Calculating the Meridional Volume, Heat, and Freshwater Transports from an Observing System in the Subpolar North Atlantic: Observing System Simulation Experiment

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ABSTRACT

A transbasin monitoring array from Labrador to Scotland was deployed in the summer of 2014 as part of the Overturning in the Subpolar North Atlantic Program (OSNAP). The aim of the observing system is to provide a multiyear continuous measure of the Atlantic meridional overturning circulation (AMOC) and the associated meridional heat and freshwater transports in the subpolar North Atlantic. Results from the array are expected to improve the understanding of the variability of the subpolar transports and the nature and degree of the AMOC’s latitudinal dependence. In this present work, the measurements of the OSNAP array are described and a suite of observing system simulation experiments in an eddy-permitting numerical model are used to assess how well these measurements will estimate the fluxes across the OSNAP section. The simulation experiments indicate that the OSNAP array and calculation methods will adequately capture the mean and temporal variability of the overturning circulation and of the heat and freshwater transports across the subpolar North Atlantic.

1. Introduction

The Atlantic meridional overturning circulation (AMOC) plays a critical role in the global climate system by redistributing heat and freshwater (FW) between high latitudes and the tropics. A linkage between AMOC variations and global temperature change in the geologic past has been made with the use of model and/or paleoclimate proxy records (Ganopolski and Rahmstorf 2001; Clark et al. 2002; Rahmstorf 2002; McManus et al. 2004; Lynch-Stieglitz et al. 2007, 2011; Böhm et al. 2015). AMOC variations in the geologic past have been widely attributed to changes in the amount of deep water formed in the high-latitude North Atlantic and in the Nordic seas. Similarly, current IPCC projections of an AMOC slowdown in the twenty-first century are attributed to changes in the amount of deep water formed in the high-latitude North Atlantic (Biastoch et al. 2008; Stepanov and Haines 2014; Pillar et al. 2016), and AMOC variability over the modern observational record (Lozier 2012, and references therein). While such a connection may indeed exist, observations to date have been insufficient in spatial and/or temporal coverage to firmly establish it.

Since 2004, the 26°N RAPID–MOCHA program has been providing a continuous measure of the AMOC in the subtropical North Atlantic (Kanzow et al. 2007; Cunningham et al. 2007). Direct observations from RAPID–MOCHA have revealed important intra-seasonal and interannual variability in the AMOC (Cunningham et al. 2007; McCarthy et al. 2012) and in the heat (Johns et al. 2011) and FW transports (McDonagh et al. 2015) at that latitude. Measurements at this site for over a decade have revealed an AMOC decline (for the period of 2004–12) with an average rate of $-0.54 \text{Sv}\text{yr}^{-1}$ (1 Sv = $10^6 \text{m}^3\text{s}^{-1}$; Smeed et al. 2014). While model studies indicate that the AMOC at 26°N has a lagged response to buoyancy forcing in the subpolar gyre over interannual to decadal time scales (Biastoch et al. 2008; Stepanov and Haines 2014; Pillar et al. 2016), the relationship of this change to observed
deep-water mass variability has yet to be determined. Moreover, it has been shown that AMOC changes lack latitudinal coherence on interannual (Bingham et al. 2007; Zhang 2010) and decadal time scales (Lozier et al. 2010), such that AMOC changes at 26°N are unlikely to reflect AMOC changes in the subpolar North Atlantic on those time scales. Therefore, direct and synoptic observations of the AMOC in the subpolar North Atlantic are needed to gain a full understanding of AMOC variability, its latitudinal coherence, and the governing mechanisms.

In the summer of 2014, an international community of ocean scientists deployed an observing system for sustained AMOC observations in the subpolar North Atlantic as part of the Ovturning in the Subpolar North Atlantic Program (OSNAP; Lozier et al. 2017). The OSNAP array of current meter and dynamic height moorings has two legs: OSNAP West extends from Labrador to southwestern Greenland and OSNAP East extends from southeastern Greenland to Scotland (Fig. 1). The OSNAP observing system also consists of two sustained glider surveys and RAFOS float deployments. The reader is referred to Lozier et al. (2017) for a full description of OSNAP.

Estimation of the overturning circulation and the net heat and FW transports across the OSNAP sections from an observational array that spans several basins—and uses a variety of instruments—requires careful consideration of the calculation methods. Prior to the acquisition of the data necessary to calculate the observed OSNAP overturning, and heat and FW transports, the calculation methods have been developed and tested using a series of observing system simulation experiments (OSSEs), whereby the deployed observing system is recreated within the context of an ocean circulation model. The degree to which the observing system can provide an accurate estimate of the meridional overturning circulation (MOC), meridional heat transport (MHT), and meridional FW transport (MFT) is assessed by the match (or mismatch) between the subsampled model estimates and the model estimates calculated from the fully resolved model fields. In this study, the calculation methods for the OSNAP metrics are described and their efficacy is assessed using OSSEs.

The structure of this paper is as follows: Section 2 describes the model output used for the OSSEs throughout this paper and the observational data used to validate an interpolation method used in the OSSEs. Section 3 describes the methods used to calculate the cross-sectional velocity and property fields, and the MOC, MHT, and MFT across each OSNAP section. Section 4 presents the results from a suite of OSSEs, and the paper is summarized in section 5.

2. Data

In this section we describe the model output and how it is used to simulate temperature, salinity, and velocity measurements for use in the OSSEs. The simulated data

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**Figure 1.** OSNAP line (black) plotted on the 1993–2014 mean ADT. ADT is masked where the water depth is shallower than 1000 m. Also denoted are the OSNAP glider path (red line), the OSNAP moorings (green circles), three French moorings (red circles) as part of the Reykjanes Ridge Experiment (RREX), and the 1000-, 2000-, and 3000-m isobaths (solid gray lines). Domains used for the collection of Argo floats for OA (dashed boxes) are shown. The x axis of the OSNAP grid, defined for calculating the cross-sectional fluxes, follows the black line (positive eastward), and the y axis is perpendicular to the black line.
are referred to as “pseudo-observations” throughout this paper. We also introduce the observational data used to validate an interpolation method.

a. Model output and pseudo-observations for the OSSEs

1) MODEL OUTPUT

The numerical model output used in this study is from ORCA025, an eddy-permitting configuration of the Nucleus for European Modelling of the Ocean (NEMO) package that combines a primitive equation, z-level ocean model, and an ice model (Barnier et al. 2006; DRAKKAR Group 2007). The model domain, divided into 46 levels in the vertical, is spanned by a global, tripolar, curvilinear grid with a nominal resolution of $\frac{1}{4}^\circ$ at the equator and $\sim\frac{1}{2}^\circ$ in the subpolar basin. Five-day averaged temperature, salinity, and velocity for 1990–2004 are used in this study. As described in section 2a, the ORCA025 model output will be used to produce pseudo-observations from OSNAP used to calculate the MOC, MHT, and MFT.

We note here that the goal of this OSSE study is not to test the degree to which ORCA025 faithfully reproduces the observed overturnings, but rather to develop and optimize the MOC, MHT, and MFT calculation methods using a free-surface eddy-permitting model. Nevertheless, it is important that the model reproduce the main circulation components. ORCA025 captures sufficiently several observed features of the subpolar circulation, as described in later sections. Thus, it can provide a meaningful context for the OSSE calculations.

2) SETTING UP THE OSSE

To compute fluxes across the OSNAP sections, which are aligned neither zonally nor meridionally (Fig. 1), we define a grid that follows that section. Specifically, we use a Cartesian coordinate system with the $x$ axis parallel to the OSNAP line that passes through all moorings, the $y$ axis perpendicular to that line, and the $z$ axis pointing upward. We refer to this grid defined for the OSSEs as the “OSNAP grid,” to avoid confusion with the actual OSNAP sections. The horizontal resolution of this section is $\sim\frac{1}{4}^\circ$, which is the native resolution of ORCA025. All mooring locations are kept as grid nodes; thus, the horizontal resolution is variable but never greater than $\frac{1}{4}^\circ$. For the vertical grid of the section, we use 200 levels, which span from 5 to 4000 m with a uniform interval of 20 m. This vertical resolution exceeds the native resolution of the model (ORCA025 has 46 levels in the vertical) in order to accommodate the positions of moored instruments in the water column.

Model velocity and property fields (temperature and salinity) are interpolated onto the OSNAP grid. Interpolating model output onto the OSNAP grid serves as a reference to validate the OSSE results (see section 4). The interpolation is done in two steps: first, the model output is horizontally interpolated onto the OSNAP grid at each of the original 46 depth levels; then the resultant velocity and property data at each horizontal grid are vertically interpolated, using a shape-preserving piecewise cubic Hermite interpolating polynomial to fill the vertical grid of 200 levels. The velocity data have been rotated to the OSNAP grid. Similarly, the model sea surface height and model surface wind stress are interpolated onto the OSNAP grid. The temporal resolution for all OSSE calculations is 30 days. Thus, the fields used for the flux calculations (see section 3) are averaged over 30 days.

3) PSEUDO-OBSERVATIONS FOR THE OSSEs

No observations from the OSNAP array have been used in this paper. For the OSSEs, pseudo-observations are taken from the model output, which are used for the MOC, MHT, and MFT calculations. Specifically, we use model output to produce the pseudo-observations from the OSNAP moorings and gliders (Fig. 2) and from Argo floats in the region. Thus, the ORCA025 output is used to produce: 1) directly measured temperature, salinity, and velocities from moored instruments; 2) temperature and salinity measurements from gliders; and 3) temperature and salinity profiles from Argo floats. Each of these three simulations is explained below:

1) Mooring: OSNAP instruments are “deployed” into the model at the exact locations of the instruments on the OSNAP moorings. Five-day model outputs from the grid are vertically interpolated to the exact position of each instrument via a shape-preserving spline interpolation, and then averaged every 30 days, to produce a time series for each instrument.

2) Glider: We use the information that OSNAP gliders measure temperature and salinity over the upper 1000 m of the water column during each dive, and they travel along the OSNAP line at a horizontal speed of $-0.25 \text{ m s}^{-1}$. With that speed, the OSNAP gliders traverse the dark blue area in Fig. 2a in about 30 days. For the OSSEs, we use the same depth range for our virtual glider and assume that the glider covers the dark blue area in each 30-day period. All model temperature and salinity vertical profiles within that area are then averaged over each 30-day period to produce the pseudo-observations of temperature and salinity from the glider.

3) Argo: We randomly select a number of model temperature/salinity profiles for the upper 2000 m of the water column in the vicinity of the OSNAP
East and West sections every 30 days (see Fig. 1 and appendix A for the domain choice). The number of selected profiles for a 30-day period is the average number of actual Argo profiles within the vicinity of the OSNAP line available for a 30-day period between 2014 and 2015—that number is 207 for OSNAP East and 112 for OSNAP West. For our simulations, we do not vary these numbers.

b. Property fields for the OSSEs: An OA method

Time-varying property fields in the area away from the moorings (blue areas in Fig. 2) are needed for calculating the heat and FW transports (see section 3c). In addition, density fields in the dark blue areas are needed for the thermal wind calculations (see section 3a). A uniform grid of temperature, salinity and density on the OSNAP section is created for each 30-day period using an objective analysis (OA; appendix A). These gridded property fields serve as intermediate data products for the flux estimates. In the real ocean, the input for OA will be Argo data and OSNAP mooring/glider data. For the OSSEs, the pseudo-observations from Argo and the OSNAP mooring/glider taken from the model (section 2a) are used instead as input to OA.

In this section, we validate the OA method by comparing the OA property fields to those derived from
full-depth CTD stations collected during the July 2014 OSNAP East survey (see more details on the OSNAP4 cruise at http://www.o-snap.org/observations/research-cruises/). That survey followed the OSNAP line from the eastern Irminger Basin to Hatton Bank (~500–1500 km; Fig. 2a). We refer to the property fields from the OA method as OA-derived fields and those based only on CTD stations as the observed fields.

For the validation of the OA mapping we use Argo data during the approximate time of the hydrographic survey, from 20 to 26 July 2014, and we use a subset of CTD stations from that survey. The temporal span of the collected Argo data exceeds the span of the cruise by 15 days on either end, since we are calculating property fields over a 30-day moving window. CTD data from the cruise are used as substitutes for OSNAP mooring and glider measurements, since not all of the latter measurements for that period are available. Therefore, in obtaining the OA product for the purpose of this validation, we use Argo data as planned, but we use temperature and salinity measurements from the CTD stations instead of from the mooring instruments and gliders. It is important to note that we use the CTD data only at the sites of the moorings and gliders (in the red and dark blue areas, Fig. 2a). Furthermore, the cross section of properties obtained from the hydrographic survey is quasi-synoptic, therefore we create the OA data fields so as to simulate this quasi synopticity. Argo profiles and the simulated mooring and glider data (from the CTD stations) within 15 days before and after the date of each CTD station are used to calculate the temperature, salinity, and density at that station location via OA.

For the OSNAP calculations, we will be using the OA property fields only in those regions without direct property measurements from moorings (see section 3b). Thus, for validation of our OA method, we use the OA property fields only in the blue (light and dark) and white areas shown in Fig. 2a. In these areas, the temperature root-mean-square difference (RMSD) from the observed field is 0.2°C, and the salinity RMSD is 0.02.

We also compare geostrophic velocities calculated from the OA density field in the dark blue area (Fig. 2a) to geostrophic velocities calculated from the CTD data in that area. This is the region of the glider domain where the OA property fields are heavily weighted by the simulated glider measurements, and they will be heavily weighted by actual glider measurements. Elsewhere (in the light blue, green, and white areas) we will have density information directly available only from bounding moorings, so our test of the OA method’s ability to construct geostrophic velocities at each grid focuses on this area only. Absolute geostrophic velocities are calculated by referencing the observed and OA-derived thermal wind shears to surface absolute geostrophic velocities from the satellite-derived absolute dynamic topography (ADT). We refer to the velocity fields based on the OA density field and those based only on CTD stations as the OA-derived velocity and the observed velocity, respectively.

Both the observed and OA-derived velocity fields (Fig. 3) show similar features, with the main branch of the northward-flowing North Atlantic Current (NAC) over the western flank of Hatton Bank (250 km). The velocity RMSD between the two sections is 0.05 m s⁻¹, resulting in a difference of ~0.2 Sv in the total volume transport.

Overall, we conclude that the OA method, using data from Argo floats and the mooring and glider sites, is sufficient for the reconstruction of the property fields across the section, and for the reconstruction of geostrophic velocities in the domain of the glider survey.

3. Calculation methods

The goal of the OSSE simulations is to produce estimates of the MOC, MHT, and MFT for each 30-day period over the temporal period from 1990 to 2004 for OSNAP West and East. The methods for calculating velocity, potential temperature, salinity, and density at each grid cell of the OSNAP grid and the fluxes across that grid are described in this section. We use the color designations in Fig. 2 to guide the discussion of the calculation methods.

a. Cross-section velocity field

The method for calculating the meridional velocity $V$ is based on the one used by Baehr et al. (2004) and Hirschi and Marotzke (2007). Velocity $V$ is given by

$$V(x, z, t) = V_{\text{uncorrected}}(x, z, t) + V_{\text{comp}}(t), \quad \text{(m s}^{-1})$$

where $V_{\text{uncorrected}}$ is the cross-sectional velocity obtained from directly measured velocity, the zonal density gradients, the sea surface slope, and the surface wind stress [section 3a(1)], and $V_{\text{comp}}$ is the compensated depth-independent velocity obtained from the mass-conservation constraint, added to ensure there is no mass transport across the entire section [section 3a(2)]. Terms $V_{\text{uncorrected}}$, $V_{\text{comp}}$, and $V$ are calculated for each 30-day interval. Note that all velocities are perpendicular to the OSNAP section and therefore are not strictly meridional. Nonetheless, we will refer to these velocities (as well as all fluxes) as meridional and all northward velocities and fluxes are designated as positive.

1) **UNCORRECTED VELOCITY FIELD:**

$$V_{\text{uncorrected}}(x, z, t)$$

The term $V_{\text{uncorrected}}$ is calculated differently across each OSNAP section, as described below using the color designations in Figs. 2a and 2b:
For the light blue areas: $V_{\text{uncorrected}}(x, z, t) = V_g(z, t) + V_{\text{ek}}(x, t)$

The geostrophic velocity $V_g$ is derived from thermal wind based on the zonal density gradient from the bounding dynamic height moorings. We refer to this method as endpoint geostrophy. The absolute geostrophic velocity is defined as

$$V_g(z, t) = \frac{g}{f\rho_0} \frac{\partial}{\partial x} \int_{z_{\text{ref}}}^{z} \rho(z,t) \, dz + V_b(t), \quad (\text{m s}^{-1}),$$

where $g = 9.81 \text{ m s}^{-1}$ is the acceleration due to gravity, $\rho_0 = 1027 \text{ kg m}^{-3}$ is a reference density, $f = 2\Omega \sin \phi$ is the Coriolis parameter in which $\phi$ is latitude, and $\rho(z,t)$ is the density profile obtained from the simulated temperature and salinity measurements from moorings. The barotropic velocity $V_b$ is calculated by subtracting the surface geostrophic velocity derived from thermal wind (referenced to either the directly measured velocity from short moorings or a bottom level of no motion) from the surface geostrophic velocity derived from the model sea surface slope between the two bounding density profiles. A contribution from barotropic velocities to the MOC arises when bottom-reaching currents occur above sloping boundaries (e.g., Lee and Marotzke 1998; Hirschi and Marotzke 2007). As demonstrated later in a sensitivity experiment (section 4a), the inclusion of the barotropic velocity is particularly important for the flux estimates at OSNAP East.

The Ekman velocity $V_{\text{ek}}$ is derived from the model surface wind stress as follows:

$$u_{\text{ek}}(x,t) = \frac{\tau_x(\text{lon, lat}, t)}{f\rho_0 d}, \quad (\text{m s}^{-1}),$$

$$v_{\text{ek}}(x,t) = -\frac{\tau_y(\text{lon, lat}, t)}{f\rho_0 d}, \quad (\text{m s}^{-1}),$$

where $(u_{\text{ek}}, v_{\text{ek}})$ are the zonal and meridional Ekman velocities, respectively; $(\tau_x, \tau_y)$ are the zonal and meridional wind stresses, respectively; and $d$ is the Ekman layer depth. The Ekman velocities $(u_{\text{ek}}, v_{\text{ek}})$ are rotated to generate the velocity field $V_{\text{ek}}$ whose direction is normal to the OSNAP cross section. Term $V_{\text{ek}}$ is applied to every grid cell in the Ekman layer in all blue areas, and it is zero elsewhere below the Ekman layer.

We use a constant Ekman depth of 90 m for all OSSE calculations, obtained by assuming a typical wind speed of 11 m s$^{-1}$ at 58°N. We use a constant depth for two...
reasons: 1) the model Ekman transport is quite small in the OSNAP region ($\sim 1\text{ Sv}$), consistent with observations at similar latitudes (Mercier et al. 2015; Holliday et al. 2016, manuscript submitted to J. Geophys. Res. Oceans); and 2) calculations with variable Ekman depths along the section do not significantly impact the flux estimates. As discussed below, for the observational estimate, we plan to use variable Ekman depths along the section.

(ii) For the dark blue area: $V_{\text{uncorrected}}(x, z, t) = V_g(x, z, t) + V_{\text{ek}}(x, t)$

In this glider domain, data (temperature and salinity) for the density field estimation are available at each grid cell. This density information is critical to our calculations, especially over the western flank of Hatton Bank because otherwise we would not be able to assess the velocity field associated with the NAC, which is bounded to the west by a dynamic height mooring but has no bounding mooring to the east. Therefore, rather than relying on endpoint geostrophy, here we use what we refer to as full-grid geostrophy.

We calculate thermal wind and the barotropic velocity across each grid cell using the OA density field and the model sea surface slopes, respectively, as input to Eq. (2) to solve for $V_g$. As discussed in section 2b, full-grid geostrophy provides a robust reconstruction of the velocity structure of the NAC. Finally, in this dark blue area, $V_{\text{ek}}$, described above, is applied to every grid cell in the Ekman layer.

(iii) For the white areas (bottom triangles):

$$V_{\text{uncorrected}}(x, z, t) = V_b(t)$$

Vertical velocity shears are set to zero in the bottom triangles; thus, $V_{\text{uncorrected}}$ at each grid cell is equal to the $V_b$ estimated from the sea surface slope [see Eq. (2)].

(iv) For the red areas: $V_{\text{uncorrected}}(x, z, t) = V_{\text{measured}}(x, z, t)$

Velocities in the boundary current regions are estimated from simulated direct measurements of the current meters and ADCPs on the boundary moorings. The velocity field is calculated using distance-weighted interpolation between adjacent moorings. To preserve the strength and structure of bottom-intensified currents, the linear interpolation is calculated following the topography for the area between the seafloor to 200 m above the seafloor. In addition, in the eastern Rockall Trough, the velocity measurements from the tall mooring adjacent to the continental slope are used to fill the bottom triangle to its east (red area below the maximum common depth of the adjacent moorings near 2100 km, Fig. 2a).

(v) For the green areas (inshore unmeasured areas):

$$V_{\text{uncorrected}}(x, z, t) = V_{\text{climatology}}(x, z, t).$$

Climatological velocity from ORCA025 is used for every grid cell in these areas.

2) Compensation velocity: $V_{\text{comp}}(t)$

The vertical and horizontal integration of the uncorrected velocity field provides an estimate of the net volume transport across each OSNAP section over each 30-day period [Eq. (5)]. The double integral is taken over the full depth $H$ and between the western boundary $x_w$ and the eastern boundary $x_e$.

$$T_{\text{net}}(t) = \int_{x_w}^{x_e} \int_{-H}^{0} V_{\text{uncorrected}}(x, z, t) \, dx \, dz, \quad (\text{m}^3 \text{s}^{-1}), \quad (5)$$

where $T_{\text{net}}$ is the net volume transport for each 30-day period. A spatially uniform compensation velocity is applied to $V_{\text{uncorrected}}$ to ensure zero net meridional mass transport across the section, without affecting the vertical velocity shears (Hall and Bryden 1982). Term $V_{\text{comp}}$ is therefore defined as

$$V_{\text{comp}}(t) = -\frac{T_{\text{net}}(t)}{A_{\text{total}}}, \quad (\text{m} \text{s}^{-1}), \quad (6)$$

where $A_{\text{total}}$ is the cross-sectional area across the OSNAP section. Term $V_{\text{comp}}$ is added to every grid cell, as shown in Eq. (1).

b. Cross-sectional property fields

The cross-sectional potential temperature $\theta$, salinity $S$, and density $\rho$ are reconstructed for each 30-day interval for the purpose of computing the MHT and MFT. Density $\rho$ is obtained as a function of temperature, salinity, and pressure.

The reconstructions are implemented differently across the OSNAP grid, as described below using the color designations in Fig. 2.

1) For the white, green, and blue areas:

$$\theta(x, z, t) = \theta_{\text{OA}}(x, z, t), \quad S(x, z, t) = S_{\text{OA}}(x, z, t), \quad \rho(x, z, t) = \rho_{\text{OA}}(x, z, t)$$

The 30-day mean $\theta_{\text{OA}}(x, z, t), S_{\text{OA}}(x, z, t)$, and $\rho_{\text{OA}}(x, z, t)$ (subscript OA indicates objectively analyzed value) are used for every grid cell. In the coastal area and the area below the 2000-m water depth, the OA product is practically the climatological field because the pseudo-observations from Argo profiles are not available. In the dark blue area in Fig. 2a, the OA values are essentially direct measurements, since the pseudo-observations from the glider in that area were used to
Table 1. OSNAP East: MOC, MHT, and MFT estimates from the OSSEs and the model truth. Correlation coefficient R and RMSD between the OSSE and the model truth are given. One standard deviation of the 15-yr mean is indicated, which was estimated from MC simulations.

<table>
<thead>
<tr>
<th></th>
<th>MOC (Sv)</th>
<th>MHT (PW)</th>
<th>MFT (Sv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model truth</td>
<td>13.65±1.56</td>
<td>0.36±0.04</td>
<td>-0.14±0.05</td>
</tr>
<tr>
<td>OSSE</td>
<td>12.13±2.57</td>
<td>0.32±0.07</td>
<td>-0.15±0.06</td>
</tr>
<tr>
<td>R</td>
<td>0.87</td>
<td>0.83</td>
<td>0.98</td>
</tr>
<tr>
<td>R²</td>
<td>0.76</td>
<td>0.69</td>
<td>0.96</td>
</tr>
<tr>
<td>RMSD</td>
<td>1.83</td>
<td>0.05</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 2. OSNAP West: MOC, MHT, and MFT estimates from the OSSEs and the model truth. Correlation coefficient R and RMSD between the OSSE and the model truth are given. One standard deviation of the 15-yr mean is indicated, which was estimated from MC simulations.

<table>
<thead>
<tr>
<th></th>
<th>MOC (Sv)</th>
<th>MHT (PW)</th>
<th>MFT (Sv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model truth</td>
<td>7.65±1.68</td>
<td>0.10±0.03</td>
<td>-0.16±0.05</td>
</tr>
<tr>
<td>OSSE</td>
<td>7.78±1.73</td>
<td>0.10±0.03</td>
<td>-0.18±0.05</td>
</tr>
<tr>
<td>R</td>
<td>0.89</td>
<td>0.94</td>
<td>0.90</td>
</tr>
<tr>
<td>R²</td>
<td>0.79</td>
<td>0.88</td>
<td>0.81</td>
</tr>
<tr>
<td>RMSD</td>
<td>0.77</td>
<td>0.01</td>
<td>0.03</td>
</tr>
</tbody>
</table>

produce the OA values and thus will heavily weight the variables there.

2) For the red areas: \( \theta(x, z, t) = \theta_{\text{measured}}(x, z, t), S(x, z, t) = S_{\text{measured}}(x, z, t), \rho(x, z, t) = f[\theta(x, z, t), S(x, z, t)] \) or \( \theta(x, z, t) = \theta_{\text{OA}}(x, z, t), S(x, z, t) = S_{\text{OA}}(x, z, t), \rho(x, z, t) = \rho_{\text{OA}}(x, z, t) \)

Pseudo-observations of temperature and salinity from two bounding moorings are used to fill the grid cells between the moorings and between the sea surface and the maximum common depth of these two moorings for each 30-day interval, using distance-weighted horizontal interpolation. In the bottom triangles below the maximum common depth of adjacent moorings, the 30-day mean \( \theta_{\text{OA}}, S_{\text{OA}}, \) and \( \rho_{\text{OA}} \) are used.

c. MOC, MHT, and MFT

The MOC is defined here as the sum of all northward transports from the section-width integrated volume flux profile,

\[
\text{MOC}(t) = \int_{x_w}^{x_e} T(\sigma, t)\,d\sigma, \quad (\text{Sv}), \quad \text{for } T(\sigma, t) > 0, \quad (7)
\]

where

\[
T(\sigma, t) = \int_{x_w}^{x_e} V(x, \sigma, t)\,dx, \quad (\text{Sv}), \quad (8)
\]

\( \sigma \) is the potential density coordinate, and the integration is taken between \( x_w \) and \( x_e \). We choose to calculate the MOC in density space rather than depth, since the former gives a measure of the transformation of the waters from one density class to another.

The MHT across the section is computed as

\[
\text{MHT}(t) = \int_{\sigma_{\max}}^{\sigma_{\min}} \int_{x_w}^{x_e} V(x, \sigma, t) \times \rho(x, \sigma, t) \times \theta(x, \sigma, t)
\times C_p(x, \sigma, t)\,dx\,d\sigma, \quad (\text{W}), \quad (9)
\]

where \( C_p \) is the specific heat of seawater calculated as a function of \( \theta \) and \( S \) under a standard atmosphere for each grid cell, and the double integral is taken over all \( \sigma \) surfaces and between the western and eastern boundaries.

The MFT across the section is defined as

\[
\text{MFT}(t) = -\int_{\sigma_{\max}}^{\sigma_{\min}} \int_{x_w}^{x_e} V(x, \sigma, t) \times \frac{S(x, \sigma, t) - \bar{S}}{\bar{S}}\,dx\,d\sigma, \quad (\text{Sv}),
\]

where \( \bar{S} \) is the area-weighted section mean salinity (34.9322 for OSNAP East, 34.8648 for OSNAP West in ORCA025). The resultant MFT from Eq. (10) is an equivalent FW transport that can be interpreted as the volume of water, with the section-mean salinity, needed to balance the salinity flux across the section in each 30-day period.

d. Uncertainty of the flux estimates

The uncertainty of all flux estimates is evaluated using Monte Carlo (MC) simulations. The inputs into the MC simulations are the mean observed variables and their standard deviations over each 30-day period. The output is a statistical description of the MOC, MHT, and MFT over the averaging intervals used to produce the mean variables. In addition, the mean fluxes and their standard deviations during each 30-day period are used as input into additional MC simulations in order to estimate the uncertainty of the 15-yr mean fluxes (the results are shown in Tables 1 and 2). Details on the MC simulations are in appendix B.

4. OSSE results

In this section, the estimated MOC, MHT, and MFT from the OSSEs are compared with those derived from the full model velocity, temperature, and salinity fields for assessing the efficacy of the array and our calculation methods. We refer to the estimated results as the OSSE results and those based on the model data fields as the model truth.
a. **OSNAP East**

1) **VELOCITY AND PROPERTY FIELDS COMPARISON**

Both the OSSE and model mean velocity fields (Figs. 4a and 4b) across OSNAP East reveal, from west to east, a southward boundary current along the Greenland continental slope (100–200 km), a northward (southward) current on the western (eastern) flank of the Reykjanes Ridge (600–700 km), and northward NAC branches over a broad region from the Iceland Basin to the Rockall Trough. Overall, the OSSE captures these well-defined circulation features. Velocity differences between the two fields are quite small across the section (Fig. 4c; RMSD = 0.01 m s$^{-1}$). Relatively large differences are restricted to the area over the eastern flank of the Reykjanes Ridge above the short moorings (750–950 km). Such differences are owing to endpoint geostrophy, which yields the actual net transport between the two bounding dynamic height moorings without resolving the velocity distribution in between. Ignoring the spatial velocity variations does matter when calculating the MHT and MFT. We will show later that the velocity differences are a likely source of error for our MHT estimate across OSNAP East. In addition, relatively large velocity differences appear in the bottom triangle west of Hatton Bank (~1400 km). The OSSE velocity here is simply the barotropic velocity from the sea surface slope [section 3a(1)].

We next examine the RMSD for the OSSE velocity, temperature, and salinity time series at each grid (Fig. 5). The velocity RMSD is <0.02 m s$^{-1}$ in areas where direct velocity measurements are available or where the mean circulations are weak. It increases to ~0.05 m s$^{-1}$ in some of the geostrophic segments, for example, in the eastern Iceland Basin (between the moorings at ~1150 and ~1350 km in Fig. 5a). Those large velocity RMSDs are concomitant with large velocity differences (Fig. 4a) in the areas where the main branches of the NAC cross through the OSNAP line.

Turning to the reconstruction of the temperature and salinity fields, Figs. 5b and 5c show that for a majority portion of the section, the temporal variability of temperature and salinity is well reproduced: the temperature RMSD is <0.2°C and the salinity RMSD is <0.02. Relatively large RMSD values in temperature (~1°C) and salinity (0.1) are confined to the surface layer on both sides of the Reykjanes Ridge (at ~600 and 800 km), where there are no direct measurements from the moorings. By comparison, temperature and salinity
variability in the surface waters in the eastern Iceland Basin and over the western flank of the Hatton Bank (1150–1700 km) are well captured by the pseudo-observations from gliders and hence the RMSDs in those areas are close to zero.

2) MOC, MHT, AND MFT COMPARISONS

How well the OSSE captures the MOC, MHT, and MFT across OSNAP East is revealed in Fig. 6 and in Table 1. The model overturning streamfunction at
OSNAP East, with its "classic" MOC—an upper limb with warm and saline waters flowing northward and a lower limb with cold and fresh waters flowing southward—is reproduced from the OSSE (Fig. 6a). Similarly, the zonally integrated temperature and FW transports (Figs. 6c and 6e, respectively) closely match those from the model truth. Note that the vertical profile in Fig. 6c illustrates temperature transport relative to 0°C as a function of depth. The heat transport across the entire section is given by the full-depth integrated temperature transport (the endpoint at the bottom of the plot, Fig. 6c). Since there is no mass transport associated with this integration, the heat transport is independent of temperature reference (e.g., Johns et al. 2011). As shown in Table 1, the mean MOC is underestimated by about 1.5 Sv and the MHT is underestimated by 0.04 PW, while the OSSE reproduces nearly all the MFT. All differences are well within one standard deviation of the model mean. The temporal variability of the OSSE time series nicely matches the model truth variability, as evidenced by strong correlations for all three variables. We note that the weakest match, the OSSE MHT, still captures about 70% of the variance of the model truth. The best match, the OSSE MFT, captures 96% of the model’s variability.

3) CONTRIBUTION OF THE BAROTROPIC VELOCITY TO THE OVERTURNING TRANSPORT

As described in section 3a, a barotropic velocity is added to the relative geostrophic velocity and therefore enters the MOC calculation. Here we show that these barotropic velocities are needed for an accurate reconstruction of the MOC at OSNAP East. We compare the OSSE result above (Fig. 4b; Table 1) to one calculated where instead of using a barotropic velocity in the blue areas as described in section 3a [Eq. (2)], we use a bottom level of no motion (or the velocity from short moorings wherever applicable). We refer to estimates from this OSSE run as OSSE_Lnm results, where “Lnm” is shorthand for “level of no motion.” OSSE_Lnm underestimates the mean MOC by an additional 1.95 Sv and the mean MHT by another 0.05 PW. The RMSDs for the OSSE_Lnm volume and heat transports from the model truth are 3.57 Sv and 0.09 PW, respectively, both outside of one standard deviation of the model means. A comparison of the OSSE_Lnm and the model truth cross-sectional velocity (Fig. 7) shows that velocity differences are largely depth independent and largest in the eastern Iceland Basin and over the western flank of Hatton Bank (1150–1700 km; that is, they are associated with the
NAC branches. It is noted that the velocity differences between OSSE_lnm and the model truth are smaller than those between OSSE and the model truth above the Reykjanes Ridge (750–950 km; Fig. 4c). The presence of short moorings in that area allows the velocity shears in OSSE_lnm to be referenced to the velocity from the short moorings instead of a bottom level of no motion. Therefore, it provides a better reconstruction of the velocity structure in that area than OSSE, which references the shears to the surface geostrophic velocity derived from the sea surface slope between two bounding moorings (at 750 and 950 km, respectively).

Overall, we conclude that the use of a bottom level of no motion significantly degrades the reconstruction of the absolute velocity field and, as a result, the reconstruction of the volume and heat transports. For this reason, we use the ORCA025 model, which has free surface, for the OSSEs. This choice has allowed us to develop and test a calculation method that employs sea surface height data. For the observational estimates, we will use a merged, gridded altimetry product in the flux estimates.

As for OSNAP West, since the interior circulation is composed of weak recirculating gyres and the topography there is relatively flat (blue area, Fig. 2b), a contribution to the MOC from barotropic velocities is negligible.

b. OSNAP West

1) VELOCITY AND PROPERTY FIELDS COMPARISON

Both the OSSE and model mean velocity fields across OSNAP West (Figs. 8a and 8b) show strong cyclonic boundary currents over the continental slopes on each side of the Labrador Basin with weak recirculating gyres in the basin interior. Therefore, the mean velocity structure is well captured from the OSSE. Differences in the mean velocity fields mainly appear near the bottom above the slopes and in the vicinity of the dynamic height moorings (at ~500 and 1150 km, respectively, Fig. 8c). The former is attributed to the model’s discontinuous staircase topography, and the latter is related to the recirculating gyres that are not resolved from the calculated geostrophic velocities.

We next examine the RMSD for the OSSE velocity and property fields at each grid cell (Fig. 9). The velocity RMSD is overall small and on the order of 0.01 m s$^{-1}$ (Fig. 9a). The overall temperature (Fig. 9b)
and salinity RMSDs (Fig. 9c) are about 0.2°C and 0.02, respectively. However, larger temperature (~0.4°C) and salinity RMSDs (~0.1) appear near the surface above the Labrador continental slope (400 km; Figs. 9b and 9c), owing to the large distance between the two adjacent moorings there, making linear interpolation less accurate. The RMSD also varies with depth, since the accuracy of the reconstruction depends on the property gradient between the moorings. Not surprisingly, there are large discrepancies between the model and OSSE property fields over the Labrador shelf (100–300 km). Such discrepancies are associated with the temperature and salinity variability of the shallow inshore component of the Labrador Current, which the climatological temperature and salinity values used in the OSSE for this region obviously cannot reproduce.

2) MOC, MHT, AND MFT COMPARISON

The MOC, MHT, and MFT across the OSNAP West section are reconstructed from the OSSE as shown in Fig. 10 and Table 2. The OSSE time-mean overturning streamfunction closely matches that from the model truth (Fig. 10a), showing a northward transport in the density range of 27.7–27.8 kg m⁻³, part of which is transformed to lighter waters and transported southward and the remainder is transformed to denser waters and also transported southward. Similarly, the vertical temperature and FW flux profiles (Figs. 10c and 10e, respectively) are reproduced from the OSSE. As shown in Table 2, the time-mean transports and their temporal variability are well captured from the OSSE. The mean MOC is slightly overestimated by 0.13 Sv and the mean MFT is overestimated by 0.02 Sv, while the OSSE reproduces nearly all the MHT. All differences are well within one standard deviation of the model mean. The variability of the transports is also reconstructed from the OSSE, as evidenced by strong correlations for all three variables. The weakest match, the OSSE MOC, captures 79% of the variance of the model truth, while the best match, the OSSE MHT, captures 88% of the model’s variability.

c. Alternative MOC definition

We tested the use of an alternative definition of the MOC, namely, one defined as the maximum of the overturning streamfunction in density space (MOC_max), rather

![Fig. 9. OSNAP West: Velocity, temperature, and salinity RMSDs between the model truth and the OSSE. The OSNAP moorings (vertical black lines) are plotted.](http://journals.ametsoc.org/doi/abs/10.1175/JTECH-D-16-0247.1?journalCode=ktec)
than the sum of all northward transports (section 3c). We find the OSSE mean MOC\textsubscript{max} to be 10.35 ± 2.18 Sv for OSNAP East, compared to 12.27 ± 1.74 Sv for the model truth using the same definition. The temporal variability of MOC\textsubscript{max} largely matches the model truth variability (R = 0.87, RMSD = 1.38 Sv). At OSNAP West, the OSSE and model truth MOC\textsubscript{max} are 1.93 ± 1.13 Sv and 1.80±1.24 Sv, respectively. The MOC\textsubscript{max} temporal variability compares well with the model truth (R = 0.83, RMSD = 0.72 Sv). The magnitude of the overturning for OSNAP West clearly depends on the MOC definition, a fact attributable to the complicated structure of the overturning in ORCA025, with two discrete overturning cells and where the depth (or density) of the overturning streamfunction maximum varies significantly in time (not shown). Because of this structure and variability, the simple maximum overturning metric appears insufficient to fully capture the nature of the overturning in the Labrador Sea, which is why we use the MOC as defined in Eq. (7) as our primary metric for the overturning strength. By contrast, the MOC strength in OSNAP East is comparable using either metric, due to the simpler (single cell) structure of the overturning across it. Nevertheless, the accuracy of the OSSE in reconstructing the overturning circulation—and by inference that of the OSNAP array—is not highly sensitive to the MOC definition used.

5. Summary and discussion

The OSNAP observing system is composed of moorings and gliders that span the width of the subpolar North Atlantic from Labrador to Scotland. Observations from these instruments will provide a direct measure of the MOC variability in the subpolar North Atlantic and its associated heat and FW transports over intraseasonal to interannual time scales.

In the present work, we demonstrate with OSSEs that the OSNAP array is capable of capturing both the strength and variability of the overturning transports in the subpolar North Atlantic. The OSSE mean overturning transports compare well with the model truth transports, with differences within one standard deviation of the model mean. The correlation between the overturning in the OSSE and the model is 0.89 (0.87) for OSNAP West (East). Comparisons for the heat and FW across OSNAP West and East are also favorable.

Our study provides a valid framework for computing the actual flux estimates from the observing array.
wherein real ocean data collected at the measurement sites are inserted into the OSSE in place of pseudo-observations. Moreover, the experiences gained and the lessons learned from OSSEs have value that goes beyond that of simply testing a deployed observing system. For example, the OSSE framework also can—and will—be used to guide our choices in how to include additional information, such as satellite altimeter data, in the calculation of fluxes. The sea surface height from satellite altimeters will be utilized to enhance our estimates of the barotropic reference for computing absolute geostrophic velocities, which has proven to be important for the MOC and MHT estimates at OSNAP East.

The OSSE framework will also be used to evaluate alternative observing strategies, assess which measurements are critical for the determination of the fluxes across the OSNAP lines, and help develop an optimally efficient long-term MOC monitoring system in the subpolar region that would include other existing observations. Previous studies have found a close relationship between sea surface height changes and MOC variability across the North Atlantic Ocean from both model simulations (e.g., Lorbacher et al. 2010; Robson et al. 2012) and observations (Li et al. 2012, 2016; McCarthy et al. 2015). Moreover, Willis (2010) used a combination of altimeter and Argo data for reconstructing the MOC at 41°N, though their method is limited to particular latitudes. Recently, Frajka-Williams (2015) showed the feasibility of using altimeter sea surface height for capturing the interannual variability of the midocean component of the MOC. Therefore, further investigations will be needed in order to assess the relationship between the sea surface height anomalies at high latitudes and the overturning variability at OSNAP for developing MOC metrics at high latitudes.

There are several things that are either not included in the current method or are specific to the model output that need to be considered in the future when using observations for the calculations. First, all the OSSE runs use a constant Ekman layer depth of 90 m along the entire section. During the actual experiments, the Ekman layer depth will be calculated as a function of wind speed (e.g., from a reanalysis product), latitude, and time along the section grid. Second, during the actual experiment, the inshore unmeasured areas (green areas in Fig. 2) will be filled with proxy estimates from nearby moorings and/or observed climatological data over the shelves. Finally, constraining the volume transport at the OSNAP sections will take into account long-term mean transports at the Bering Strait (0.8 Sv; e.g., Woodgate et al. 2005; McDonagh et al. 2015) and the Davis Strait (−1.6 Sv, Curry et al. 2011). Appropriate constraints ensure robust flux estimates at OSNAP and are especially important for calculating FW transport (Holliday et al. 2016, manuscript submitted to J. Geophys. Res. Oceans).

Once data from the OSNAP array are available, we will calculate basin-width integrated overturning, net heat, and FW transports for OSNAP West and OSNAP East separately and combined. The earliest expected delivery of the first OSNAP products is one year after the retrieval of the data necessary for the calculations, that is, fall of 2017 (Lozier et al. 2017).

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APPENDIX A

Objective Analysis

Temperature, salinity, and density sections along the OSNAP line are produced from an OA method. OA assumes a known functional form for the covariance of the field to be mapped, and further assumes that the measurement error and the signal are not correlated (Bretherton et al. 1976; Böhme and Send 2005; Hadfield et al. 2007). First, available Argo profiles in the vicinity of the subsection (OSNAP East: 56°–63°N, 45°–5°W; OSNAP West: 50°–62°N, 55°–40°W; see dashed boxes in Fig. 1) are selected, and together with the temperature/salinity observations from the OSNAP mooring and gliders are prepared for OA. As part of this preliminary step, the climatological seasonal cycle, interpolated to individual Argo profile positions, is removed, since OA is designed to map anomalies (Bretherton et al. 1976). This climatology is subsequently reintroduced before any analysis is performed. OA returns the best least squares linear estimator of the temperature/salinity/density at each section grid cell along with a formal estimate of the associated error variance. The covariance of the data is assumed to be Gaussian, with a
decorrelation radius of 3° in both the zonal and meridional directions. It is noted that the use of smaller decorrelation length scales (e.g., 1.5°) improves the OSSE results in some regions. We plan further work on this OA method in order to optimize its application to the full in situ array. Data points are discarded where the formal error returned by OA is larger than 80% of the signal variance. Since Argo profiles provide only temperature/salinity data for the upper 2000 m in the water column, temperature/salinity at 2000 m in the water column, temperature/salinity at the grid cell below the 2000-m depth along the section is filled directly with climatology. The estimate of the temperature \( T_{\text{obj}} \) at each grid cell for each depth surface is given by

\[
T_{\text{obj}} = T_{\text{clim}} + \mathbf{w} \cdot (\mathbf{T} - T_{\text{clim}}),
\]

where \( \mathbf{T} \) is a matrix of all the data points \( T_i \), \( T_{\text{clim}} \) is the climatological temperature, and the centered dot ‘\( \cdot \)’ indicates element-by-element multiplication. For the OSSEs, the climatology is from the model. For the observations (section 2b), the climatology is from the World Ocean Atlas 2013 (Locarnini et al. 2013; Zweng et al. 2013). The weighting matrix \( \mathbf{w} \) is given by

\[
\mathbf{w} = C_{\text{dg}} \left( C_{\text{dd}} + \mathbf{I} \cdot \eta^2 \right)^{-1},
\]

where \( \mathbf{I} \) is the identity matrix, and

\[
C_{\text{dg}}(i) = \sigma^2_i \cdot \exp \left[ - \frac{(D_{x_{i,\text{grid}}} + D_{y_{i,\text{grid}}})}{L_x^2 + L_y^2} \right],
\]

\[
C_{\text{dd}}(i,j) = \sigma^2_i \cdot \exp \left[ - \frac{(D_{x_{i,\text{grid}}} + D_{y_{i,\text{grid}}})}{L_x^2 + L_y^2} \right],
\]

\[
s^2 = \frac{1}{N} \sum_{i=1}^{N} (T_i - T_{\text{clim}})^2,
\]

\[
\eta^2 = \frac{1}{2N} \sum_{i=1}^{N} (T_i - T_{\text{obj}})^2.
\]

In Eqs. (A2)–(A5), \( C_{\text{dg}} \) is the data–grid covariance, which takes into account the distances between a data point and a grid cell in the zonal and meridional directions \( (D_{x_{i,\text{grid}}}, D_{y_{i,\text{grid}}} \), respectively). Term \( C_{\text{dd}} \) is the data–data covariance, which, instead, depends on the distances between data points in the zonal and meridional directions \( (D_{x_{i,j}}, D_{y_{i,j}} \), respectively). Terms \( s^2 \) and \( \eta^2 \) are the signal and noise variance, respectively. The \( (L_x, L_y) \) are the zonal and meridional decorrelation length scales, respectively. The subscripts \( i \) and \( j \) indicate the index of data points, ranging from 1 to \( N \) (\( N \) is the total number of data points). In Eq. (A6), \( T_i \) is the data point with the shortest distance from \( T_{\text{obj}} \). The estimate of salinity and density is implemented in the same way as described above.

**APPENDIX B**

**Monte Carlo Simulation**

We use a Monte Carlo method to provide statistically robust estimates on the variability of the fluxes crossing the OSNAP sections. The Monte Carlo method is based on the idea of taking a small, randomly drawn sample from a population and estimating the desired outputs from this sample. That is, the distribution, typically the mean and the standard deviation of the temperature, salinity, and velocity observed from the OSNAP array and of wind stress and sea surface height along the OSNAP line, is used to estimate the desired probabilistic outputs and the uncertainty in these outputs. At OSNAP, these steps are followed to produce a Monte Carlo simulation:

1. The first step is to generate a random sample of the variables \( T(x, z, t), S(x, z, t), \) and \( V(x, z, t) \) from each instrument along with random sea surface height and surface wind stresses at each section grid for each time interval, using the assumption that these variables are normally distributed during that period. For example, the distribution of all temperature measurements within 30 days is given by \( T(x, z) = \bar{T}(x, z, t) + \text{std}[T(x, z, t)] \), where the overbar indicates a temporal average and std is the standard deviation. Next, a number of temperature values are drawn randomly from this normal distribution \( T_n(x, z), n = 1, 2, 3, \ldots \). Random draws are made for all other variables.

2. The second step is to compute the MOC at this time interval, in which the randomly drawn variables will be used to compute \( \text{MOC}_n \). The calculation is repeated \( N \) times until the following criterion is fulfilled:

\[
\left| \frac{1}{N} \sum_{i=1}^{N} \text{MOC}_n - \frac{1}{N-1} \sum_{i=1}^{N-1} \text{MOC}_n \right| < 0.005 \text{ Sv}. \quad (B1)
\]

Note that the threshold of 0.005 Sv is arbitrary. A statistical description of the MOC over the averaging interval is obtained as

\[
\text{MOC} = \overline{\text{MOC}}_n + \text{std}(\text{MOC}_n), \quad n = 1, 2, 3, \ldots, N,
\]

(B2)

where \( N \) is the total number of Monte Carlo iterations.
3. The third step is to repeat steps 1 and 2 for all the time intervals to generate a time series of MOC(t) based on Eq. (B2).

4. The last step is to perform another Monte Carlo simulation in order to calculate the statistical distribution of the MOC over the full time span of the data based on MOC(t). This is done by randomly drawing MOC values from every time interval and calculating the mean MOC for 500 iterations.

The same procedure described above is also applied for computing the MHT and MFT.

REFERENCES


