Application Example: A Multi-Decadal Time-Average Ocean

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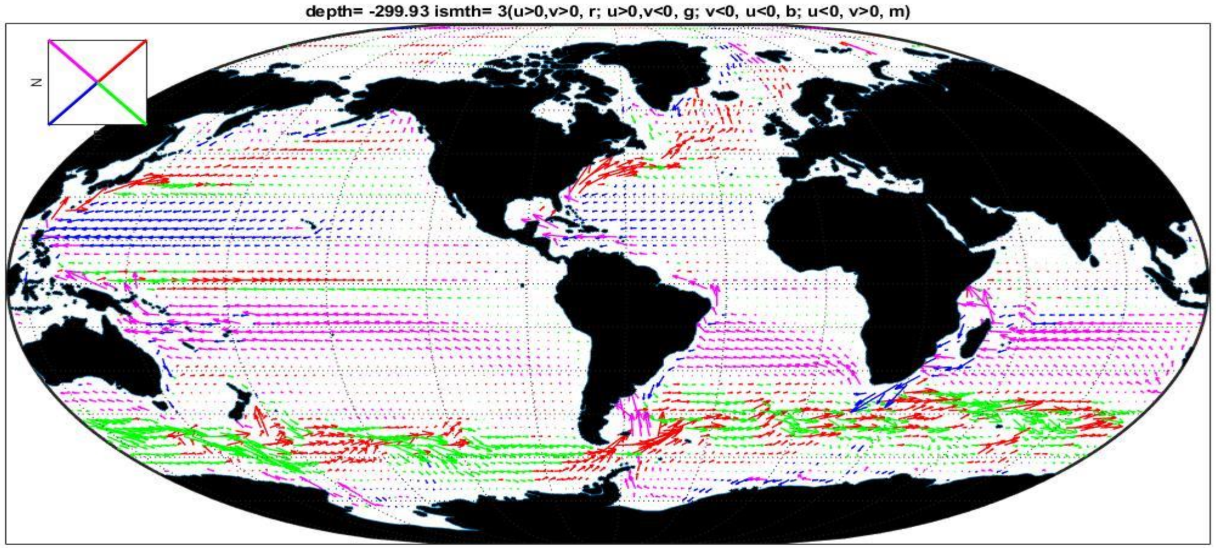


Papers available at: http://ocean.mit.edu/~cwunsch/

Can study *variability* about the time-mean: hourly, daily, monthly, yearly, and now decadal.

- In the context of the theoretical background, does a multi-decadal time-average resemble the assumed laminar steady-state??
- What are the robust, quasi-quantitative elements of the time-mean ocean circulation? Do any of the elegant theories pre-dating the WOCE+ era survive?
- Is every point or small region different? (Consider geology).

Immediate goal is to analyze using classical methods as much as possible.

Lots of questions, some fundamental, emerge---

General Inferences from piecing together 100 years of ship data :

- Ocean circulation was large-scale, with the exception of the western boundary currents and changing only slowly if at all.

- Interior ocean was in geostrophic balance (in practice, thermal wind balance):

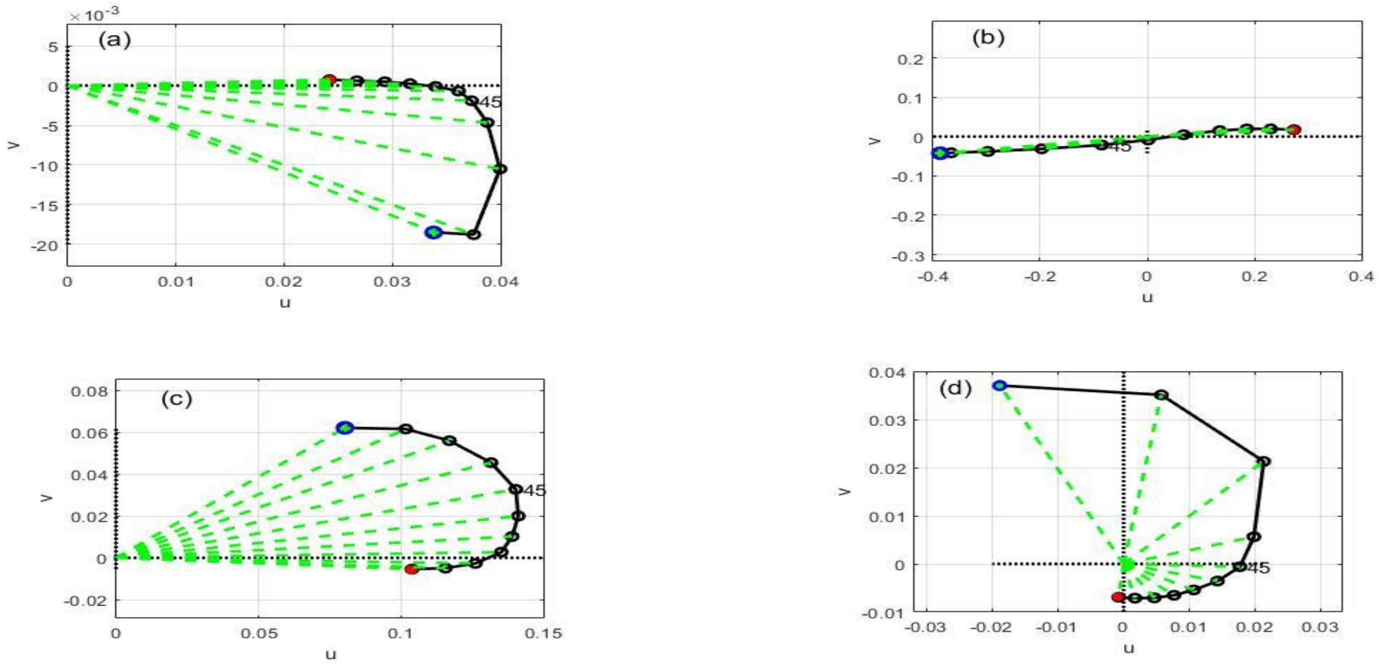
$$f\frac{\partial v}{\partial z} = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial x},$$
$$f\frac{\partial u}{\partial z} = \frac{g}{\rho_0}\frac{\partial \rho}{\partial y},$$

Could measure temperature, salinity and depth by purely mechanical means. Vertical velocity derivatives then known from the density field (using an equation of state) up to an integration constant

- Led to the assumption of the existence of a level-of-no-horizontal motion. Became a “fact”.

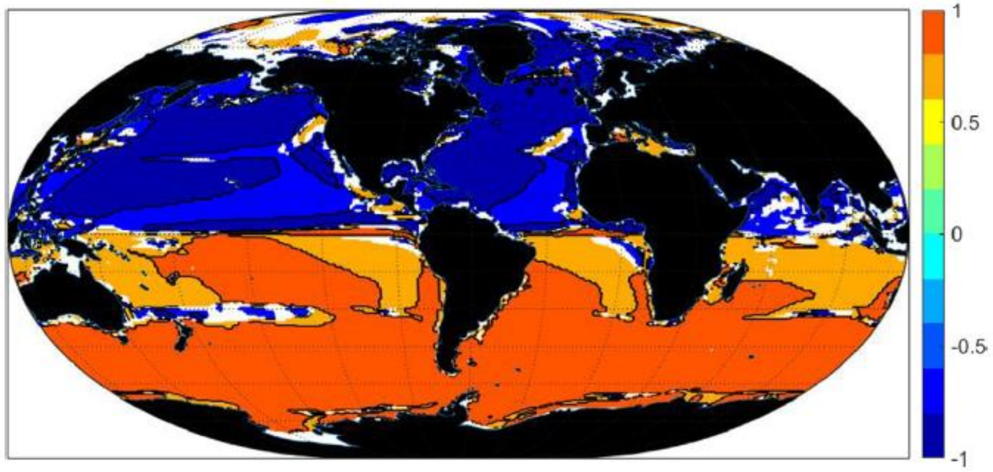
- Wind stress drove a circulation acting through an Ekman layer of thickness of order 100m. Sverdrup interiors, ….etc.

Here: Treat the time-average ECCO estimate as though an “observed” mean ocean

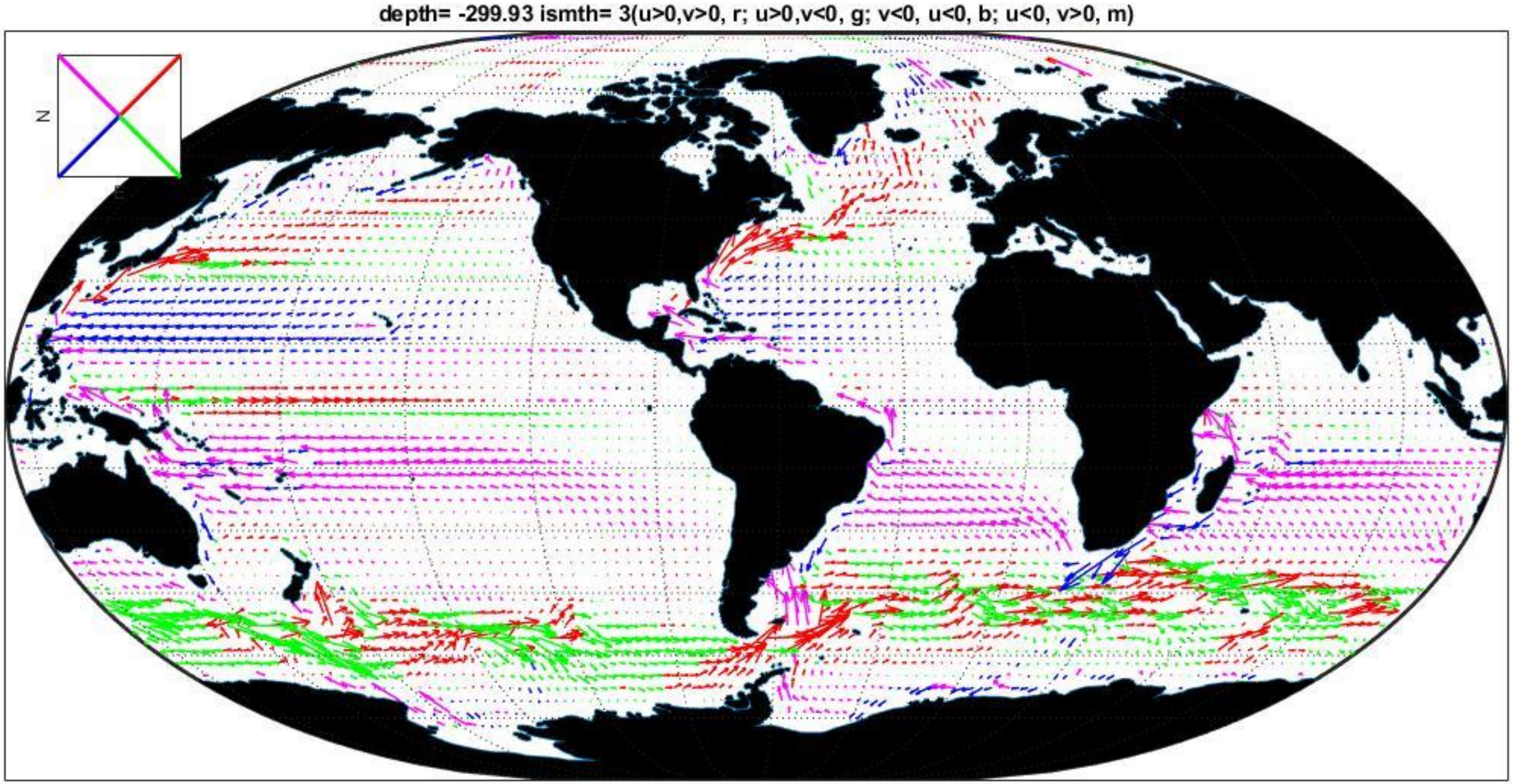


Near classical!

Hodographs to 300m 165W. Note change in sign across equator.

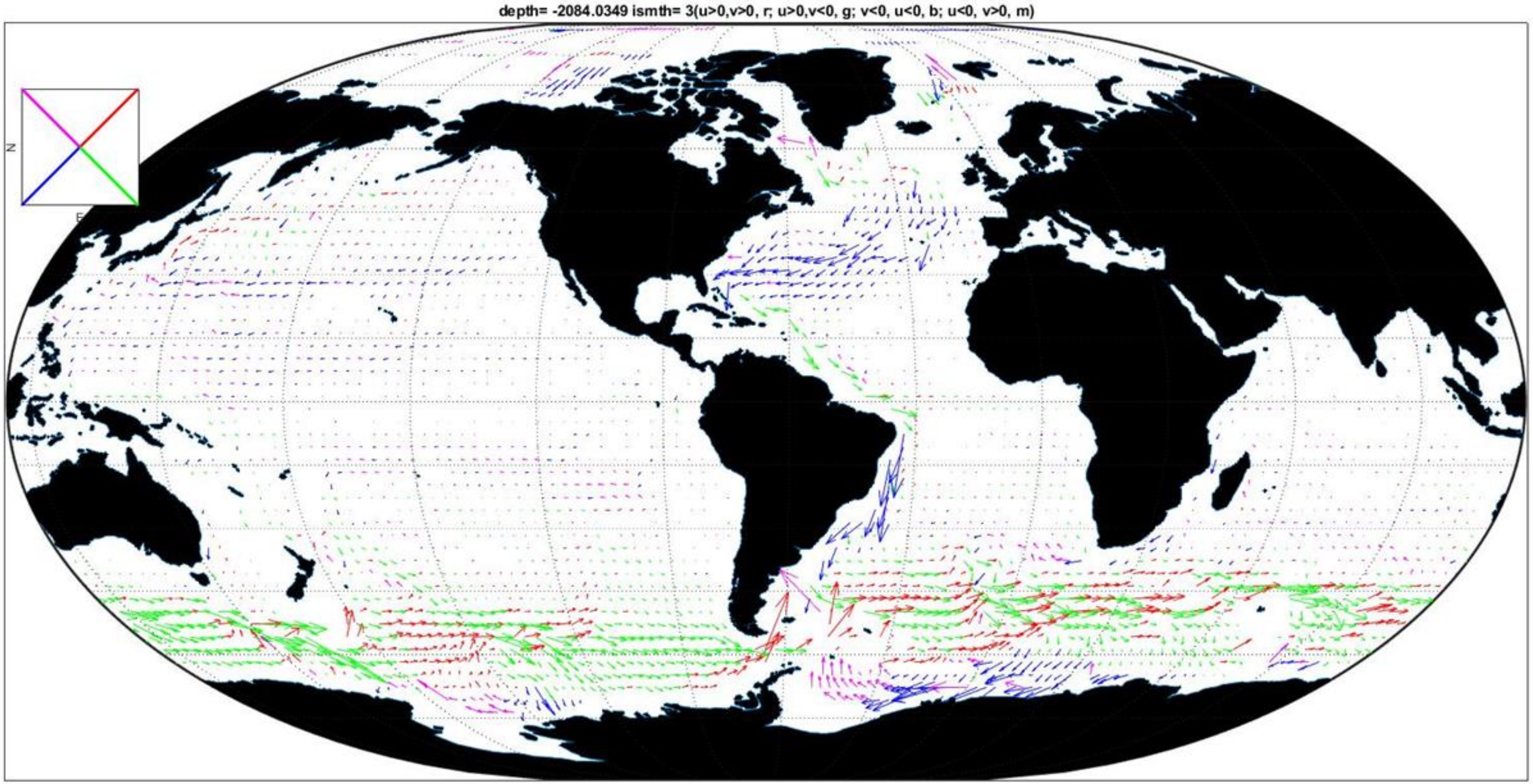


Fit of a spiral to the upper ocean velocity field. Bright colors indicate near-perfect fit of an Ekman layer.

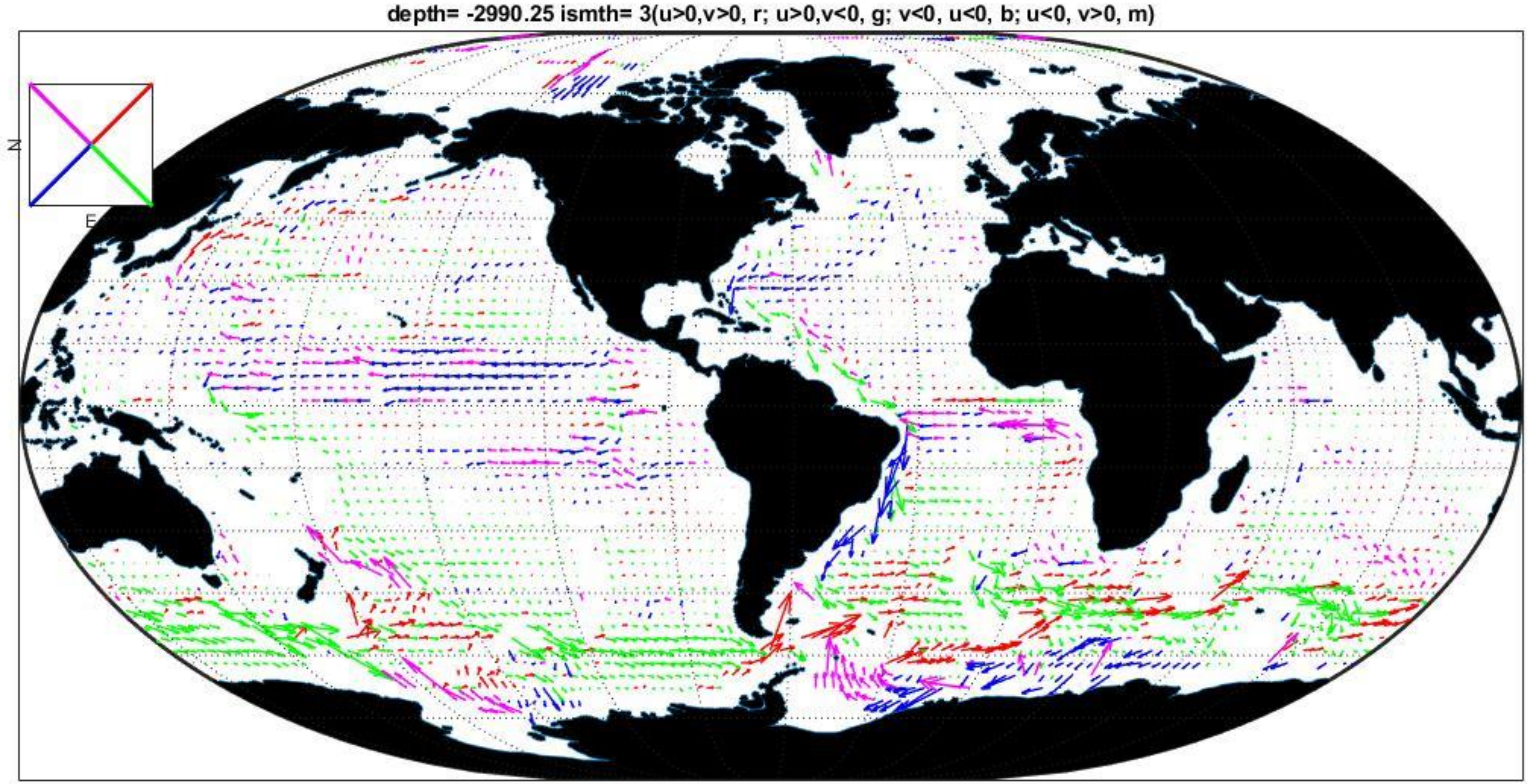


300m velocity. 3 degree smoothing

Average formed over 26 years starting in 1992.



Velocity 2000m Smoothed 3 degrees

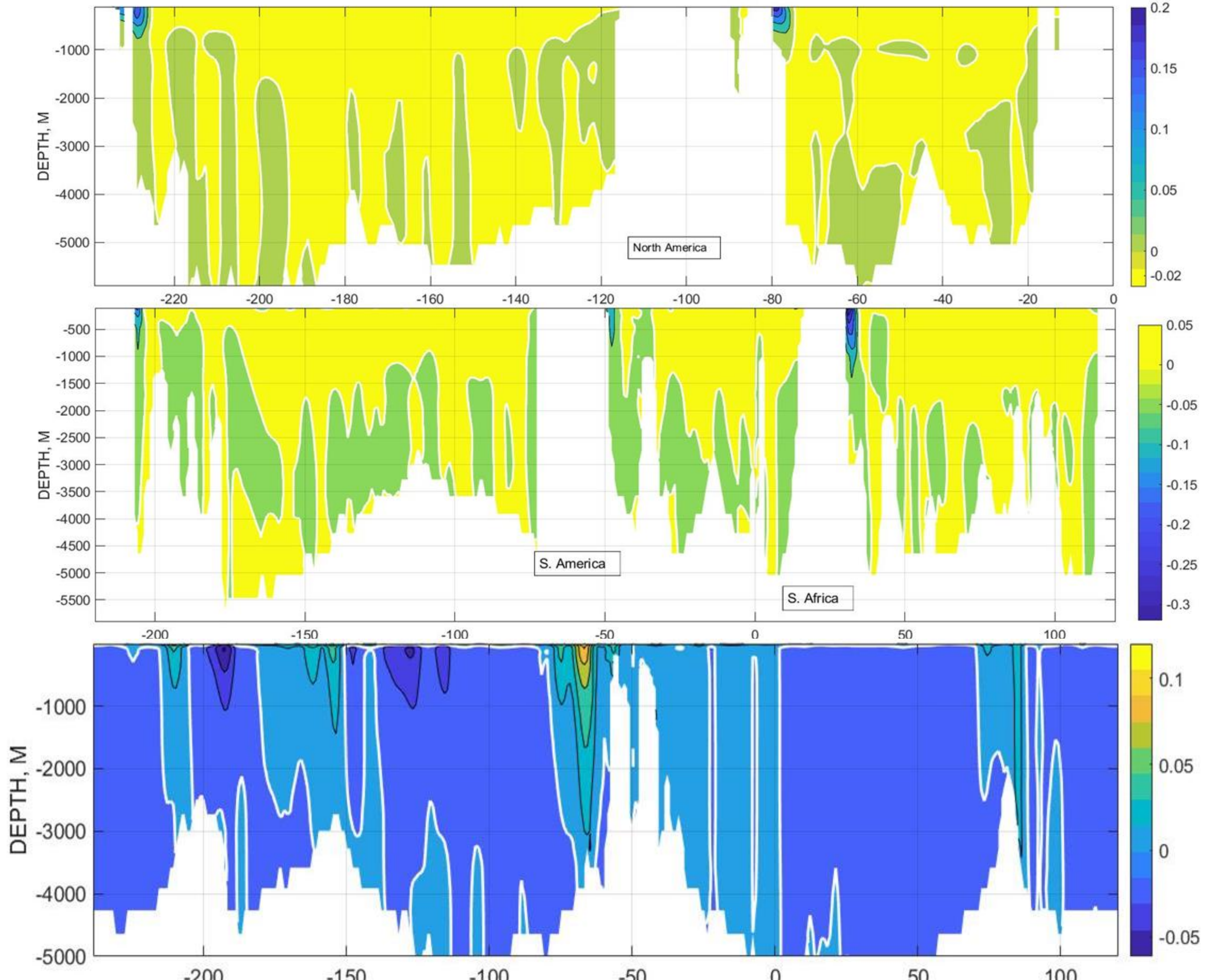


Velocity 3000m smoothed 3 degrees

30N

30S

60S



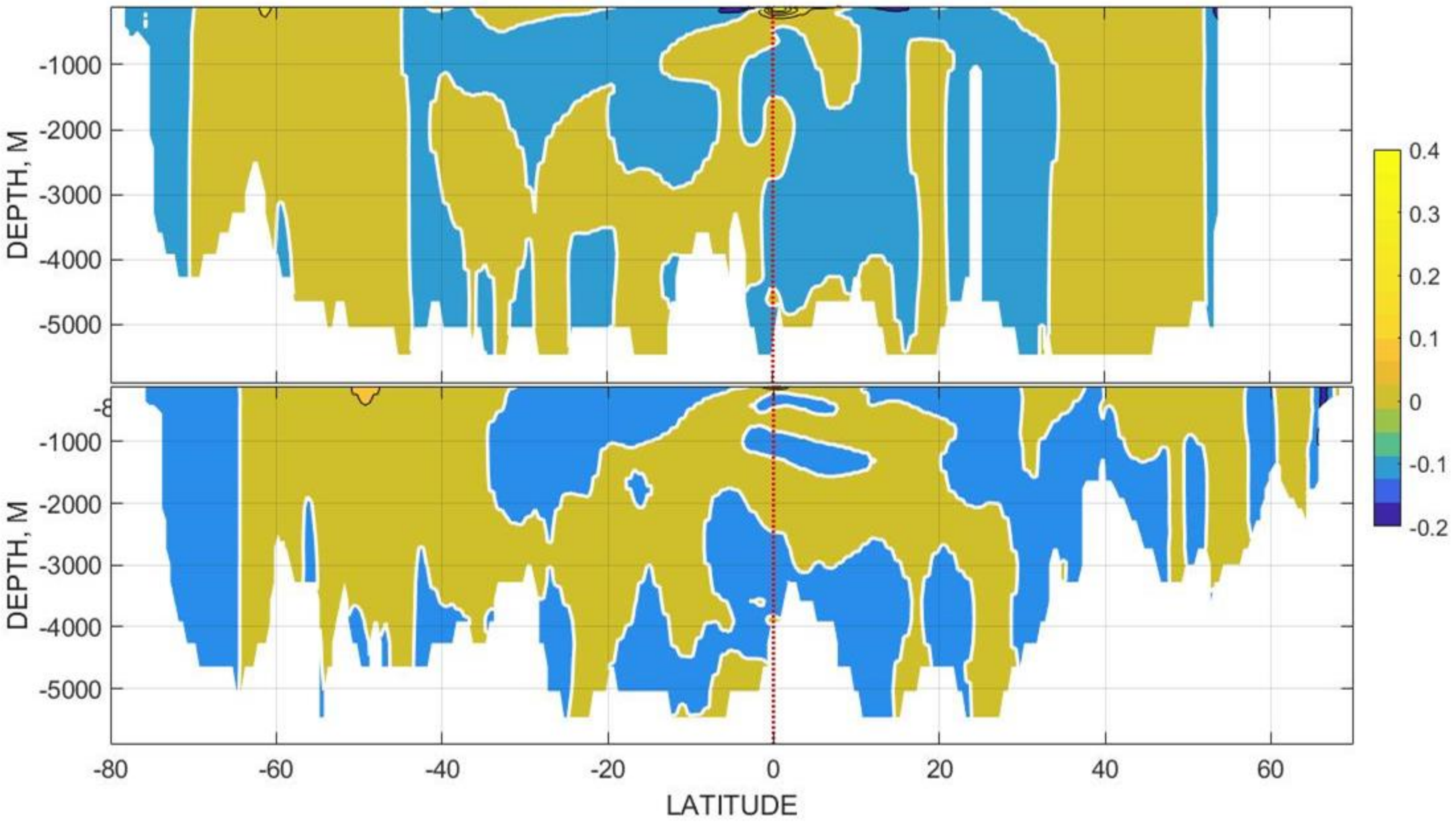
Structure persists for 26 years.
Simple abyss??

Yellow is equatorward

Time-mean meridional flow--v

165W
Mid-Pacific

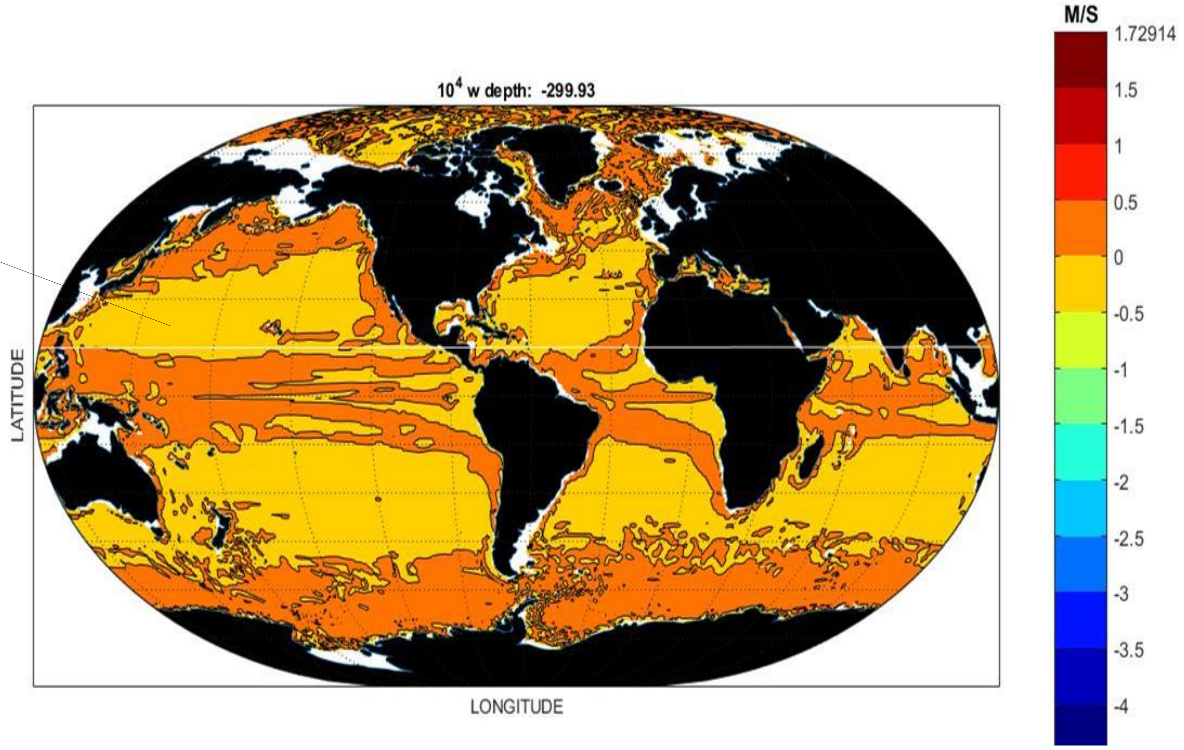
30W
Mid-Atlantic



Time-mean zonal flow-u

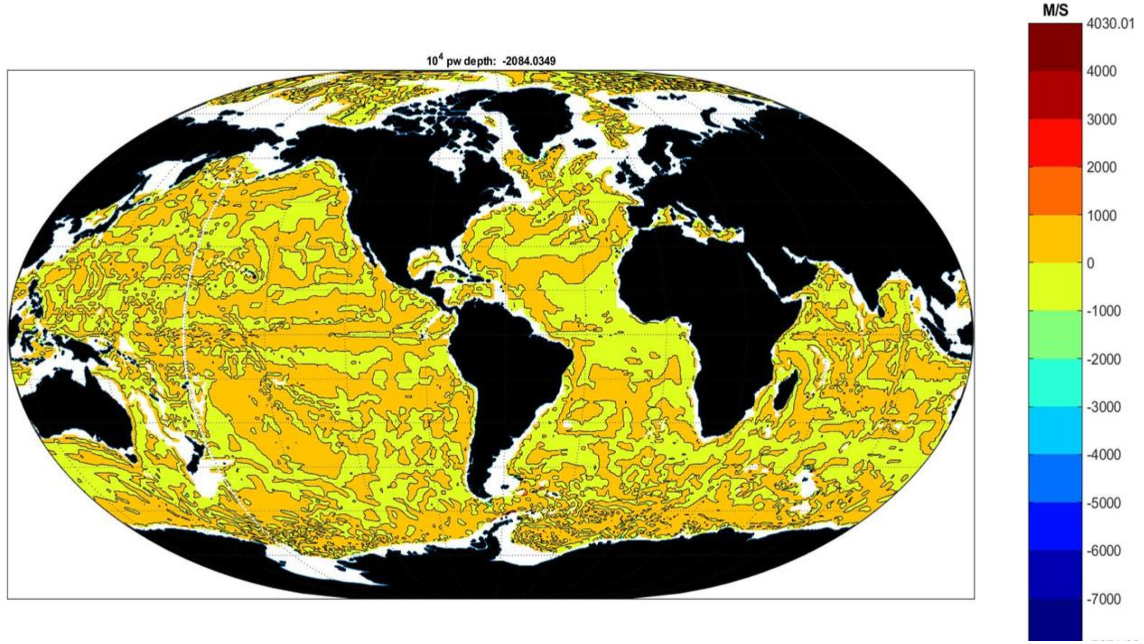
Downwelling
Ekman pumping,
Sverdrup flow

W, 300m



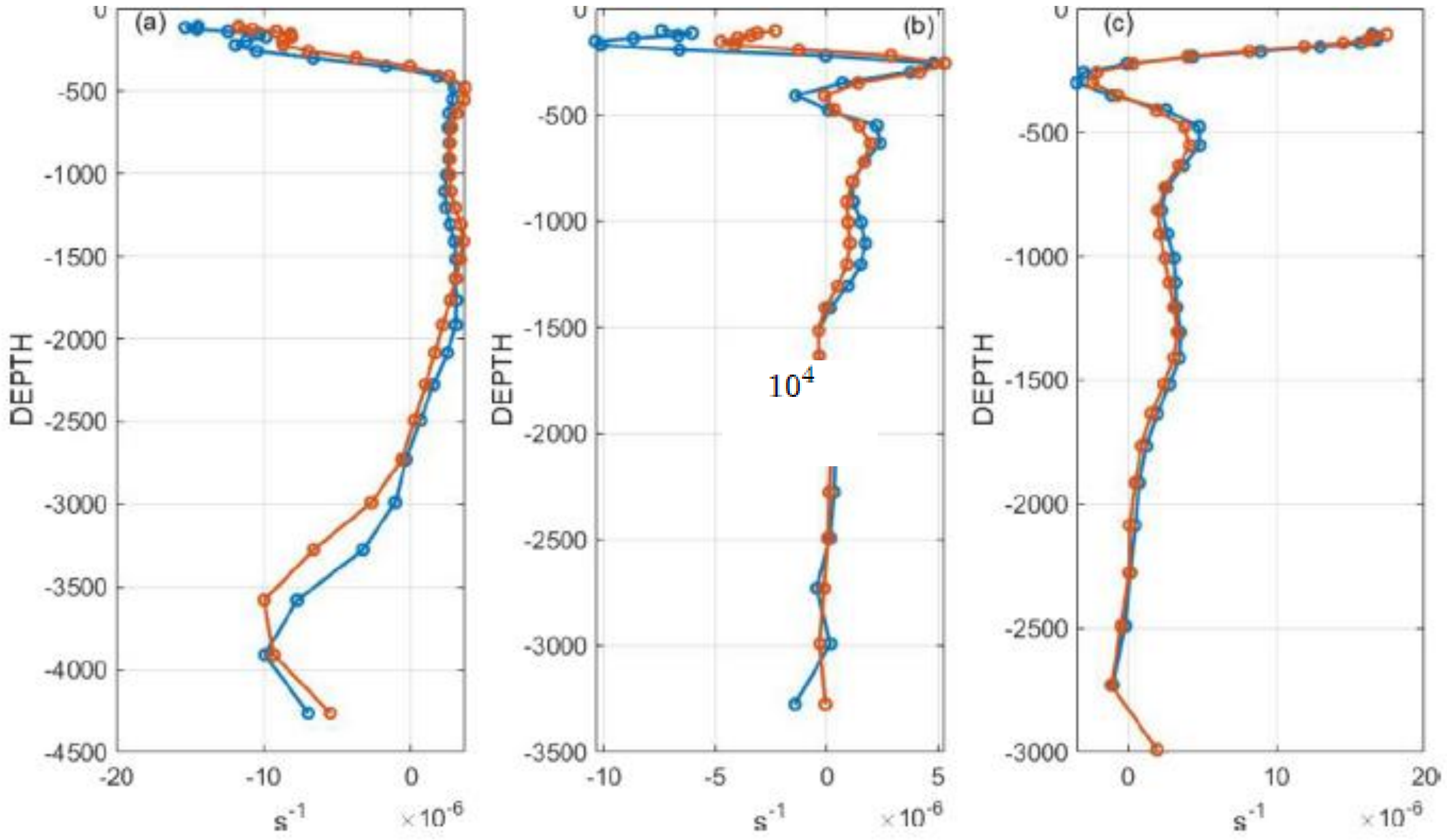
Near classical!
Also, equatorial & SO
upwelling

W 2000m



30S 10^4 (dv/dz, & thermal wind)

$$f\frac{\partial v}{\partial z} = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial x},$$



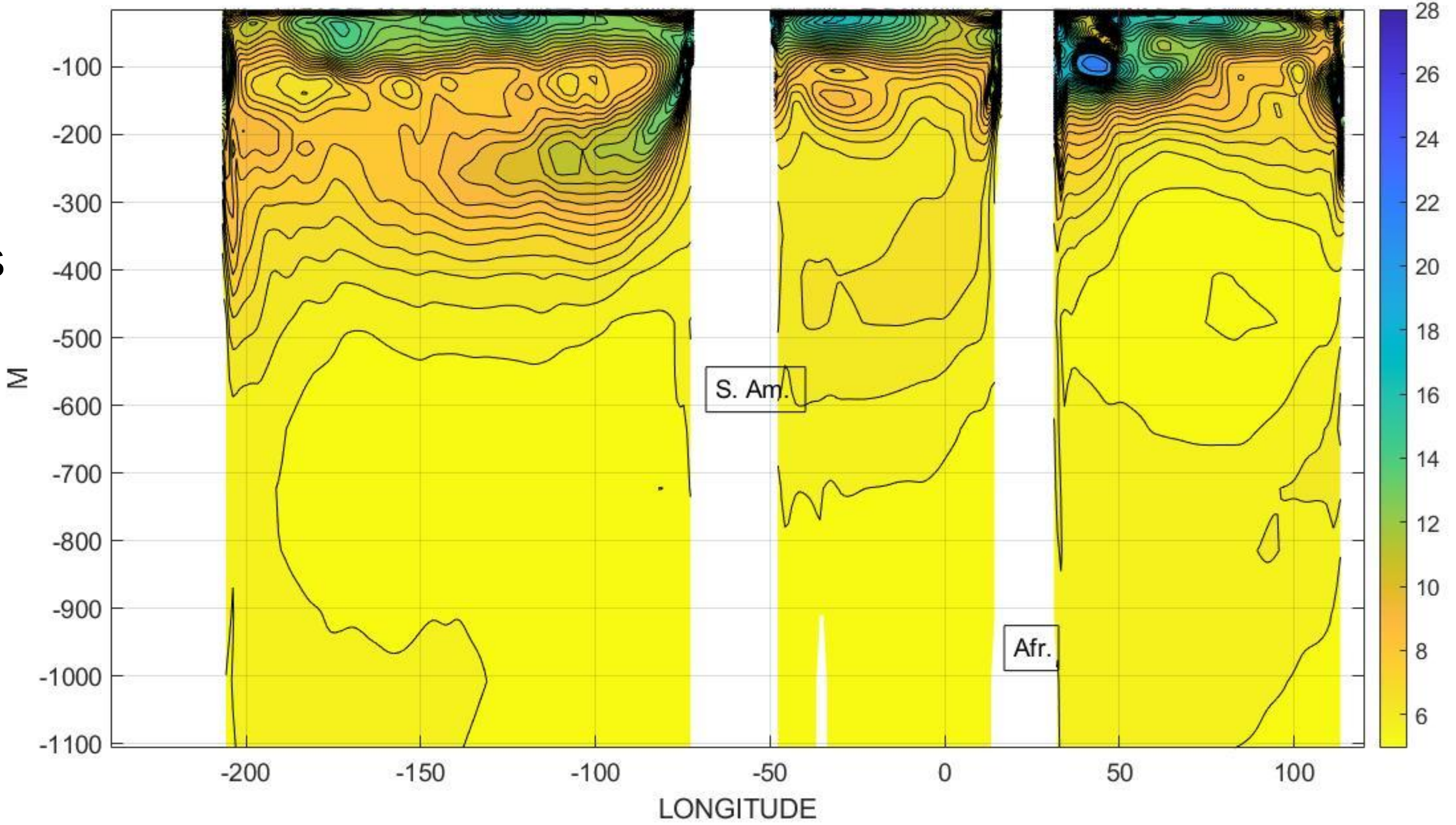
Profiles with depth of the thermal wind shear (blue) and of $\partial v/\partial z$ (red) at three Pacific longitudes 170°W, 120°W, −15°W at 30°S. Shallowest point is at 100 m.

Again, near classical balance (real deviations exist in some places).

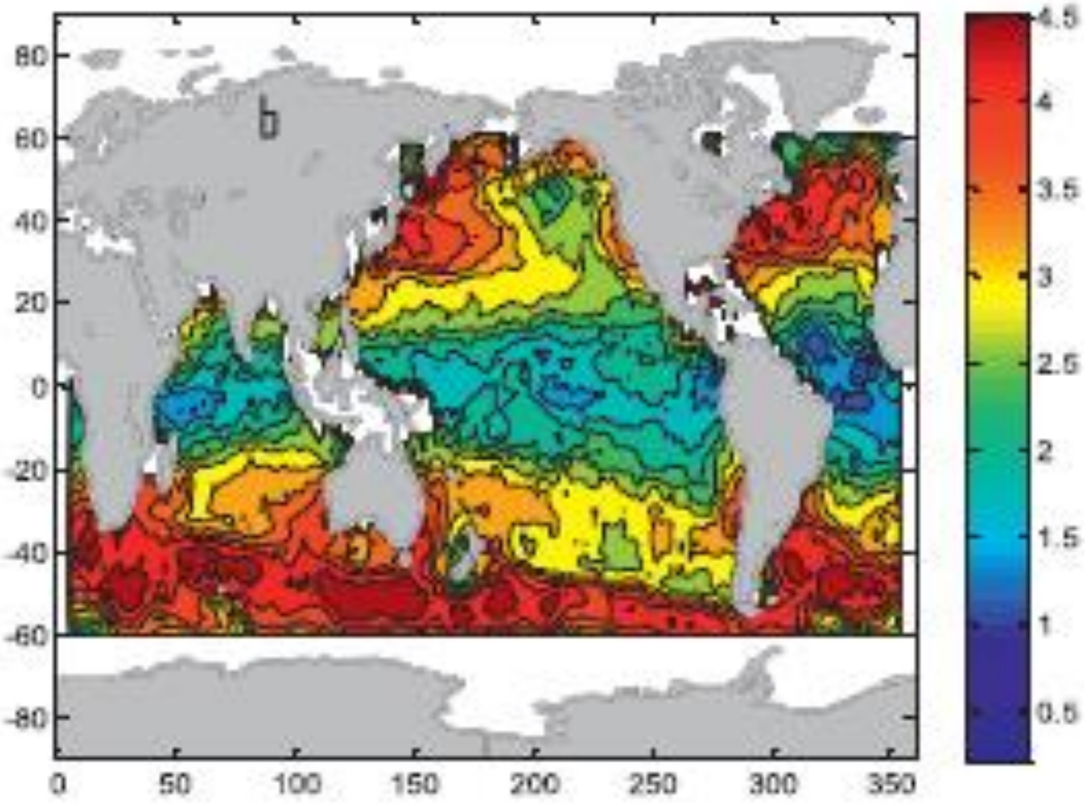
What is "the" main thermocline depth?

$$\frac{\partial \rho}{\partial z}$$

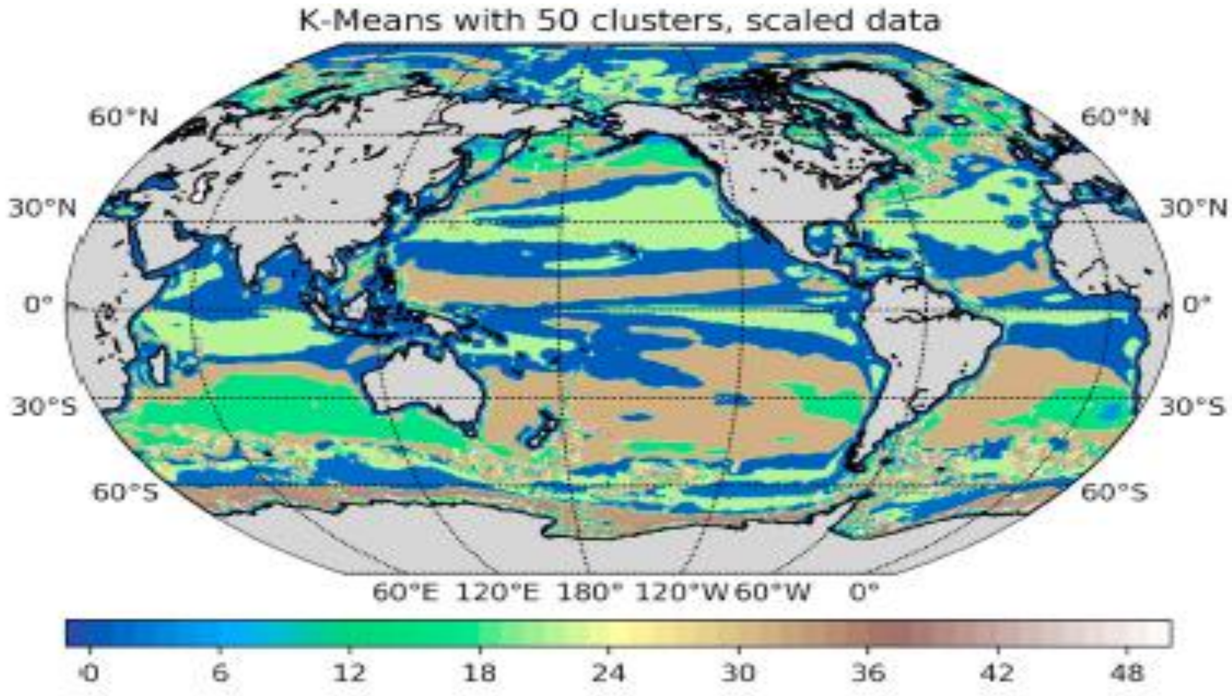
30S



Expectations of numerous distinctly different physics, perhaps anticipaed:



Xu & Fu, JGR 2012
Spectral slopes in SSH from altimeter



Sonnewald et al, 2019, Earth,Space Sci.
Regions of similar barotropic vorticity dynamics.

In the search for simple large-scale statements about the ocean circulation,
Consider the famous Munk (1966) “abyssal recipes”, which determines a scale-height:

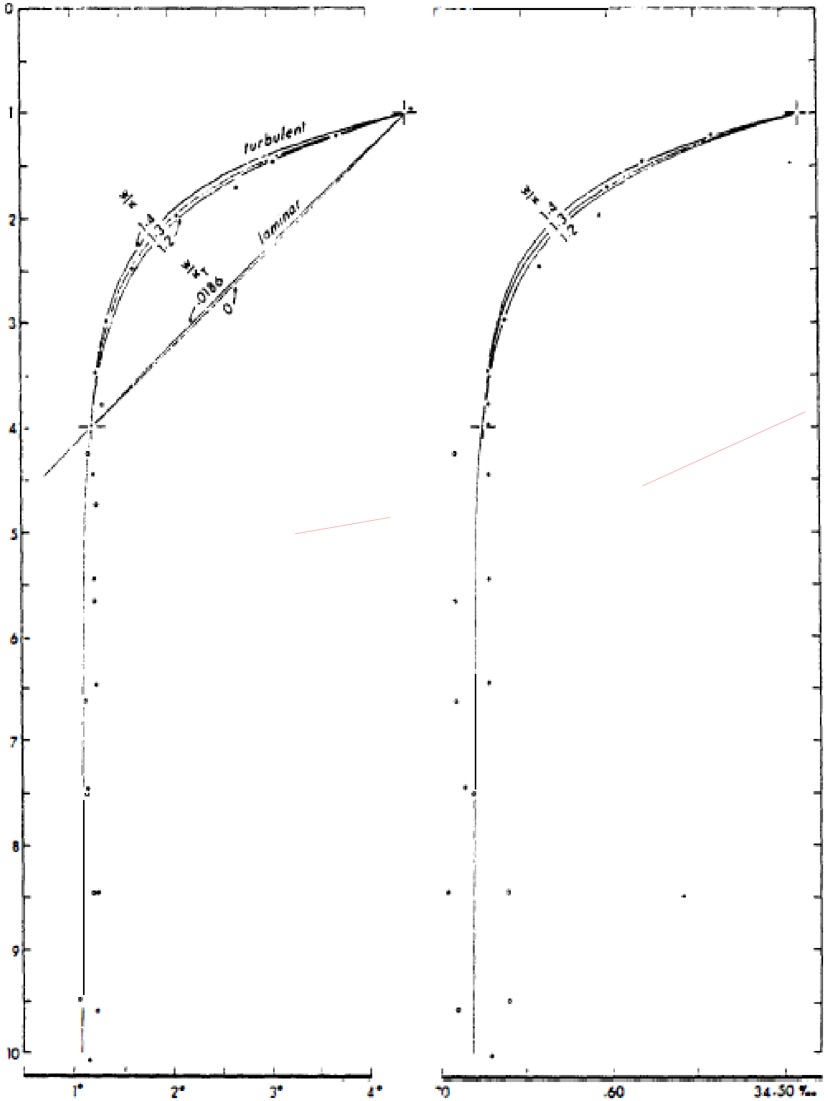


Fig. 1. Potential temperature and salinity as functions of depth (km) at stations *Snellius* 1930 : # 262, 9° 41'N, 126° 51'E, (closed circles) and *Galathea* 1951 : # 433, 9° 51'N, 126° 51'E, (open circles). Curves labeled w/κ (in units km^{-1}) are based on equations (1) and (2) for turbulent and laminar diffusion, respectively.

$$w\frac{\partial C}{\partial z} - K\frac{\partial^2 C}{\partial z^2} = F, \text{ or } 0$$

Scale height: K/w

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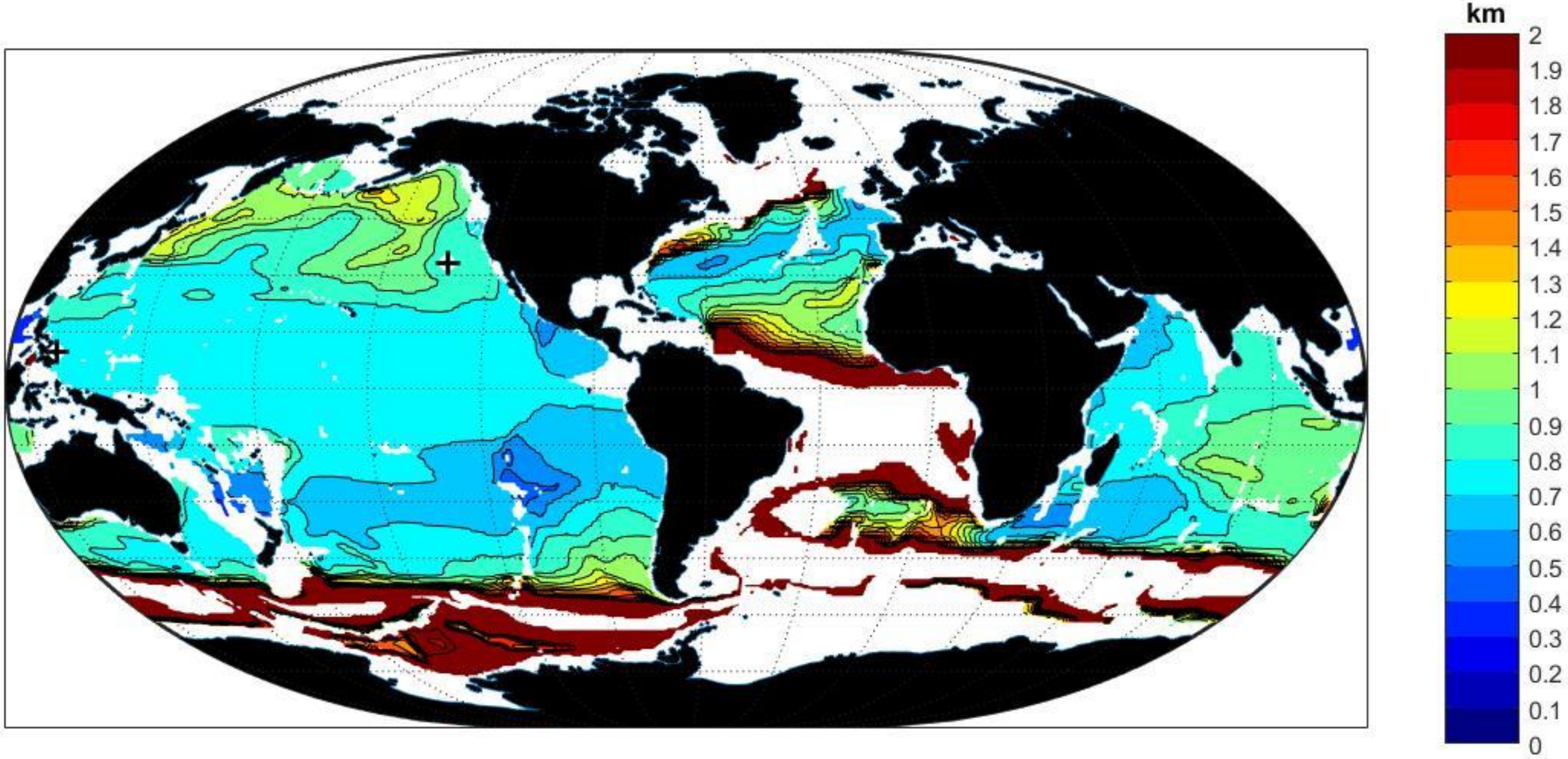
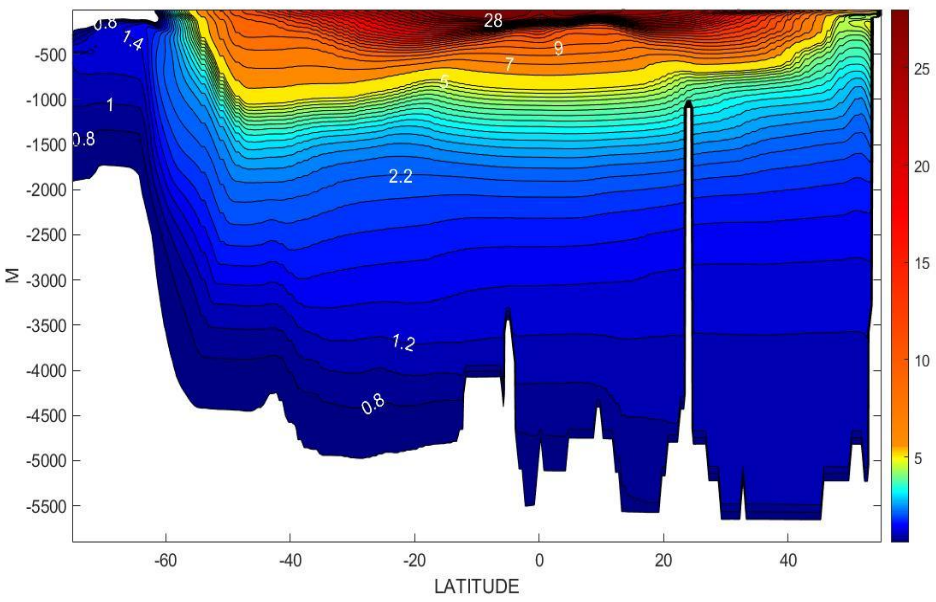
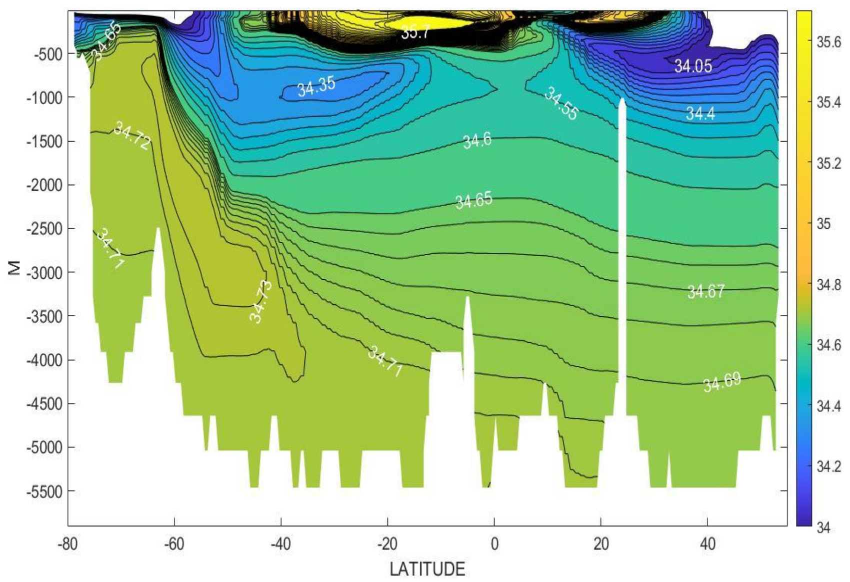


turbulent and laminar diffusion, respectively.



Potential temperature, 165W



Salinity 165W

Where the two scale heights agree within 20%

Original interpretation not very useful
(Works for density. Why?)

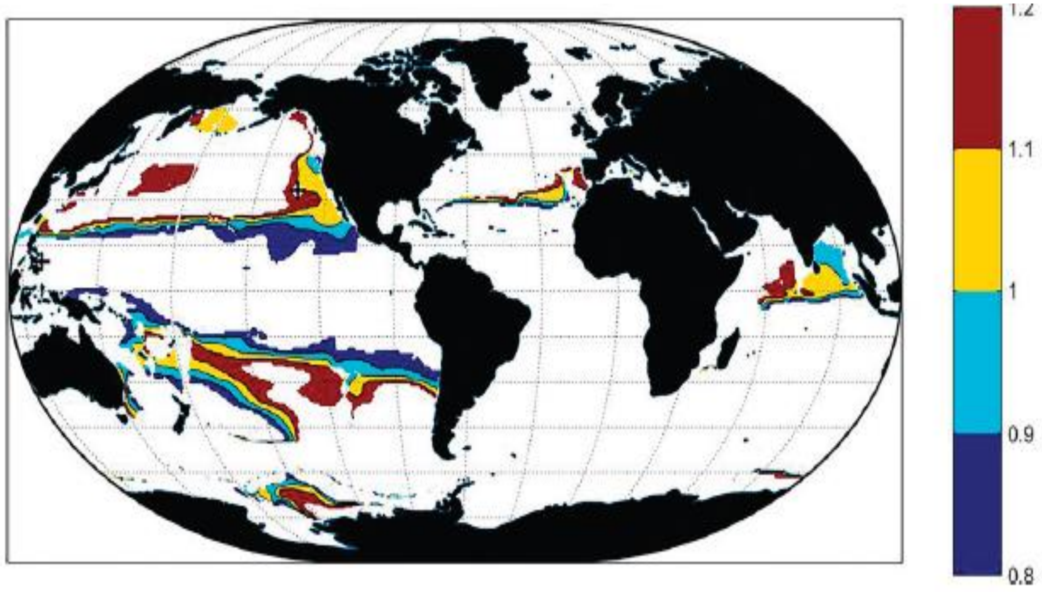


FIG. 14. Colored shading shows where the ratio h_S/h_T lies within 0.8–1.2. The M66 eastern mooring result falls within this range.

THE DAY AFTER TOMORROW

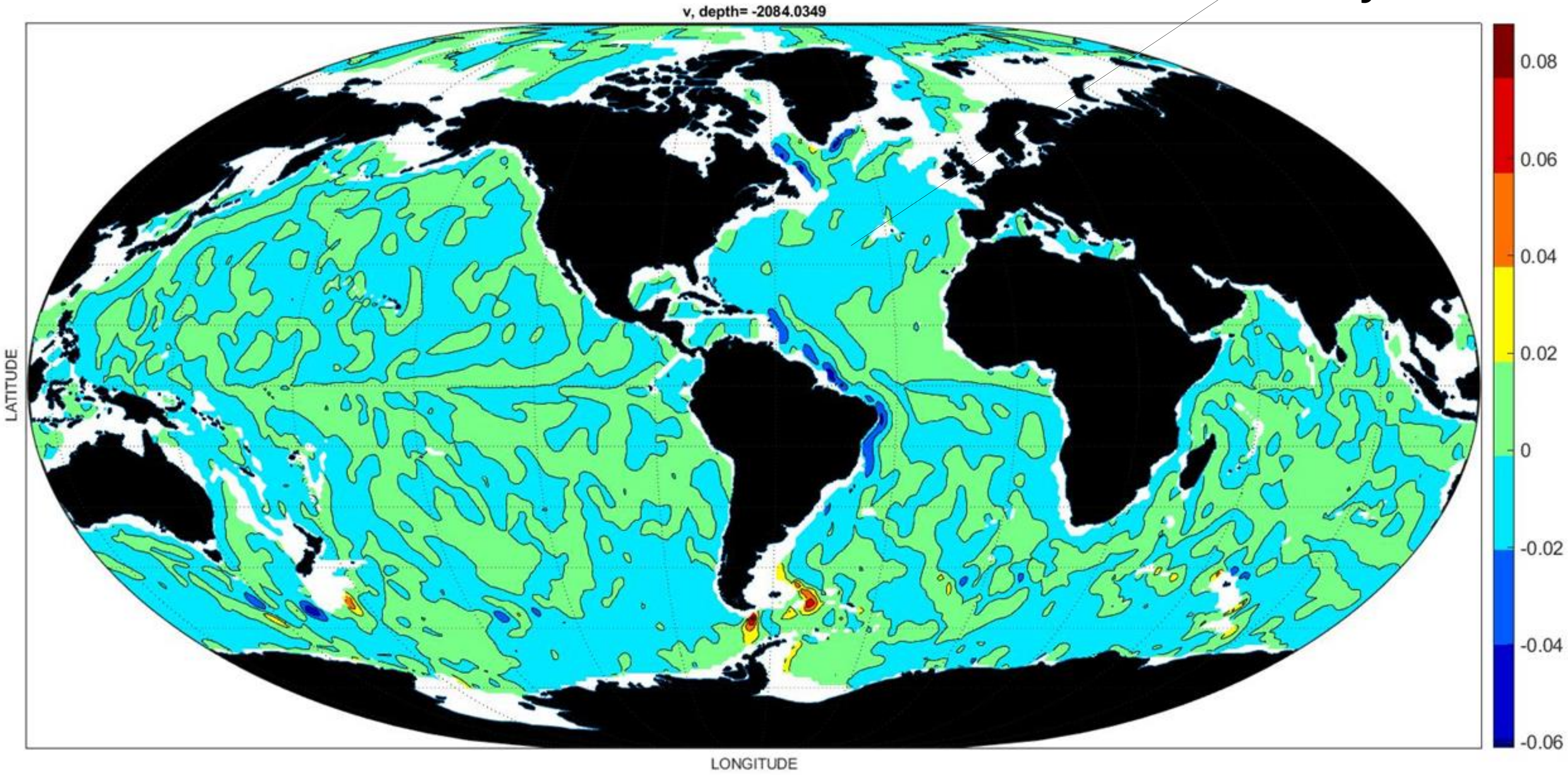
A quiet academic field has become exciting!

See also, BBC Horizon programme, The Big Chill.

The AMOC Fantasies:

Everywhere southward

Meridional flow 2000m

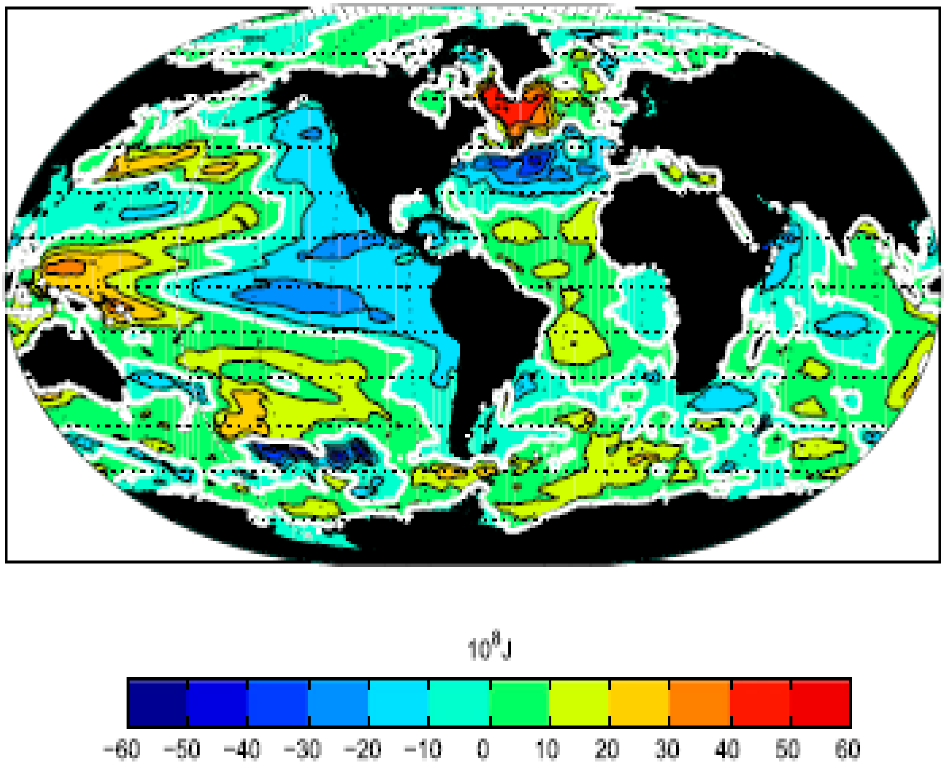


See Liu et al., 2024:
Suggest is controlled by wind.
(Consistent with Wüst, 1936)

Many applications, including energetics (input, transfer, dissipation), carbon, oxygen uptake and exchange, sea ice behavior, acoustic fields, equatorial circulations, tracers, biology,.......

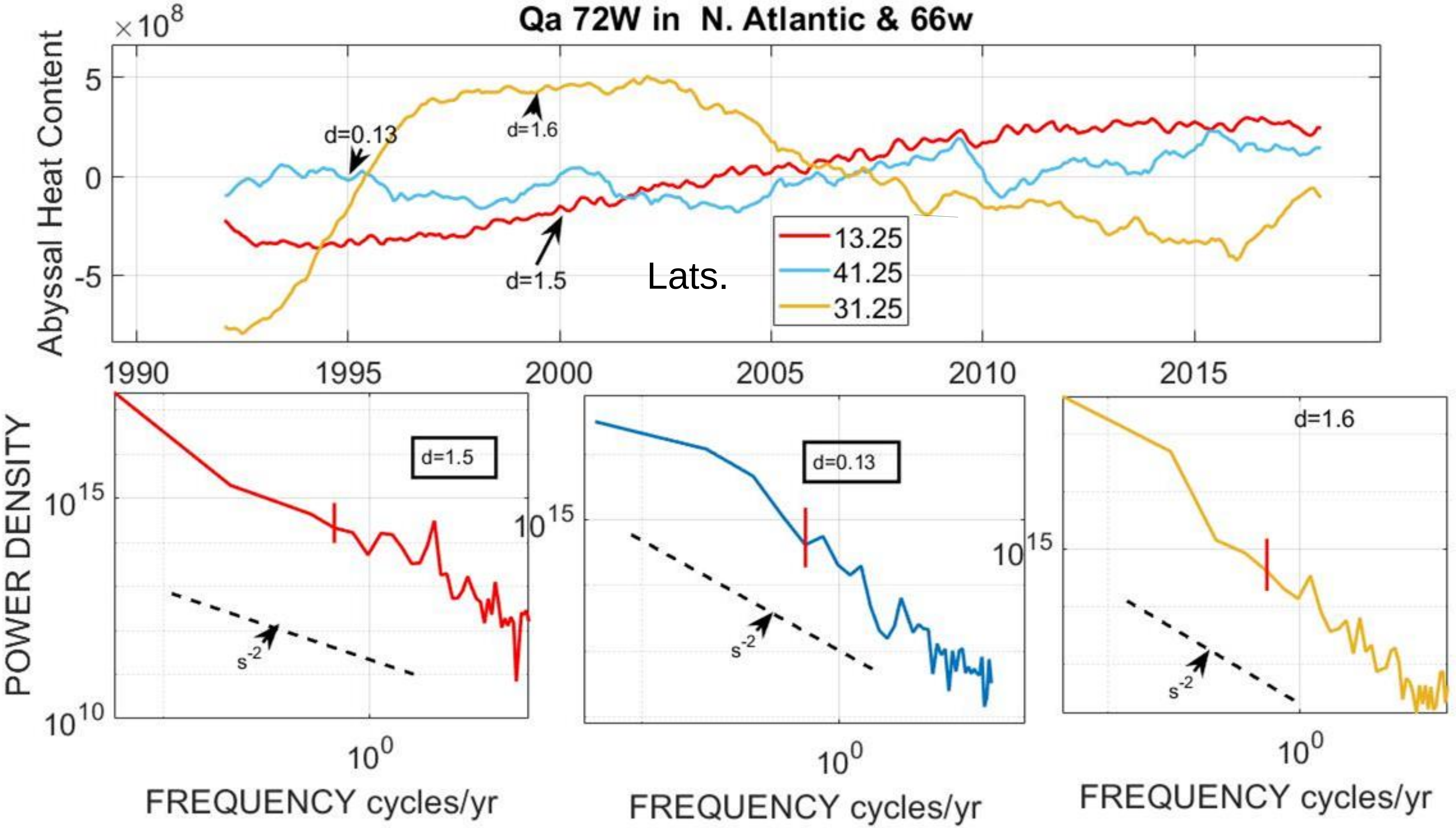
Estimated ocean heat content change: 2011-1993. Top to bottom.

Wunsch and Heimbach, 2014

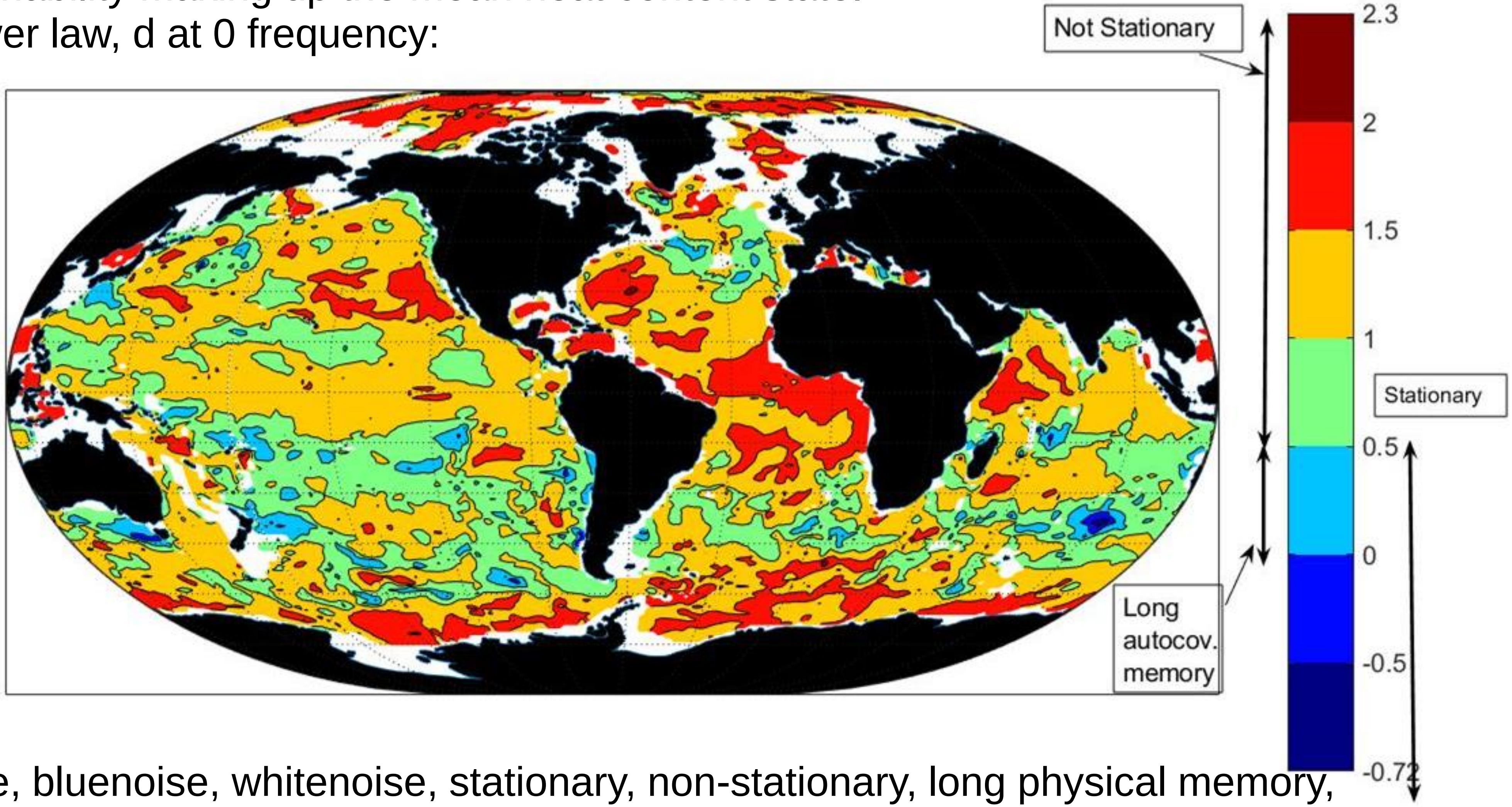


Net heating is about 0.2+/-0.1W/m^2. Not simple!

Radically different temporal variation behavior with region.



Consider the time variability making up the mean heat content state.
Spectral density power law, d at 0 frequency:



A mixture of rednoise, bluenoise, whitenoise, stationary, non-stationary, long physical memory, long autocovariance memory,.... The global mean heat content/temperature, and their global mean trends represent an average of statistically very different time-variability.
What is their uncertainty??? Answer appears to be beyond existing statistical tools.

And consider the spatial/temporal sampling problem!

Some Conclusions:

- *A great deal of sub-gyre scale structure persists even in a multi-decadal average. To understand the time-mean and time-variable global ocean circulation and its implications, one must also understand its intense regionality. Understanding the ocean is simultaneously a problem of global and regional physics (and chemistry and biology).*
- Geostrophy & thermal wind are very useful over large areas.
- Ekman-like theory is robust.
- Sverdrup-balance applies widely
- Abyssal recipes does not apply in its original form
- Stommel-Arons flow (and associated AMOC arguments) does not exist in the N. Atlantic.
- Difficult to define a depth for the main thermocline.
- Little evidence for the beta-spiral.
- Measureable annual and semi-annual cycles in the abyss
- ...

Major Issues Arising Simply From Ability to Calculate a Mean State:

- Does a time-averaged ocean circulation have any meaning? Is the ocean in a steady-state? Has it ever been?

- Does time-averaging simplify the flow? Do any of the classical theoretical constructs apply to the time-average ocean? (Answer: Some.)

- After averaging, which of the remaining structures are statistically significant?

- In a complicated “container” shape (sidewalls, bottom topography) is it reasonable to expect regional-scale effects to vanish with averaging? (Geometry has zero frequency.)

- Is a coarse resolution representation (model) adequate as a turbulence closure? Is it adequate in not resolving various boundary layers and topographic features? How sensitive is the large scale structure to the eddy-parameterizations and to unresolved boundary layers? Effects of fractal container boundary?

- What is the formal uncertainty of the time-mean state estimate? (Dimension of the state vector!) Of trends?

Thank You