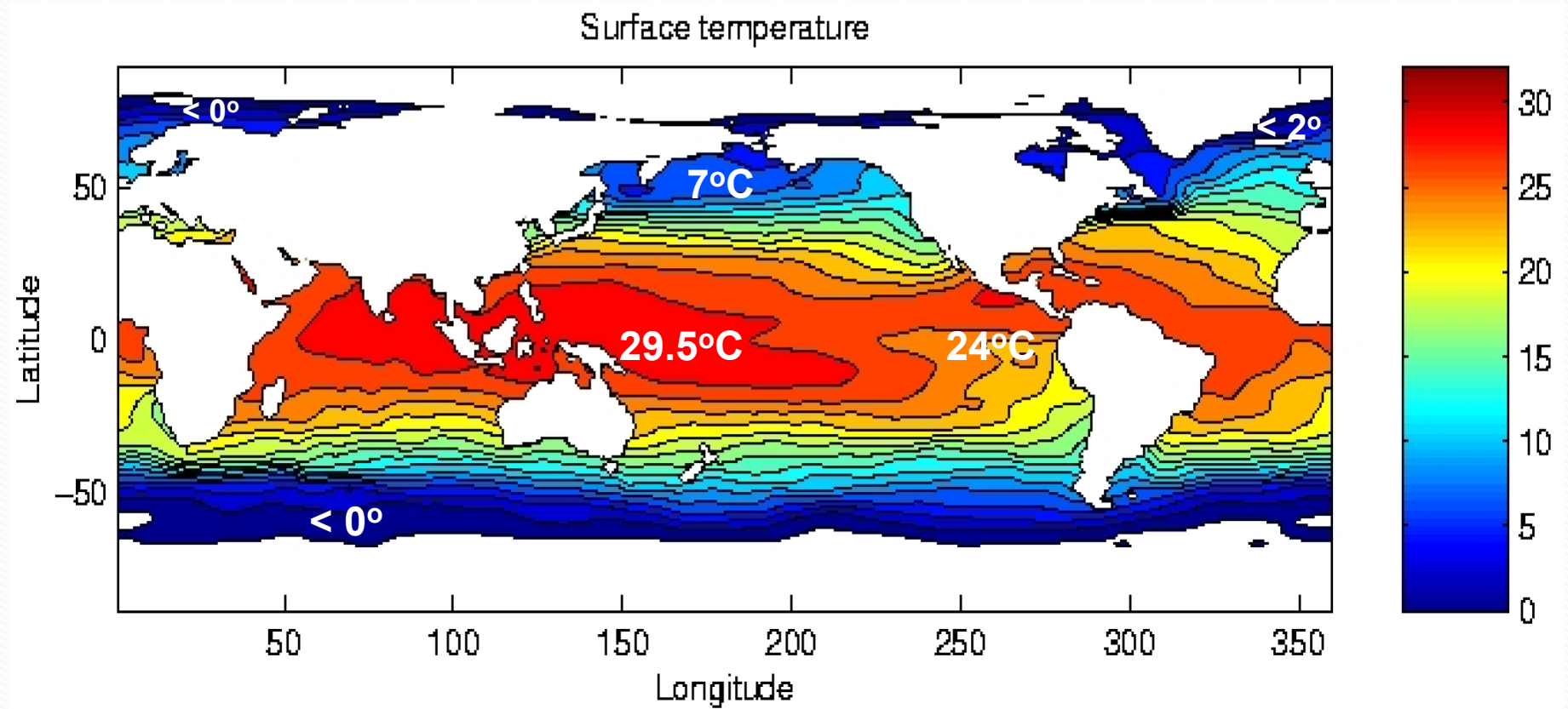




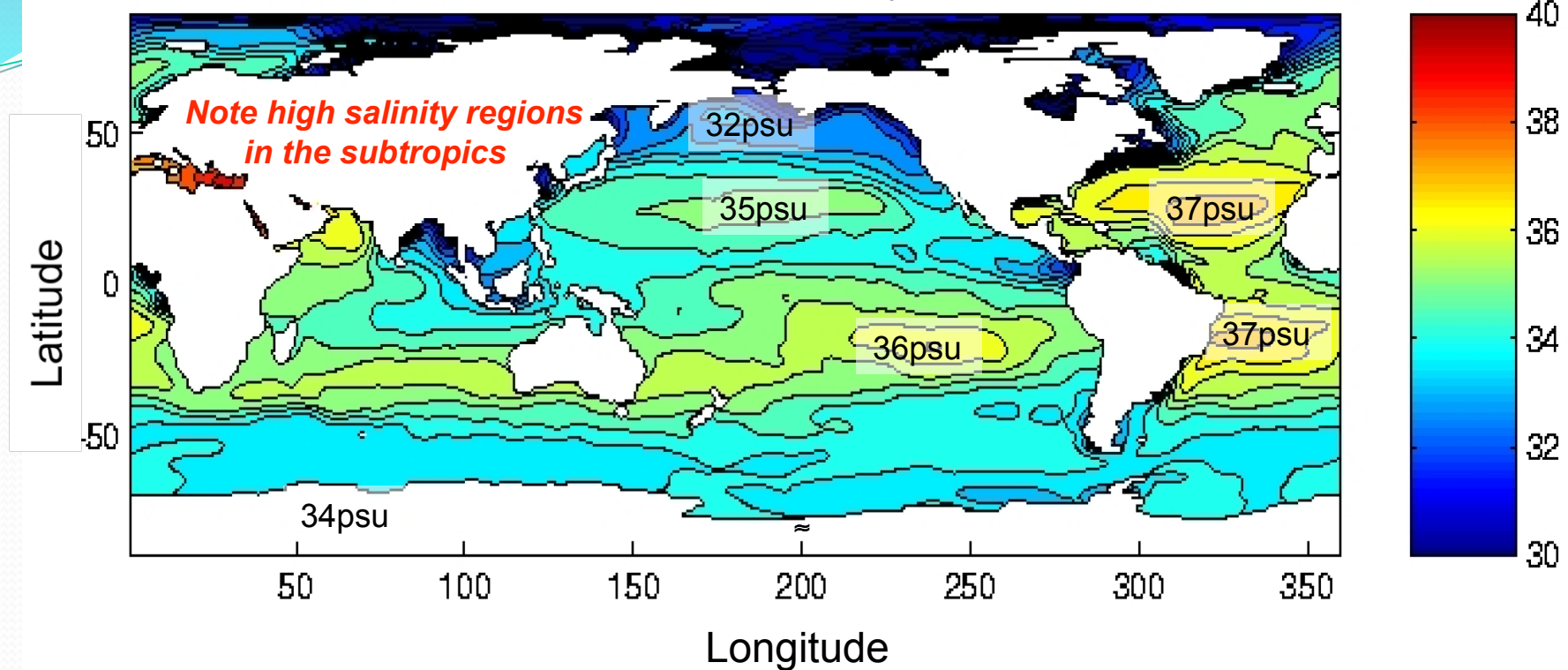
Ocean thermal structure

Ocean thermocline and mixed layer

Annual mean distribution of ocean surface temperature (SST)



Surface Salinity



The Red Sea – up to 39 psu (strong evaporation) ;

The Mediterranean Sea – up to 38psu (strong evaporation);

The Arctic Ocean, near surface – 30psu (sea ice melting + river run-off);

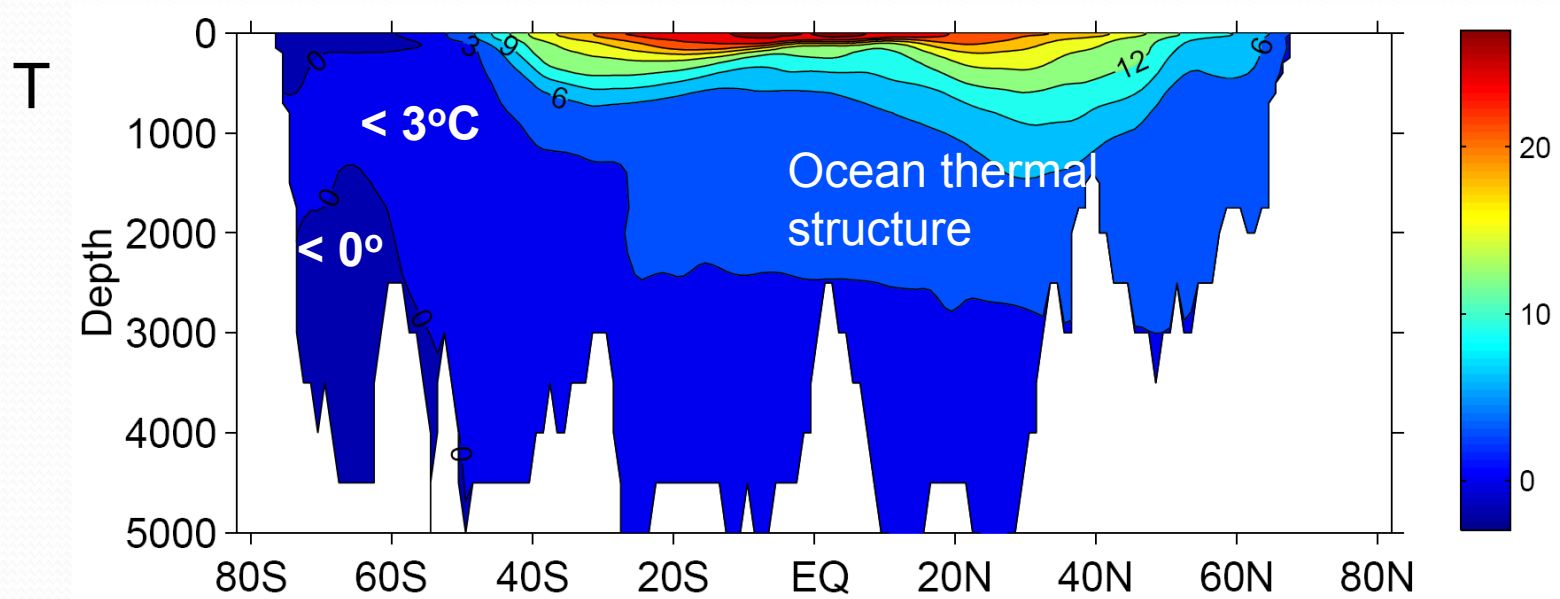
The Black Sea, the Baltic Sea – 17psu (river run-off)

Mean ocean salinity ~35 psu

psu - practical salinity unit

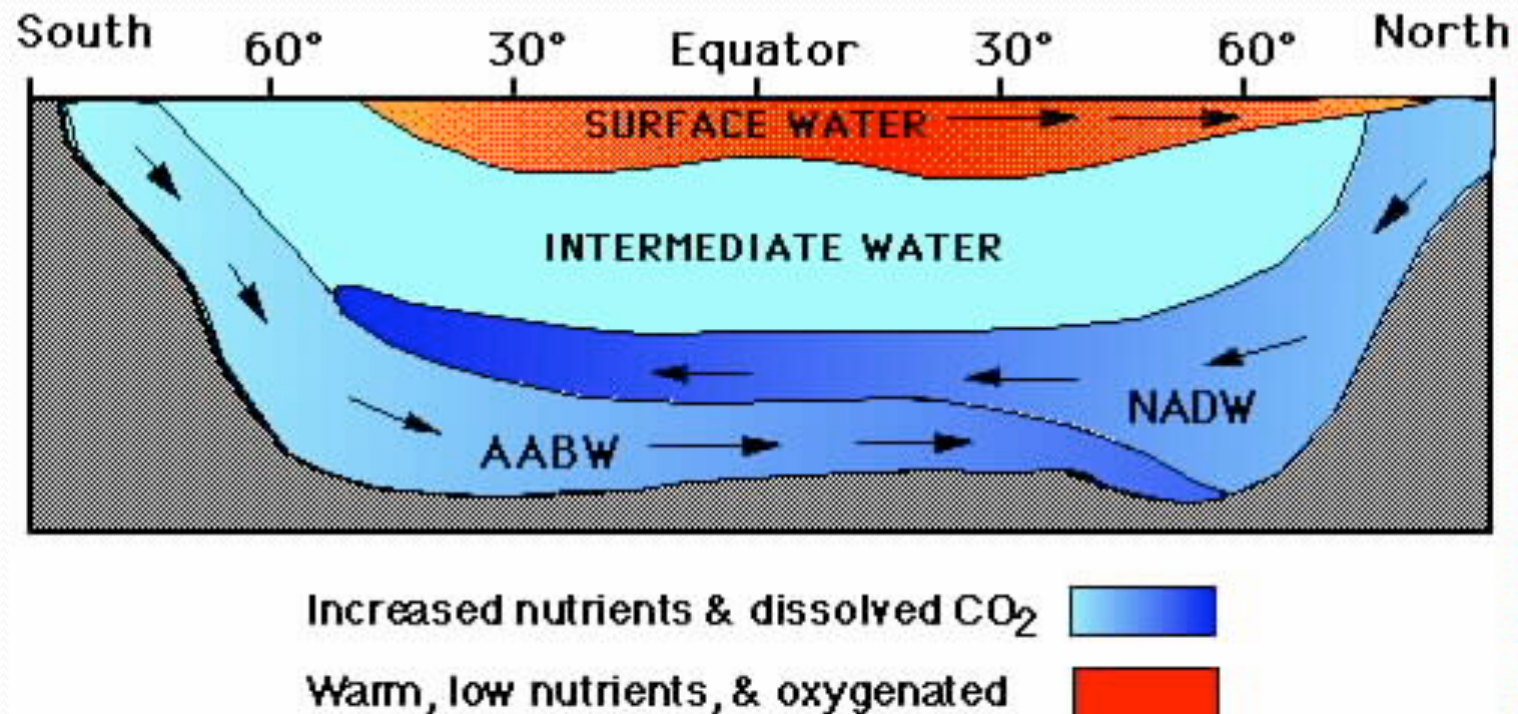
psu $\approx$ ppt = g/kg

Atlantic Ocean



The average ocean temperature is 3.8°C

Ocean water masses and circulation routes



*Why is the ocean cold: most of the ocean water comes from high latitudes. Sometimes this process is called **ocean “ventilation”** (also the thermohaline circulation – the THC, the ocean meridional overturning, ocean abyssal circulation)*

NADW – the North Atlantic Deep Water

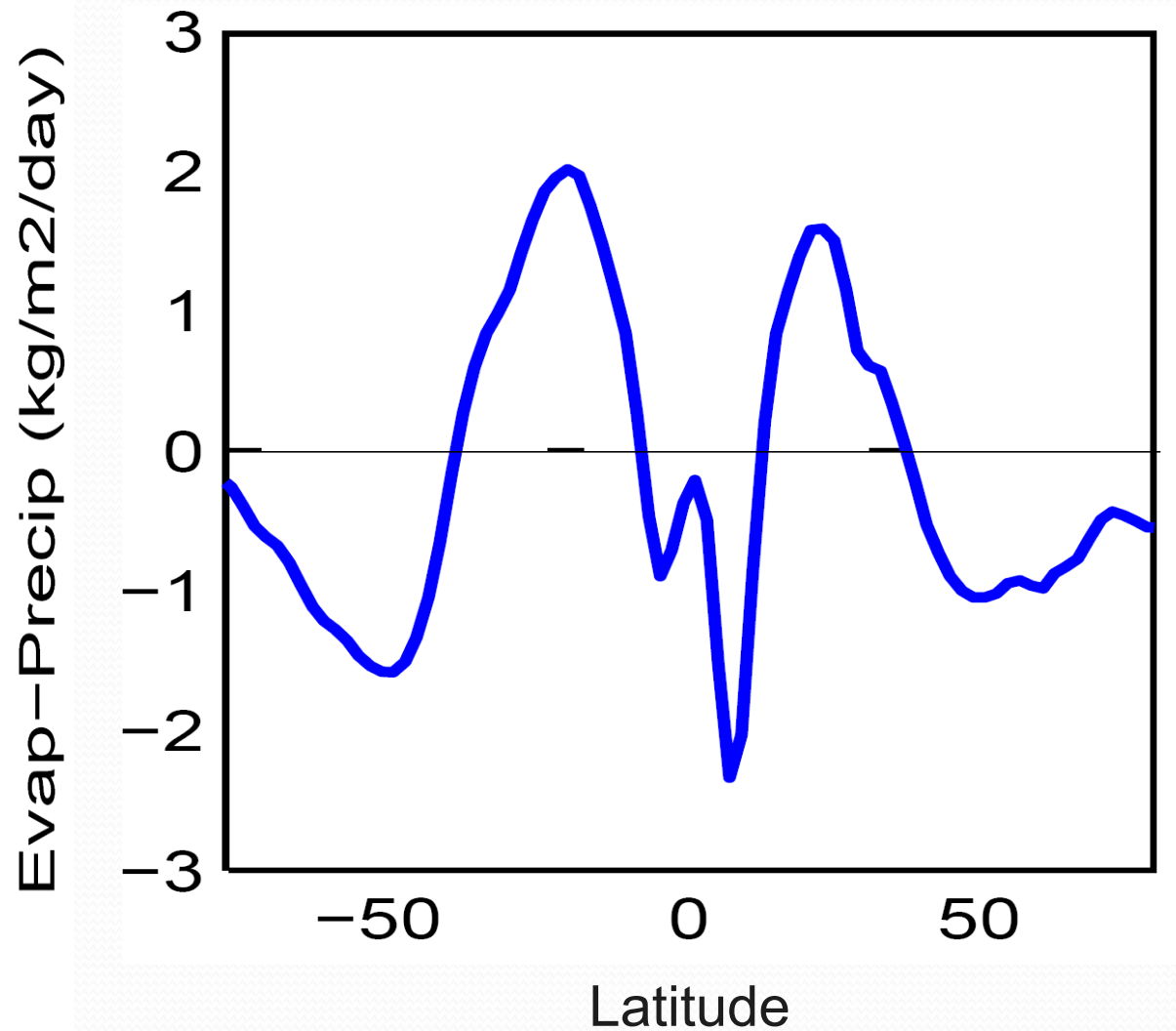
AABW – the Antarctic Bottom Water

Important points:

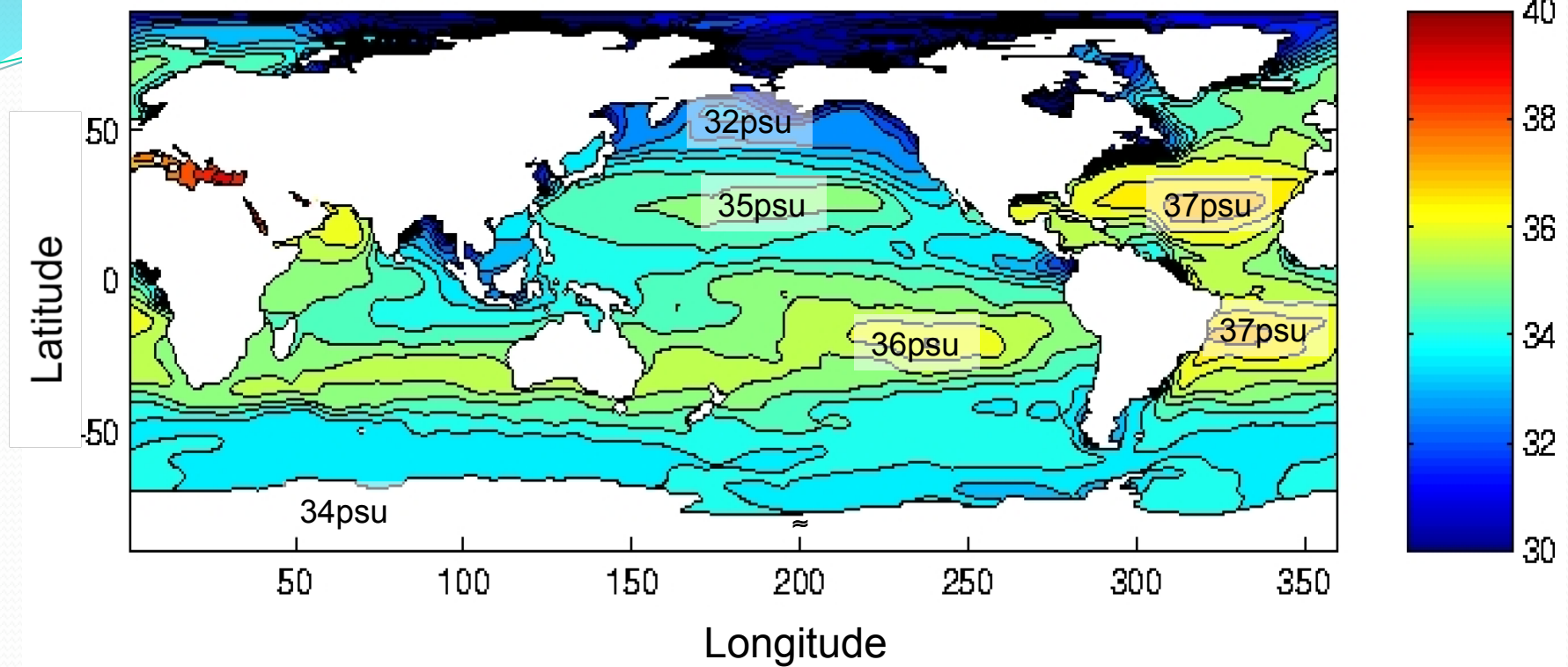
- 1) *Variations in ocean density with depth in many parts of the ocean (tropics to mid-latitudes) are predominantly controlled by temperature (not salinity). In other words, ocean vertical **stratification** is typically controlled by temperature.*
- 2) *Usually there is a layer of relatively uniform temperature near the ocean surface – the so-called **mixed layer**. Depth – typical from 20m to 100m, but can go to ~1000m.*
- 3) *In the tropics, subtropics and mid-latitudes the warm surface waters and colder deep waters are separated by a layer with rapidly changing temperatures (large dT/dz) – **the thermocline**. There are two types of thermocline – seasonal and permanent.*
- 4) ***Abyssal water** – cold deep water with very weak stratification.*

***Forcing at the ocean atmosphere interface:
Heat Fluxes, Evaporation-Precipitation,
Wind Stress***

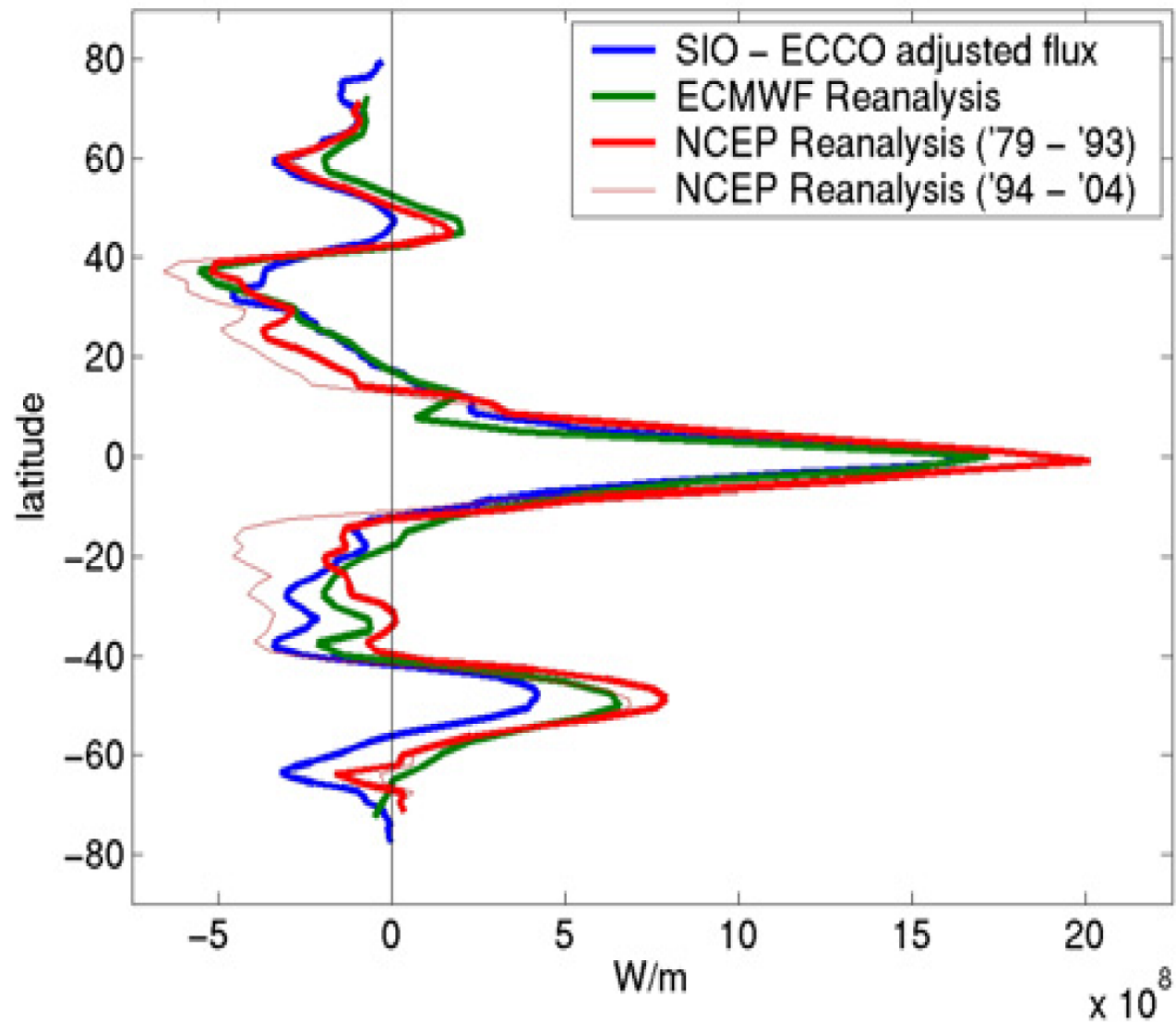
Zonally-averaged freshwater fluxes at the ocean surface (E-P)



Surface Salinity



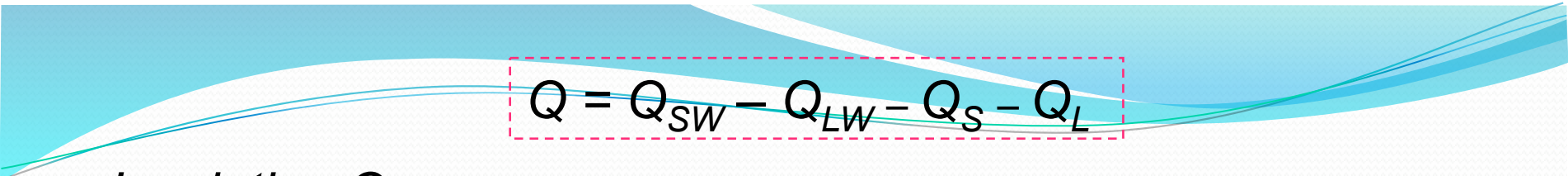
Zonally-integrated heat fluxes at the ocean surface





The net download heat flux into the ocean Q can be calculated as a sum of separate flux components:

$$Q = Q_{SW} - Q_{LW} - Q_S - Q_L$$

A diagram showing a cross-section of the ocean surface and upper layers. A dashed red box highlights the equation $Q = Q_{SW} - Q_{LW} - Q_S - Q_L$.
$$Q = Q_{SW} - Q_{LW} - Q_S - Q_L$$

Insolation Q_{SW}

-the flux of sunlight into the sea (short wave radiation)

Net Infrared Radiation Q_{LW}

- net flux of infrared radiation from the sea (i.e. long wave radiation emitted by the ocean surface minus long wave radiation emitted by the atmosphere in the direction of the ocean – the greenhouse effect is hidden here);

Sensible Heat Flux Q_S

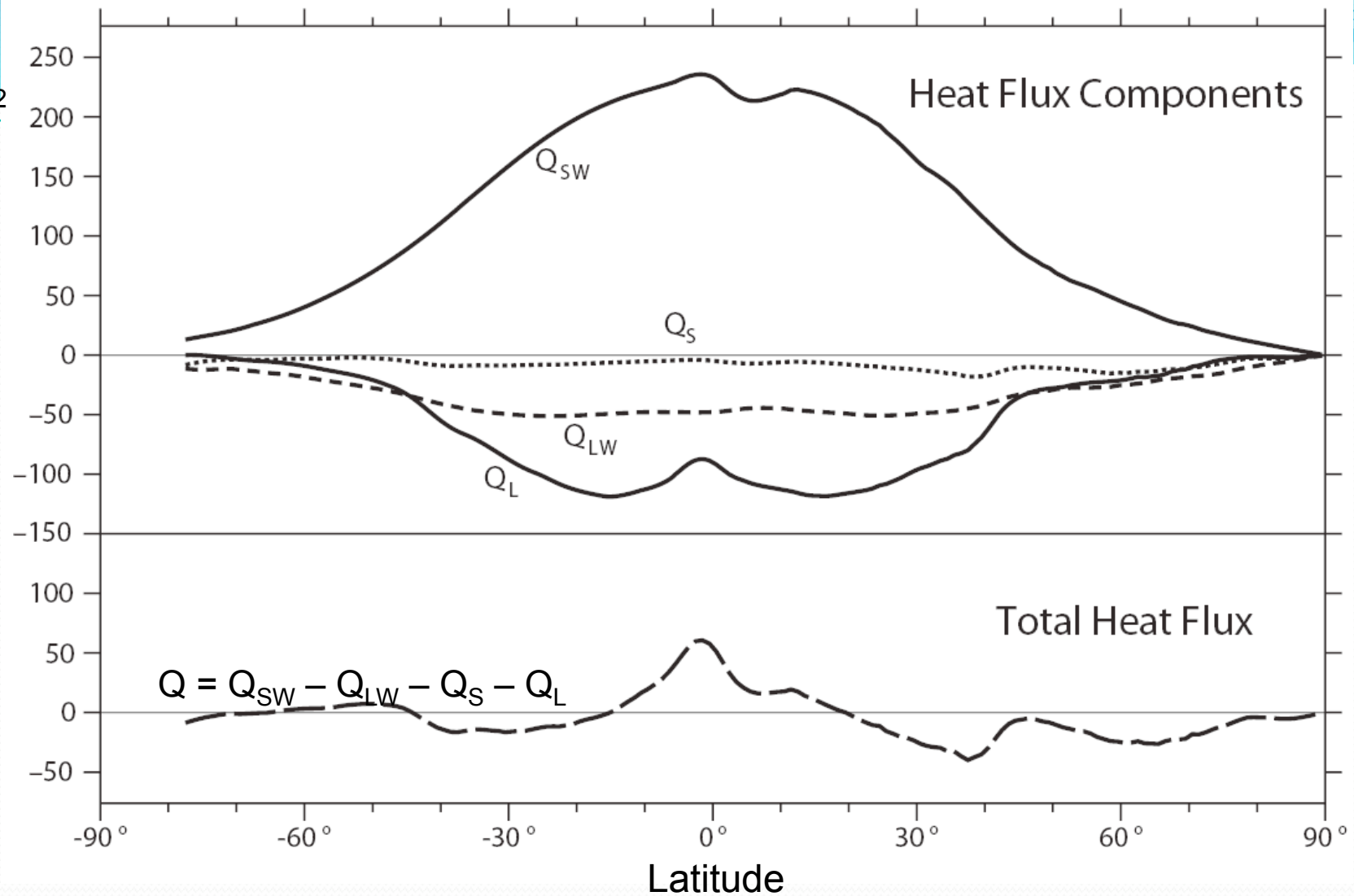
- the flux of heat out of the sea due to conduction (i.e. heat transfer by turbulent convection between two surfaces with different temperatures);

Latent Heat Flux Q_L

-the flux of heat carried by evaporated water;

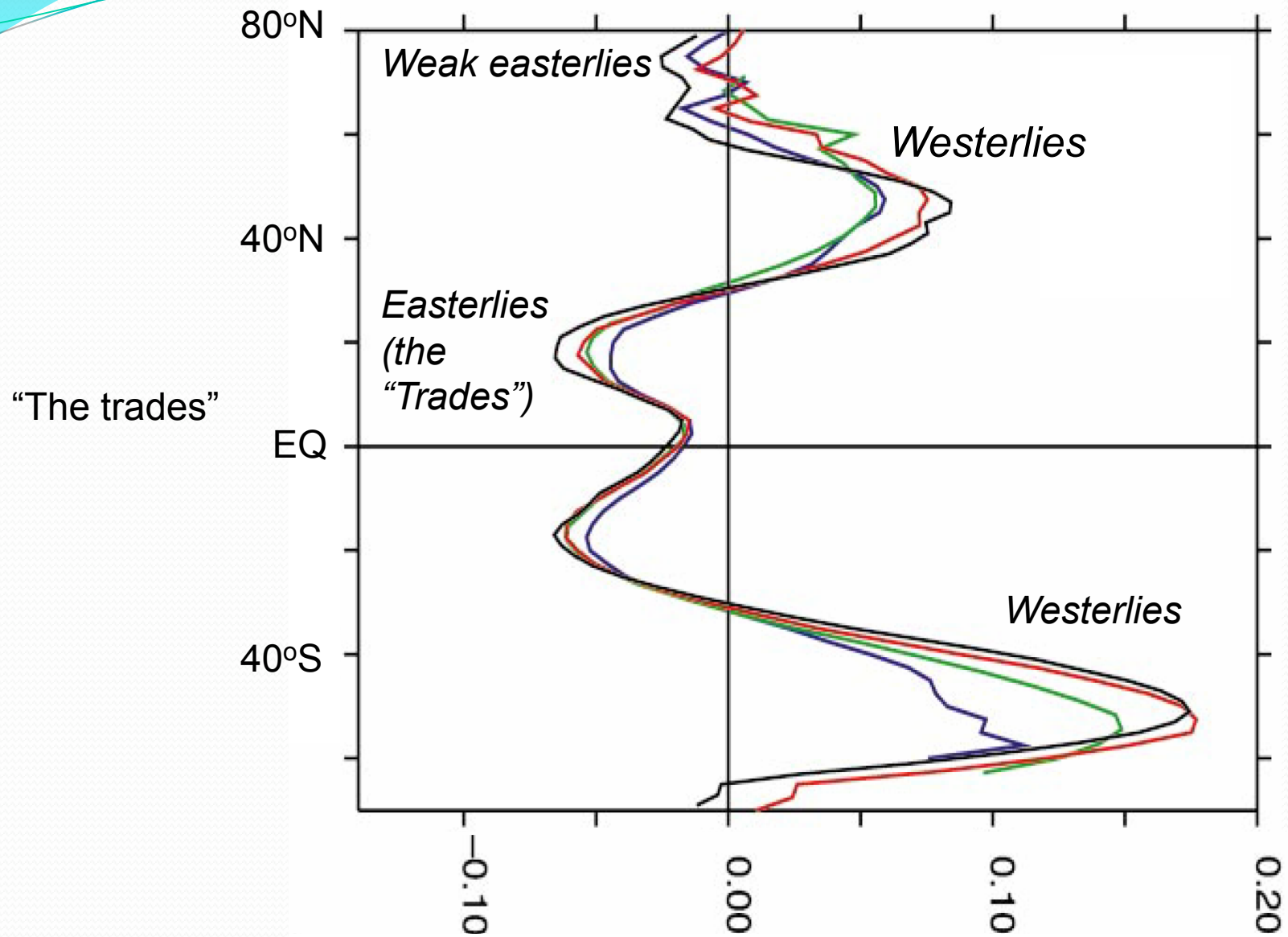
$$Q = Q_{SW} - Q_{LW} - Q_S - Q_L$$

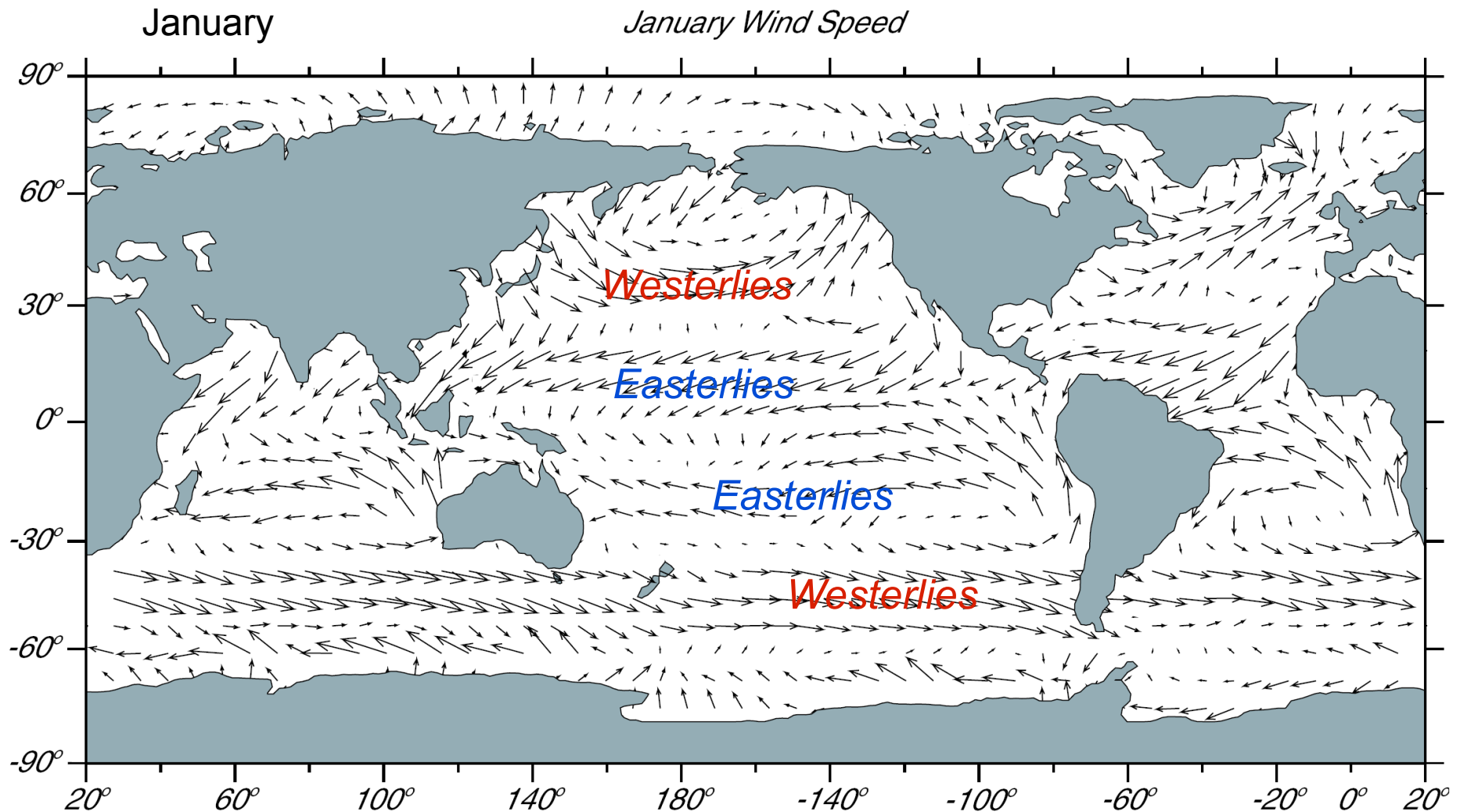
W/m²



Upper panel: Zonal averages of heat transfer to the ocean by insolation Q_{SW} , and loss by net infrared radiation Q_{LW} , sensible heat flux Q_S , and latent heat flux Q_L . **Lower panel:** Net download heat flux through the sea surface calculated from the data above (DaSilva et al 1995).

Mean zonal-averaged wind stress (Pa) over the ocean





Mean, sea-surface winds for January (Trenberth et al 1990). The winds near 140°W in the equatorial Pacific are about 8 m/s.

*Note (1): The combination Easterlies/ Westerlies drive subtropical gyres
(2): the strong Westerlies in the Southern Hemisphere drive the ACC*

Ocean general circulation:

1. Wind-driven circulation

(relatively shallow, relatively fast)

2. The thermohaline circulation (includes abyssal circulation) – circulation that depends on large-scale meridional gradients of temperature and salt

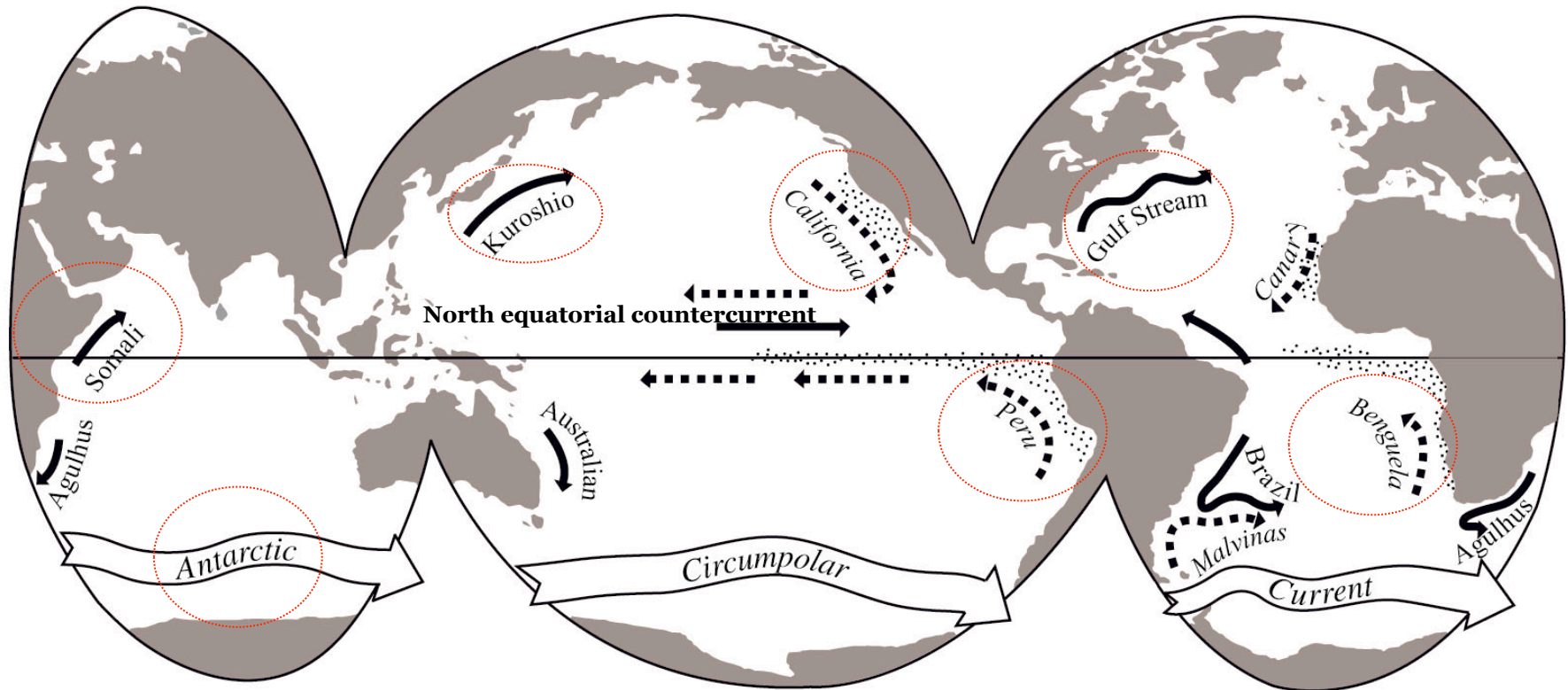


1. Gyre Circulation

Franklin-Folger map of the Gulf Stream made in 1769



Ocean wind-driven circulation



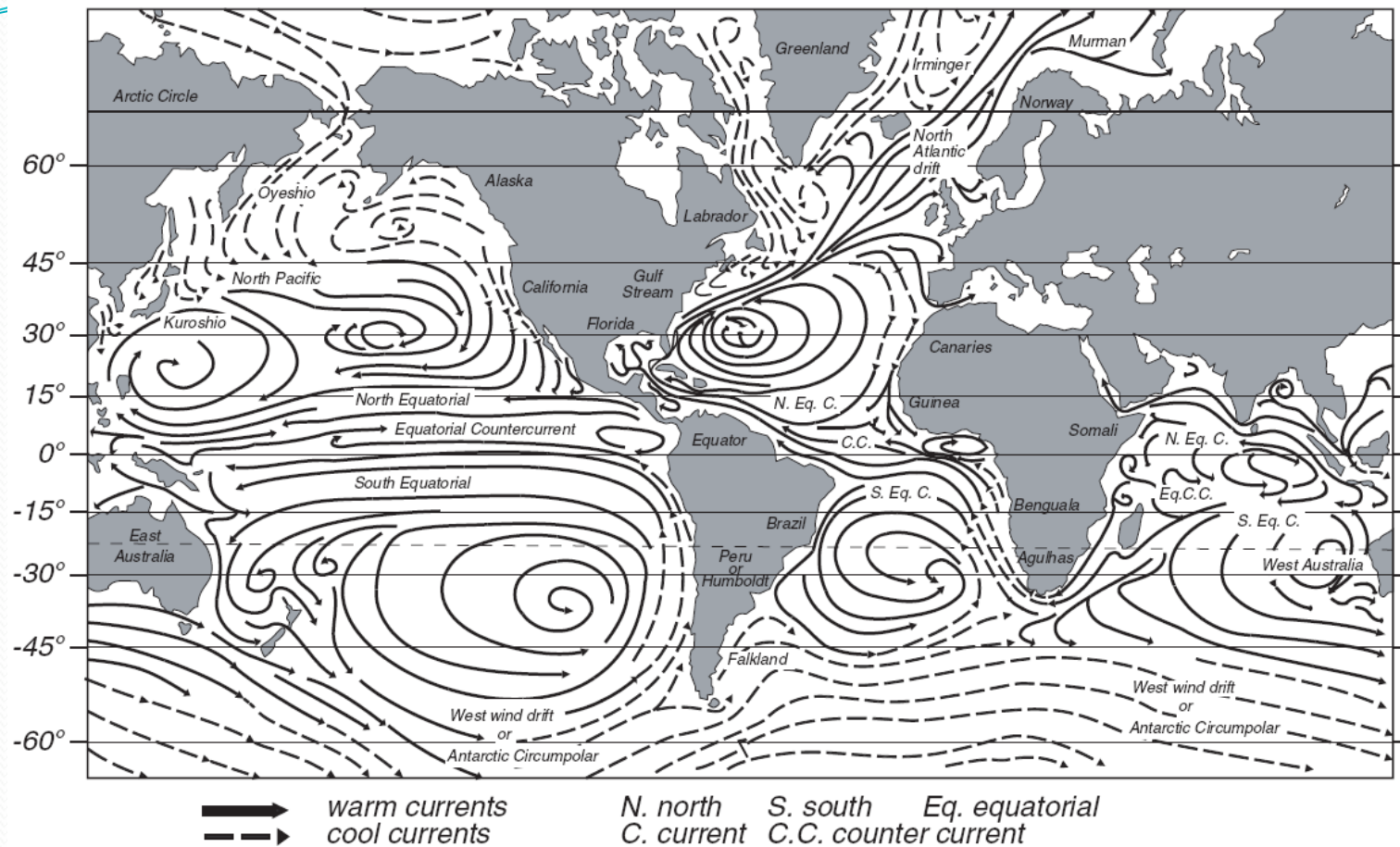
Regions of Upwelling



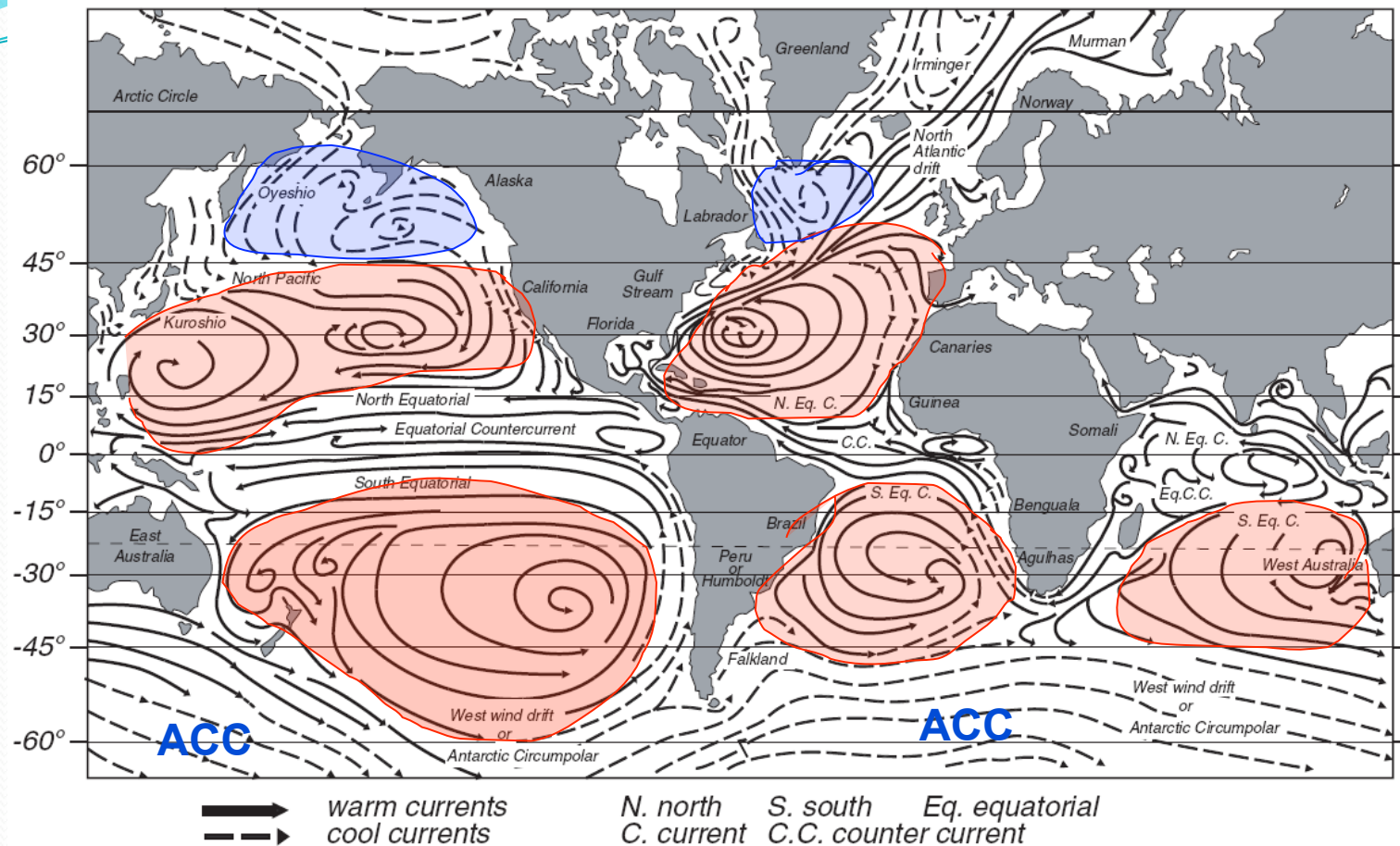
Warm Currents



Cold Currents



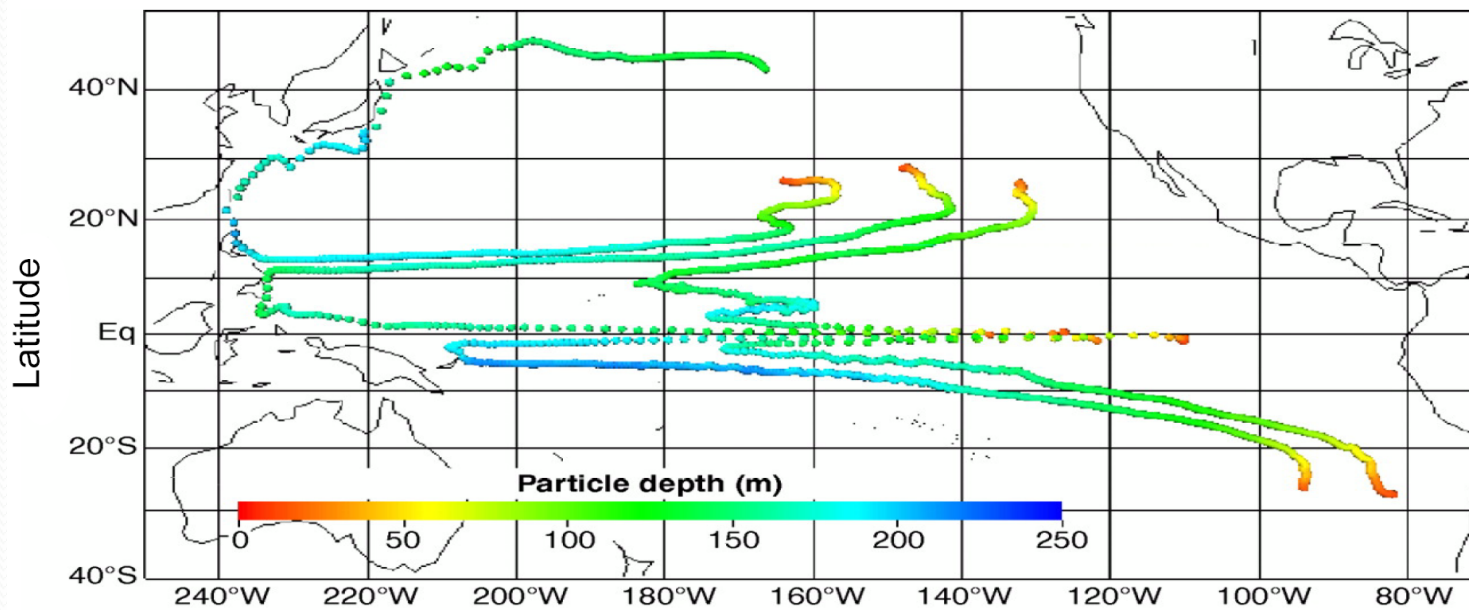
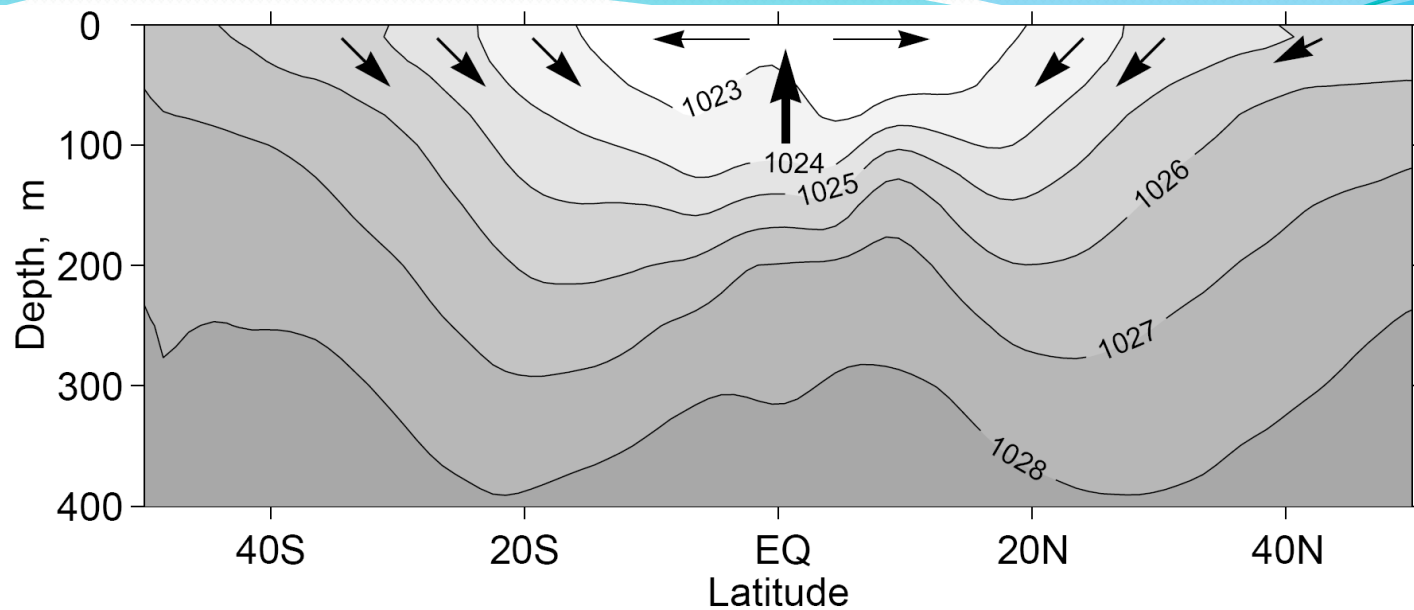
The time-averaged, surface circulation (mostly-wind-driven) of the ocean during northern hemisphere winter deduced from a century of oceanographic expeditions. After Tolmazin (1985).



Main components of the ocean wind-driven circulation:

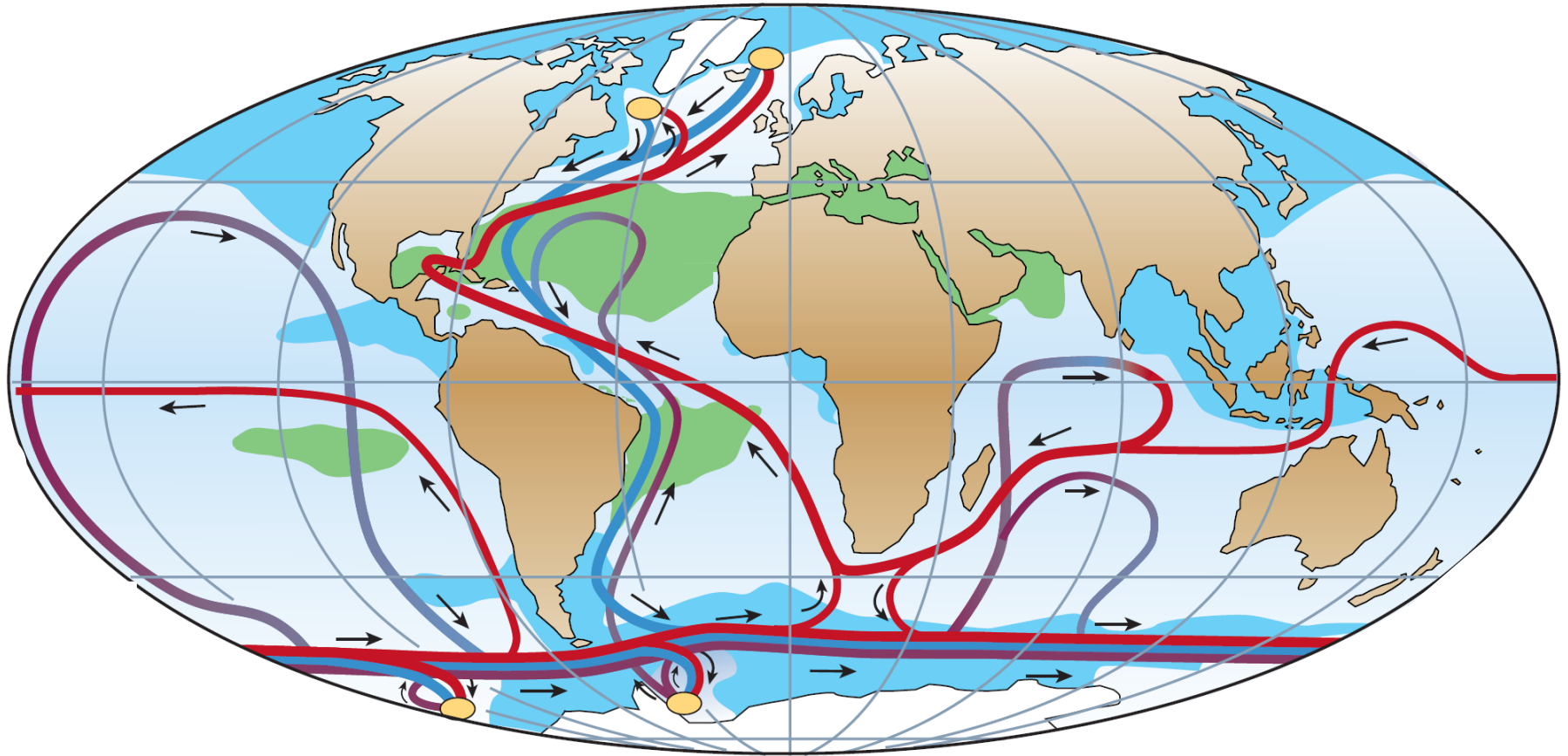
- 1) Subtropical gyres
- 2) Subpolar gyres
- 3) Equatorial circulation
- 4) The Antarctic Circumpolar current (ACC)

Water-parcel (Lagrangian) representation of the wind-driven circulation



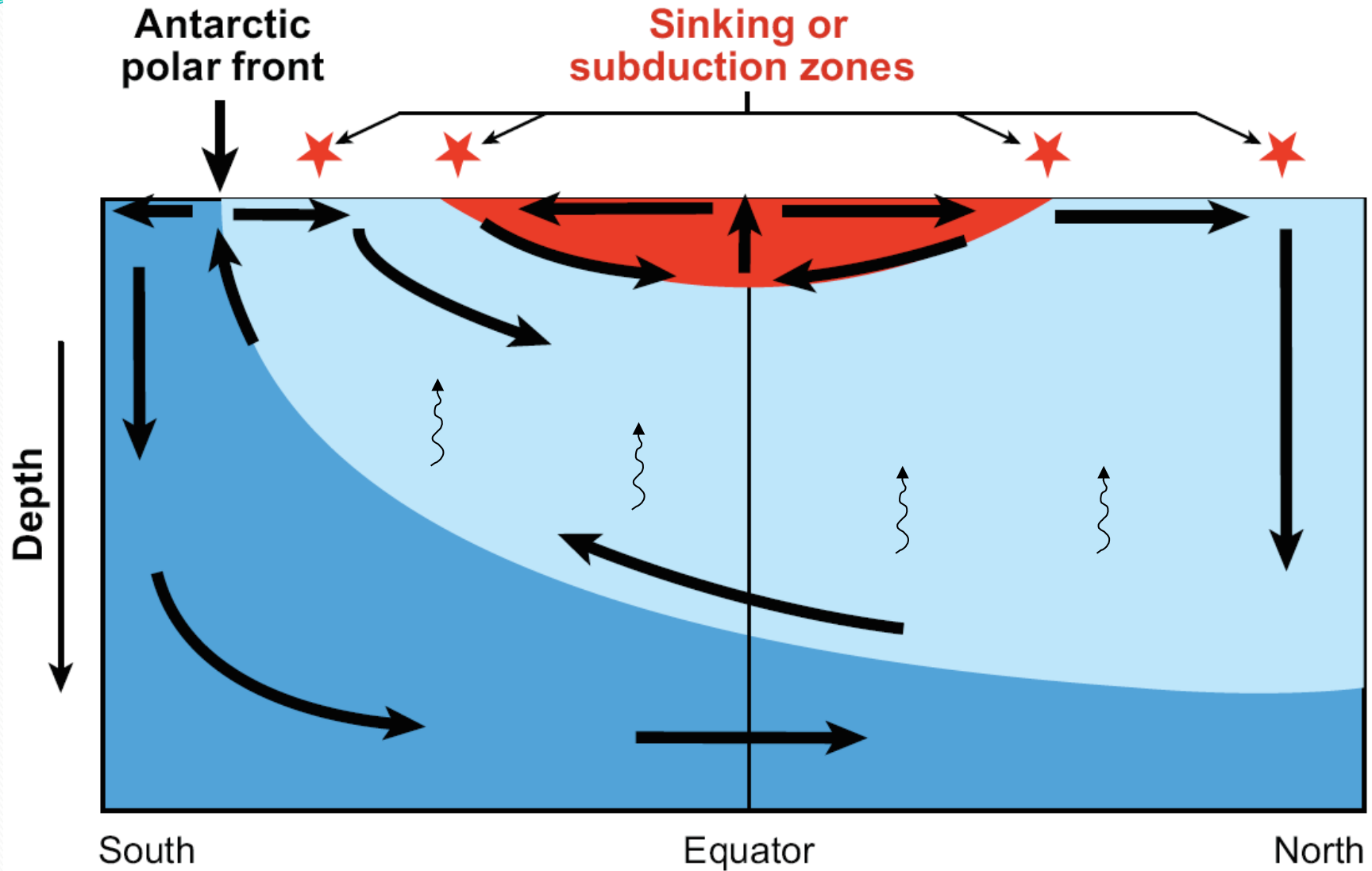


2. The Meridional Overturning Circulation (ThermoHaline Circulation)



A simplified cartoon of the global **thermohaline circulation** (the so-called 'conveyor belt', originally by Broecker, After Rahmstorf).

Ocean meridional overturning



Barreiro, Fedorov and co-authors 2007

Scales: ocean general circulation

Horizontal spatial scale: 100 to 10000 of kilometers

Vertical spatial scale: 1 to 5 km

Aspect ratio: $H/L = O(0.01)$ to $O(0.001) \ll 1$

Time scales: many years (from annual to, to decadal, to 100s of years). Seasonal, interannual to decadal/century fluctuation in flows which may or may not retain the same patterns.

Average current speeds:

1-5 cm/sec (horizontal) in the interior of the ocean,

50-150 cm/sec (horizontal) in the fastest currents such as the Gulf Stream and the Antarctic Circumpolar Current.

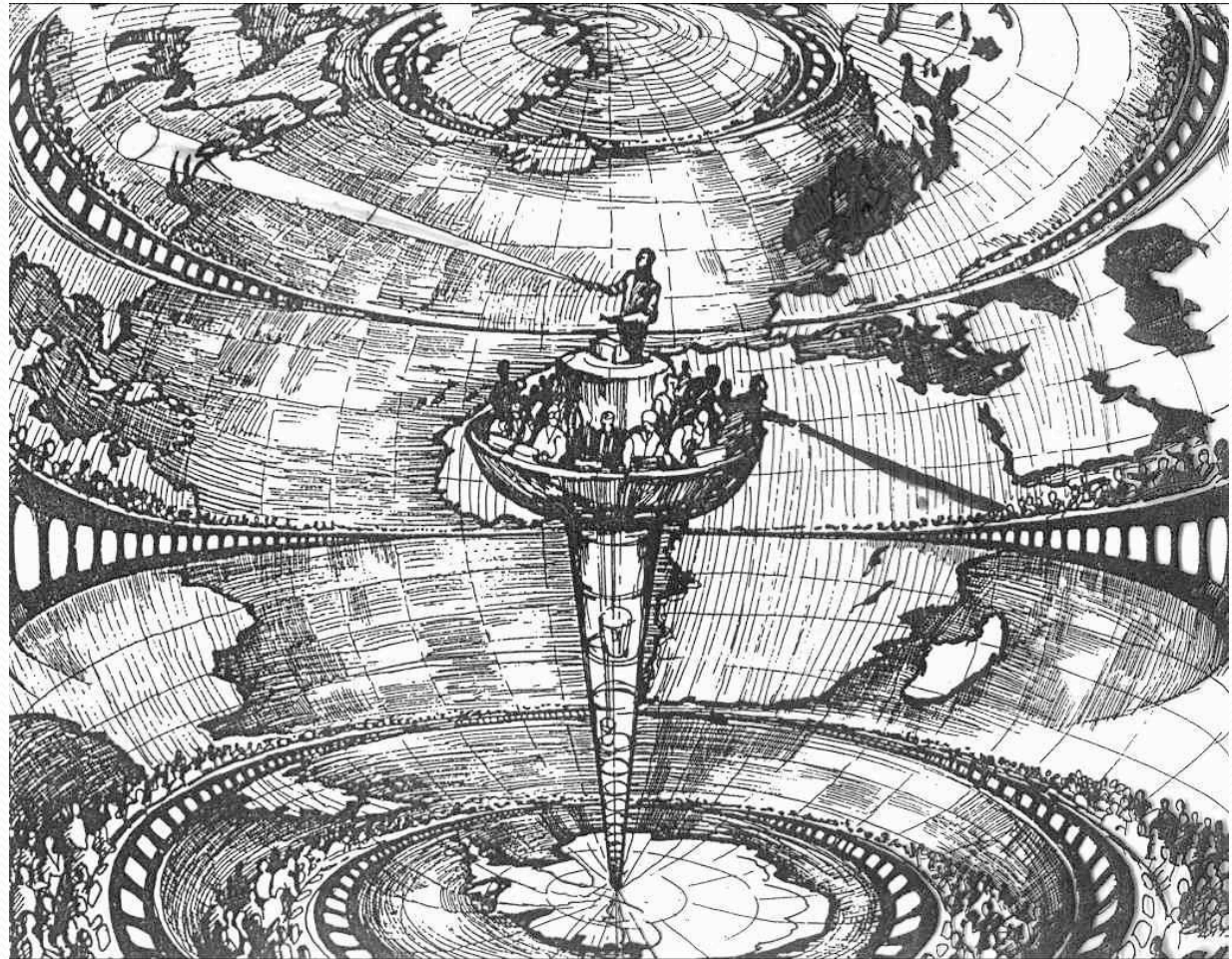
The vertical velocity for the general circulation is on the order of 10^{-4} cm/sec and is almost always inferred, not measured.



Modeling of the Ocean:

Modeling of the Ocean:

An artist view of
Richardson's
Forecast Factory

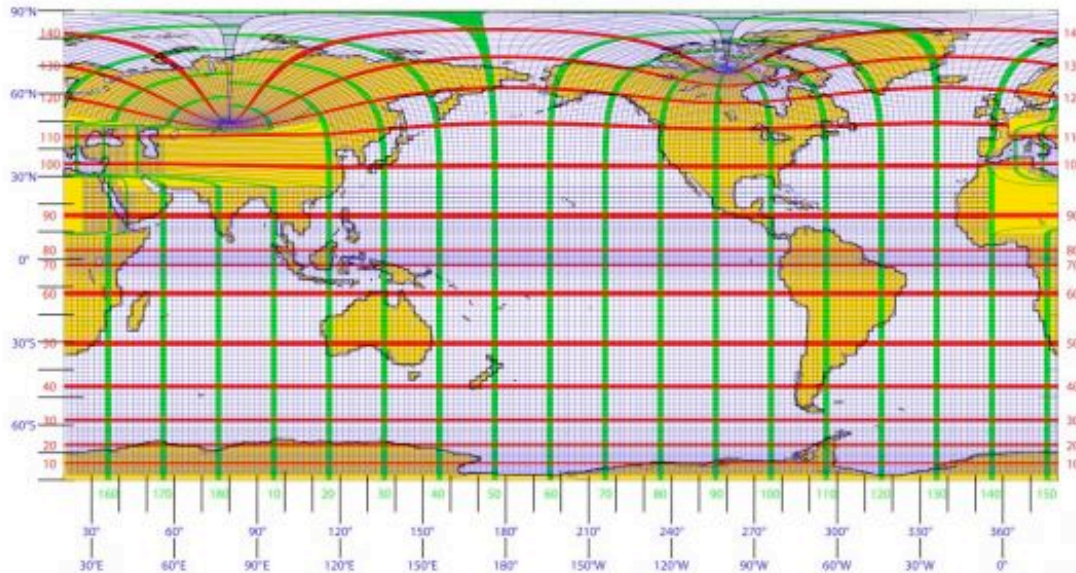


Discretisation:

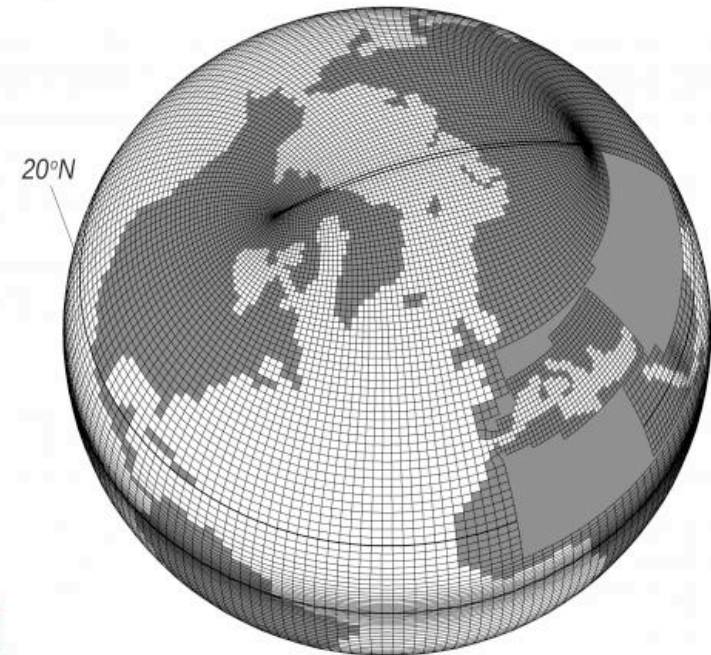
- Splitting the continuous problem in a finite number of variables

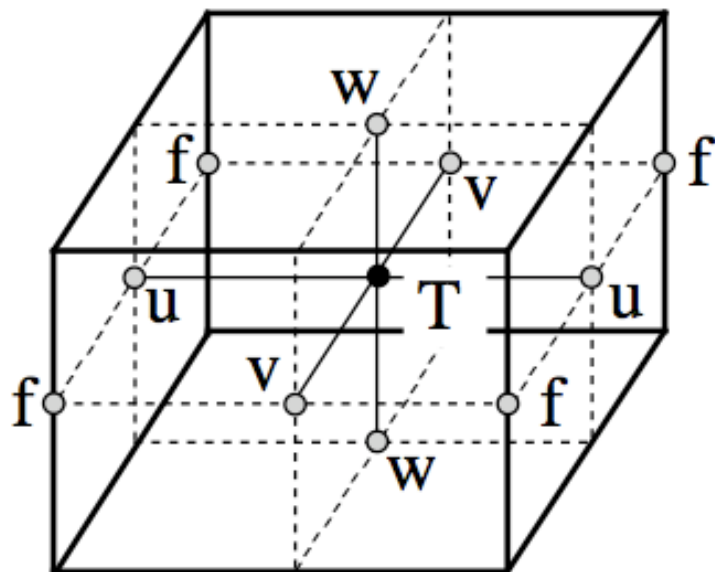
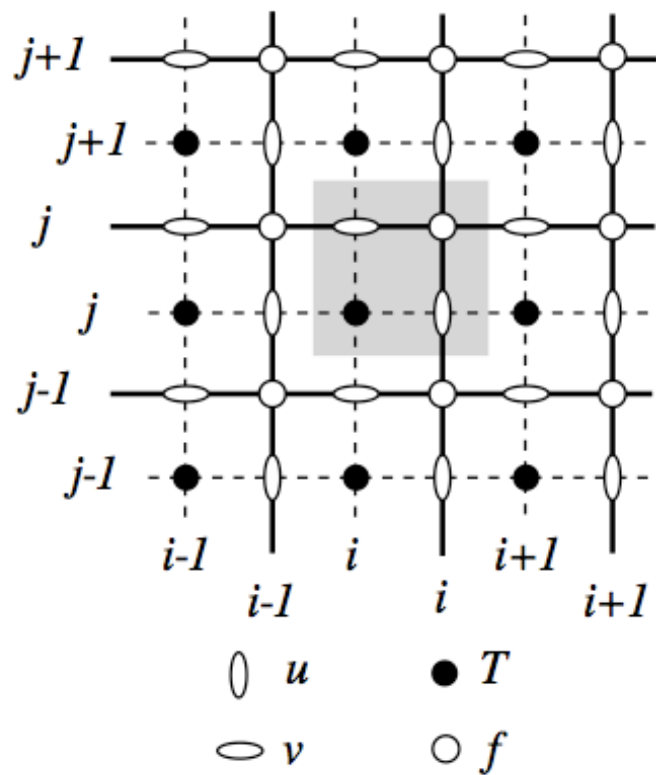


ORCA R2 : mesh indexation



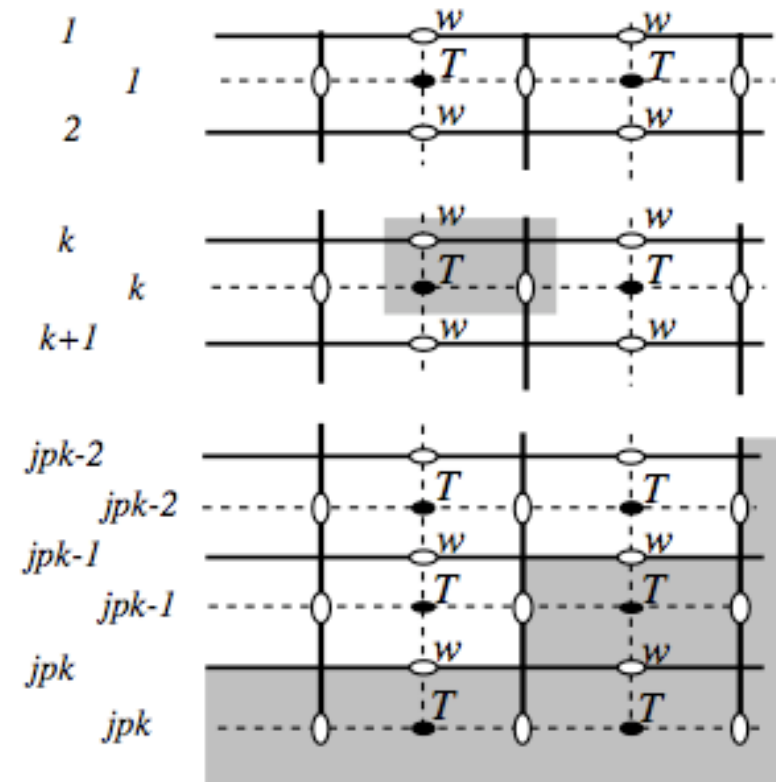
ORCA mesh





Discretisation

LEVELS



Set of Equations

- Prognostic equations:

Tracer evolution = Adv + Diff

Acceleration = Cor + Adv + Visc

- Diagnostic equations:

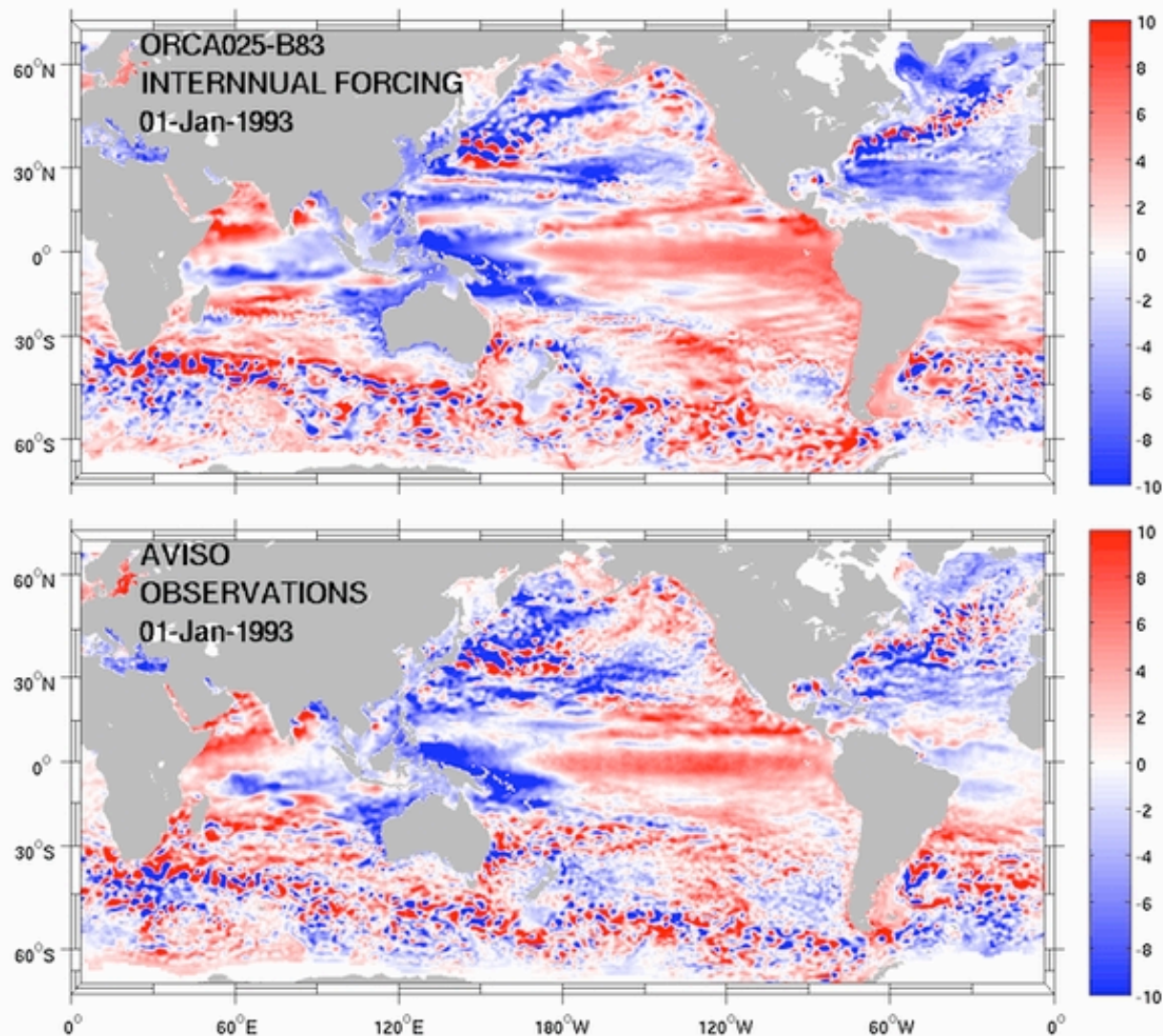
Hydrostatic

Equation of State for seawater

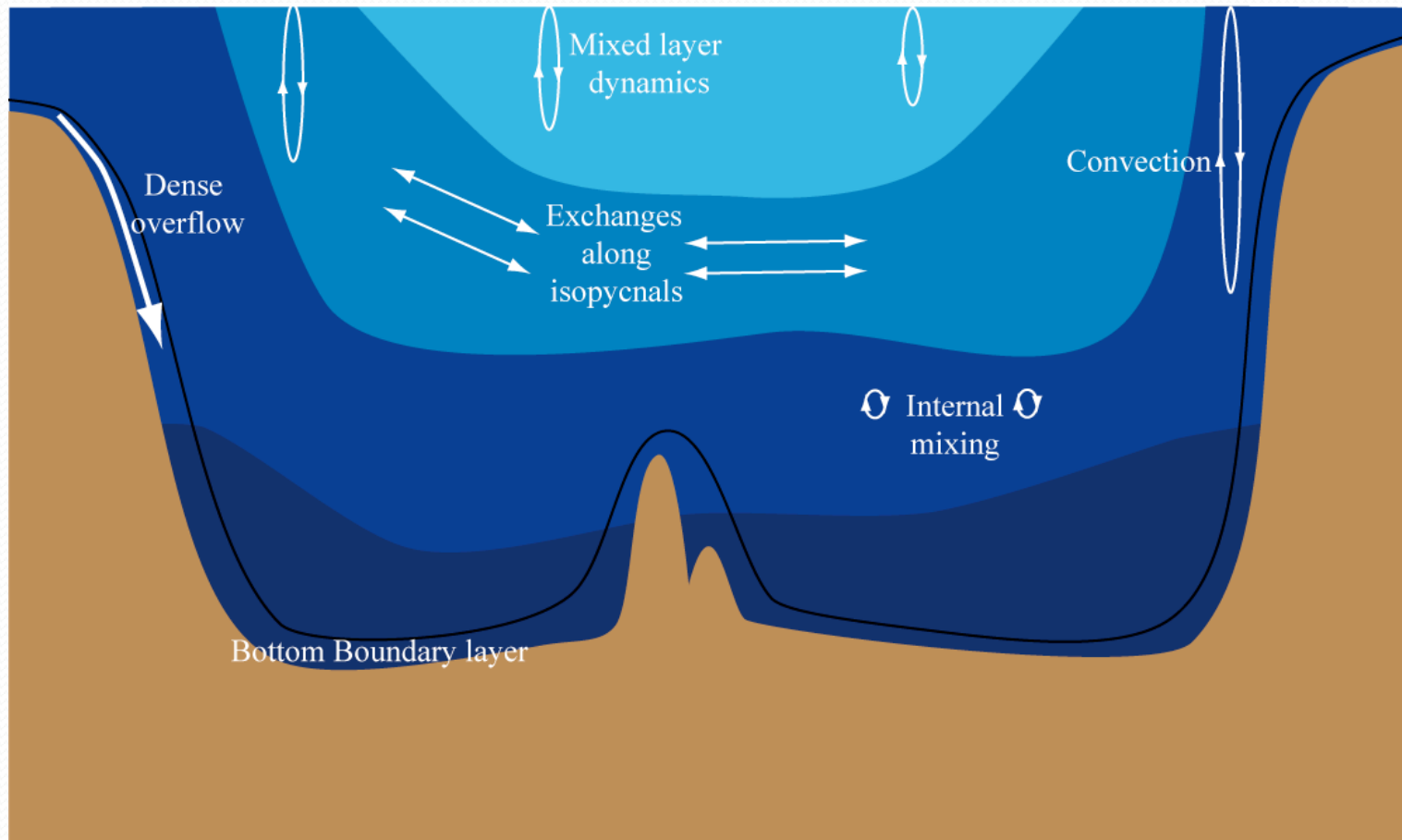
Non-divergence

Example of Solution:

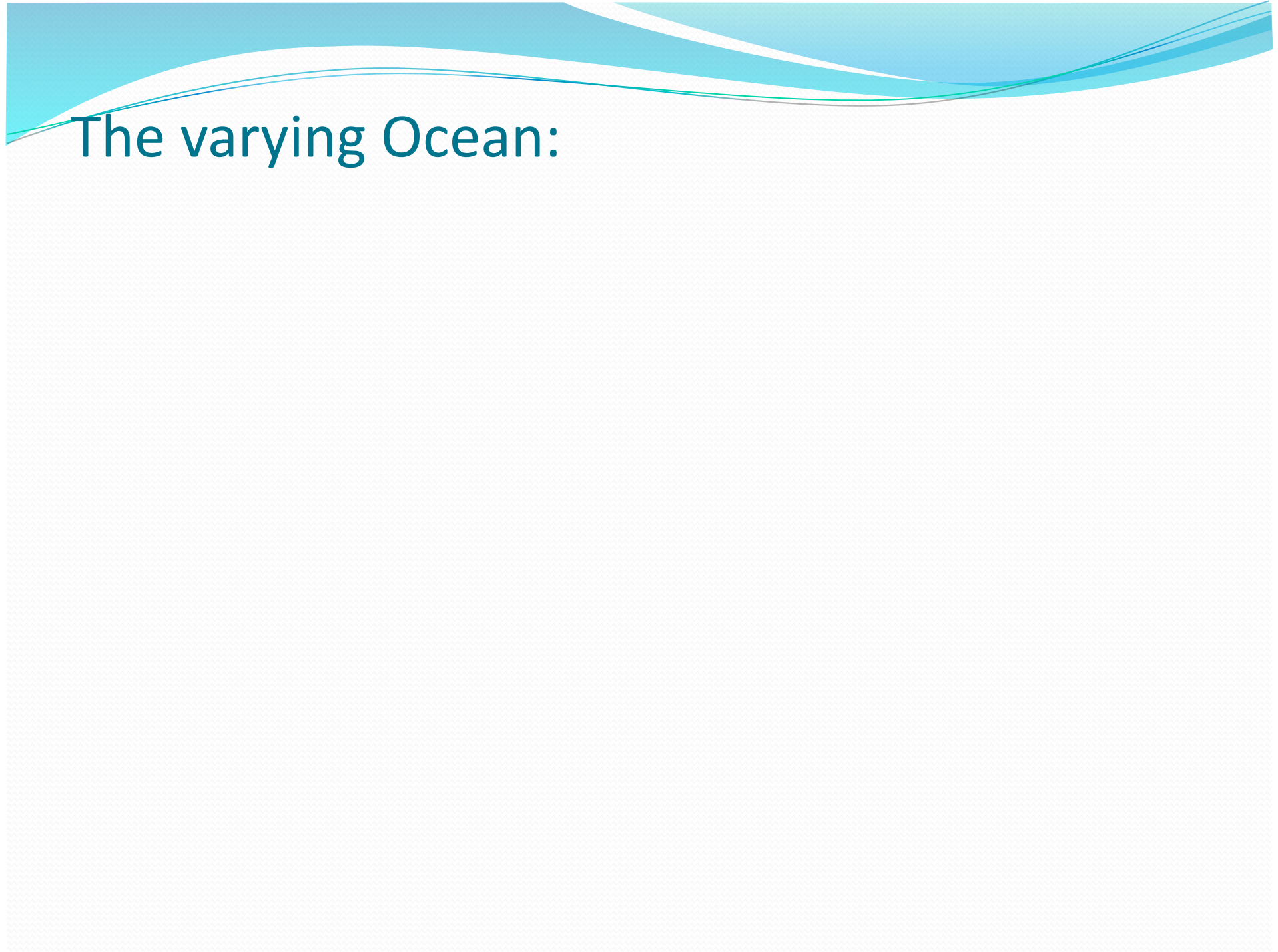
- Sea Surface Height field in a high resolution Ocean GCM (1/4°)



Unresolved processes:



- Sub-grid physics should be parameterized since they cannot be explicitly solved



The varying Ocean:

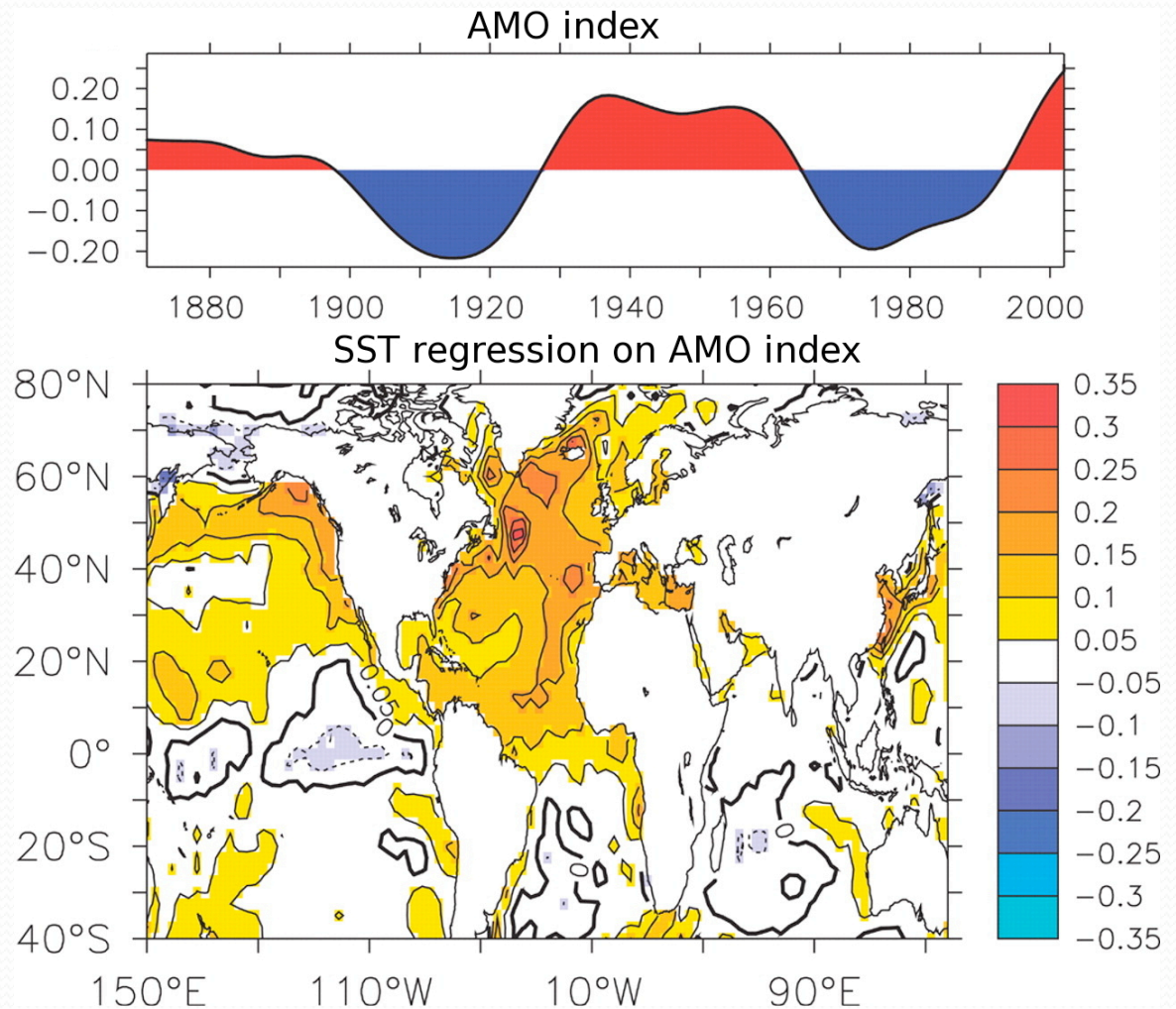


The varying Ocean:

- Two examples:
 - Decadal timescale variability
The Atlantic Multidecadal Variability
 - Millennial timescale variability
The Dansgaard-Oeschger Events

The Atlantic Multidecadal Variability

- North Atlantic Var.
- “Period” of 20-50 yr
(Kushnir et al., 1994)

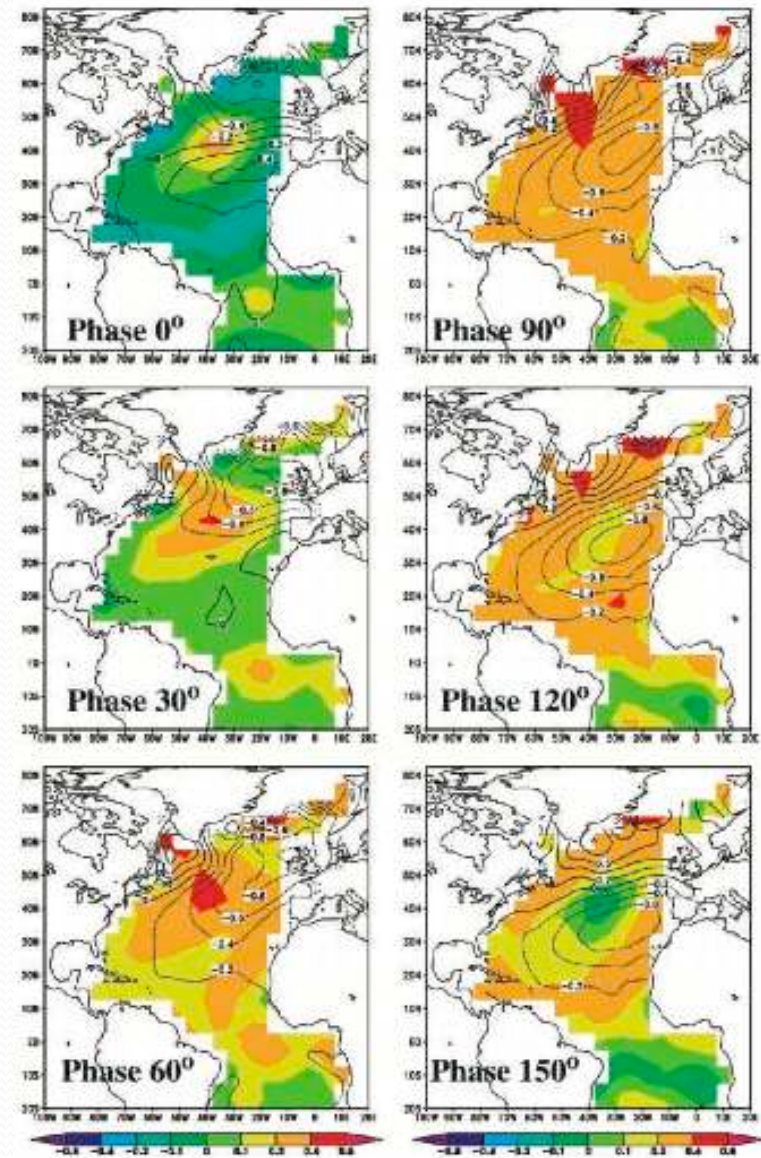


(Sutton and Hodson, 2005)

The Atlantic Multidecadal Variability

Propagation Characteristics:

- Westward propagation of SST
- Dominant period of 50 yr



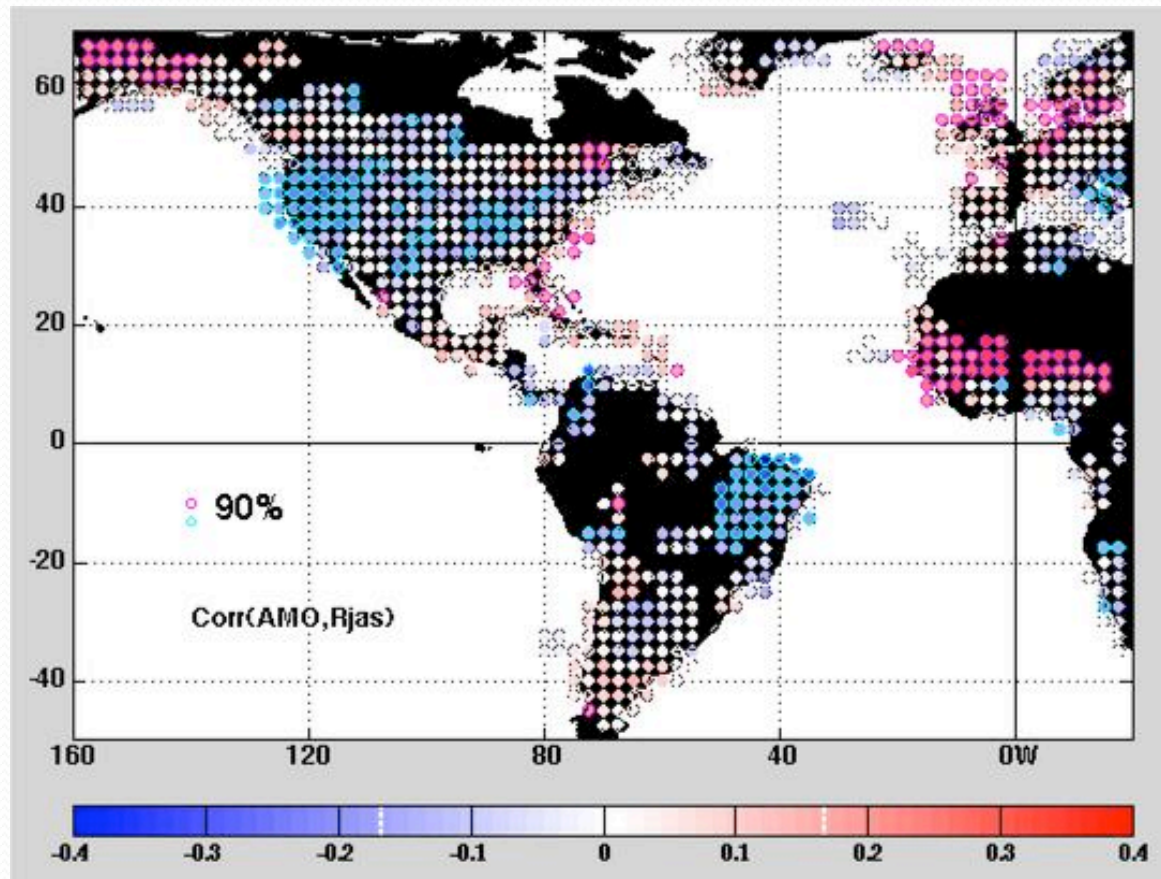
Delworth and Mann (2000)

Color: anomaly of SST, Contour Anomaly of SLP)

The Atlantic Multidecadal Variability

Consequences: [Rainfall/Drought](#) :

Correlation between Jul-Aug-Sep Rainfall and AMO index

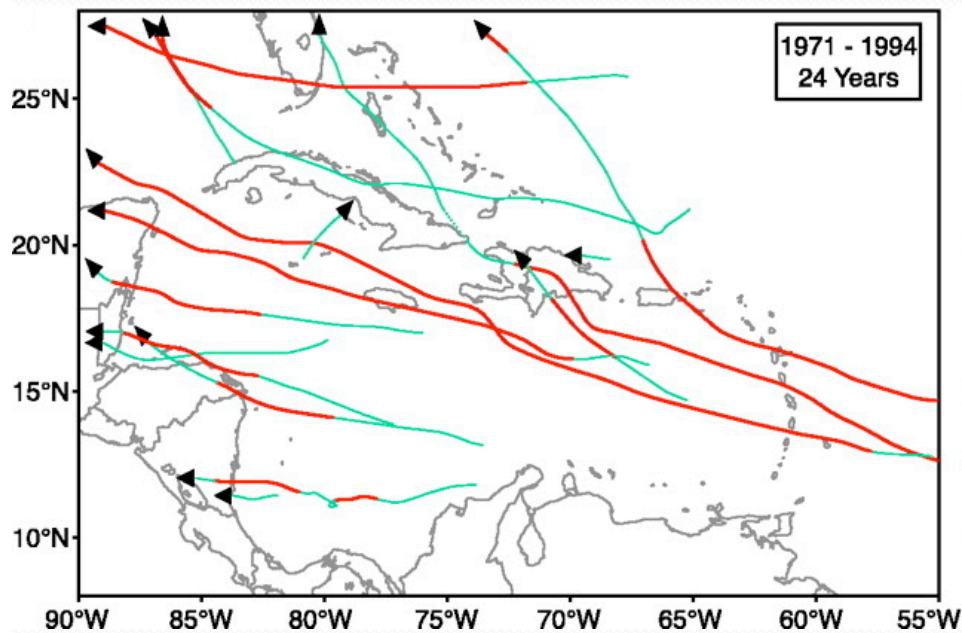


NOAA Atlantic Oceanographic and Meteorological Laboratory

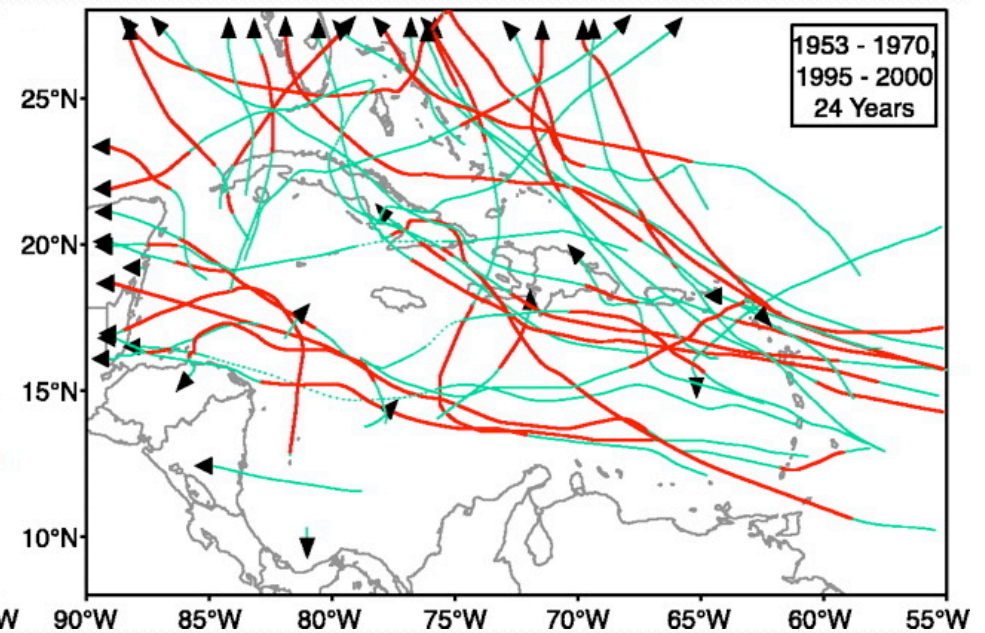
The Atlantic Multidecadal Variability

Consequences: Caribbean Hurricanes

Cold Phase of the AMV



Warm Phase of the AMV

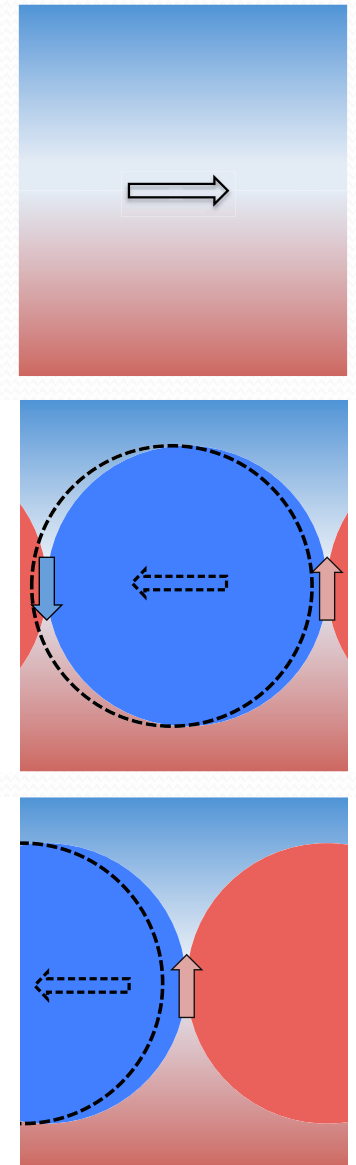
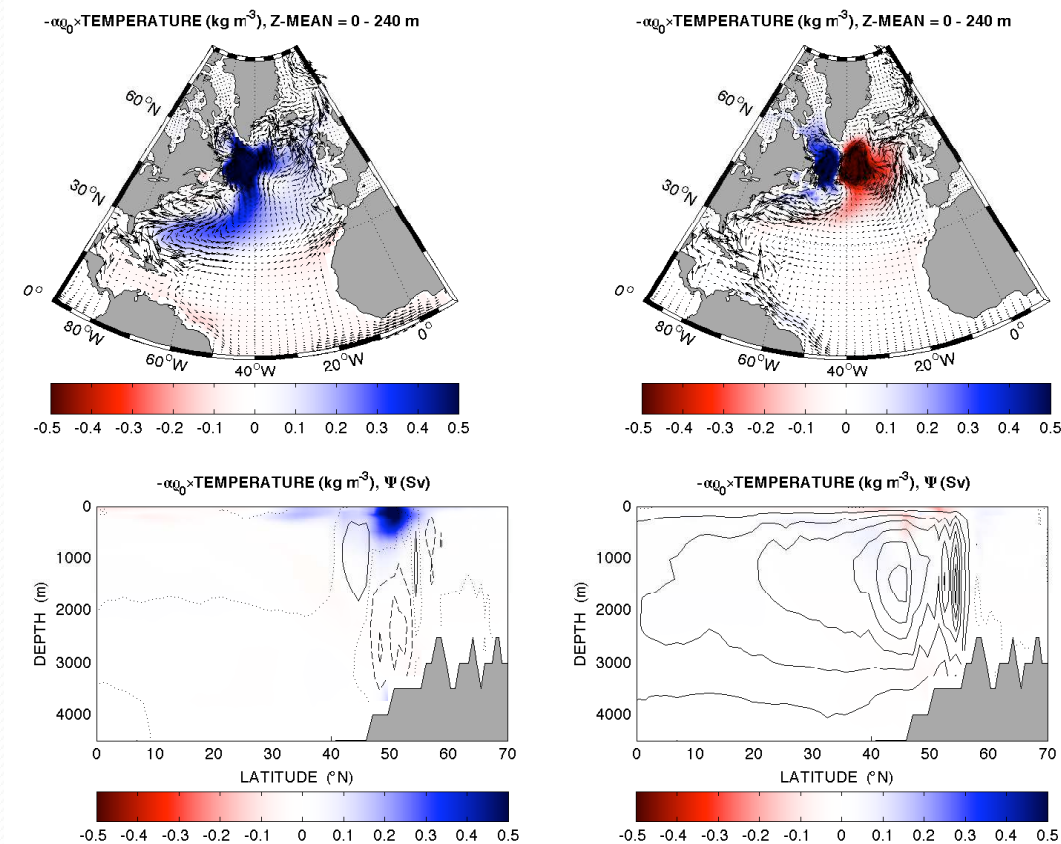


Goldenberg et al. (2001)

The Atlantic Multidecadal Variability

Internal mode of the Ocean dynamics:

Period 24 yr, E-folding time scale -40 yr



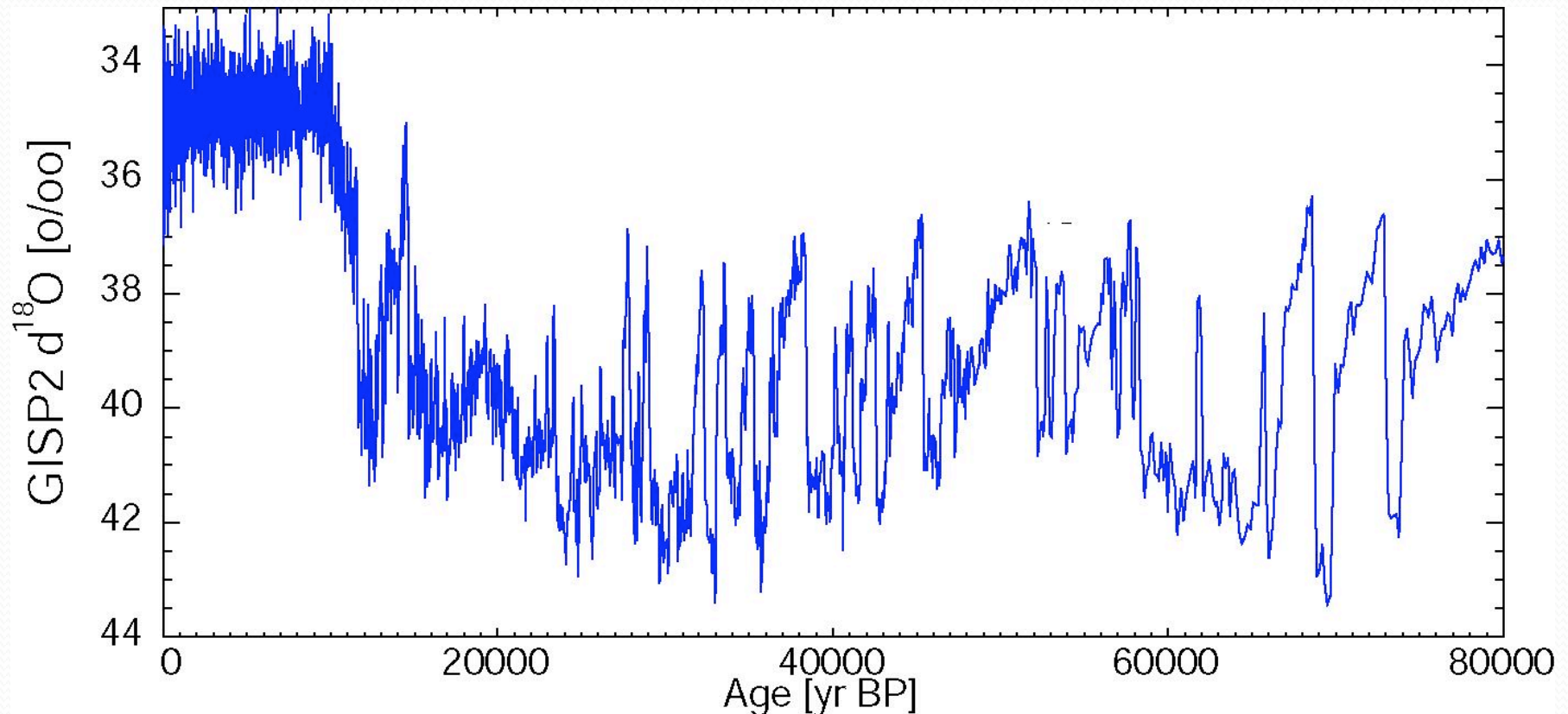
Sévellec and Fedorov (submitted to J. Clim., 2011)



The varying Ocean:

- Millennial timescale variability
The Dansgaard-Oeschger Events

The Dansgaard-Oeschger events

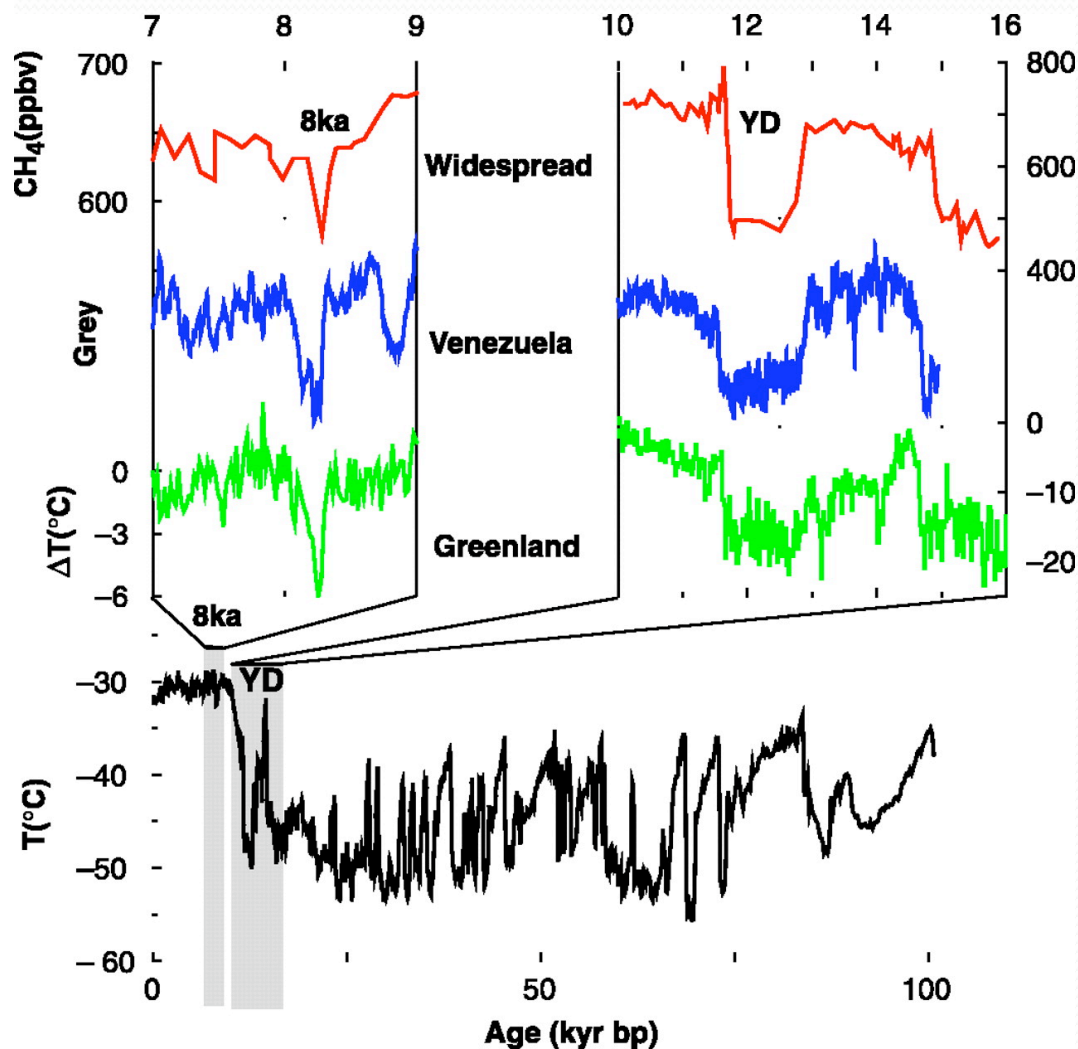


$\delta^{18}\text{O}$ is linked to

- the temperature of the sea water
- the amount of ice

- Relative stability of the past 10,000 yr (Holocene)
- Variability at 1450 yr during glacial period (D-O events)

The Dansgaard-Oeschger events

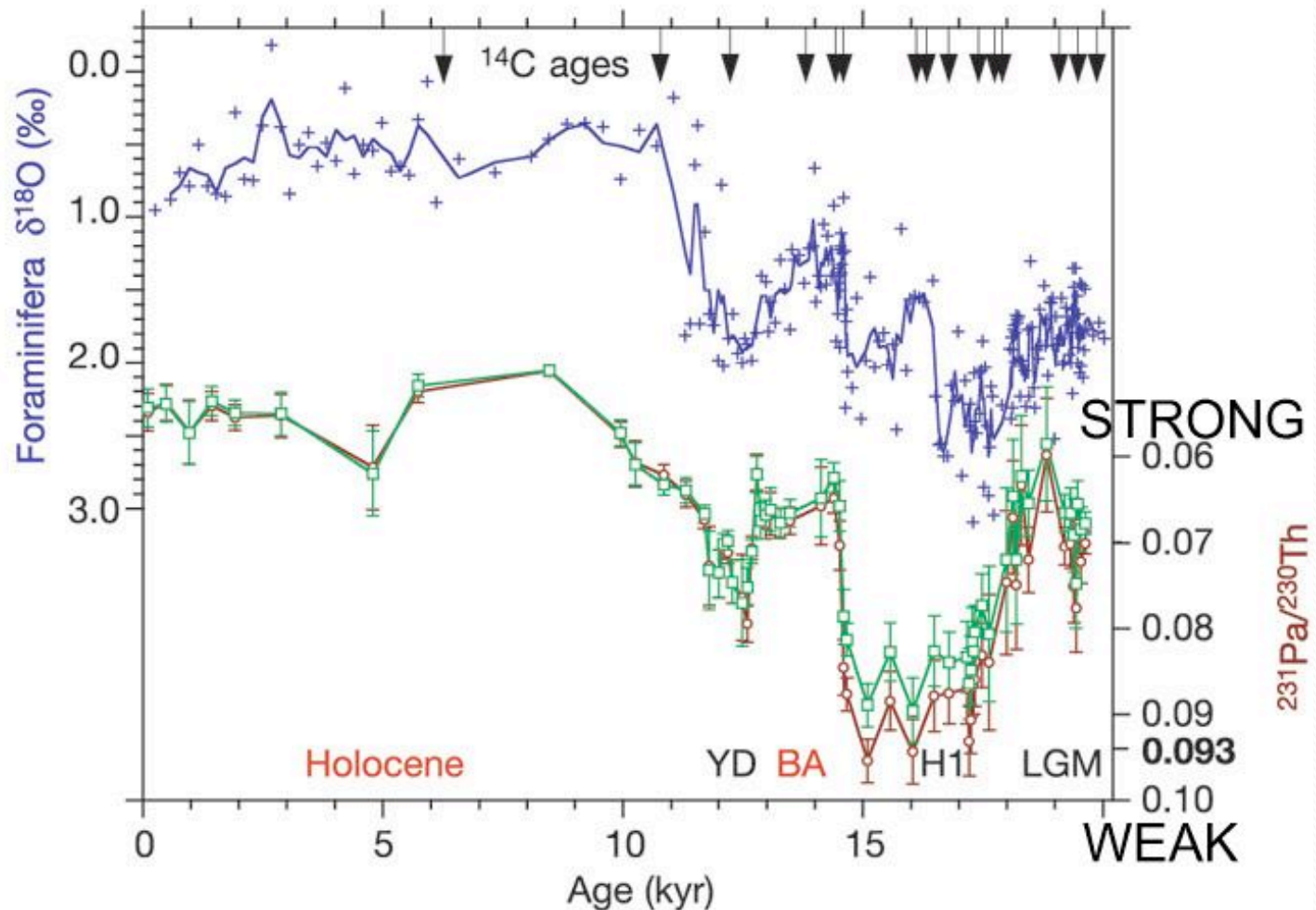


➤ Presence of Cold events

Alley et al. (2005)

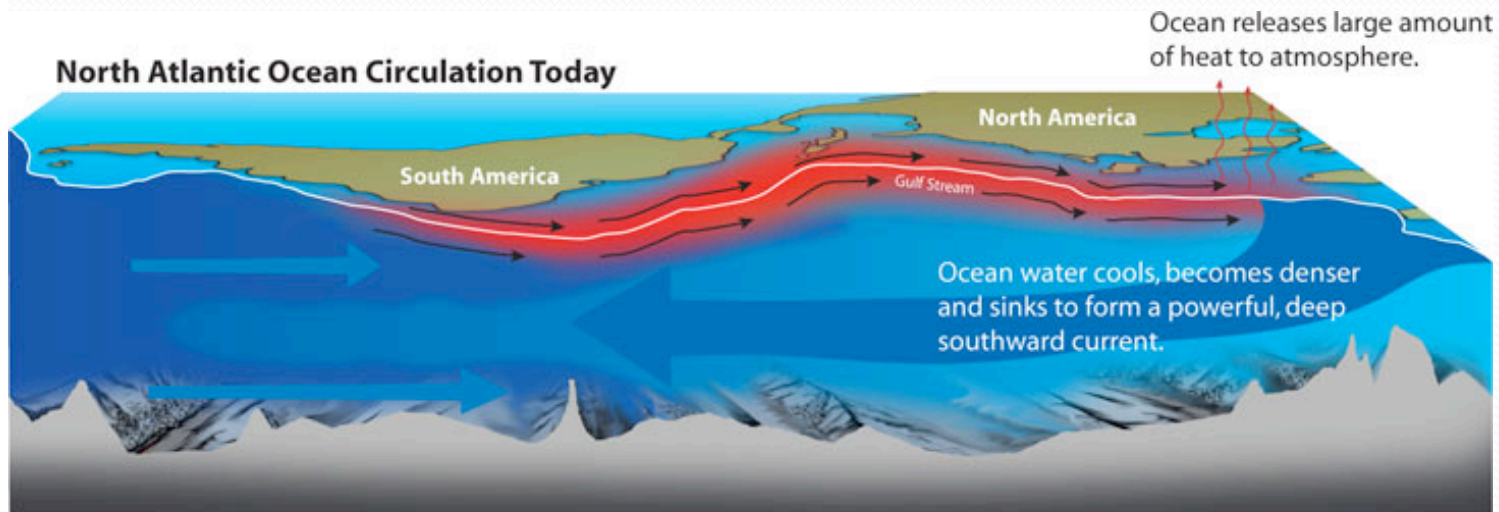
The Dansgaard-Oeschger events

- These cold events have been related to a shutdown of the MOC:

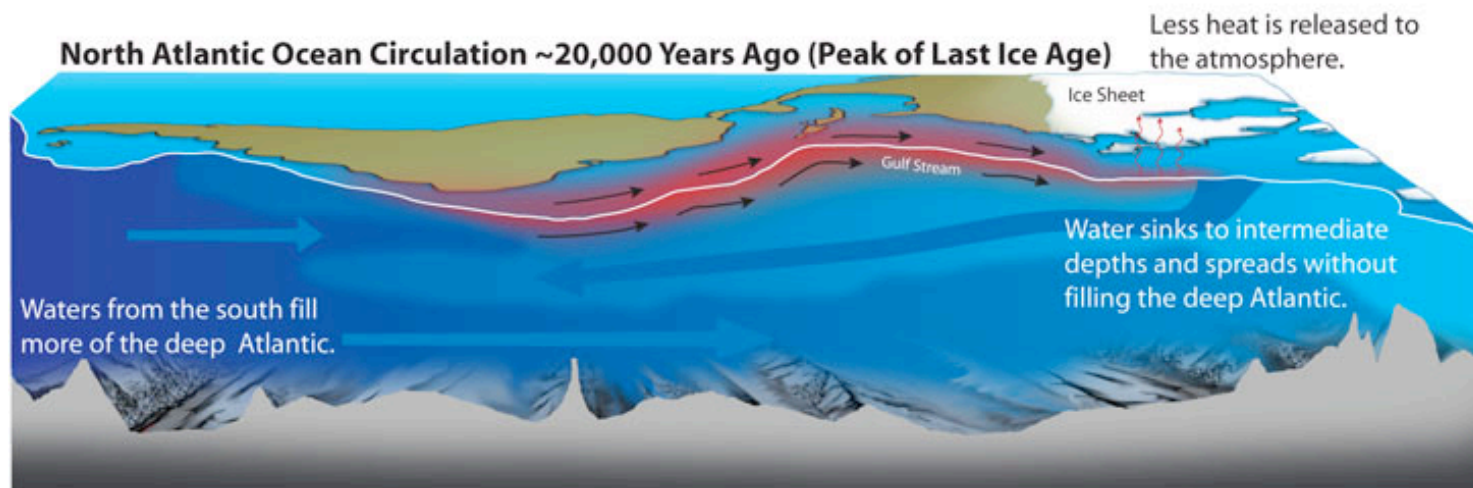


McManus et al. (2004)

The Dansgaard-Oeschger events



Warm phase



Cold phase

McManus et al. (2004)

Under global warming could “The Day After Tomorrow” be a reality?



! Under Investigation !

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- *Modeling the Ocean*

- *The varying Ocean and its impact on Climate*