The global dominance of the Atlantic circulation, seen through boundary pressures.

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Part of this work can be found in

Hughes, C. W., J. Williams, A. Blaker, A. Coward and V. Stepanov, 2018: A window on the deep ocean: The special value of ocean bottom pressure for monitoring the large-scale, deep-ocean circulation. *Progress in Oceanography* **161**, 19-46. doi: 10.1016/j.pocean.2018.01.011.

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Why boundary pressure

- The continental slope is especially steep, and connected around the world over very long distances.
- The ocean contained horizontally between such continental slope regions is more than half of the total ocean volume, and an even greater fraction of the dynamically active region.
- The mesoscale is strongly suppressed over the slope, meaning pressure here reflects large scale dynamics. Scaling argument: Vorticity balance limits bottom w to smaller values than would be produced by mesoscale eddies hitting a slope (see paper for details)

kinematic boundary condition (no flow through the bottom, which slopes in the x direction):

$$w_b = -u_b \frac{\partial H}{\partial x} = \frac{1}{\rho f} \frac{\partial p_b}{\partial y} \frac{\partial H}{\partial x}$$

If S is the slope: $w_b \sim u_b S$

vorticity balance $\boldsymbol{\omega}$ is vorticity, ζ is its vertical component) :

$$\zeta_t + \boldsymbol{v} \cdot \nabla (f + \zeta) = \nabla \cdot [w (f\hat{\boldsymbol{k}} + \boldsymbol{\omega})]$$

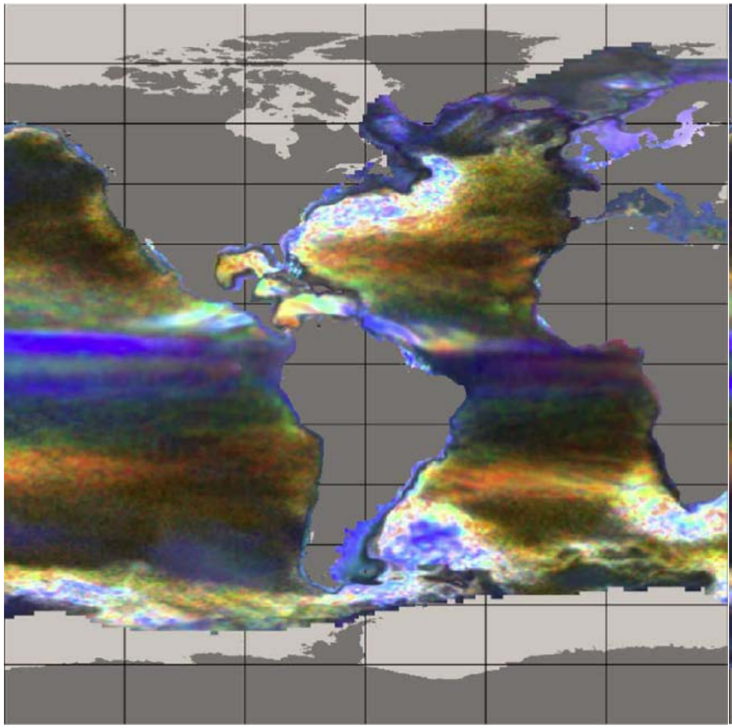
gives another scaling for the bottom velocity, when integrated over depth. Equating these scalings (see Hughes et al., Prog in Oceanogr. 2018 for details) gives

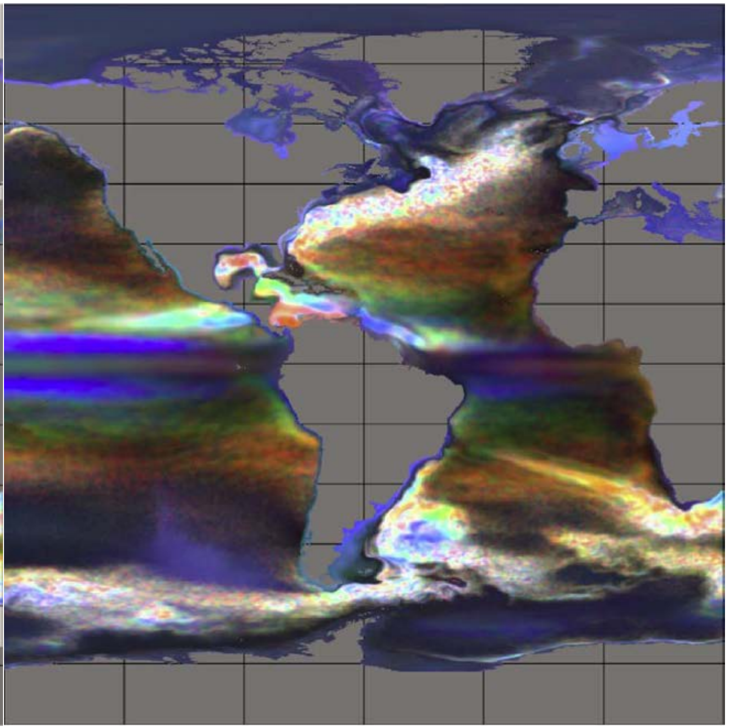
$$\frac{u_b}{U} \sim \frac{H\mathrm{Ro}}{LS(1 \pm \mathrm{Ro})}$$

Bottom flow much smaller than typical flow if 1) Rossby number is small (not submesoscale), and/or 2) Slope is steep compared to aspect ratio of flow (S >> H/L).

Overall: the slope averages out the eddies. Mesoscale variability is suppressed on continental slope as long as contours are long compared to the eddy scale.

Diagnostics from a model



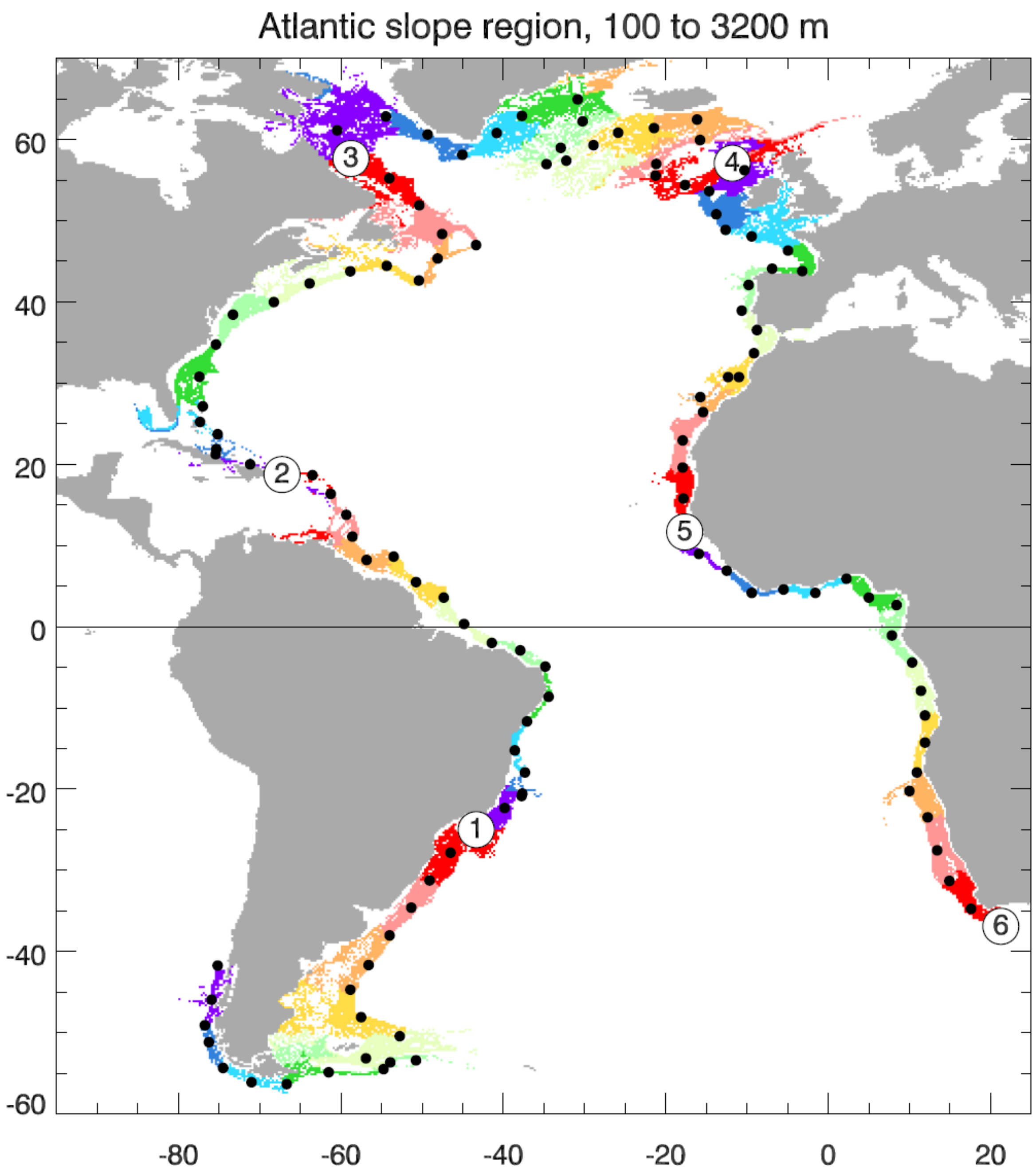


- NEMO at 1/12 degree resolution.
- 60-year model run.
- Linear trends, annual and semiannual cycles removed in all diagnostics.
- 5-day means, or monthly means for MOC (later).

Observations
20 years of satellite altimetry – AVISO gridded data

Model
28 years of 5-day means

In these plots, brightness is a measure of amplitude of variability, and colour is a measure of shape of the spectrum. Clearly the model does a good job of representing both. The mesoscale has realistic amplitude and spectrum.

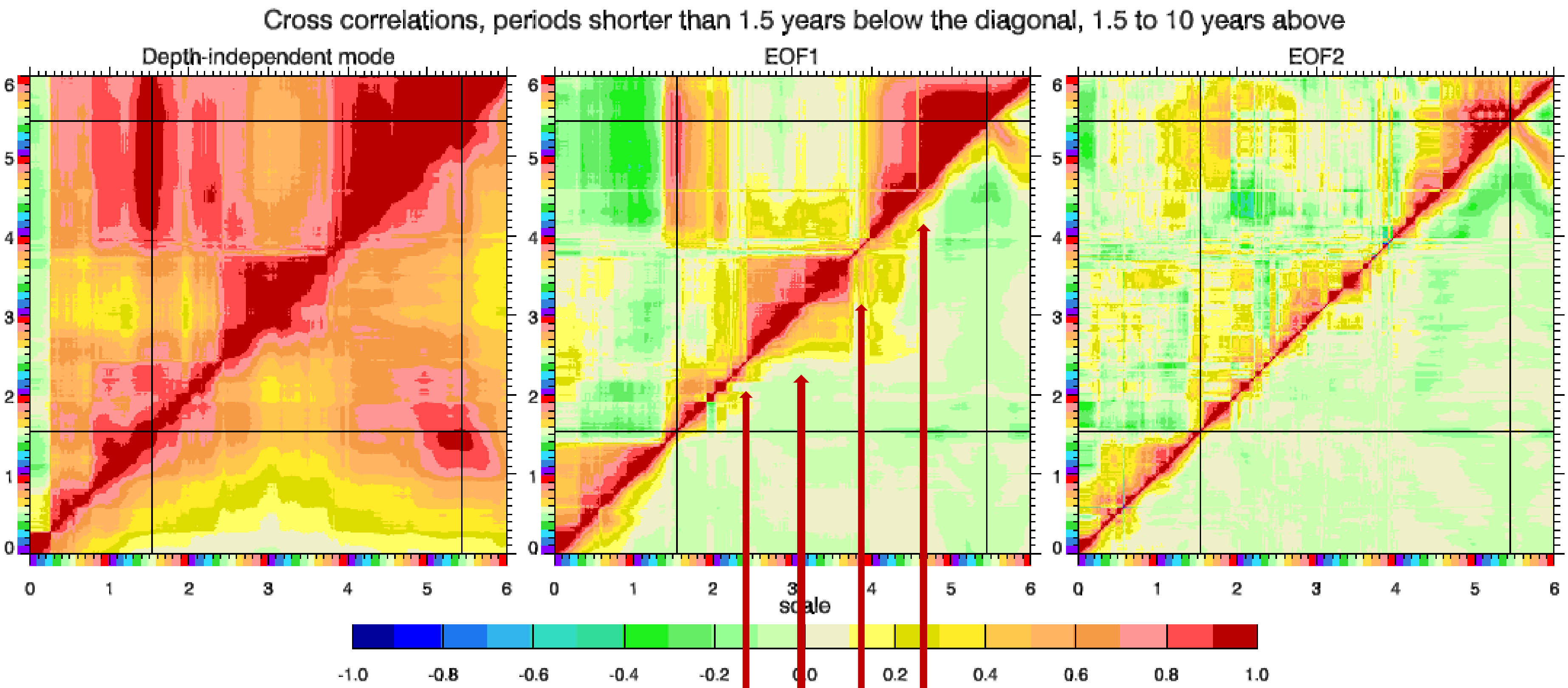


Focus on time dependent variability in the Atlantic only

Depths 100 – 3200 m.

Extract bottom pressure anomaly as a function of depth and distance along the slope.

Numbers represent distances in units of 10,000 km. Dots are every 500 km, colour changes every 1000 km.



Highly coherent variability over distances of ~10-20,000 km

(N.B. scale is in units of 10,000 km)

Off-diagonal block = correlation between western boundary and eastern boundary at the equator (black lines are equator)

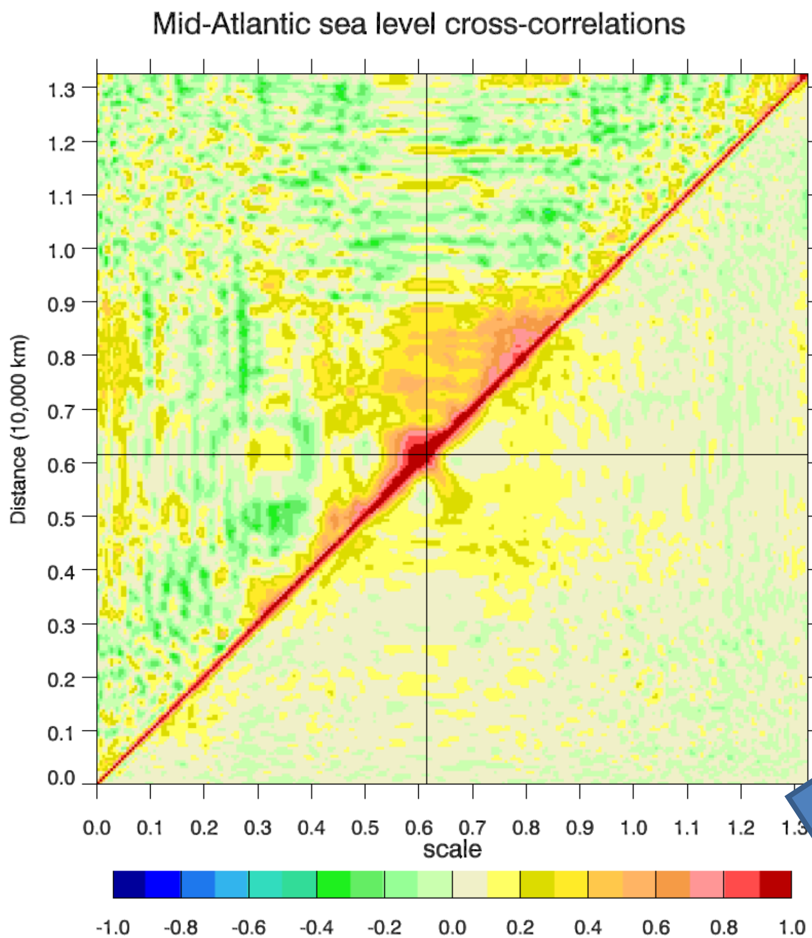
EOFs of (z,t) are calculated independently at each x, and represent different "vertical" modes.

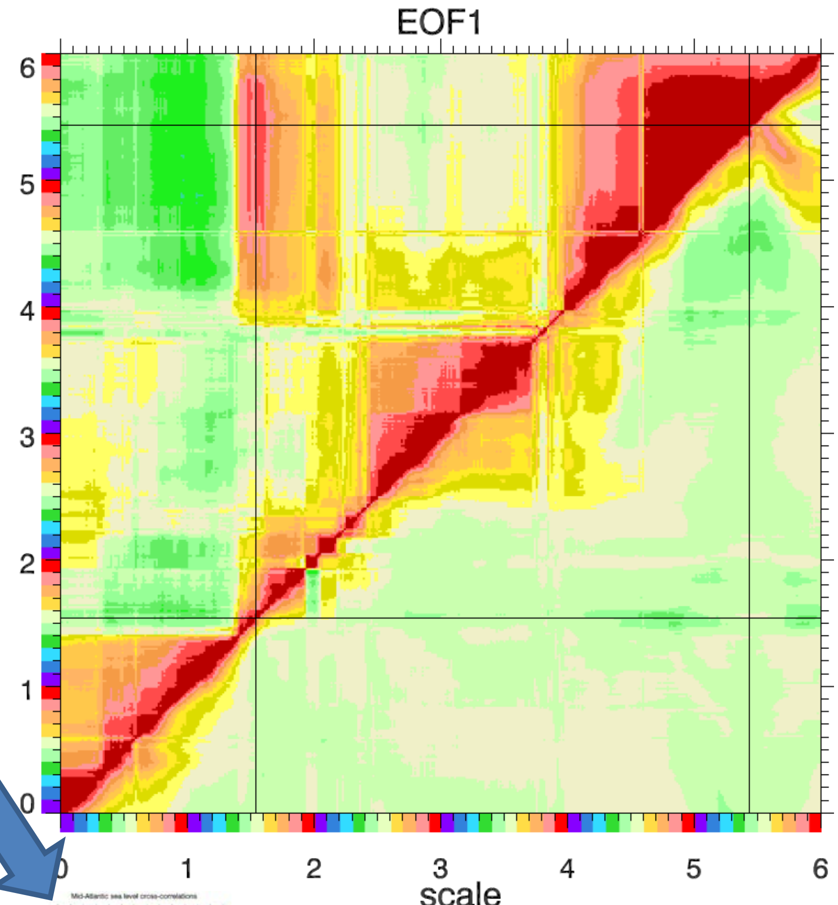
For comparison:

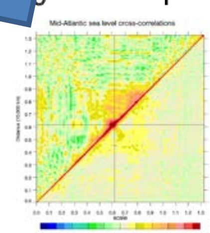
Sea level correlations in open ocean (along a meridian in the N Atlantic)

Bottom pressure correlations on the continental slope

Scale is in units of 10,000 km







Sea level correlations in open ocean, with length scales matched to above.

We find that:

- There is a "barotropic" mode which is coherent over the entire Atlantic boundary. Our main results are after this has been subtracted out, to look at residuals with vertical structure. For these:

- Pressures along the eastern boundary are highly coherent, with small variability, which gets smaller still at longer periods.

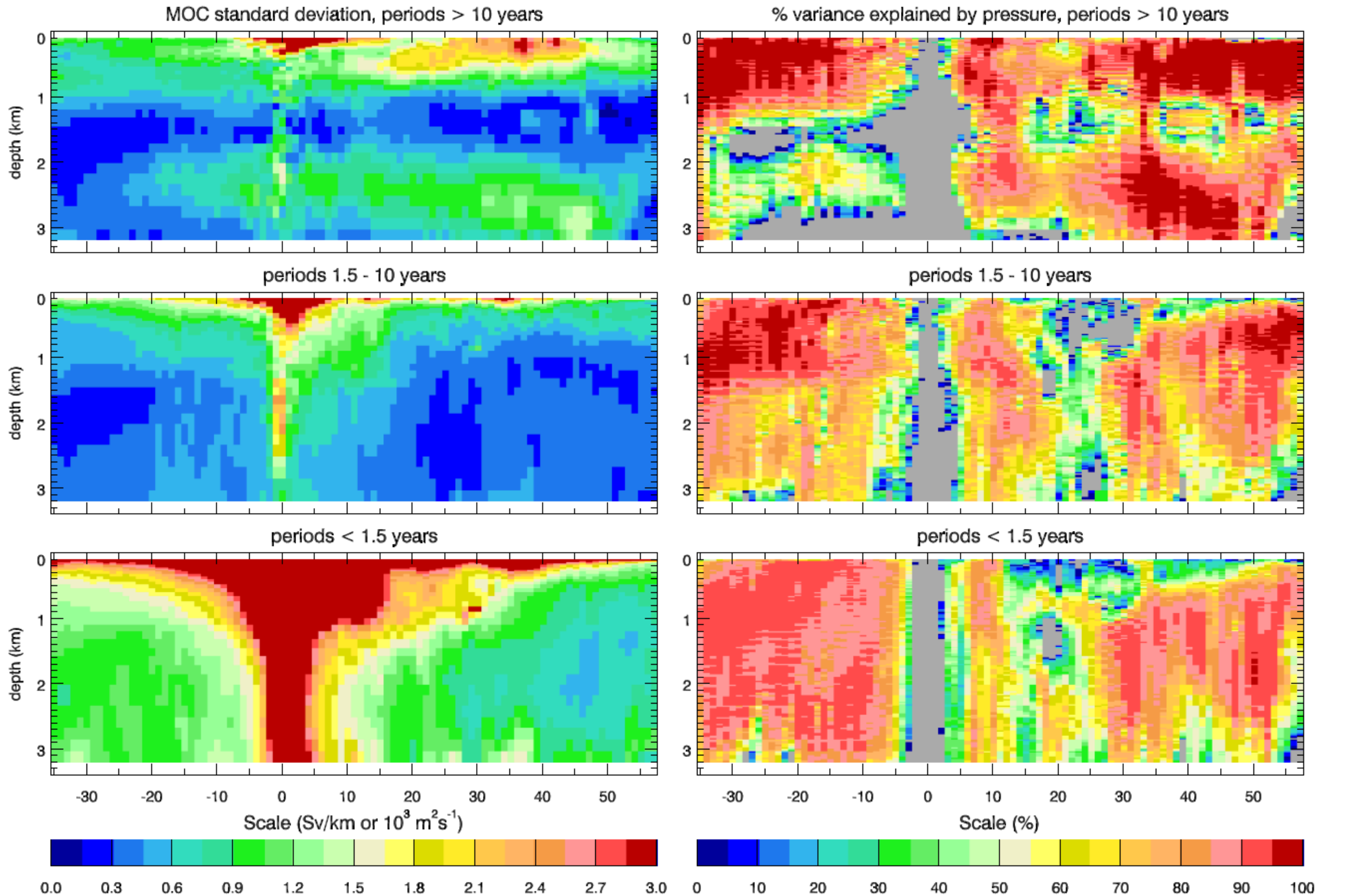
- Pressures on the western boundary are also coherent over long scales, but less so, and with marked changes in the region of Cape Hatteras/Florida.

- Signals take about 115 days to complete a circuit of the North Atlantic.

- On longer time scales, we should be looking at basin scale processes, even at an individual point. The E-W pressure differences should tell us the total meridional geostrophic transport (balancing Ekman transport, and including the MOC).

AMOC predicted from east-west pressure differences, and actual model AMOC, at different time scales. Agreement is very good except

1) where signal is very small
2) near the equator
3) where marginal seas complicate the geometry



So we have established that:

1) Bottom pressure reflects large scale processes in the Atlantic.
2) Signals propagate rapidly, and on basin scales.
3) Eastern boundary pressures are very constant in time and space.
4) The West-East difference is a good measure of the MOC.

But the continental slope above about 3200 m is continuous around the Atlantic, Indian and Pacific oceans (with complications for marginal seas and the Indonesian throughflow region). This implies a connectivity mediated by bottom pressure signals.

The following plots show results in mbar, approximately equivalent to cm of water. For comparison (Woodworth et al., 2012):

- Global mean sea level has a range of over 3 m (high southeast of Japan, low in the Weddell Sea)
- Western boundary sea level has a range of about 70 cm in the Atlantic
- Eastern boundary sea level has a range of about 25-35 cm (Atlantic and Pacific)

So, how big are the variations in time-mean bottom pressure along the global continental slope? Are there big discontinuities between basins, or is there real dynamical connectivity?

Problem:

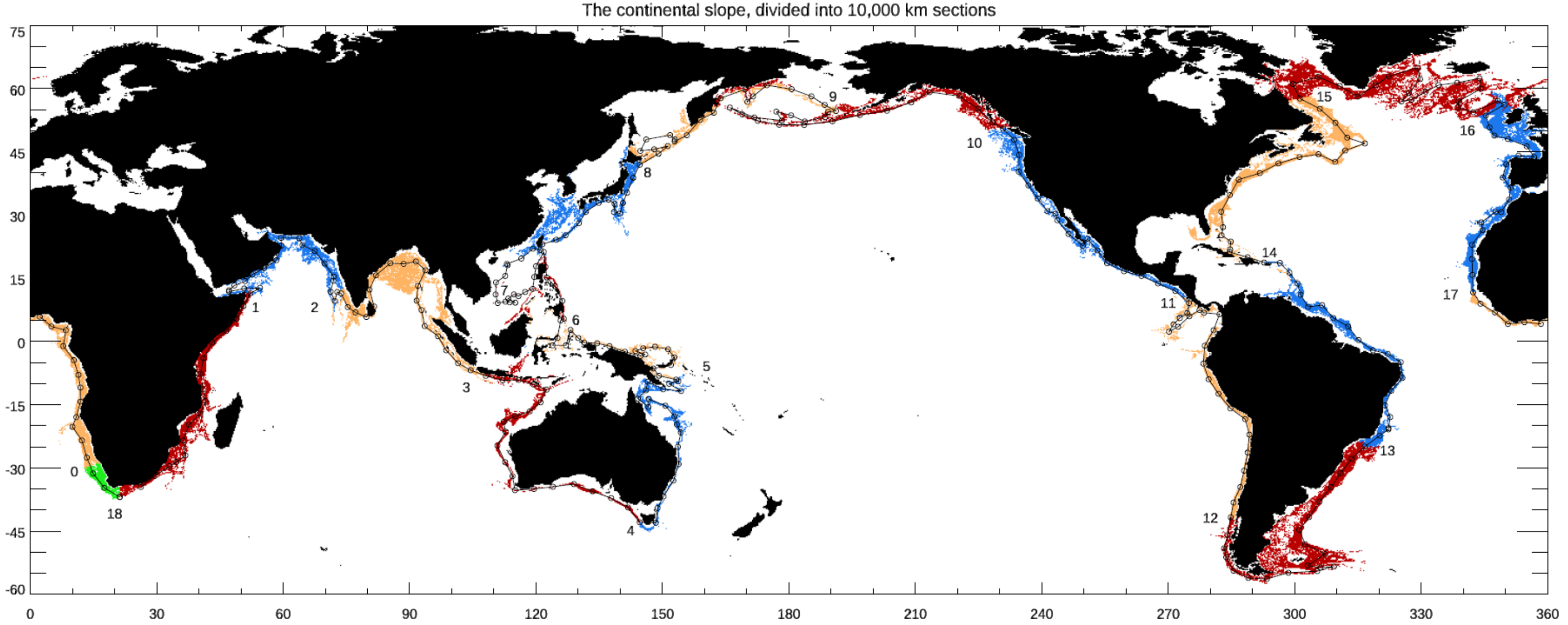
The time mean bottom pressure is dominated by a function of depth. Need to subtract this out (and it's not clear beforehand that this can be done effectively when each grid point is at a different depth).

Answer:

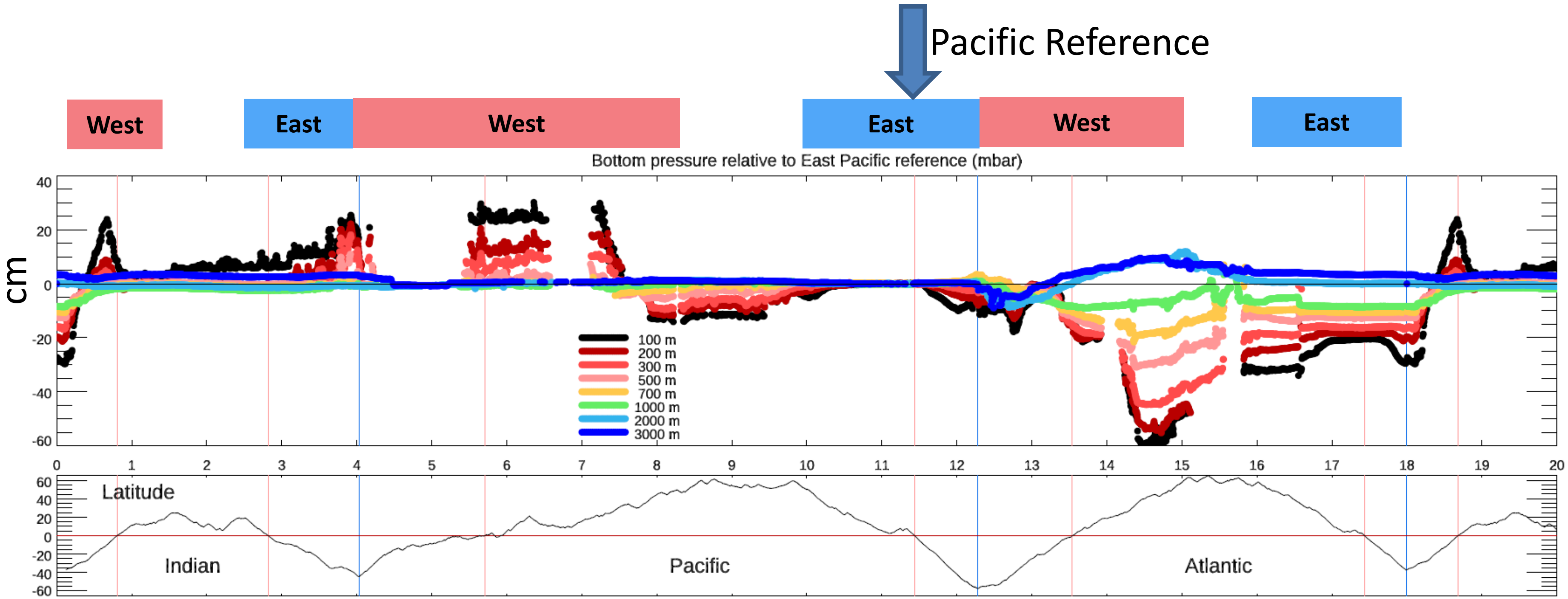
A bit of experimentation showed that a polynomial fit of pressure on depth, for eastern boundary pressures, worked well. This leaves the question of which part of which eastern boundary.

For reasons which will become apparent, we chose the equatorial region (within 5 degrees of the equator was sufficient to obtain a robust fit), and varied between the three different ocean basins to see the effect.

Globally, looking at the time-mean bottom pressure



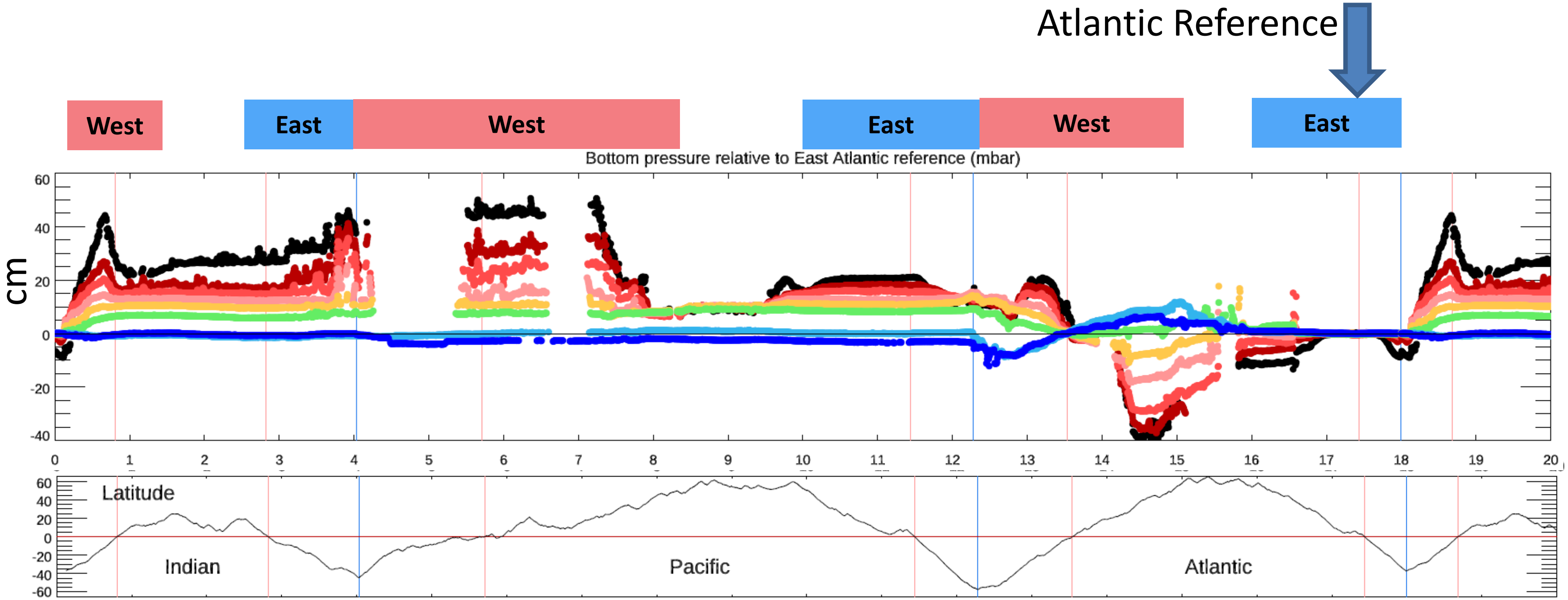
The global slope, in units of 10,000 km along the slope:
0.1 to 4 is Indian, 4 to 12.2 is Pacific, 12.2 to 18 is Atlantic (180,000 km total)
(the green patch appears twice, at start and end)



Each colour represents bottom pressure along a depth contour

Black/Red=shallow, Green=1000 m, Light Blue = 2000 m, Dark Blue = 3000 m

- Below about 1000 m, variations above about 5 cm are limited to the western Atlantic (related to the MOC)
- Outside the Atlantic, the numbers seen here are very small compared with the > 3 m of global mean dynamic topography (sea level).
- Large changes are associated with western boundary currents (Gulf Stream, Agulhas, Kuroshio) and the Indonesian throughflow.
- Eastern boundary variations are small compared to sea level, at depths below about 300 m.
- The continental slope is strongly influencing dynamics globally: the basins are tightly coupled.



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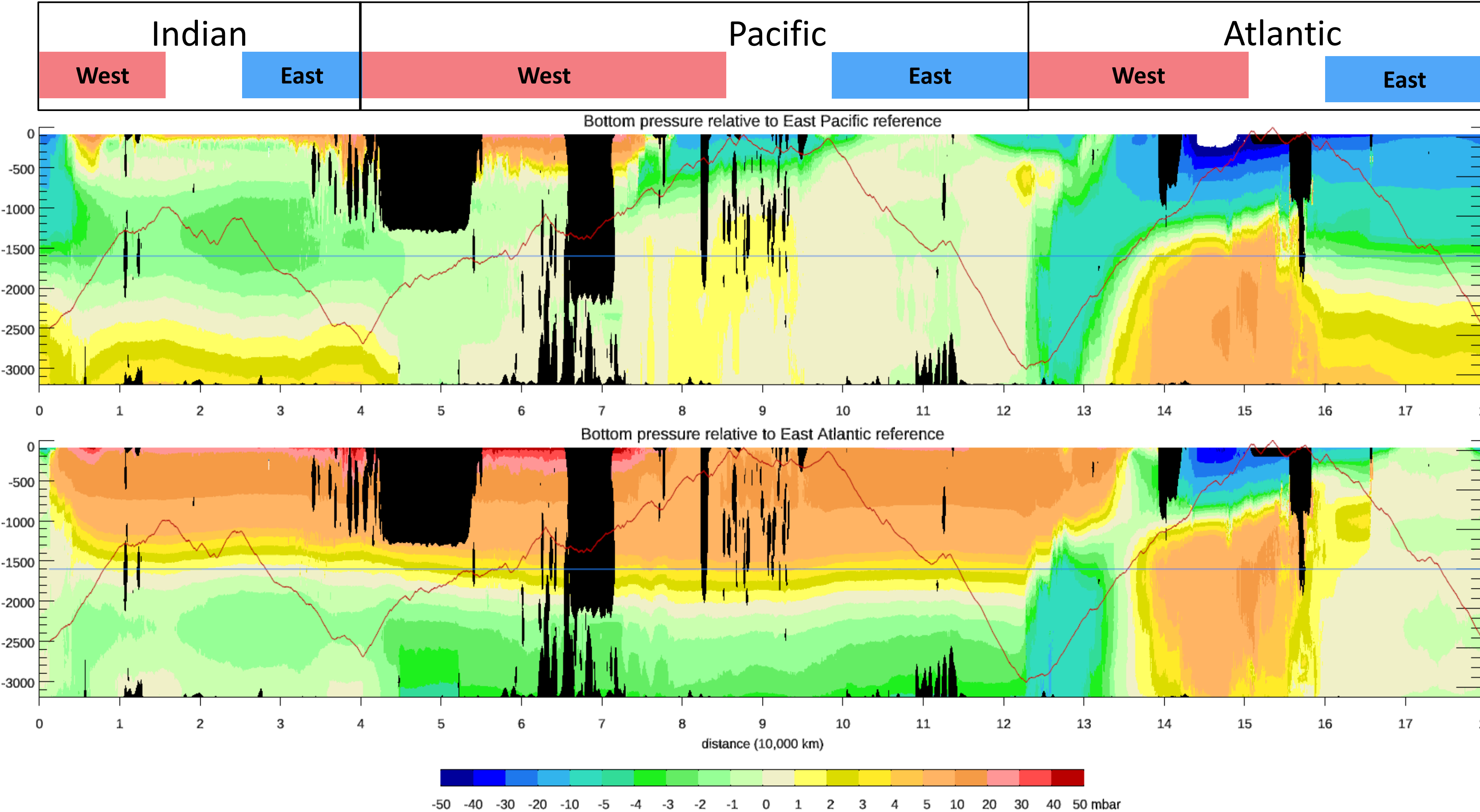
Black/Red=shallow, Green=1000 m, Light Blue = 2000 m, Dark Blue = 3000 m

- Highlights the close coupling of Indian and Pacific compared to the Atlantic.
- Shows how, compared to the eastern Atlantic, the western Atlantic signal changes sign at the equator and between deep (>1000 m) and shallower regions, as expected for the AMOC.
- Shows how the shallow branch of the AMOC is reflected in an offset between the Atlantic and rest of the world (continuity of the pressure between western Atlantic and eastern Pacific).



- The same information plotted as a function of depth and distance (Pacific reference above, Atlantic reference below).
- Note the nonlinear colour scale. Highlights the extremely small variations (< 2 mbar) over a wide range of depths (black is where the continental slope is too far from the 2000 m reference contour – gaps and marginal seas).
- Lower plot shows the effect of Mediterranean water (distance about 16.6) and Arctic/Labrador water (15-16) in setting up the MOC.

Conclusions

- Bottom pressure on the continental slope is a measure of large scale flows and the connectivity of the ocean basins.
- The AMOC is by far the largest signal, and is strongly linked to the Atlantic/Pacific eastern boundary differences.
- Eastern boundaries are very quiet, and the eastern boundary sea level signals all originate from processes at depths shallower than about 300 m.
- The bottom pressure gradient link to western boundary currents (Hughes and de Cuevas, 2001; Jackson et al., 2006) is apparent, and the global connectivity can be considered in terms of bottom pressure through the generalisation of Godfrey's Island Rule (Godfrey, 1989; Hughes, 2002).
- Bottom pressure is the tool we need to link the idealised theory of global ocean circulation with the dynamics of an ocean with a fully-developed eddy field.