1. Introduction

Previous modeling and observational studies have established that it is possible to accurately monitor the Atlantic Meridional Overturning Circulation (AMOC) at 26.5°N by a coast-to-coast array of instrumented moorings supplemented by direct transport measurements in key boundary regions (the RAPID/MOCHA/WHTS Arrays). Here we quantify and evaluate 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 1979–2010. The rapid streamfunction, $\psi_R$, is derived from measurements as follows:

$$\psi_R = \int T_y + T_{yWW} - T_x + T_{yABW} + C d\tau$$

Where $T_y$ and $T_{yWW}$ are transports through Florida Strait and the Western Boundary Wedge (See Figure 1b), $T_x$ is the Ekman transport derived from the wind stress $T_y$ is the geostrophic transport (reference) at 4800 dbars in the observations, 4320 dbars in the model, between the WWB and the eastern boundary (between positions $x_1$ and $x_2$ in Fig 1b), $T_{yABW}$ is an estimate of the mean northward Antarctic Bottom Water transport in the Atlantic as a compensation transport to ensure zero net transport through the meridional section.

For 5 days 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 larger, 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 0.2 Sv on annual timescales. This observed features such as the decline in the AMOC since ~2005 and the major reductions in 2009 and 2010 are comfortably above the structural errors.

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

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 where the compensation and reference level terms cancel each other. Below 4320 m mass compensation is the only contributing term.

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 bias of ~1.6 Sv.

2. Mean streamfunction bias

The mean streamfunction bias has a maximum of 15.25 Sv at a depth of ~857 m (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 bias of ~1.6 Sv.

3. Error statistics

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 layers between 2500 and 4500 m the deep eastern boundary triangle contributes a strong positive transport, while the western 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.

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.

