Climate Change and (Ocean) Variability

The memory of climate

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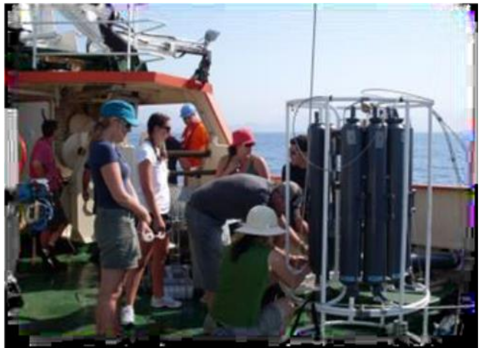


Outline

- **Observations**

  temperature (heat content),

  sea level,

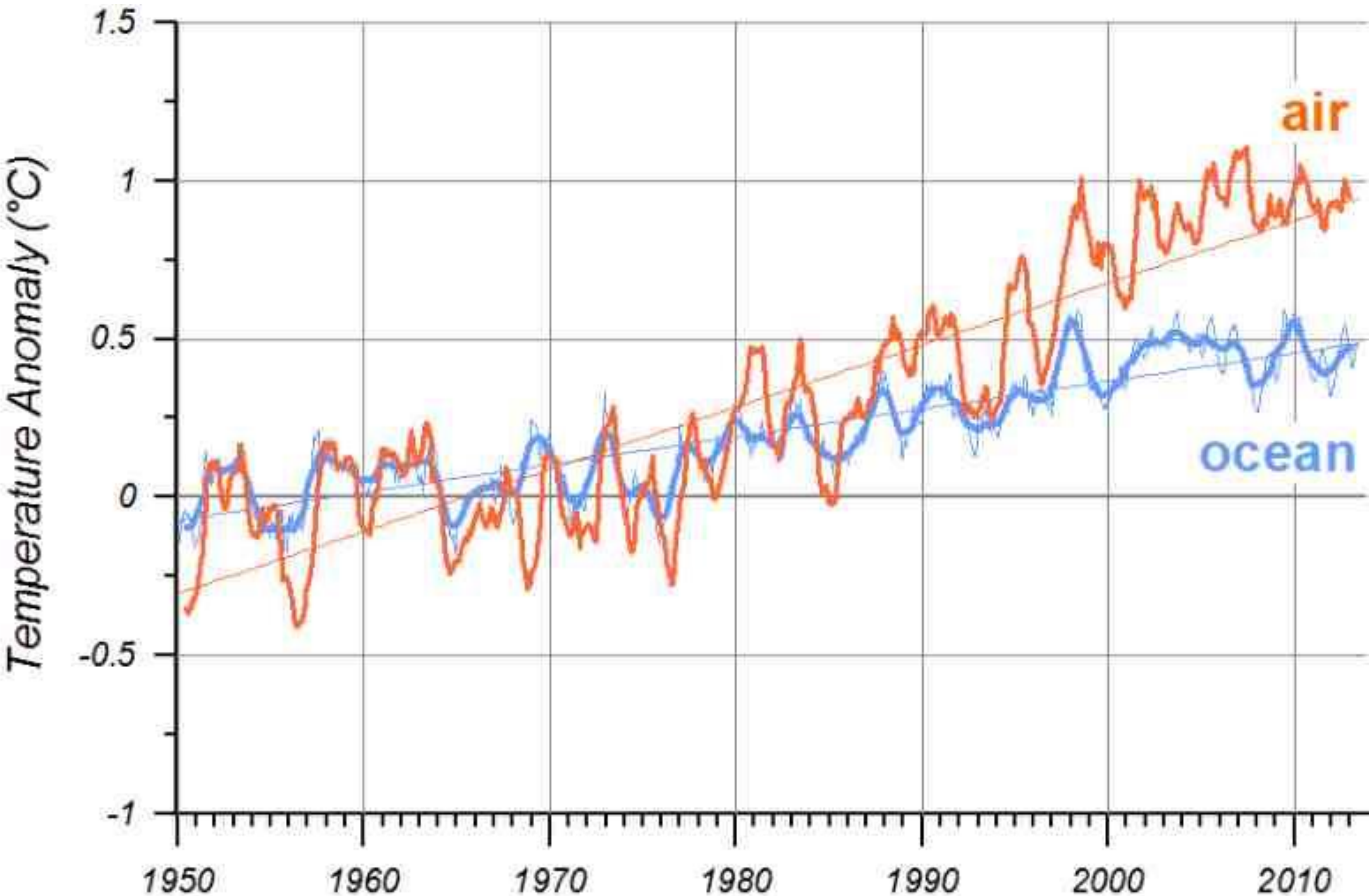
  salinity and the hydrological cycle

- **Meridional overturning**

  variability

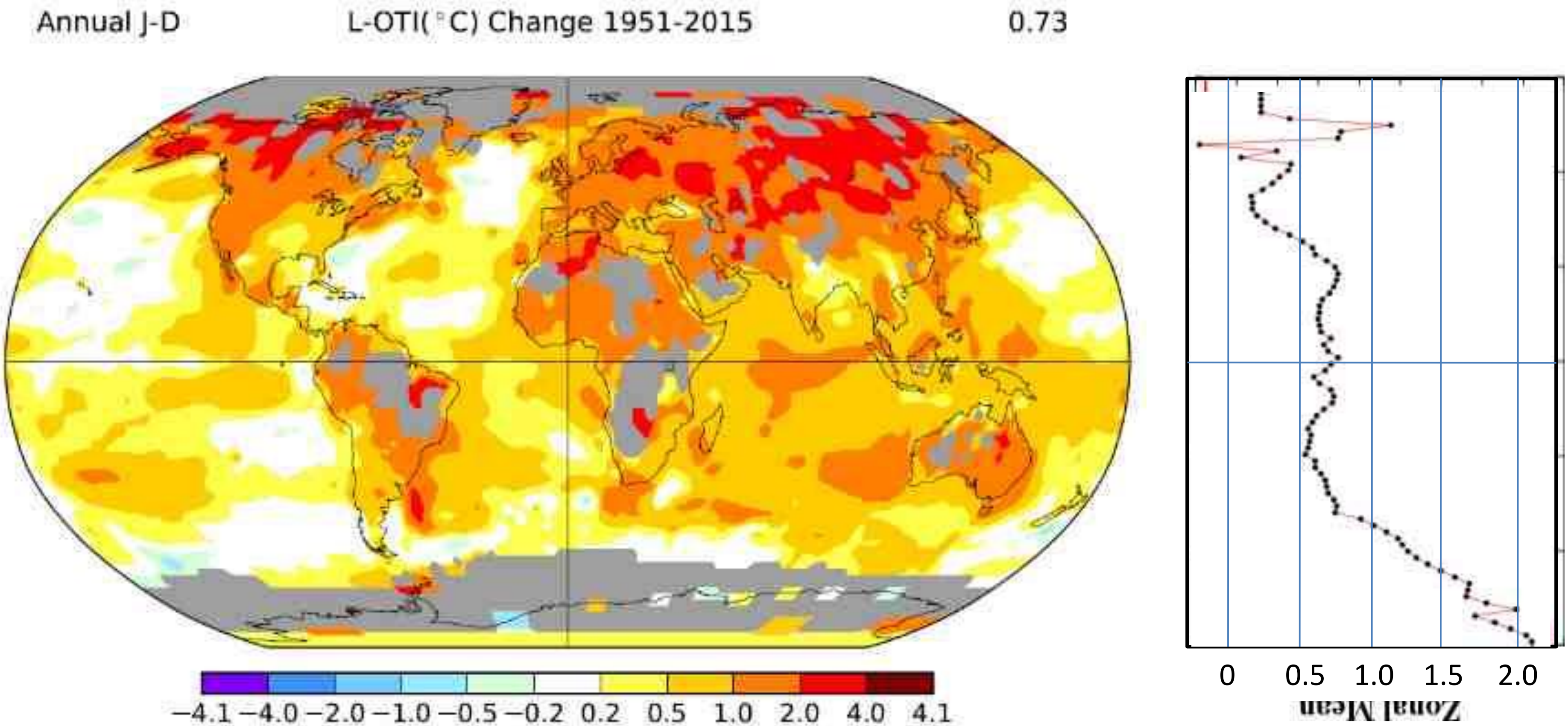
  impact on climate

Global warming – atmosphere and ocean



http://vlb.ncdc.noaa.gov/cmb-faq/anomalies.php#mean

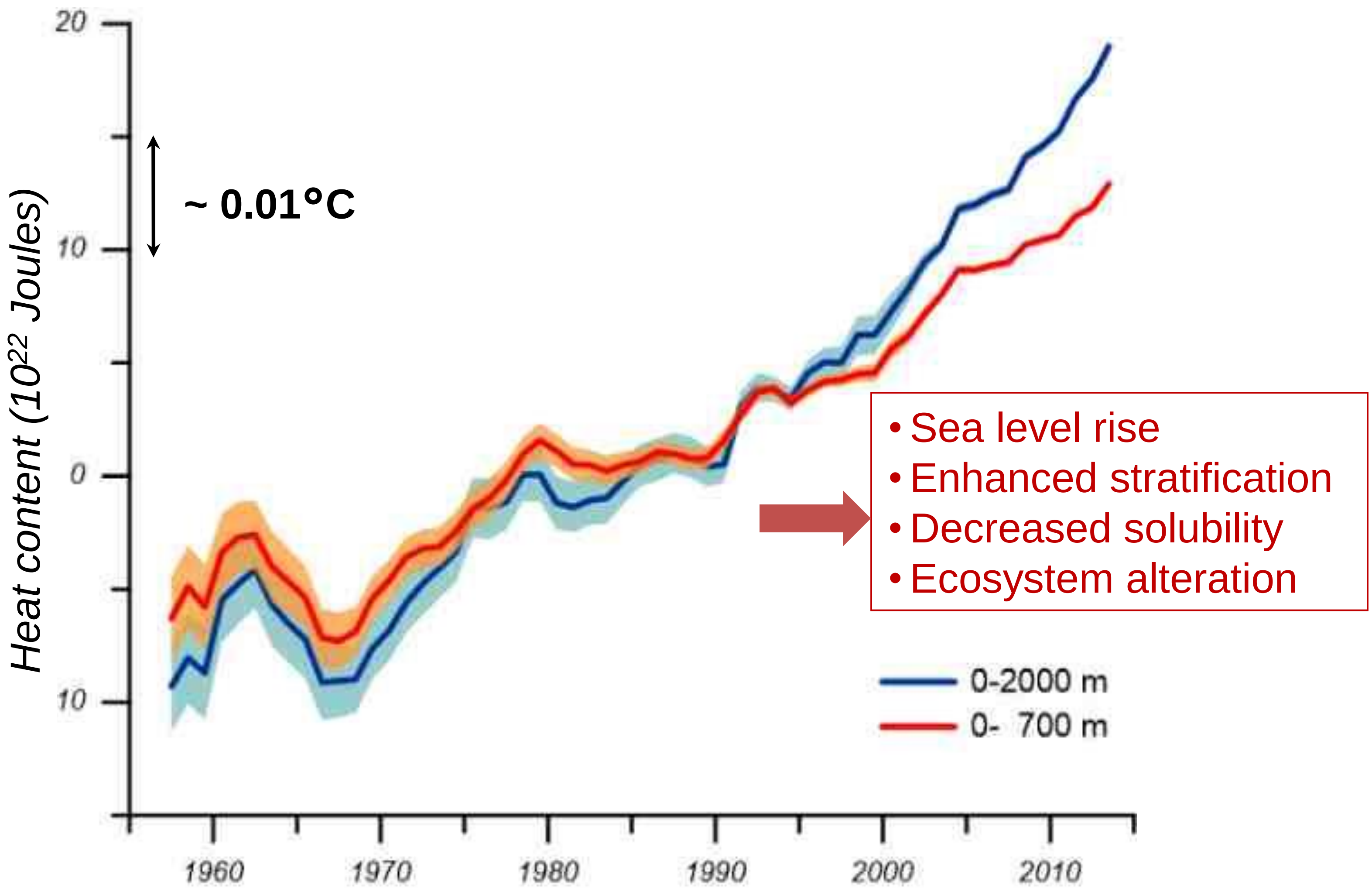
1951-2015, °C



Data Sources
Land: Goddard Inst. Space Studies - *Ocean*: Hadley/Reynolds v.2

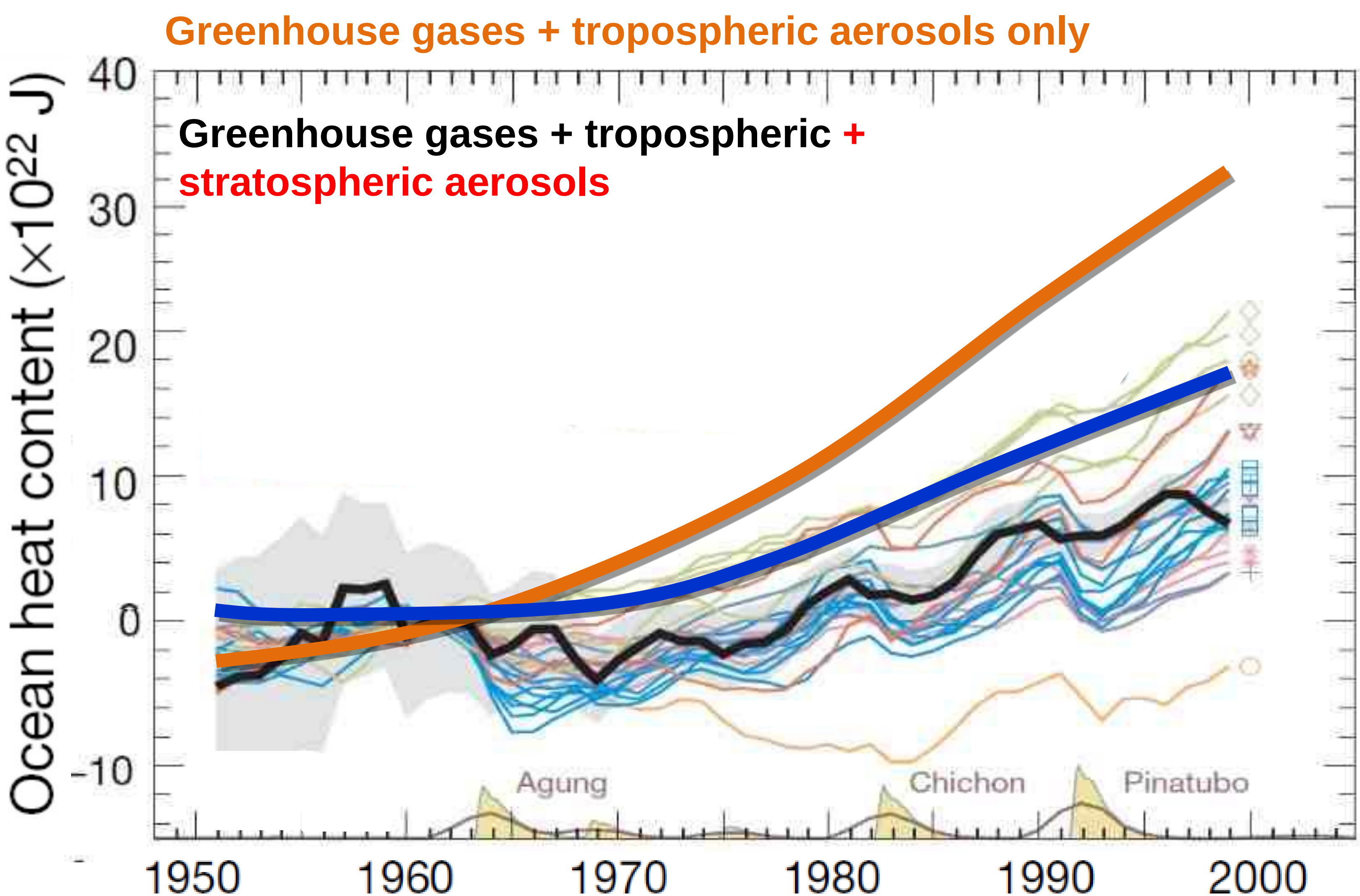
http://data.giss.nasa.gov/gistemp/maps/

Changes in ocean heat content



Data from https://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/

Attribution of warming trends in the upper ocean



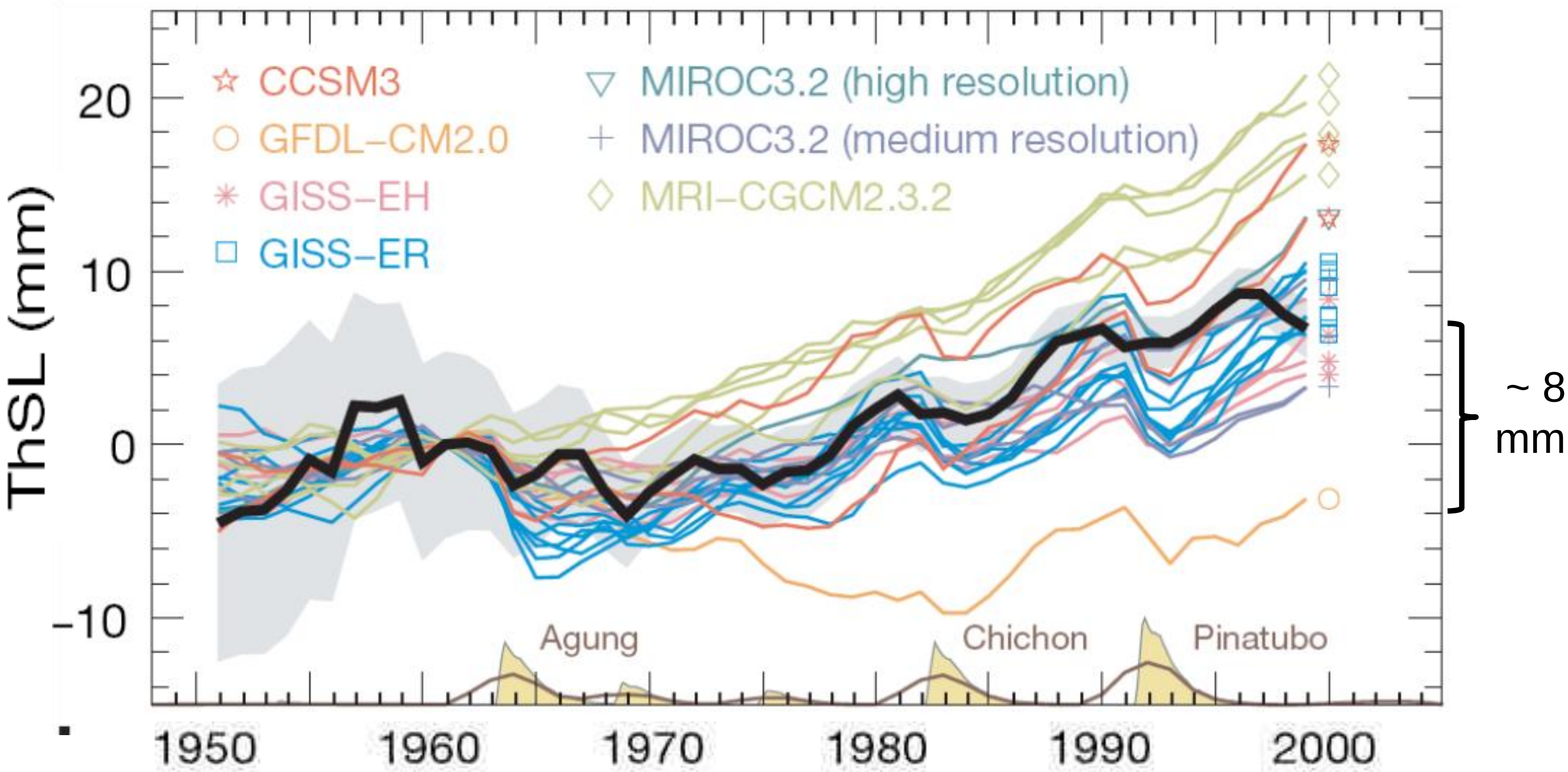
Comparison of observed and simulated ocean heat content

Adapted from Domingues et al., *Nature*. 2008

Recall thermal expansion $\alpha \Delta T = \Delta V/V$

warmer ocean $\Rightarrow$ larger volume

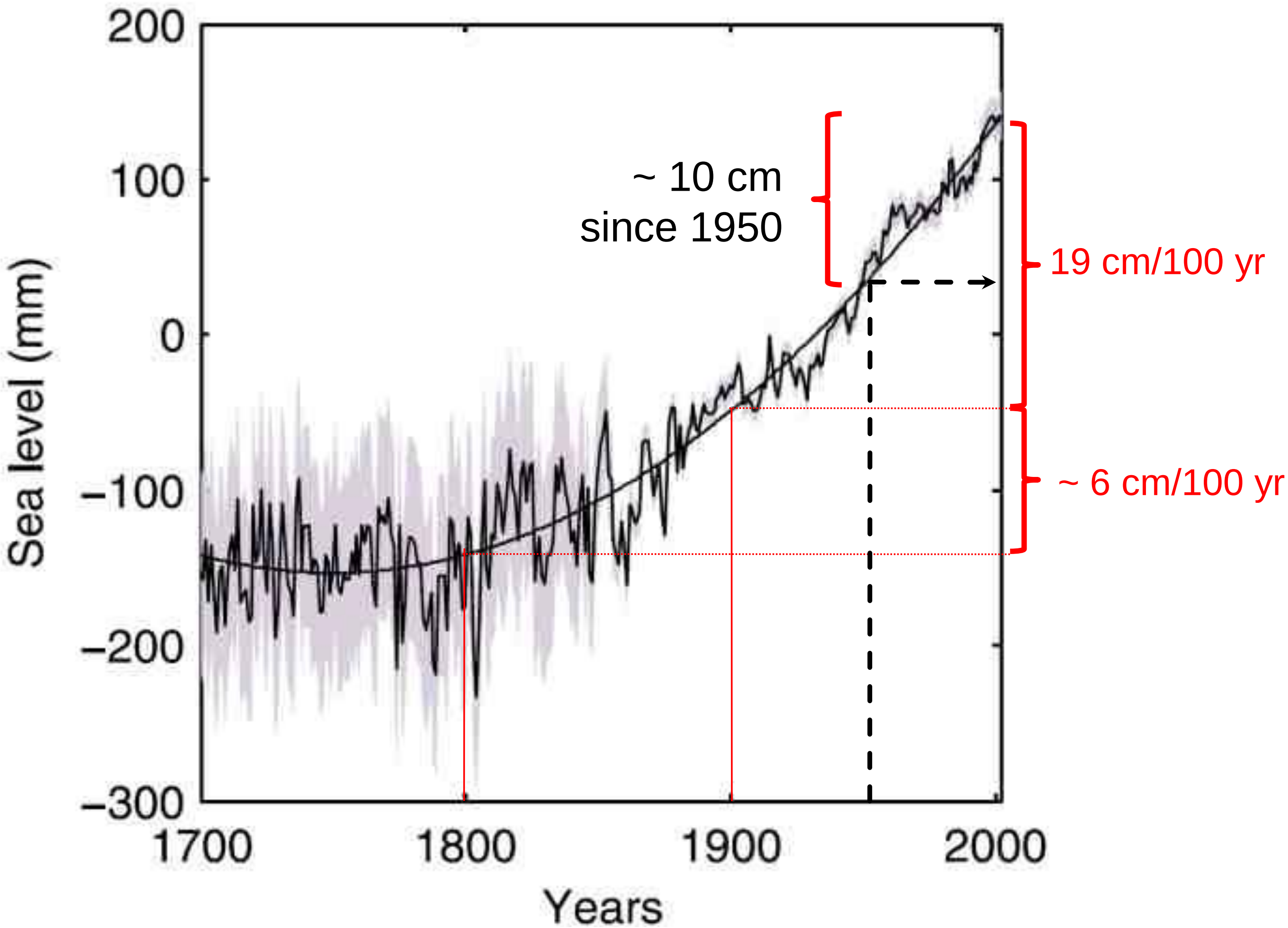
Greenhouse gases + tropospheric and stratospheric aerosols



~ 1.6 ± 0.2 mm/yr

Adapted from Domingues et al., *Nature*. 2008

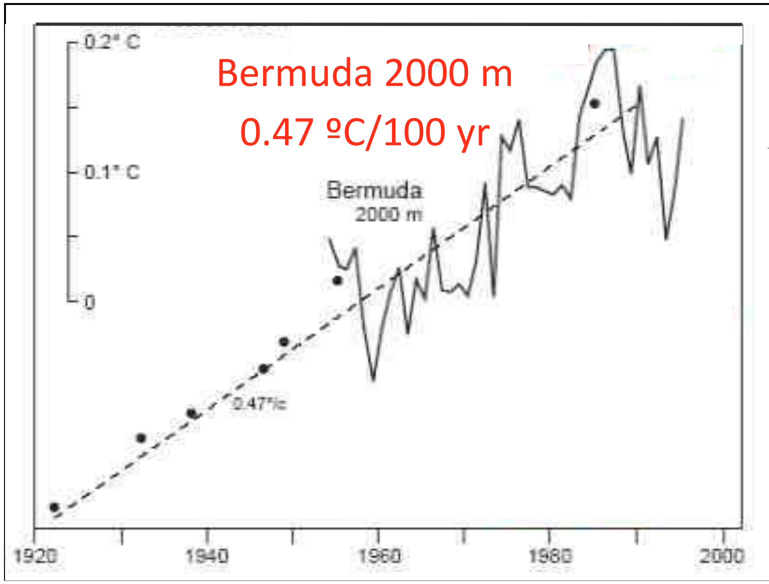
Sea level rise - II

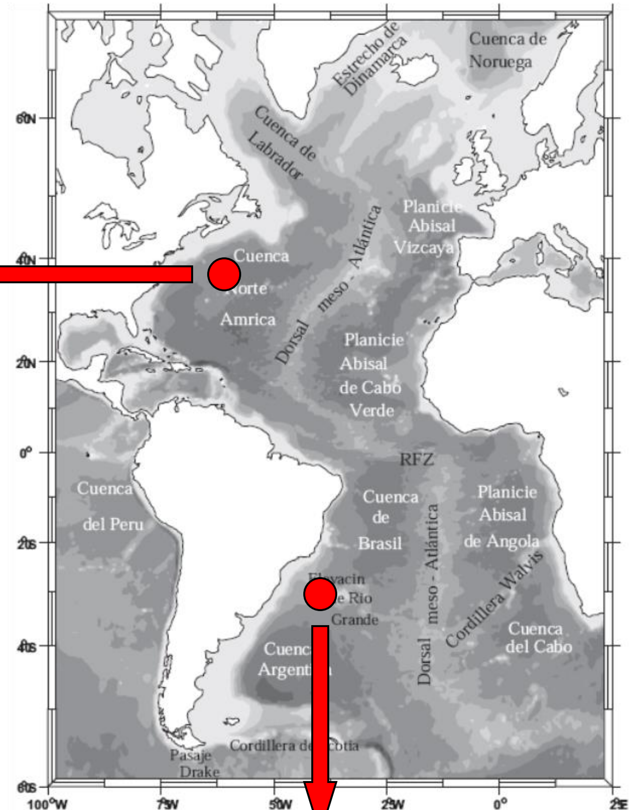


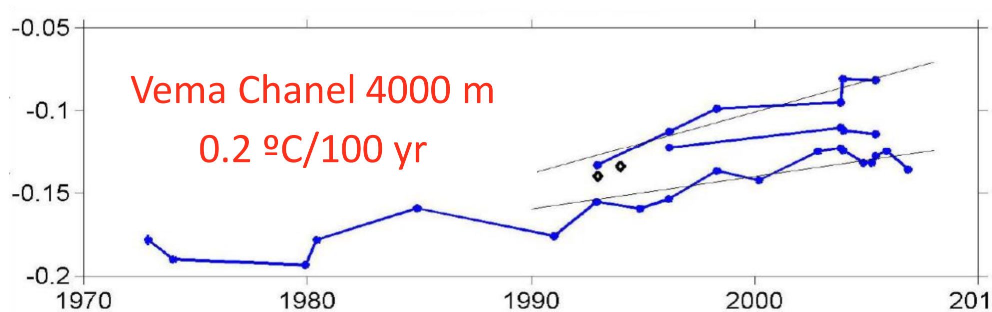
Recent rise started in late 19th century. Trend is non linear (~0.01 mm/yr^2)

Jevrejeva et al., *GRL*, 2006

Temperature trends in the deep ocean

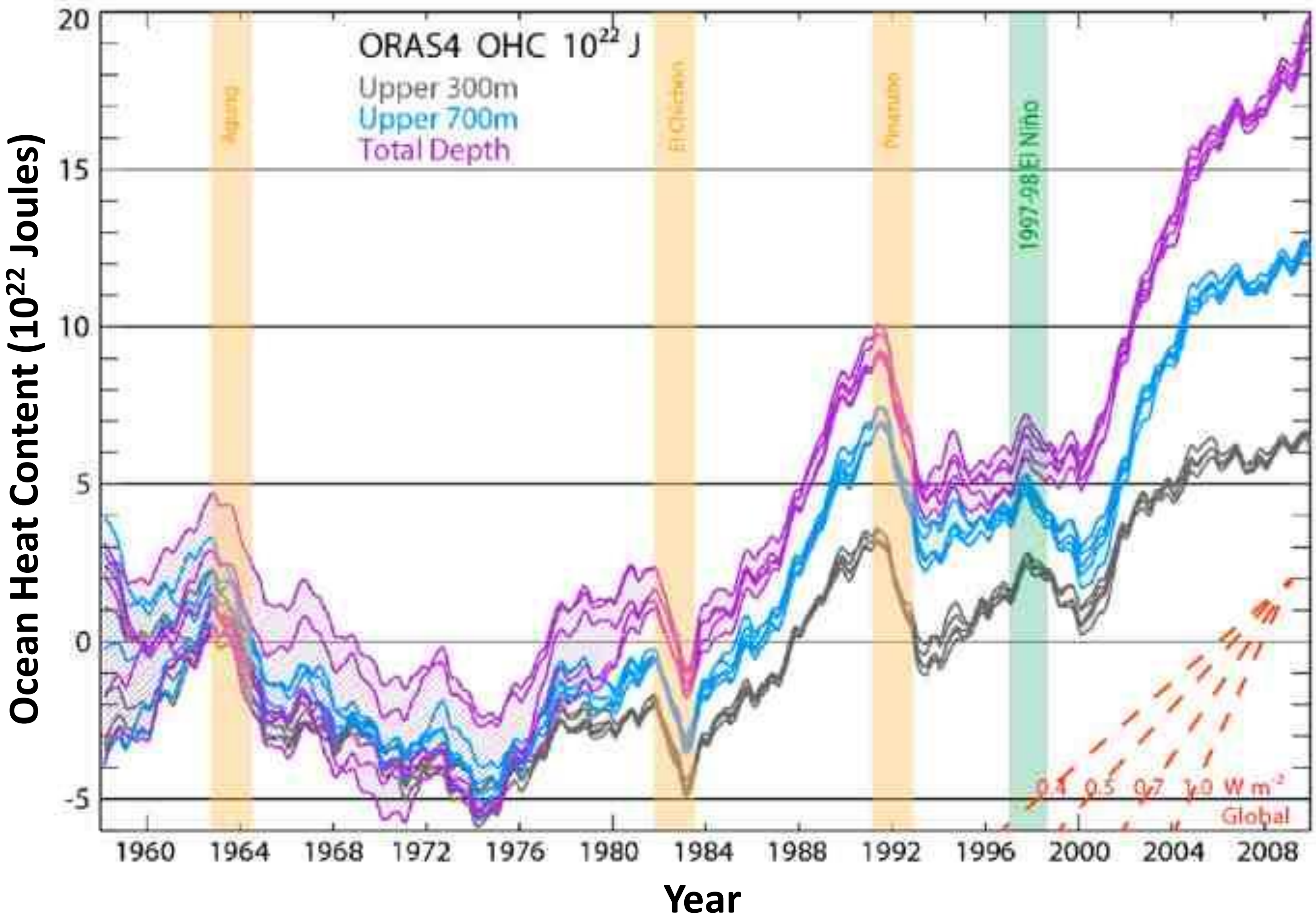






Zenk & Morozov, *GRL*, 2007

Recent changes in upper ocean heat content



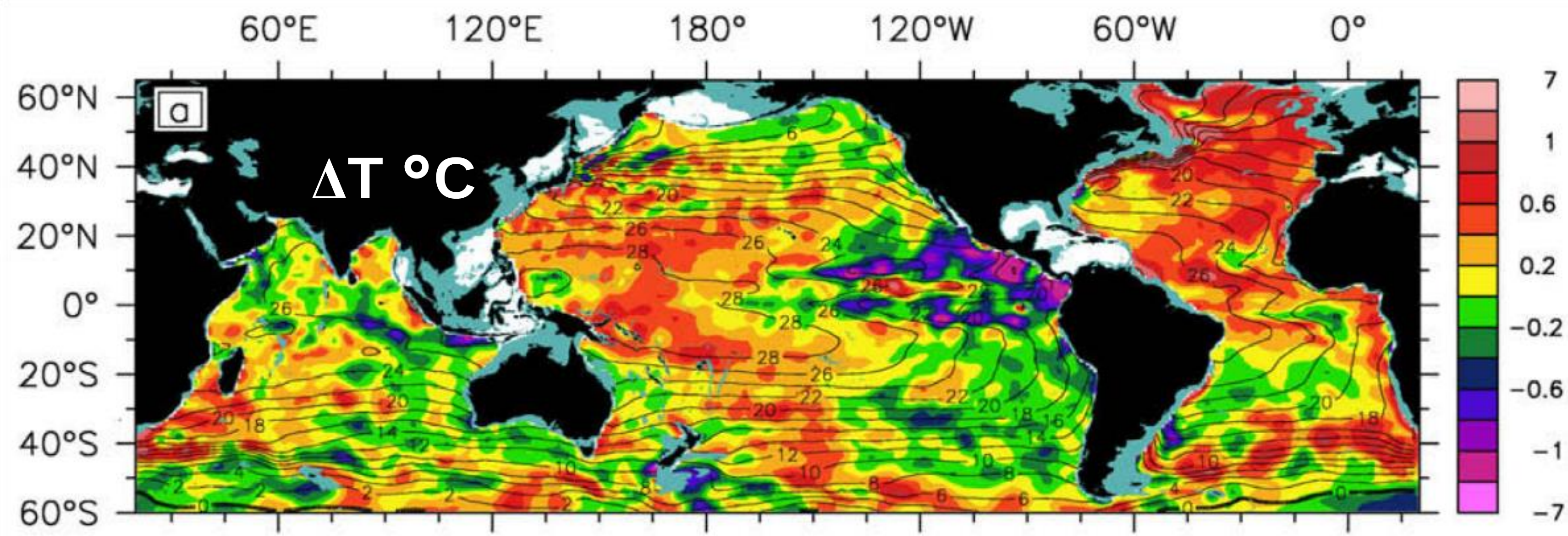
Heat content from an ocean reanalysis based on forced ocean model and T and S observations from various sources. 5 ensembles are shown for each layer.

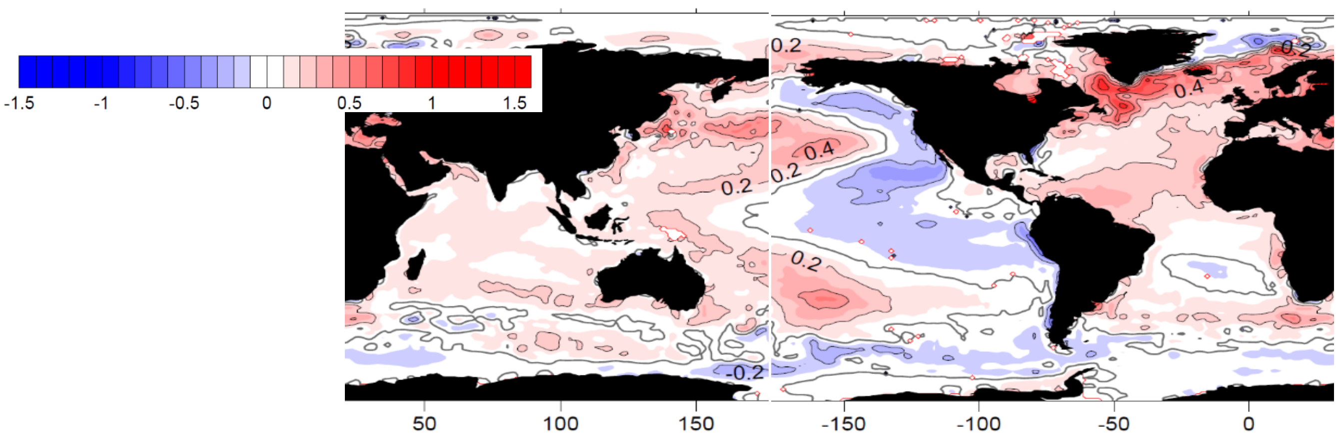
Balmaseda et al., *GRL*, 2013

Global temperature changes - I

Argo 5yr (2004-2008) mean- WOA01
0-100 dbar

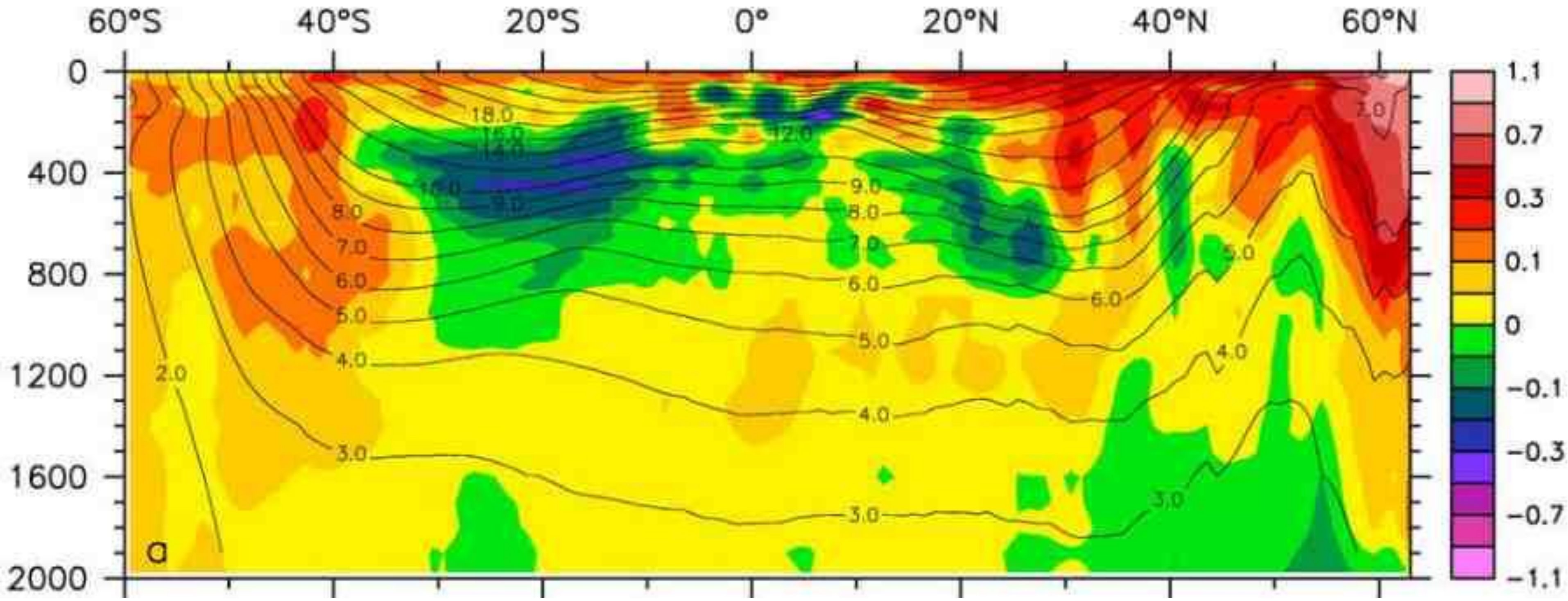
Roemmich & Gilson, *Progr. Oceanogr.*, 2009





Reynolds SST trend °C/decade (1981-2012)

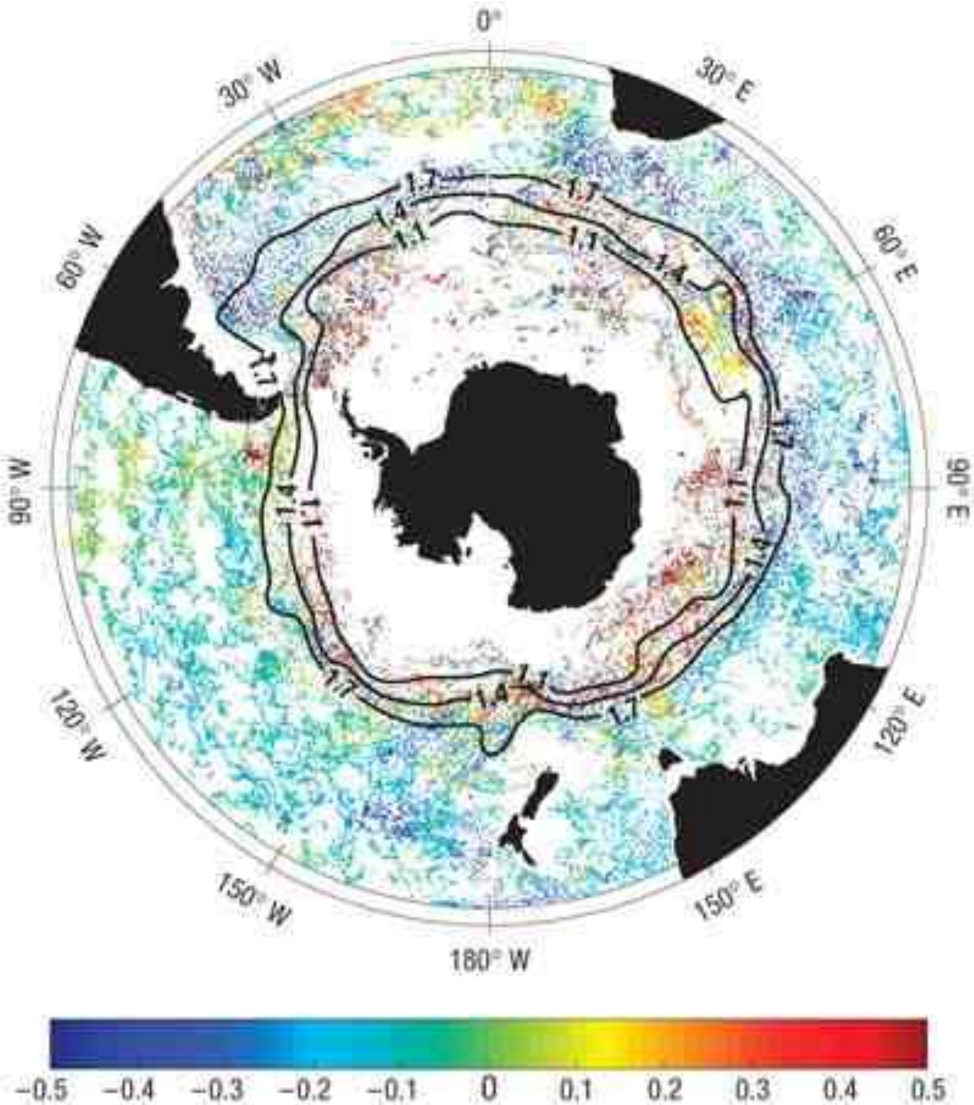
Global temperature changes - II



Zonally averaged temperature versus pressure for the Argo 5-year mean (contours) and Argo-minus-WOA01 difference (color shading).

Roemmich & Gilson, *Progr. Oceanogr.*, 2009

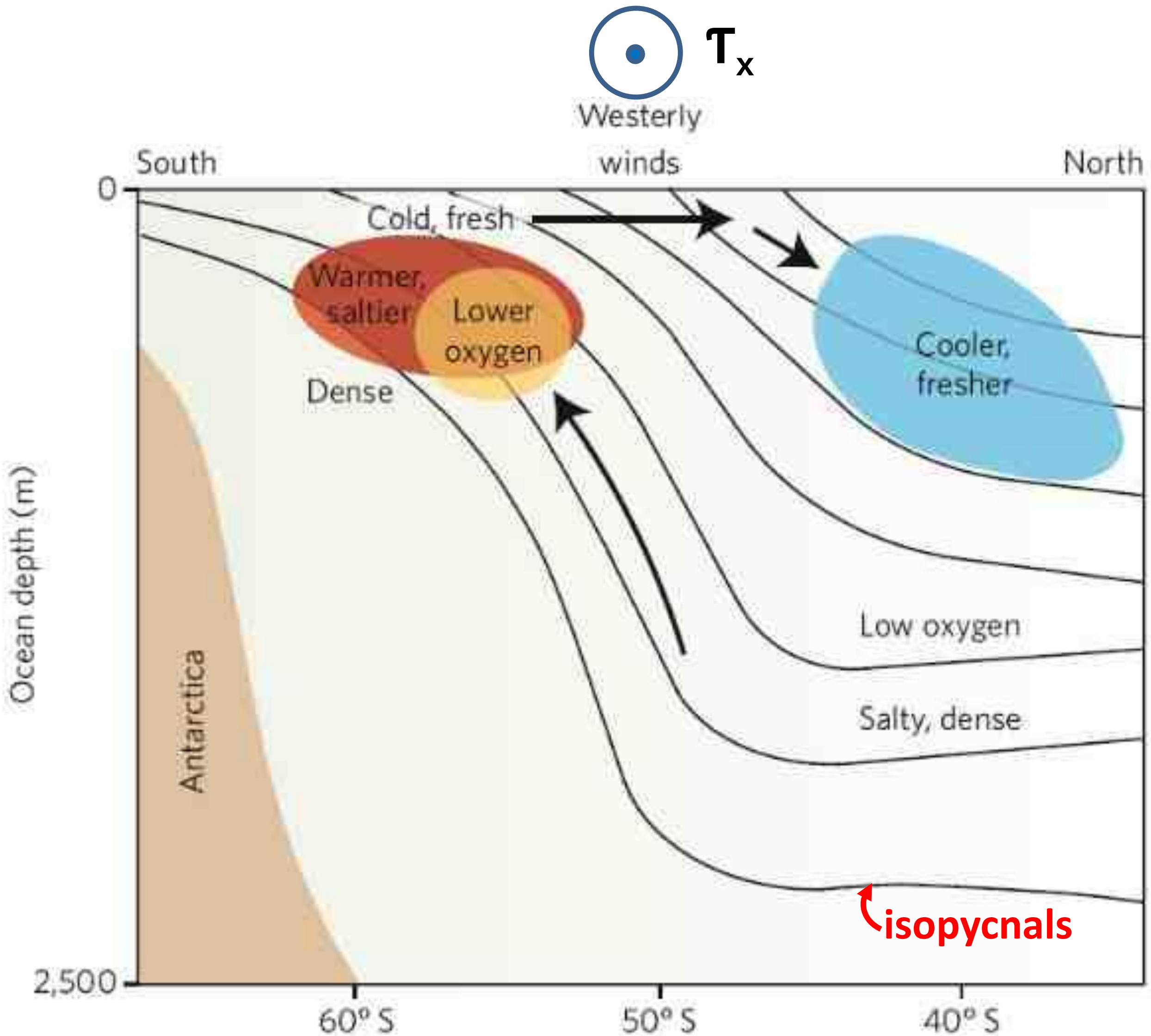
Temperature changes Southern Hemisphere



Recent temperature changes in the 26.9-27.7 kg/m^3 neutral density range from a comparison of 52400 Argo profiles and climatology. Lines represent geostrophic streamlines of the Antarctic Circumpolar Current approximately following the Subantarctic and Antarctic (Polar) front (1.7 y 1.4 dyn meters, respectively).

Boning et al., *Nature Geosc*., 2008

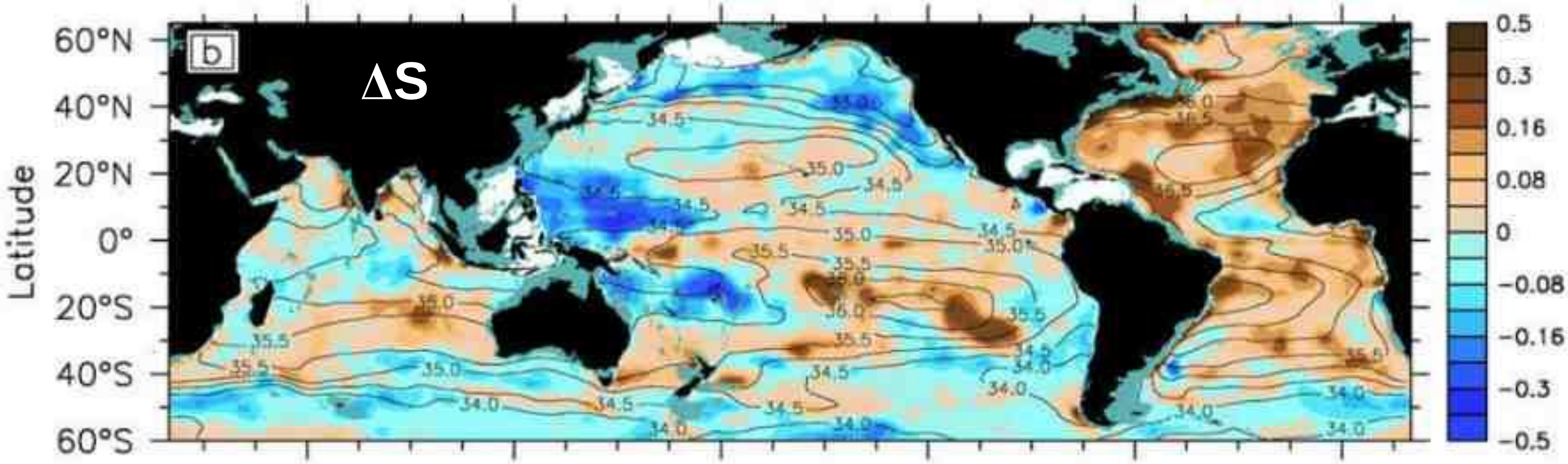
Increased SH westerlies and expected variability



Schematic density section across the ACC and the expected temperatura, salinity and disolved oxygen changes due to an increase in SH westerlies. (Aoki et al., *GRL*, 2005; Togwiller et al., *Nature*, 2009).

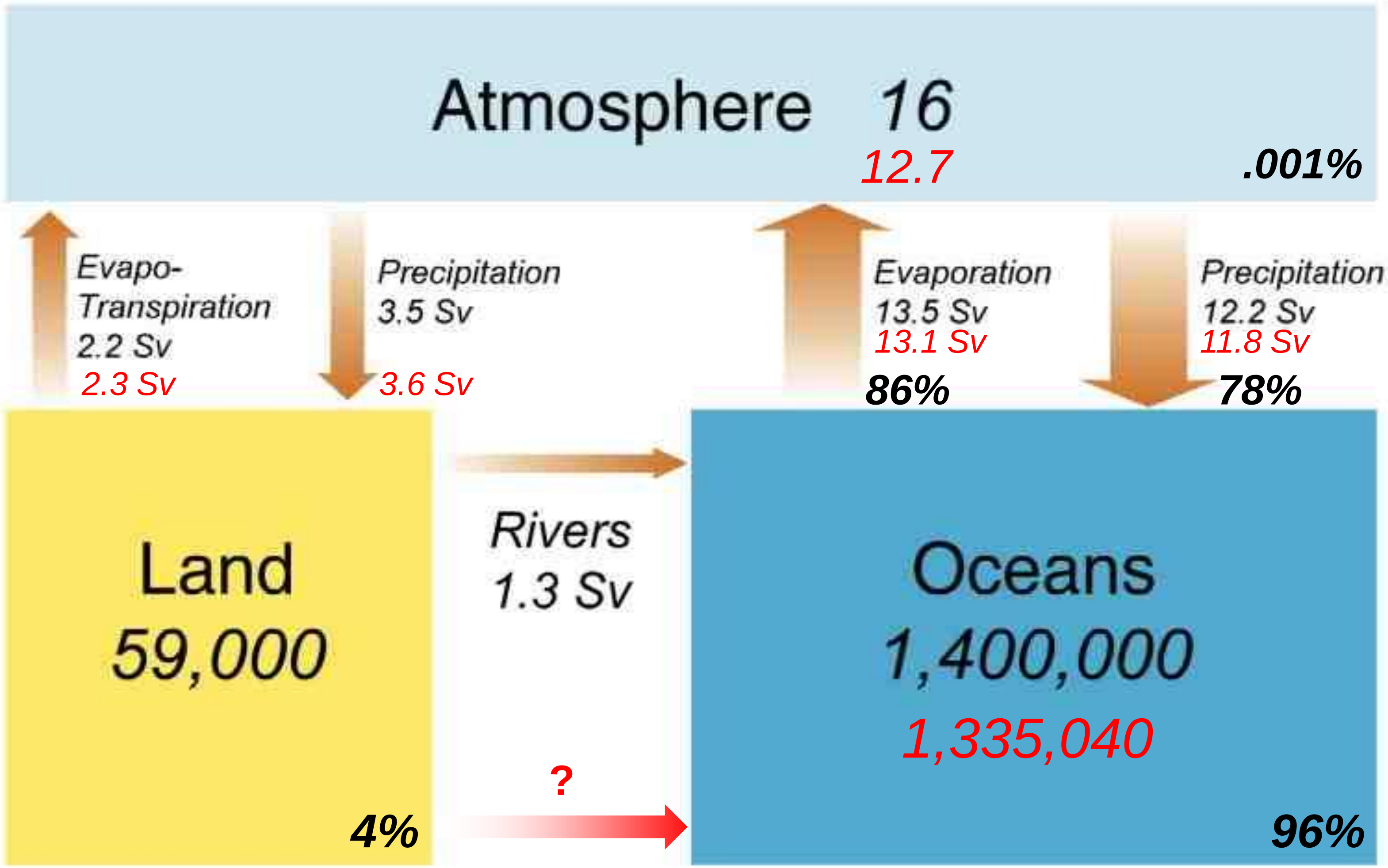
Argo 5yr (2004-2008) mean- WOA01

0-100 dbar



Map of 0–100 dbar vertically averaged salinity from the Argo 5-year mean (contours) and Argo-minus-WOA01 difference (color shading)

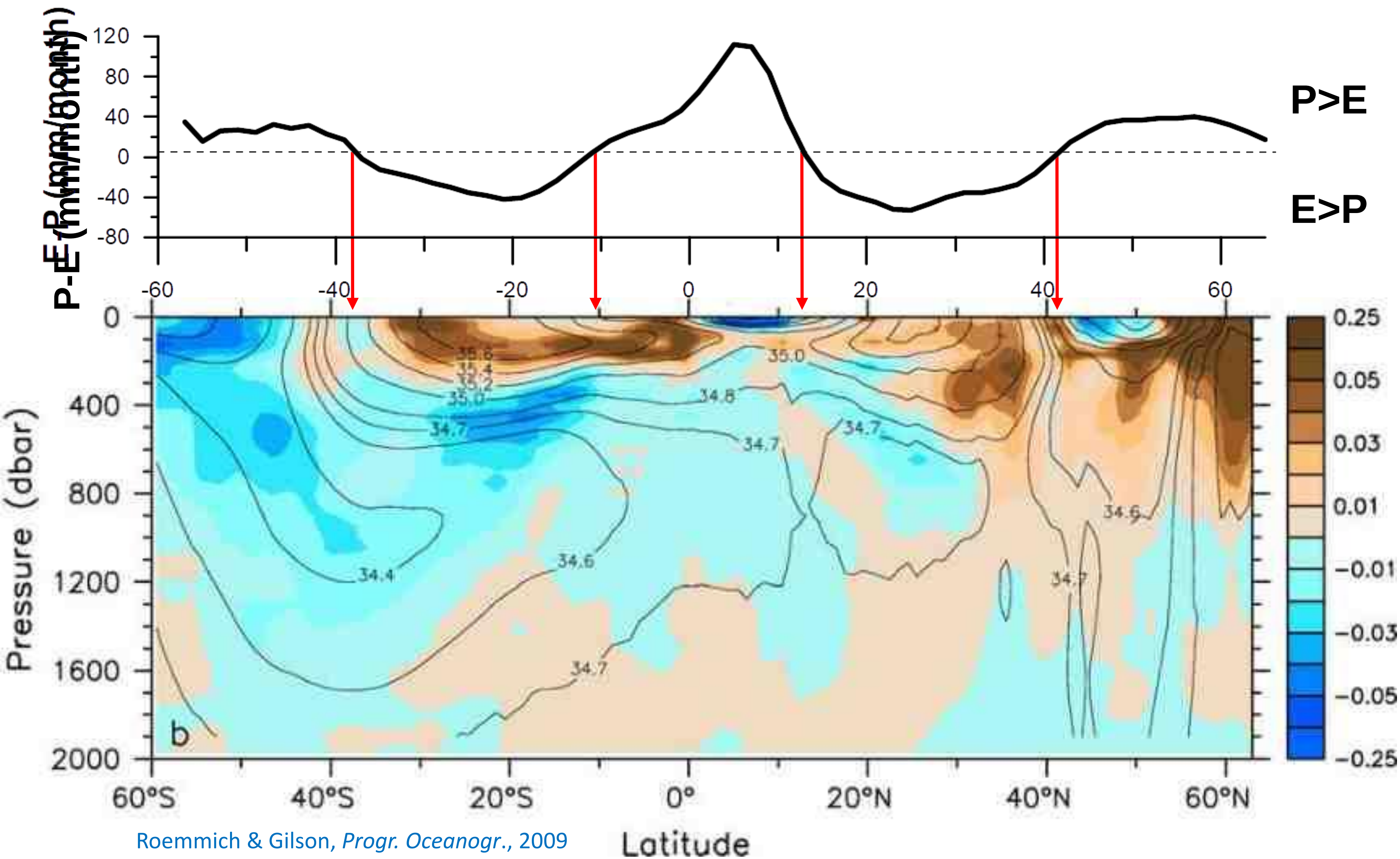
Roemmich & Gilson, *Progr. Oceanogr.*, 2009



Reservoirs in 10^3 km^3, Fluxes in 10^6 m^3/s (= Sv)

Courtesy Ray Schmitt, WHOI, http://www.whoi.edu/sbl/liteSite.do?litesiteid=18912&articleId=28406
In red: updated from Trenberth et al., *J. Hydromet*., 6, 758-769, 2007

Global salinity changes - II

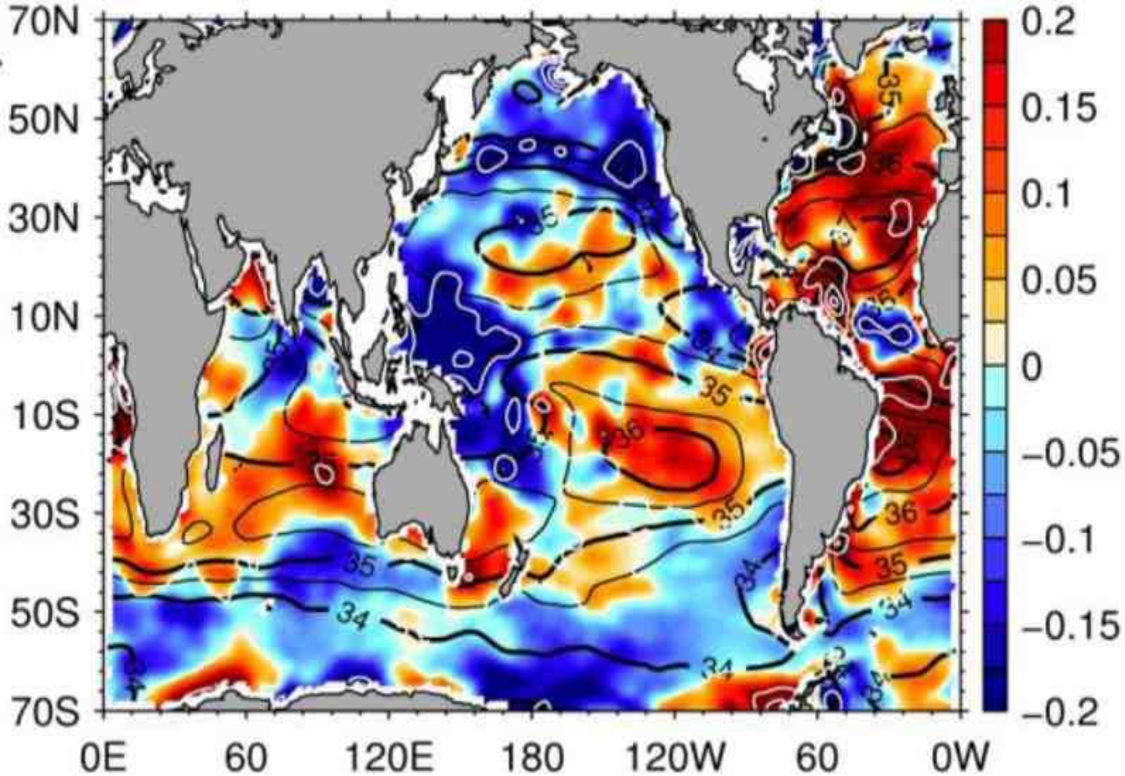


Roemmich & Gilson, *Progr. Oceanogr.*, 2009

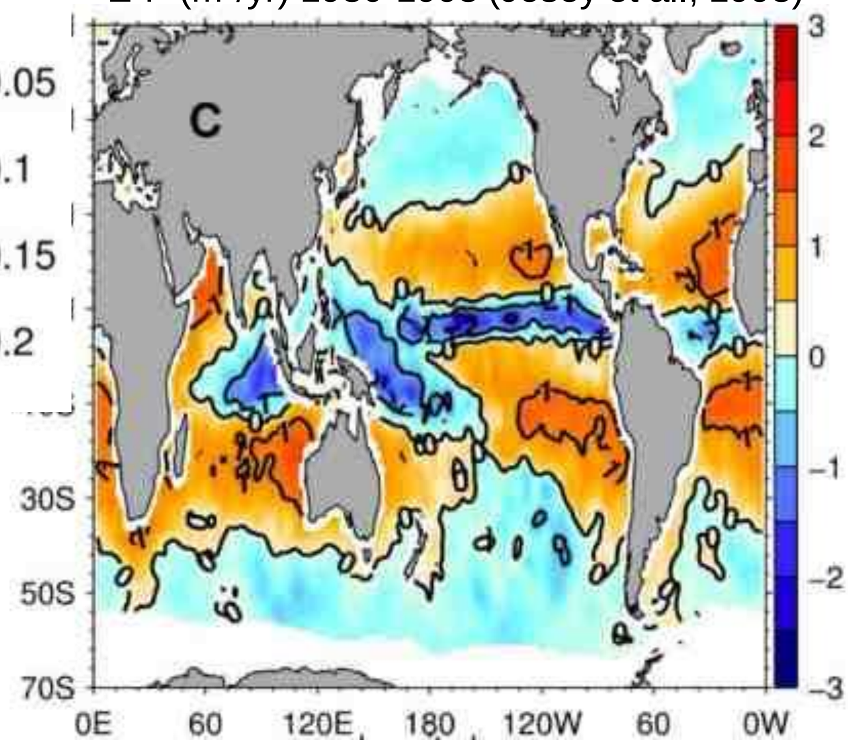
Zonally averaged salinity versus pressure for the Argo 5-year mean (contours) and Argo-minus-WOA01 difference (color shading).

Global salinity changes - III

50-year (1950-2000) linear surface salinity trend (pss/50 yr)



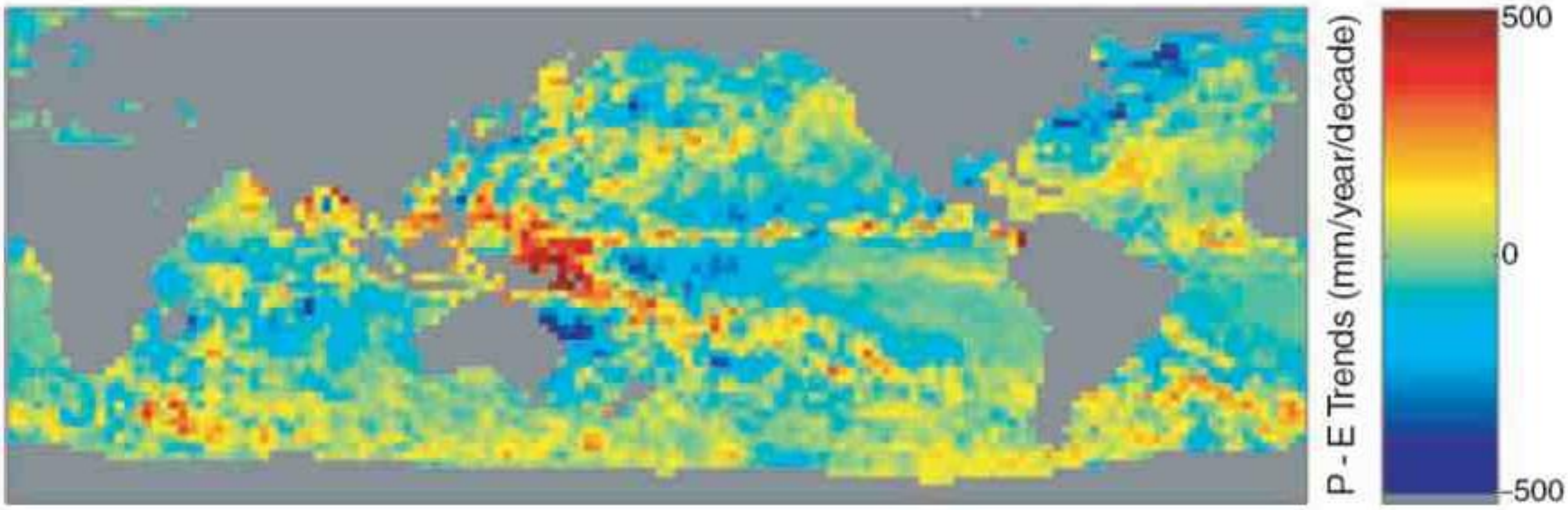
E-P (m³/yr) 1980-1993 (Josey et al., 1998)



Courtesy Durack and Wijffels, *J. Clim*., 2010

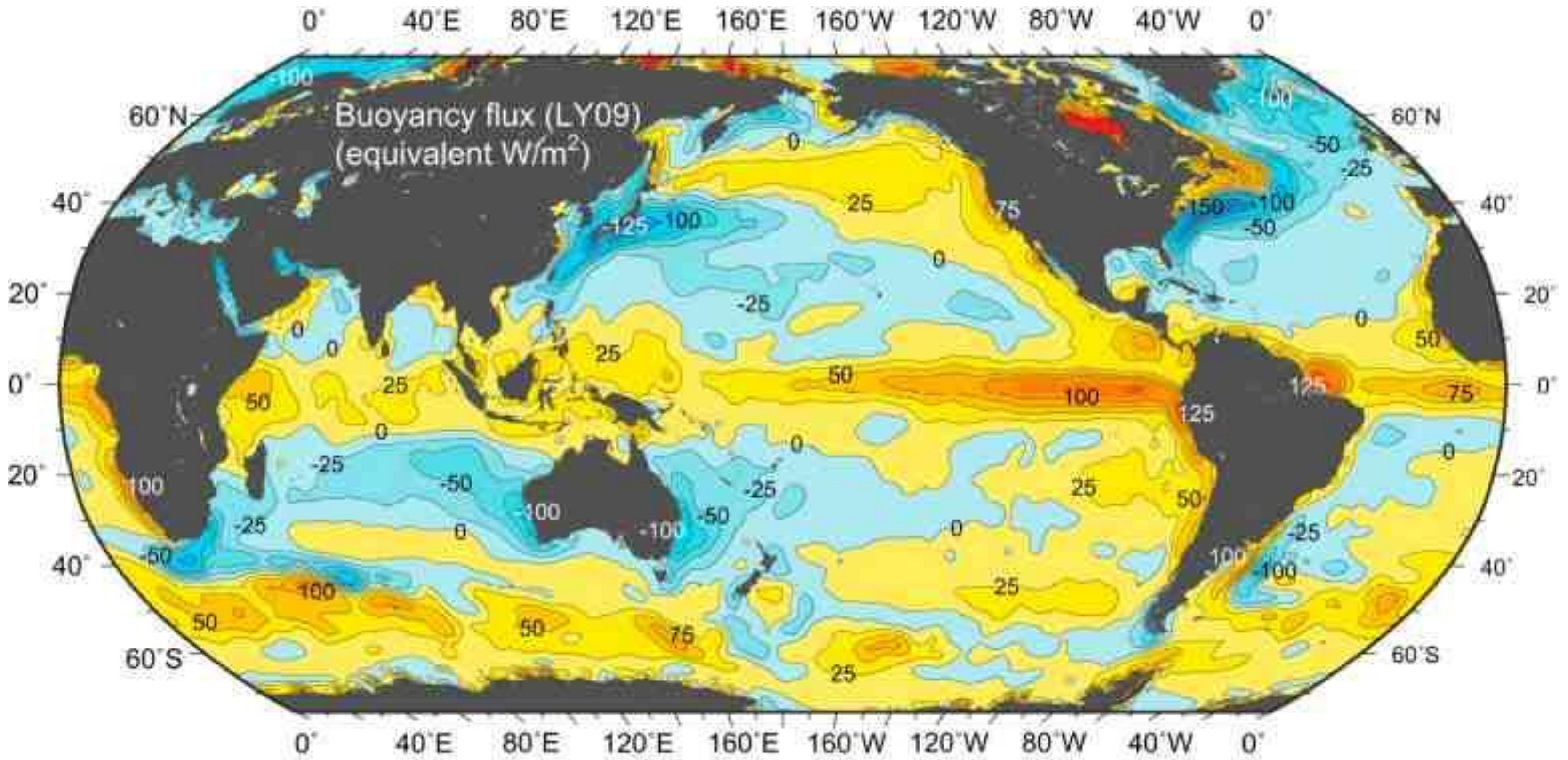
Trends in satellite-derived P – E

July 1987 - August 2006



Wentz et al., *Science* 2007

Surface Buoyancy Flux

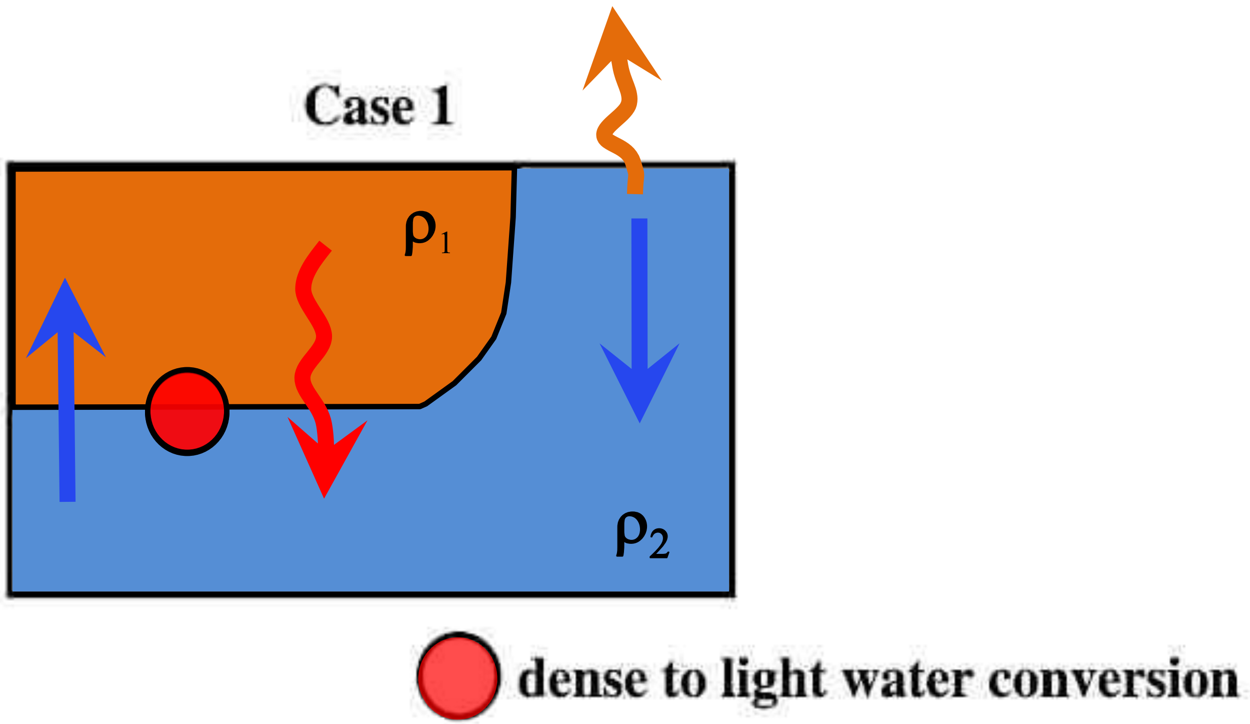


Annual mean air–sea buoyancy flux converted to equivalent heat fluxes (W/m^2), based on Large and Yeager (2009) air–sea fluxes. **Positive values indicate that the ocean becomes less dense.** Contour interval is 25 W/m^2.

Large and Yeager, *Clim. Dynamics*, 2009
Adapted from Talley et al., 2011, Descriptive Physical Oceanography, 6th Edition, Academic Press / Elsevier

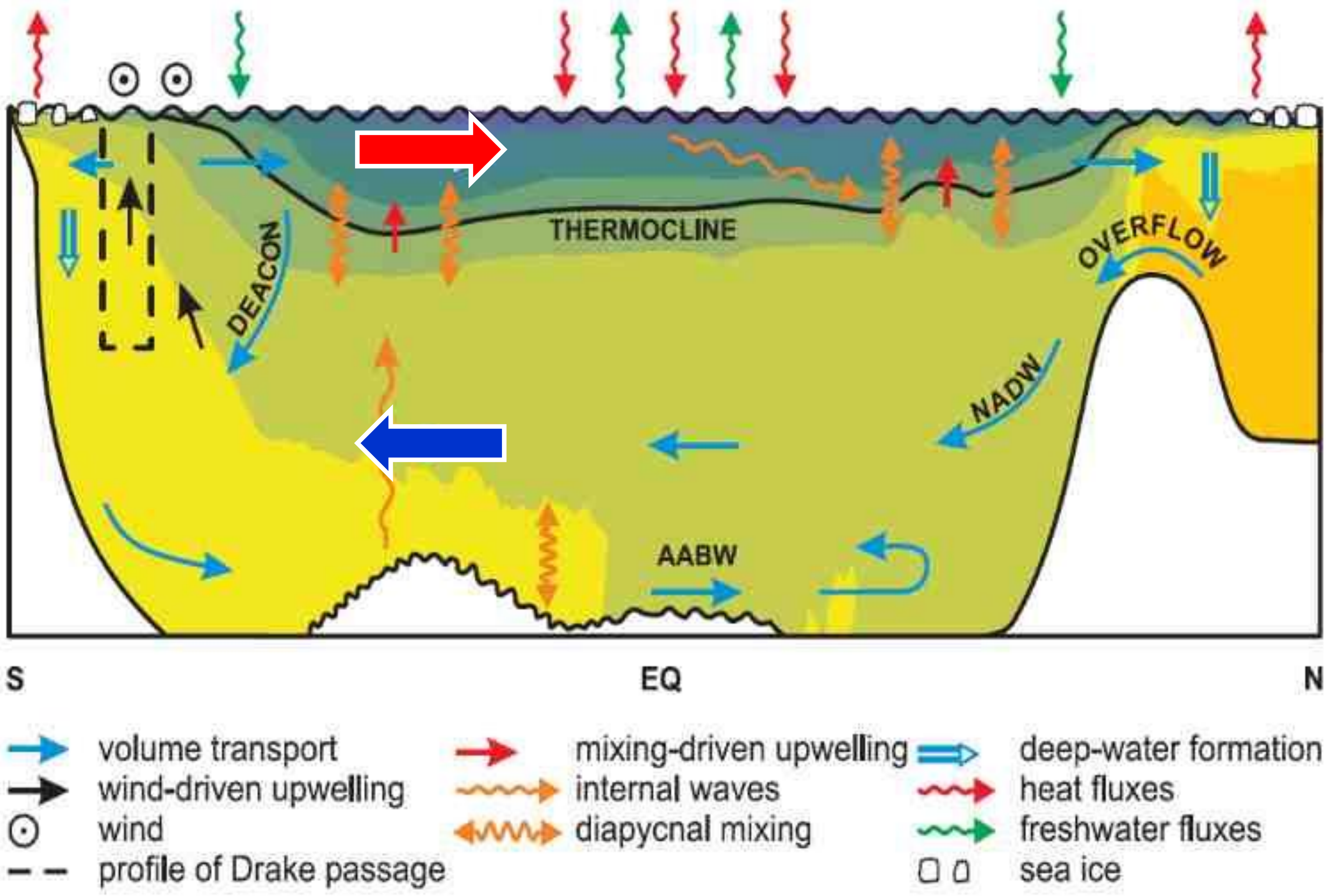
Extreme cases

$$w\, \partial T / \partial z = \kappa\, \partial^2 T / \partial z^2$$

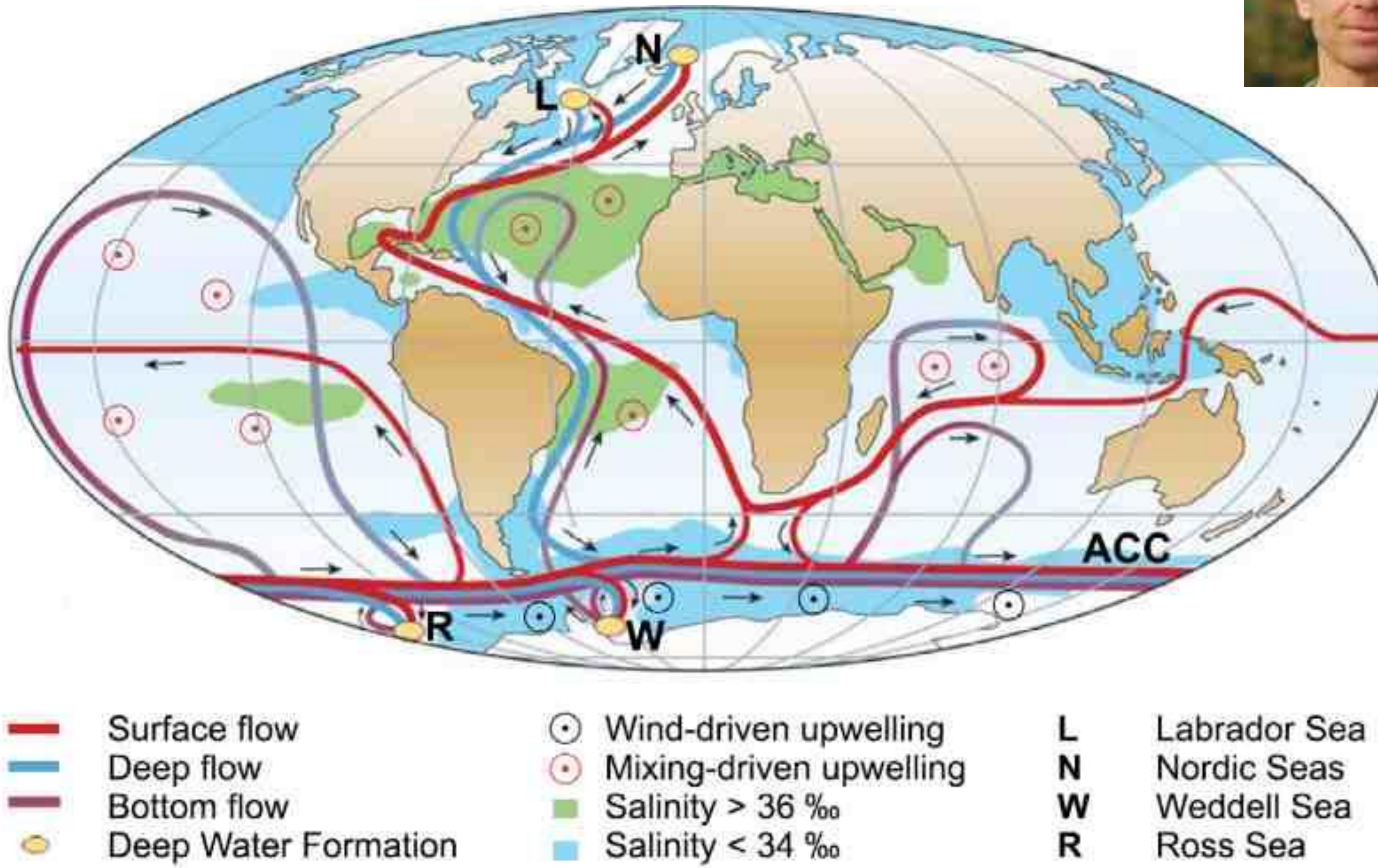


Adapted from Kuhlbrodt et al., *Rev. Geophys*, 45, 1-32, 2007.

Overturning, more realistic (?)

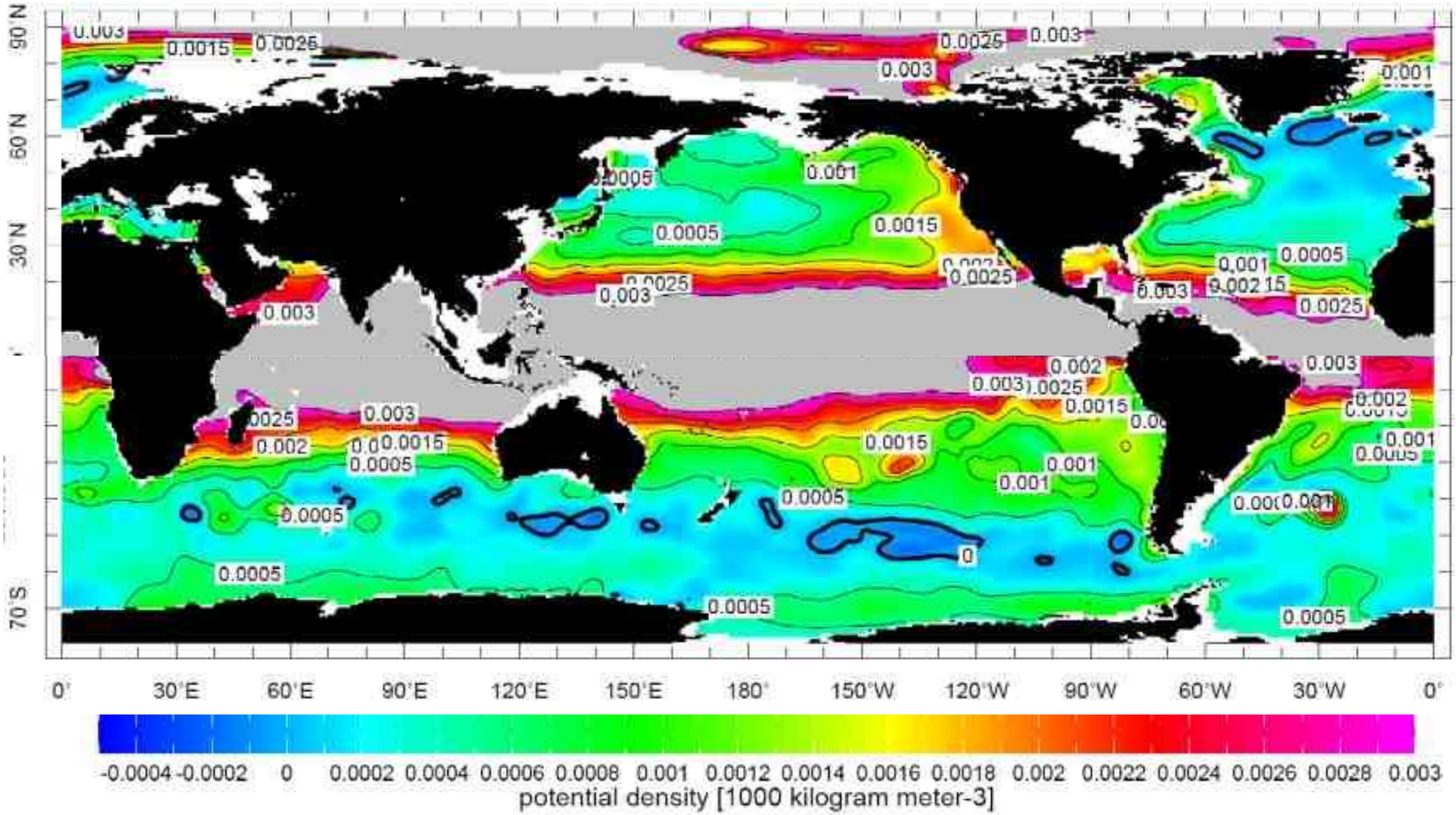


Kuhlbrodt, et al., *Rev. Geophys*, 2007



From Kuhlbrodt et al., *Rev. Geophys*, 45, 1-32, 2007.

$\Delta\sigma_\theta$ (kg/m³) 0-300 m winter (**Feb-NH** / **Aug-SH**)

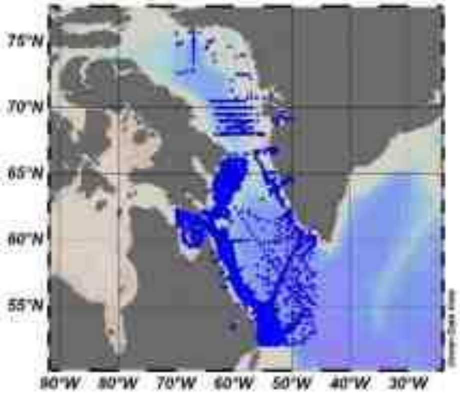


Weakly stratified Strongly stratified

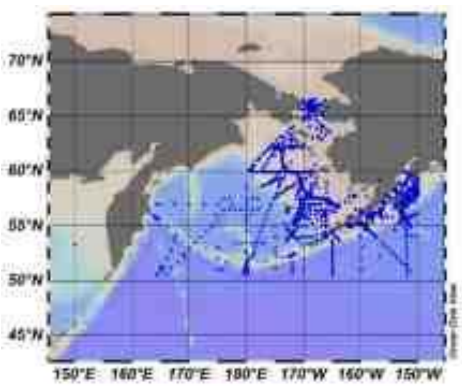
Vertical stratification – observations

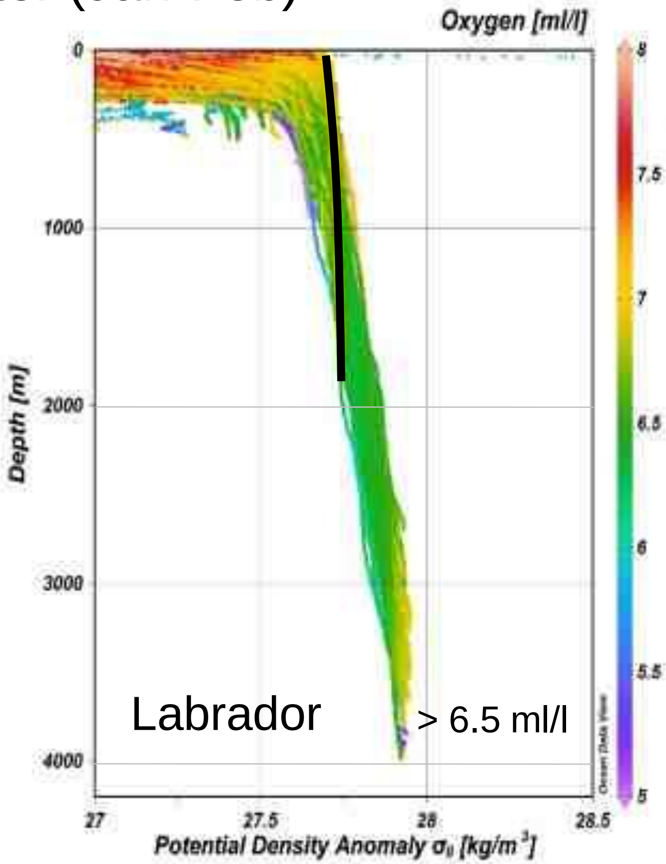
σ_θ (kg/m^3) winter (Jan-Feb) –

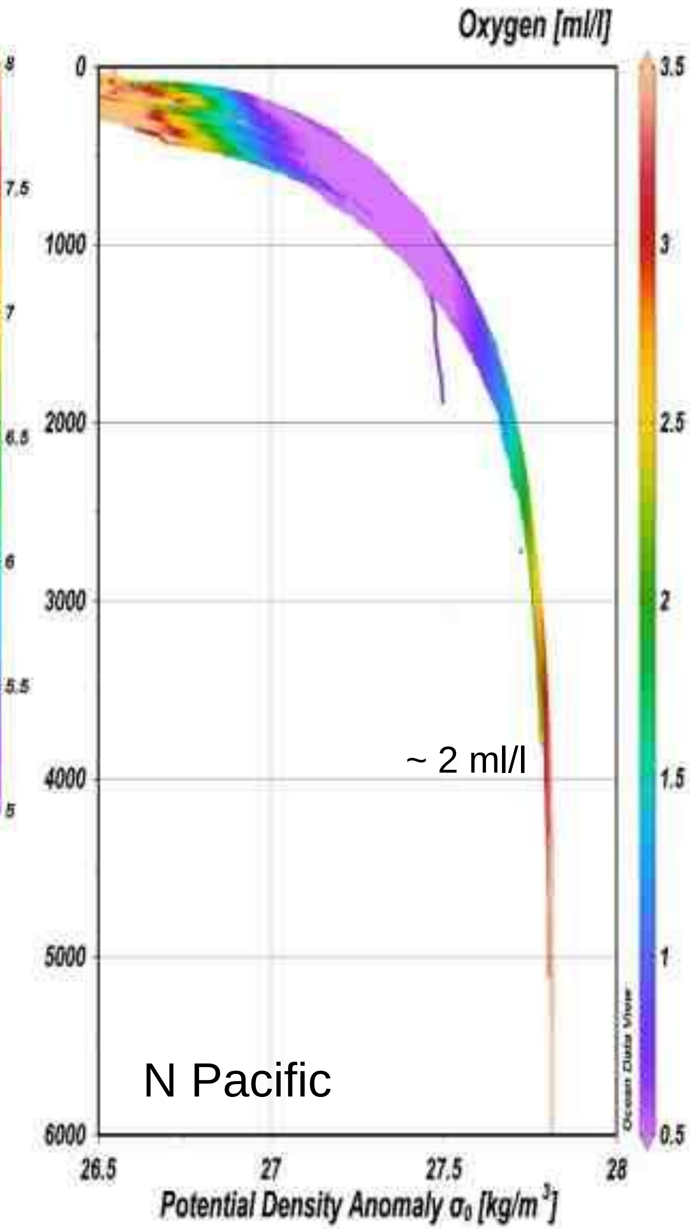
Labrador



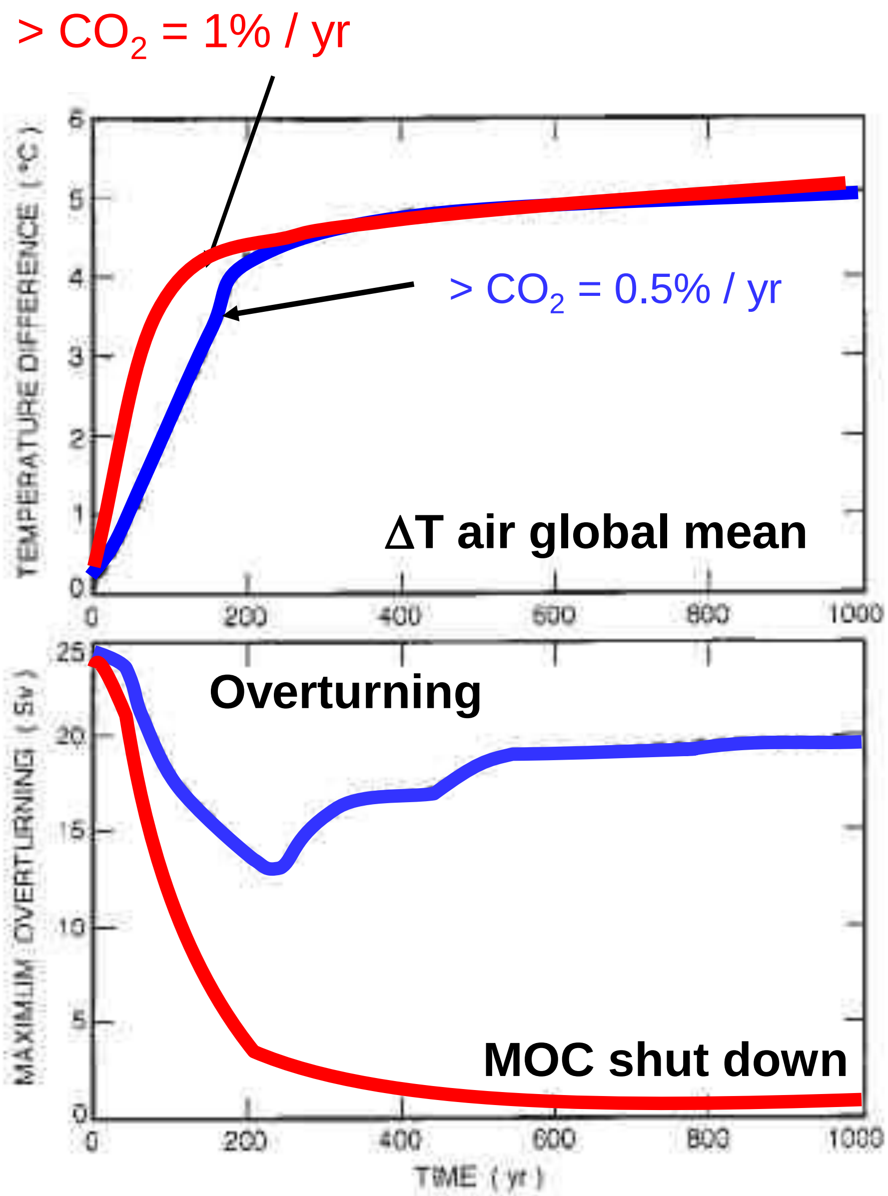
N Pacific





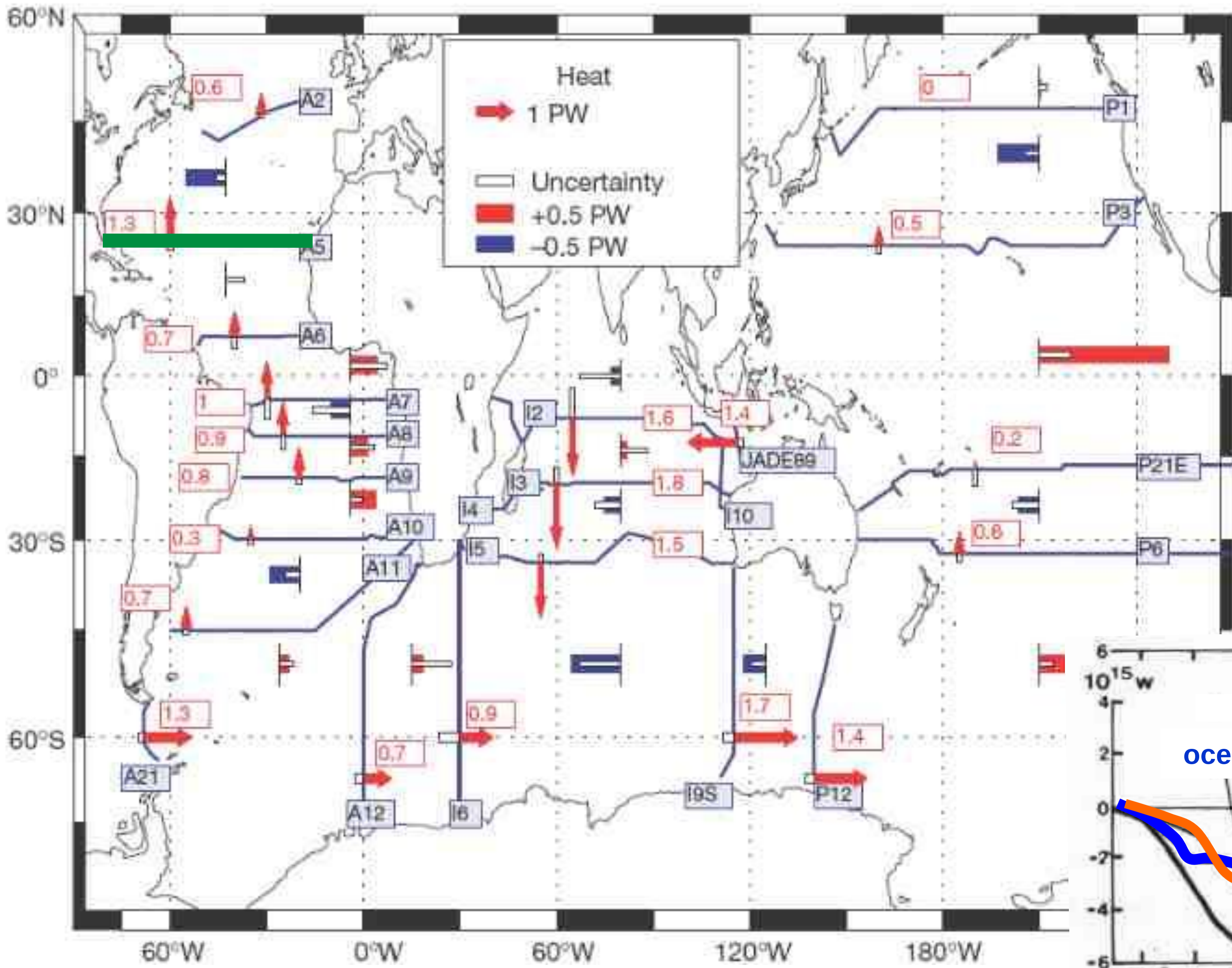


MOC sensitivity based on a simple 3 basin coupled model forced with different rates of CO_2 increase, both to 750ppm

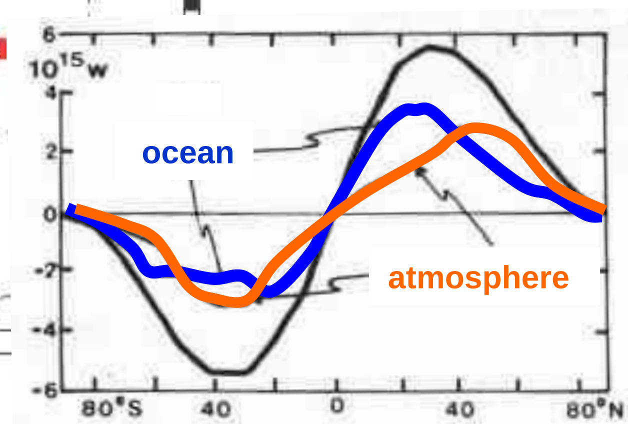


Schmittner & Stocker, *J. Climate*, 1999

Global ocean meridional heat flux

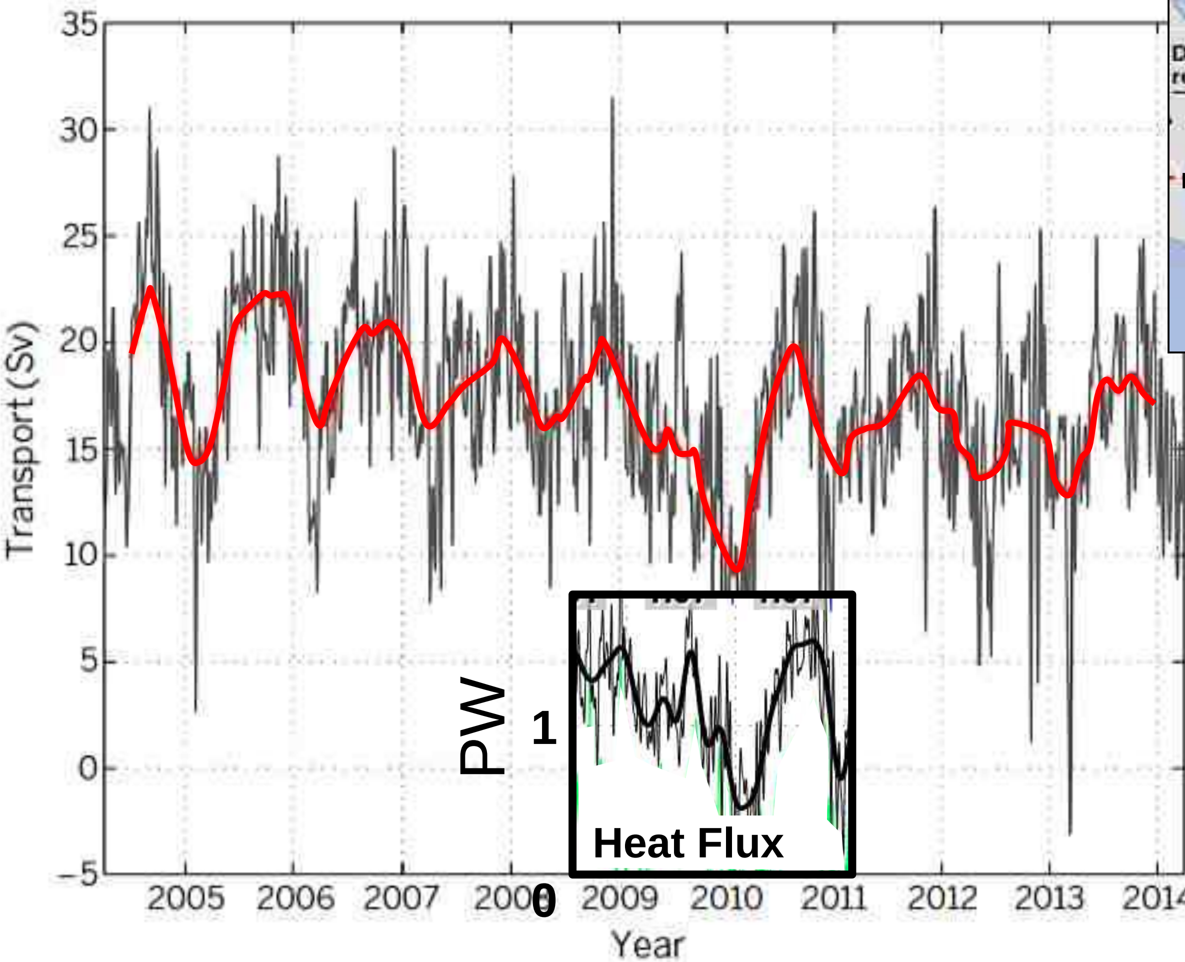


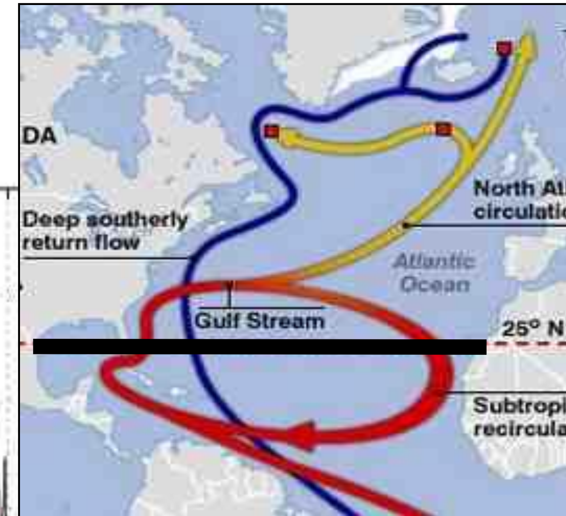

C. Wunsch



Ganachaud & Wunsch., *Nature*, 2000

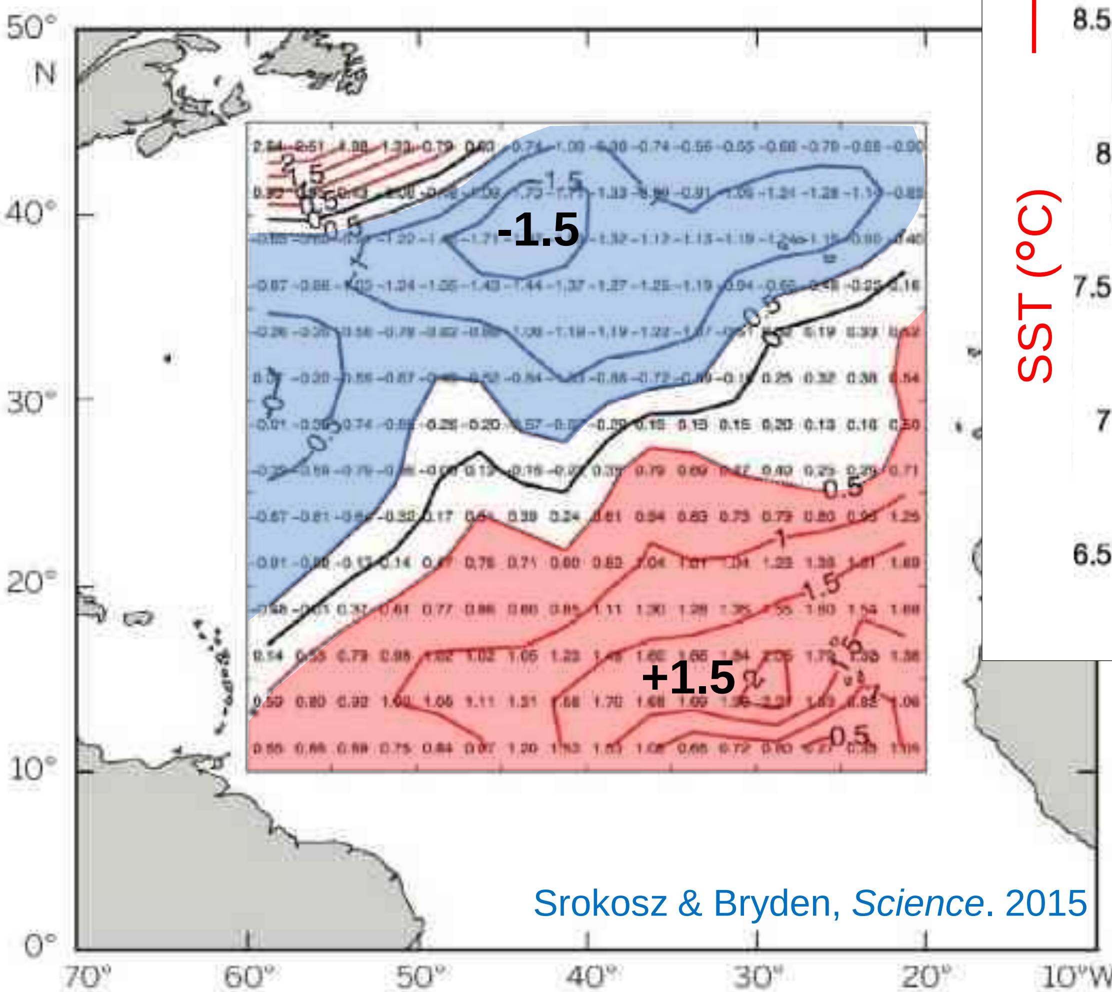
Atlantic meridional overturning at 26°N





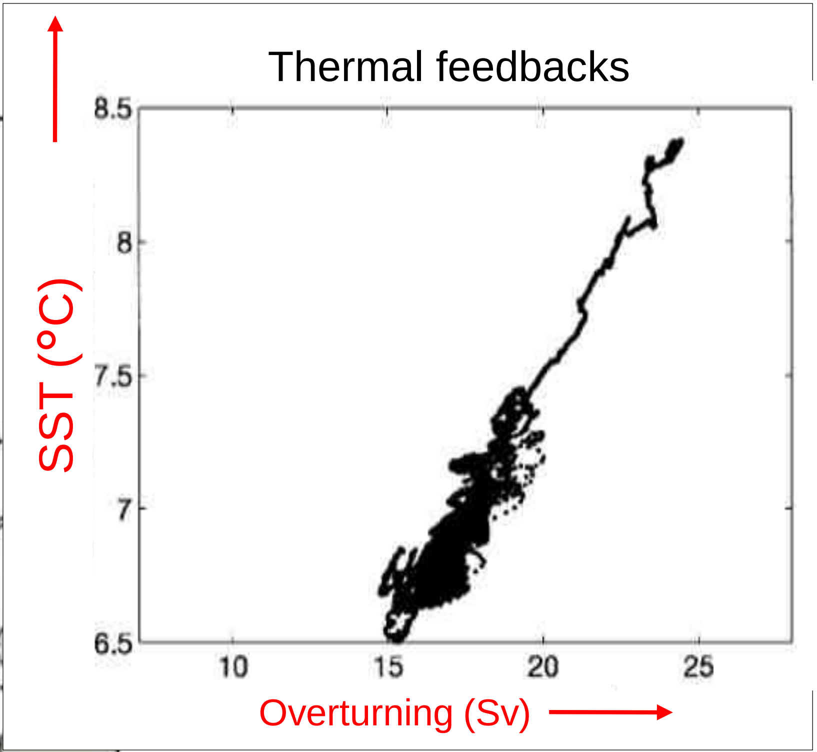
Srokosz & Bryden, *Science*. 2015

Impact of MOC drop in 2010



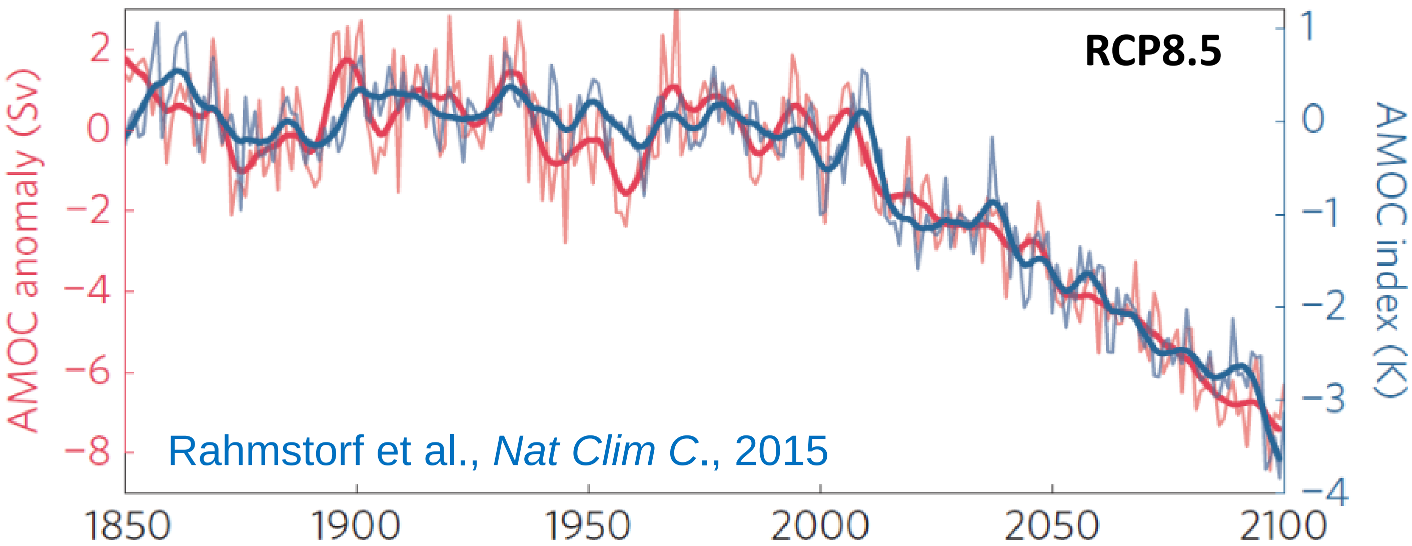
Srokosz & Bryden, *Science*. 2015

Temperature anomaly @ 50-m at the end of the 2009 - 2010 AMOC slowdown event

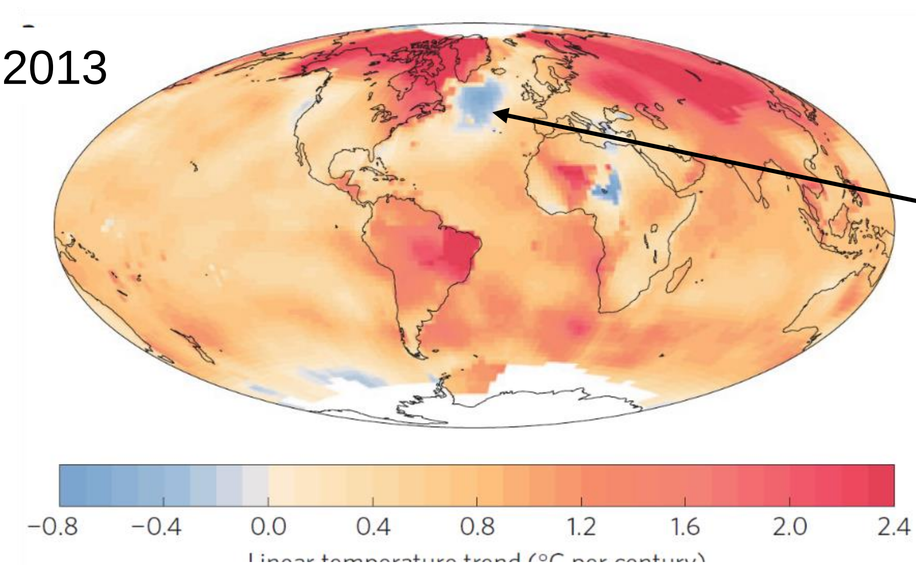


Rahmstorf & England, *JPO*. 1997

Subpolar surface temperature based AMOC *proxy*



1901-2013

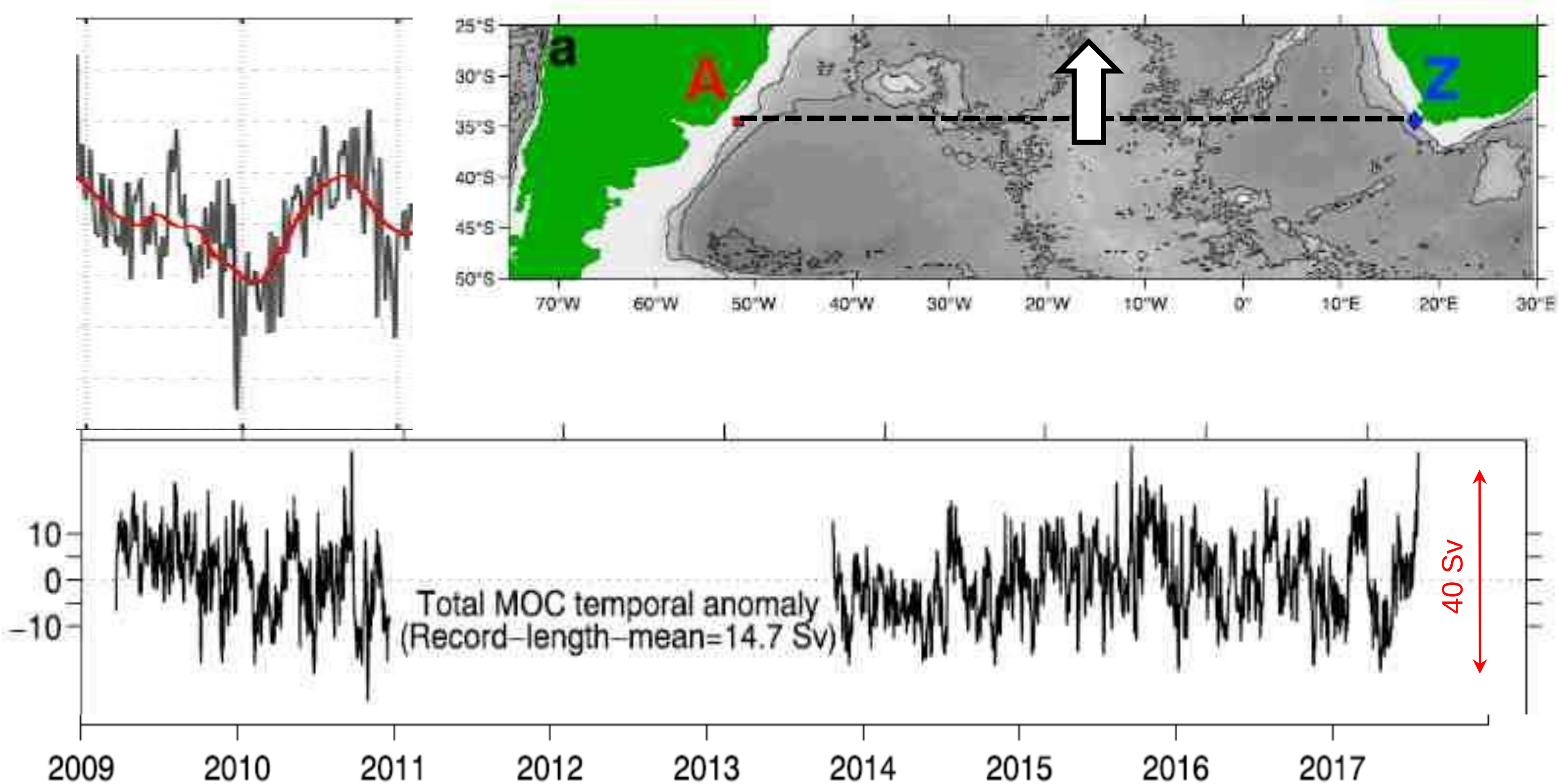


Cooling sub-polar N. Atlantic. Why isn't the AMOC recovering?

Observed SST trend (°C/century)

Observed Atlantic overturning – 34ºS

Total MOC variability at South Atlantic gateway



from Meinen et al., *GRL, 2018*

Summary

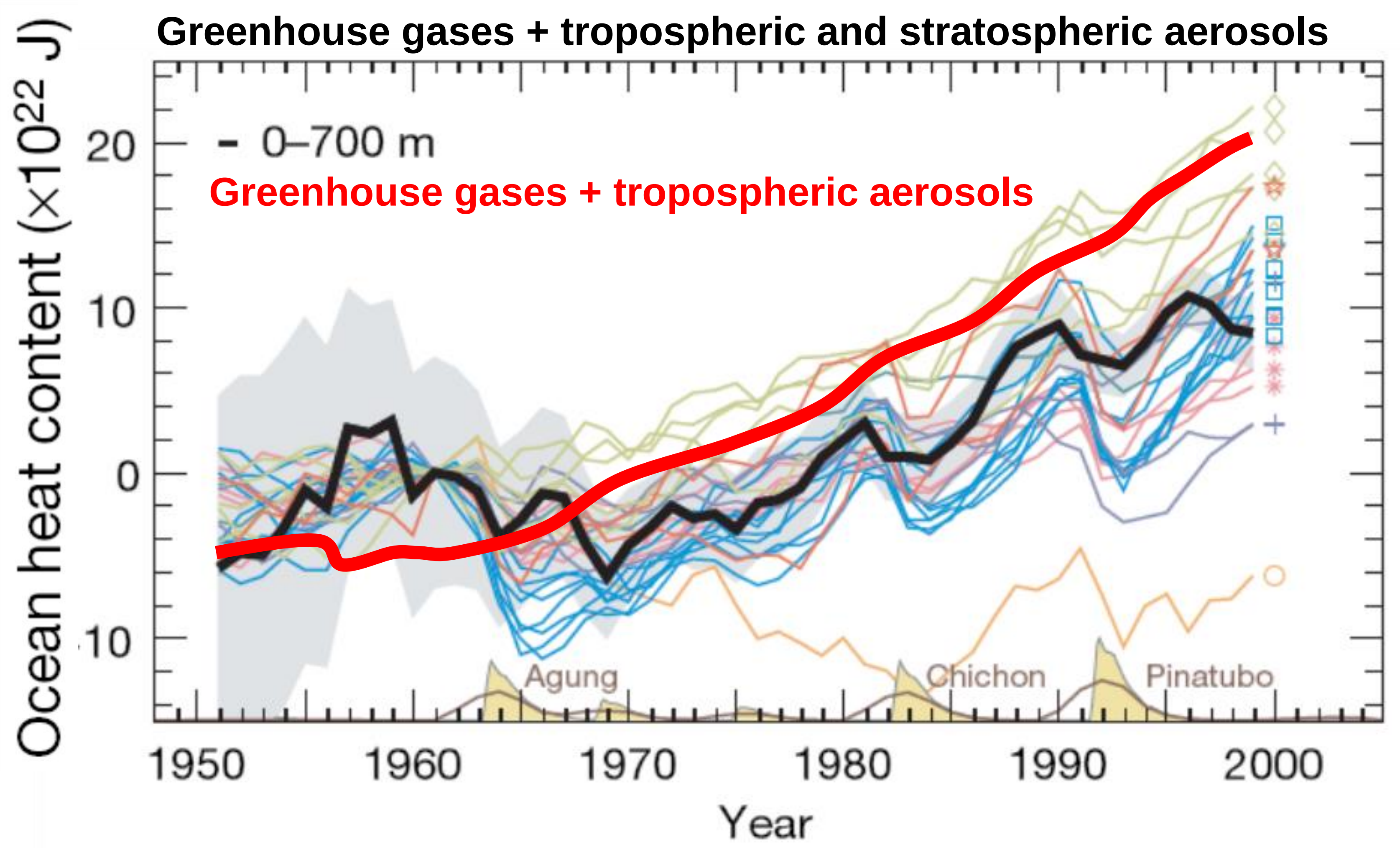
- The ocean contributes to about 30% of the meridional redistribution of heat on Earth
- Buoyancy fluxes, surface wind stress and vertical mixing sustain a vigorous meridional overturning circulation in the ocean, particularly in the Atlantic basin
- The MOC also contributes to the meridional heat flux, which is largest in the Atlantic and Indian Oceans
- Models and observations show that there are large changes in the intensity of the MOC and the associated heat transport
- Recent warming of the upper ocean may be associated with an acceleration of the hydrological cycle.
- There is strong evidence suggesting that these changes in the freshwater forcing at the surface have lead to changes in water mass properties and circulation, whose impact on the MOC is still poorly understood

Obrigada,

Thank you!

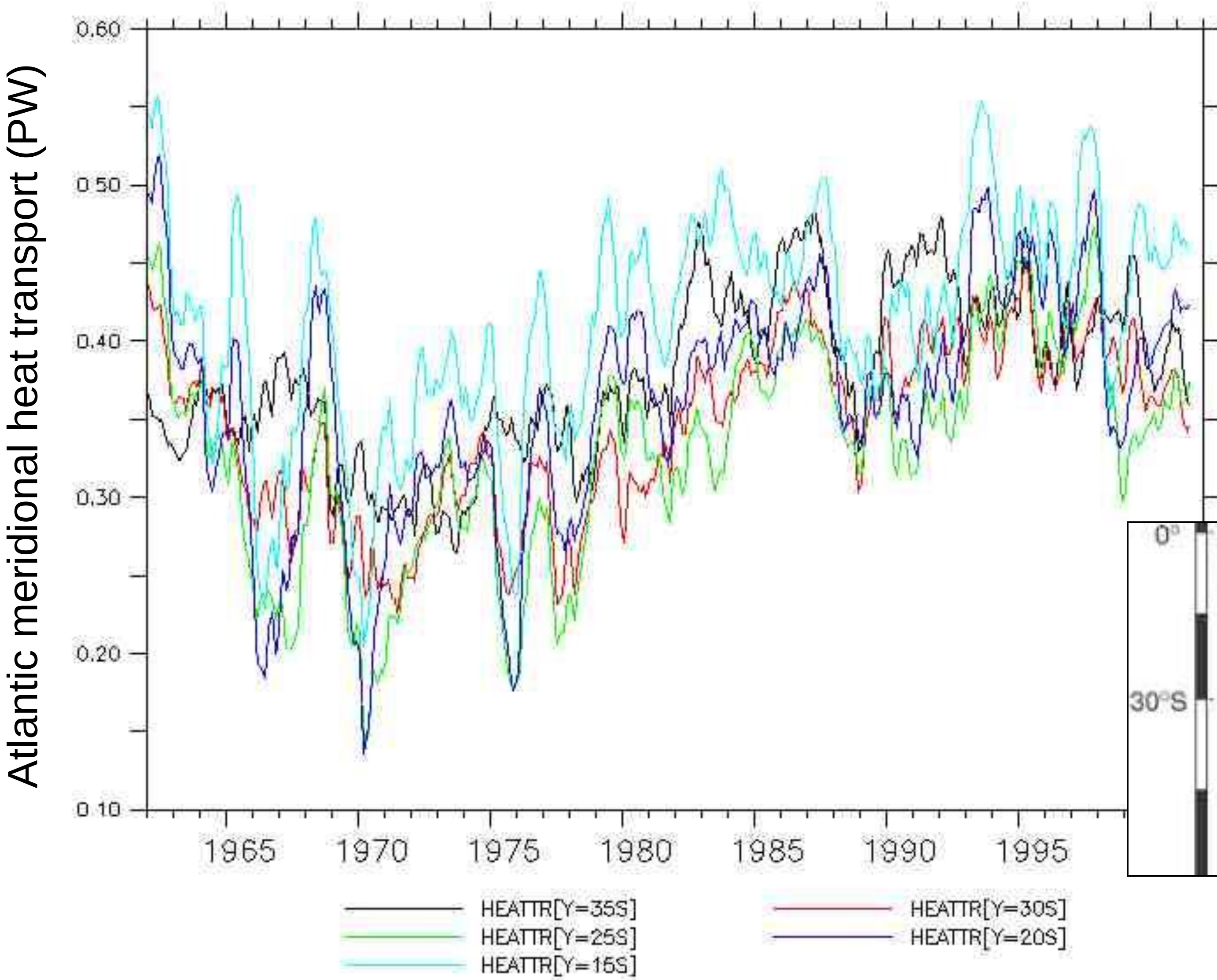
Supplementary Material

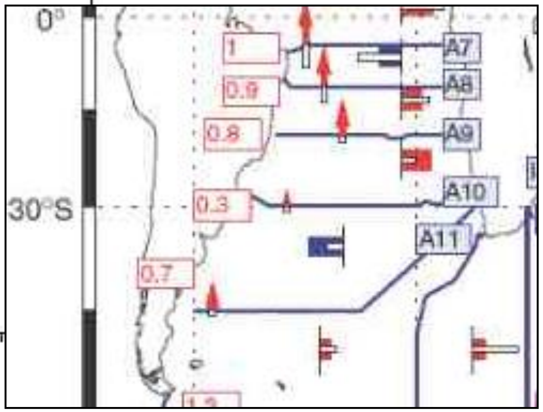
Warming trends in the upper ocean



Adapted from Domingues et al., *Nature*. 2008

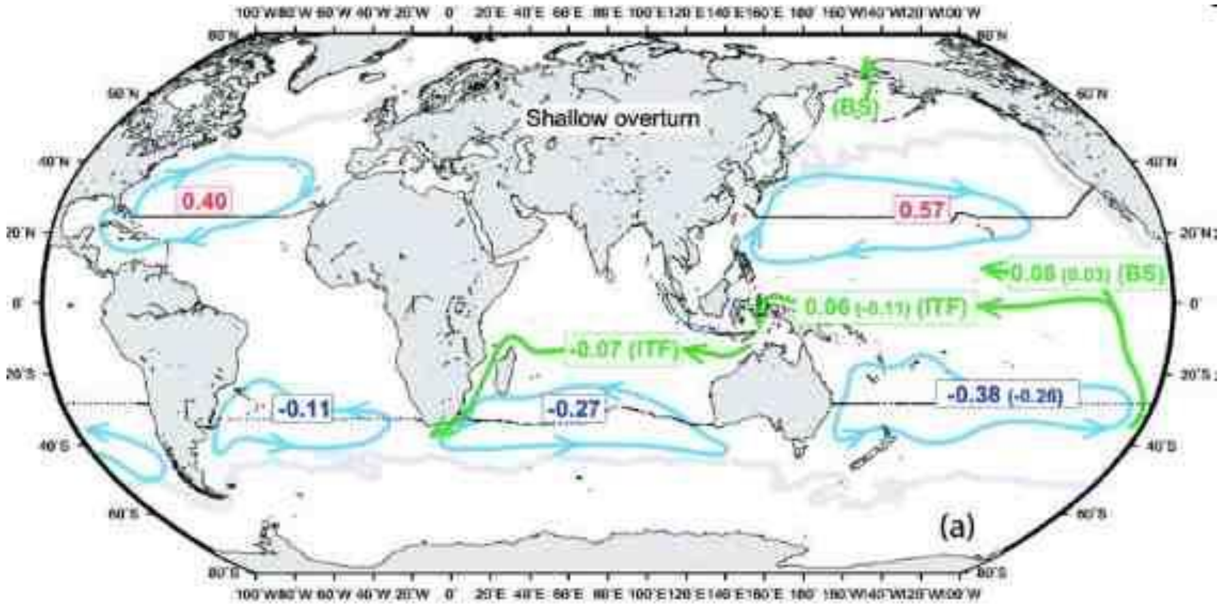
South Atlantic meridional heat transport (gECCO)

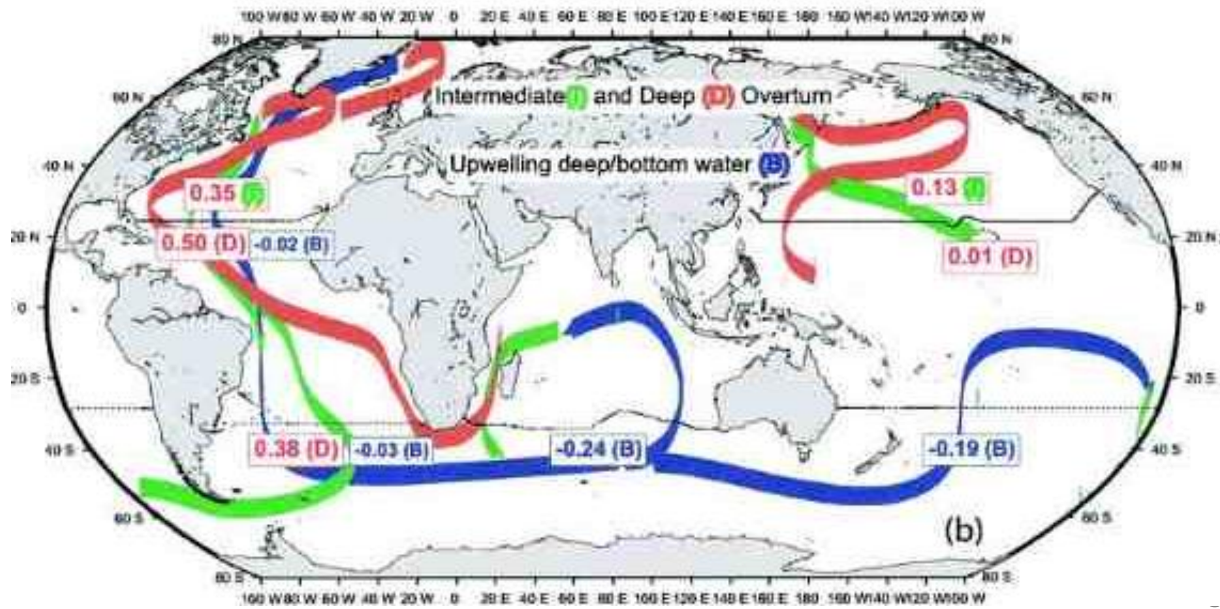




Stammer & Kohl, pers. Comm. 2009

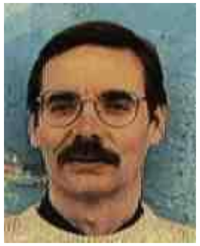
Ocean heat flux mechanisms





Talley, *J.Phys.Oceanogr.*, 2003

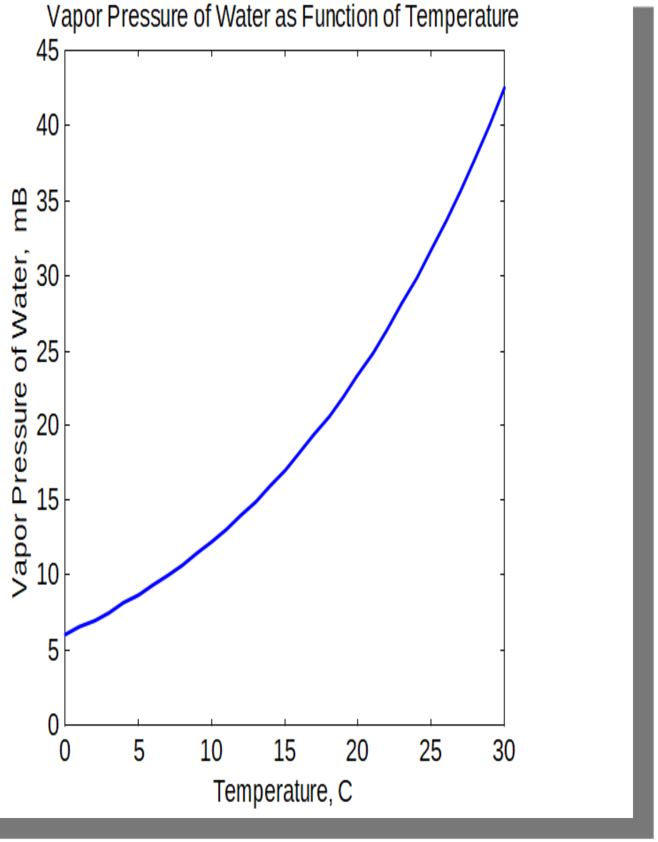
indirect effects of warmer atmosphere



R. Schmitt

- **A warmer atmosphere will carry more water vapor, because of the exponential increase of vapor pressure with temperature.**
- **An <u>enhanced water cycle</u> will change the distribution of salinity in the upper ocean.**

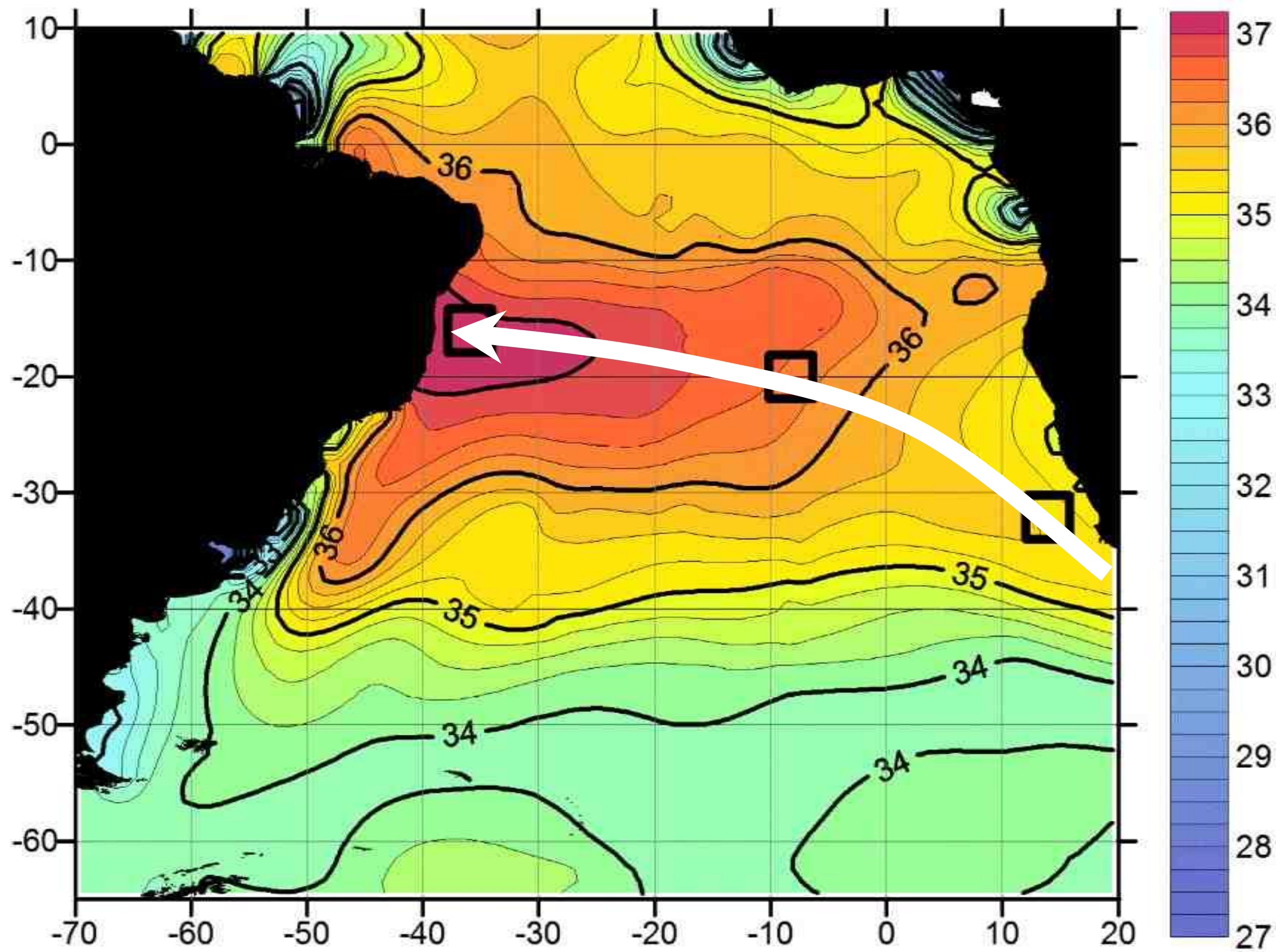
Vapor Pressure, mB



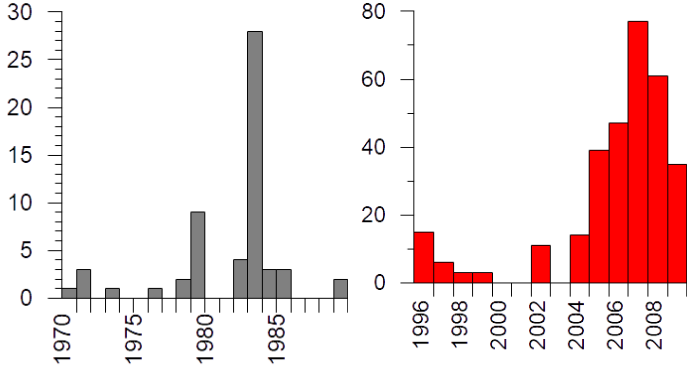
Courtesy Ray Schmitt, WHOI, http://www.whoi.edu/sbl/liteSite.do?litesiteid=18912&articleId=28406

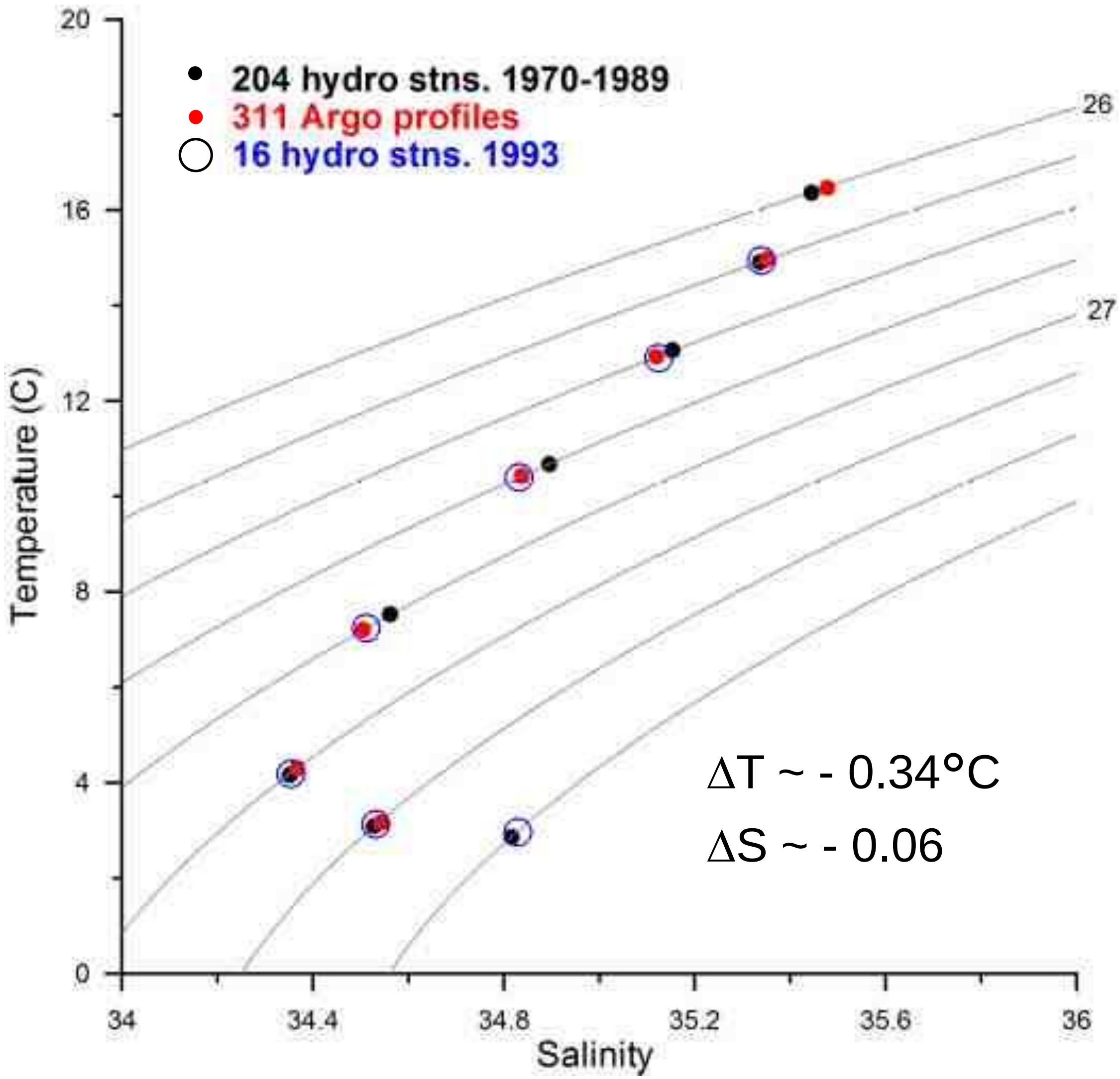
Local Upper Ocean Modifications in the South Atlantic

The South Atlantic is the entry pointt for the upper layer flow into the North Atlantic, required to compensate the export of deep water to the global ocean.



T - S changes on isopycnals - Benguela

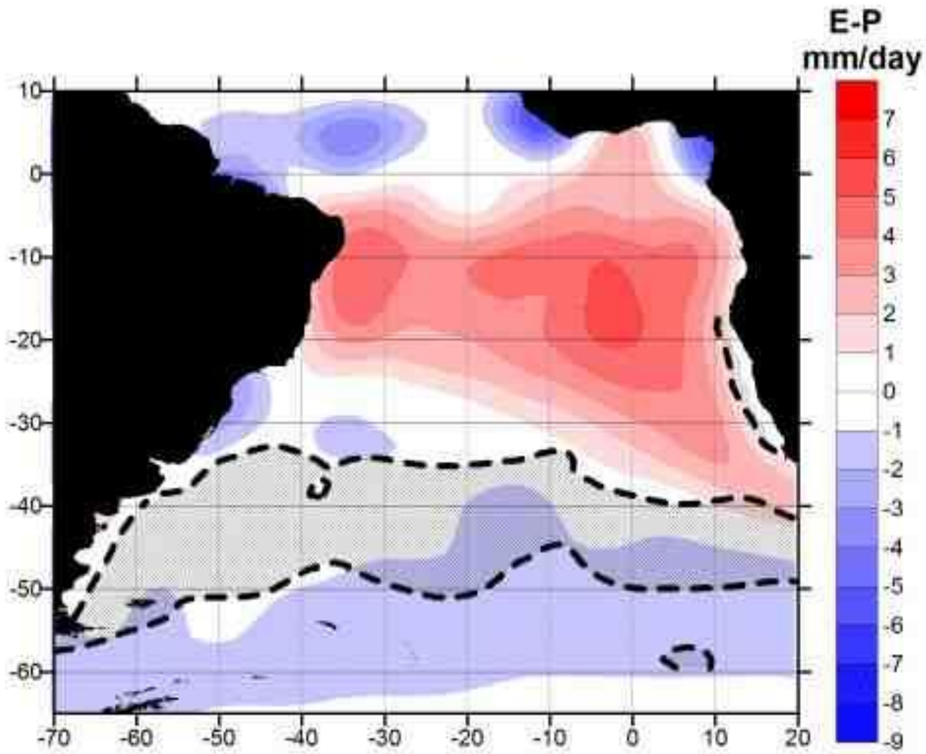


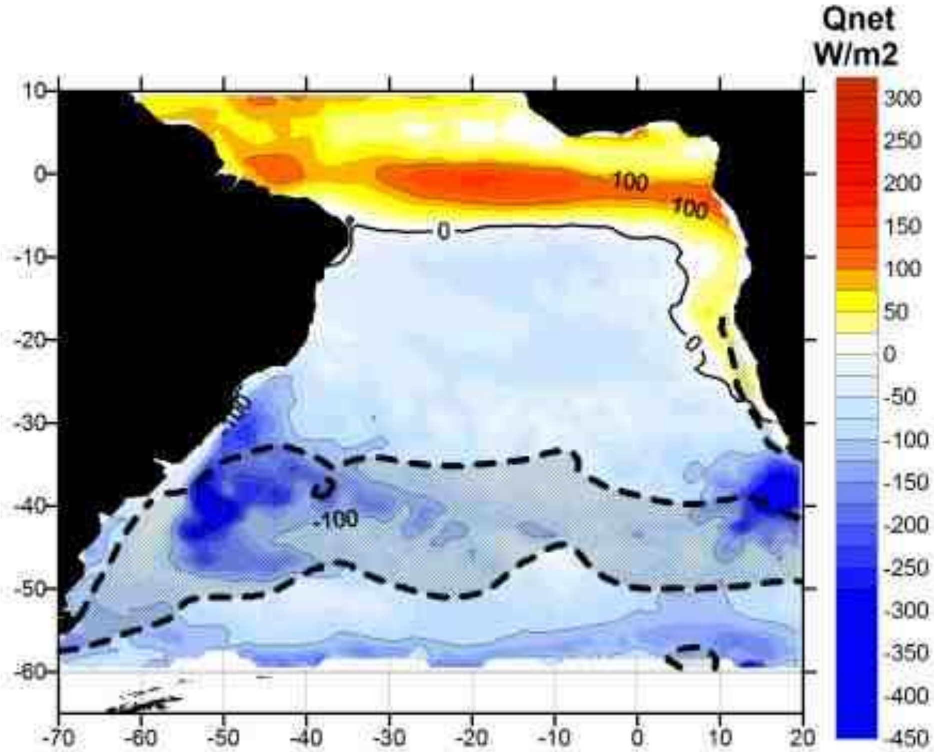


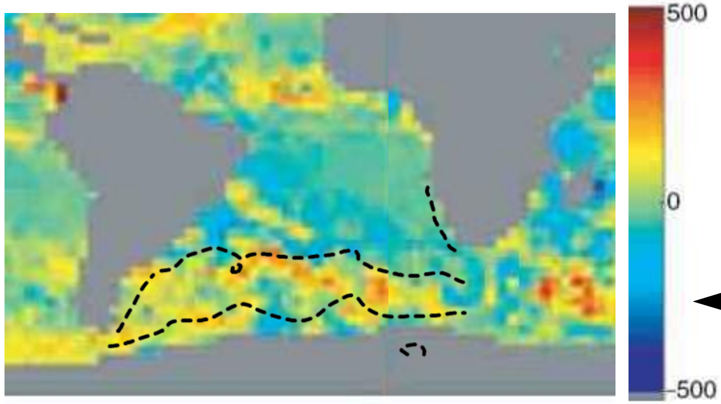
SEC: no significant changes are observed

Bifurcation: changes similar to Benguela, but noisier hydro data.

The outcrop regions

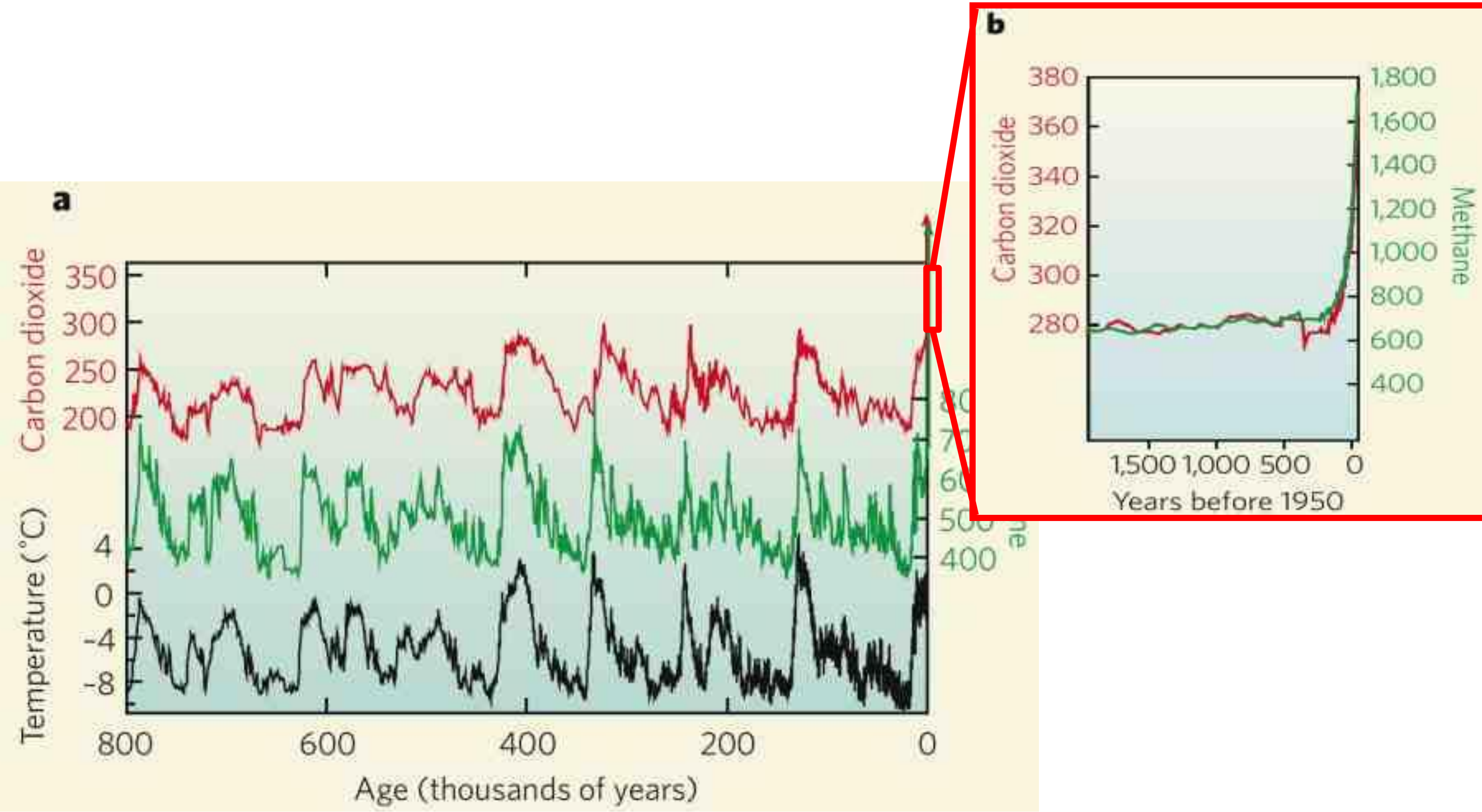






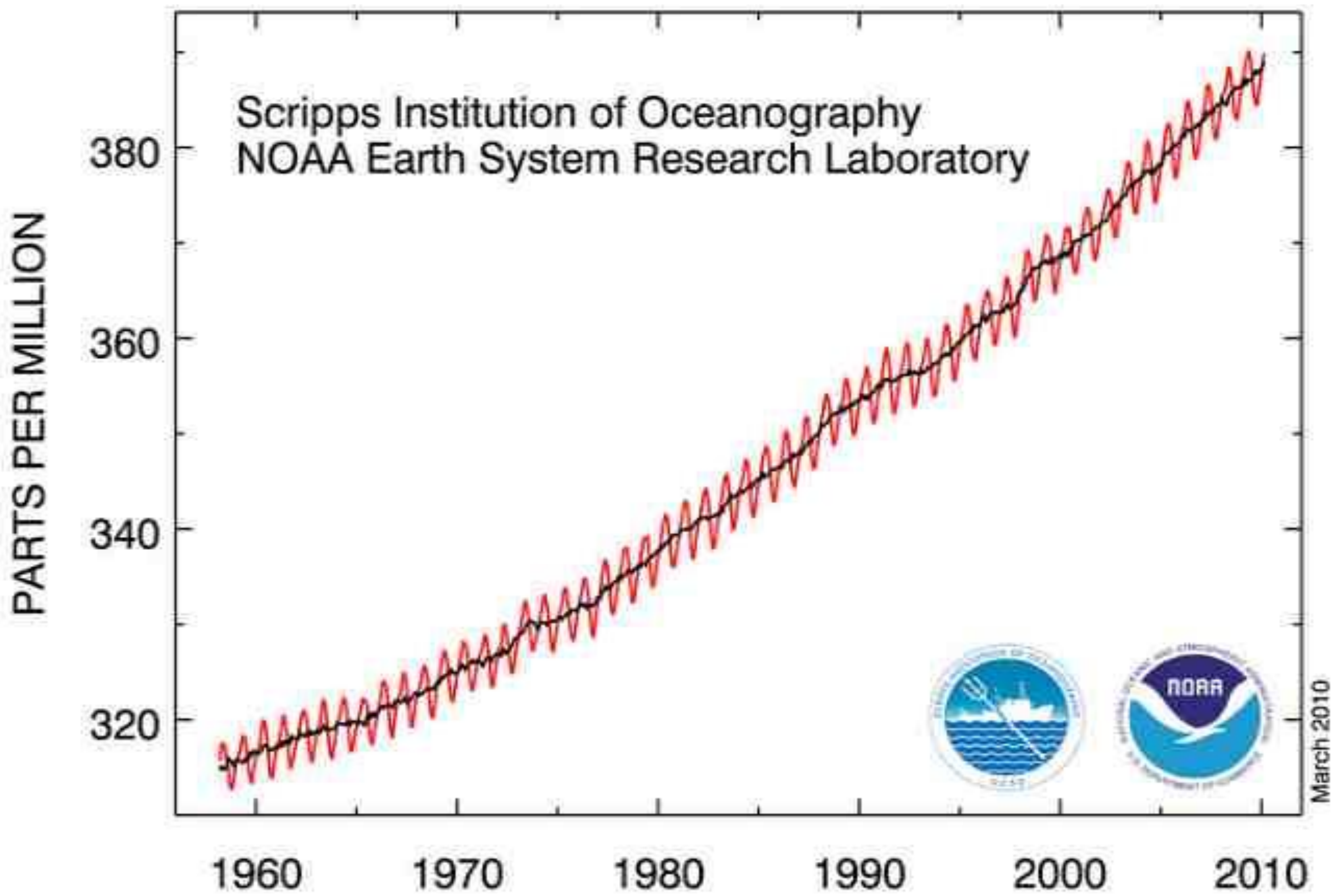
Precipitation trend (mm/yr/decade)
1987-2006 (Wentz et al., 2008)

Atmospheric CO_2 and global temperature records



Mean global temperature (black) and atmospheric CO_2 and CH_4 (red and green) during the last 800.000 yrs. Atmospheric CO_2 concentrations increased by 30% during the industrial period.

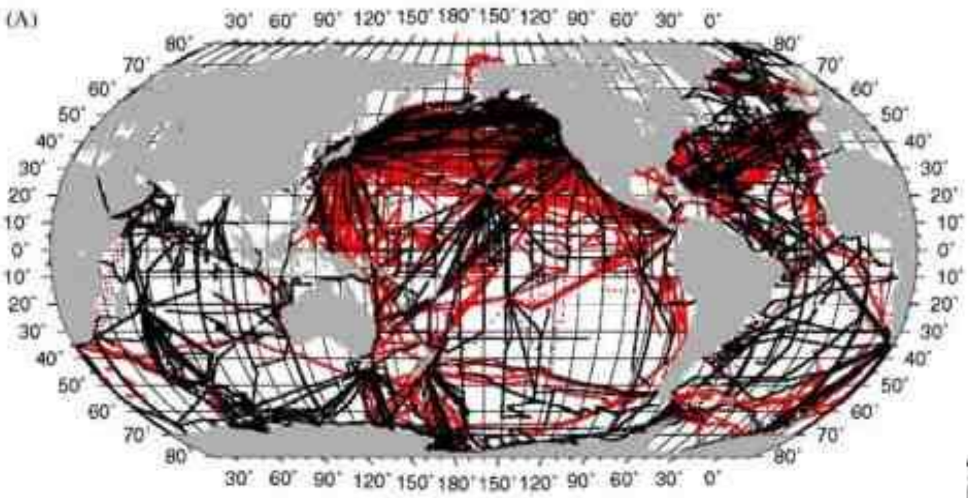
Recent atmospheric CO_2

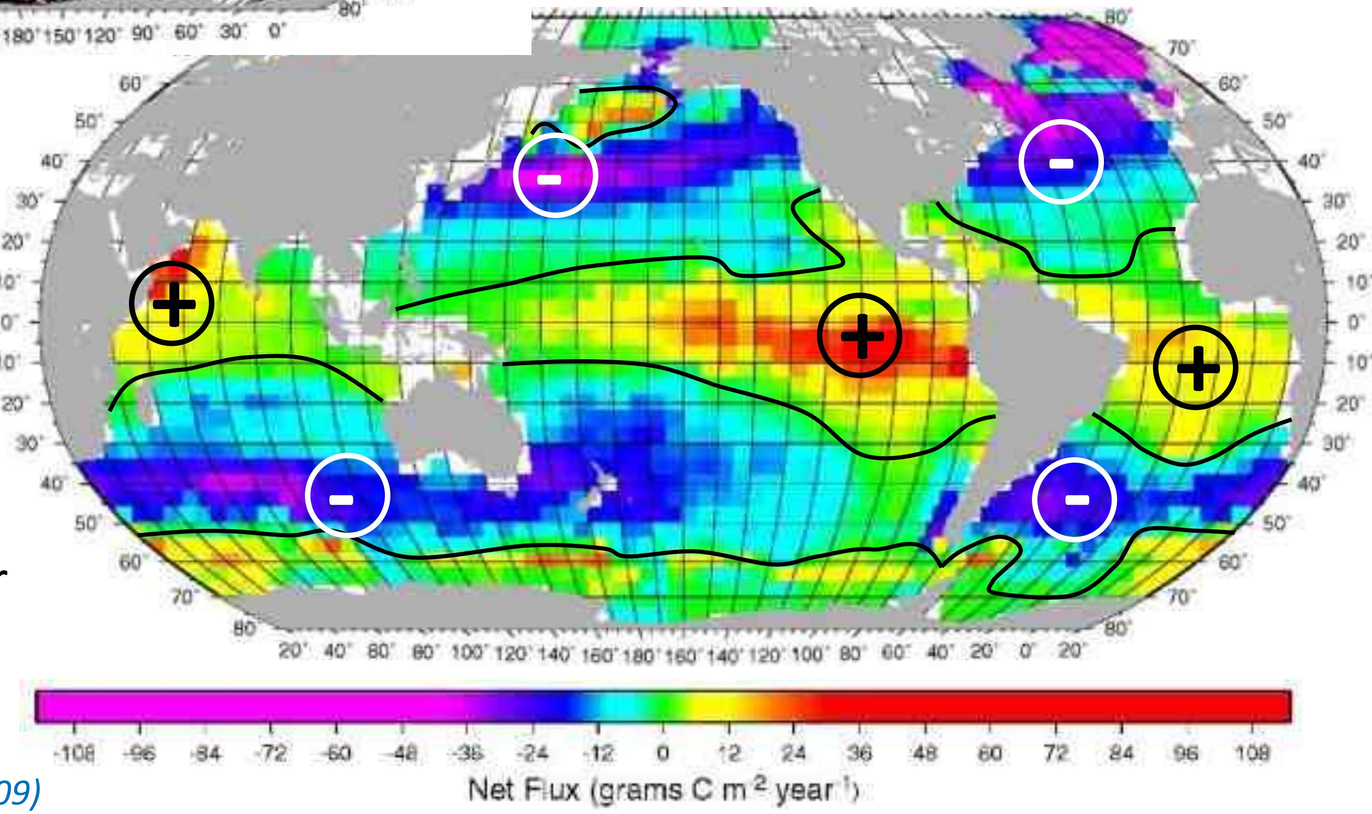


Atmospheric CO_2 data from the Mauna Loa observatory, Hawaii since1959

http://www.esrl.noaa.gov/gmd/ccgg/trends/

Impacts: absorption of atmospheric CO_2



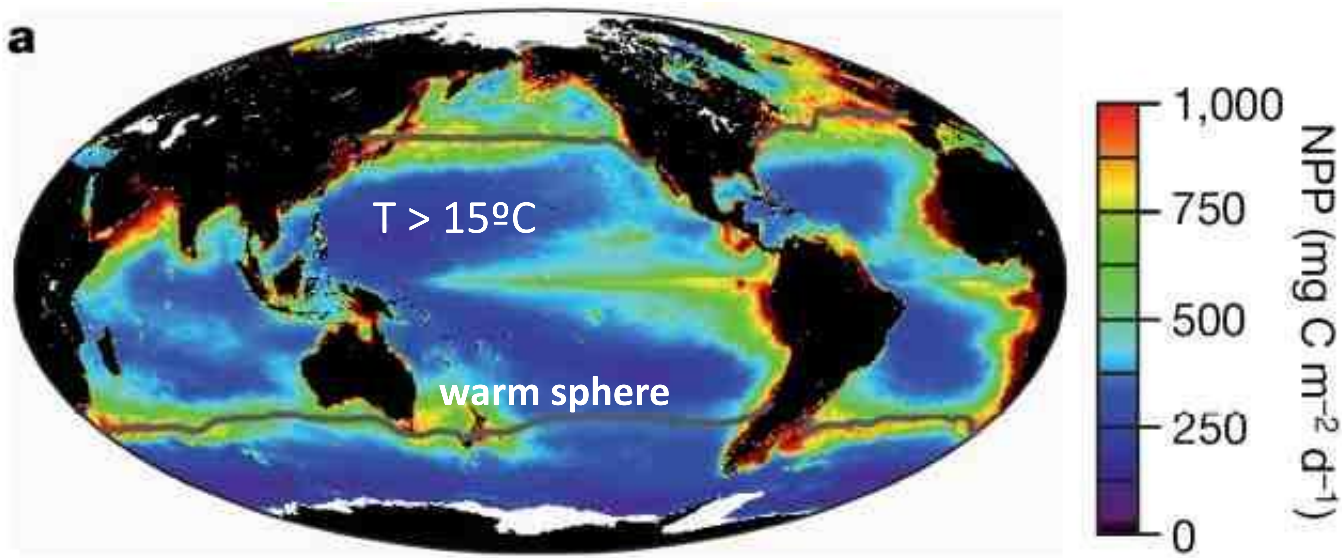


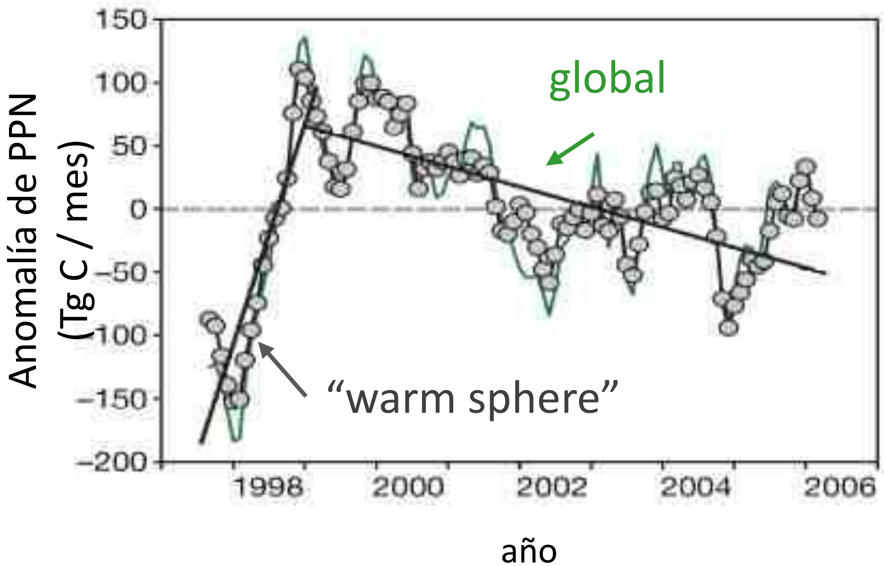
$$\int FCO_2 \, dA =$$

- 1.6 (± 0.9) Pg C/yr

Takahashi et al., DSR (2009)

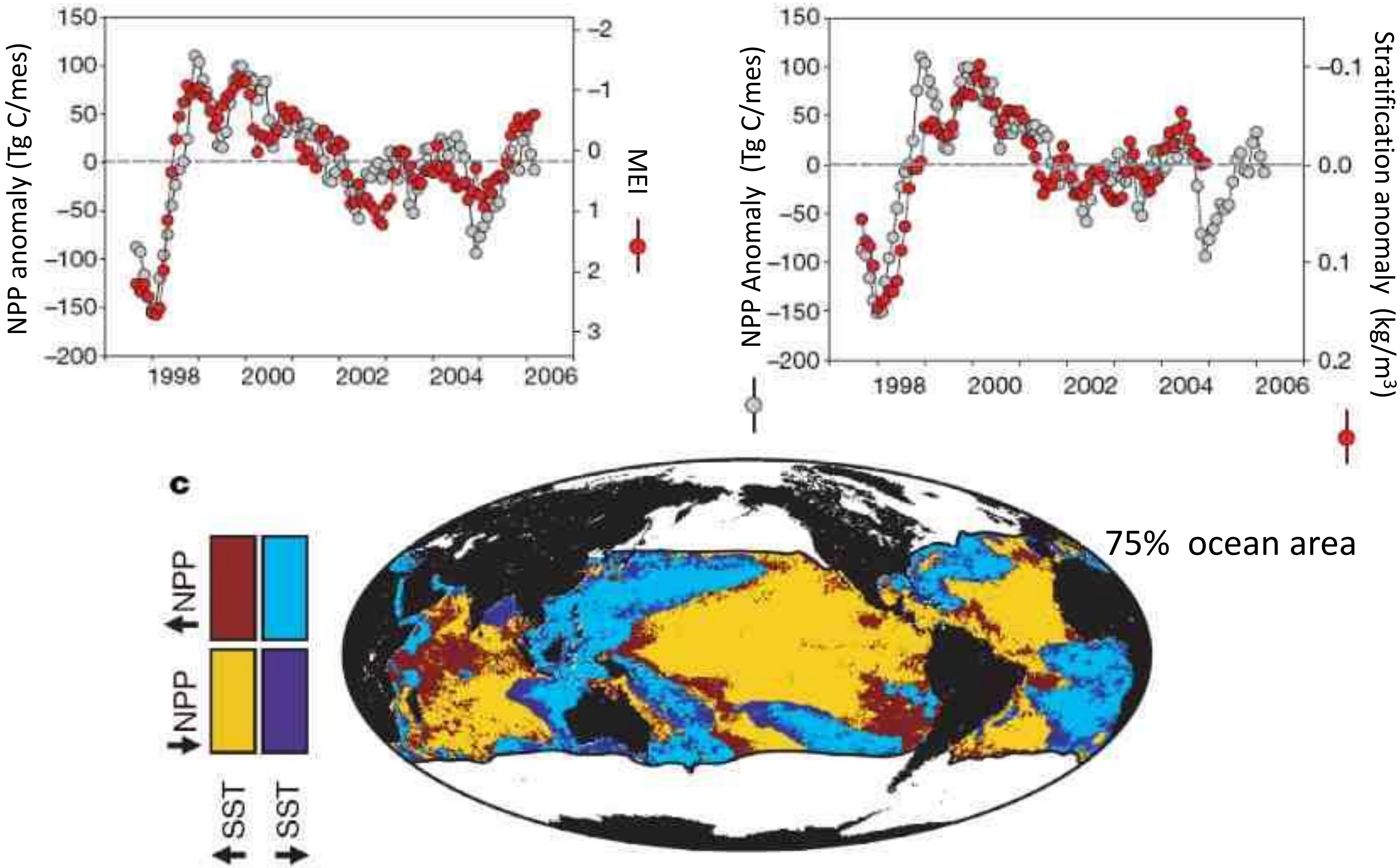
Net primary production: Lessons from a strong Niño





Behrenfeld et al., Nature, 2006

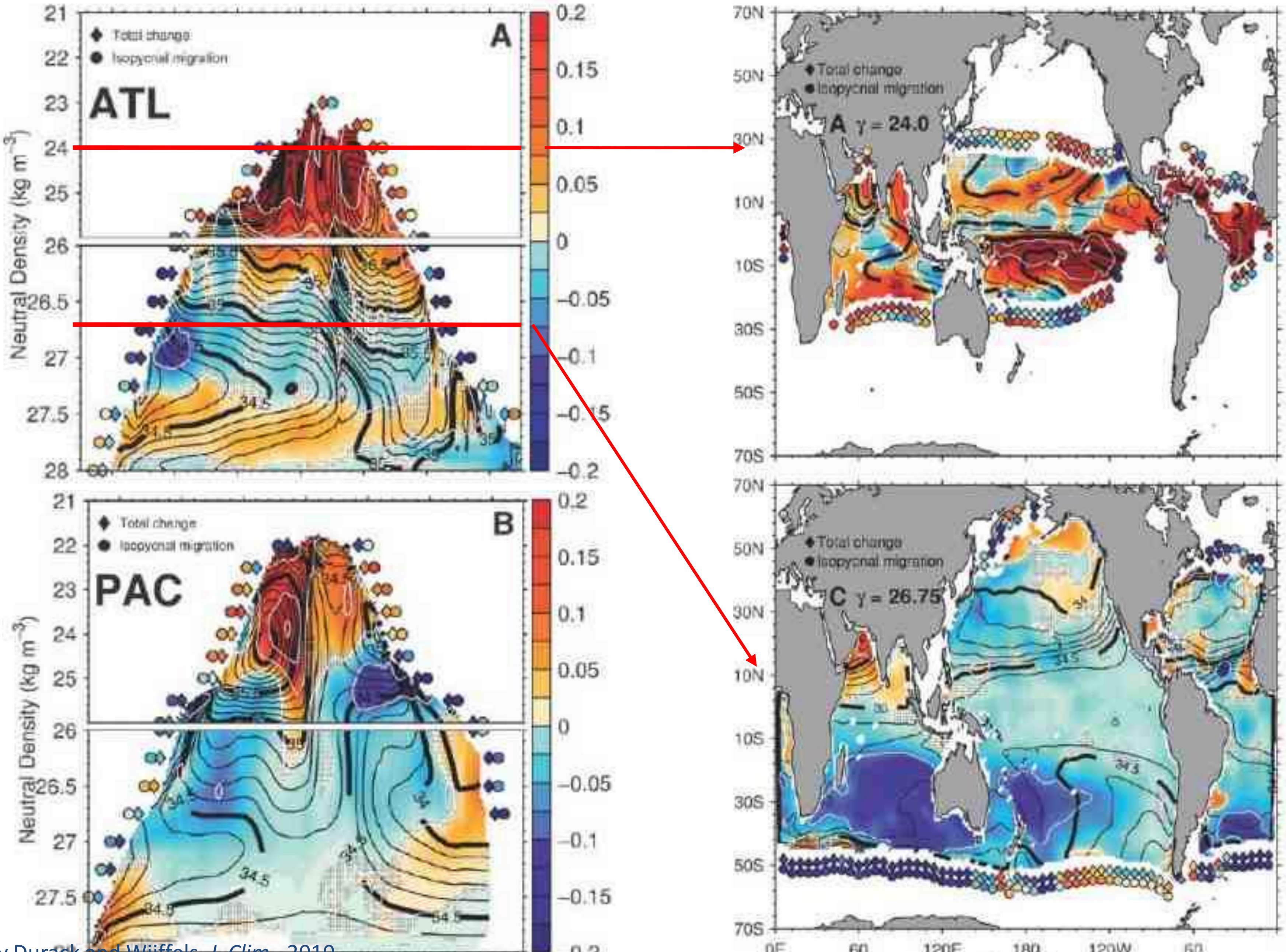
NPP variability – warm sphere, T > 15ºC



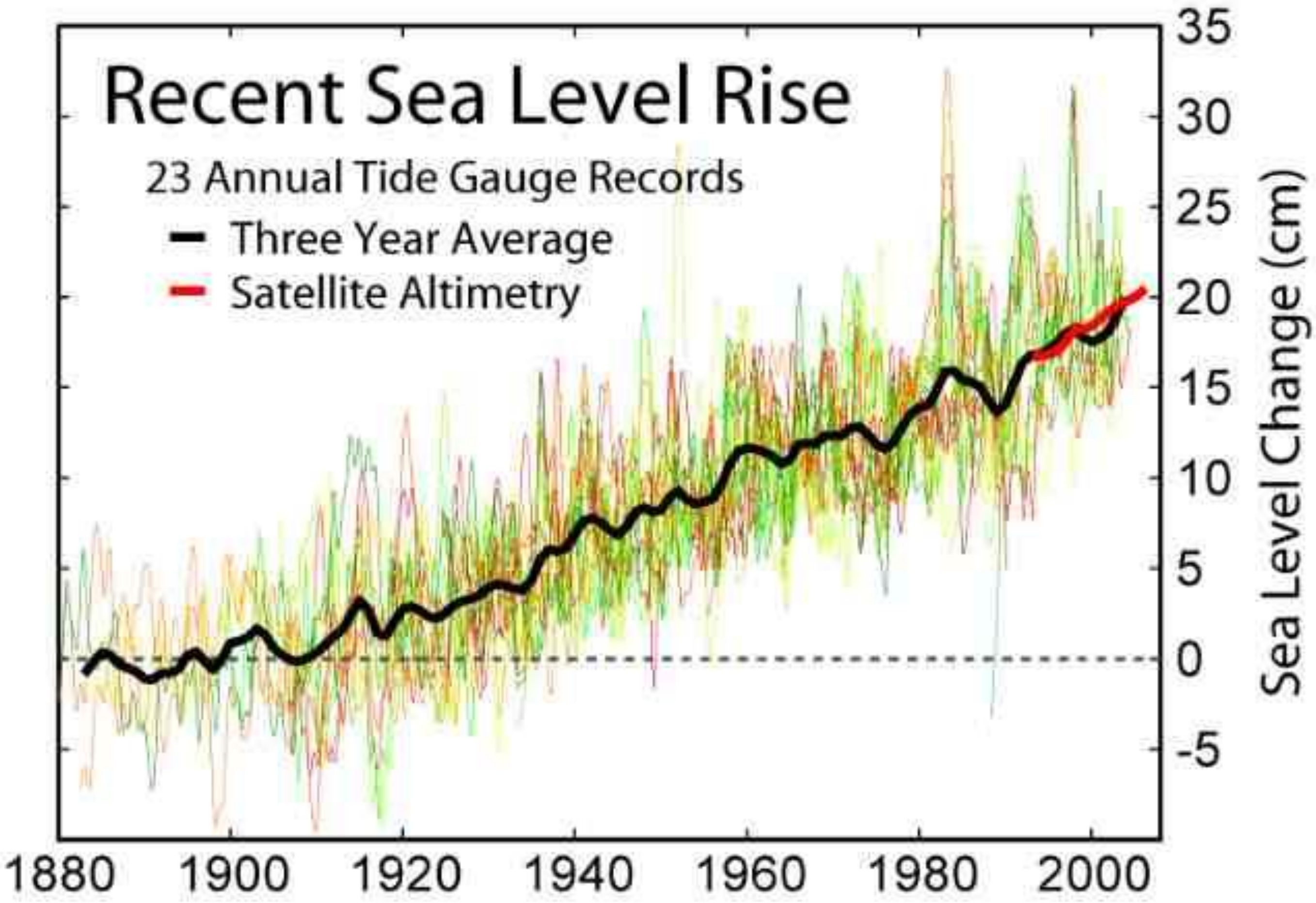
75% ocean area

Behrenfeld et al., Nature, 2006

Global salinity changes - IV

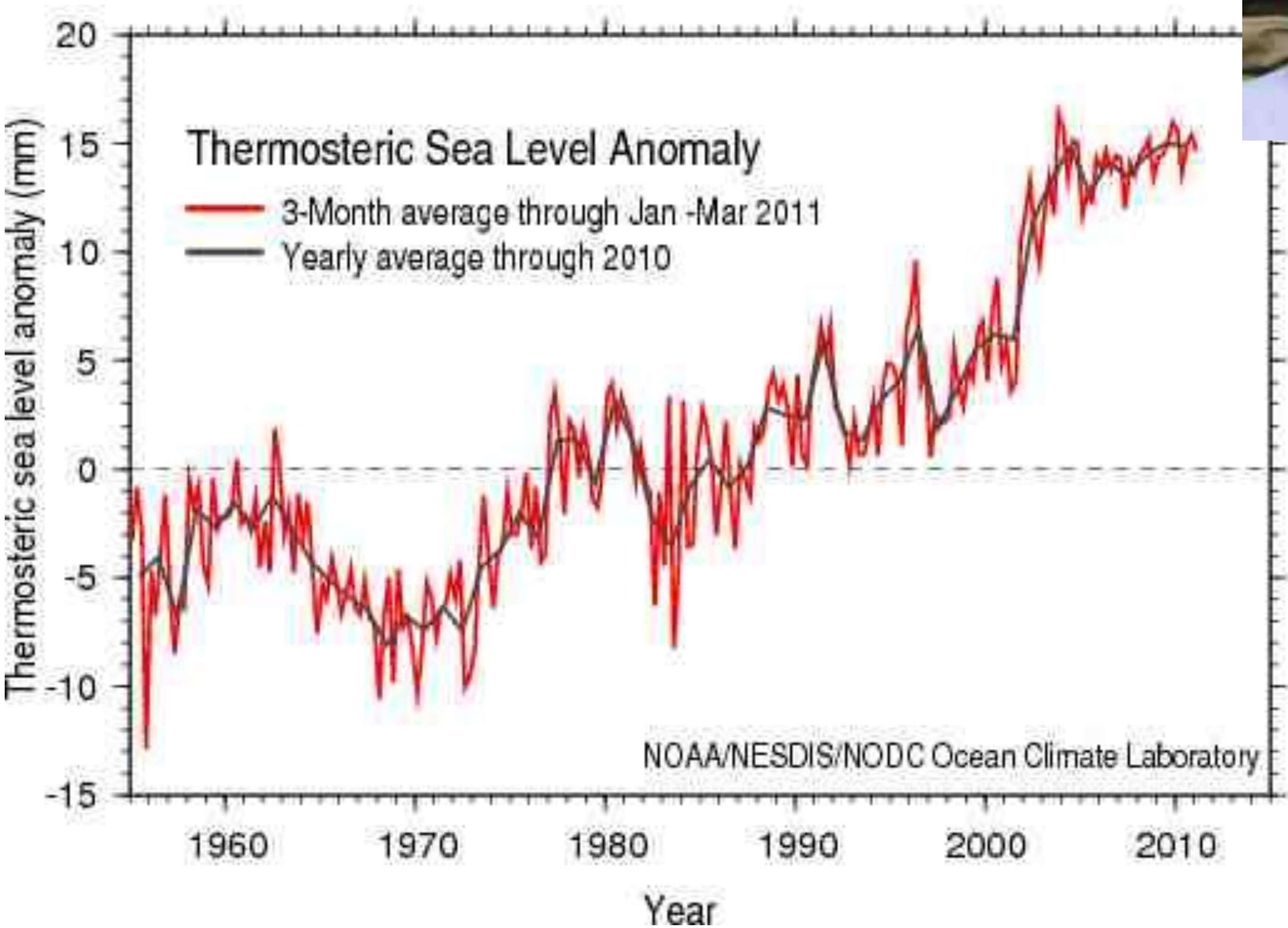


Courtesy Durack and Wijffels, *J. Clim.*, 2010



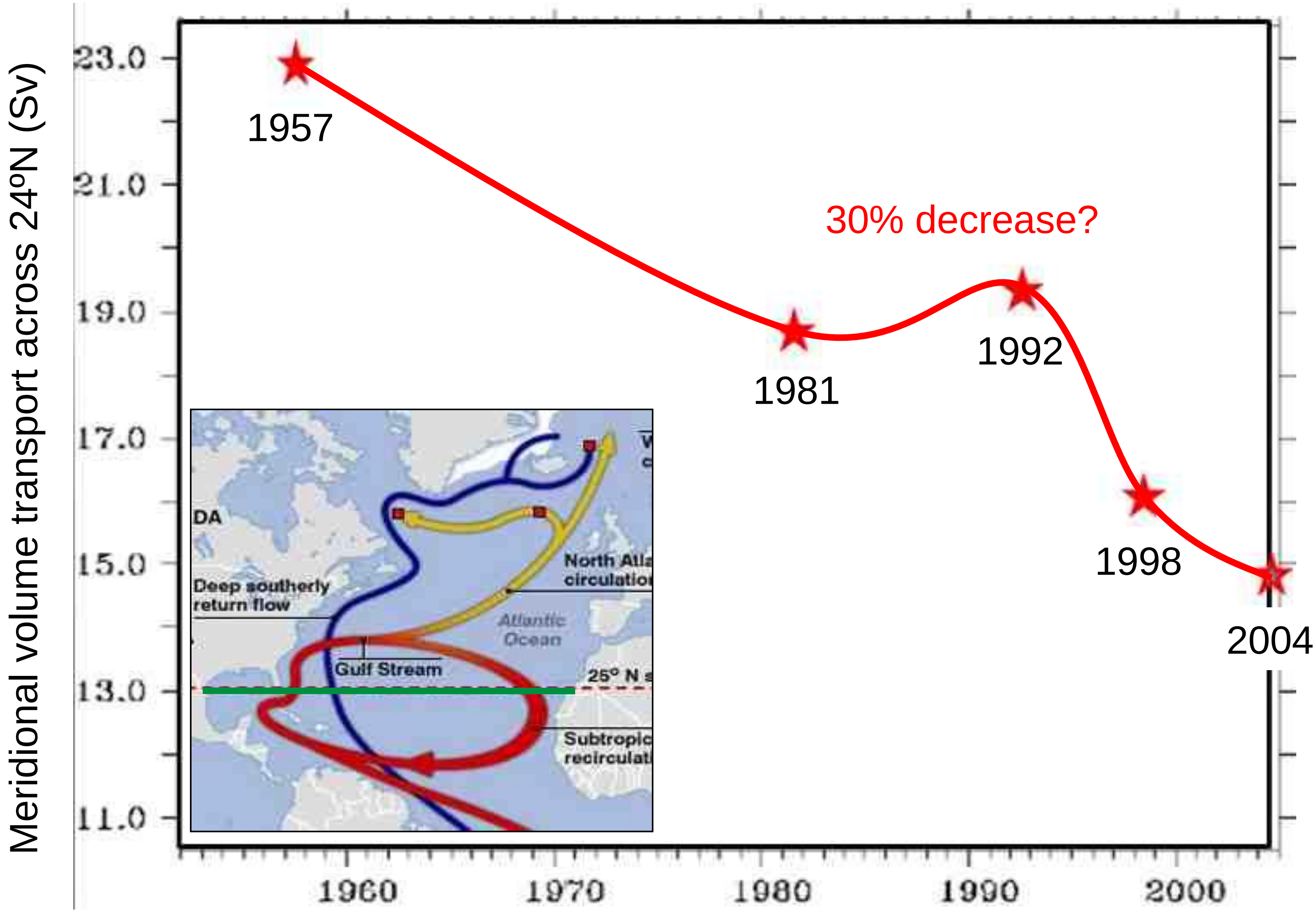
Changes en mean sea level based on 23 tide long-term gauge records (black), and satellite altimeters (red).

Thermosteric sea level rise



http://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/

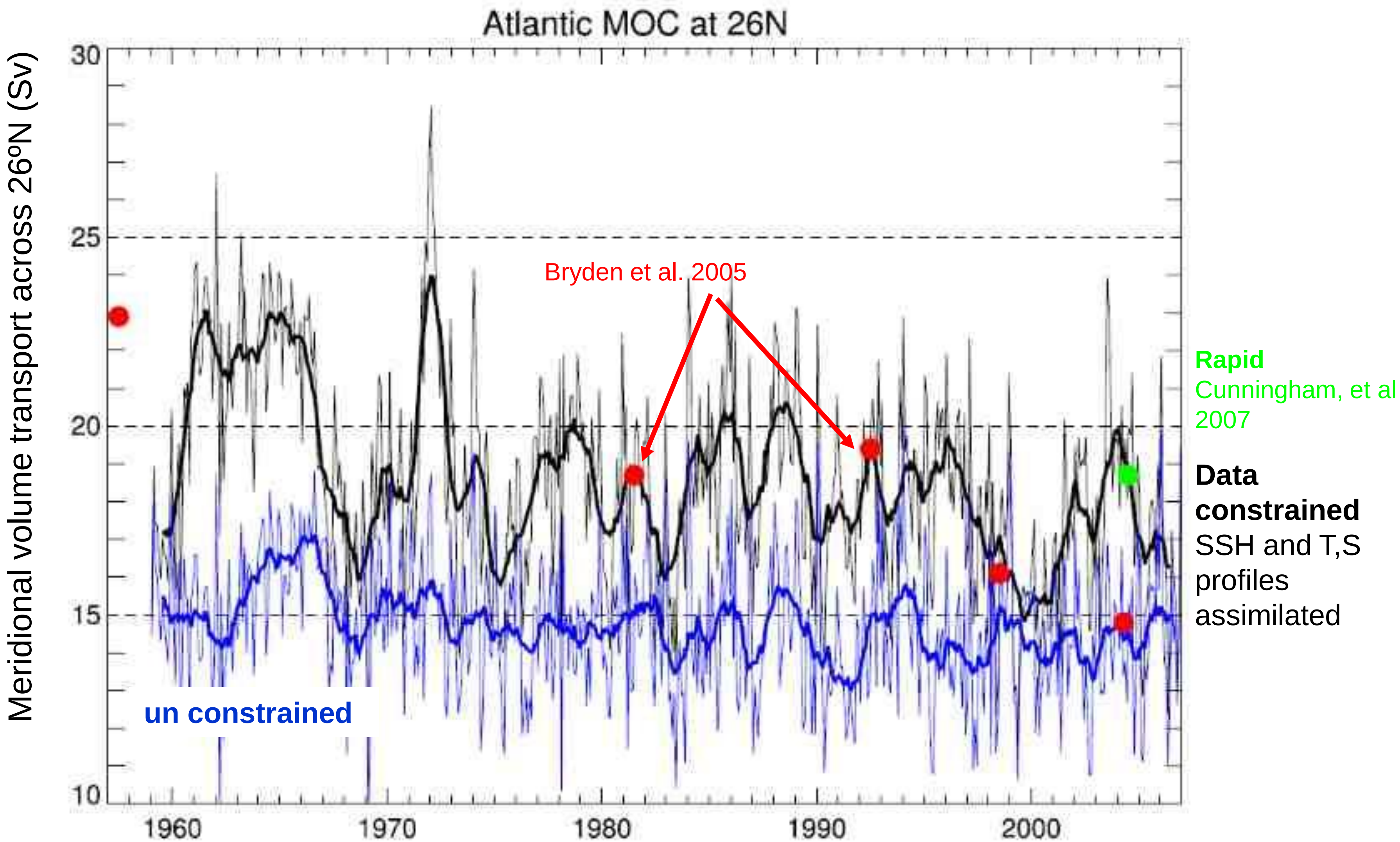
Observed Atlantic overturning – I – variability



Bryden et al., *Nature*, 2005

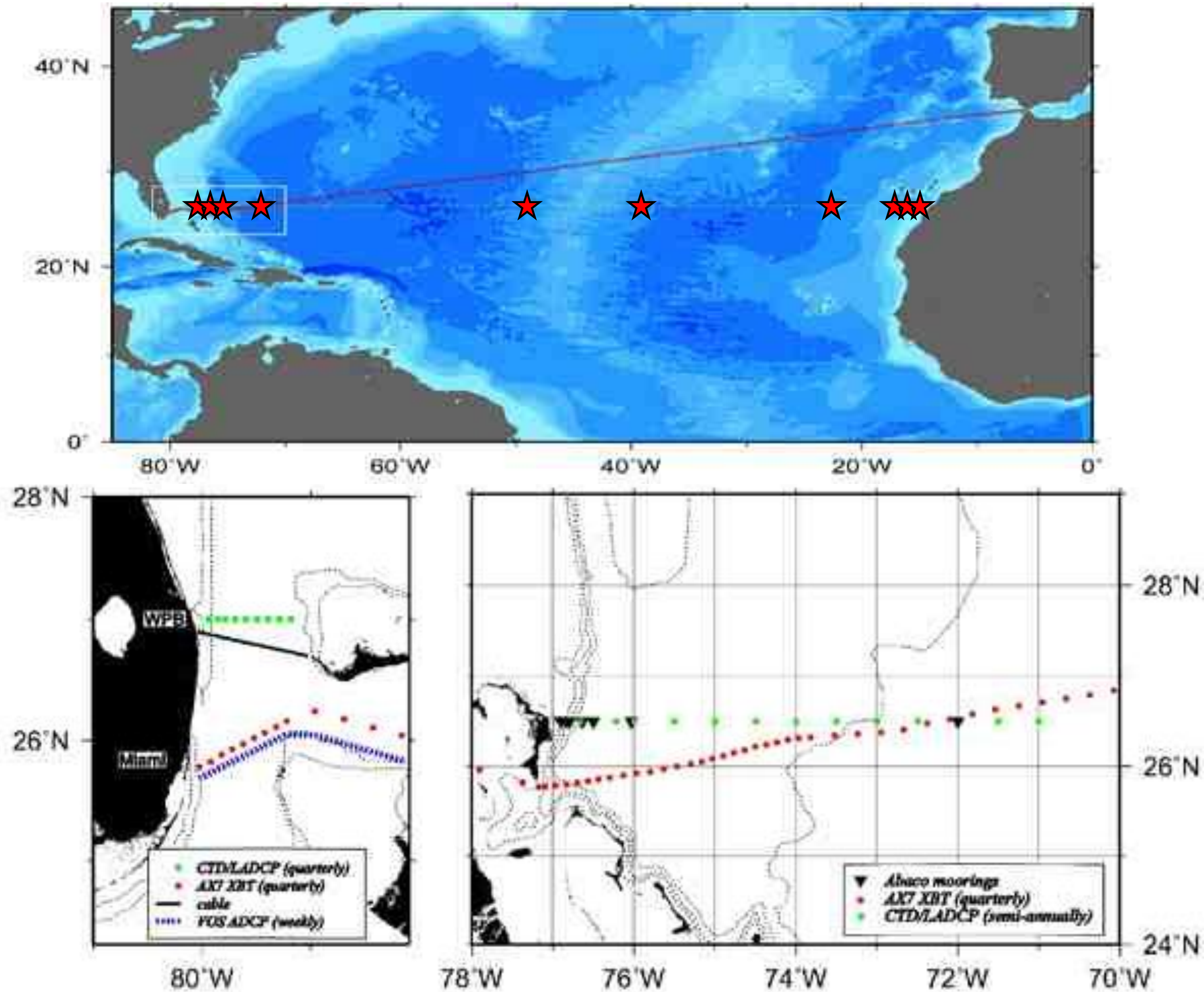
Atlantic overturning – III – variability

Contrasting models and observations



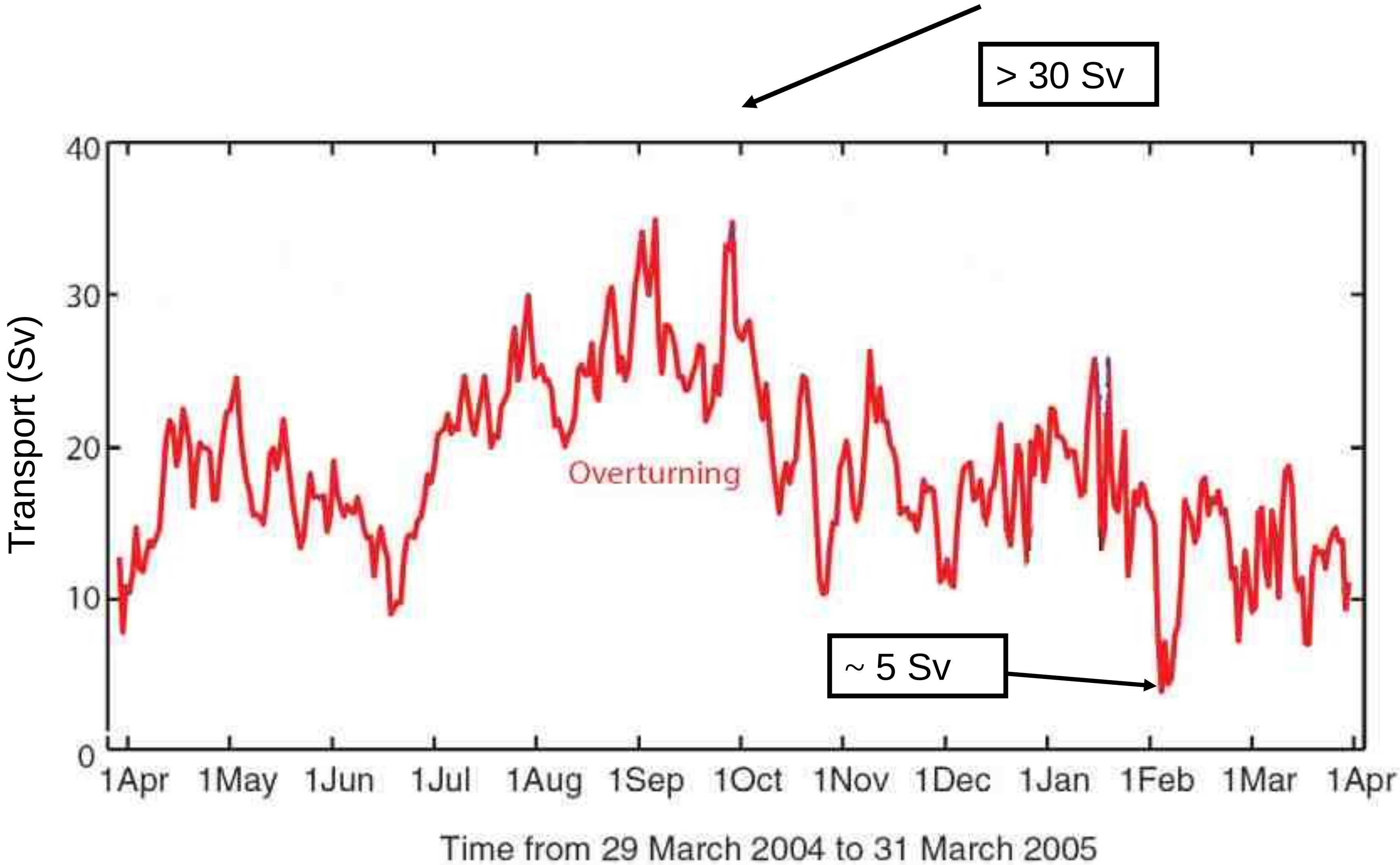
Balmaseda et al., *GRL*, 2007

Observed Atlantic overturning – I



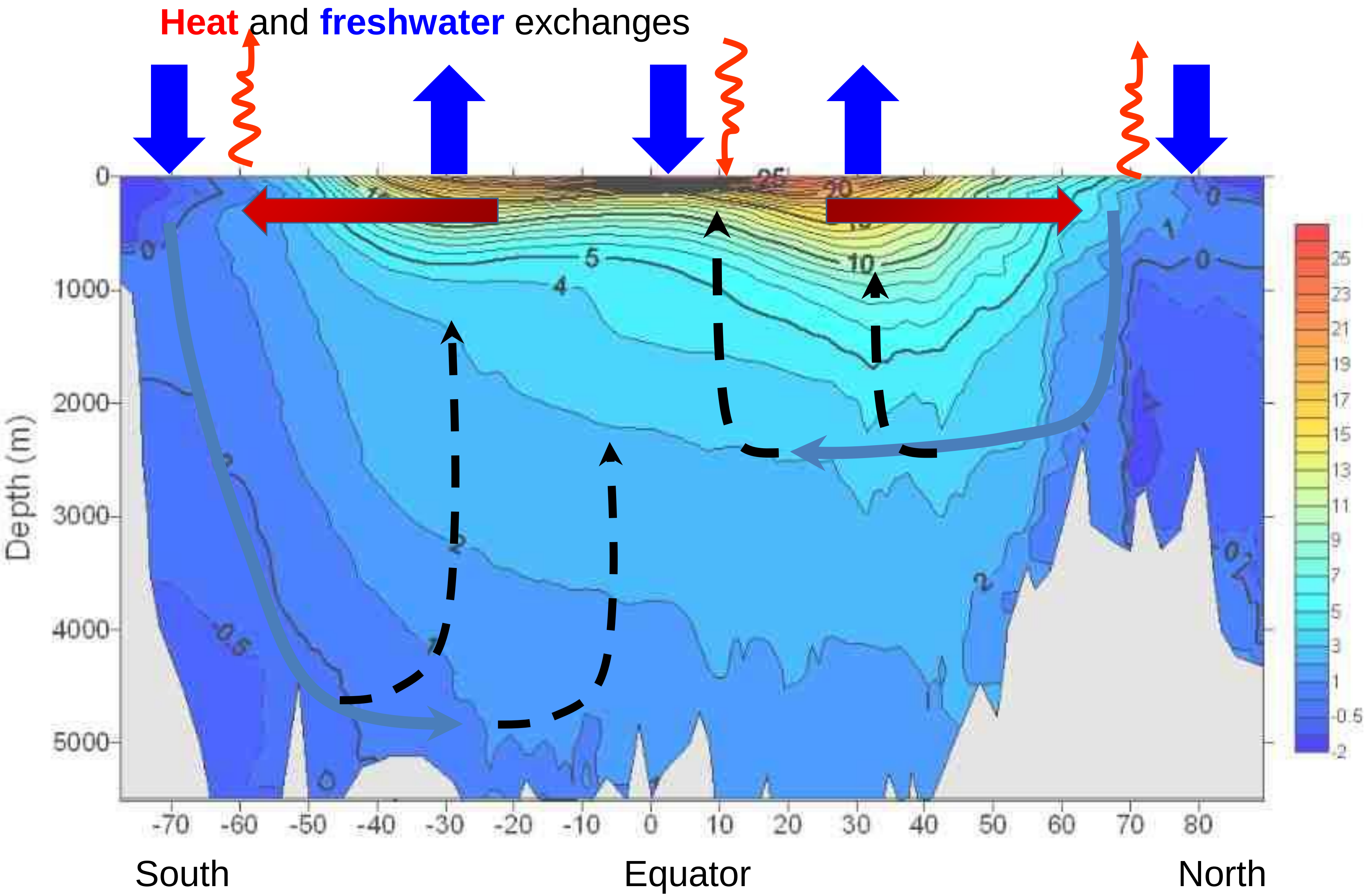
http://www.rsmas.miami.edu/users/mocha/new/

Observed Atlantic overturning – II



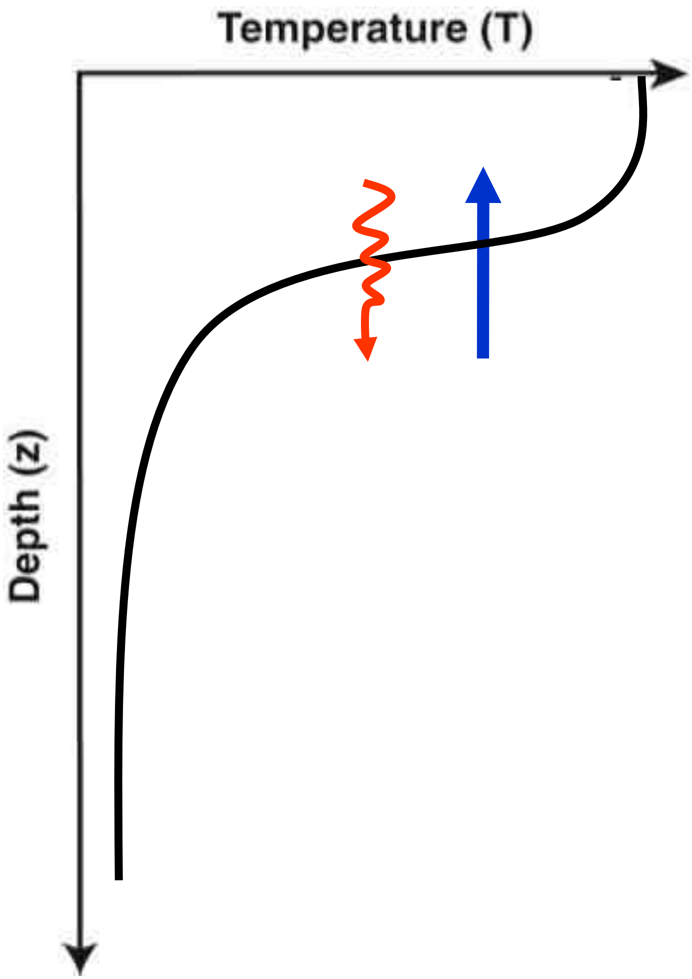
Adapted from Kanzow et al., *Nature*, 2007

Overturning *a la* Rumford



Sustaining the vertical structure

(and the MOC)



$$w\, \partial T / \partial z = \kappa\, \partial^2 T / \partial z^2$$

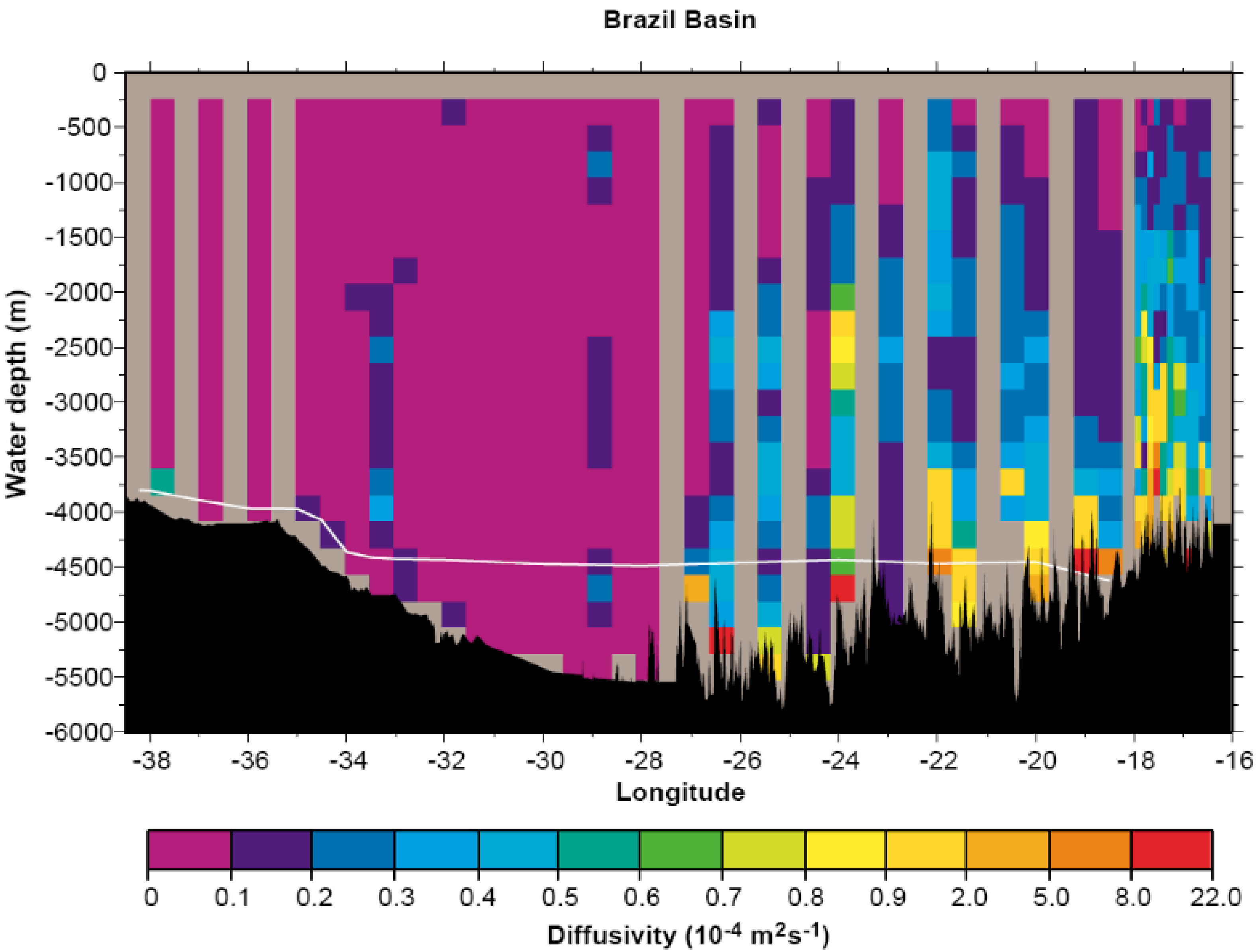
Downward turbulent diffusion of heat (RHS) is compensated by upwelling of cold water (LHS).

Globally averaged turbulent heat diffusivity (κ) needs to be ~ **10^{-4} m^2 s^{-1}** or about three orders of magnitude larger than molecular diffusivity.

This balance provides the upwelling necessary to balance water formation at high latitude.

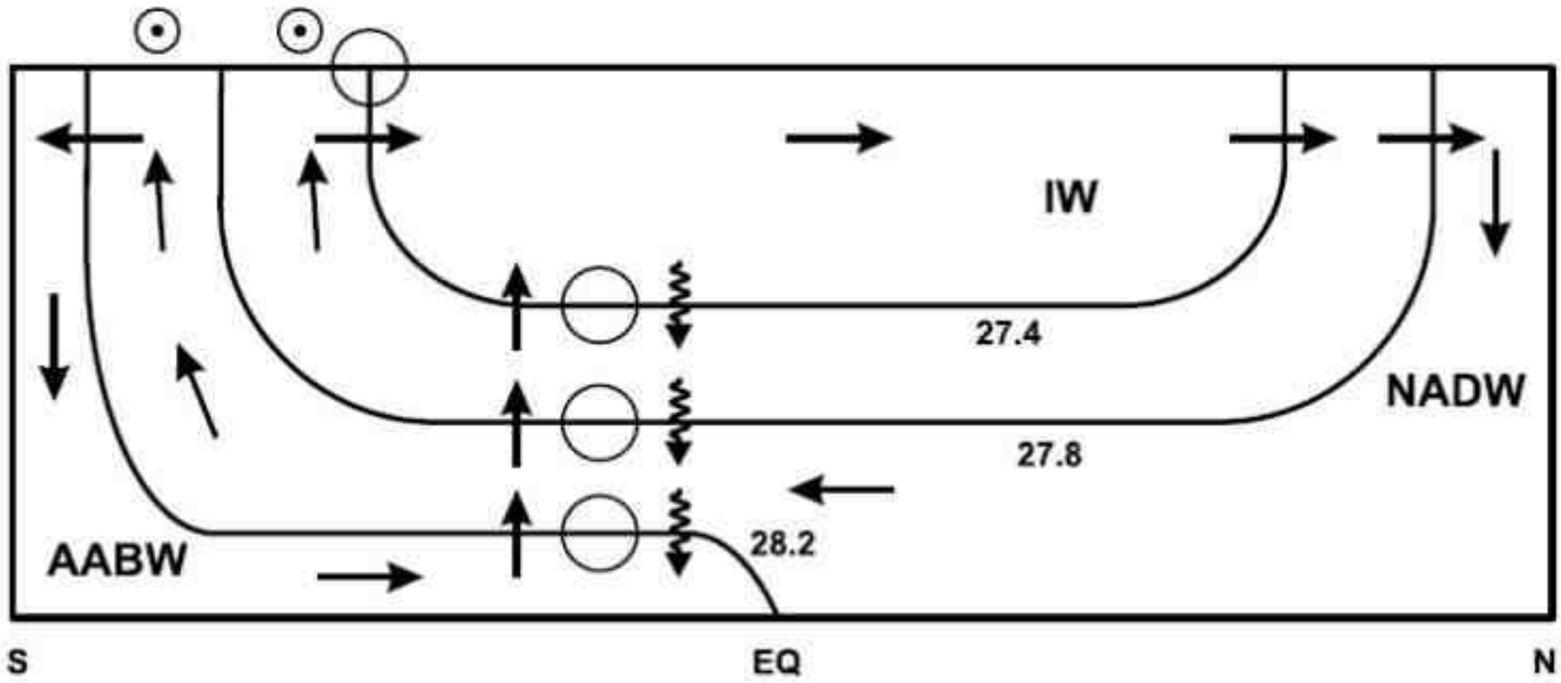
Munk, *Deep-Sea Res.*, 13, 707-730, 1966.
Available at http://empslocal.ex.ac.uk/people/staff/gv219/classics.d/index.html
Munk and Wunsch, *Deep-Sea Res.*, 45, 1977-2010, 1998.

Non homogeneous diffusivities



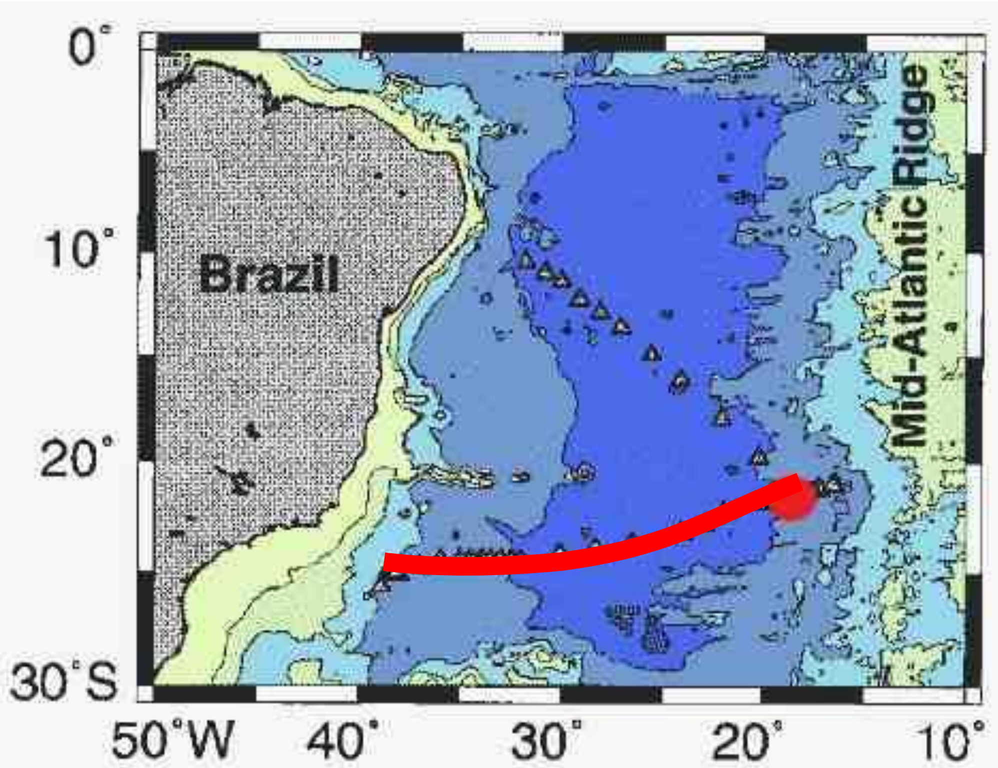
Polzin et al., *Science*, 1997

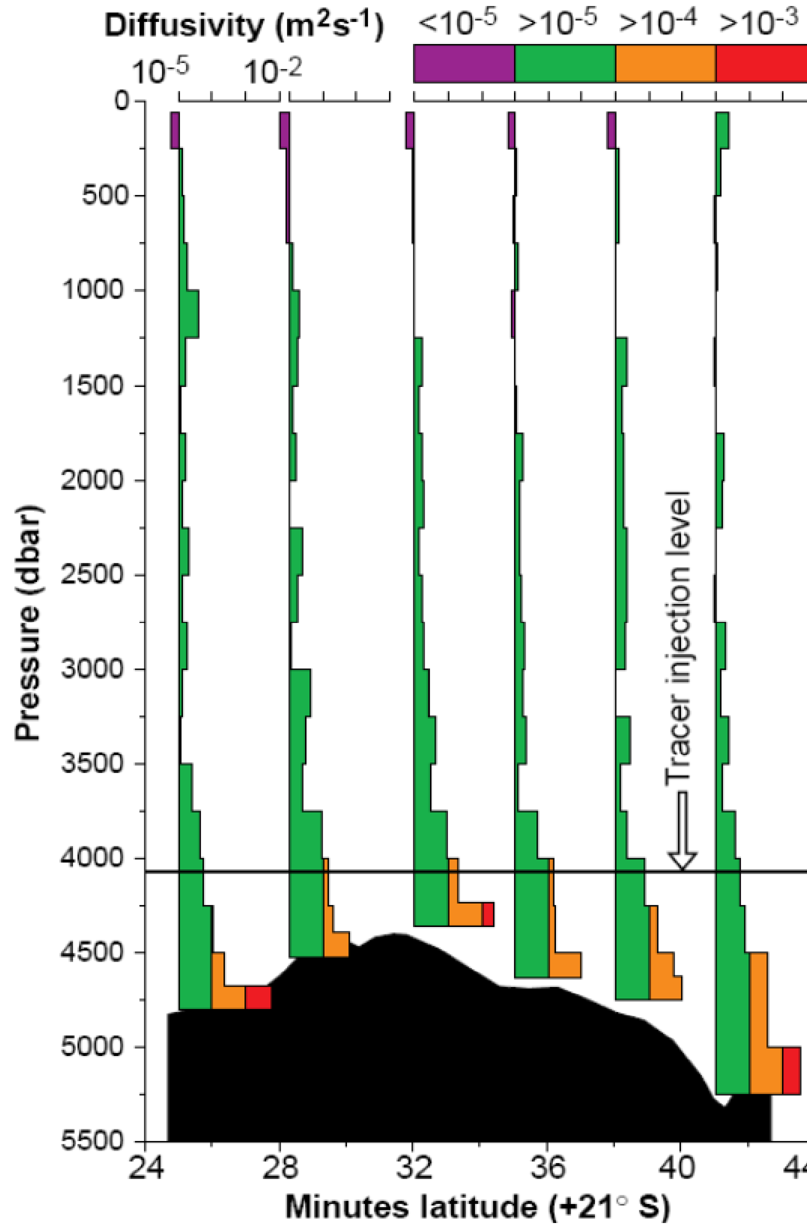
Schematic overturning modes - II



From Kuhlbrodt et al., *Rev. Geophys*, 45, 1-32, 2007.

Non homogeneous diffusivities





Polzin et al., *Science*, 1997