

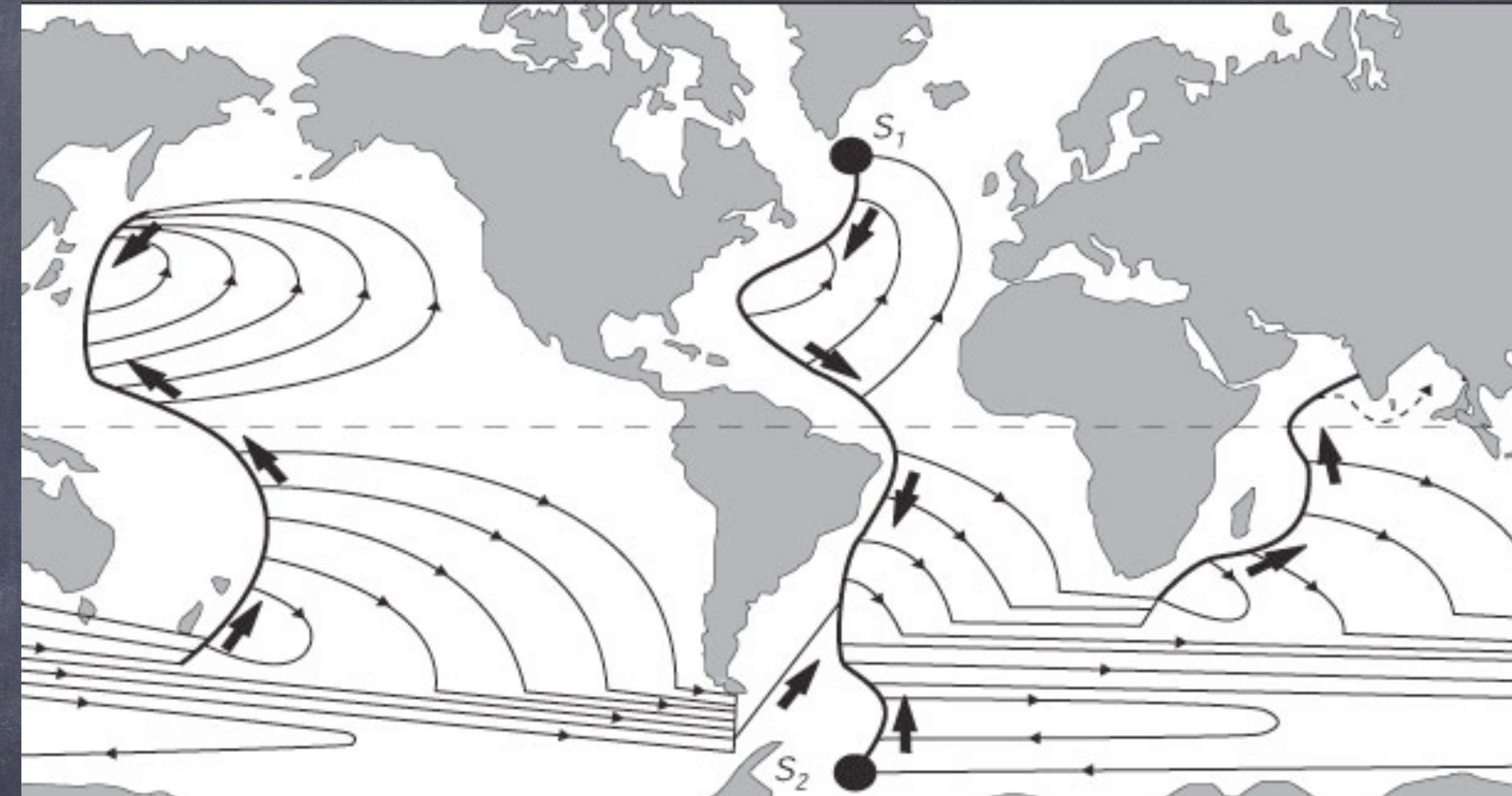
Oceans and Climate Variability

Global Thermohaline / Overturning
Circulation

& Ocean-atmosphere Coupled Modes

What have we learned about the deep and abyssal circulation...?

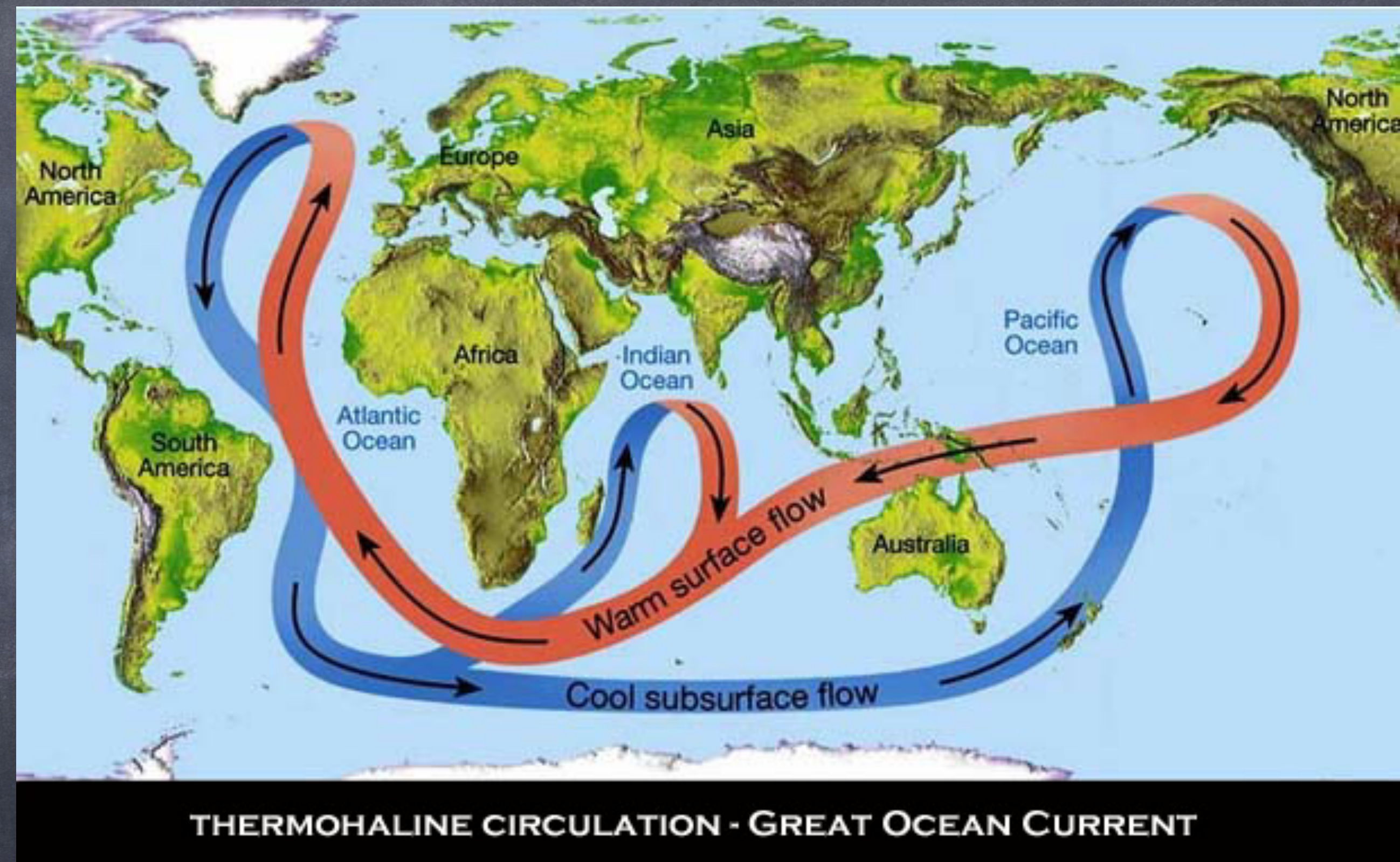
- The primary sources of deep and abyssal waters are overflows and convection in the **Arctic (NADW) and Antarctic (AABW) subpolar gyres**.
- These waters **flow away from their sources in DWBCs**, except in the South Atlantic where NADW continues southward.
- The abyssal circulation is driven by a balance between polar buoyancy loss and topographic/dynamic upwelling



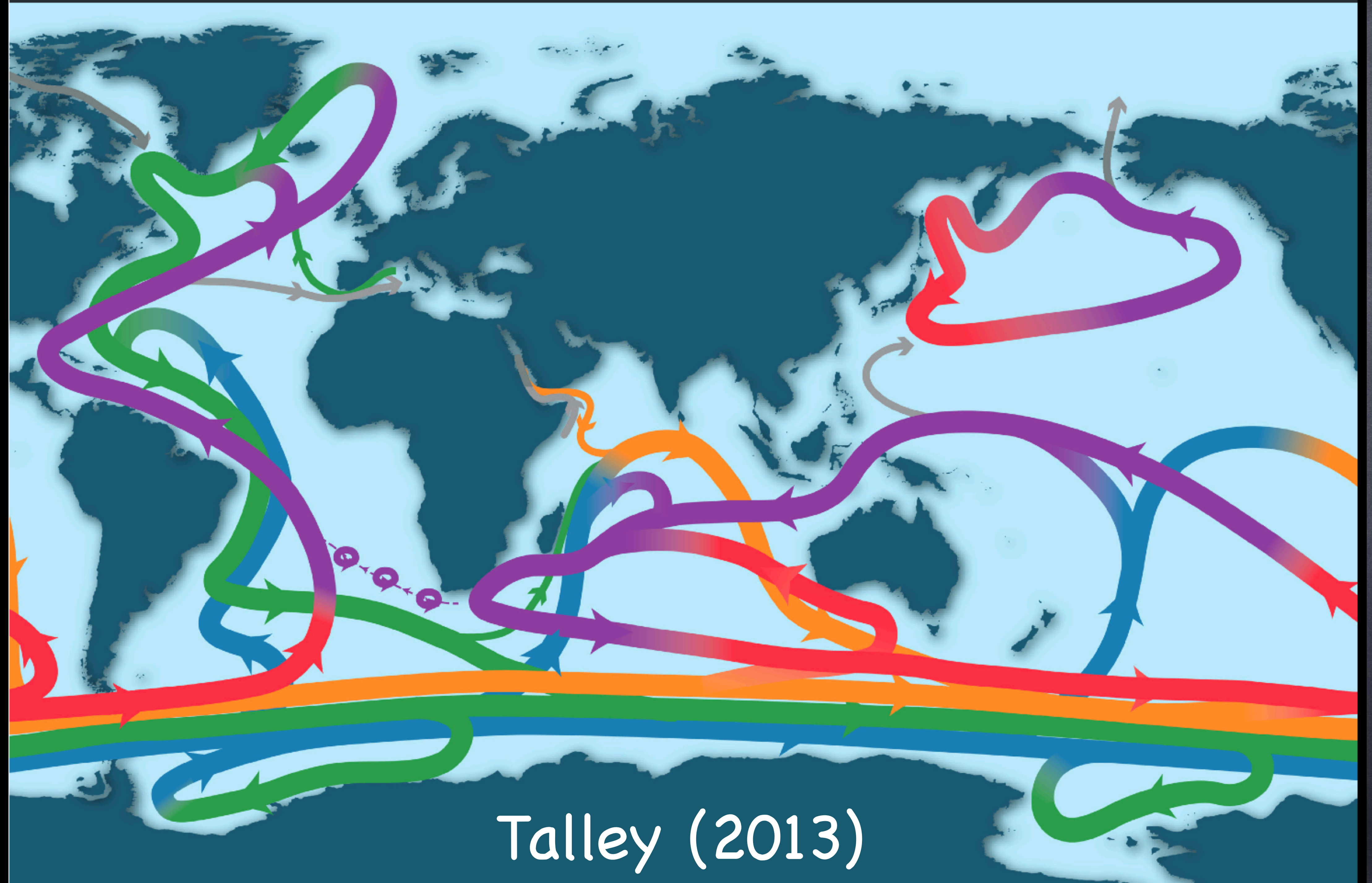
Stommel-Arons theory of abyssal circulation (1958-1960): Driven by uniform upwelling

Global Thermohaline / Overturning Circulation

- Somehow, the abyssal source waters are replenished: Waters in the upper ocean must flow back towards the poles to “feed” sinking and convection sites.
- The upper and lower flows together form the thermohaline, or overturning, circulation.
- 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, with a maximum at mid-latitudes.



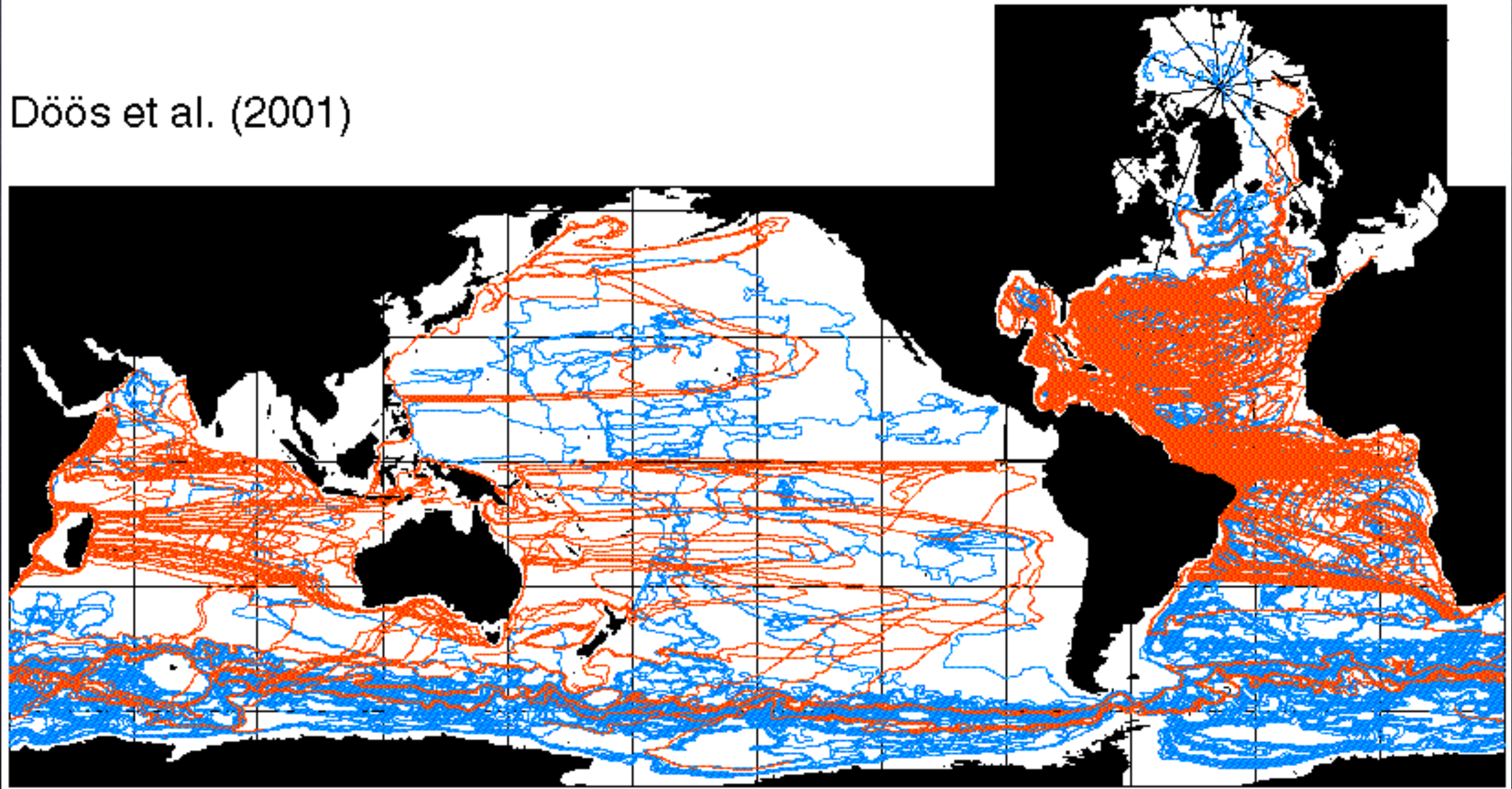
Broecker. Gordon.

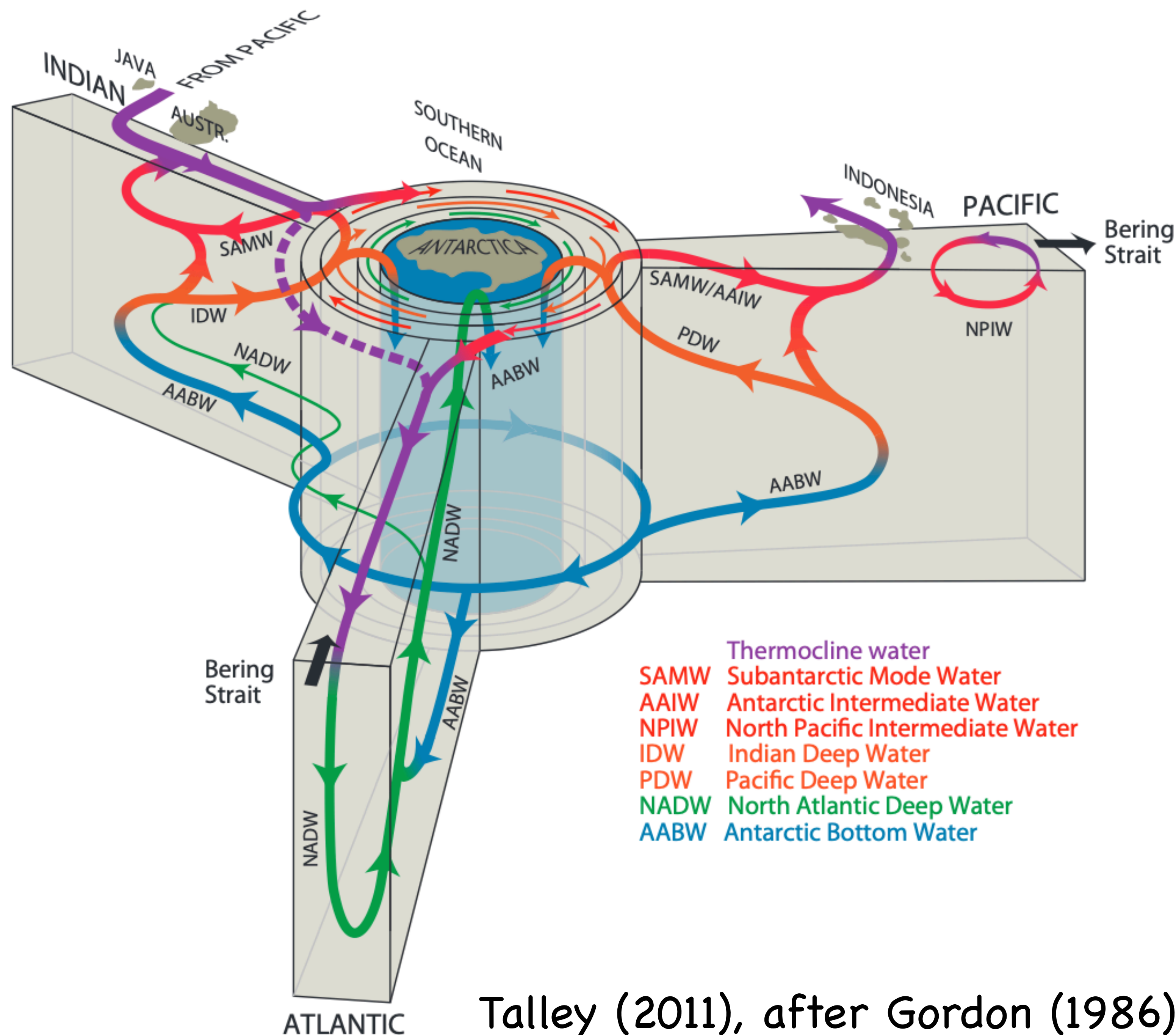


Talley (2013)

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

Döös et al. (2001)



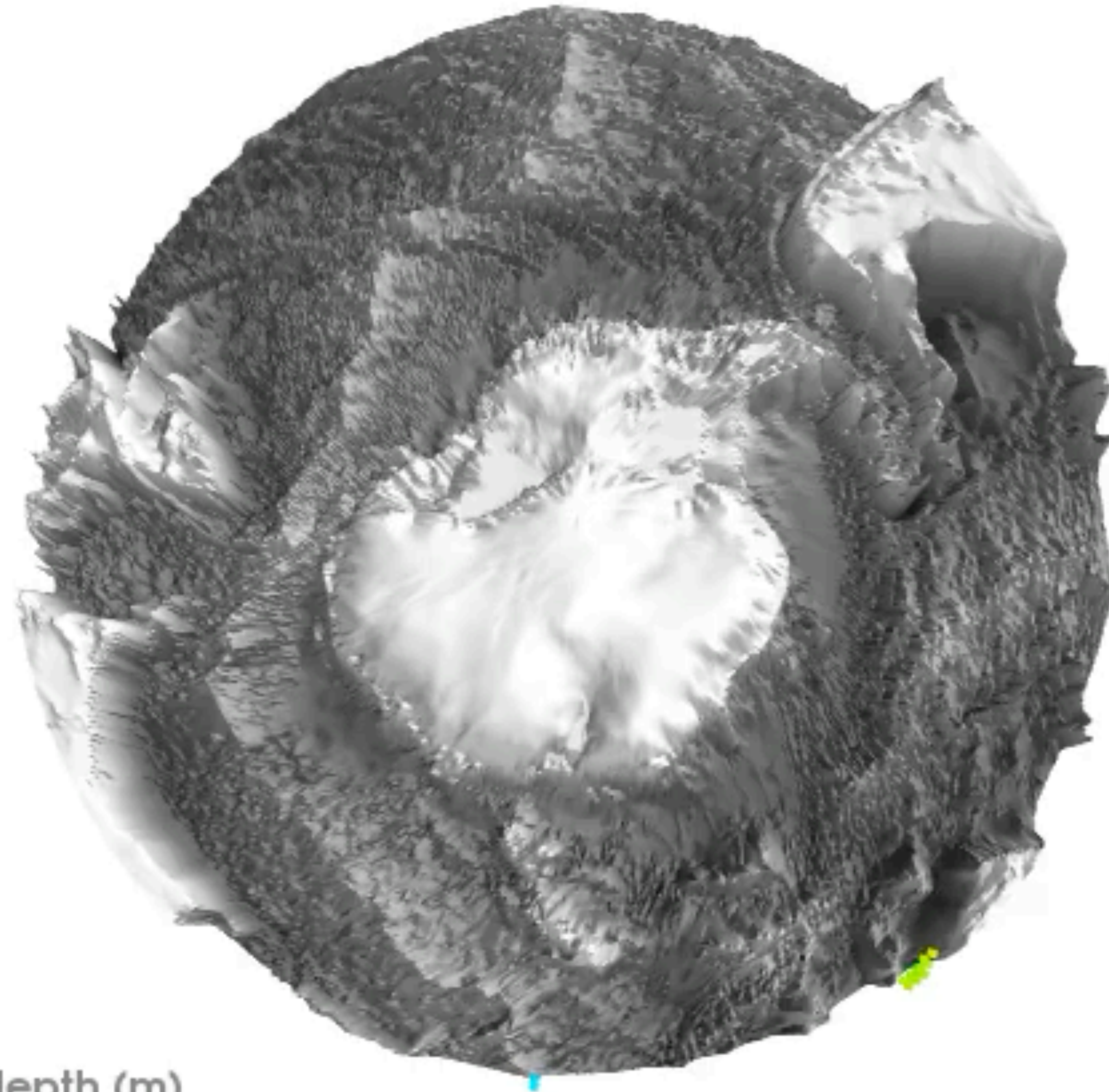


NADW is the most direct source of AABW

IDW and PDW (created by upwelling of AABW in Indian and Pacific) are the most direct sources of SAMW and AAIW waters.

Talley (2011), after Gordon (1986)

CM2.6 Indian Ocean particle pathways with >2.25% particle-transport
Year 00.08



Tamsitt et al., 2018

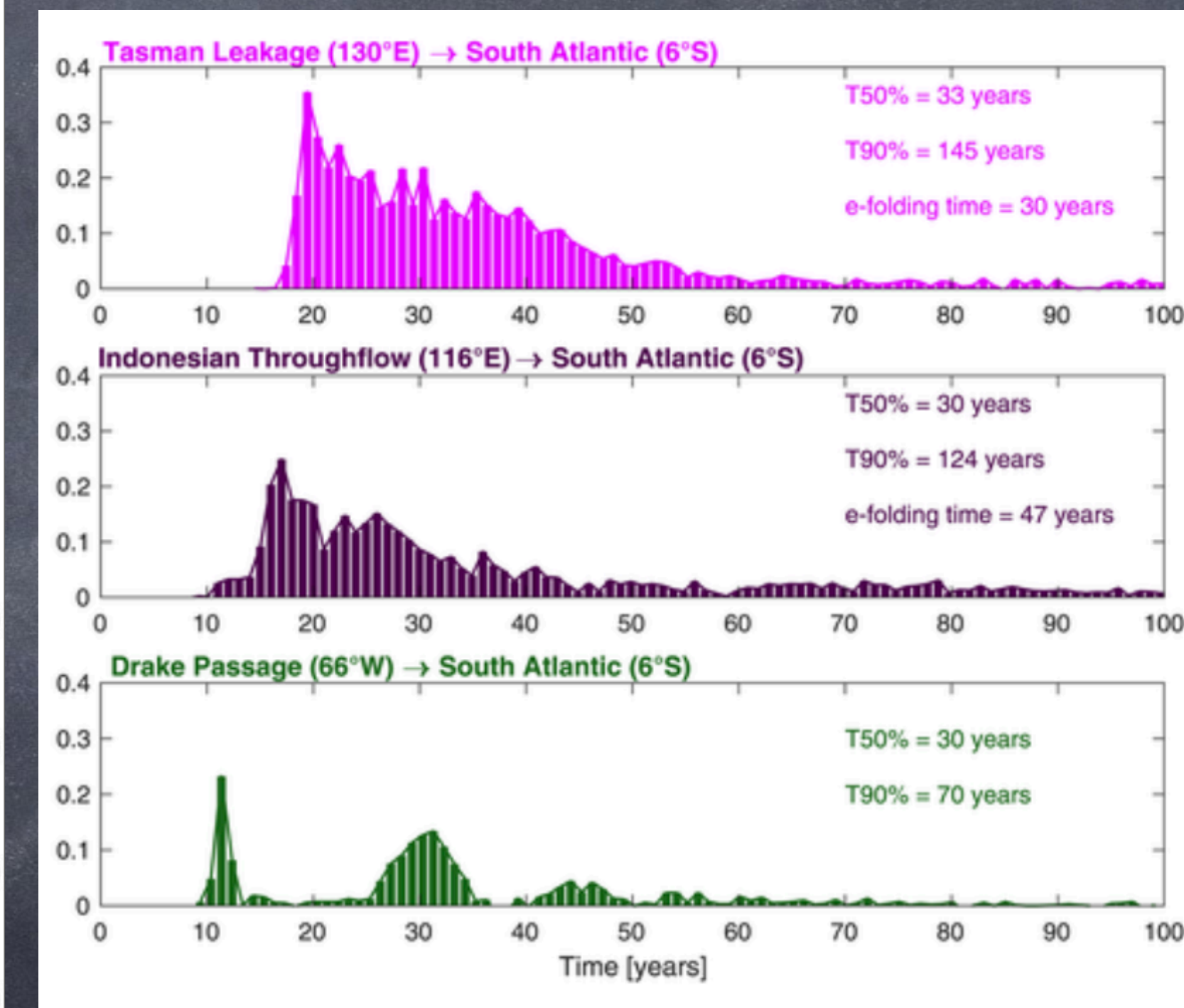
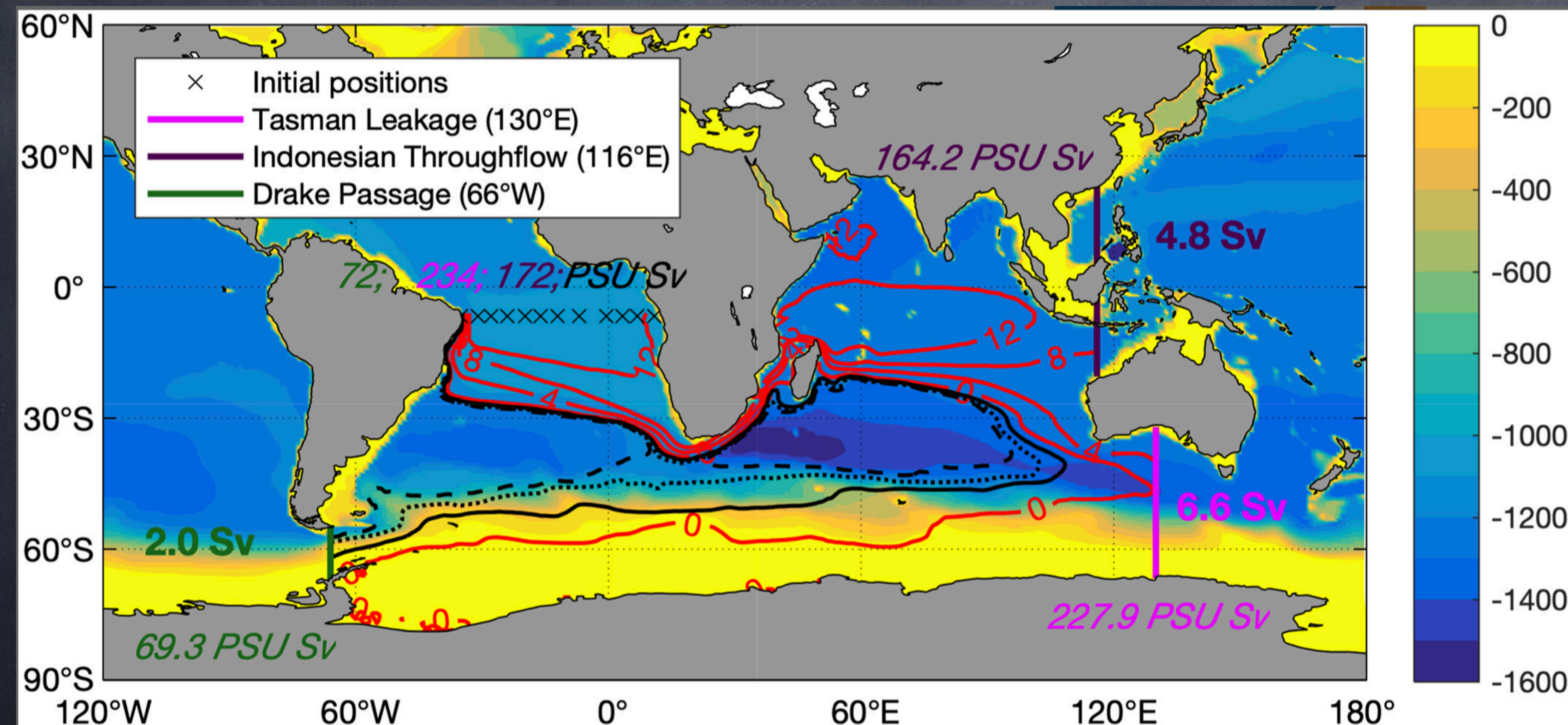
Particle depth (m)

-3000 -2500 -2000 -1500 -1000 -500 0



Upper ocean return paths: From the Pacific and Indian Oceans back to the Atlantic.

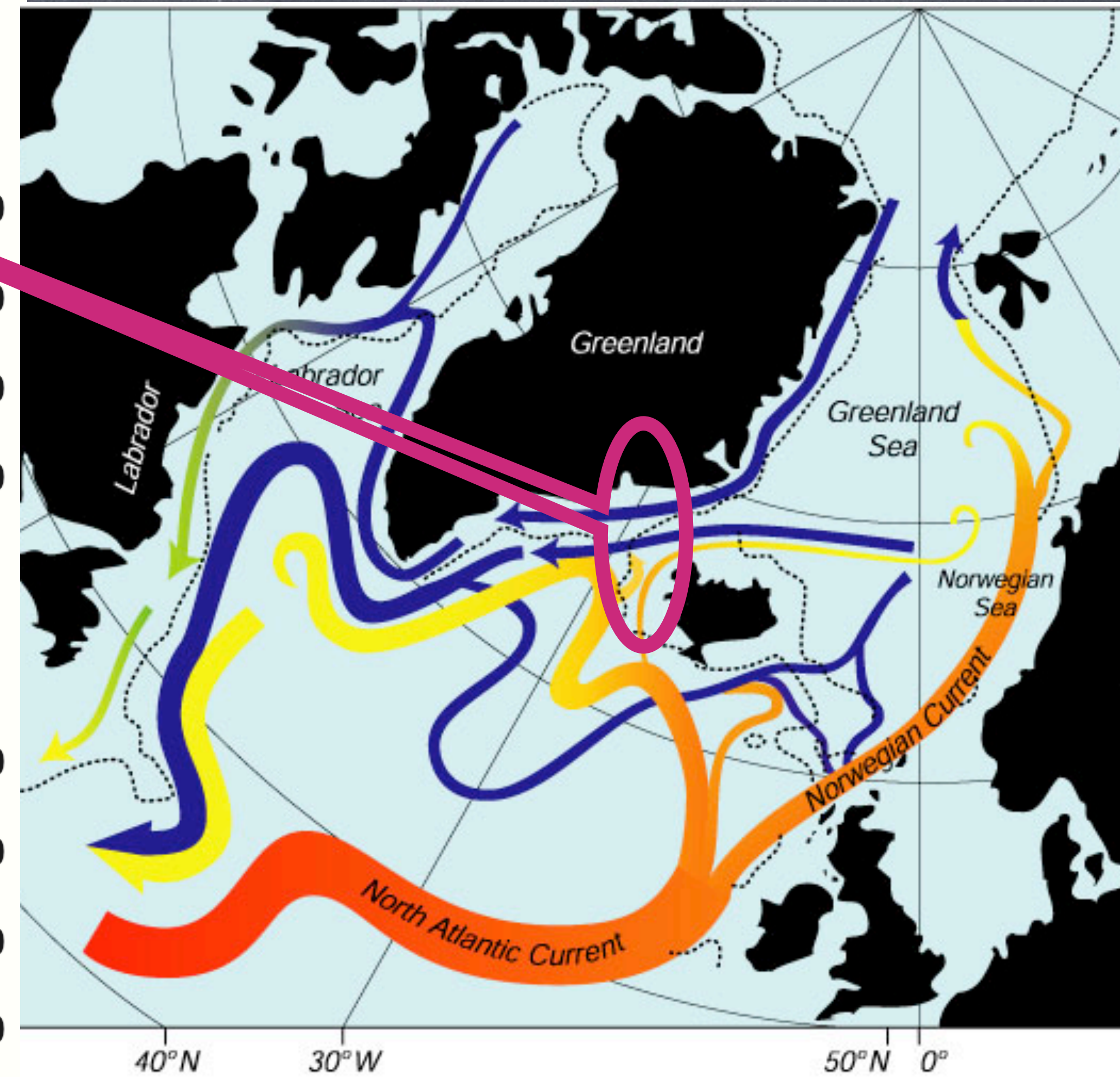
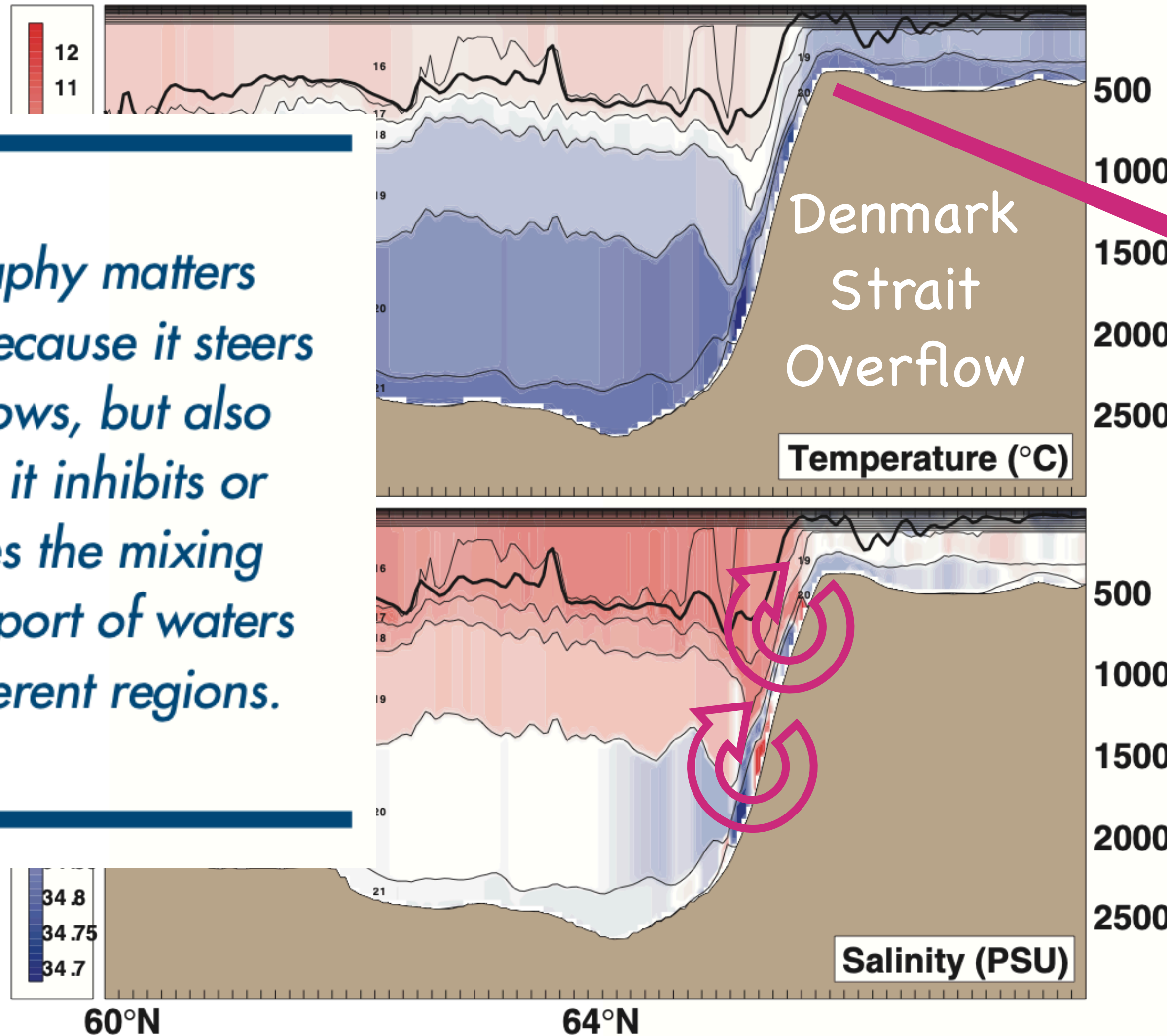
12 Sv via the Agulhas, 1 Sv direct via Drake Passage



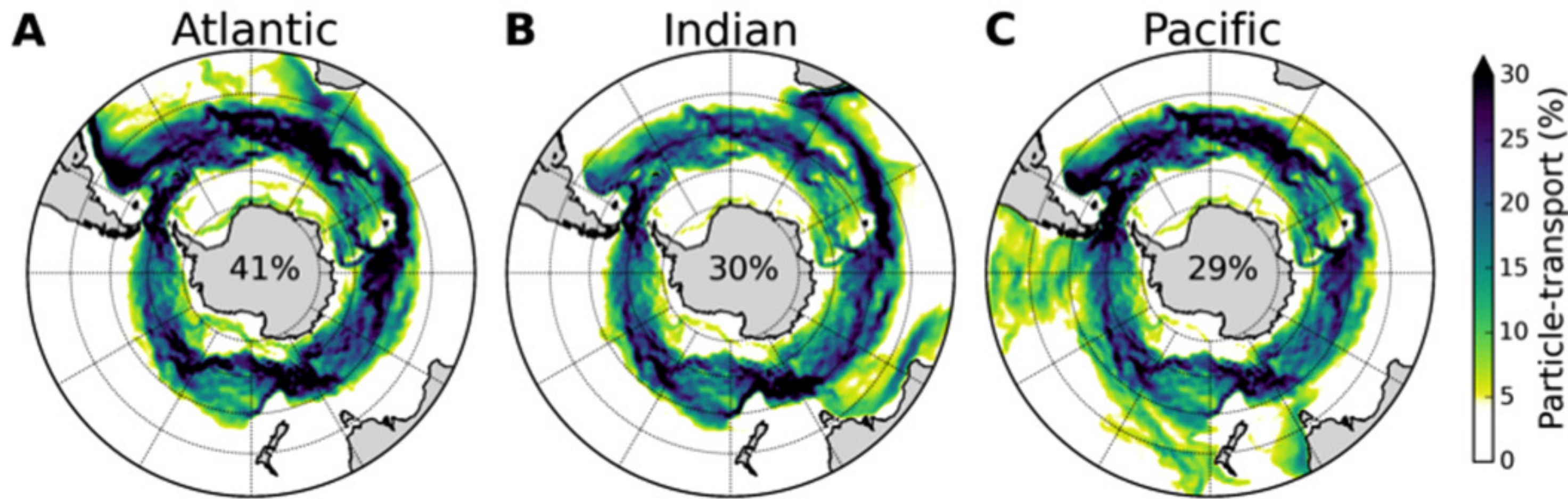
Rousselet et al. (2020) From ocean state estimate ECCOv4

Importance of Topography

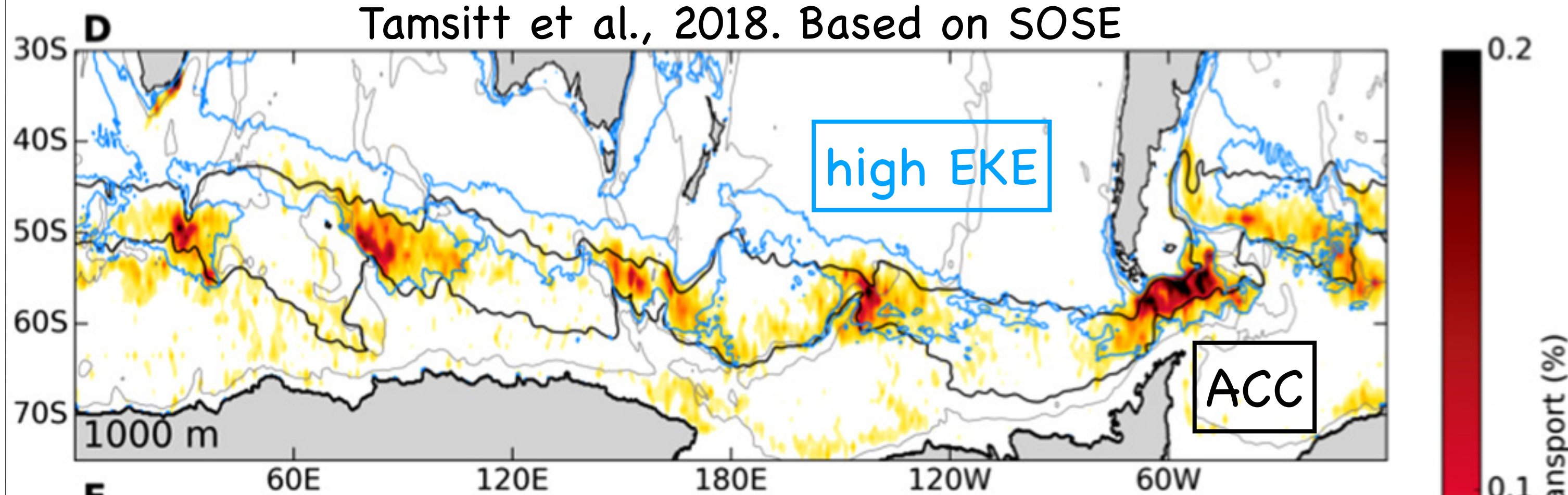
Topography matters not only because it steers ocean flows, but also because it inhibits or enhances the mixing and transport of waters from different regions.



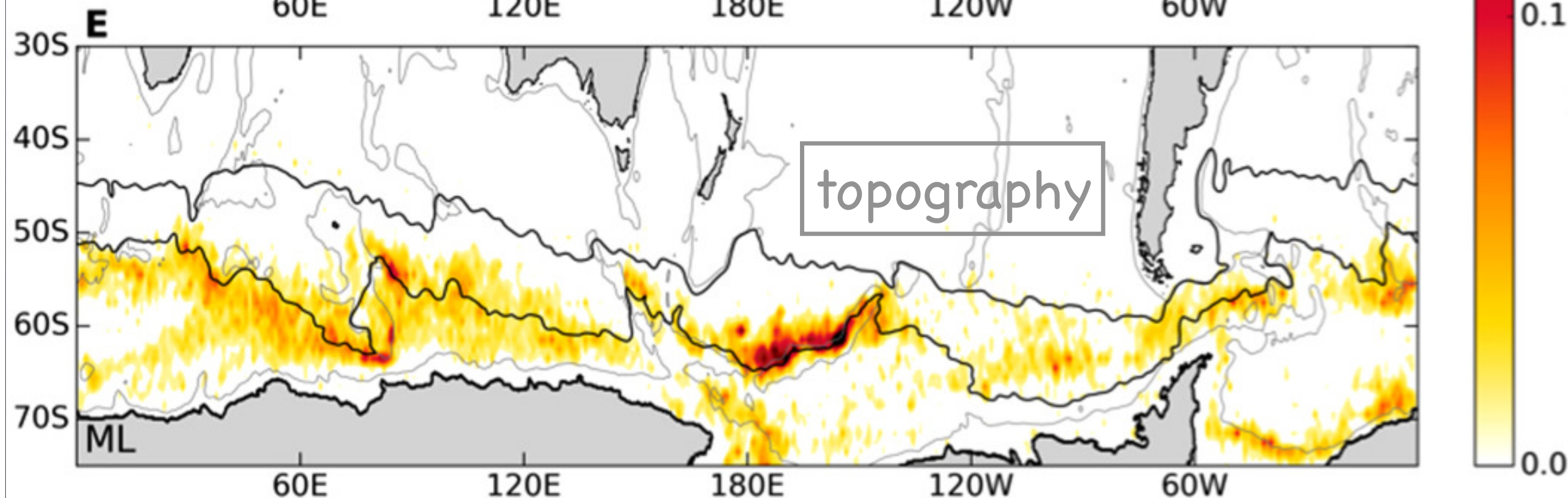
(A, B, C)
Waters
from 30 S
outcropping
in Southern
Ocean



(D) Parcels
upwelling
thru 1000 m

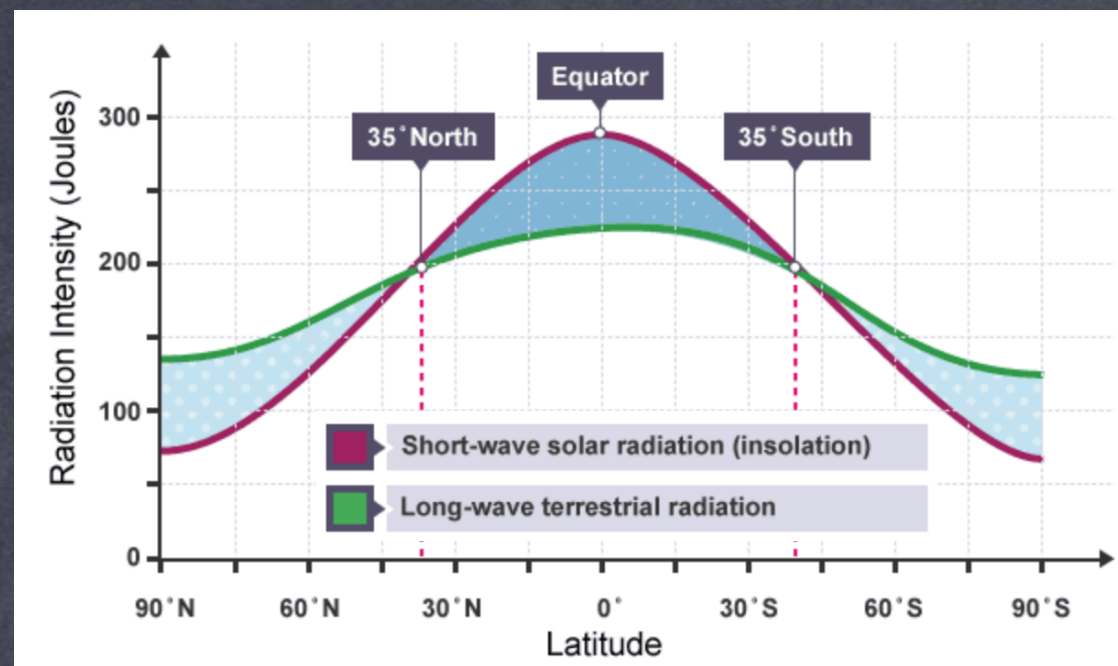


(E) Parcels
upwelling
into mixed
layer

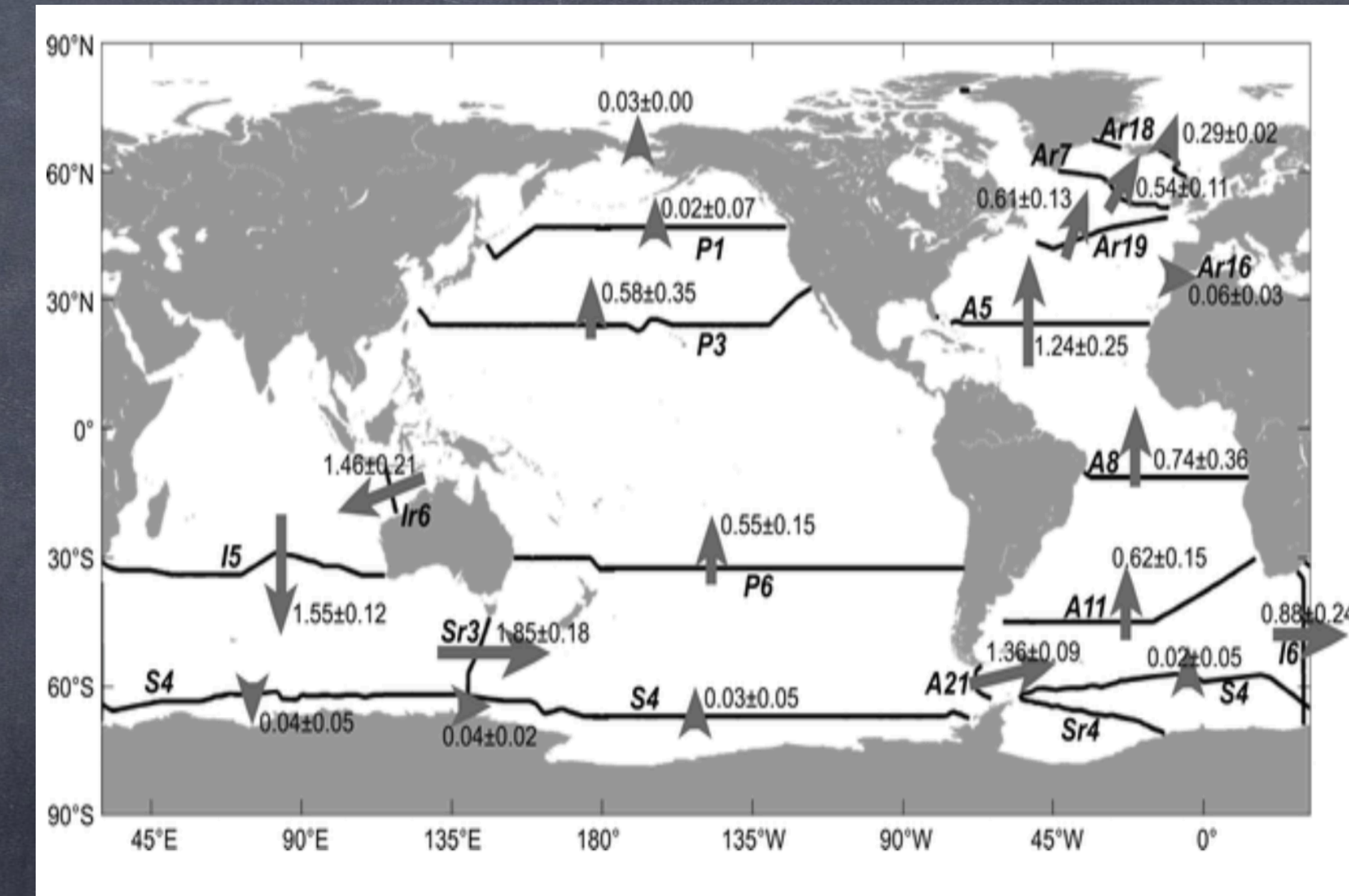
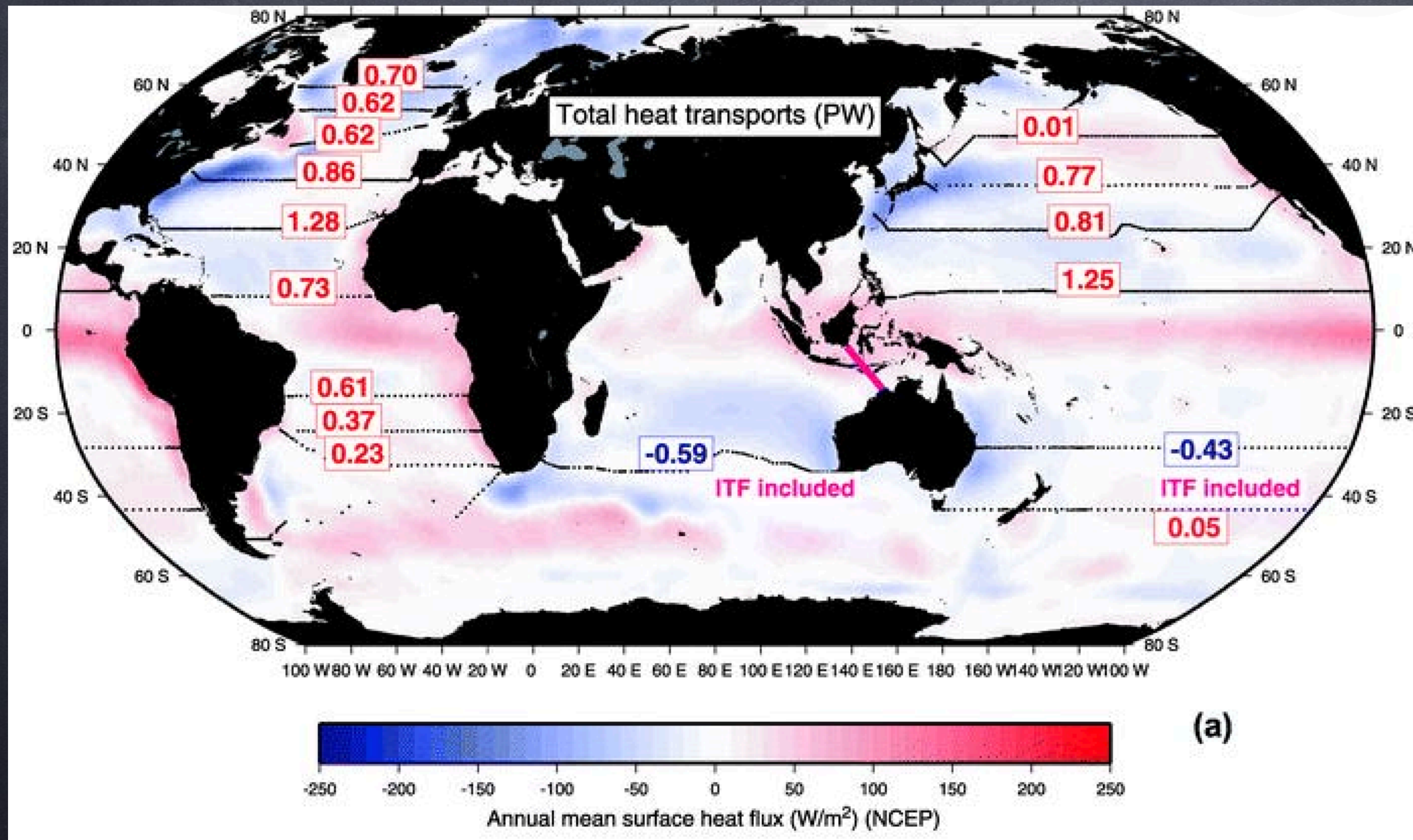


Most upwelling of
deep waters
occurs in the
Southern Ocean,
due to:

- (1) sloping density
surfaces
- (2) meanders and
eddies (induced
by topo)
- (3) topographic
steering and
mixing



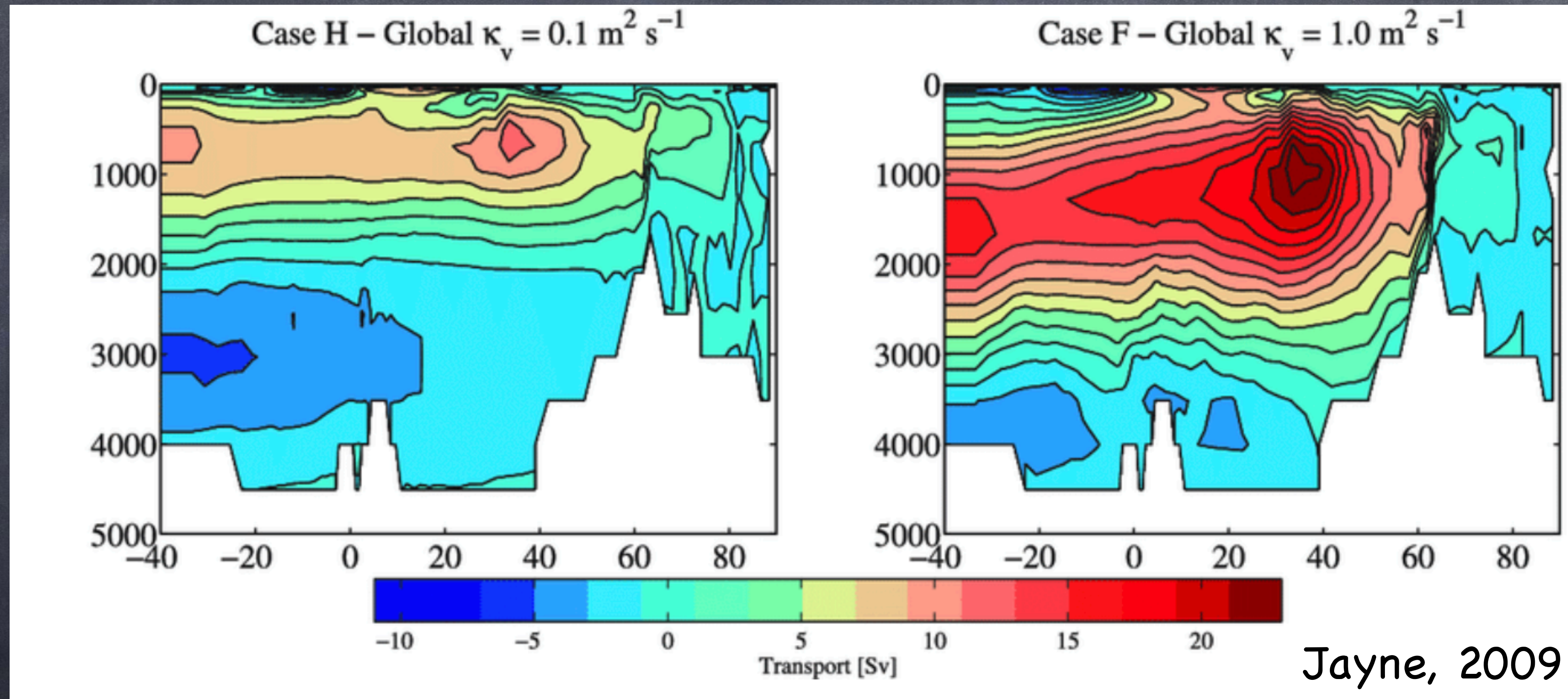
Meridional heat transport in ocean carried by overturning circulation



Lumpkin & Speer (2007),
based on inverse model

Talley (2003), based on Reid water mass analysis

Overturning Stream function



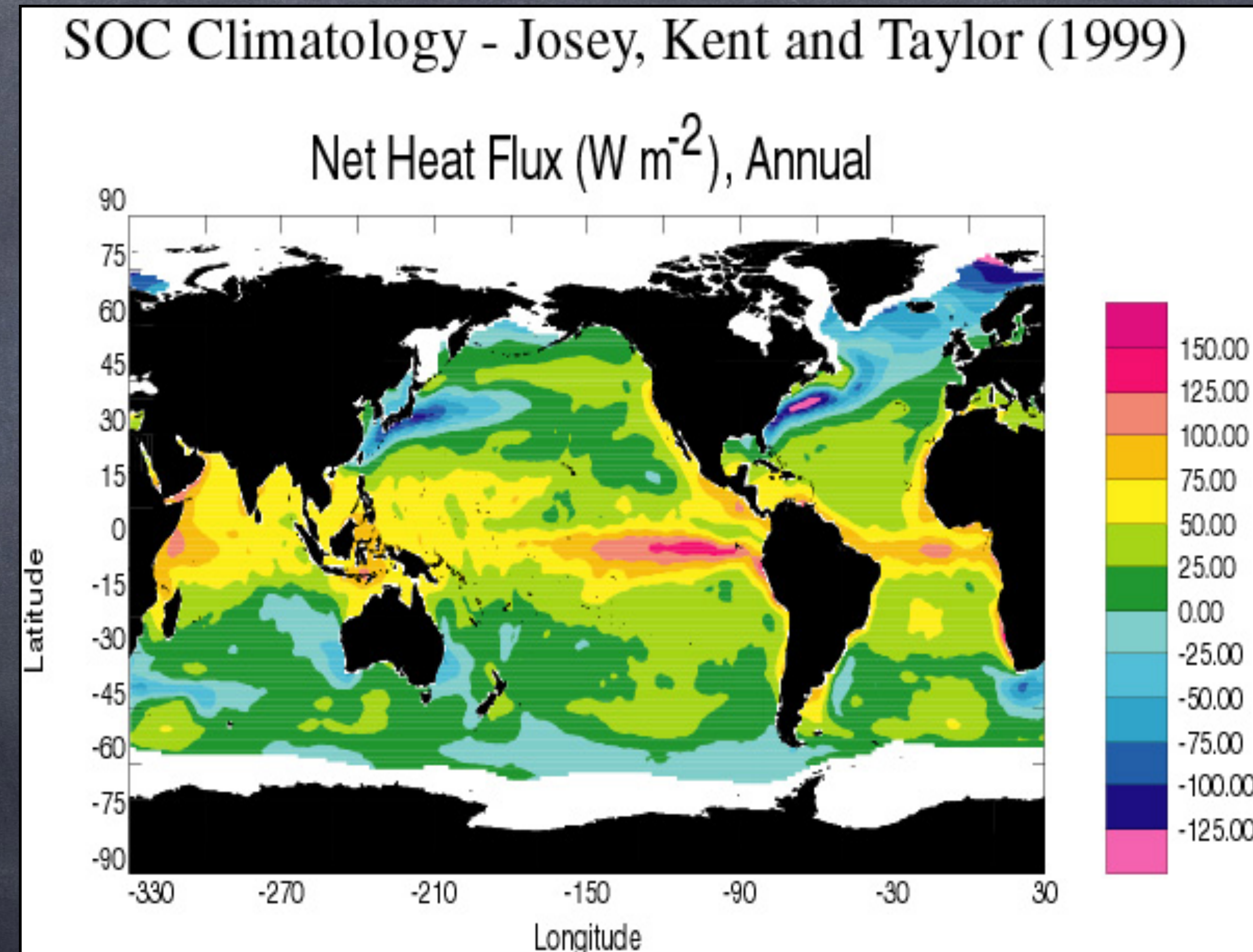
As for evaporative basins and estuarine flows, mixing determines the size of the exchange

Three ways to estimate meridional ocean heat transport

- **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 geostrophic velocity and temperature.

Oceanic heat transport from air-sea fluxes

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



Global bias of 30 Wm^{-2} is typical

Residual Method

- Large errors in atmospheric heat transport lead to huge uncertainties in oceanic heat transport.
- Uncertainties primarily in atmospheric moisture transport (clouds, precipitation...)
- Recent results suggest that ocean, atmosphere, and moisture (latent heat) transport contribute roughly equally to meridional heat transport.

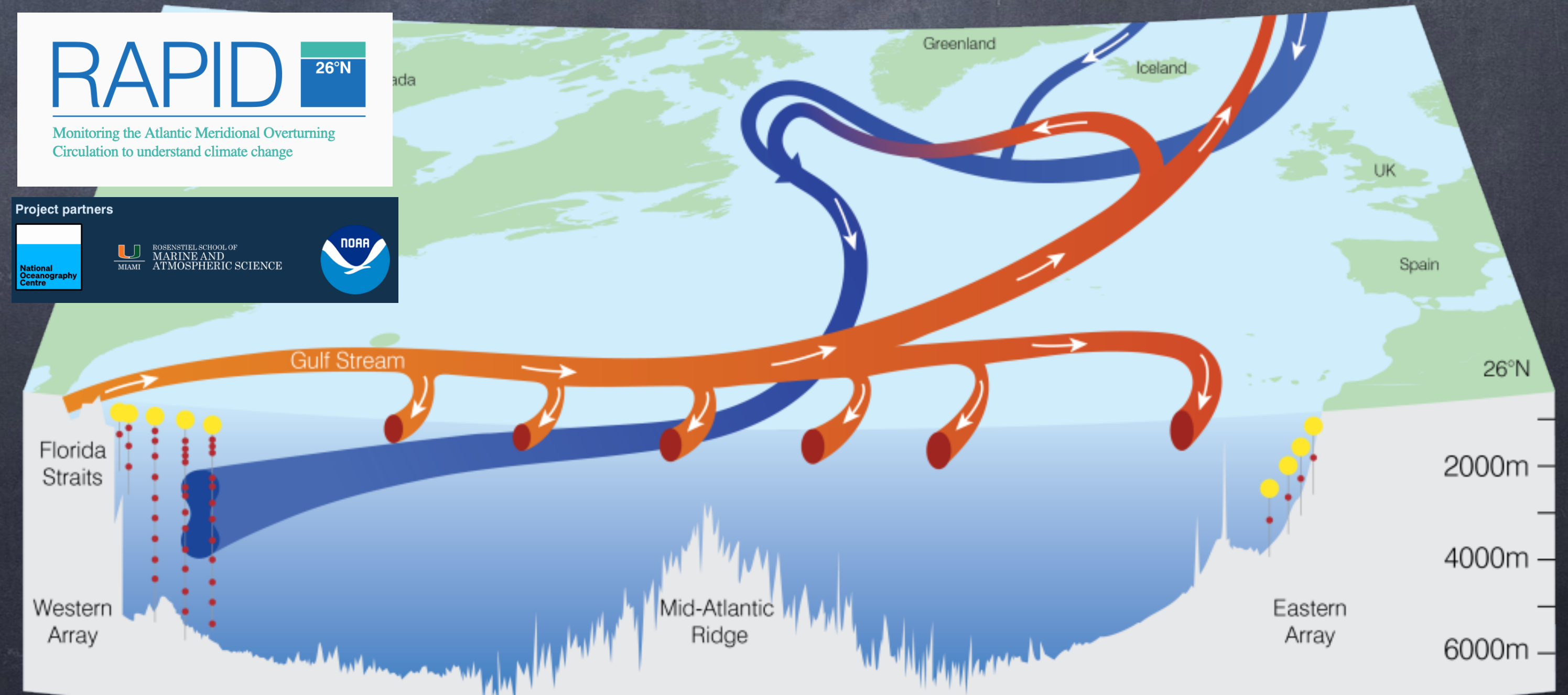
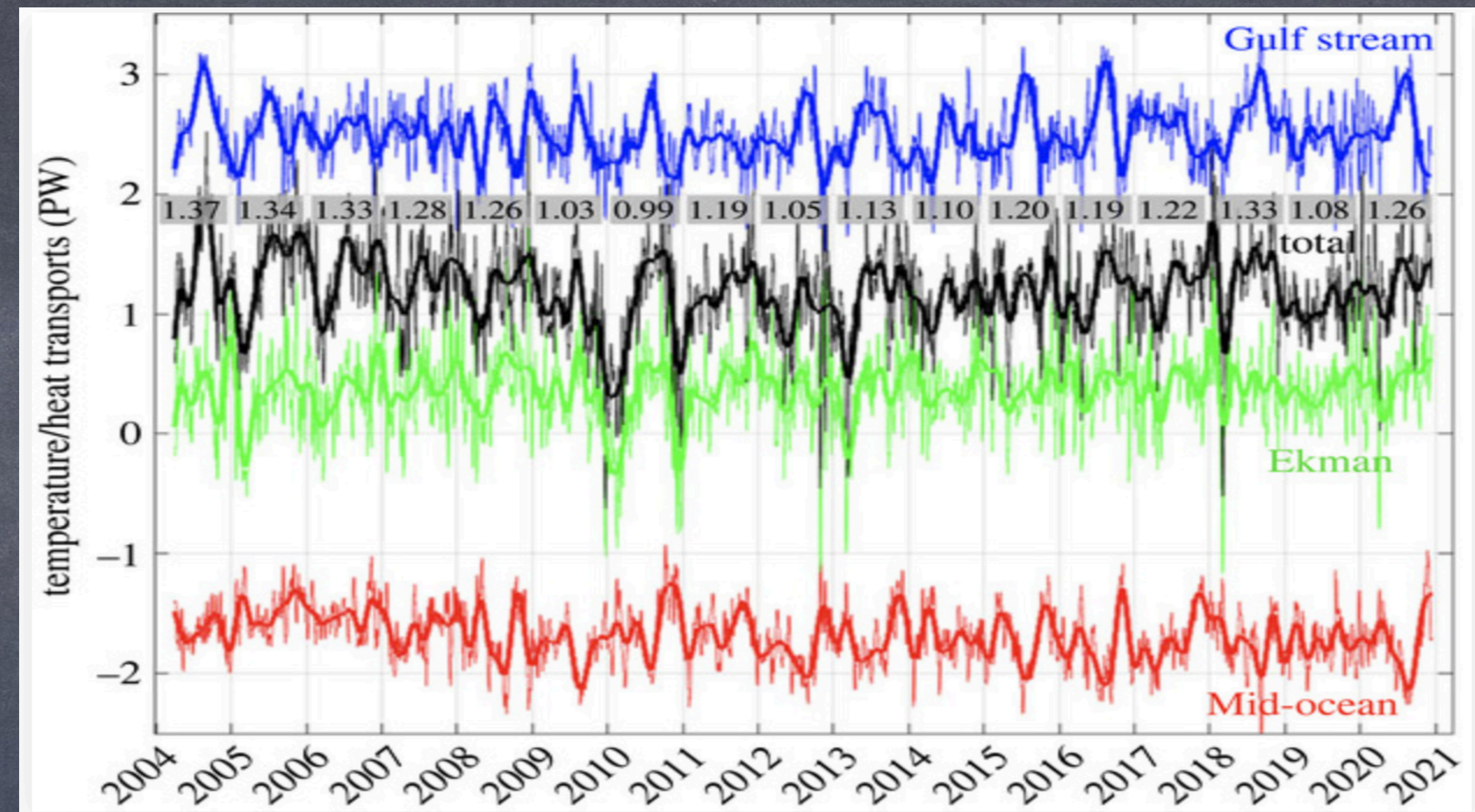
Direct Method

- From hydrography (one time) or moorings (time series).

$$Q = \int_{x_w}^{x_e} \int_H^0 \rho c_p v \theta \, dx \, dz,$$

- WBC velocity and temperature from moorings; Ekman heat transport from satellite winds and SST; Mid-ocean from T,S,p and mass balance (Hall & Bryden, 1982; Johns et al., 2023)

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



Atlantic overturning predicted to weaken due to anthropogenic climate change (IPCC AR6)

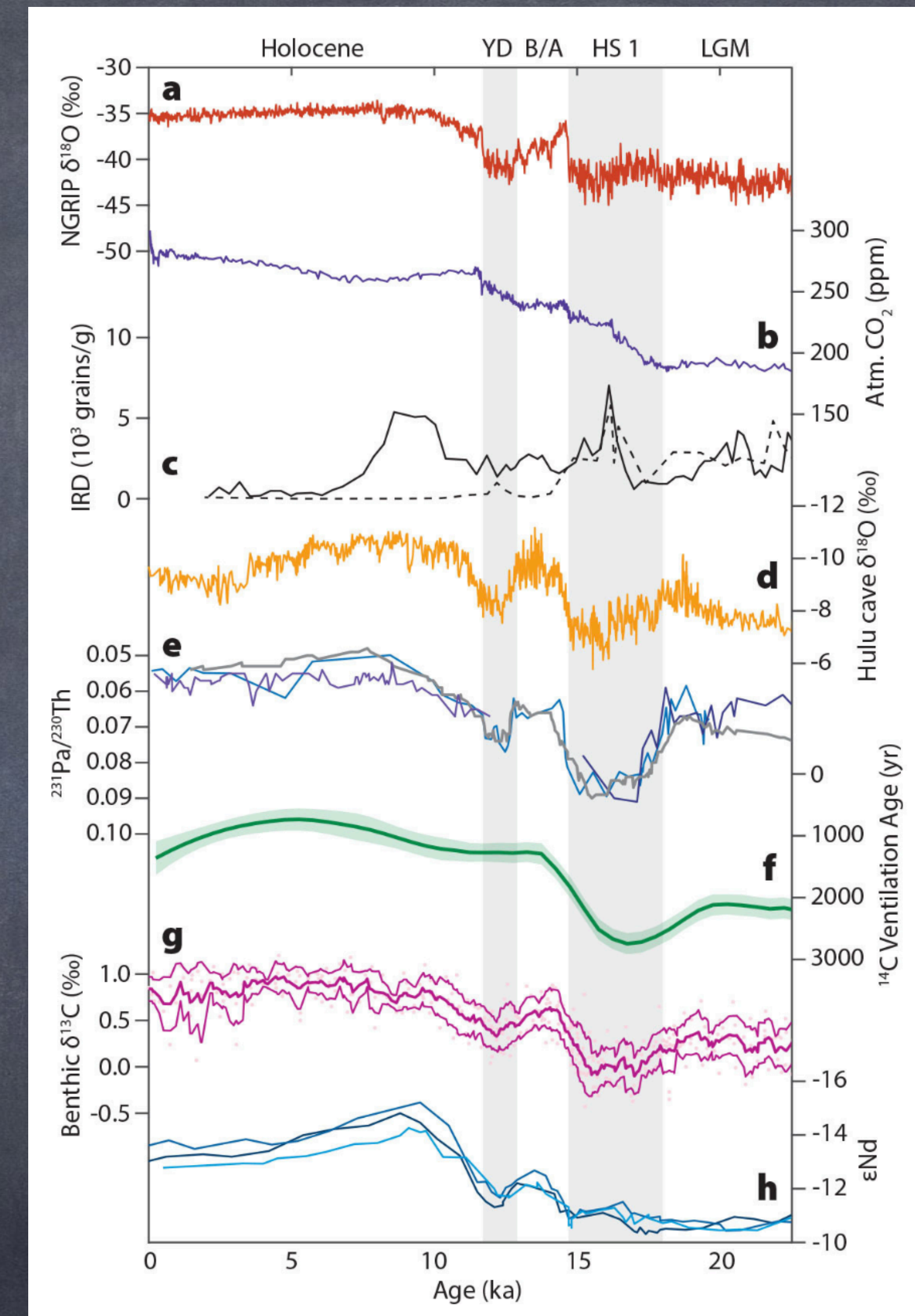
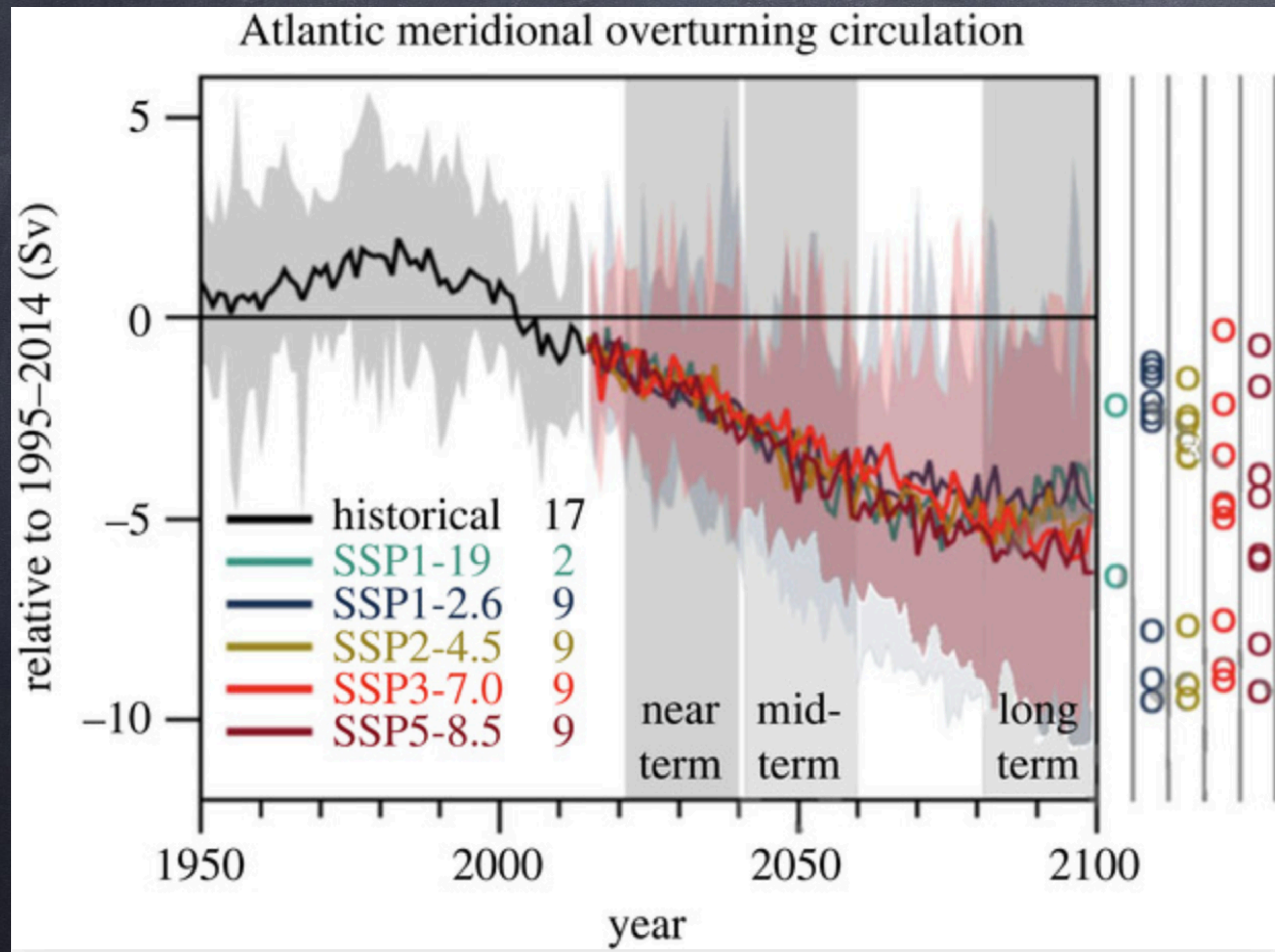


FIGURE 2. Paleoclimate records across the deglaciation. (a) Northern Hemisphere temperature from NGRIP $\delta^{18}O$ of ice (North Greenland Ice Core Project Members, 2004; Andersen et al., 2006; Rasmussen et al., 2014). (b) Atmospheric CO_2 from the West Antarctic Ice Sheet (Marcott et al., 2014). (c) Ice-rafted debris concentration in the Northwest Atlantic at sites DY081-GVY001 (solid) and EW9309-37/PC (dashed) (Zhou et al., 2021). (d) Hulu cave $\delta^{18}O$ (Cheng et al., 2016). (e) $^{231}Pa/^{230}Th$ from the Bermuda Rise (thin lines: McManus et al., 2004; Lippold et al., 2009, 2019) and across the North Atlantic (thick line: Ng et al., 2018). (f) Compiled deep Atlantic ^{14}C ventilation age (Rafter et al., 2022). (g) Deep North Atlantic $\delta^{13}C$ (as in Lynch-Stieglitz et al., 2014; data from Hodell et al., 2008; Tjallingii et al., 2008; Mulitza et al., 2008; Zarriess and Mackensen, 2011; Shackleton et al., 2000; Skinner and Shackleton, 2004; Skinner et al., 2007). (h) ϵNd from the Blake Bahama Outer Ridge (Pöppelmeier et al., 2019). YD = Younger Dryas, B/A = Bølling-Allerød, HS 1 = Heinrich Stadial 1, LGM = Last Glacial Maximum. IRD = Ice-rafted debris. > [High res figure](#)

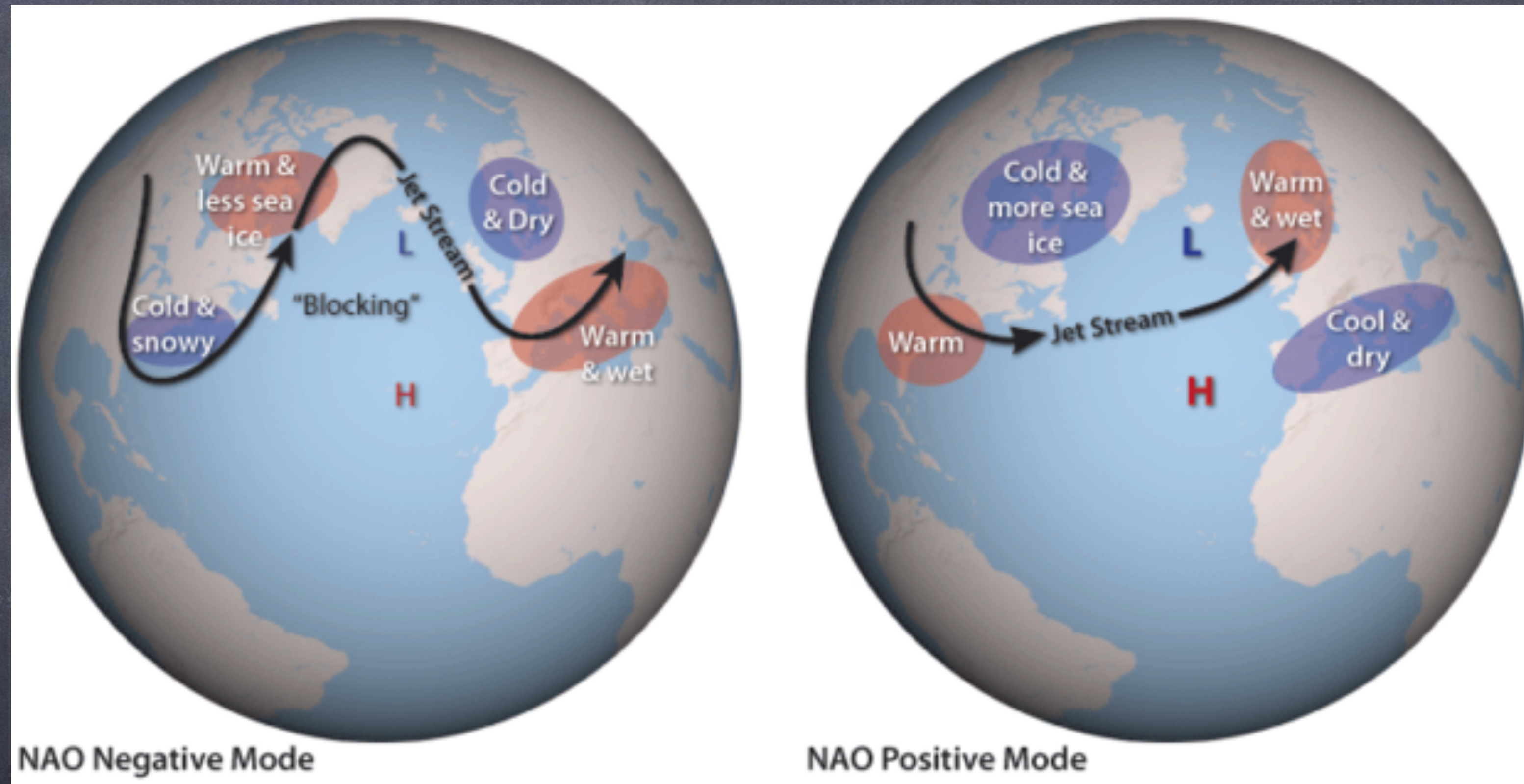
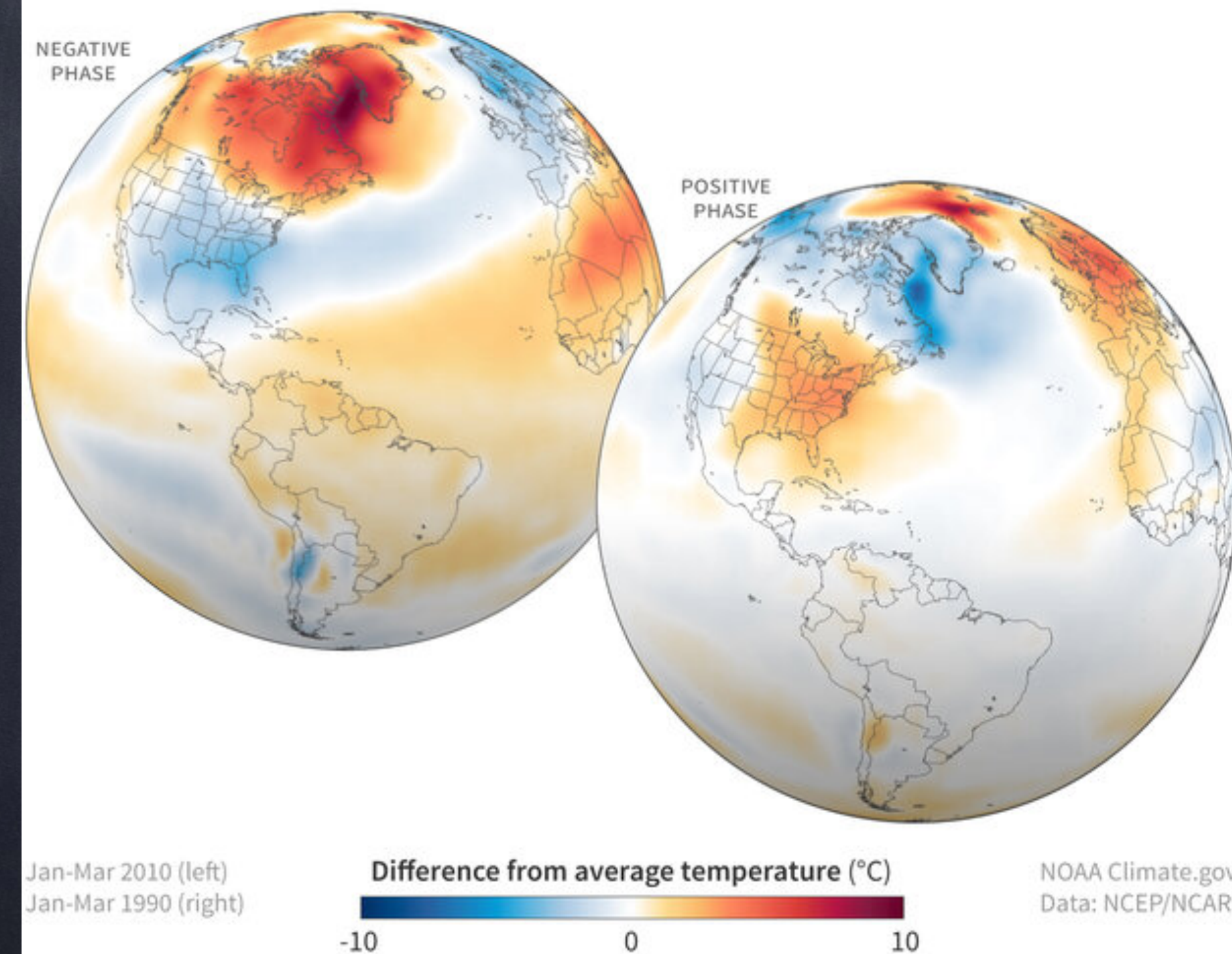
Paleo evidence links AMOC to past climate transitions (Hines et al., 2025)

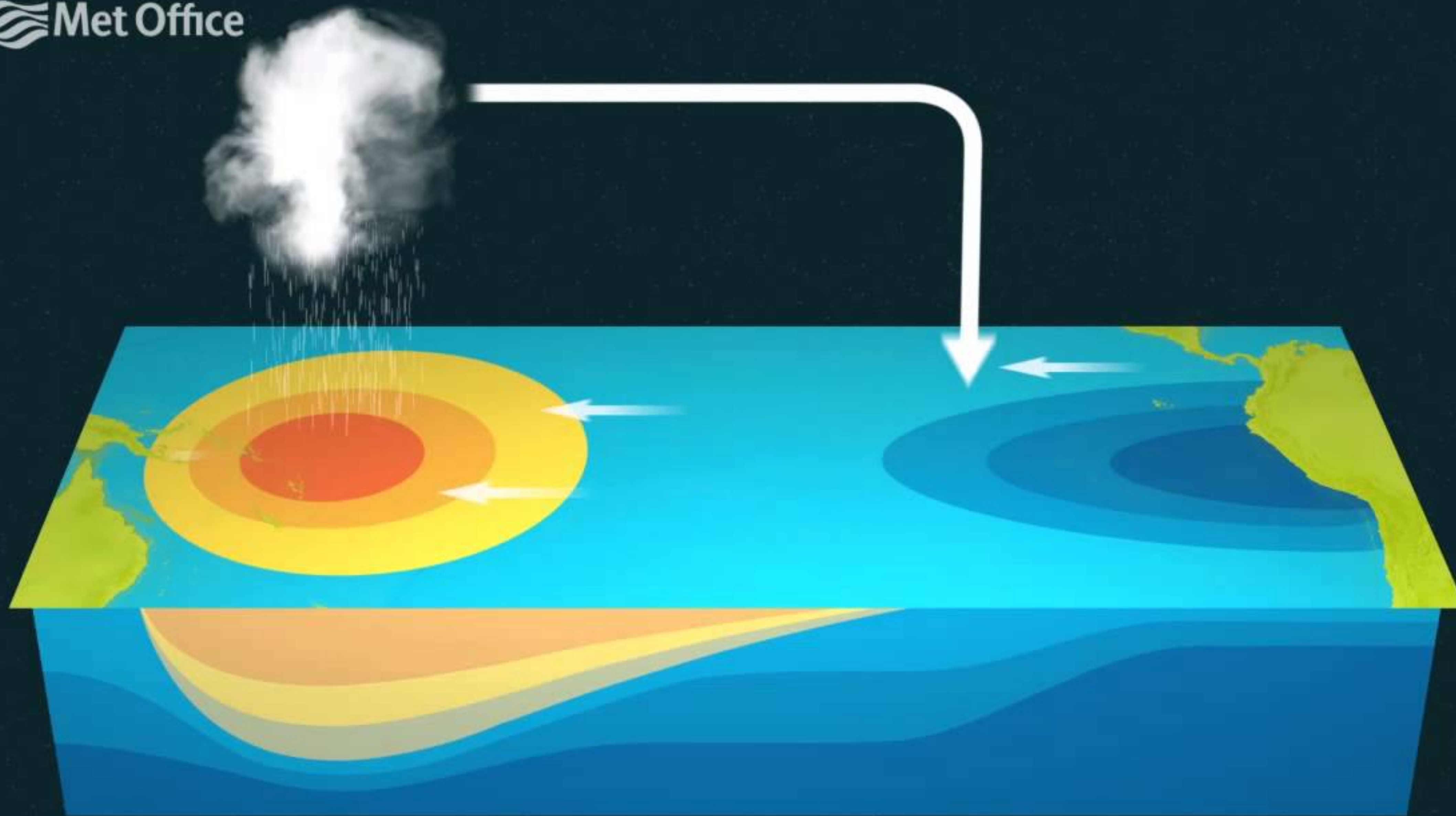


WHAT IS THE AMO?

North Atlantic Oscillation: Interannual. Feedback between Rossby waves in the atmosphere and ocean

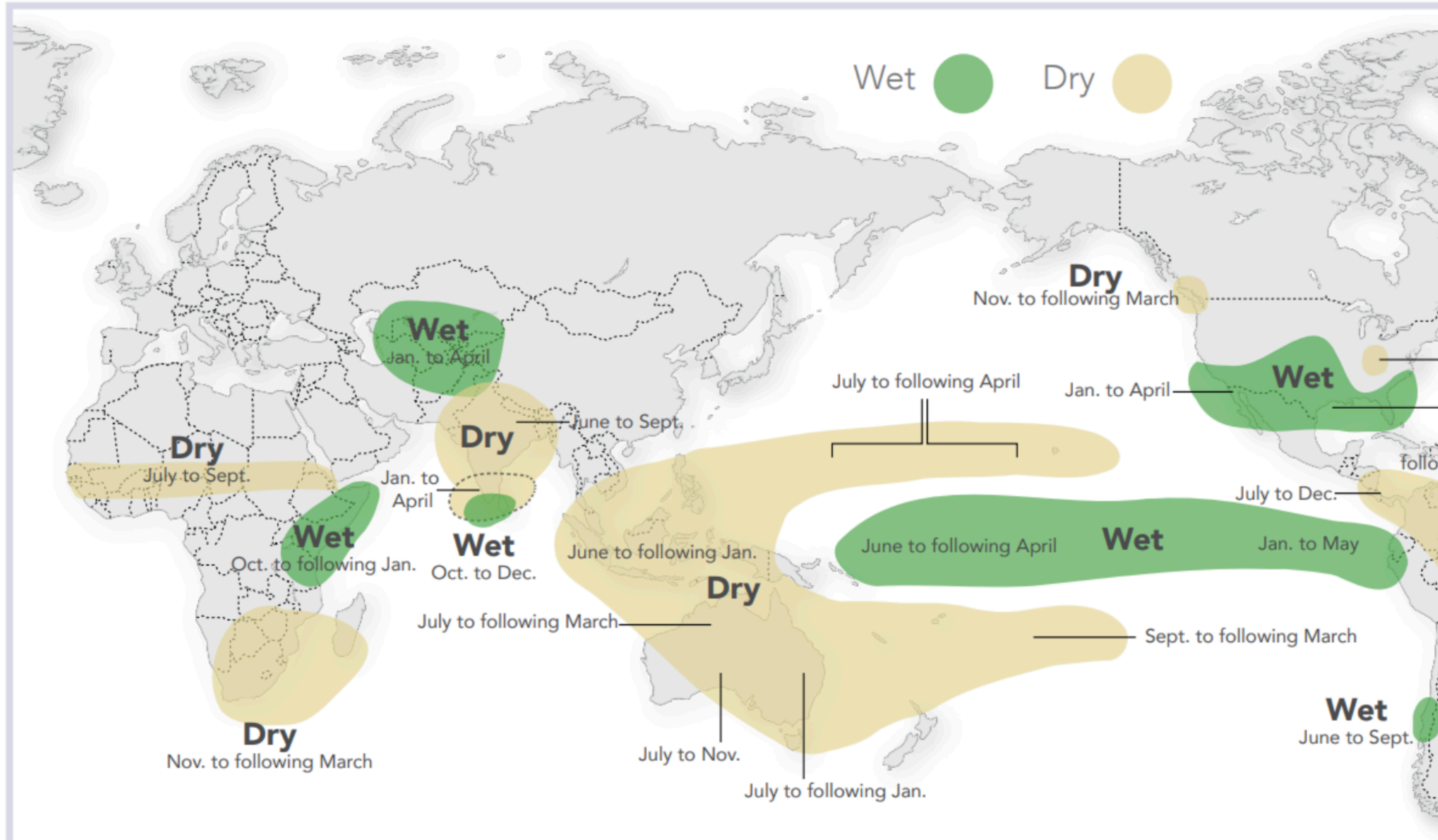
NAO TEMPERATURE PATTERNS





El Niño and Rainfall

El Niño conditions in the tropical Pacific are known to shift rainfall patterns in many different parts of the world. Although they vary somewhat from one El Niño to the next, the strongest shifts remain fairly consistent in the regions and seasons shown on the map below.



For more information on El Niño and La Niña, go to: <http://iri.columbia.edu/enso/>

Sources:

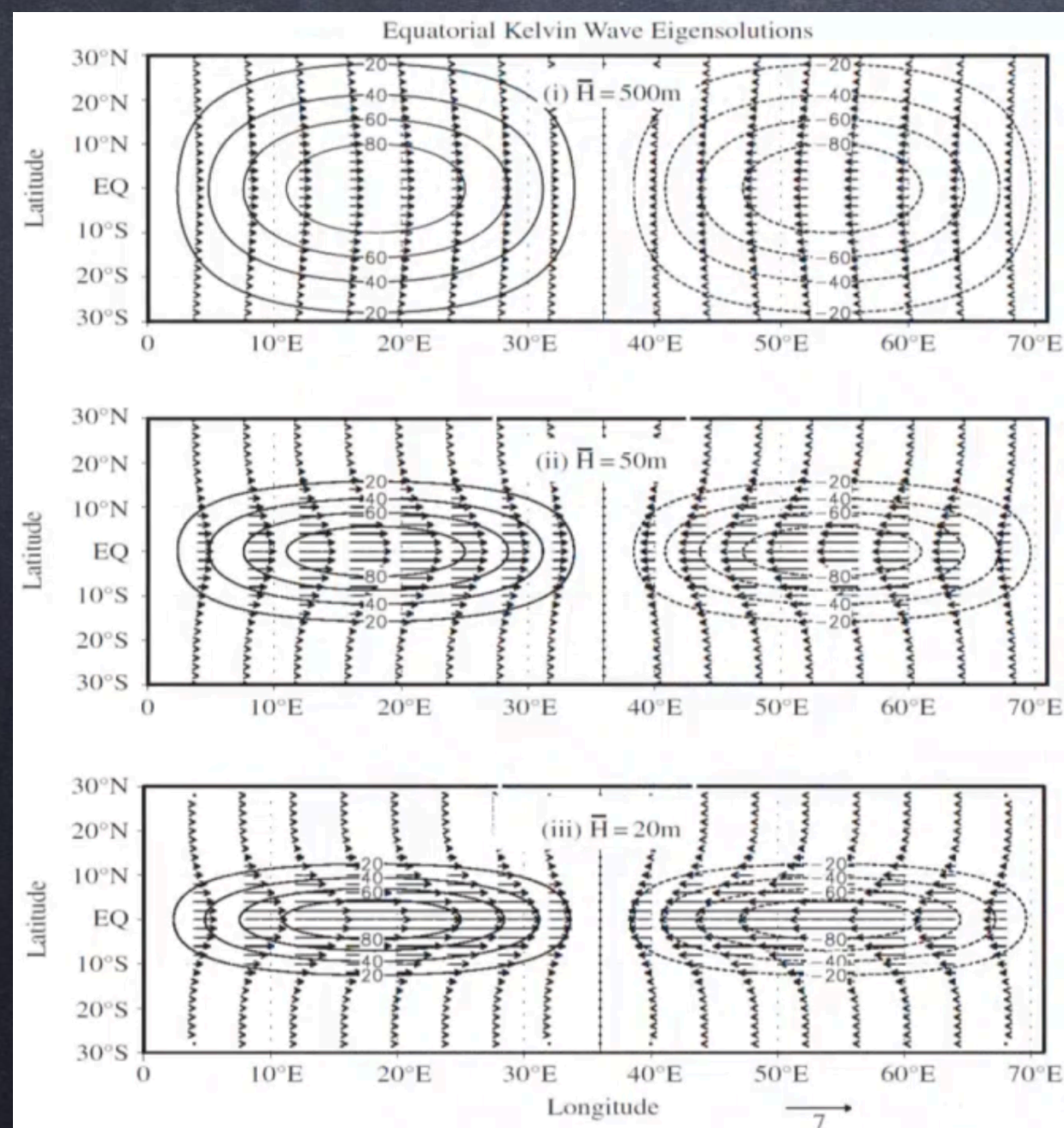
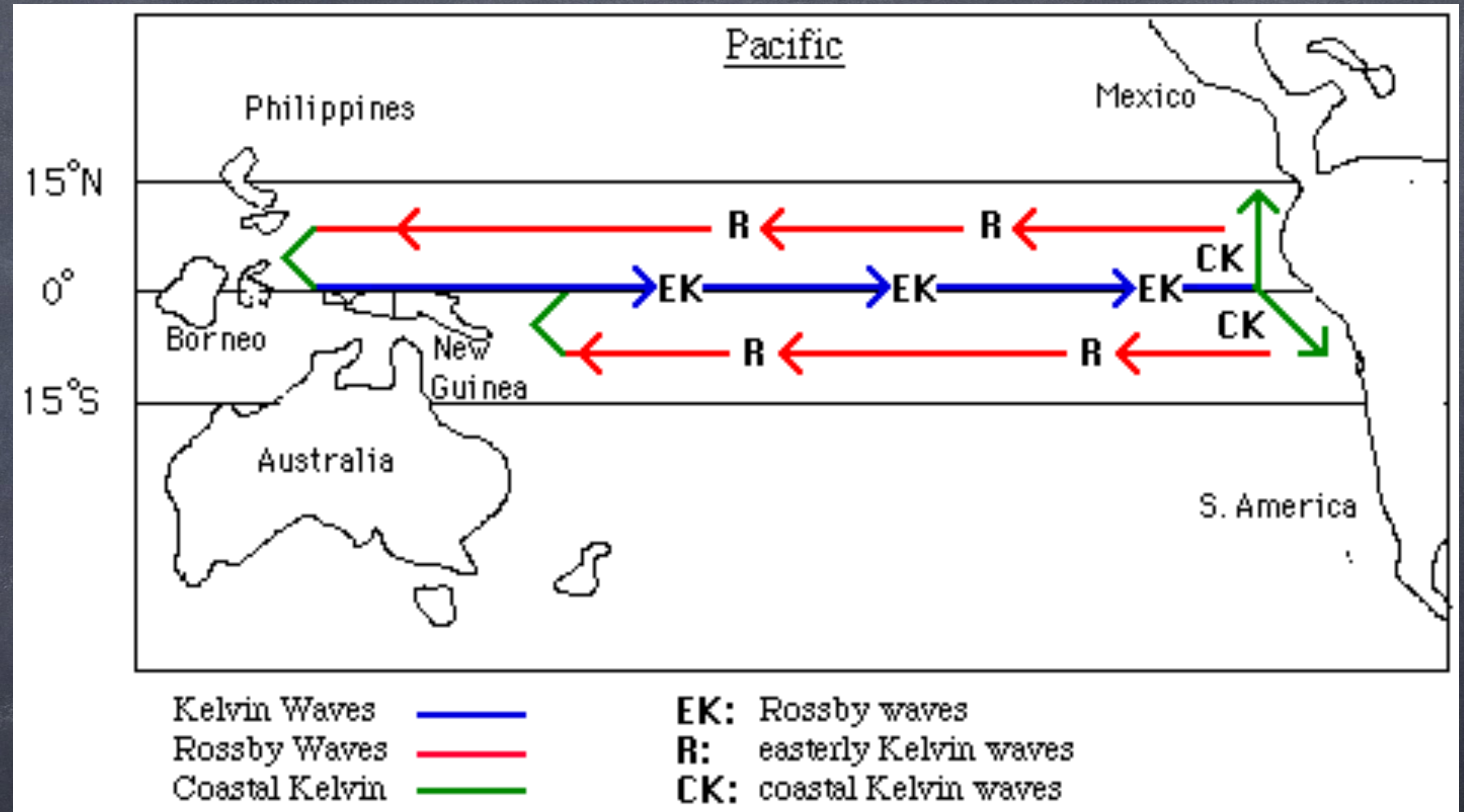
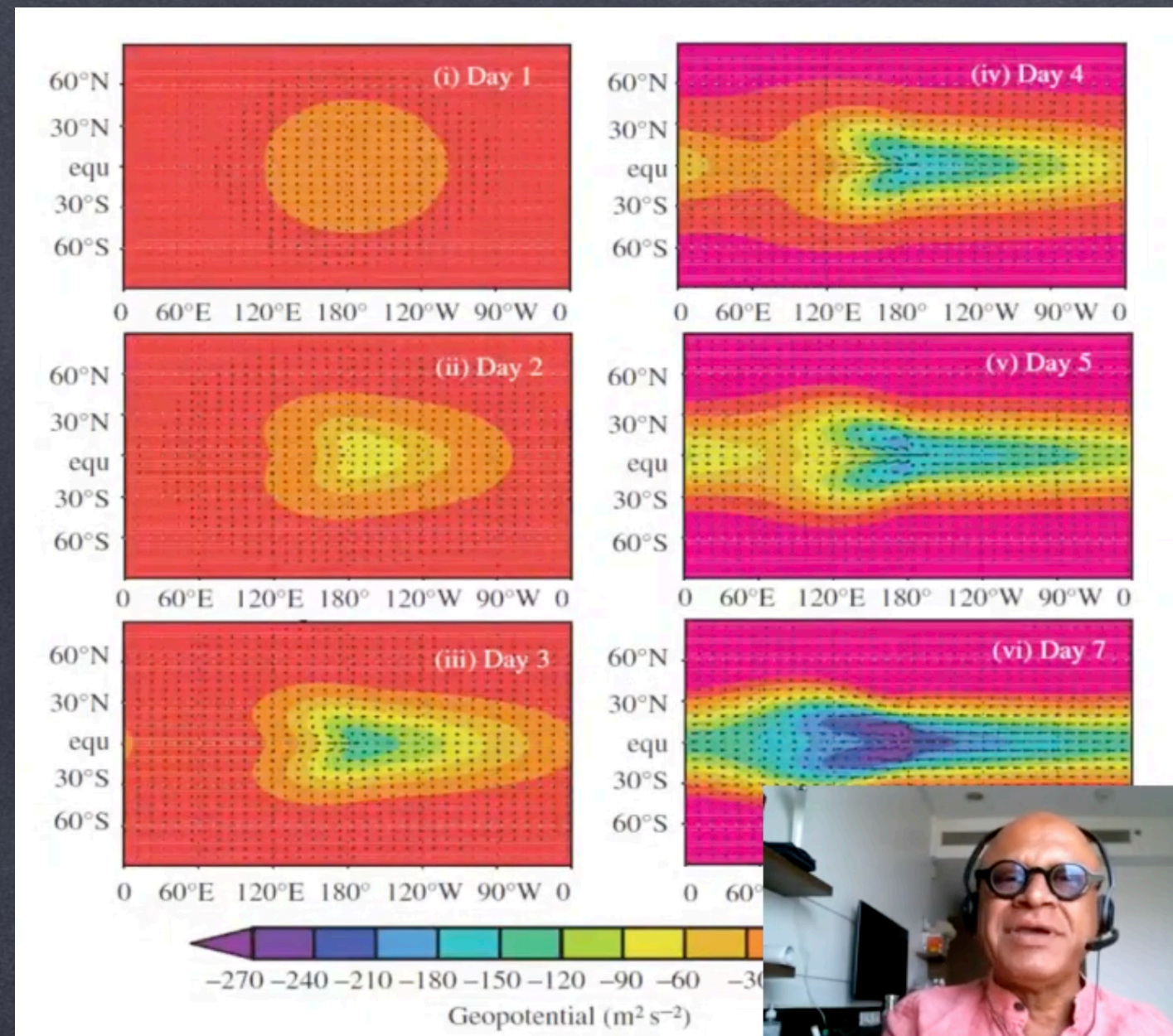
1. Ropelewski, C. F., and M. S. Halpert, 1987: Global and regional scale precipitation patterns associated with the El Niño Southern Oscillation. Mon. Wea. Rev., 115, 1606-1626;
2. Mason and Goddard, 2001. Probabilistic precipitation anomalies associated with ENSO. Bull. Am. Meteorol. Soc. 82, 619-638



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ENSO: Rossby and Kelvin waves set interannual oscillator



Stratification sets meridional scale. Wavelength sets phase speed. Boundary causes reflection.

Bureau of Meteorology

Understanding the MJO

