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Observed and simulated variability of the Atlantic Meridional Overturning Circulation at 41°N

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ABSTRACT

The Atlantic Meridional Overturning Circulation (AMOC) at 41°N from a global 1/16° eddying simulation is compared with ARGO-based transport estimates over the 2004–2013 period. Three different methods for calculating the modelled meridional transports are used. The first method (MOCmod) is simply based on simulated velocity fields. The second method (MOCob) is based on the same hydrostatic and geostrophic relationships applied to ARGO observations, and the third (MOCob2) relies on the same assumptions, but does not use a reference depth of known motion. MOCmod and MOCob2 methods correctly reproduce the time-mean AMOC strength, while the MOCob result is ~7% weaker.

The comparison of the three overturning calculations demonstrates that ignoring transports near the western boundary (ARGO floats are restricted to ocean regions deeper than 2000 m) leads to the seasonal cycles of the non-Ekman component of the AMOC from the model and observation to be out of phase. Due to a lack of ARGO data and the consequent use of extrapolation/average processes near the western boundary, uncertainties exist in the definition of density field near the western boundary, which can enlarge discrepancy between modelled and observed variability.

Furthermore, the meridional covariability of the modelled AMOC at 26.5°N and 41°N is analysed and compared to the covariability of the Rapid Climate Change programme and the ARGO-based time series. Similar to other model comparisons, the model output shows covariability between the two latitudes at some frequency bands, while the phasing differs for the observed data.

1. Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is an essential component of today's climate system, responsible for ~25% of the total (ocean and atmosphere) poleward heat transport in the northern hemisphere. Therefore, it strongly affects the climate of Western Europe and other regions bordering the North Atlantic (e.g., Knight et al., 2005; Sutton and Hodson, 2005; Latif and Keenlyside, 2011). Seasonal AMOC variations significantly impact the seasonal sea surface temperature and ocean-atmosphere heat budget in the North Atlantic, which affects a variety of climate phenomena at different timescales (e.g., Collins et al., 2006; Zhang and Delworth, 2006; Pohlmann et al., 2009). Therefore, a deep understanding of the AMOC and its natural variability is crucial for identifying the mechanisms of climate variability and climate prediction on seasonal to decadal scales. Correct representations of the AMOC seasonal cycle are a starting point for ocean and climate modelling.

Currently, continuous observation-based estimates of the AMOC and associated meridional heat transport (MHT) are limited in time and restricted to two latitudes: at 26.5°N from the Rapid Climate Change programme (RAPID, Cunningham et al., 2007) and at 41°N from data gathered by ARGO floats and altimetry (Willis, 2010, henceforth W10). A joint analysis of two observed AMOC time series in the North Atlantic shows that the volume transport at 41°N presents a clear seasonal cycle, but the seasonal range and the time mean are reduced compared to the estimates at 26.5°N. That is in agreement with previous studies suggesting that the AMOC variability might be gyre-specific, with higher variability in the subtropical gyre (Bingham et al., 2007; Lozier et al., 2010).

The upper branch of the AMOC can be decomposed into Ekman and geostrophic components, both contributing to the seasonal cycle of the AMOC. Model study by Zhao and Johns (2014a) demonstrated that the seasonal AMOC variability at 26.5°N is mainly dominated by the varying Ekman transport (wind forcing dominates short-term variability through its effect on Ekman transport and coastal upwelling). However, in situ observations show that the geostrophic transport also makes significant contributions to the seasonality of the AMOC. The AMOC time series from the RAPID estimates at 26.5°N suggested that the seasonal

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cycle of the AMOC is dominated by the geostrophic mid-ocean and Gulf Stream transports (Kanzow et al., 2010). The geostrophic contribution to the seasonal variation of the AMOC is also confirmed at 41°N and 35°S (W10; Baringer and Garzoli 2007; Dong et al., 2009). Therefore, a proper representation of the geostrophic transport is crucial to simulate and better understand the seasonal cycle of the AMOC.

On subannual time scales, variations in the non-Ekman component of the AMOC (henceforth indicated by the acronym AMOC-Ek) at 26.5°N are largely driven by the local wind stress curl at both the western and eastern boundaries (Polo et al., 2014; Duchez et al., 2014). In particular, Duchez et al. (2014) showed that the pumping effect of the spatial pattern of wind stress curl south of the Canary Islands results in deep density fluctuations at the eastern boundary at 26.5°N. Zhao and Johns (2014a) showed that the geostrophic transport involves a complex adjustment to the wind forcing, and that the seasonal cycle of the AMOC in the extratropics is mainly governed by local boundary effects. At different latitudes, either the western or the eastern boundary can dominate the seasonal variability. Wind forcing can also impact the interannual variability by modifying the density profiles at the western edge through the excitation of Rossby waves (the first baroclinic mode) in the central Atlantic Ocean, which propagate westward and interact with the western boundary (Polo et al., 2014; Zhao and Johns, 2014a, 2014b).

Processes near the boundaries are important for seasonal and interannual variability of the AMOC. Results by Bingham and Hughes (2008) demonstrated that, for periods longer than one year, it is possible to recover more than 90% of the variability of AMOC at 42°N, only using the western boundary pressure (if the depth-averaged boundary pressure signal is removed). That suggests a significant contribution of the transport at the western boundary to the AMOC variability also at 41°N. Since Argo floats cannot operate over the continental shelf and slope (they drift off shore at a depth of 1000–2000 m), the Argo-based array cannot adequately represent the narrow currents and the hydrographic profiles at the ocean boundaries. Neglecting those measurements at the boundaries may cause some biases in ARGO-derived estimates of the AMOC.

Although the observational estimates at 26.5°N and 41°N allow unprecedented insights in the temporal variability of the AMOC, it is still unclear if they represent the AMOC variability throughout the entire Atlantic Ocean. Over the years, many numerical studies have focused on the AMOC variability and its latitudinal dependence. The multi-model analysis by Ba et al. (2014) demonstrated that the AMOC modelled at 26.5°N, after application of a decadal time scale filter, owns a very strong correlation with the overturning calculated at other latitudes. This result suggests that the AMOC at 26.5°N can represent the overturning circulation in the North Atlantic Ocean. On the other hand, other model studies show that the AMOC's modes of variability do not match within different latitude bands on interannual timescales (Bingham et al., 2007; Zhang, 2010), and even on decadal timescales (Lozier et al., 2010). The relation between modelled AMOC transports and its variability at the two latitudes, 26.5°N and 41°N, is still not well understood. Mielke et al. (2013) compared AMOC-Ek at 26.5°N and 41°N from a 1/10° ocean model simulation and observations. They found that the seasonal cycles of the observed AMOC-Ek component between 26.5°N and 41°N are 180-degrees out-of-phase: RAPID (ARGO-based) transport has a maximum (minimum) in autumn and a minimum (maximum) in spring. On the other hand, their model results demonstrated that the AMOC is meridionally covariable between these latitudes at seasonal timescales, with a maximum in autumn and a minimum in spring.

The simulated AMOC presents similar variability in a preliminary analysis of 1/4° ocean reanalyses (Haines et al., 2012) and numerical results from a 1/12° ocean model (Xu et al., 2014). It is still unclear why models and observations agree on AMOC-Ek at 26.5°N, but not at 41°N.

In this study, we investigate the volume and heat transport and their variability at 41°N, as estimated by observations and computed by an eddying ocean model. We use numerical results from a global eddying ocean model at 1/16° horizontal resolution (hereafter called GLOB16) that is described and validated in Iovino et al. (2014, 2016). Similar analysis of the GLOB16 Atlantic volume and heat transports at 26.5°N and 34°S, are presented in Stepanov et al. (2016a,b), and compared with observation-based estimates. While the GLOB16 AMOC seasonal cycles agree with the observations at 26.5°N and 34°S, we found an inverse phasing at 41°N, as we will show in Section 5.

The main aim of this study is, hence, to investigate the discrepancy between the modelled and the observed AMOC seasonality at 41°N and to suggest an explanation of the inverse phasing. Firstly, numerical results from GLOB16 are compared to ARGO-based estimates of AMOC and MHT at 41°N (W10; Hobbs and Willis, 2012, henceforth HW12). Secondly, they are used to examine the meridional covariability of the simulated AMOC between 26.5°N and 41°N, compared to the observed records.

The paper is organized as follows. Section 2 briefly introduces observed-based estimates of the AMOC at 26.5°N and 41°N, and the numerical simulations. In Section 3 we describe the different methods used to compute the transports. Section 4 deals with the key factors that link the MHT and AMOC, and presents the comparison between the modelled and observed MHT, while Section 5 compares components of the simulated volume transports with observations. In Section 6 we analyze the seasonal to interannual variability of the AMOC transport time series at 26.5°N and 41°N from both observations and a numerical model. Section 7 provides discussion and conclusions.

2. Description of observations and model

2.1. Observation-based AMOC

The key observations used in this study are the volume and heat transport estimates at 41°N derived using a combination of ARGO floats and sea-surface height (SSH) data from satellite altimeters (Willis and Fu, 2008; W10; HW12). Data are available as three-month running means, from January 2002 to December 2013. The displacement of the Argo floats provides an estimate of reference velocity at 1000 m, and density field from the surface to 2000 m derived from ARGO temperature and salinity profiles are used to estimate geostrophic shear. These two are combined to produce geostrophic velocity in the upper 2000 m (at a grid with 1/4° resolution). High-resolution SSH estimated from altimeter data are used to reduce the sampling error induced by mesoscale eddies. The sum of the AMOC-Ek transport (integrated from the surface to the average depth of known motion, placed at 1130 m) and the Ekman transport (derived from the NCEP/NCAR reanalysis wind-stress) gives the AMOC transport. Willis also assumed that all the northward transport in the upper 1130 m is returned at depth.

ARGO floats cannot properly sample currents and hydrographic profiles on the continental shelf and slope because they drift off shore at a depth of 1000–2000 m, and because fast barotropic currents move them rapidly through and away from the boundary areas. Since ARGO floats are restricted to regions where the ocean depth is greater than 2000 m, they are more appropriate for estimating transport in regions characterized by a small transport over the continental shelf (HW12). For this reason, the 41°N latitude was chosen. Using results from the high resolution ECCO2, global ocean general circulation model (Meinen et al., 2013), W10 found that the lack of sampling in shallow regions (<2000 m) in a narrow band of latitudes (40–41.5°N) resulted in RMS errors of 1.1 Sv (1 Sv = 10^6 m^3/s) that was smaller than his model mean value of the AMOC. Our analysis in Section 5.1 will show that the lack of shallow velocities can result in a wrong representation of the seasonal cycle of the AMOC-Ek at 41°N.