Lagrangian Decomposition of the Atlantic Ocean Heat Transport at 26.5°N

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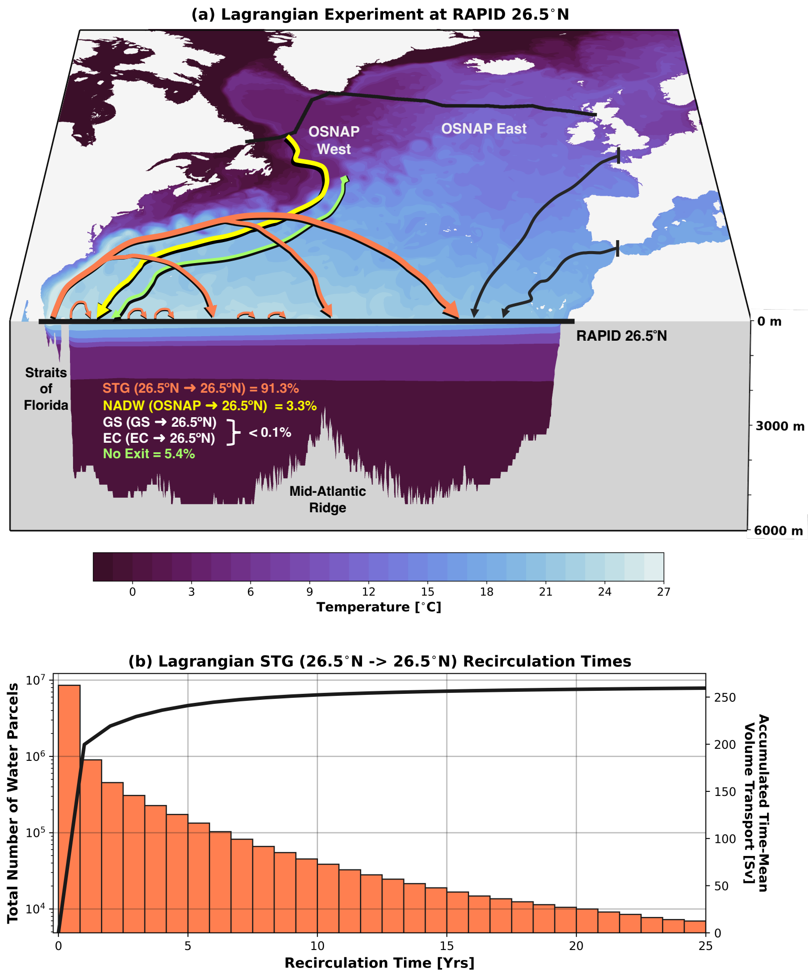
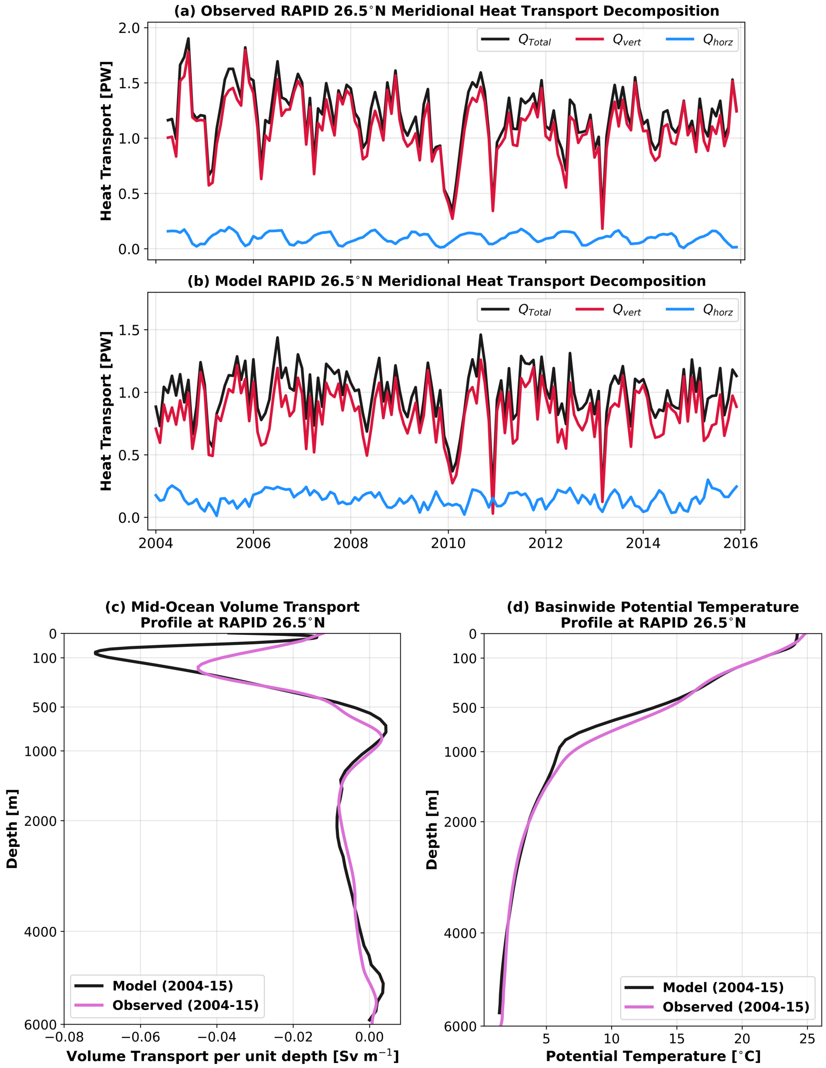
Abstract

The Atlantic Meridional Overturning Circulation (AMOC) plays a critical role in the global climate system through the redistribution of heat, freshwater and carbon. At 26.5°N, the meridional heat transport has traditionally been partitioned geometrically into vertical and horizontal circulation contributions; however, attributing these components to the AMOC and Subtropical Gyre (STG) flow structures remains widely debated. Using water parcel trajectories evaluated within an eddy-rich ocean hindcast, we present the first Lagrangian decomposition of the meridional heat transport at 26.5°N. We find that water parcels recirculating within the STG account for 37% (0.36 PW) of the total heat transport across 26.5°N, more than twice that of the classical horizontal gyre component (15%). Our findings indicate that STG heat transport cannot be meaningfully distinguished from that of the basin-scale overturning since water parcels cooled within the gyre subsequently feed the northward, subsurface limb of the AMOC.

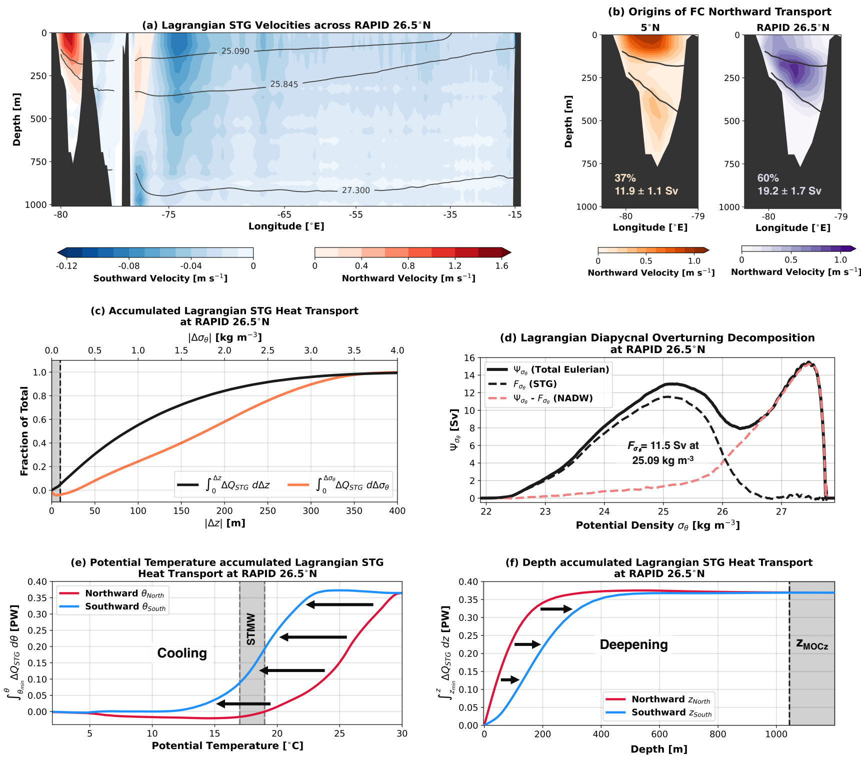
Manuscript Pre-Print & Supporting Information

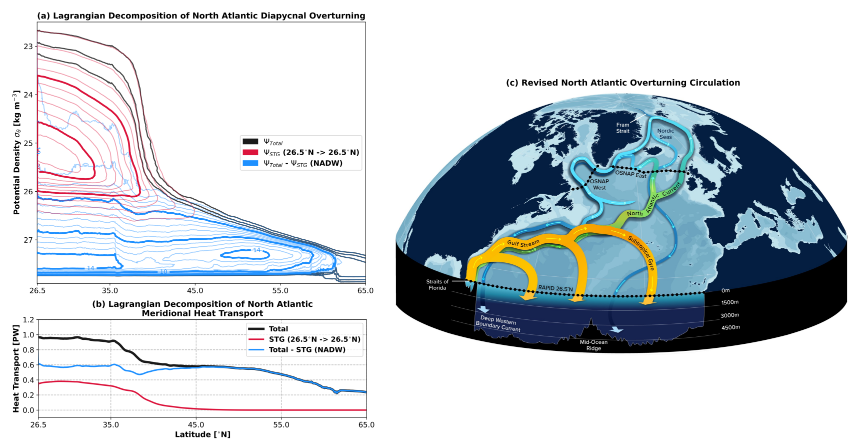
Figures





(a) Observed RAPID 26.5°N Meridional Heat Transport Decomposition
(b) Model RAPID 26.5°N Meridional Heat Transport Decomposition
Heat Transport [PW]
Q_{Total}
Q_{vert}
Q_{horz}
(c) Mid-Ocean Volume Transport Profile at RAPID 26.5°N
Depth [m]
Volume Transport per unit depth [Sv m^{-1}]
Model (2004-15)
Observed (2004-15)
(d) Basinwide Potential Temperature Profile at RAPID 26.5°N
Potential Temperature [°C]


(a) Lagrangian STG Velocities across RAPID 26.5°N
Depth [m]
Longitude [°E]
25.090
25.845
27.300
Southward Velocity [m s⁻¹]
Northward Velocity [m s⁻¹]
(b) Origins of FC Northward Transport
5°N
RAPID 26.5°N
37%
11.9 ± 1.1 Sv
60%
19.2 ± 1.7 Sv
(c) Accumulated Lagrangian STG Heat Transport at RAPID 26.5°N
Fraction of Total
|Δz| [m]
(d) Lagrangian Diapycnal Overturning Decomposition at RAPID 26.5°N
Ψσθ (Total Eulerian)
Fσθ (STG)
Ψσθ - Fσθ (NADW)
Fσθ = 11.5 Sv at 25.09 kg m⁻³
Potential Density σθ [kg m⁻³]
(e) Potential Temperature accumulated Lagrangian STG Heat Transport at RAPID 26.5°N
Northward θNorth
Southward θSouth
Cooling
STMW
Potential Temperature [°C]
(f) Depth accumulated Lagrangian STG Heat Transport at RAPID 26.5°N
Deepening
zMOCz
Northward zNorth
Southward zSouth
Depth [m]


(a) Lagrangian Decomposition of North Atlantic Diapycnal Overturning
Potential Density σθ [kg m⁻³]
ΨTotal
ΨSTG (26.5°N -> 26.5°N)
ΨTotal - ΨSTG (NADW)
(b) Lagrangian Decomposition of North Atlantic Meridional Heat Transport
Heat Transport [PW]
Total
STG (26.5°N -> 26.5°N)
Total - STG (NADW)
Latitude [°N]
(c) Revised North Atlantic Overturning Circulation
Fram Strait
Nordic Seas
OSNAP East
OSNAP West
North Atlantic Current
Gulf Stream
Subtropical Gyre
Straits of Florida
RAPID 26.5N
Deep Western Boundary Current
Mid-Ocean Ridge
0m
1500m
3000m
4500m

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Key Points:

- Water parcels recirculating in the subtropical gyre account for 37% of the total heat transport at 26.5°N in an eddy-rich ocean hindcast
- The heat transport of the subtropical gyre is associated with shallow vertical overturning rather than the horizontal circulation at 26.5°N
- Both horizontal and vertical circulation cells are fundamental components of the Atlantic Meridional Overturning Circulation

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Abstract

The Atlantic Meridional Overturning Circulation (AMOC) plays a critical role in the global climate system through the redistribution of heat, freshwater and carbon. At 26.5°N, the meridional heat transport has traditionally been partitioned geometrically into vertical and horizontal circulation cells; however, attributing these components to the AMOC and Subtropical Gyre (STG) flow structures remains widely debated. Using water parcel trajectories evaluated within an eddy-rich ocean hindcast, we present the first Lagrangian decomposition of the meridional heat transport at 26.5°N. We find that water parcels recirculating within the STG account for 37% (0.36 PW) of the total heat transport across 26.5°N, more than twice that of the classical horizontal gyre component (15%). Our findings indicate that STG heat transport cannot be meaningfully distinguished from that of the basin-scale overturning since water parcels cooled within the gyre subsequently feed the northward, subsurface limb of the AMOC.

Plain Language Summary

The Atlantic Meridional Overturning Circulation transports heat northward by converting warm, surface waters into cold waters returning at depth. In the subtropical North Atlantic, the heat transported by the overturning circulation has traditionally been separated from the wind-driven gyre circulation by assuming that the gyre flows horizontally along constant depth levels. By tracing the pathways of virtual water parcels in a high-resolution ocean model, we show that the heat transported by the subtropical gyre is larger than traditional estimates because water parcels spiral downwards across depth levels. Our results indicate that the subtropical gyre should not be considered separate from the overturning circulation, since the water parcels cooled within the gyre subsequently flow northwards to form cold, dense waters in the subpolar North Atlantic.

1 Introduction

Throughout the coming century, the Atlantic Meridional Overturning Circulation (AMOC) will play a critical role in shaping the response of the global climate system to anthropogenic activity through the redistribution of excess heat, freshwater and carbon. Since 2004, the Rapid Climate Change-Meridional Overturning Circulation and Heatflux Array (RAPID-MOCHA, herein referred to as RAPID) trans-basin observing system has made continuous measurements of the strength of the AMOC and the associated meridional transports of heat and freshwater across 26.5°N (Cunningham et al., 2007). Here, the subtropical North Atlantic Ocean transports ∼1.2 PW of heat northwards (Hall & Bryden, 1982; Johns et al., 2011; McCarthy et al., 2015a), accounting for 30% of the total ocean-atmosphere Meridional Heat Transport (MHT) (Ganachaud & Wunsch, 2000; Trenberth & Fasullo, 2017).

Traditionally, the total ocean heat transport across 26.5°N has been partitioned into zonally-averaged vertical and residual horizontal circulation components (Bryan, 1982; Böning & Herrmann, 1994; Johns et al., 2011), typically referred to as overturning and gyre heat transports, respectively. However, the degree to which these 2-dimensional geometric components represent the actual contributions made by the 3-dimensional flow structures of the AMOC and Subtropical Gyre (STG) to the total MHT at 26.5°N has been widely debated (e.g., Talley, 2003; Johns et al., 2023a). Previous studies have criticised this interpretation of the horizontal gyre circulation because the waters flowing northward within the western boundary current of the STG do not recirculate horizontally along constant depth surfaces, but rather spiral downwards to form Subtropical Mode Water (STMW) in a shallow local overturning cell (Spall, 1992; Talley, 2003; Burkholder & Lozier, 2014; Berglund et al., 2022). According to Talley (2003), this wind-driven STMW cell within the STG could account for up to 0.4 PW of the total MHT observed at 24°N, much larger than the traditionally defined horizontal gyre heat transport. In contrast, the modelling study of Xu et al. (2016) concludes that the STG makes a negligible contribution to the total heat transport at 26.5°N since the authors argue that the near-surface waters of the Florida Current participate directly in the basin-scale AMOC rather than circulating around the STG.

The long-standing uncertainty regarding the relative contributions of the AMOC and the STG flow structures to the total MHT at 26.5°N ultimately reflects the subjective nature of approaching this problem within the confines of the traditional Eulerian framework (Johns et al., 2023a). To overcome this challenge, we present the first Lagrangian decomposition of the MHT and overturning across the RAPID 26.5°N array using water parcel trajectories evaluated within an eddy-rich ocean sea-ice hindcast simulation.

2 Materials and Methods

2.1 Ocean General Circulation Model

To investigate the meridional overturning and heat transport at 26.5°N, we use output from the ORCA0083-N06 ocean sea-ice hindcast simulation, documented in Moat et al. (2016). The simulation uses a global implementation of the Nucleus for European Modelling of the Ocean (NEMO) ocean circulation model version 3.6 (Madec, 2014) coupled to the Louvain-la-Neuve Ice Model version 2 (LIM2) sea-ice model (Bouillon et al., 2009). The ocean component is configured with a nominal horizontal resolution of 1/12° (equivalent to 8.3 km at 26.5°N) and with 75 unevenly spaced z-coordinate levels ranging from 1 m to 250 m depth increments. The hindcast simulation is integrated for the historical period from 1958-2015 using the Drakkar Forcing Set 5.2 (Dussin et al., 2016). Here, we make use of the 5-day mean velocity and tracer fields output for the period 1980-2015.

Throughout this study, we compare the results derived from the ORCA0083-N06 simulation to observations made along the RAPID array at 26.5°N for the overlapping period 2004-2015 (Johns et al., 2023b). To ensure consistency between model and observational diagnostics, we implement a zero net volume transport constraint across 26.5°N, equivalent to that imposed by the RAPID program (e.g., Kanzow et al., 2010), in all Eulerian meridional overturning and heat transport calculations.

2.2 Lagrangian Particle Tracking

To determine the contributions of the STG and the basin-scale overturning circulation to the total MHT at 26.5°N, we calculate the Lagrangian trajectories of virtual water parcels advected by the time-evolving velocity fields of the ORCA0083-N06 hindcast using TRACMASS version 7.1 (Aldama-Campino et al., 2020).

To compare the results of our Lagrangian experiment with observations made along 26.5°N, we track water parcels flowing southward across the RAPID section backwards-in-time to determine their origin. In total, we initialised more than 12.3 million water parcels sampling the full-depth southward transport across 26.5°N over 144 months between 2004-2015. At the beginning of each month, the number of water parcels to be distributed evenly across each grid cell face (N_{gc}) is determined by:

$$N_{gc} = ceil\left(\frac{V_{gc}}{V_{max}}\right) \tag{1}$$

where V_{gc} is the absolute southward transport and V_{max} represents a maximum volume transport of 0.005 Sv per parcel (1 Sv $\equiv$ 1x10^6 m^3 s^{-1}).

Water parcels are advected backwards-in-time using 5-day mean velocity fields for a maximum of 25 years to trace their origins. Water parcel trajectories are terminated on reaching this maximum advection time or when they meet any one of the following criteria (Fig. 1a): (i) returning to the RAPID 26.5°N section, (ii) reaching the Overturning in the Subpolar North Atlantic (OSNAP) array in the subpolar North Atlantic, or (iii) reaching either the Gibraltar Strait (GS) or English Channel (EC). The overwhelming majority of trajectories initialised across 26.5°N also originate from 26.5°N (91.3%), indicating a robust recirculation of waters at this latitude. This large recirculating transport is dominated by short-lived trajectories capturing eddy recirculations in the ocean interior (197.3 ± 22.0 Sv), whereas only 20.6 ± 3.0 Sv is sourced directly from the Florida Current at 26.5°N. Importantly, Figure 1b shows that the 25-year maximum advection time is sufficient to fully resolve the STG circulation because the accumulated volume transport originating from 26.5°N has stabilised within this period.

We perform an additional Lagrangian experiment to determine the origins of the northward Florida Current transport by tracking trajectories backwards-in-time from the Florida Straits. We use the same water parcel initialisation and advection strategy outlined above for consistency. In this experiment, we terminate water parcel trajectories on crossing one of two geographic boundaries (5°N or 26.5°N in Fig. S1) or upon reaching the 25-year maximum advection time ($< 3\%$).

2.3 Diagnosing Meridional Overturning and Heat Transport at 26.5°N

We quantify the strength of the Eulerian overturning at 26.5°N by calculating meridional overturning streamfunctions in both depth (ψ_z) and density (ψ_{σ_θ}) coordinates:

$$\psi_z(z,t) = \int_z^0 \int_{x_w}^{x_e} v(x,z,t)\, dx\, dz \tag{2}$$

$$\psi_{\sigma_\theta}(\sigma_\theta,t) = \int_{x_w}^{x_e} \int_{z(x,\sigma_\theta,t)}^0 v(x,z,t)\, dz\, dx, \tag{3}$$

where $v(x,z,t)$ is the meridional velocity and $z(x,\sigma_\theta,t)$ is the time-evolving depth of the isopycnal σ_θ across the trans-basin section between the eastern (x_e) and western (x_w) boundaries. We account for the time-evolving net volume transport across the section using a spatially uniform compensating meridional velocity (Kanzow et al., 2010).

The northward MHT across 26.5°N is calculated following Moat et al. (2016) by integrating the product of the meridional velocity $v(x,z,t)$ and potential temperature (θ) over the full depth $H(x)$:

$$Q_{Total}(t) = \int_{-H(x)}^0 \int_{x_w}^{x_e} \rho_o c_p\, v(x,z,t)\, \theta(x,z,t)\, dx\, dz \tag{4}$$

where the product of the seawater density and the specific heat capacity of seawater is given by $\rho_o c_p = 4.1\text{x}10^6$ J m^{-3} °C^{-1} following Johns et al. (2011). We further partition the total MHT across the RAPID section (Q_{Total}) into horizontal (Q_{horz}) and vertical (Q_{vert}) components (Bryden & Imawaki, 2001; Johns et al., 2011), as follows:

$$Q_{vert}(t) = \int_{-H}^0 \int_{x_w}^{x_e} \rho_o c_p\, \langle v \rangle \langle \theta \rangle\, dx\, dz \tag{5}$$

$$Q_{horz}(t) = \int_{-H}^0 \int_{x_w}^{x_e} \rho_o c_p\, v^*(x,z,t)\, \theta^*(x,z,t)\, dx\, dz \tag{6}$$

where $\langle v \rangle$ and $\langle \theta \rangle$ represent the zonally averaged velocity and potential temperature profiles (both functions of depth), and v^* and θ^* represent deviations from these zonally averaged profiles.

To complement the Eulerian diagnostics outlined above, we additionally quantify the strength of overturning and MHT across 26.5°N from the Lagrangian water parcel trajectories initialised between 2004-2015. To determine the vertical and diapycnal overturning taking place within the STG, we calculate partial Lagrangian overturning streamfunctions (Blanke et al., 1999; Döös et al., 2008) using only the water parcel trajectories which return to 26.5°N within the $\tau = 25$-year maximum advection period as follows (Tooth, Johnson, et al., 2023):

$$F_z(z,t) = \int_z^0 V_{North}(z, t-\tau) - V_{South}(z,t)\, dz \tag{7}$$

$$F_{\sigma_\theta}(\sigma_\theta, t) = \int_{\sigma_\theta \geq \sigma'_\theta} V_{North}(\sigma'_\theta, t-\tau) - V_{South}(\sigma'_\theta, t)\, d\sigma'_\theta \tag{8}$$

where V_{North} and V_{South} represent the absolute volume transport distributions of all recirculating STG water parcels on their northward and southward crossings of the RAPID 26.5°N section.

Since Döös et al. (2008) showed that, provided a sufficiently large number of water parcels are initialised, the total Lagrangian overturning streamfunction will converge towards the time-mean Eulerian streamfunction, it follows that the time-mean overturning of the NADW and AABW cells can be estimated by the residual $\overline{\psi_{\sigma_\theta}} - \overline{F_{\sigma_\theta}}$ (see Text S2). Our Lagrangian decomposition uses the time-mean Eulerian overturning averaged over 2000-2015 because more than 90% of STG water parcels return to 26.5°N within 4 years of their initialisation (Fig. 1b).

We additionally define a Lagrangian measure of the net change in heat transport of the water parcels recirculating within the STG using their potential temperatures on their northward (θ_{North}) and southward (θ_{South}) crossings of the RAPID section at 26.5°N:

$$\Delta Q_{STG}(t) = \rho c_p \sum_{i=1}^{N} V_i \left(\theta_{North}(t-\tau) - \theta_{South}(t)\right) \tag{9}$$

where V_i is the volume transport conveyed by an individual water parcel i returning to 26.5°N, which is conserved along its Lagrangian trajectory.

3 Evaluating Eulerian Meridional Overturning and Heat Transport at 26.5°N

We begin by adopting the traditional Eulerian frame of reference to compare the meridional overturning and heat transport simulated in ORCA0083-N06 to RAPID observations between 2004-2015. Although there is strong agreement between the modelled and observed time-mean vertical overturning streamfunctions at 26.5°N (see Fig. S2), we find that the simulated 15.1 ± 2.8 Sv of vertical overturning is significantly weaker compared with observations (17.0 ± 3.6 Sv).

Figures 2a-b present equivalent decompositions of the Eulerian heat transport across 26.5°N in both RAPID observations and the ORCA0083-N06 hindcast. Concordant with its weaker than observed overturning, the model time-mean MHT is 0.98 ± 0.21 PW compared with 1.2 ± 0.28 PW in observations. The model does, however, reproduce many features of the overturning and heat transport variability recorded in observations (Moat et al., 2016), including the reduction in overturning between 2009-2010 (McCarthy et al., 2012). Observations show that both the magnitude and variability of the MHT at 26.5°N is dominated ($> 90\%$) by the vertical component, while $< 10\%$ is associated with the horizontal circulation (Johns et al., 2011; McCarthy et al., 2015b; Johns et al., 2023a). Figure 2b shows a similar vertical-horizontal partition in ORCA0083-N06; the vertical cell accounts for 85% (0.84 ± 0.21 PW), and the horizontal cell for the remaining 15% of the total MHT.

A closer examination of the simulated hydrography along 26.5°N shows that both the volume transport (31.3 ± 1.8 Sv) and temperature transport (2.56 ± 0.14 PW) of the Florida Current are well represented in the model compared with observed estimates reported in Meinen et al. (2010) and Johns et al. (2023a). However, Moat et al. (2016) highlighted the larger than observed southward Mid-Ocean (WB2 mooring to Africa) heat transport component in ORCA0083-N06 as a likely source of the model's underestimation of the observed total MHT. Further investigation indicates that, in the model, more of the warm and shallow waters transported northwards in the Florida Current are returned in the upper 100 m of the Mid-Ocean region along the RAPID array compared with observations (Fig. 2c). This is in contrast to previous studies, which have attributed the widespread underestimation of subtropical MHT in numerical models (e.g., Liu et al., 2022) to the overly diffusive thermocline simulated in z-coordinates (Msadek et al., 2013; Roberts et al., 2020), which results in a warmer than observed AMOC lower limb. Notably, there is good agreement between the basin-wide average potential temperature profiles simulated in ORCA0083-N06 and observed along the RAPID array (Fig. 2d), with even a slightly sharper main thermocline (between depths of 400-800m) in the model than in observations.

Since we propose that the excess shallow return flow in the STG accounts for the model's underestimation of MHT compared with RAPID observations, we next consider how this bias might influence the relative contribution of the STG circulation to total MHT across 26.5°N. By examining the Lagrangian trajectories sourced from the upper Florida Current, we determine that rapidly recirculated water parcels return southward in the upper 100 m of Mid-Ocean region between 75.5°W and 72°W (Fig. 3a) where potential temperatures typically exceed 23°C. We will later show that STG water parcels flowing southward across 26.5°N in this potential temperature range contribute negligibly to the time-mean MHT when averaged on longer than seasonal timescales (see Fig. 3e). As such, we do not expect the underestimation of MHT in ORCA0083-N06 to impact the relative heat transport contributions of the STG and basin-scale overturning circulations identified in this study.

Overall, we find sufficient agreement between the structure and variability of both the vertical overturning and MHT simulated by ORCA0083-N06 and observations to justify our use of the model to better understand the contributions made by the STG and basin-scale overturning circulation to the MHT at RAPID 26.5°N.

4 Lagrangian Decomposition of Meridional Overturning and Heat Transport at 26.5°N

To complement the traditional Eulerian vertical-horizontal decomposition, we use our Lagrangian trajectories to quantify the contribution made by water parcels which recirculate in the STG to the time-mean MHT at 26.5°N. We find that the STG circulation accounts for 0.36 ± 0.09 PW or 37 ± 9% of the total MHT across 26.5°N in the model. This implies that the heat transport of the STG is more than twice that of the horizontal gyre heat transport component and is in closer agreement with the observed estimate of 0.4 PW at 24°N (Talley, 2003). Figure 3a additionally confirms the assumption of Talley (2003) that the lightest waters flowing northward in the upper Florida Current ($\sigma_\theta < 25.875$) are returned across 26.5°N via the broad southward interior flow ($\sigma_\theta < 27.3$) between the Bahamas and Africa. In total, we find that 72% of STG heat transport is sourced from water parcels flowing northward in the upper 150 m of the Florida Current, which overwhelmingly originate from the tropical North Atlantic (5°N in Fig. 3b). Further, Figure 3b clearly shows that the thermocline waters flowing northward in the Florida Current are predominantly sourced from the STG along 26.5°N.

On classifying recirculating water parcels according to those which vertically overturn (which we here define as $|\Delta z| > 10$ m) and those which recirculate horizontally along approximately constant depth surfaces ($|\Delta z| \leq 10$ m shaded region in Fig. 3c), we find that the MHT of the STG is dominated by water parcels which participate in a shallow vertical overturning cell north of 26.5°N (Fig. 3c). Figure 3c also highlights the strong dependence of STG heat transport on along-stream diapycnal transformation and thus calls into question the use of isopycnal circulation as a means to estimate gyre heat and freshwater transports (e.g., Li et al., 2021).

A particularly surprising finding is the large 6.7 Sv discrepancy between the strength of vertical (4.8 Sv, not shown) and diapycnal (11.5 Sv in Fig. 3d) overturning in the STG. Previous studies in the subpolar North Atlantic have interpreted such a discrepancy as evidence for a substantial horizontal gyre circulation across sloping isopycnals (Zhang & Thomas, 2021). However, further investigation reveals that this discrepancy is, in fact, due to the underestimation of STG vertical overturning, which results from compensation between the large volume transports of lighter northward and denser southward flowing waters when accumulated along constant depth levels. This is analogous to that of the Deacon cell in the Southern Ocean (Döös & Webb, 1994) and illustrates how the downward spiralling behaviour of the STG circulation (Berglund et al., 2022) is concealed by superimposing many shallow overturning cells in the vertical overturning streamfunction (Döös et al., 2008).

Although the strength of vertical overturning within the STG (4.8 Sv) broadly agrees with the magnitude of classical STMW formation north of 26.5°N (4.0 ± 1.0 Sv between $\theta = 17$-19°C), STMWs explain less than a third of the total MHT of the STG (Fig. 3e). Diapycnal transformation within the STG instead peaks at lighter density classes ($\theta \approx$ 22.7°C or $\sigma_\theta = 25.09$ kg m^{-3} in Fig. 3d), including Subtropical Underwater (STUW; O'Connor et al., 2005), which account for 47% of the STG heat transport ($\theta_{South} > 19$°C in Fig. 3e).

Figure 3f shows that the entire MHT of the STG can be accounted for by water parcels which spiral downwards within the upper 500 m of the AMOC upper limb ($z_{MOC} \leq$ 1045 m). By subtracting the diapycnal overturning associated with these water parcels from the time-mean Eulerian overturning streamfunctions in Figures 3d and 4a, we obtain an estimate for the contribution of the NADW cell to the total overturning in density-space at 26.5°N. The residual diapycnal overturning streamfunctions, in combination with Figure 3b (RAPID 26.5°N), confirm the earlier propositions of Burkholder and Lozier (2014) and Qu et al. (2013) that the mode waters returned in the southward limb of the shallow STG overturning cell are the principal source waters for the northward, subsurface limb of the NADW cell. Meanwhile, the remainder of the NADW cell is sourced directly from denser waters ($\sigma_\theta > 26.5$ kg m^{-3}) originating in the tropical North Atlantic, which flow northward across 26.5°N at depth in the Florida Current (Fig. 3b).

5 Discussion and Conclusions

In this study, we present the first Lagrangian decomposition of the meridional overturning and heat transport at 26.5°N using an eddy-rich ocean hindcast. We show that water parcels circulating around the STG account for 37% (0.36 PW) of the total MHT across 26.5°N, more than twice that of the classical horizontal gyre component (15%). This long-standing underestimation of STG heat transport is attributable to the downward spiralling nature of the STG recirculation (Spall, 1992; Berglund et al., 2022), which imprints onto a shallow vertical overturning cell rather than the horizontal circulation across 26.5°N.

Our Lagrangian analysis demonstrates that the MHT of the STG overturning cell is synonymous with a subtropical mode water cascade (Blanke et al., 2002) in which water parcels arriving in the upper Florida Current are successively transformed toward intermediate densities. This downwards cooling spiral (Spall, 1992) begins with the formation of STUW varieties via vertical Ekman pumping (O'Connor et al., 2005; Qu et al., 2016), which accounts for 47% of STG heat transport. Surprisingly, the subsequent transformation of recirculating STUW into STMW via intense wintertime cooling along the path of the Gulf Stream (e.g., Joyce et al., 2013) explains less than a third of STG heat transport. The downwards cooling spiral, which typically spans several decades (Berglund et al., 2022), concludes when STG water parcels reach the required depth ($z > 200$ m) and density ($\sigma_\theta > 25.5$ kg m^{-3}) to be exported northward in the subsurface limb of the NADW cell (Fig. 3b).

In contrast to the STG overturning cell, the NADW cell spans both subtropical and subpolar latitudes (Fig. 4a), because the weaker potential vorticity gradient across the Gulf Stream at depth permits water parcels to be advected north-eastward via the subsurface pathways of the North Atlantic Current (Jacobs et al., 2019; Burkholder & Lozier, 2011; Bower & Lozier, 1994; Gary et al., 2014). The northward subsurface branch of the NADW cell was arguably first identified as a 'nutrient stream' from the biogeochemical observations of Pelegrí and Csanady (1991). This nutrient stream plays a fundamental role in maintaining biological productivity at high latitudes by transporting large concentrations of nutrients along shoaling isopycnals which outcrop within the eastern subpolar gyre (SPG) (Williams et al., 2011). There are two important implications of this subsurface subtropical to surface subpolar connectivity (Burkholder & Lozier, 2014). Firstly, water parcels flowing northward in the NADW cell experience negligible heat loss prior to reaching the southern limit of the SPG ($\sim$47°N in Fig. 4b) and hence the heat transport divergence between 26.5°N and the inter-gyre boundary is equivalent to the STG heat transport (0.36 PW). Secondly, no inter-gyre pathway exists for sea surface temperature anomalies originating in the Gulf Stream to propagate advectively towards the eastern SPG (Foukal & Lozier, 2016). This highlights the central challenge of inferring large-scale circulation from Eulerian streamfunctions since the streamlines of the total diapycnal overturning presented in Figure 4a misleadingly suggest a continuous meridional pathway from the lightest to the densest water masses in the North Atlantic while, in fact, there are two overlapping diapycnal cells.

Although the strength of our conclusions is limited by the use of a single eddy-rich ocean hindcast, we note the strong agreement between our findings and those of Ferrari and Ferreira (2011), who used model sensitivity experiments to show that 40% of North Atlantic MHT is associated with the wind-driven STG circulation, whereas the remaining 60% is due to high latitude convection. Moreover, when our estimate of STG heat transport (37%) is applied to observations along 26.5°N, this translates to 0.44 PW of the total 1.2 PW due to the STG circulation, which is in remarkable agreement with the 0.42 PW (35%) estimated by Johns et al. (2023a) when applying the approach of Talley (2003) to RAPID observations. The remaining 0.76 PW (63%) of the total observed MHT across 26.5°N is hence due to the formation of NADW, which is more appropriately attributed to the horizontal SPG circulation across sloping isopycnals rather than to a classical vertical overturning cell (Chafik & Rossby, 2019; Zhang & Thomas, 2021).

In contrast to the traditional conveyor-belt view of North Atlantic overturning, our Lagrangian analysis demonstrates that both vertical and horizontal circulation cells are fundamental components of the AMOC and thus basin-scale overturning cannot be meaningfully distinguished from the gyre circulations of the North Atlantic (Fig. 4c). A more natural decomposition of the AMOC is between the STG and NADW diapycnal overturning cells shown in Figure 4a since these capture the successive transformations required to form dense NADW from the lightest waters flowing northward in the Florida Current. Extending the Lagrangian analysis presented here to reveal the phenomenology of overturning variability within each of these circulation cells and their interconnectivity across timescales is the subject of future research.

6 Open Research

The Lagrangian trajectory crossings of the RAPID 26.5°N section used in our analysis can be obtained from Tooth, Foukal, et al. (2023). The Lagrangian trajectory code TRACMASS was developed by Aldama-Campino et al. (2020). Data from the RAPID-MOCHA program are funded by the U.S. National Science Foundation and U.K. Natural Environment Research Council and are freely available to the public at https://www.rapid.ac.uk/rapidmoc and https://mocha.rsmas.miami.edu/mocha. The specific version of the observed RAPID-MOCHA heat transport data used in this study is Johns et al. (2023b).

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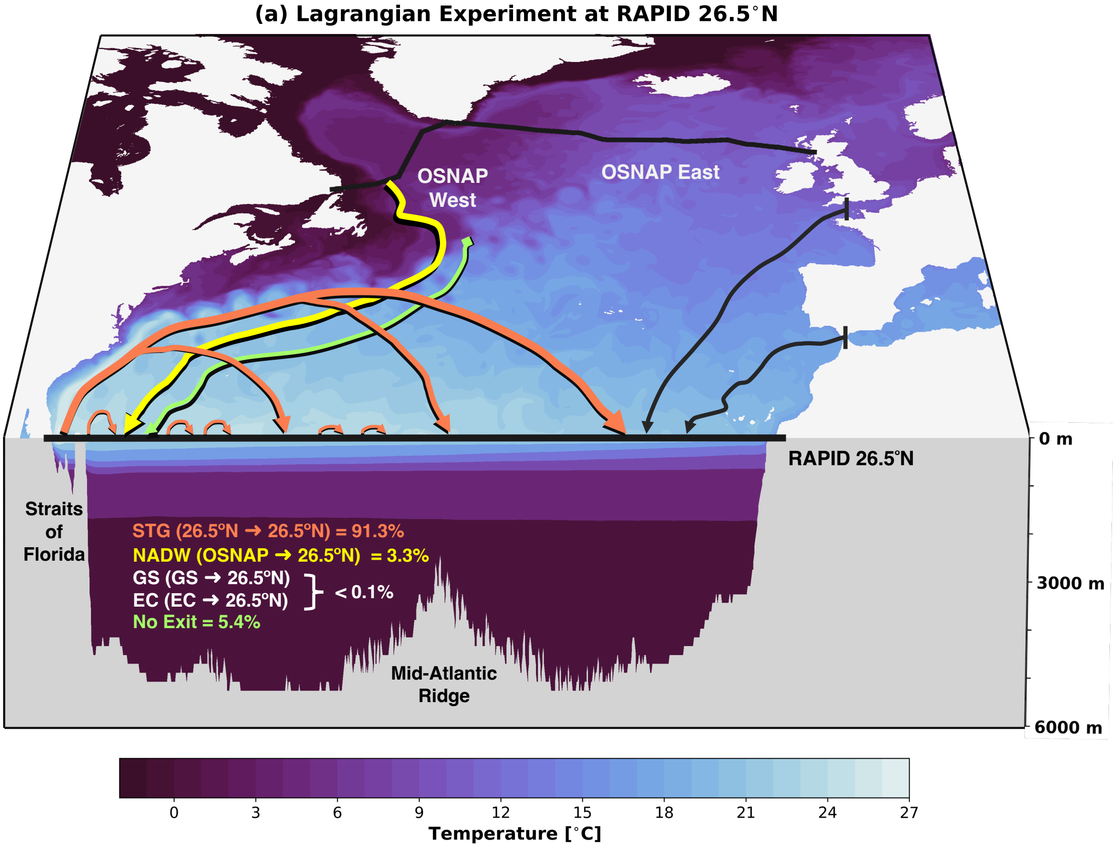

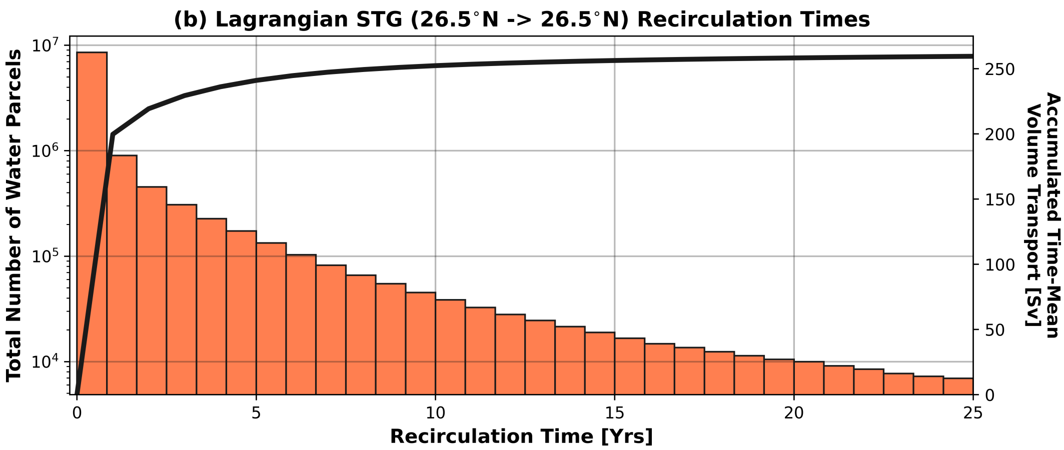

Figure 1. (a) Schematic representation of the Lagrangian pathways north of the RAPID array at 26.5°N. (b) Distribution of recirculation times for STG water parcels returning to 26.5°N within the 25-year maximum advection period. The solid black line overlaid shows the accumulation of the time-mean volume transport (Sv) of the STG pathway as a function of water parcel recirculation time.

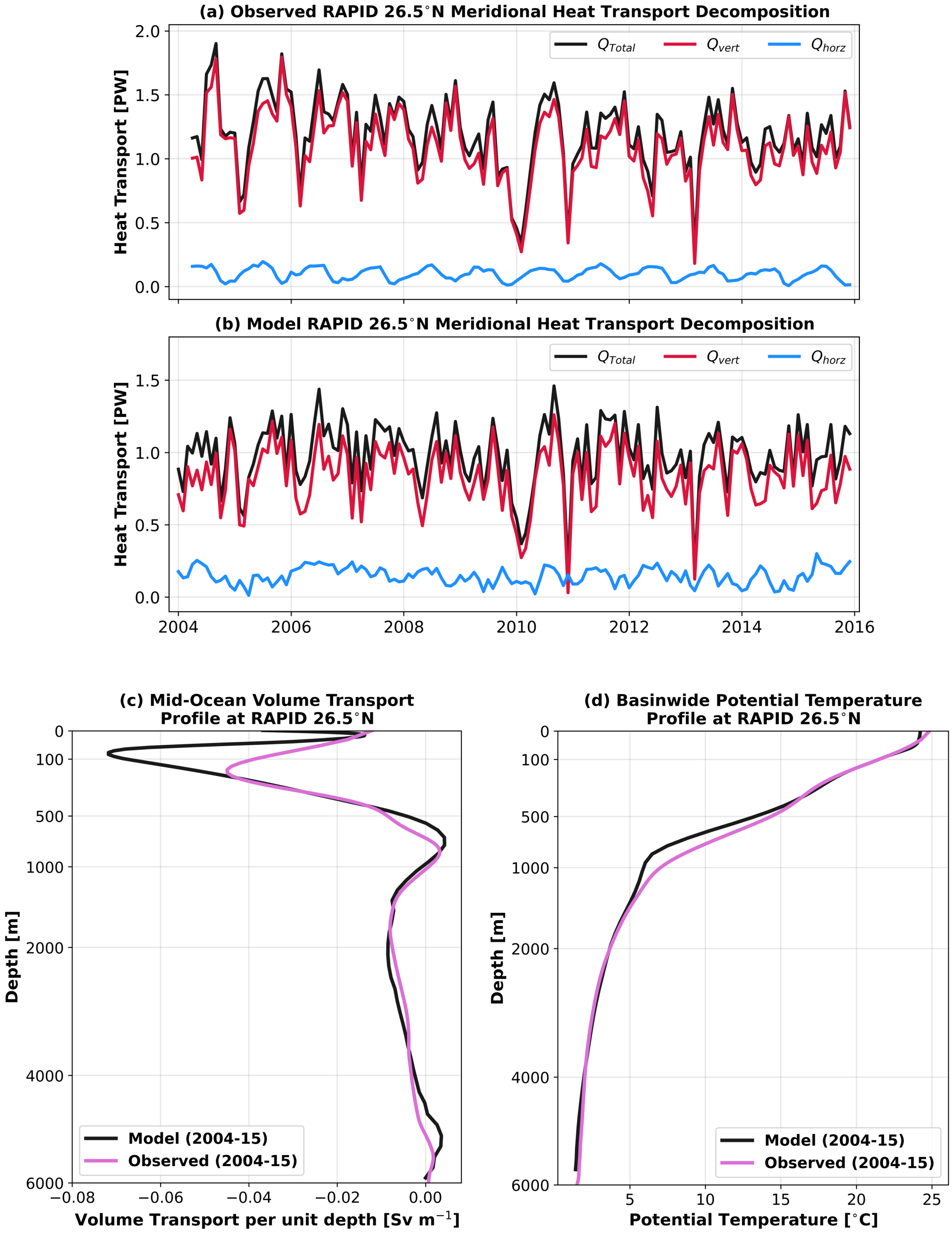

Figure 2. (a) Total observed MHT (black) at 26.5°N decomposed into a zonally-averaged vertical cell (Q_{vert}, red) and a residual horizontal cell (Q_{horz}, blue). (b) As in (a) but calculated using model Eulerian meridional velocity and potential temperature fields at 26.5°N. (c) Model (black) and observed (pink) time-mean (2004-2015) meridional volume transport per unit depth (Sv m^{-1}) in the Mid-Ocean region (Bahamas to Africa). (d) Time-mean (2004-2015) potential temperature profiles (°C) for the entire basin (Straits of Florida to Africa) in the model (black) and RAPID observations (pink). Note that we use non-linear vertical axes in (c) and (d) to highlight the upper 500 m.

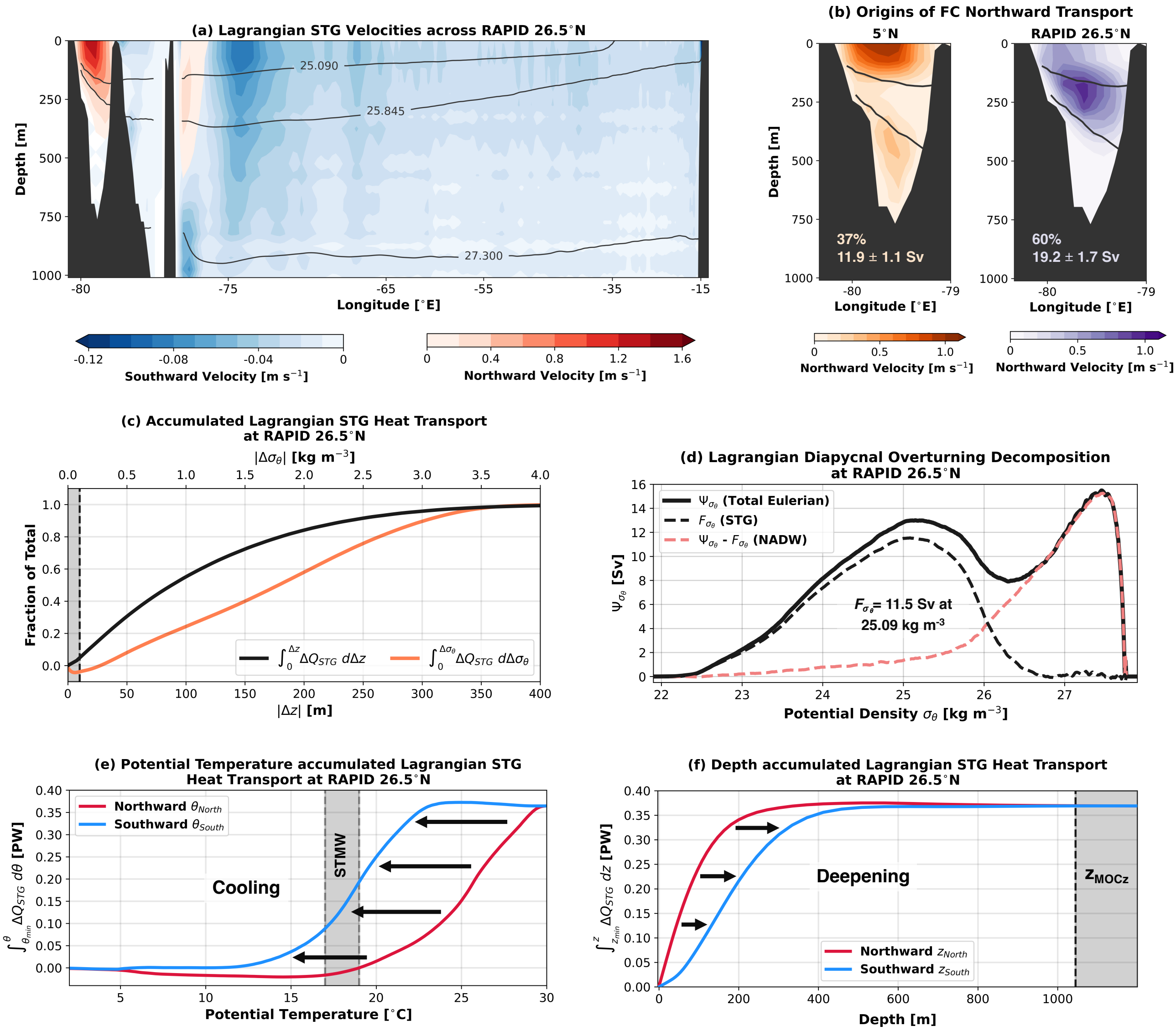

Figure 3. (a) Distribution of STG water parcel northward (red contours) and southward (blue contours) crossings of the RAPID 26.5°N section shown as an effective velocity in m s^{-1}. Note that the longitude axis is stretched to highlight the Florida Current. (b) Origins of the Florida Current (FC) northward transport shown as the effective velocity (m s^{-1}) of waters sourced from the tropical North Atlantic (5°N) and the STG recirculation (RAPID 26.5°N). The $\sigma_\theta = 25.09$ kg m^{-3} and 26.5 kg m^{-3} time-mean isopycnal surfaces are overlaid. (c) Heat transport of the STG circulation accumulated as a function of the absolute change in depth (black) and potential density (orange) of recirculating water parcels between their northward and southward crossings of 26.5°N. (d) Lagrangian decomposition of the time-mean (2004-2015) diapycnal overturning stream function at 26.5°N (Ψ_{σ_θ}, black solid) into a STG component (F_{σ_θ}, black dashed), determined from recirculating water parcel trajectories, and a residual NADW component (Ψ_{σ_θ} - F_{σ_θ}, pink dashed). Heat transport of the STG circulation accumulated as a function of the (e) potential temperature and (f) depth of recirculating water parcels on their northward (red) and southward (blue) crossings of 26.5°N. The shaded region in (e) defines STMW (17-19°C) following Kwon and Riser (2004). The depth of maximum Eulerian overturning in depth-space, z_{MOC} = 1045 m is indicated by the black dashed line in (f).

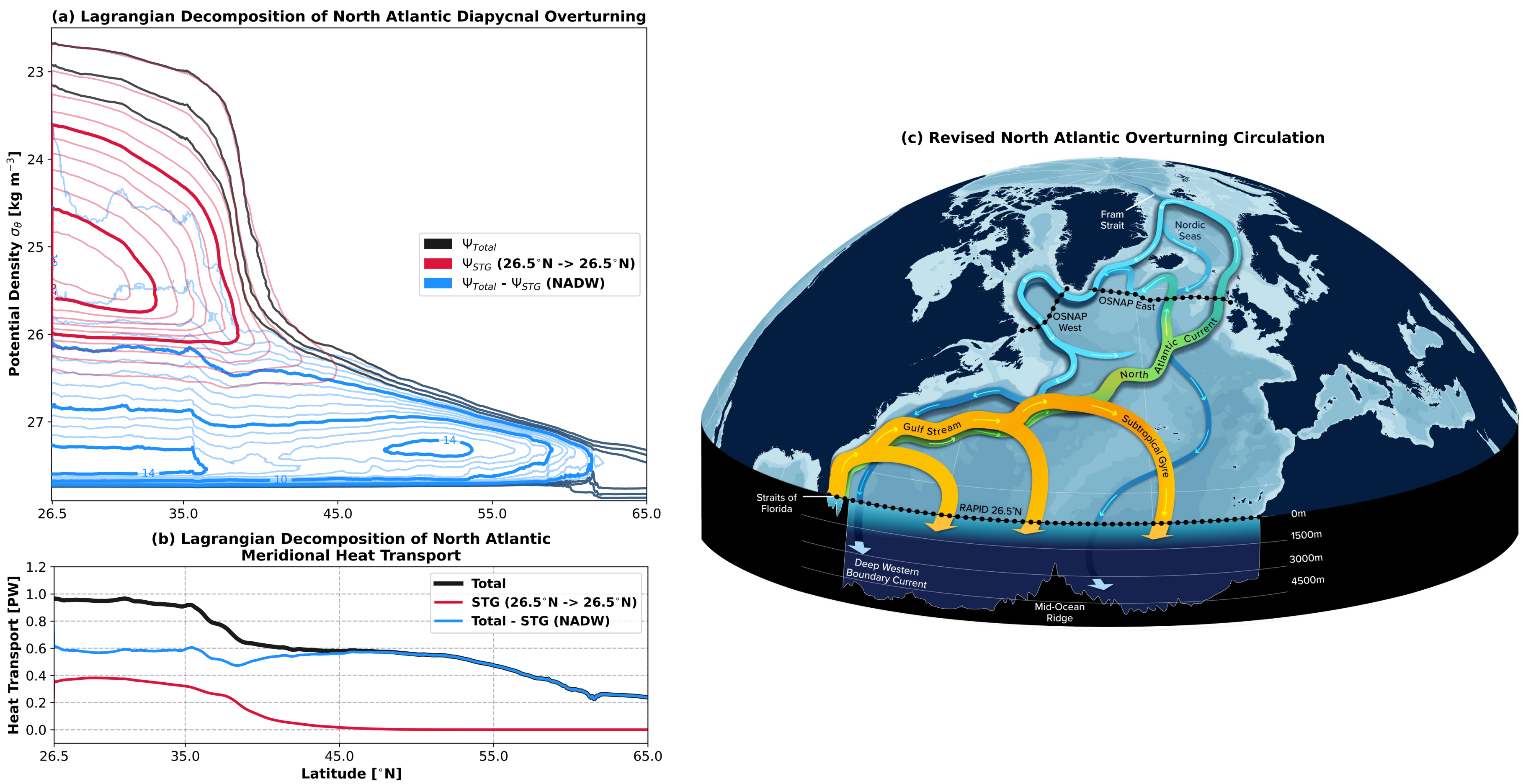

Figure 4. (a) Lagrangian decomposition of the time-mean (2000-2015) North Atlantic Ocean diapycnal overturning stream function north of RAPID 26.5°N into a STG component (red), derived from recirculating water parcel trajectories, and a residual component (NADW cell, blue). Selected streamlines (1-3 Sv) of the total Eulerian overturning stream function are overlaid in black. (b) Lagrangian decomposition of the latitudinal distribution of the time-mean North Atlantic Ocean MHT (black) into the contributions of the STG cell (red) and residual NADW cell (blue). (c) Schematic depicting the principal circulation components of the Atlantic Meridional Overturning Circulation (AMOC) north of the RAPID 26.5°N section.

Supporting Information for "Lagrangian Decomposition of the Atlantic Ocean Heat Transport at 26.5°N"

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Introduction Here we provide additional details on the Lagrangian particle tracking experiments and construction of the Lagrangian overturning streamfunctions discussed in the manuscript. Section S1 further describes the backwards-in-time Lagrangian particle tracking experiments undertaken at the RAPID 26.5°N section in the ORCA0083-N06 ocean sea-ice hindcast. Section S2 outlines the methodology used to construct Lagrangian overturning streamfunctions from the water parcel trajectories evaluated in this study.

Text S1.

Further information on the backwards-in-time Lagrangian particle tracking experiments undertaken at RAPID 26.5°N in ORCA0083-N06.

To evaluate the Lagrangian trajectories of water parcels released along the RAPID section at 26.5°N in the ORCA0083-N06 ocean sea-ice hindcast, we used the Lagrangian particle tracking tool TRACMASS v7.1 (Aldama-Campino et al., 2020). TRACMASS uses a mass conserving scheme which determines the trajectory path of each water parcel analytically by solving a differential equation for the unique streamlines of the flow in each model grid cell (Döös et al., 2008). Here we use the stepwise stationary scheme, which divides the time between successive 5-day mean velocity fields into a series of 100 intermediate time steps. The velocity field at each intermediate time step is determined by linear interpolation and is assumed to be steady for the duration of the step (Döös et al., 2017). Since ORCA0083-N06 uses a Boussinesq ocean circulation model (Nucleus for European Modelling of the Ocean [NEMO] version 3.6), the volume transport conveyed by each water parcel is conserved along its entire trajectory. To ensure mass is conserved within each model grid cell, we do not parameterise sub-grid scale convective mixing along water parcel trajectories. This enables us to advect water parcels backwards-in-time and construct partial Lagrangian streamfunctions from their trajectories (see Text S2.). For further details of TRACMASS and its associated trajectory schemes, readers are referred to Döös et al. (2017).

The location, conservative temperature and absolute salinity of each water parcel are recorded at every model grid cell crossing north of the RAPID 26.5°N section. The potential density referenced to the sea surface (σ_θ) is calculated along each trajectory using the TEOS-10 equation of state (McDougall et al., 2012) as implemented in the ORCA0083-N06 simulation.

To demonstrate that we have initialised a sufficiently large number of water parcels to obtain robust Lagrangian statistics, we compare the results of a subset of our primary Lagrangian experiment (**Original**) using a maximum volume transport of 0.005 Sv per parcel to a repeat of this experiment (January-December 2004) in which a substantially smaller maximum volume transport of 0.001 Sv per parcel is used (**High-Res.**). Table T1 shows that the time-mean meridional heat transport and diapycnal overturning determined from Lagrangian trajectories which recirculate within the Subtropical Gyre (STG) is unchanged by further increasing the number of water parcels initialised along 26.5°N and hence the conclusions of our study are insensitive of the "Lagrangian resolution" (Döös et al., 2008) of our primary experiment.

Text S2.

Further information on the definition of Lagrangian overturning streamfunctions and their use to decompose the time-mean Eulerian overturning at RAPID 26.5°N.

To compute the vertical Lagrangian overturning from the backwards-in-time trajectories initialised at time t, we first determine the absolute volume transport distributions of all water parcels recirculating within the subtropical gyre in discrete depth bins on their initial southward V_{South} and final northward V_{North} crossings of the RAPID 26.5°N section. We then calculate the Lagrangian overturning streamfunction F_z in-depth coordinates as the cumulative sum of the net volume transport distribution from the seafloor to the ocean surface as follows:

$$F_z(z,t) = \int_z^0 V_{North}(z, t-\tau) - V_{South}(z,t)\; dz \tag{1}$$

where $\tau = 25\ yrs$ corresponds to the maximum advection time of water parcels in our Lagrangian experiment.

Similarly, the diapycnal Lagrangian overturning streamfunction F_{σ_θ} can be computed by accumulating the net volume transport distribution of recirculating water parcels in potential density coordinates:

$$F_{\sigma_\theta}(\sigma_\theta, t) = \int_{\sigma_\theta \geq \sigma'_\theta} V_{North}(\sigma'_\theta, t-\tau) - V_{South}(\sigma'_\theta, t)\; d\sigma'_\theta \tag{2}$$

The equations outlined above, defined as Lagrangian overturning functions in Tooth, Johnson, Wilson, and Evans (2023), are, in fact, a specific case of the more general Lagrangian meridional overturning streamfunctions first introduced by Blanke, Arhan, Madec, and Roche (1999). Blanke et al. (1999) showed that, for a given collection of water parcels flowing from an initial section to a final section, the Lagrangian meridional overturning streamfunctions $\Psi_{j,k}$ ($\Psi_{j,\sigma}$) in depth (potential density) coordinates are given by:

$$\Psi_{j,k} = \sum_{k_{min}}^{k} \sum_i \sum_n V^y_{i,j,k,n} \tag{3}$$

$$\Psi_{j,\sigma} = \sum_{\sigma_{min}}^{\sigma} \sum_{i} \sum_{n} V^{y}_{i,j,\sigma,n} \tag{4}$$

where i, j and k are the zonal, meridional and vertical indices of the discretised model grid and σ represents a discrete potential density space. $V_{i,j,k,n}$ is the volume transport of a water parcel n crossing a line of constant latitude y.

An important property of the Lagrangian meridional overturning streamfunctions defined above is that, provided a sufficiently large number of water parcel trajectories are initialised from the chosen section, Döös et al. (2008) showed that $\Psi_{j,k}$ and $\Psi_{j,\sigma}$ will converge towards their equivalent time-mean Eulerian streamfunctions. Thus, since we fully resolve the subtropical gyre recirculation within our Lagrangian experiment, we can estimate the contributions made by the outstanding NADW and Antarctic Bottom Water cells to the total Eulerian overturning streamfunction by calculating the residual between the time-mean Eulerian quantity and the Lagrangian overturning streamfunction for the subtropical gyre circulation (i.e., $\overline{\psi}(y, \sigma_\theta) - \overline{\Psi}^{STG}_{j,\sigma_\theta}$). A further consideration when using Lagrangian water parcel trajectories to decompose the Eulerian overturning is the choice of time-averaging window to use when calculating the time-mean Eulerian overturning streamfunction. Here we seek a time window that optimises the sampling of the meridional velocity and potential density field along 26.5°N by water parcels recirculating within the STG circulation. Given that more than 90% of STG water parcels return to 26.5°N within 4 years of their initialisation (see Fig. 1b), we use the time-mean Eulerian overturning averaged over 2000-2015 in our Lagrangian decomposition (starting 4 years prior to the earliest water parcel initialisation in 2004).

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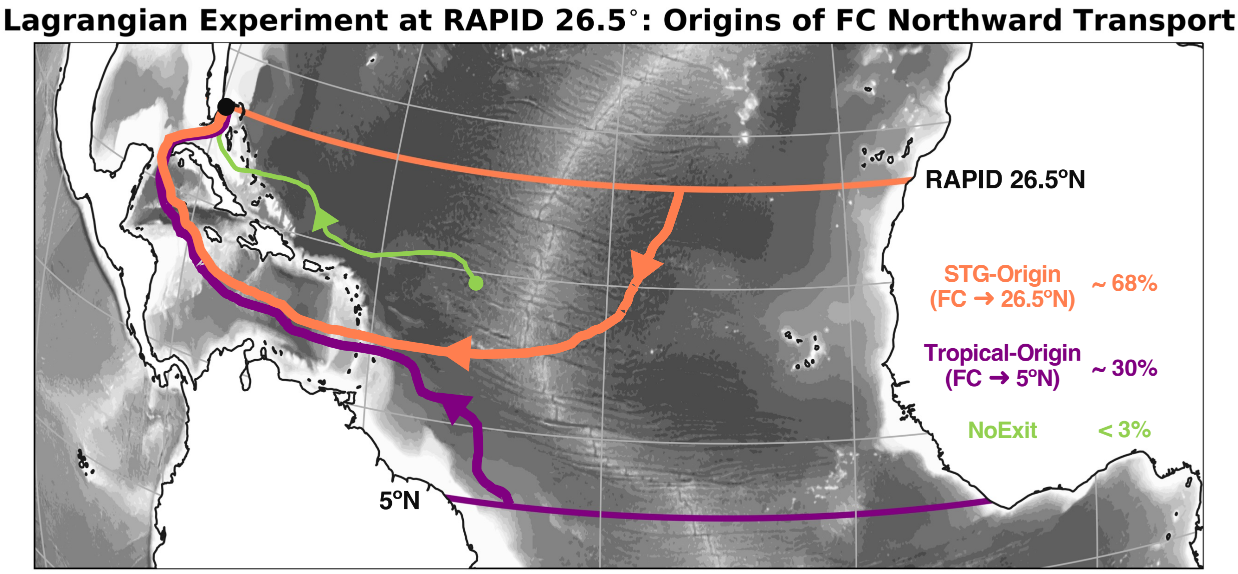

Figure S1. Schematic representation of the Lagrangian experiment used to determine the origins of water parcels flowing northward in the Florida Current (FC, indicated by the black dot along RAPID 26.5°). Water parcel trajectories, sampling the full-depth northward transport of the FC, are advected backwards-in-time for a maximum of 25 years or upon returning to the RAPID 26.5° array within the Subtropical Gyre (STG-origin, orange) or transiting to the trans-basin section along 5°N (Tropical North Atlantic-origin, purple). Note that less than 3% of all water parcels initialised within the FC remain within the experiment domain following their 25-year maximum advection period (NoExit, green).

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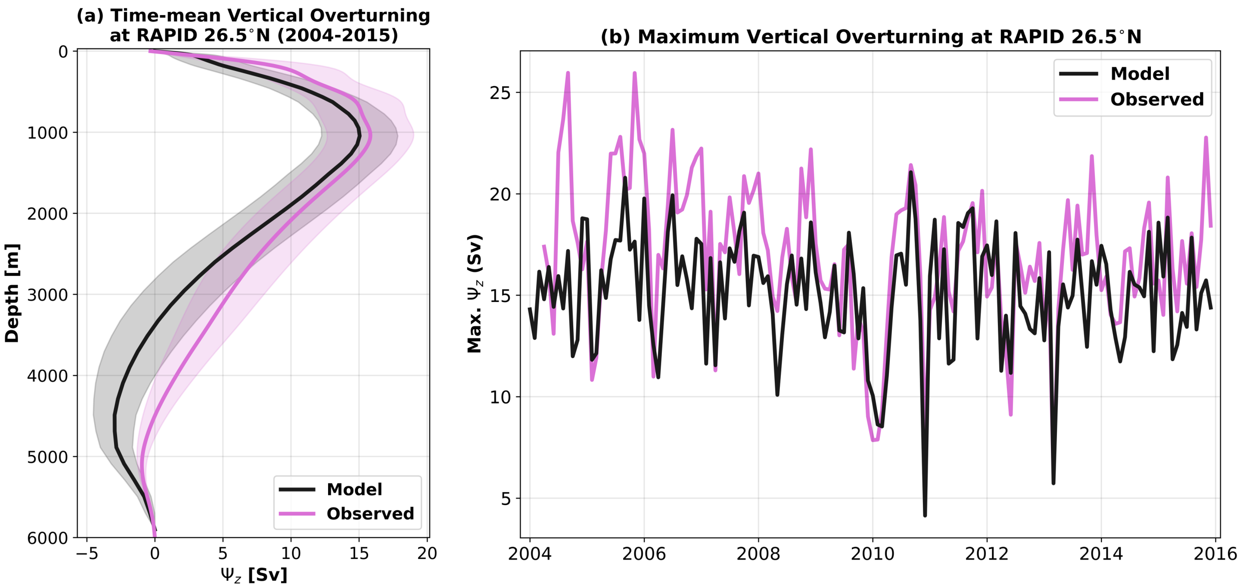

Figure S2. (a) Model (black) and observed (pink) time-mean (2004-2015) Eulerian vertical overturning streamfunctions calculated at RAPID 26.5°N. Shading denotes the standard deviation of the modelled and observed time-mean vertical overturning stream functions. (b) Monthly-mean modelled (black) and observed (pink) maximum Eulerian vertical overturning at 26.5°N.

Table T1.

Time-mean (± std.) Lagrangian volume, heat and overturning transports for water parcels initialised between January-December 2004 which return to 26.5°N in the Subtropical Gyre (STG) circulation within a 25-year maximum advection period. In the **Original** Lagrangian experiment, documented in the main text, we initialise water parcels across each model grid cell face along 26.5°N using a maximum volume transport of 0.005 Sv per water parcel. The **High-Res.** Lagrangian experiment is a repeat of the year 2004 in our **Original** experiment in which we substantially reduced the maximum volume transport per water parcel to 0.001 Sv.

Lagrangian Diagnostic	**Original Experiment**	**High-Res. Experiment**
Max. Volume Transport per Parcel (Sv)	0.005	0.001
Mean Volume Transport per Parcel (Sv)	0.003	0.0008
STG Volume Transport (Sv)	265.57 ± 16.52	265.53 ± 16.48
STG MHT (PW)	0.40 ± 0.07	0.40 ± 0.07
STG Diapycnal Overturning (Sv)	14.01 ± 3.57	14.00 ± 3.56