Meridional heat transport variability induced by mesoscale processes in the subpolar North Atlantic

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The ocean’s role in global climate change largely depends on its heat transport. Therefore, understanding the oceanic meridional heat transport (MHT) variability is a fundamental issue. Prevailing observational and modeling evidence suggests that MHT variability is primarily determined by the large-scale ocean circulation. Here, using new in situ observations in the eastern subpolar North Atlantic Ocean and an eddy-resolving numerical model, we show that energetic mesoscale eddies with horizontal scales of about 10–100 km profoundly modulate MHT variability on time scales from intra-seasonal to interannual. Our results reveal that the velocity changes due to mesoscale processes produce substantial variability for the MHT regionally (within sub-basins) and the subpolar North Atlantic as a whole. The findings have important implications for understanding the mechanisms for poleward heat transport variability in the subpolar North Atlantic Ocean, a key region for heat and carbon sequestration, ice–ocean interaction, and biological productivity.
Oce an heat transport is fundamental to maintaining the earth’s energy balance. While the time-mean oceanic heat transport has been reasonably well documented using hydrographic observations and air–sea fluxes1–3, our knowledge of its temporal variability is less developed, in part, due to insufficient sampling of mesoscale processes in many regions. The large-scale ocean circulation, such as the Atlantic Meridional Overturning Circulation (AMOC), is found to be a big player to modulate the oceanic meridional heat transport (MHT)4–6. Some studies have shown, however, that mesoscale eddies also play an important role in the meridional transfer of heat. For example, observations and eddy-permitting models have indicated that eddy heat transport near the western boundary current (WBC) extensions and the Antarctic Circumpolar Current (ACC) is comparable to the time-mean heat transport7–13.

The Atlantic Ocean dominates the global oceanic heat transport, and its northward heat transport reaches a maximum of 1.3 PW at 26.5°N, where 1 PW = 10^{15} \text{W} (refs2,5). In the subpolar North Atlantic, northward moving warm waters release heat to the atmosphere and thereby are transformed into the deep and intermediate water masses that feed the deep limb of the AMOC. A transatlantic observing system (Overturning in the Subpolar North Atlantic Program, OSNAP)14 was initiated in summer 2014 to continuously monitor the variability of the meridional volume, heat, and freshwater transport across ~58°N and investigate the relationship between meridional transport and dense water formation. OSNAP is configured with two sections: OSNAP West extends from southern Labrador to southwestern Greenland, and OSNAP East spans from southeastern Greenland to Scotland (Fig. 1a). Previous studies have shown that almost all of the relatively warm water from southern latitudes crosses OSNAP East and leads to a mean MHT of about 0.5 PW (refs.6,15), while <0.05 PW crosses OSNAP West16 (Labrador Sea). The temporal variability for the MHT along the OSNAP East section is much greater than that along the OSNAP West17. In addition, the warm Atlantic-origin waters flow across the OSNAP East line and further enter the high latitudes, consequently maintaining a relatively warm climate in Northern Europe and modulating the Arctic sea ice extent18–20. Note that a meaningful heat transport value can only be estimated by measuring the temperature of all water column. Satellite altimetry data suggests that enhanced EKE regions two regimes coupled with the strong temperature front in the Iceland Basin significantly modifies the local heat transport and is the dominant source for the MHT variability on time scales shorter than 1 year. The numerical model results also suggest that these mesoscale processes produce sizable interannual variability for the MHT in the subpolar North Atlantic Ocean.

Results

Observations. Previous studies have shown that the MHT variability on seasonal to interannual time scales is more closely tied to variability in velocity or volume transport, rather than temperature4–6. In the subpolar North Atlantic, where the currents have a relatively strong barotropic component27, the surface eddy kinetic energy (EKE) provides valuable information about the spatial distribution of ocean velocity variability over the whole water column. Satellite altimetry data suggests that enhanced EKE is located in the eastern part of the subpolar region, especially in the Iceland Basin and Rockall Trough (Fig. 2), coincident with the branches of the NAC26,30,31. Along the OSNAP East line, the EKE maximum is co-located with the MHT variability, with the highest values located in the Iceland Basin.

To investigate the potentially important role of eddies in modulating northward heat transport in this region, we successively deployed two gliders—autonomous buoyancy-driven underwater vehicles—in June and November 2015, respectively. The gliders profiled from the surface to about 1,000 m along the OSNAP East line at 58 °N between 24.5 °W and 21 °W, where both the maximum EKE and largest heat transport variability are located (Fig. 2b and Methods). Our analysis uses observed profiles of temperature, salinity, and depth-averaged velocity for the period between July 2015 and May 2016. In July 2015, a mesoscale anti-cyclonic eddy occupied the glider section (Fig. 3). The eddy had a radius of about 60 km and was characterized by a core of relatively homogenous warm and salty water (Fig. 3c, e). Similar anti-cyclonic eddies are often found in this region25,26. Detailed examination of the 23-year altimeter-derived absolute dynamic topography (ADT) indicates that the

Current (EGC) against the Greenland continental slope before flowing into the Labrador Sea28,29.

The contributions of different currents to the MHT are reflected in the Zonally Accumulated Heat Transport (ZAHT) over the full water column starting from the Greenland coast towards Scotland (Fig. 1b). The mean ZAHT from observations and a high-resolution (1/12°) numerical simulation suggest that the relatively cold water carried by the southward EGC and deep WBC (DWBC) leads to about ~0.5 PW MHT, which is gradually compensated by the northward transport of relatively warm waters in the east. After incorporating flows in the Irminger Sea and over the Reykjanes Ridge, the ZAHT increases to ~0.2 PW, indicating that these regions transport about 0.3 PW northward heat transport, which more than compensates for the southward heat transport and generates a net poleward heat transport.

This study utilizes new high-resolution hydrographic and velocity observations in the Iceland Basin and an eddy-resolving model to investigate the mesoscale processes there and quantify their influence on the MHT. The observational data identifies two circulation regimes: a mesoscale eddy-like circulation pattern and the northward NAC circulation pattern. The transition between the two regimes coupled with the strong temperature front in the Iceland Basin significantly modifies the local heat transport and is the dominant source for the MHT variability on time scales shorter than 1 year. The numerical model results also suggest that these mesoscale processes produce sizable interannual variability for the MHT in the subpolar North Atlantic Ocean.
Eddy usually occupies the glider transect for more than 2 months at a time, and that a new eddy is generated every few months, so that an eddy is apparent in the long-term mean ADT map (Supplementary Fig. 1). In October 2015, the eddy center moved to around 59°N, and a simpler frontal structure began to develop along 58°N, separating the warm, salty water to the east from the relatively cold, fresh and high oxygen water to the west. The hydrographic features associated with the eddy and front circulation patterns also project onto the velocity field and consequently affect the MHT (see Methods and Supplementary Fig. 2). A new anti-cyclonic eddy emerged in March 2016 and its characteristics were quite similar to those observed in July–September, 2015. During the observational period, the ocean circulation near the glider transect appears to be dominated by the alternation between eddy and front patterns.

The glider observations were used to generate monthly MHT over the top 1,000 m between July 2015 and May 2016. The mean heat transport for the monthly time series was 0.23 PW with standard deviation of 0.07 PW. Using the surface circulation pattern identified in the maps of ADT, the heat transport estimates have been separated into “eddy” (6) and “front” (3) groups (Fig. 4a). The mean heat transport is lower when the eddy is present, 0.19 PW, and increases to 0.30 PW when the eddy is replaced by a frontal pattern. These means, differing by 0.11 PW,
are statistically different at the 95% confidence level using the Student’s t test.

To further identify the underlying physical processes associated with the eddy and frontal patterns, we break the observed heat transport \( Q_{\text{total}} \) down into several components using standard Reynolds decomposition, which individually represent the heat transport variability induced by temperature \( Q_{\text{temp}} \), velocity \( Q_{\text{vel}} \), and correlations between the two \( Q_{\text{cor}} \) (see Methods). \( Q_{\text{vel}} \) is the dominant term and its standard deviation is 0.06 PW, very close to the variability of \( Q_{\text{total}} \) (0.07 PW). This indicates that the observed MHT variability is mainly driven by the ocean velocity change, which results from the alternating mesoscale eddy and frontal patterns. After examining the ADT structure in the Iceland Basin between 1992 and 2015, we conclude that the alternating mesoscale eddy and frontal structure is a common occurrence, suggesting that the mesoscale processes and the corresponding MHT variability observed by the 1-year glider observations to date are generally representative of long-term conditions.

**Model results.** To put the limited observational results in a larger context, the MHT variability on different time scales is evaluated using monthly output from a high-resolution (1/12°) numerical simulation. The simulated mean MHT across the glider transect in the top 1,000 m between 1992 and 2014 is about 0.24 PW, and its variability, in terms of standard deviation, reaches about 0.1 PW. These long-term statistics are not directly comparable with the glider observations, collected over only 1 year. However, when the simulated monthly mean MHT in the top 1,000 m is separated into eddy and front cases (Fig. 4b), we found that the maximum MHT mostly occurs under the frontal pattern when the local flow is mainly northward, and the minimum is mostly associated with the eddy structure when the local circulation is dramatically modified by the rotational currents of the eddy. The mean MHT estimates during the front and eddy patterns are 0.38 ± 0.07 and 0.11 ± 0.06 PW, respectively, yielding a difference of 0.27 PW. This difference is statistically significant at the 95% confidence level. Even if the similarity of this difference with that estimated from the gliders, 0.11 PW, is somewhat fortuitous, the tendency for higher heat transport with the frontal pattern and lower with the eddy pattern suggests that the impacts of eddy and front on the MHT variability are successfully captured by the model. Similar to the observations, the role of eddy and frontal patterns is quantified by \( Q_{\text{vel}} \), which has variability of 0.09 PW and is significantly correlated with \( Q_{\text{total}} \) (correlation coefficient is 0.97). In contrast, the variations for temperature-induced heat transport \( Q_{\text{temp}} \) and eddy heat transport \( Q_{\text{eddy}} \) are only 0.02 and 0.01 PW, respectively. In addition, the comparison between \( Q_{\text{vel}} \) and \( Q_{\text{total}} \) indicates that the variability of \( Q_{\text{total}} \) on time scales from subseasonal to interannual is mostly induced by the velocity change (i.e., \( Q_{\text{vel}} \)).

In addition to modifying the velocity structure along the glider transect (Supplementary Fig. 2), the alternating eddy and front events can also alter the velocity field for the regions surrounding the glider track. To quantify the broader influence of mesoscale features on MHT variability, a spatial filter is applied to the numerical model output to separate the large-scale and mesoscale variability in the temperature and velocity fields. The spatially low-pass and high-pass temperature and velocity are used to
compute the MHT induced by large-scale and mesoscale processes, respectively (see Methods and Supplementary Fig. 3).

Focusing first on the Iceland Basin, the standard deviation for the unfiltered monthly mean MHT across the section 29–19°W between 1992 and 2014 is 0.11 PW. The standard deviation associated with just the large-scale variability is 0.09 PW, and for the mesoscale, 0.06 PW. So it appears that the MHT variability in the Iceland Basin is almost equipartitioned between large-scale and mesoscale processes.

One might expect that the mesoscale processes dominate the MHT variability on shorter time scales, that is, <1 year, and that the larger spatial scale variability dominates on interannual and longer time scales. However, we found that mesoscale processes also contribute significantly to MHT variability on these longer time scales. To demonstrate this, we time filtered the unfiltered (i.e., the raw MHT), mesoscale, and large-scale time series of MHT for the Iceland Basin (Fig. 4c). The MHT interannual variability associated with mesoscale phenomena is about 0.03 PW, more than half of that induced by the large-scale circulation (0.05 PW). In fact, the model results show that the MHT anomalies produced by mesoscale processes are larger than that due to large-scale processes in some years (e.g., 2000 and 2006; Fig. 4c). The superposition of the individual processes at different spatial scales recovers the total MHT interannual variability in the Iceland Basin, and its standard deviation reaches about 0.06 PW. This indicates that both large-scale and mesoscale processes need to be fully resolved to accurately recover the MHT variability in the Iceland Basin, even on interannual and longer time scales.

Subpolar mesoscale processes are not limited to the Iceland Basin, and they also contribute to substantial MHT variability in the Irminger Sea and Rockall Trough (Supplementary Fig. 3). To evaluate the impact of mesoscale processes on MHT variability across the entire OSNAP East section, the unfiltered, mesoscale, as well as large-scale time series of MHT across the whole East

Fig. 3 Circulation and hydrographic properties in the Iceland Basin for mesoscale eddy and frontal circulation patterns near 58°N. The left panels show the ocean state in 3–13 August 2015, for absolute dynamic topography (a), glider potential temperature (c), and glider salinity (e). The corresponding ocean state in 14–20 December 2016 is displayed in the right panels (b, absolute dynamic topography; d, potential temperature; f, salinity). Glider transect is marked by black lines in (a and b). The isobaths in (a and b) are represented by gray lines. The gray contour lines from (c to f) display the relative potential density (unit: kg m$^{-3}$).
Not surprisingly, the time-mean MHT (0.61 PW) is dominated by the large spatial scales (mean of 0.72 PW), and the mesoscale actually generates a southward MHT across the section (mean of \(-0.11\) PW), induced by mesoscale activity east of Greenland (Supplementary Fig. 3).

Of particular interest here is how the mesoscale and large scale contribute not just to the mean, but to interannual MHT variability across the OSNAP East (Fig. 5). While the large scale dominates the total MHT interannual change, mesoscale processes also lead to sizable interannual variability, for example, in 2006 and 2010 (Fig. 5). Similar to the Iceland Basin, the velocity change on the mesoscale in space is the leading mechanism to generate the mesoscale MHT variability. Here the mesoscale MHT reflects the integral effects of all different types of mesoscale phenomena along the OSNAP East section. Its standard deviation is about 0.01 PW, or about 20% of the basin-wide MHT variability (about 0.05 PW). Therefore, the overall impact of mesoscale processes is non-negligible to the MHT variability in the subpolar North Atlantic.

Discussion
It is widely accepted that mesoscale processes have critical consequences for the global climate through redistribution of heat and other properties in various ocean regions. For example, eddies in the tropics, the Southern Ocean, and WBC extensions were found to significantly contribute to both the time mean and the variability of the total heat transport\(^8,10–12,37,38\). Here, results from new in situ observations in the Iceland Basin provide a fresh perspective on the dynamics responsible for the poleward heat transport in the subpolar North Atlantic Ocean, revealing that the alternating eddy and front patterns contributes significantly to the total poleward heat transport variability on time scales from subseasonal to interannual. For the Iceland Basin, the MHT variability induced by velocity changes associated with mesoscale processes can produce about 50% of the total heat transport variability. Similarly, mesoscale processes in the Irminger Sea and Rockall Trough also play important roles in producing MHT variability. The overall mesoscale MHT variability in different sub-basins accounts for about 20% of the MHT variability across the OSNAP East section. This is different from our understanding about the mechanisms for oceanic heat transport variability, where large-scale circulation changes are believed to be the main driver\(^5,6\). Our results emphasize the importance of resolving mesoscale processes in observations and numerical simulations to realistically capture their roles in modulating heat transport variability in the northern North Atlantic. High-resolution observational arrays capable of capturing both large-scale and mesoscale variability, such as the OSNAP observing system

Fig. 4 Meridional heat transport from observations and numerical model results. a Estimates of meridional heat transport for the upper 1,000 m across the glider section at 58°N between 24.5 and 21°W using glider observations. The estimated values, representing monthly averaged ocean state, are shown together with error bars illustrating the uncertainties due to depth-averaged velocity from the glider data. The results are separated into eddy (blue) and frontal (red) patterns. The transitional periods between eddy and front are shown in black. The magenta lines show the heat transport induced by velocity change in glider observations (a) and numerical model (b). Black line in (b) denotes the simulated monthly time series of meridional heat transport for the upper 1,000 m along the glider section. For comparison, the simulated mean heat transport across the glider section is 0.24 PW in the upper 1,000 m. Blue and red dots mark the eddy and front scenarios in the model. The months between those dots are transitional periods. c The interannual anomalies for the heat transport induced by the large-scale (black solid) and mesoscale processes (black dashed) in the Iceland Basin, respectively, are displayed. The interannual heat transport anomalies across the Iceland Basin (29–19°W, including both large-scale and mesoscale processes) is shown in blue. Unit: PW
(which includes moorings, gliders, Argo floats, and satellite altimetry), are needed to measure the basin-wide ocean MHT in the subpolar North Atlantic.

Methods

Observations. The ADT and surface geostrophic velocity fields between 1993 and 2013 were measured by the satellite altimetry. The Ssalto/Duacs altimeter products are produced and distributed by the Copernicus Marine and Environment Monitoring Service (http://www.marine.copernicus.eu). The eddy kinetic energy is defined as \( EKE = \frac{1}{2} \left( u^2 + v^2 \right) \), where \( u \) and \( v \) are derived by removing the long-term mean from the original surface geostrophic velocity. These data are used to make Figs. 2, 3 and Supplementary Fig. 1.

During the cruises in May–June 2014 and June–July 2015, conventional conductivity/temperature/depth (CTD) profiles were acquired using a SeaBird SBE-911plus pumped system, and direct velocity profiles were measured using a dual-ADCP system mounted on the CTD package (lowered ADCP (LADCP)). Since summer 2015, G2 Slocum gliders have been jointly operated by the Woods Hole Oceanographic Institution and Ocean University of China (OUC) and serve as an important element of OSNAP to monitor the meridional volume and heat transport in the energetic Iceland Basin. The data analyzed here were collected by two gliders deployed in June and November 2015, respectively. Moving at approximately 0.2 m s\(^{-1}\), gliders “fly” through the ocean from surface to 1,000 m. In each dive-climb cycle, they navigate along a sawtooth trajectory and measure temperature, conductivity (salinity) and pressure with a SeaBird pumped CTD sensor package. The horizontal sample spacing averages to be about 3 km, but near the surface and 1,000 m turnaround points, distance ranges from hundreds of meters to 6 km. The collected data are binned to profiles with vertical resolution of 1 m (Supplementary Fig. 4). The surveyed section is along 58°N with endpoints at 24.5°W and 21°W, respectively. The section is about 200 km in length and a one-way transect is usually completed in 7–10 days.

The barotropic, or depth-averaged component of the velocity, is calculated directly from the gliders using both the glider surfacing positions and a glider drift was found in the conductivity measurements. According to calibration results, drift in the conductivity measurements. According to calibration results,
the measurement uncertainty of the temperature, salinity and pressure are estimated to be 0.003°C, and 0.002 and 0.02 dbar, respectively. Incorporating them into the estimation of the geostrophic velocity relative to 1,000 m \((v_{\text{geostrophic}}(x, z, t))\), the corresponding uncertainty is \(1 \text{ cm s}^{-1}\).

The largest uncertainty in the depth-averaged velocity is caused by the errors in the records of pitch, roll and heading when the glider is underwater. According to our calibrations, the uncertainties of pitch, roll and heading are about \(10^\circ\) at sea surface. Therefore, the errors induced by the wind-driven motions are irregularly distributed in space and time, so their overall impacts on the Ekman current are negligible.

The front structures are assumed to be established when the anomalies are calculated. The standard deviation of the anomalies is 5.4 Sv (1 Sv = \(10^6\) m\(^3\) s\(^{-1}\)).

Reynolds decomposition. To reveal the physical process for the MHT variability, standard Reynolds decomposition is used to separate the heat transport into several components: \(Q_{\text{net}} = Q_{\text{Ad}} + Q_{\text{temp}} + Q_{\text{eddy}}\), where the left side is the heat transport and right side is the heat transport induced by velocity, temperature, and eddy, respectively.

\[
Q_{\text{total}} = \int_{x}^{x} \int_{h}^{0} \rho C_p v(x, z, t) \theta(x, z, t) dx dz,
\]

where \(h\) is the depth to integrate heat transport.

Spatial filter. In order to separate the large-scale and mesoscale features, a spatial Butterworth filter with a cutoff length scale of 10° in longitude (about 600 km) is applied to the velocity and temperature field of the monthly HYCOM results along the OSNAP East section. The cutoff length scale is determined by the spatial scale for the zonal shift of the NAC and eddies diameters in the Iceland Basin, which is estimated in the satellite altimetry maps. The low-pass spatially filtered velocity and temperature are defined as large-scale process. The variables for the mesoscale process are obtained by removing the low-pass filtered from the original model outputs and are named as high-pass filtered dataset. The unfiltered (i.e., the original), low-pass and high-pass spatially filtered variables are used to compute the MHT for the total, large-scale and mesoscale processes, respectively.

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Author contributions

J.Z. conceived the research, conducted the model simulations, and performed the data analyses. J.Z. wrote the manuscript with improvement by all co-authors. A.B., J.Y., and X. L. designed and led the field experiments. All authors contributed to the project. N.P.H. calculated the observed Zonally Accumulated Heat Transport along the OSNAP east section.

Additional information

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