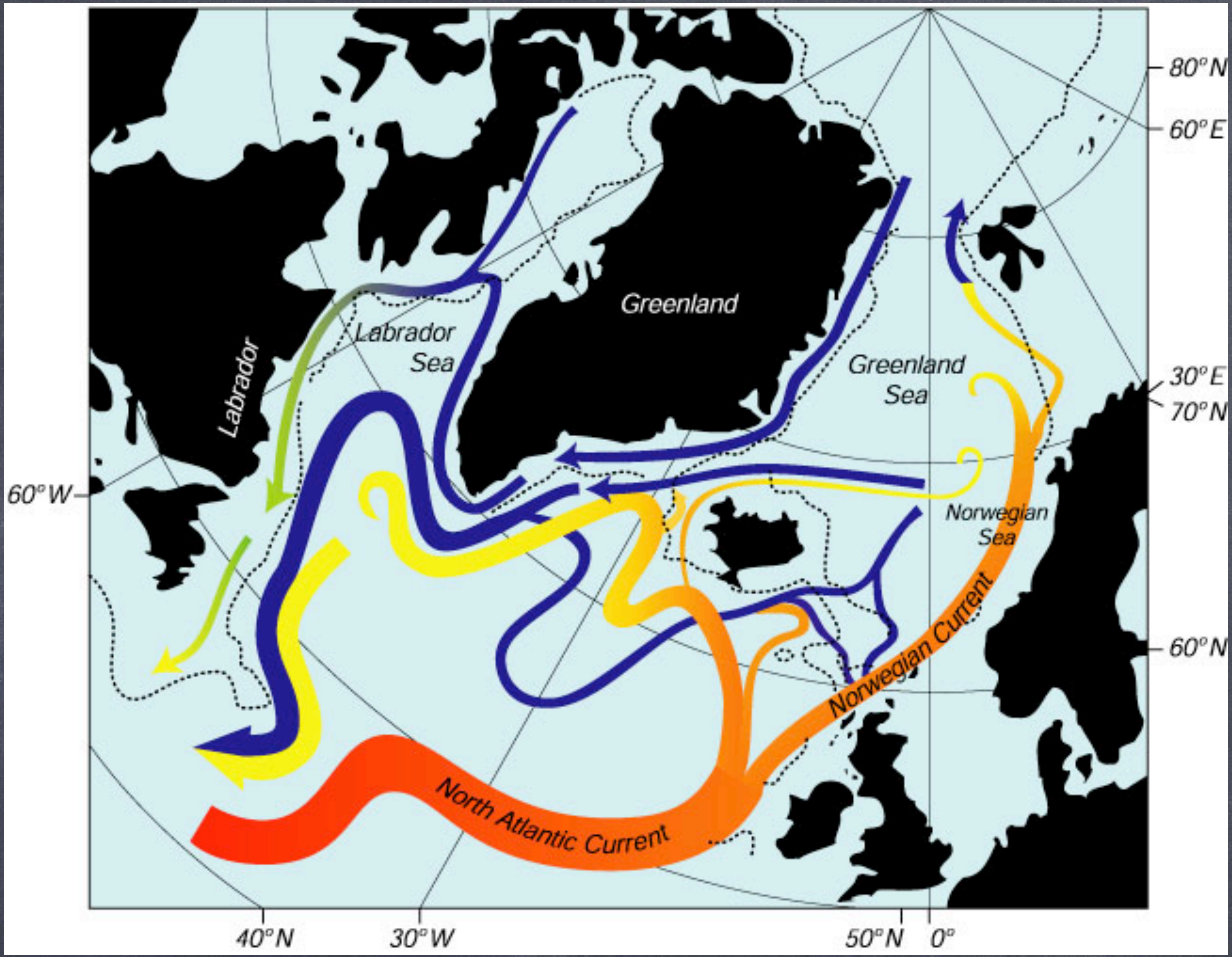
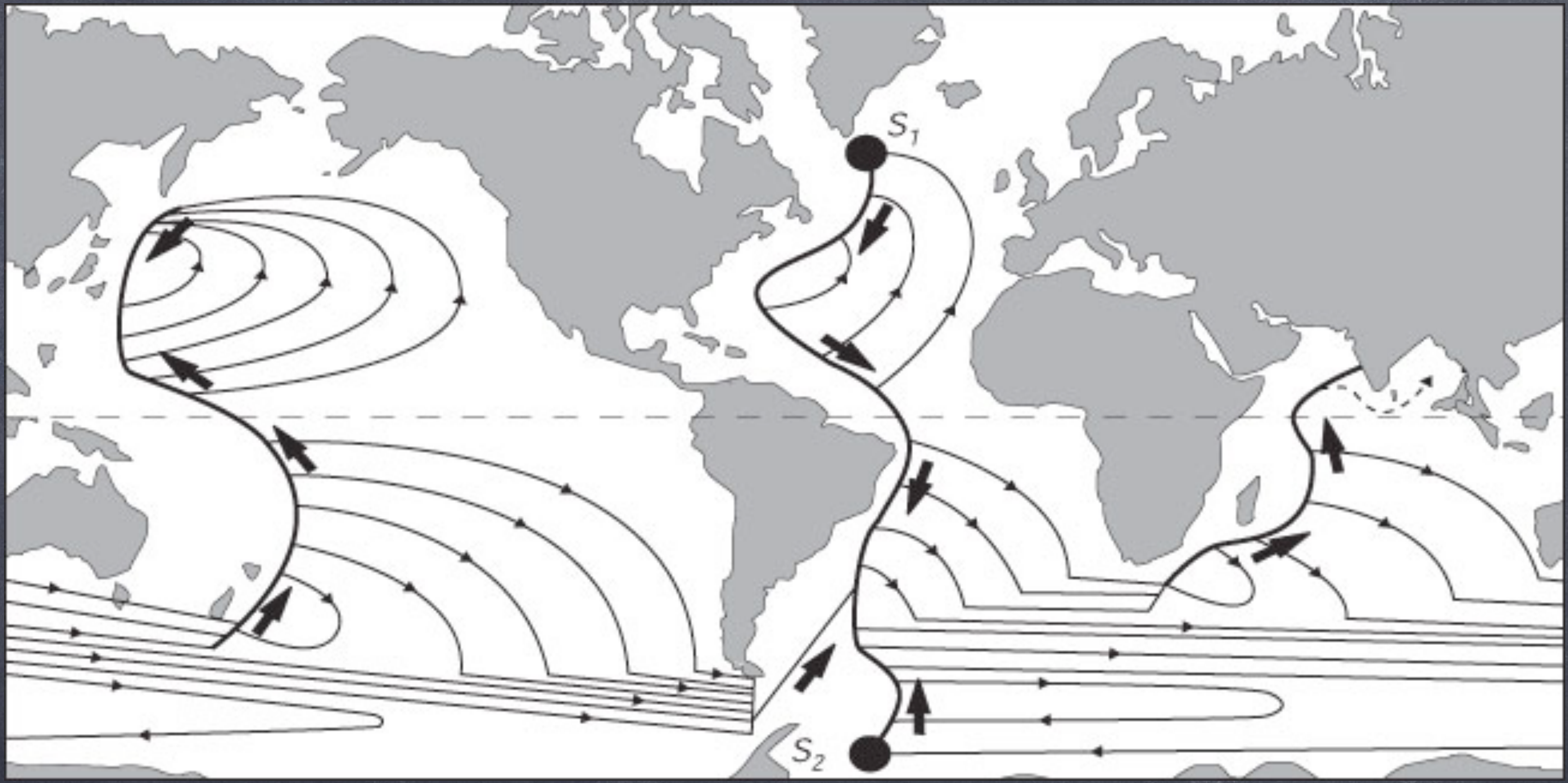
Global Thermohaline Circulation (THC) OR Meridional Overturning Circulation (MOC)



The surface (red, orange, yellow) and deep (violet, blue, green) currents in the North Atlantic. The North Atlantic Current brings warm water northward where it cools. Some sinks and returns southward as a cold, deep, western-boundary current. Some returns southward at the surface. (Woods Hole Oceanographic Institution)

Stommel-Arons theoretical abyssal circulation (1958-1960)



Sources in the North Atlantic and Southern Ocean.

Notice southward DWBC everywhere in Atlantic.

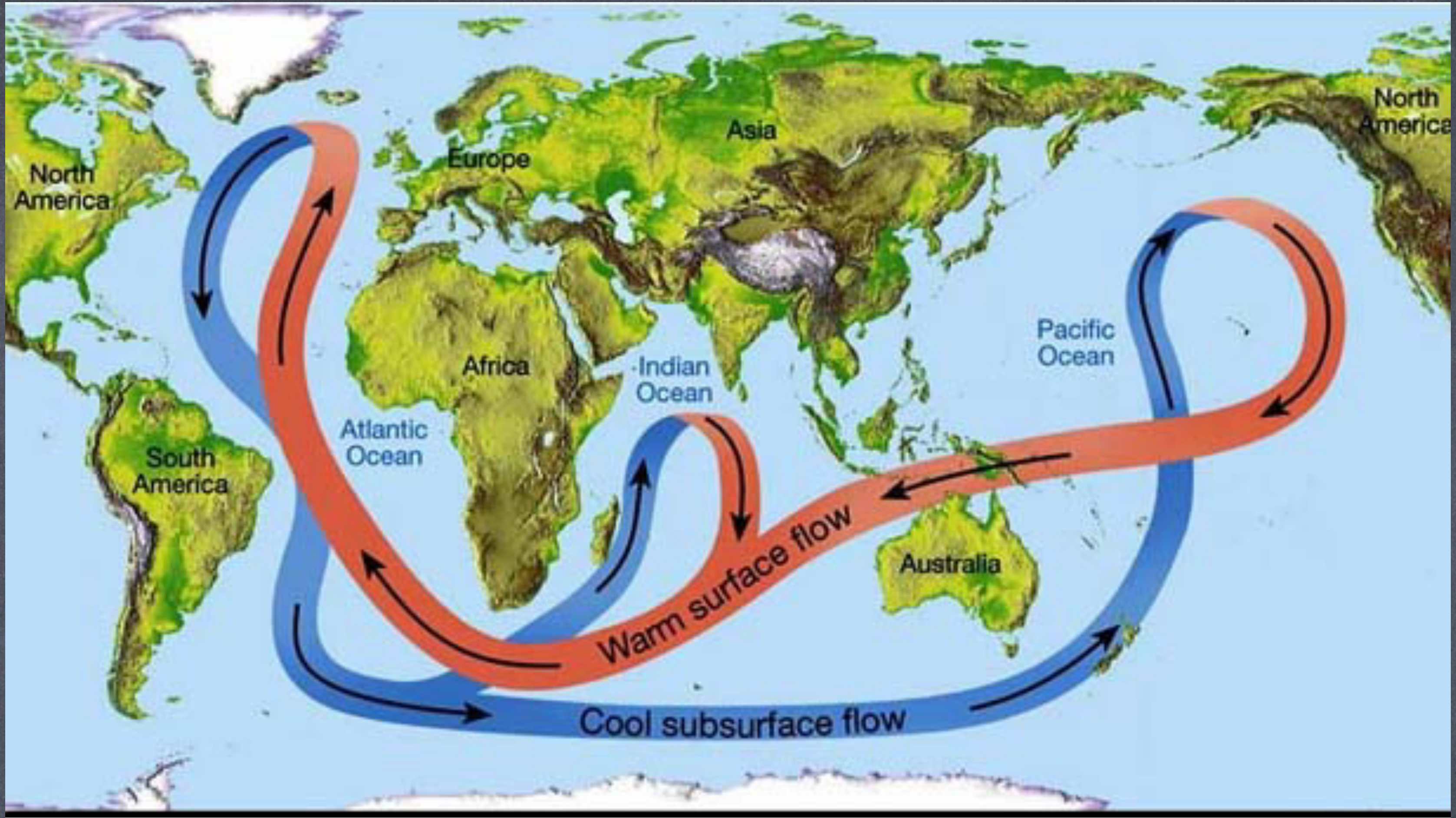
What have we learned so far about the abyssal circulation...?

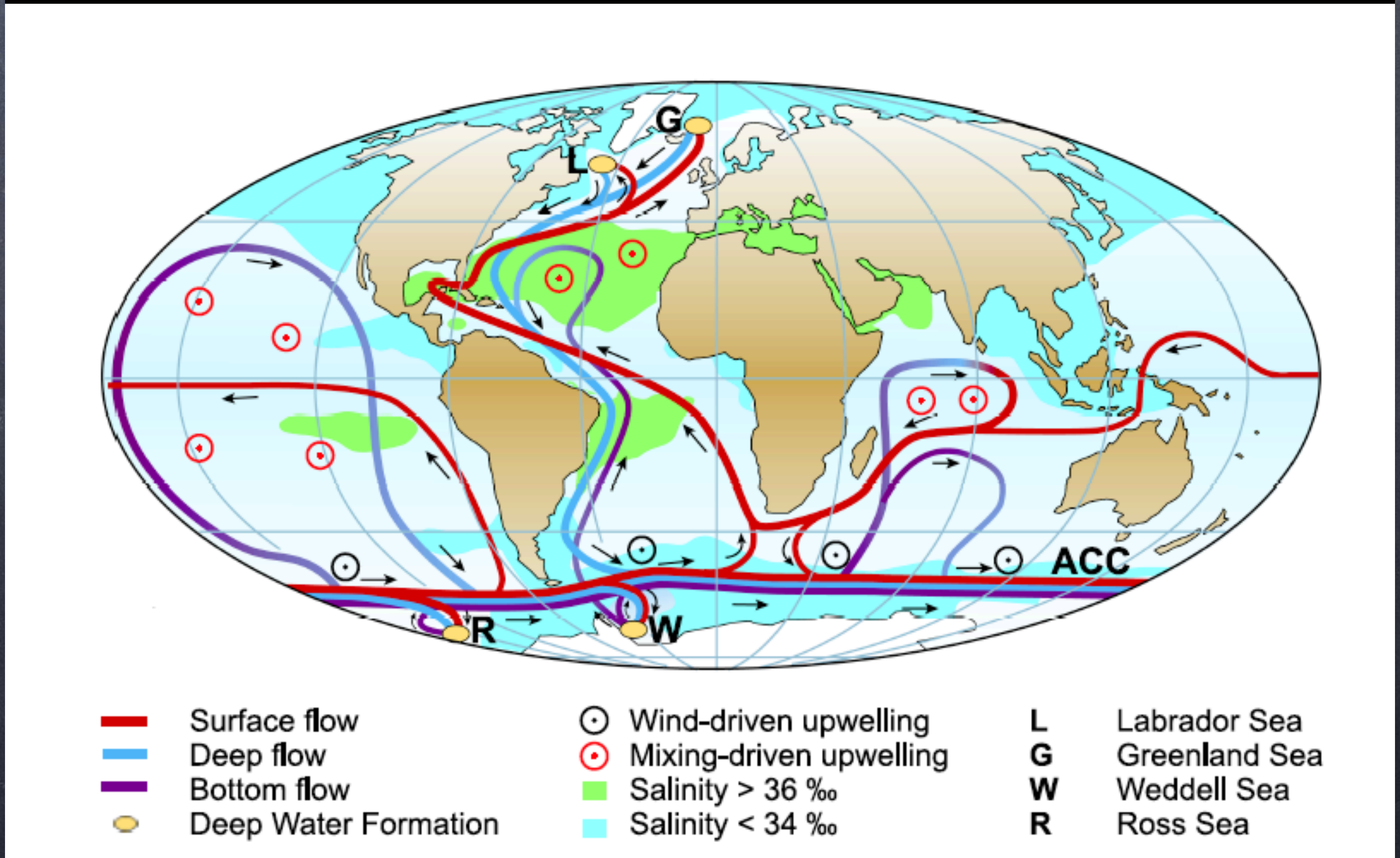
- The primary sources of deep water are the Arctic overflows and around the margins of the Labrador Sea.
- These sources combine (NADW) to flow south in a DWBC along the continental slopes of North and South America.
- To balance this deep southward flow, there must be a compensating transport of upper (upwelled) waters to the north.

- These upper and lower arms together are called the ThermoHaline Circulation (THC) or the Meridional Overturning Circulation (MOC).
- These circulations are essentially buoyancy-driven (as opposed to the horizontal gyres which are wind-driven).
- The upper waters are far warmer than the deep waters they “replace” - hence there is a large oceanic transport of heat associated with the THC or MOC.

Global thermohaline circulation

Broecker's (1989) "conveyor belt"

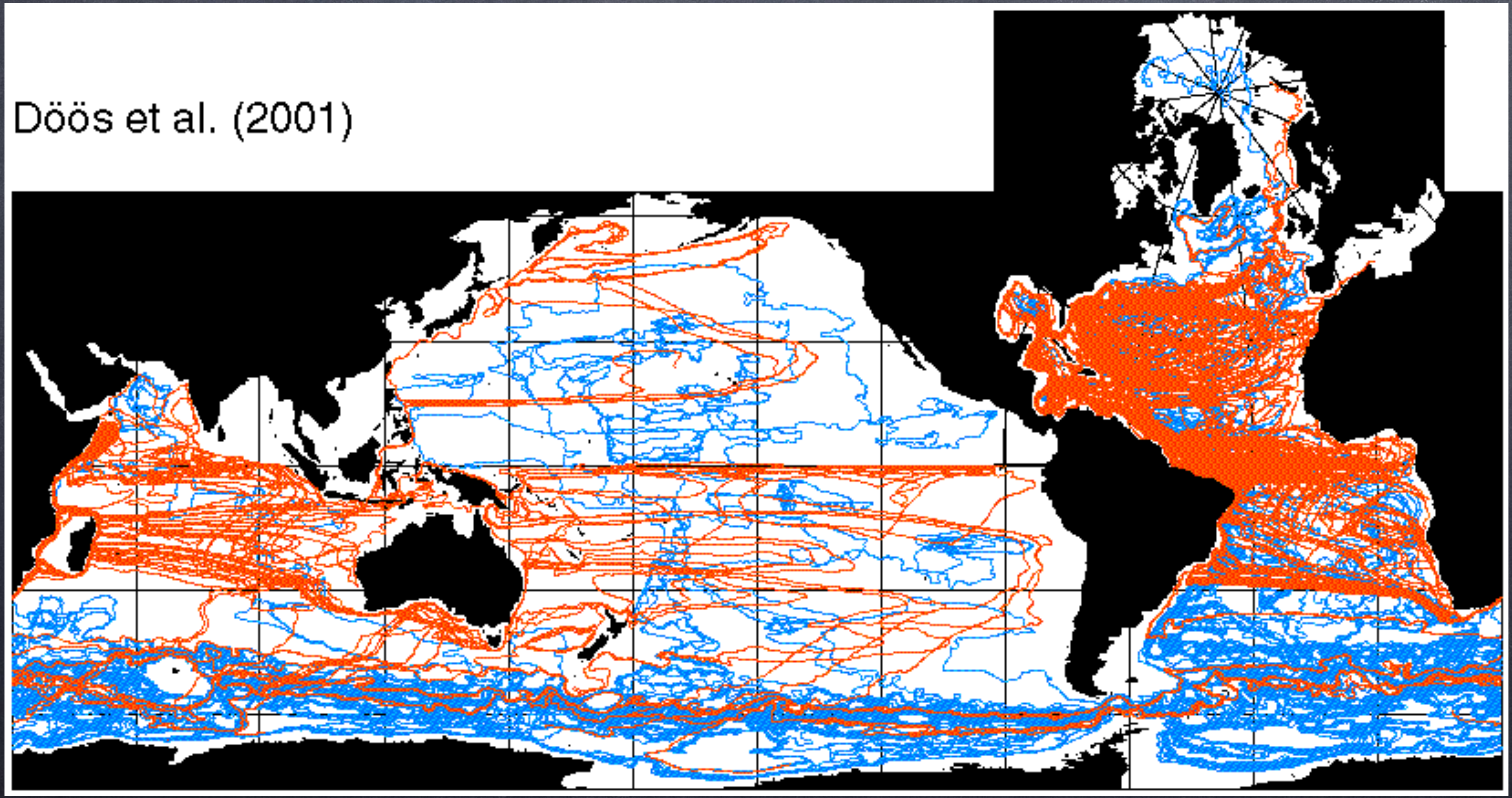


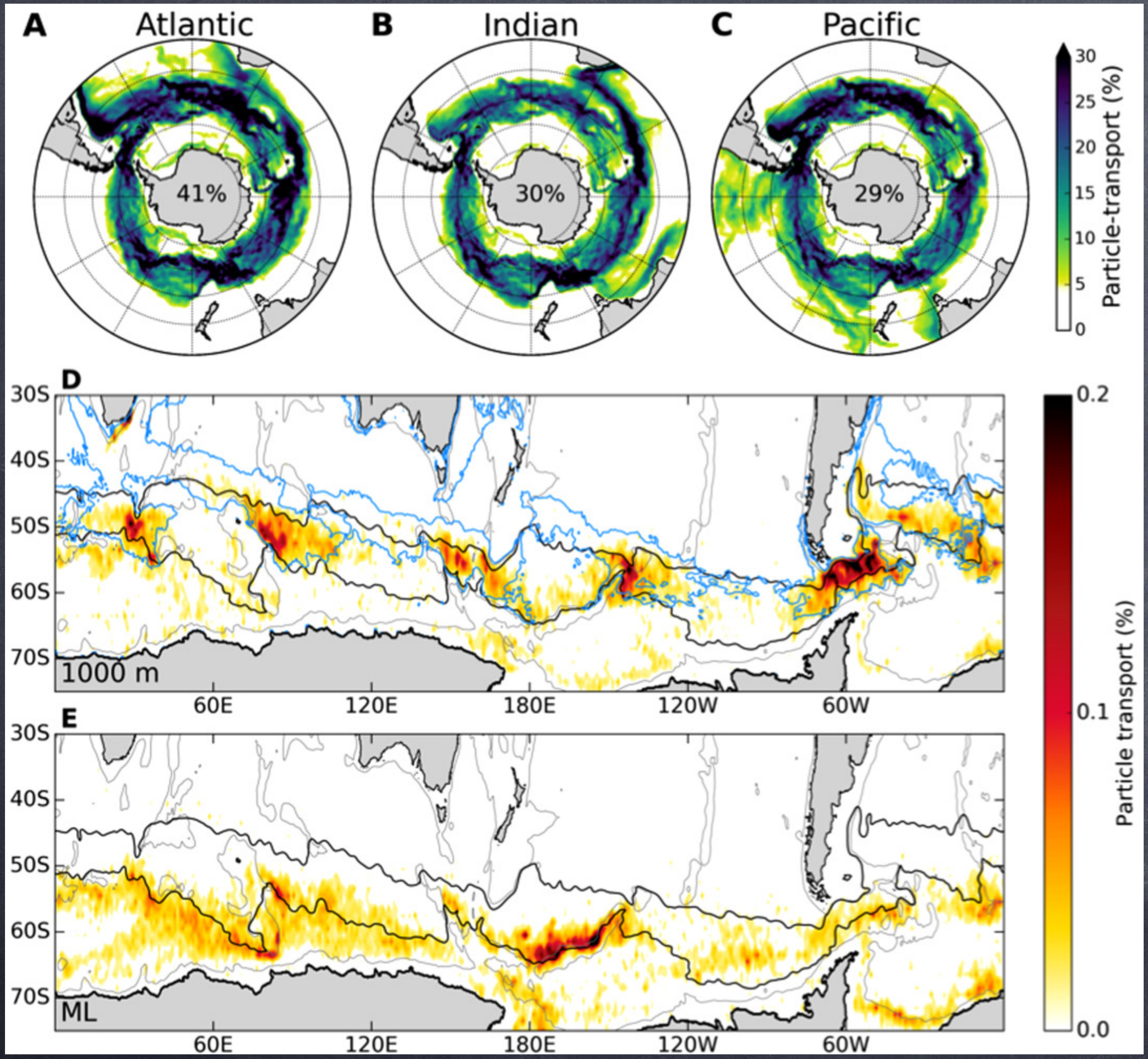


Schmitz 1996

- How does deep water return to the surface?
- what is the Southern Ocean's role?

The global THC or "Conveyor Belt" depicted by particle trajectories in ocean general circulation model OCCAM (Doos et al, 2001)





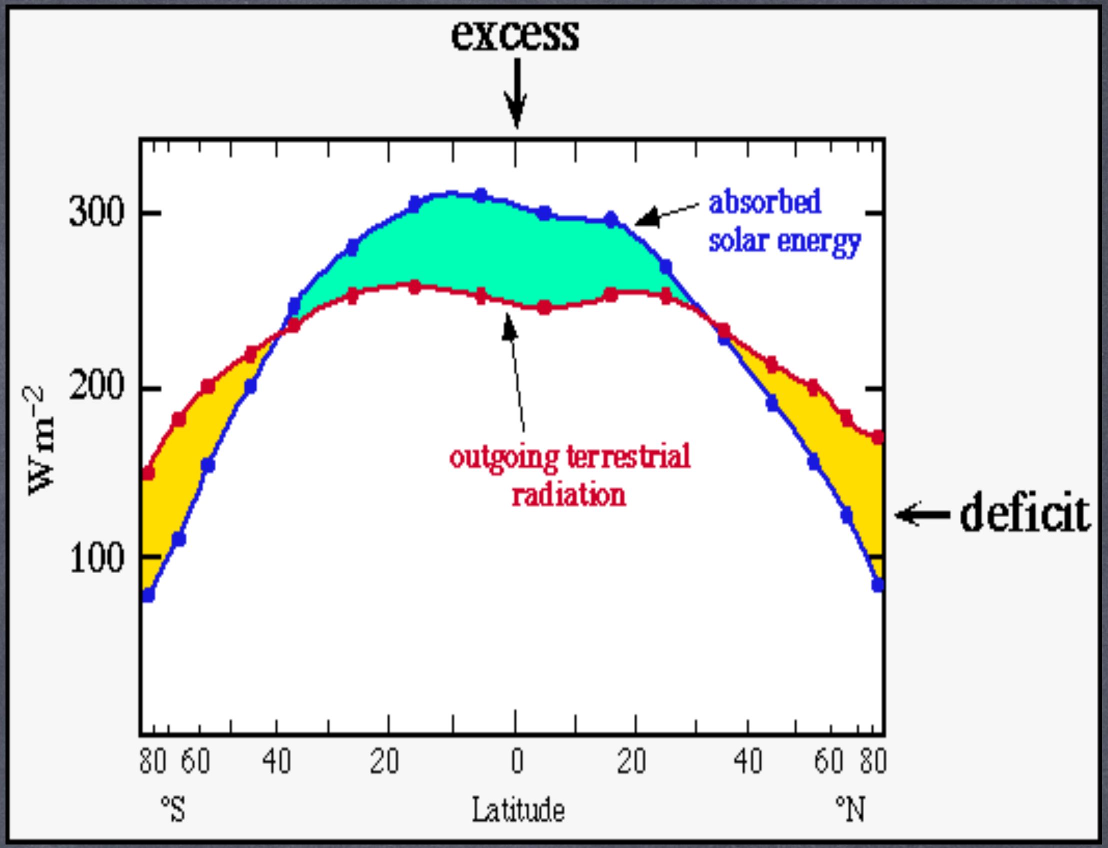
A, B, C: % of waters from 30 S in each ocean basin that upwell into mixed layer

D: Particles upwelling across 1000 m (blue high EKE, black ACC boundaries, grey topo)

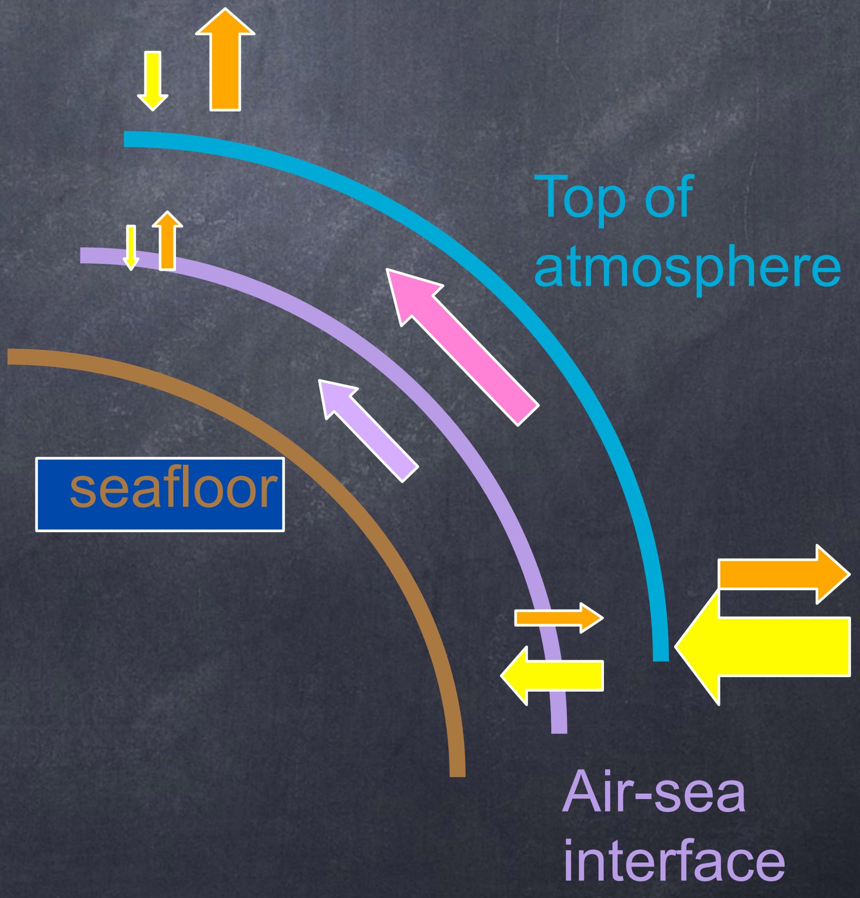
E: Particles upwelling into ML

Tamsitt et al., 2018

Oceanic heat transport



- Recall that in the global heat budget there is an excess of heat from the equator up to 35 degrees latitude.
- Poleward of 35 degrees there is a solar energy deficit.
- The atmosphere and ocean must carry heat from low latitudes to high latitudes.



…in the ocean it is predominantly the THC/MOC that transports heat meridionally.

How do we estimate the ocean heat transport?

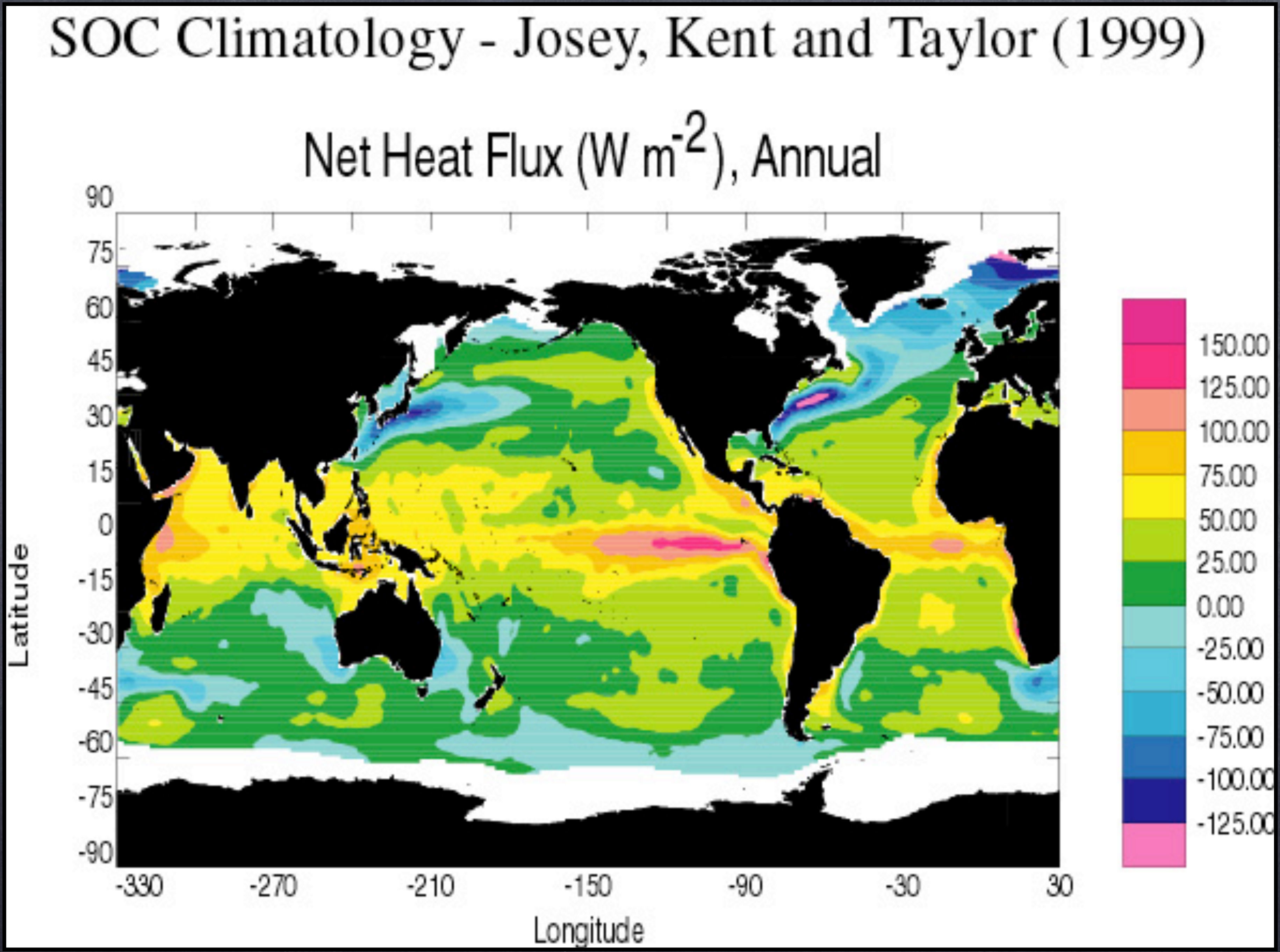
- Traditional bulk formulae method - estimate air-sea heat exchange locally.
- Residual method - subtract atmospheric heat transport from the total required by radiation balance.
- Direct method - use ocean velocity and temperature.

Bulk formulae

- $Q_{ocean} = R_{net} + E + S$
- R_{net} = incoming solar - outgoing infrared. Depends on air and sea temperatures, water vapor pressure, cloudiness.
- E = Latent heat flux = $\rho C_E(q_s - q_{10})U_{10}$ where q_s is saturation specific humidity and q_{10} is atmospheric specific humidity at 10 m.
- S = Sensible heat flux = $\rho C_H C_P(T_s - T_{10})U_{10}$

C_E and C_H are exchange coefficients determined empirically. There are many uncertainties in these and in how they vary with wind speed etc.

Bulk formulae



Global uncertainty of 30 Wm^{-2} remains a typical bias

Residual Method

- This method was first used 20 years ago and it caused a lot of controversy because errors in atmospheric heat transport led to huge uncertainties in oceanic heat transport.
- Now improved atmospheric circulation models appear to give more realistic answers (Trenberth and Caron, 2001).
- However, there are still large uncertainties in atmospheric moisture transport (clouds, precipitation...)
- Recent results suggest that ocean, atmosphere, and moisture (latent heat) transport contribute roughly equally to meridional heat transport.

Direct Method

- The heat transport across a line of latitude in the ocean can be calculated as: $\int \rho C_p v \theta \, dxdz$
- In practice we measure WBC transport and temperature, Ekman transport and SST, and then require the mid-ocean geostrophic mass transport to balance WBC + Ekman transports. (Hall & Bryden, 1982)
- Mass must be conserved to calculate the heat transport.
- At 26 N in the Atlantic the oceanic heat transport is about 1.3 PW.

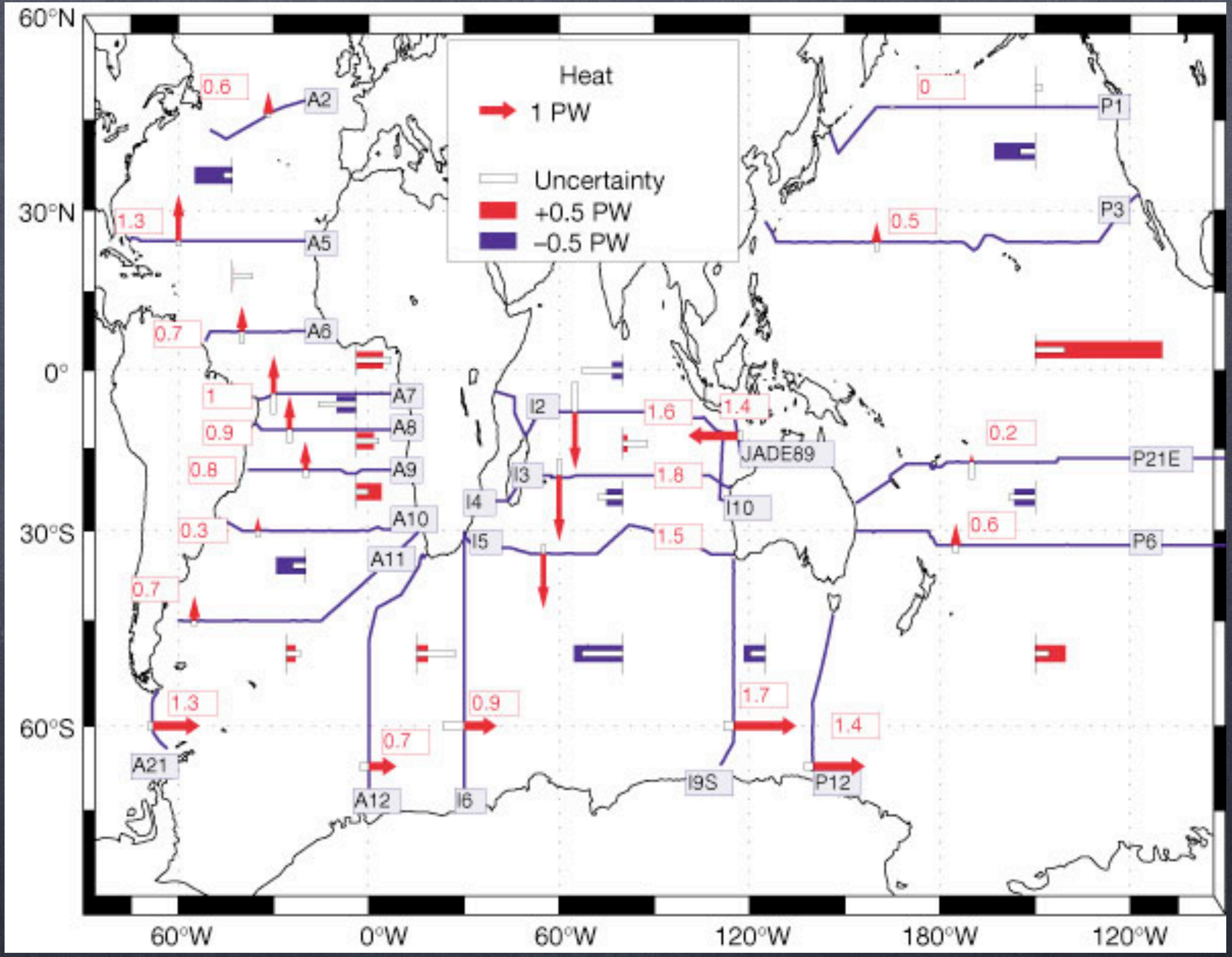
Oceanic heat transports from WOCE

Note:

Atlantic everywhere NORTH. Notice MAX at 26 N.

Indian everywhere SOUTH

Pacific very small



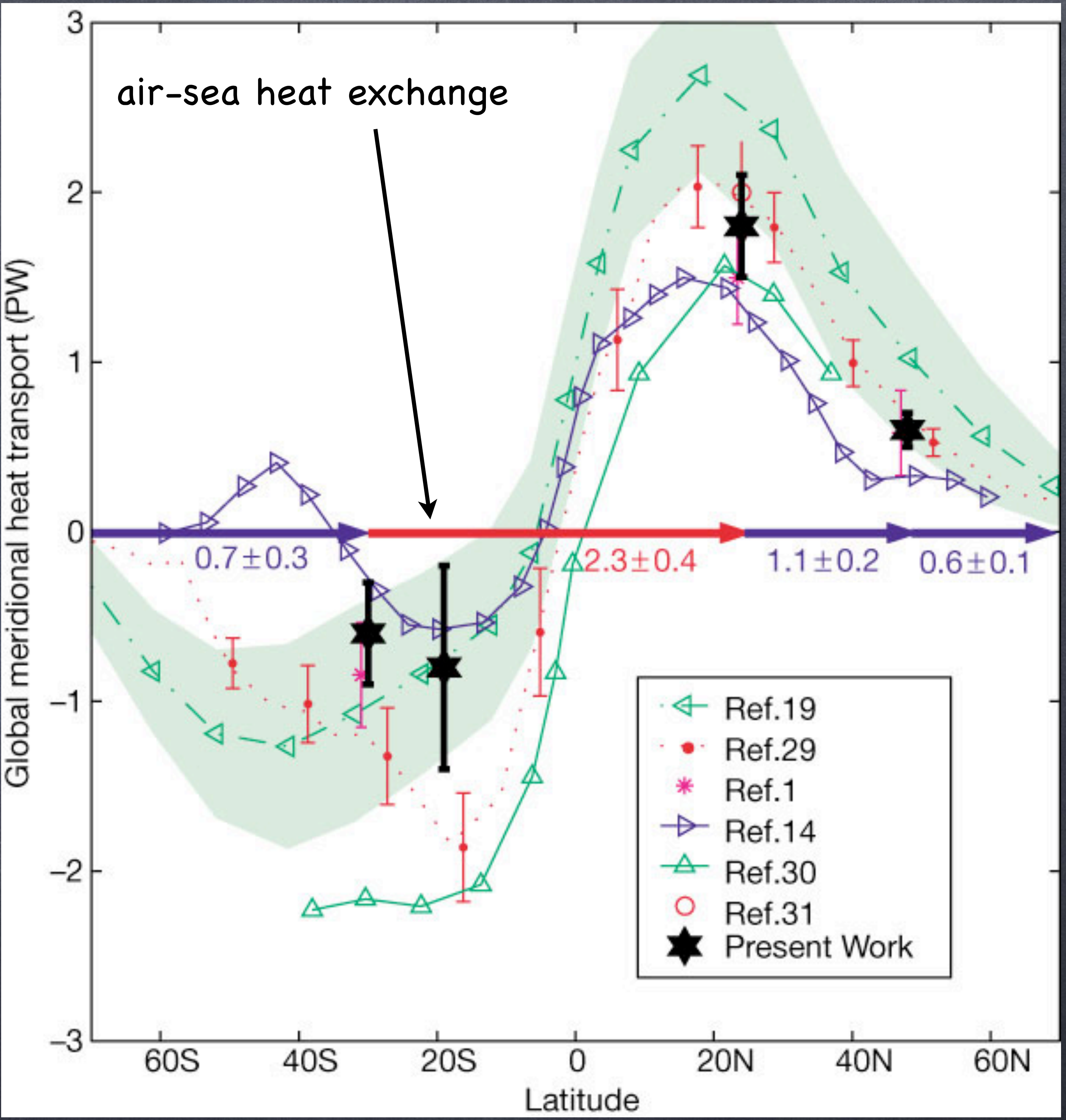
Ganachaud and Wunsch (2000)

Global meridional oceanic heat transports

Black and pink stars, 30 & 31: direct method

14,19,29: ECMWF and NCEP bulk estimates

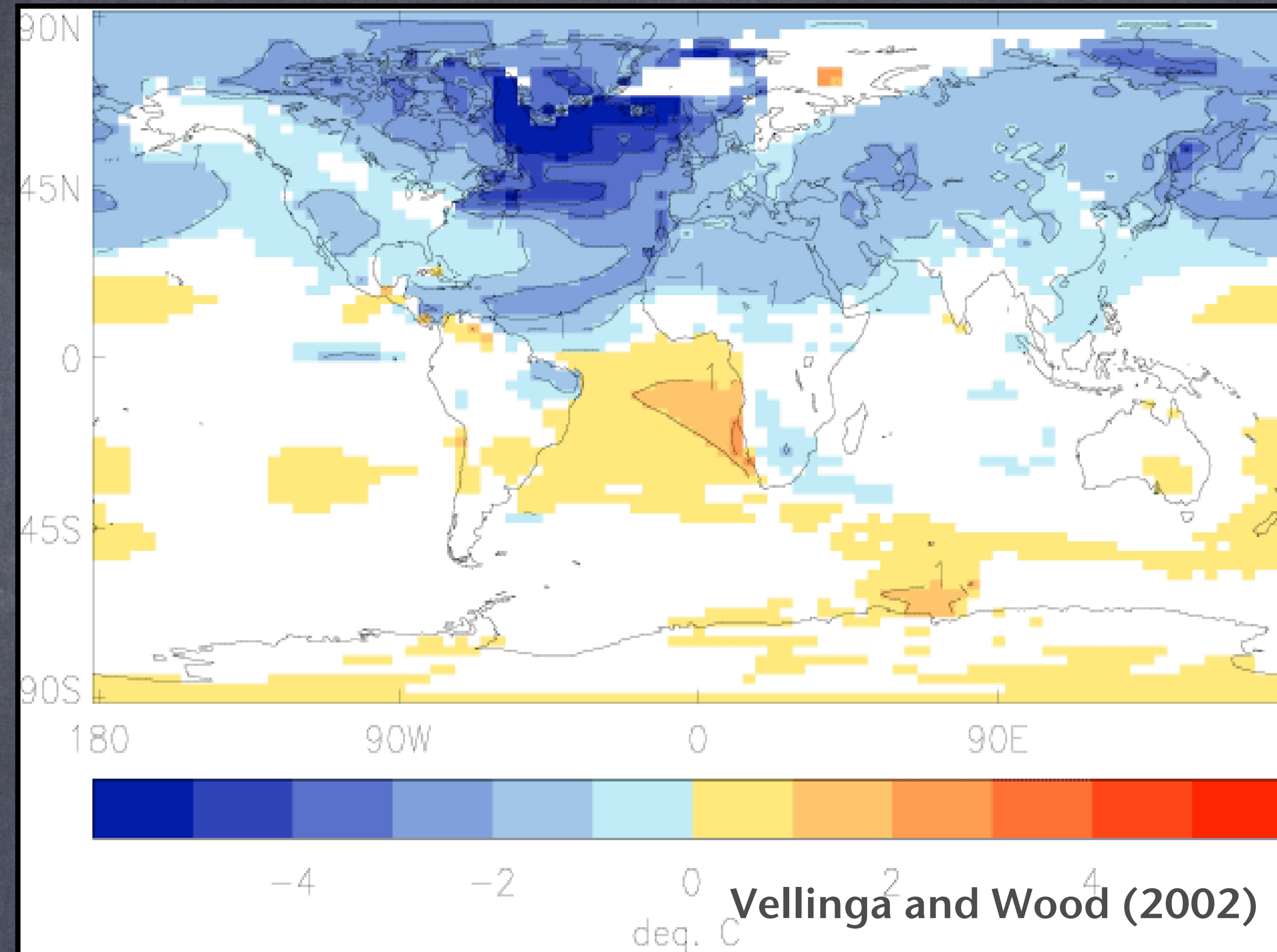
Ocean carries about 1/4-1/2 of total global meridional heat transport (about 5 PW)

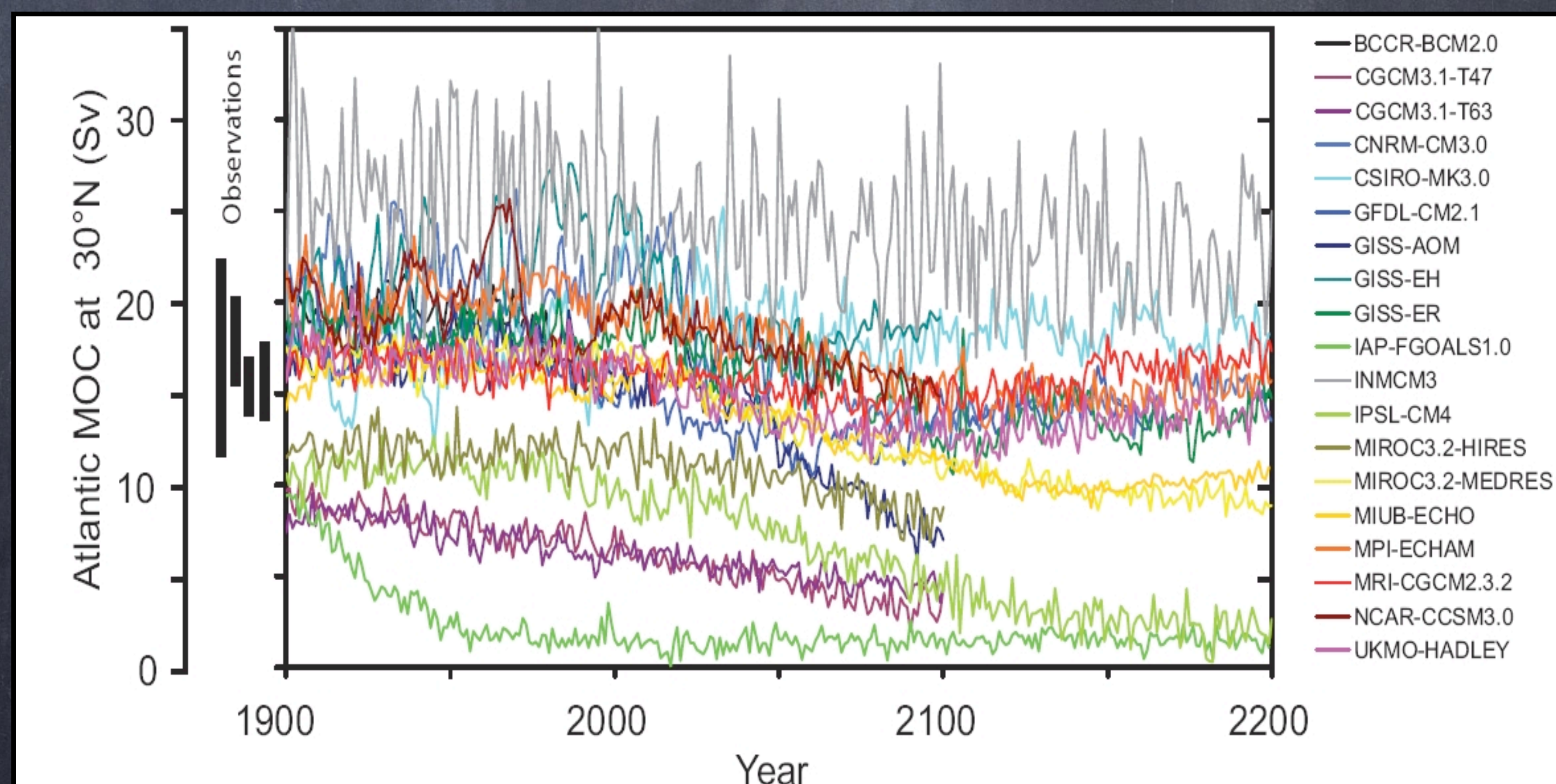


Ganachaud and Wunsch (2000)

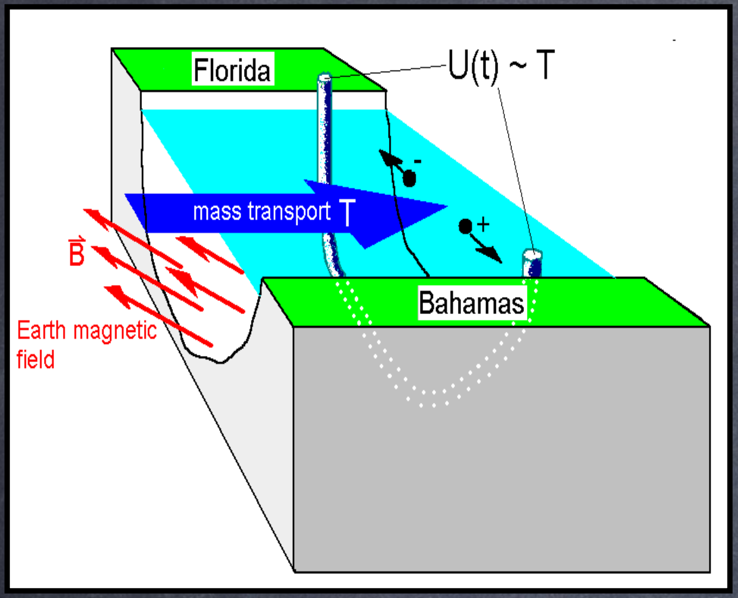
but how does it vary over time?

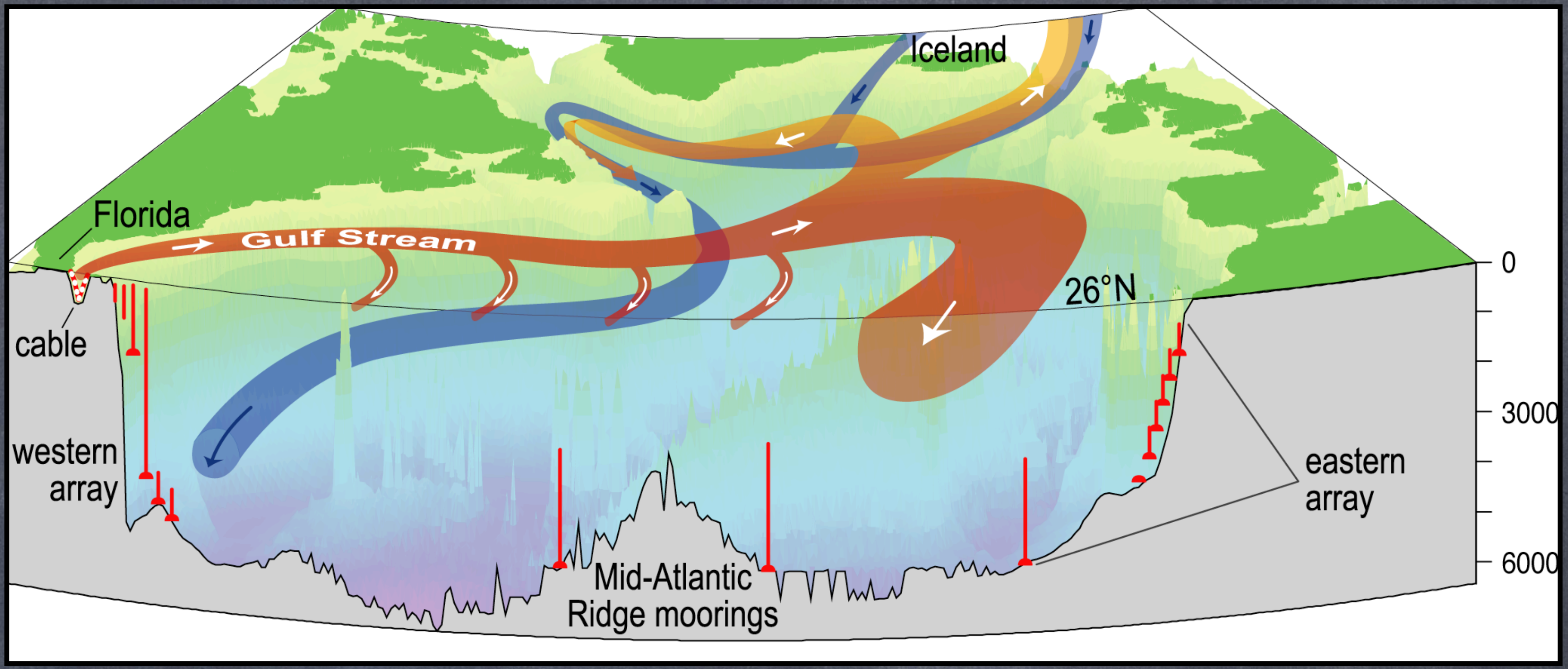
Many coupled climate models predict that under a greenhouse warming scenario the AMOC will slow over the next 100 years, possibly leading to a relative cooling of western Europe, which could have significant socio-economic impacts.



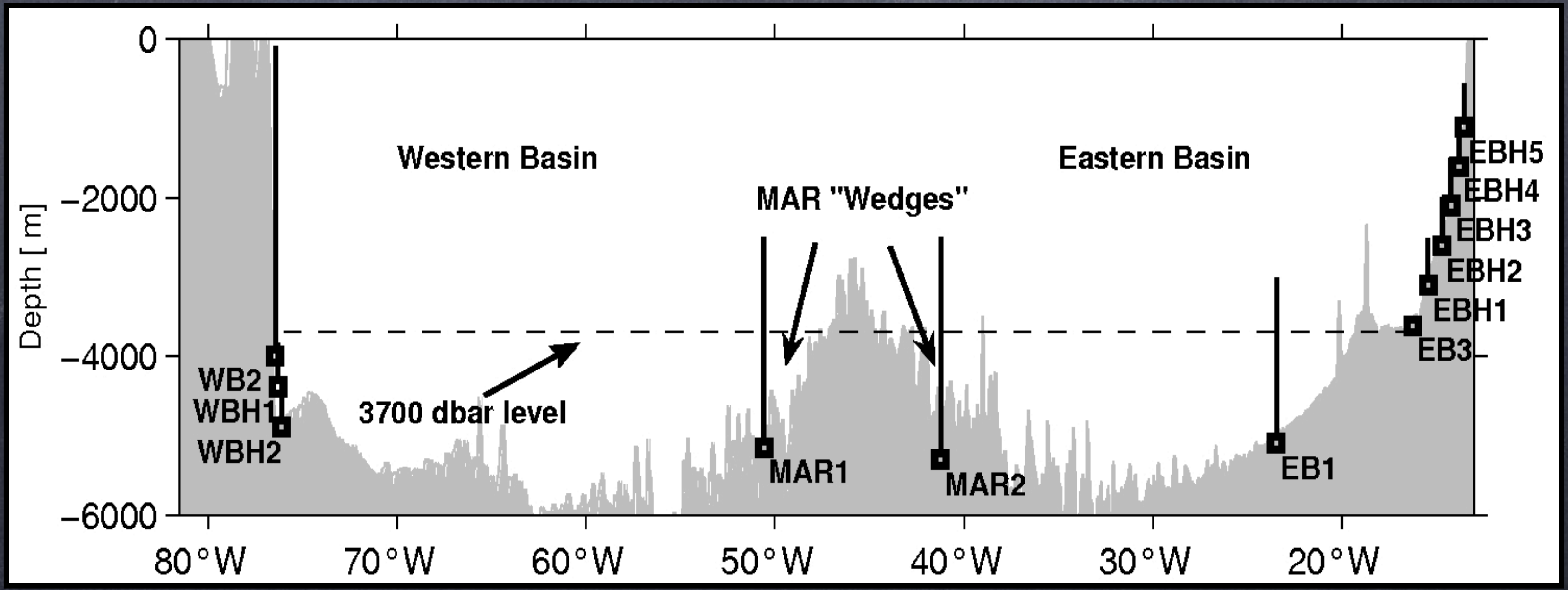


Continuous monitoring of AMOC and its heat transport at 26 N



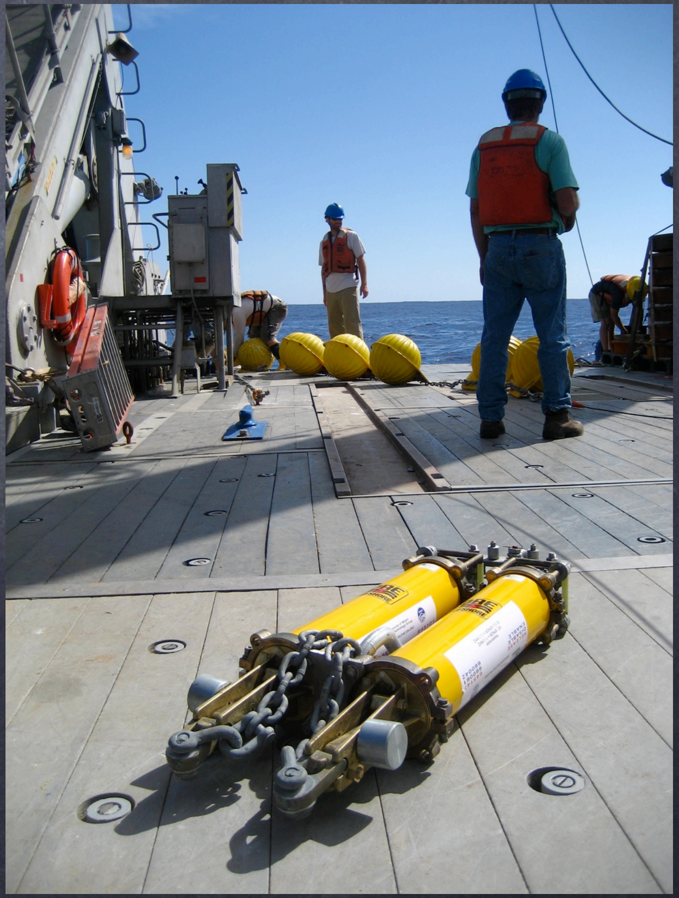


WBC + Ekman + geostrophic interior

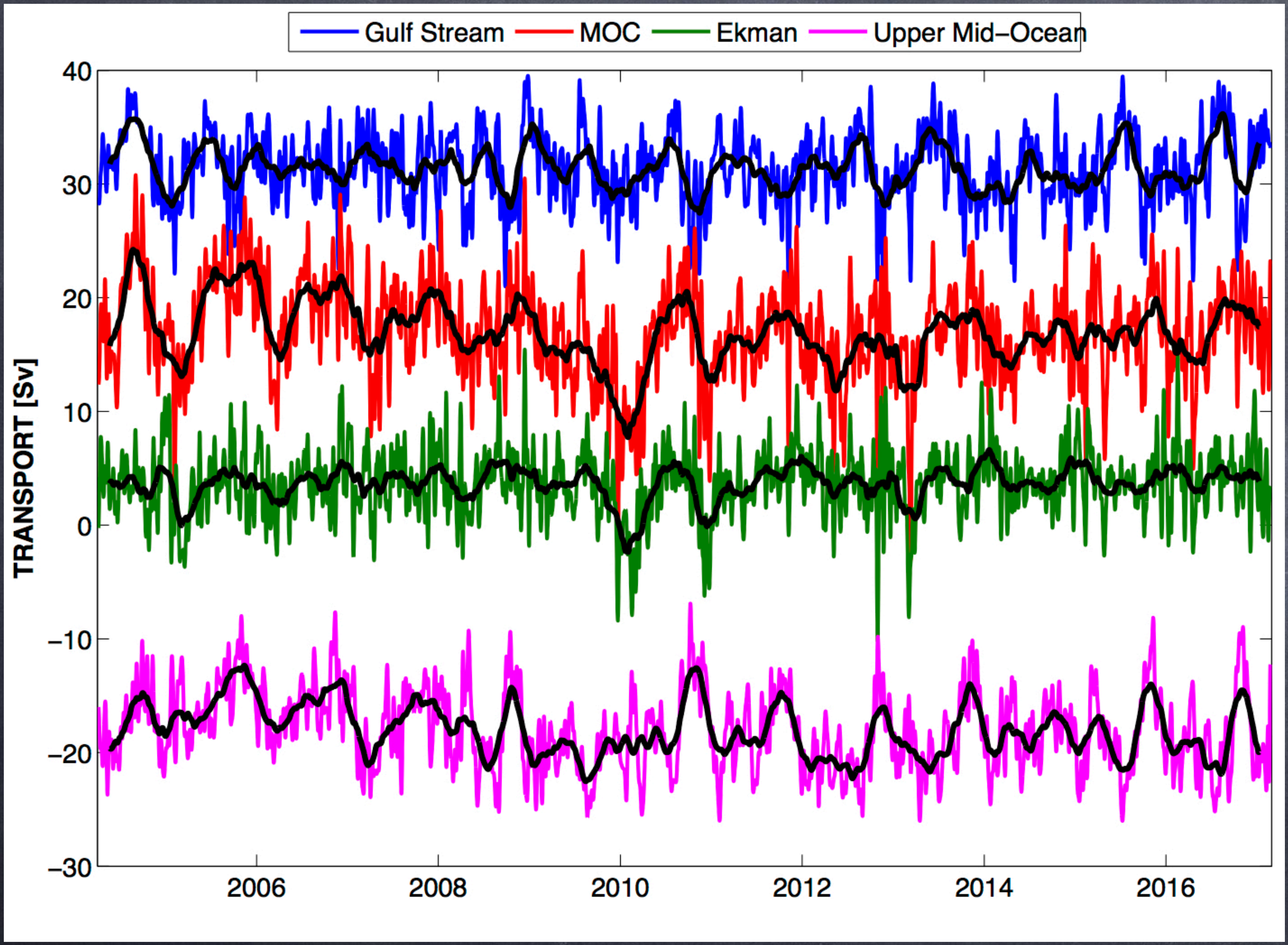


22 moorings


WESTERN BOUNDARY ARRAY
MID-ATLANTIC ARRAY
EASTERN BOUNDARY ARRAY
ADCP W
BJ A
WB1
WB2
WBH1
WBH2
BJ B
WB4
BJ E
MAR2
MAR1
MAR4
MAR3
EB1
EB2
EB3
EBH1
EBH2
EBH3
EBH4
EBH5
ADCP E



Overturning Transport Variability



Statistics

Gulf Stream
+31.7 ± 1.7 Sv

MOC
+18.7 ± 2.1 Sv

Ekman
+ 3.5 ± 1.2 Sv

Upper Mid-Ocean
-16.5 ± 2.2 Sv

https://www.rapid.ac.uk/rapidmoc/overview.php

Overturning Heat Transport Variability

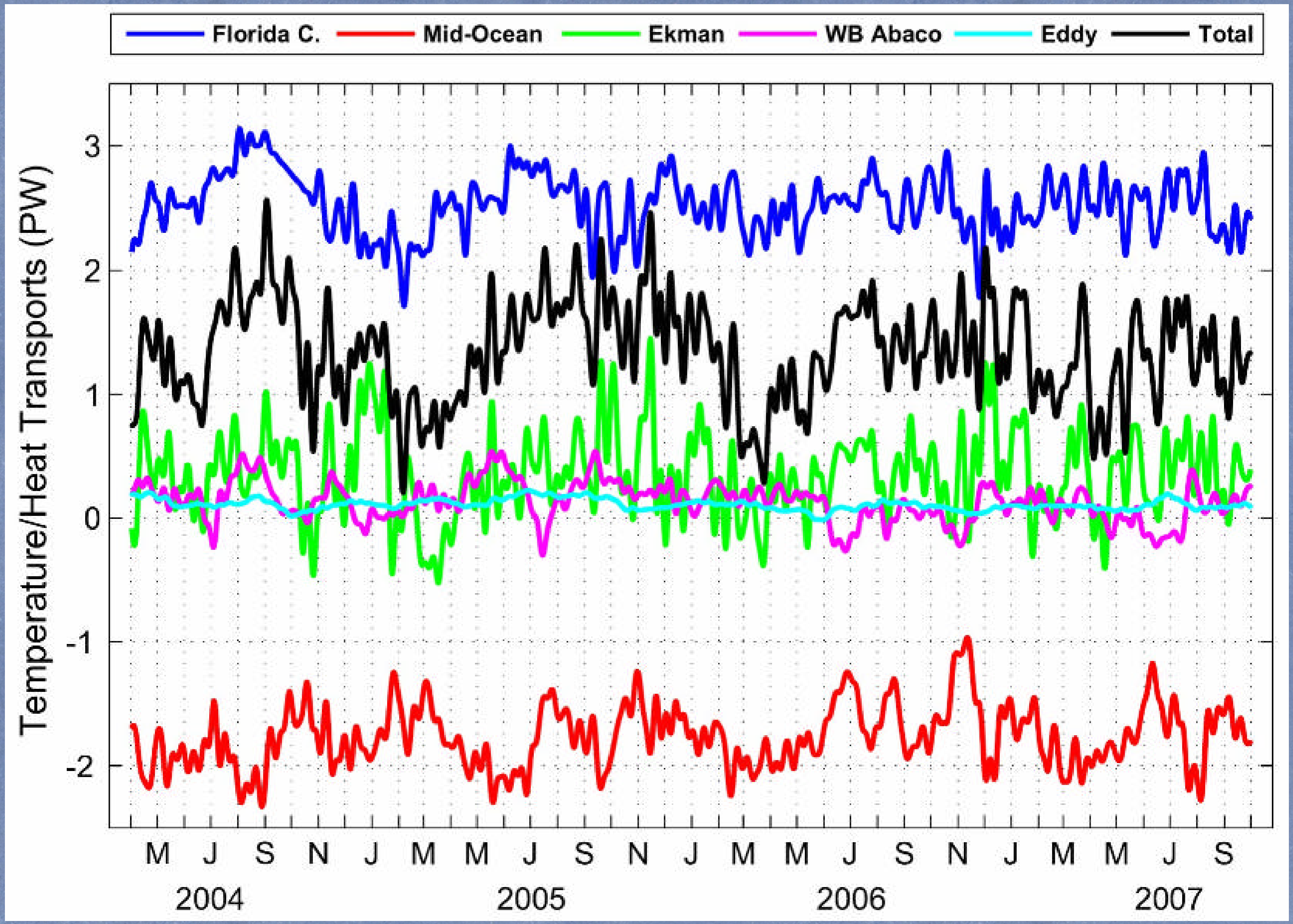


Figure 8. Temperature transports (relative to 0ºC), for each of the section contributions to the net meridional heat transport at 26.5ºN (shown in black line). See text for definitions of the individual components. All components have been low-pass filtered to remove variance at periods shorter than 10 days. The total heat transport (black) and mid-ocean "eddy" heat transport (light blue) are the only ones that represent true heat fluxes, independent of temperature reference.

Johns et al, 2010