Evaluating structural biases in the RAPID array: a perfect model study

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

Bablu Sinha[1](bs@noc.ac.uk), David Smeed[1], Gerard McCarthy[1], Ben Moat[1], Simon Josey[1], Joel Hirschi[1], Eleanor Frajka-Williams[2], Adam Blaker[1], Darren Rayner[1], and Gurvan Madec[3]
[1]National Oceanography Centre, UK, [2]University of Southampton, UK [3]L'Ocean, Centre National de la Recherche Scientifique, France.

1. Introduction

Previous modeling and observational studies have established that it is possible to accurately monitor the Atlantic Meridional Overturning Circulation (AMOC) at 26.5ºN using a coast-to-coast array of instrumented moorings supplemented by direct transport measurements in key boundary regions (the RAPID/MOCHA/WBTS Array). Here a unified framework for identifying and quantifying structural errors associated with the RAPID array-based AMOC estimates is established using a 1/12 degree ocean general circulation model, which simulates the ocean state between 1978-2010.

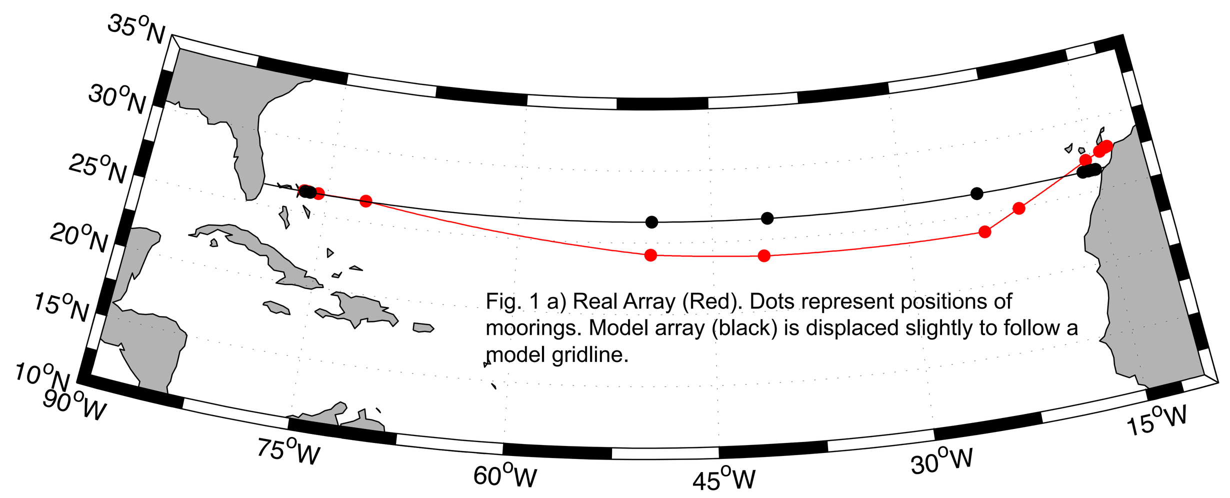


Fig. 1 a) Real Array (Red). Dots represent positions of moorings. Model array (black) is displaced slightly to follow a model gridline.

The RAPID streamfunction proxy, ψ_p, is derived from measurements as follows:

$$\psi_p = \int_z^0 T_{FS} + T_{WBW} + T_{EK} + T_P + \bar{T}_{AABW} + C\, dz'$$

Where T_{FS} and T_{WBW} are transports through Florida Strait and the Western Boundary Wedge (See Figure 1b), T_{EK} is the Ekman transport derived from the surface windstress, T_P is the geostrophic transport (referenced to 4800 dbar in the observations, 4320 dbar in the model) between the WBW and the eastern boundary (between positions x_1 and x_5 in Fig 1b), $\bar{T}_{AABW}$ is an estimate of the mean northward Antarctic Bottom Water transport below the reference level and C is a compensation transport to ensure zero net flow through the meridional section.

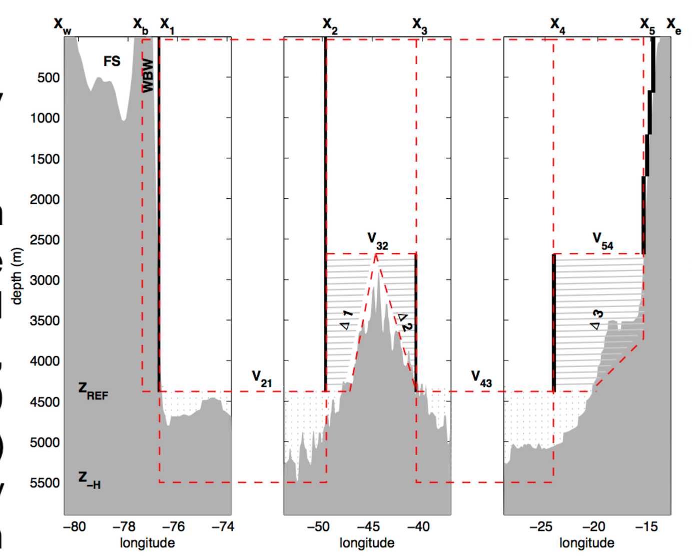


Fig. 1 b) Latitude-depth diagram showing the positions and vertical extents of the model moorings (thick black vertical lines). Florida Strait (FS) and Western Boundary Wedge (WBW) regions are labelled. Grey areas are the solid earth and horizontal stripes indicate ocean areas which are unsampled by the array.

2. Mean streamfunction bias

As shown by Sinha et al., 2018, the difference between the proxy, ψ_p and the true streamfunction, ψ i.e. the bias, $\psi_p - \psi$ is given by

$$\psi_p - \psi = \int_z^0 (T_P - T_G) + (T_{EK} - T_{AG}) + (\bar{T}_{AABW} - T_{AABW} - T_\Delta) + C dz'$$

There are four contributions to the error: the difference between the estimated and true geostrophic flow, $T_P - T_G$ due to the assumption of a level of no motion, ageostrophic transport other than Ekman, $T_{EK} - T_{AG}$, transport which is missed because it is in regions unsampled by the array, $\bar{T}_{AABW} - T_{AABW} - T_\Delta$, and the mass compensation term, C.

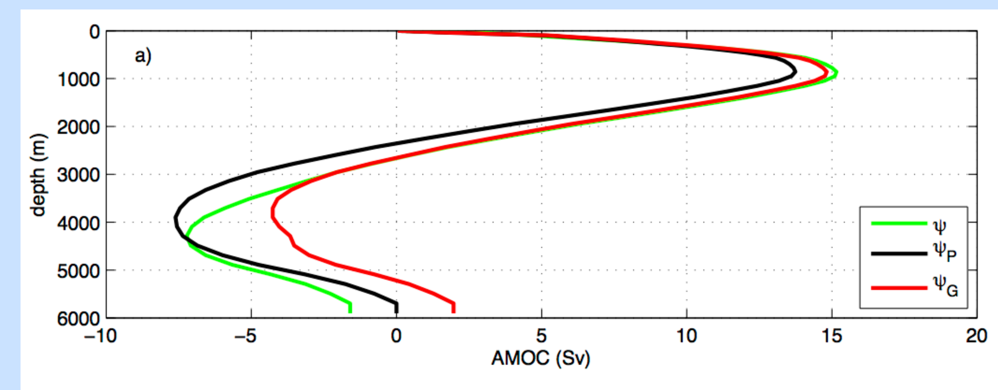


Fig. 2 Simulated AMOC (Sv) at ~26.5° N averaged over years 1990–2004 based on model prognostic velocities (green), on the RAPID proxy method (black) and based on absolute geostrophic velocities excluding unsampled regions (red)

The true streamfunction has a maximum of 15.2Sv at a depth of ~857m (green). The mean proxy streamfunction (black) displays a realistic shape, including a maximum value at the correct depth, however it underestimates the true streamfunction at virtually all depths, in particular at the depth of the maximum the mean value of the proxy streamfunction is 13.6 Sv, so there is a mean bias of −1.6 Sv.

3. Error statistics

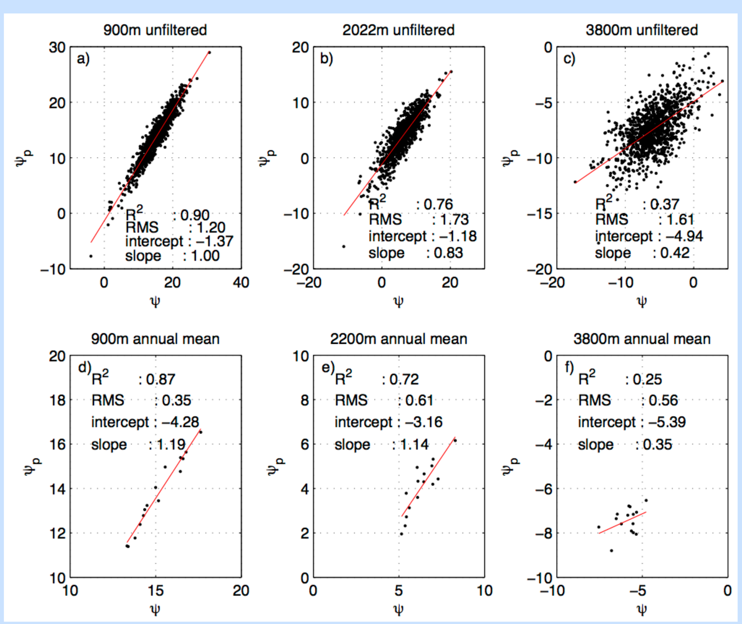


Fig. 3. Scatter plots of proxy (Ψp) versus true (Ψ) streamfunction for (a) 900 m depth (b) 2022 m depth (c) 3800 m depth. Similar plots for annual mean data are shown in panels (d), (e), (f). The timeseries are detrended prior to plotting and correlation analysis.

For 5 day means the proxy method achieves a squared correlation coefficient of 0.9 for 0–900 m volume transport, The bias is approximately −1.5. Sv and the RMS error of the correlation is 1.2 Sv. At interannual timescales the variance explained is similar and the RMS error is much lower (0.29 Sv). At deeper depths the errors become bigger, and the correlations become weaker.

The correlations are encouraging, particularly for the upper levels, suggesting that the RAPID array estimates the maximum AMOC accurate to better than 0.5Sv on annual timescales. Thus observed features such as the decline in the AMOC since ~2005 and the major reductions in 2009 and 2010 are comfortably above the structural error.

4. Decomposition of bias

The mean bias is decomposed into: reference level correction; ageostrophic term; transport in unsampled regions; and mass compensation.

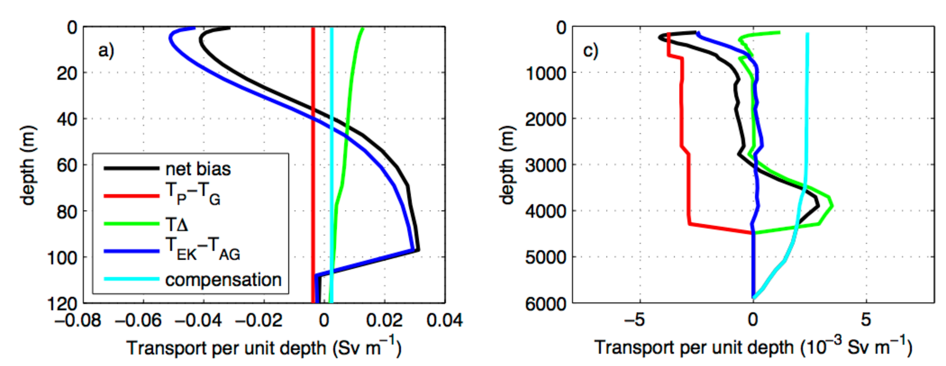
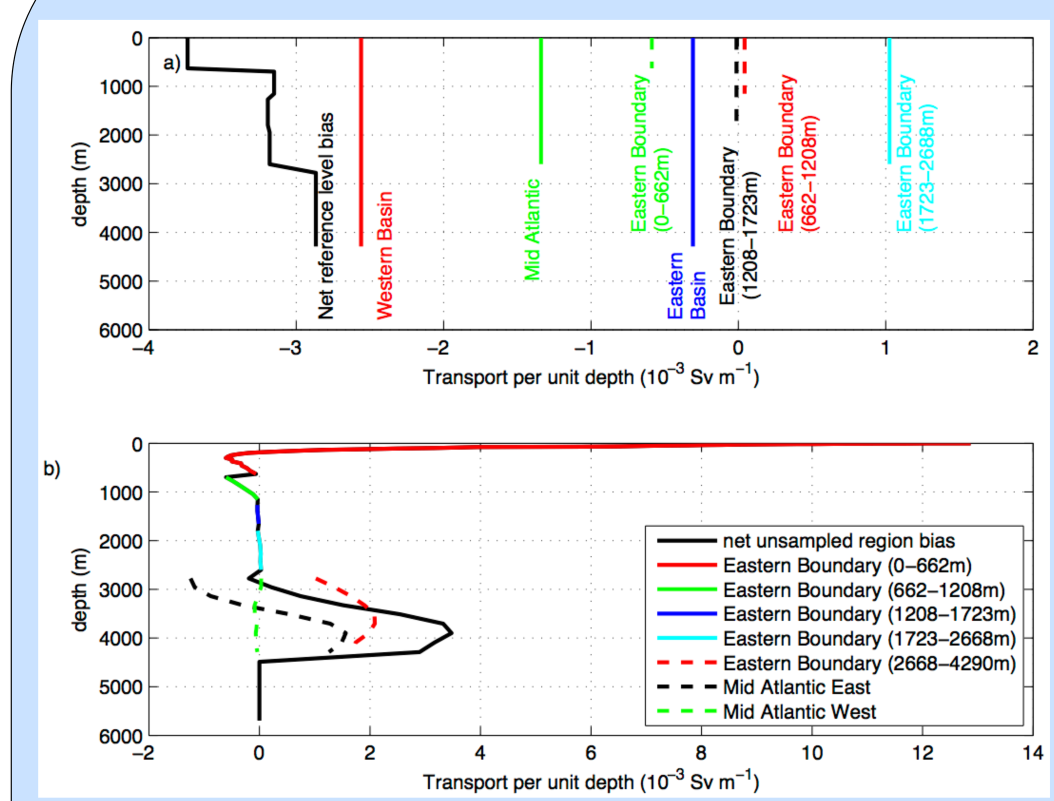


Fig. 4. (a) Net bias in transport per unit depth (Sv/m) (black), and its components associated with the reference level bias (red), unsampled regions (green), ageostrophic transport (blue) and compensation term (cyan) averaged over years 1990–2004. Left panel shows 0-120m depth, right panel shows 120-6000m.

In the top 100 m the dominant term is ageostrophic (Ekman) (blue). Between 200–2500 m the dominant terms are the reference level and mass compensation (red, cyan). The ageostrophic term is significant between 200 and 1000 m, but is small below 1000 m. Between 3000 and 4320 m, the dominant term is unsampled regions west of the MAR and at the eastern boundary since the compensation and reference level terms cancel each other. Below 4320 m mass compensation is the only contributing term.

5. Location of bias



The reference level bias can be decomposed into terms corresponding to the velocity along the base of each pair of moorings. Below the Mid Atlantic Ridge (MAR) (3000–4300 m), the net bias is composed of terms corresponding to the western and eastern basins (solid red and blue). above the MAR two further terms contribute: negative velocities (solid green) at the top of the MAR and positive velocities (cyan) at the eastern boundary which together increase the overall bias at depths of 2000–3000 m. Of the remaining terms only that associated with the shallowest eastern boundary mooring contributes significantly between 2000m and the surface (dashed green).

The direct impact of the unsampled regions (green) is decomposed according to depth. In the lower levels between 2500 and 4500 m the deep eastern boundary triangle contributes a strong positive transport, but the eastern MAR triangle makes a negligible contribution. The western MAR triangle exhibits a reversal in current direction at about 3400 m, reducing the positive bias above 3400 m but increasing it below this depth. Since at these depths there is bias compensation between the reference level term and the unsampled region term, correcting either one of these biases without correcting the other would increase the bias in the proxy streamfunction.

Fig. 7. (a) Decomposition of reference level bias in transport per unit depth (Sv/m) between mooring pairs averaged over years 1990–2004. Net bias due to reference level assumption (black), western basin (solid red), eastern basin (blue), Mid Atlantic Ridge (solid green), eastern boundary (cyan), eastern boundary (black dashed), eastern boundary (red dashed), eastern boundary (green dashed). (b) Contributions of individual unsampled regions to the net bias. Net bias due to unsampled regions (black), east of MAR (black dashed), west of MAR (green dashed), eastern boundary between 2688 and 4290 m (red dashed), eastern boundary between 1723 and 2688 m (cyan), eastern boundary between 1208 and 1723 m (blue), eastern boundary between 662 and 1208 m (green), eastern boundary between 0 and 662 m (red).

6. Summary

We have performed a thorough analysis of the possible biases arising in estimates of basin-wide volume transport using mooring arrays such as RAPID. Three main sources of error are identified: those due to an assumed fixed reference level or level of no motion, those due to ageostrophic flows and those due to unsampled regions.

The model predicts that the RAPID AMOC estimate is likely to be too low by O(1–2 Sv). However our results also show that the standard deviation of the bias at this depth is small, O (0.3 Sv) on annual and longer timescales, compared to variability in the AMOC of O(2Sv), showing that the RAPID array is well suited to the studies so far conducted (e.g. Smeed et al., 2014 McCarthy et al., 2012; Duchez et al., 2016; Moat et al., 2016).

Given the importance of the RAPID array and the development of basin-wide monitoring arrays at other locations (Lozier et al., 2017; Ansorge et al., 2014) the community needs a framework for modeling structural biases in these arrays based measurements – this is the underlying philosophy of this study. In this way advanced ocean models can be integrated into the design and redesign of observational arrays.

Ansorge, I.J. et al., 2014. Basin-wide oceanographic array bridges the South Atlantic. EOS: Trans. Am. Geophys. Union 95, 53–54. http://dx.doi.org/10.1002/ 2014EO060001.
Duchez, A. et al., 2016. Potential for seasonal prediction of the Atlantic sea surface tempera- tures using the RAPID array at 26° N. Clim. Dyn. 46 (9), 3351–3370. http://dx.doi. org/10.1007/s00382-015-2918-1.
Lozier, M.S. et al., 2017. Overturning in the subpolar North Atlantic program: a new inter- national ocean observing system. Bull. Am. Meteorol. Soc. 98, 737–752. http://dx. doi.org/10.1175/BAMS-D-16-0057.1.
McCarthy, G.D. et al., 2012. Observed in- terannual variability of the Atlantic meridional overturning circulation at 26.5° N. Geophys. Res. Lett. 39, L19609. http://dx.doi.org/10.1029/2012GL052933.
Moat, B.I. et al. 2016. Major variations in sub-tropical North Atlantic heat transport at short (5 day) timescales and their causes. J. Geophys. Res. Oceans 121, 3237–3249. http://dx.doi.org/10. 1002/2016JC011660.
Smeed, D.A et al., 2014. Observed decline of the Atlantic meridional overturning circulation 2004–2012. Ocean Sci. 10 (1), 29–38. http://dx.doi.org/10.5194/os-10-29-2014.
Sinha, B. et al.., 2018 The accuracy of estimates of the overturning circulation from basin-wide mooring arrays. Progress in Oceanography, 160. 101-123.https://doi.org/10.1016/j.pocean.2017.12.001