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The accuracy of estimates of the overturning circulation from basin-wide mooring arrays

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ABSTRACT

Previous modeling and observational studies have established that it is possible to accurately monitor the Atlantic Meridional Overturning Circulation (AMOC) at 26.5°N using a coast-to-coast array of instrumented moorings supplemented by direct transport measurements in key boundary regions (the RAPID/MOCHA/WBTS Array). The main sources of observational and structural errors have been identified in a variety of individual studies. Here a unified framework for identifying and quantifying structural errors associated with the RAPID array-based AMOC estimates is established using a high-resolution (eddy resolving at low-mid latitudes, eddy permitting elsewhere) ocean general circulation model, which simulates the ocean state between 1978 and 2010. We define a virtual RAPID array in the model in close analogy to the real RAPID array and compare the AMOC estimate from the virtual array with the true model AMOC. The model analysis suggests that the RAPID method underestimates the mean AMOC by ~1.5 Sv (1 Sv = $10^6\,\mathrm{m}^3\,\mathrm{s}^{-1}$) at ~900 m depth, however it captures the variability to high accuracy. We examine three major contributions to the streamfunction bias: (i) due to the assumption of a single fixed reference level for calculation of geostrophic transports, (ii) due to regions not sampled by the array and (iii) due to ageostrophic transport. A key element in (i) and (iii) is use of the model sea surface height to establish the true (or absolute) geostrophic transport. In the upper 2000 m, we find that the reference level bias is strongest and most variable in time, whereas the bias due to unsampled regions is largest below 3000 m. The ageostrophic transport is significant in the upper 1000 m but shows very little variability. The results establish, for the first time, the uncertainty of the AMOC estimate due to the combined structural errors in the measurement design and suggest ways in which the error could be reduced. Our work has applications to basin-wide circulation measurement arrays at other latitudes and in other basins as well as quantifying systematic errors in ocean model estimates of the AMOC at 26.5°N.

1. Introduction

Estimating ocean transports of volume, heat and freshwater is a fundamental oceanographic activity that provides data critical to the study of the ocean's role in the mean climate and climate variability. Bryden and Hall (1980) highlighted that the Atlantic Meridional Overturning Circulation (AMOC) is responsible for a large part of the climatically important ocean heat transport, which is the largest of any ocean basin (Bryden and Imawaki, 2001). The phenomenology, dynamics and climate impacts of the AMOC are a complex subject which despite extensive research are still to be fully understood (see Buckley and Marshall, 2016 for a comprehensive review of what is known and not known about the AMOC). The AMOC is typically defined as the maximum of the zonally (basin-wide) and vertically integrated meridional transport, which occurs near 30°N, coincident with the maximum poleward heat transport. The first estimates of the strength of the AMOC and associated heat transport were based on hydrographic sections (typically at 24.5°N e.g. Bryden et al., 2005) that provided a snapshot of the circulation but a growing awareness of the variability of the AMOC stimulated the development of continuous measurement using mooring arrays. The RAPID array (Cunningham et al., 2007) at 26.5°N in the Atlantic Ocean has provided continuous, basin-wide, full-depth observational estimates of the AMOC since 2004.

The RAPID/MOCHA/WBTS array (hereinafter referred to as the

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RAPID array) has revolutionized basin scale oceanography by supplying continuous estimates of the meridional overturning transport (McCarthy et al., 2015), and the associated basin-wide transports of heat (Johns et al., 2011) and freshwater (McDonagh et al., 2015) at 10-day temporal resolution. These estimates have been used in a wide variety of studies characterizing temporal variability of the North Atlantic Ocean, for instance establishing a decline in the AMOC between 2004 and 2013 (Smeed et al., 2014), recording of a substantial downturn in the AMOC in 2009–10 (McCarthy et al., 2012) and its subsequent effects on North Atlantic heat content (Bryden et al., 2014) and sea surface temperature (Duchez et al., 2016) and winters in North Western Europe (Buchan et al., 2014, Maidens et al., 2013).

The RAPID array has also been important in defining shorter timescale variability, including seasonal variations in the AMOC and their origin (Kanzow et al., 2010; Chidichimo et al., 2010; Mielke et al., 2013; Duchez et al., 2014; Pérez-Hernández et al., 2015), and extreme volume and heat transports on sub seasonal timescales (Moat et al., 2016; Cunningham et al., 2013).

With such a large number of studies reliant on the RAPID measurements and other basin-wide array data, it has become imperative to accurately establish the structural error of the RAPID array estimates as has been done for the observational error (see McCarthy et al., 2015). The original proof of concept studies which established the feasibility of the RAPID array were conducted using the (at the time) high-resolution (1/4° - i.e. eddy permitting) OCCAM and FLAME (1/3°) ocean general circulation models (Hirschi et al., 2003, 2007; Baehr et al., 2004; Hirschi and Marotzke, 2007). The demonstrated a correspondence between the true model transports and a proxy based on the basin-wide geostrophic transport, calculated from moorings on the eastern and western boundaries and over the Mid Atlantic Ridge (MAR). We do not seek to challenge these findings, but rather wish to put them on a firm quantitative footing for the real array, in all its complexity, using a state-of-the-art high resolution (eddy resolving) ocean general circulation model (OGCM).

A key problem when using geostrophic calculations is the need for an absolute velocity at the reference level (strictly, the true or absolute geostrophic velocity at the reference level). This issue has been recognized since the dawn of modern oceanography, often in the context of determining the volume transport through a hydrographic section and a number of methods have been developed to address it, from the assumption of one or more levels of no motion (e.g. Bryden et al., 2005), to much more sophisticated approaches, where further constraints such as a requirement for zero net volume transport are imposed (inverse methods, exemplified by e.g. Wunsch, 1978). Ganachaud (2003) provided a thorough exposition of potential error in one-time hydrographic sections when using the inverse method at 25°, 36° and 48°N, anticipating many of the concerns of this paper, in particular the reference level error was found to be of order ± 3 Sv at 25°N. Unsampled regions ("bottom triangles") and ageostrophy were by contrast found to be much smaller, although measurement error due to internal wave processes were found to be of the same order of magnitude to the reference level error. Rather than using classical inverse methods per se, Hirschi et al. (2003) suggested the simple method of adding a spatially constant but time variable barotropic velocity to the measured basin-wide geostrophic velocity in order to ensure zero net volume transport across the basin. In an ocean with uniform depth this method of solution will always give the correct answer even if the reference velocity varies with longitude. However, when the water depth varies across the array, then the zero net-transport assumption is not in principle sufficient and variations in the vertical structure of the circulation solution dependent on the choice of reference level emerge (Roberts et al., 2013). Whilst Hirschi et al. (2003) acknowledged this issue, they did not perform further analysis on their model simulations.

Several studies have highlighted the potential errors introduced by the imposition of the zero net-transport constraint (Searl et al., 2007; Hughes et al., 2013). Kanzow et al. (2009) and McCarthy et al. (2012) investigated the accuracy of this assumption by comparing the transport variability derived from basin-wide pressure differences in bottom pressure recorders with the transport variability derived from the application of the mass compensation constraint. The results of these studies suggest that the error associated with the mass constraint in the estimate of the maximum of the overturning stream function is comparable to the accuracy of the other elements of the array at 1.5 Sv (McCarthy et al. 2015). Further independent validation of the mass constraint was provided by Landerer et al. (2015) who verified the detrended interannual variation associated with the mass constraint using bottom pressure data derived from the GRACE gravity satellite.

There have been further concerns raised about the accuracy of the RAPID array, notably by Wunsch (2008) who worried that the dependence of the geostrophic transport calculation on the endpoints would result in large errors in the basin-wide transport estimate due to eddy variability on the boundaries. This argument has been countered by Kanzow et al. (2010) who showed that eddy variability rapidly decreases close to the boundaries, resulting in a much lower error than suggested by Wunsch's analysis.

The assumed low magnitude of the ageostrophic transport has been further questioned by Stepanov et al. (2016) who suggest that ageostrophic transport associated with mesoscale eddies in the western North Atlantic makes a significant contribution to the volume transport (and more particularly the heat transport). As the RAPID array is not able to capture this effect, it was suggested that RAPID may be missing a significant part of the meridional volume transport.

The operational design of the RAPID array introduced further assumptions, including concatenation of geographically separated moorings (McCarthy et al., 2015). These assumptions have never been rigorously scrutinized for the errors they have introduced into the volume transport estimates, although some authors have discussed the potential for errors (e.g. Roberts et al., 2013 in the eddy permitting model regime). Stepanov et al. (2016) compared model proxies (in the eddy resolving regime) calculated in a very similar way to that done using the real RAPID array, with model truth and found that the proxy slightly overestimates the model truth.

The various sources of error when using a RAPID-type array can be rigorously quantified in a model study as absolute geostrophic currents can be determined in the model given knowledge of model pressure. Ganachaud (2003) did in fact estimate the variability in the reference level velocity using absolute geostrophic currents from an eddy permitting ocean general circulation model. However he did not take the further step of conducting a perfect model study in order to directly compare an estimated geostrophic transport using the same method as with observations with the absolute geostrophic transport from the model. Furthermore, the RAPID array was not in place then, and therefore Ganachaud's work was not performed in the context of an operational array giving continuous estimates of basin-wide transport.

In this paper we go further and rigorously separate the structural bias into (sometimes mutually compensating) components due to reference level assumptions, unsampled regions, and ageostrophy.

Our analysis enables us to accurately pinpoint the magnitude, nature and spatial location of structural errors in the RAPID array-based AMOC estimates for the first time. This reaffirms the ability of the array to provide reliable transport estimates, and leads to new insights that can inform array design improvements and thus provide more accurate future estimates of the AMOC and heat transport (two key climate parameters).

In contrast to previous studies, we make use of the sea-surface height information provided by our free-surface model in order to determine the true or absolute geostrophic transport and thereby establish a rigorous framework to identify and quantify structural errors in the RAPID array and other arrays like it.

In this paper we examine sources of error due to:

(i) use of a fixed reference level and the assumption of zero net

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