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Supporting Information for

Revisiting AMOC Transport Estimates from Observations and Models

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Contents of this file

Text S1 to S2
Figure S1
Tables S1 to S3

Introduction

Additional details of the transport calculation methods are given in Text S1. Text S2 includes a short discussion on a way forward to estimate reference level velocities at the MOVE site. Figure S1 shows the annual-mean time series of the transport components at RAPID from FOSI, computed using the POP-RAPID method. The three tables provide: i) a summary of transport methods considered in this study (Table S1); ii) mean and standard deviations of the transport time series for MOVE from FOSI (presented in Figure 2a) and their correlations with the model truth (Table S2); and iii) transport trends during the 2004-2015 period from FOSI shown in Figures 1f and 2a (Table S3).

Text S1. Transport Calculation Methods

As part of this work, we have created a new python-based Meridional ovErTurning ciRculation diagnostIC (METRIC) package which is freely available on GitHub at https://github.com/NCAR/metric. This initial version of the software leverages an existing python module implemented for the RAPID array (Roberts, 2017: doi:10.5281/zenodo.1036387).

The METRIC package enables consistent calculations of Atlantic Meridional Overturning Circulation (AMOC) estimates at the MOVE (16°N) and RAPID (26.5°N) sections from observations and models. To make the most appropriate comparisons, the package evaluates the model meridional overturning circulation at these two sites using analogous *MOVE-style* and *RAPID-style* methods, respectively. It also includes a few additional, alternative approaches to calculate these transports.

AMOC at 16°N is calculated as the deep southward flowing transport across the MOVE array between the Lesser Antilles and the Mid-Atlantic Ridge, and between the pressure levels of 1200 and 4950 dbar. The transport is computed as the sum of two components (Kanzow et al., 2006; Send et al., 2011): a *boundary* component from direct current meter measurements and an *internal* component using the geostrophic shear calculated by differencing dynamic height profiles referenced to zero flow at 4950 dbar (~4950 m). The model equivalent MOVE transport computed by the METRIC package specifies the velocities in the boundary component to be the same as the model velocities. The internal meridional geostrophic velocities (v_{geo}) are calculated using

$$v_{geo} = \frac{1}{f}\frac{\partial \Phi}{\partial x}, \qquad (1)$$

$$\Phi = \int_{p_{ref}}^{p} \frac{1}{\rho}\,dp, \qquad (2)$$

where p is pressure, ρ is density, f is the Coriolis parameter, Φ is dynamic height relative to a reference pressure, p_{ref}, and x (positive eastwards) denotes the zonal direction. When calculating dynamic heights, integration starts from the bottom with a reference pressure (or depth of 4950 m – the same depth as used in the MOVE observational estimates) or the ocean bottom – whichever is shallower. By default, the package assumes a level-of-no-motion at 4950 m, matching that of the observational method. However, instead, a user can also choose to use non-zero model meridional velocities as the reference velocity at a specified depth. An internal, depth-dependent transport across the east-west section is then defined as:

$$T_{int}(z) = \int_{w}^{e} v_{geo}\,(z)\,dx = \frac{1}{f}\left(\Phi_e(z) - \Phi_w(z)\right), \qquad (3)$$

where z is the vertical direction (positive upwards) and subscripts w and e denote the values at the western and eastern mooring locations, respectively (see McCarthy et al. (2015) for details focusing on RAPID).

The total deep southward flowing North Atlantic Deep Water (NADW) volume transport used as the proxy for AMOC at MOVE is defined as, ignoring any nonzero reference level contribution:

$$T_{NADW} = \int_{4950m}^{1200m} \frac{1}{f} (\Phi_e(z) - \Phi_w(z)) dz + T_{bdry}, \qquad (4)$$

where T_{bdry} is the boundary component of the transport.

When comparing with model simulations, we also consider a model *truth* transport calculated based on the actual model meridional velocities (v):

$$T_{NADW} = \int_{4950m}^{1200m} \int_{w}^{e} v\,(x,z) dx dz. \qquad (5)$$

Alternatively, a top-down geostrophic computation can be used to evaluate v_{geo} from:

$$v_{geo} = \underbrace{\frac{g}{f\rho} \frac{\partial}{\partial x} \int_{-z}^{0} \rho(z) dz}_{V_{baroclinic}} + \underbrace{\frac{g}{f} \frac{\partial \eta}{\partial x}}_{V_{barotropic}}, \qquad (6)$$

where g is the gravitational acceleration and η is the sea surface height. In (6), the top-down approach uses the slope of the sea surface height to compute the barotropic term to calculate absolute geostrophic velocities and, as such, does not rely on a level-of-no-motion at depth.

The RAPID array estimates the total AMOC transport across the entire Atlantic Basin at 26.5°N. The transport calculation involves four components: western boundary wedge (WBW), Florida Current (FC), mass-compensated geostrophic interior mid-ocean, and the wind-driven, near-surface Ekman part (e.g., Cunningham et al., 2007; McCarthy et al., 2015). The FC transport (T_{FC}) through the narrow Florida Strait has been measured electromagnetically via a defunct submarine telecommunication cable since 1982 (Sanford, 1982; Larsen and Sanford, 1985; Meinen et al., 2010). The WBW transport (T_{WBW}) is estimated by an array of direct current meters designed to measure the core of the northward flowing Antilles Current over the quickly changing depths of the continental slope and shelf. The Ekman transport (T_{Ek}) is calculated from:

$$T_{Ek} = -\int \frac{\tau_x}{f\rho}, \qquad (7)$$

where τ_x is the zonal component of the wind stress where reanalysis products have been used recently to estimate the Ekman transport. The transport is evenly distributed over the top 100 m in the RAPID calculation.

As with MOVE, RAPID uses an end-point geostrophy approximation to obtain the interior transport (T_{int}). Following equations (1-3), in-situ moored observations are used to calculate dynamic height profiles relative to 4820 dbar, from which geostrophic shear is calculated by differencing the profiles.

After the individual components are calculated, the net transport across the section is obtain by

$$T_{net} = T_{int} + T_{FC} + T_{WBW} + T_{Ek}. \qquad (8)$$

T_{net} calculated this way produces a non-physical nonzero transport. In reality, there should only be a weak net southward transport of order 1 Sv across the section due to the Bering Strait inflow to the Arctic minus net evaporation, precipitation, and runoff into the North Atlantic basin. The nonzero transport emerging from equation (8) essentially indicates that 4820 dbar is not a level-of-no-motion. To compensate for this nonzero transport, a *compensating* or *external* transport is added to the internal geostrophic transport so that there is no net meridional flow. It is assumed that this compensating flow has a uniform velocity (hypsometric) across the basin with the associated transport given by

$$T_{ext}(z) = v_{comp}\ W(z), \qquad (9)$$

where $W(z)$ is the width of the basin and v_{comp} is calculated as the net transport T_{net} from equation (8) divided by the area of the section at 26.5°N. Applying a compensation velocity as such is effectively the same as applying a time-varying deep reference velocity across the section.

The METRIC package estimates AMOC transport at the RAPID site using outputs from ocean general circulation models. The model meridional velocities are used to evaluate both the FC and WBW transports. The Ekman transport is estimated using the model zonal wind stress component. The geostrophic interior transport is computed using dynamic height profiles relative to a level-of-no-motion at 4820 m (~4820 dbar) as in the observational estimates. A RAPID-style volume (mass) balance term or external transport is evaluated to ensure no net meridional flow across the section. Either bottom-up or top-down vertical integrals of the individual components or the total transport, including the compensation term, produces the overturning streamfunction. Usually, the maximum transport of the resulting profile is used as the AMOC transport value at this latitude.

As in MOVE calculations, the METRIC package allows a user to choose different reference depths and reference velocities as well as provides an option for use of a top-down approach to evaluate the geostrophic interior transport. Of course, a model *truth* transport based on the actual model meridional velocities can be obtained as well, akin to equation (5).

Summary of the input fields to the METRIC package: To evaluate AMOC at both sites, the package requires potential temperature, salinity, meridional velocity, and zonal wind stress fields on a model’s native grid. If the top-down geostrophic computation is chosen, sea surface height field also needs to be provided. Monthly average fields are used in the present manuscript. The initial version of the METRIC package uses the 1980 Equation of State of Seawater (EOS 80; Jackett and McDougall, 1995) to compute densities from potential temperature, salinity, and pressure (depth), which will be updated to a more recent formulation.

Text S2. A Way Forward to Estimate Reference Level Velocity at MOVE

To address the reference level used in the MOVE array, seafloor pressure records are available at both section end points (Kanzow et al., 2006). In principle, this can be used directly to replace the assumption of no motion at the reference level. However, due to sensor drift and unknown absolute vertical location of the sensor, mean and trends have to be removed from these data, making them useful only for time scales shorter than the individual instrument deployment durations. Kanzow et al. (2006) also discuss the issue of concatenating the individual time series segments. Based on these findings, the pressure observations have since been modified such that deployment durations are typically four years rather than one year, as initially used. Furthermore, the instruments are doubled up and staggered in time, such that there are two seafloor pressure instruments at each site that overlap by two years.

Koelling et al. (2020) have validated decadal trends in seafloor pressure derived from GRACE satellite observations against combinations of satellite altimetry and in-situ density observations, including from MOVE and RAPID moorings. This opens up a path forward to combine the in-situ seafloor pressure data with GRACE at the MOVE site, with the goal to get an observational estimate of the reference level velocity at all time scales. This is work-in-progress, but has potential to solve the reference level problem. As a word of caution, technical challenges with this approach will include the coarseness of the GRACE-derived data, and the inconsistency of the in-situ pressure data in terms of deployment duration and what trends were removed from them.

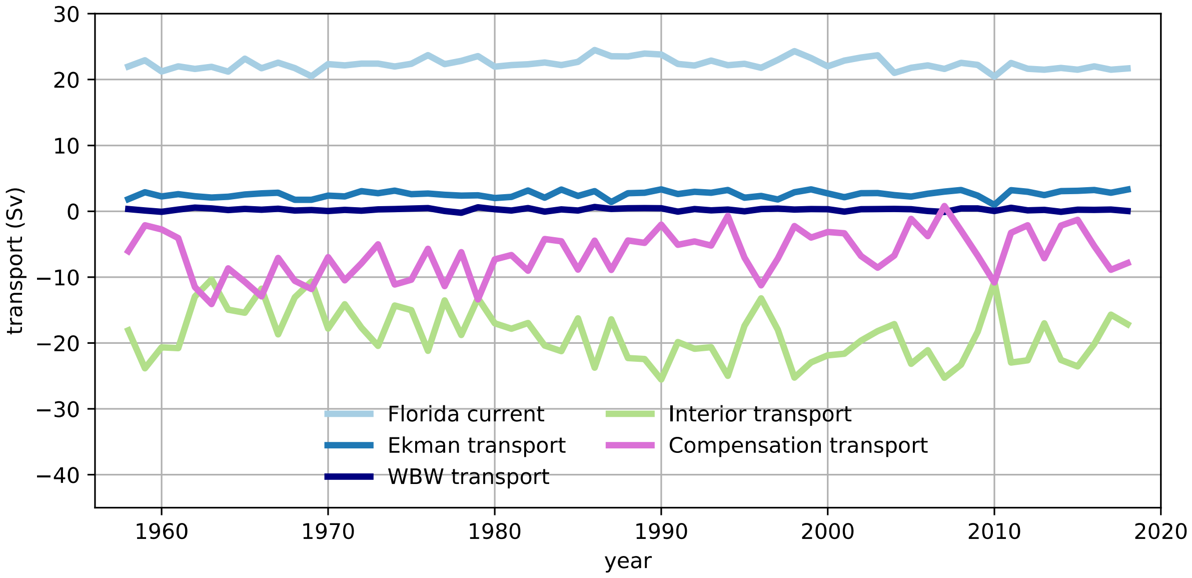

Figure S1. Annual-mean time series of the transport components at RAPID from FOSI, computed using the observational method (POP-RAPID). WBW is the Western Boundary Wedge transport. The sum of all the components is zero at all times.

Method Short Name	Brief Explanation
MOVE	Observational estimate at 16°N
MOVE-offset	Observational estimate at MOVE adjusted to zero transport at 1200 m
RAPID	Observational estimate at 26.5°N
POP-MOC	Model transport across the full basin at 16°N (used for MOVE)
POP-RAPID-vel	Model transport based on meridional velocity at RAPID (*truth*)
POP-MOVE-vel	Model transport based on meridional velocity at MOVE (*truth*)
POP-MOVE	Model MOVE transport based on observational method
POP-RAPID	Model RAPID transport based on observational method
POP-MOVE-ref	Same as POP-MOVE, but with nonzero reference velocity
POP-MOVE-td	Model MOVE transport where internal component is based on top-down approach
POP-MOVE-offset	Model MOVE transport adjusted to zero transport at 1200 m

Table S1. A summary of transport methods considered in this study.

	POP-MOVE-vel	POP-MOC	POP-MOVE	POP-MOVE-offset	POP-MOVE-ref	POP-MOVE-td
mean	16.4	15.0	22.4	12.5	12.9	18.3
std	1.5	1.3	2.0	2.0	1.7	1.7
correlation	–	0.71	0.27	0.27	0.87	0.94

Table S2. Mean and standard deviations (std) for the transport time series shown in Figure 2a for the MOVE site obtained using different methods from FOSI. The mean and std are in Sv. The simultaneous correlations of each time series with those of the model truth (POP-MOVE-vel) are also given.

Trend Period	POP-RAPID-vel	POP-RAPID	POP-MOVE-vel	POP-MOVE	POP-MOVE-ref	POP-MOVE-td
2004-2015	–1.4	–1.7	–1.4	–2.0	–1.2	–2.5

Table S3. Transport trends during the 2004-2015 period for the FOSI time series shown in Figures 1f and 2a. The trends are in Sv decade^{-1}.