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Lagrangian View of Atlantic Water Pathways toward the North Sea

ORIGINAL RESEARCH PAPER

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ABSTRACT

The influence of subpolar North Atlantic hydrographic conditions on the North Sea is well recognized, yet the precise pathways taken by Atlantic Water to reach its gateway remain uncertain. Using satellite-derived velocity fields, we map the open-ocean routes leading to the North Sea. Our Lagrangian analysis shows that the Rockall Trough serves as the primary route in a time-mean sense, with its dominance becoming particularly evident under anomalously cold subpolar conditions. During anomalously warm periods, however, Atlantic Water is preferentially routed through the Iceland Basin. Empirical orthogonal function analysis of the Lagrangian trajectories reveals a dipole mode of variability between the Rockall Trough and the Iceland Basin, with its first principal component explaining 74% ($R = 0.86$) of the variance in multi-year ocean heat content variability. These trajectories further demonstrate that this variability is closely linked to the north-south shifts of the North Atlantic Current. Such spatial shifts are likely driven by variations in northward ocean heat transport at the intergyre boundary, with the strength of the subpolar overturning circulation in preceding years potentially playing a critical role. This connection suggests that the conditions in the North Sea as well as the pathways Atlantic Water is advected along to reach it could be predictable several years in advance.

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1 INTRODUCTION

The northward heat transport into the subpolar North Atlantic (SPNA), mainly provided by the North Atlantic Current (NAC) and its branches (Figure 1a), is considered a key factor in modulating the hydrographic conditions of the North Sea (Koul *et al.*, 2019; Turrell, 1992; van der Molen and Pätsch, 2022). Variations in the flux of heat by the NAC into the eastern SPNA and its interactions with the shelf-edge current (Holliday *et al.*, 2018; Orvik and Niiler, 2002; Zhou and Nøst, 2013) can lead to substantial changes in the hydrography and biogeochemical dynamics of the North Sea, affecting nutrient transport and primary production in the region (van der Molen and Pätsch, 2022). It is, however, less understood which pathways Atlantic Water takes to reach the North Sea in the SPNA, despite previous research indicating that the NAC and its northeast extension changes position during the different hydrographic conditions of the SPNA (Chafik *et al.*, 2019; Desbruyères *et al.*, 2021). Examining the variability in the pathways of Atlantic Water toward the North Sea is therefore essential for improving our understanding of the dynamics setting of the multi-year variability in the hydrography of the North Sea, which is different from the high-frequency variability related to, e.g., variations in local winds that can directly impact the cross-shelf exchange (Akpınar *et al.*, 2022; Huthnance *et al.*, 2009; van der Molen and Pätsch, 2022).

The variability of NAC transport in the Rockall Trough on multiple timescales was analyzed by Houpert *et al.* (2020) using 4 years of mooring measurements (2014–2018) from the Overturning in the Subpolar North Atlantic Programme (OSNAP; Lozier *et al.* (2019)). They identified a significant and abrupt drop in transport from 5.7 to 2.7 Sv in January 2017, which persisted for the remainder of the time series (see Houpert *et al.* (2020), their Figure 4d). This reduction was hypothesized to result from a reorganization of the large-scale ocean currents, potentially involving a shift of the NAC pathway from the Rockall Trough to the Iceland Basin. Houpert *et al.* (2020) also discussed a possible antiphase relationship in transport between these two basins, similar to that reported in Chafik *et al.* (2014). This decline in the Rockall Trough transport coincided with the onset of observed warming in the SPNA, which started in 2016 (Chafik *et al.*, 2023; Desbruyères *et al.*, 2021), and was attributed to increased northward ocean heat transport resulting from enhanced water mass transformation in the eastern SPNA in the preceding years (Chafik *et al.*, 2023). Positive anomalies in temperature and sea surface heights in the Iceland Basin during this warming period commencing in 2016 further support the hypothesis of a pathway shift, emphasizing the need to determine whether these changes also influence the origin of water reaching the North Sea.

Here, we use a Lagrangian approach (Döös *et al.*, 2017) applied to satellite-derived geostrophic velocity fields (1993–2019) to determine the pathways of Atlantic Water leading to the North Sea. In particular, we backtrack water from the North Sea gateway to the NAC zone (Figure 1c). Based on this, we highlight the variable pathways depending on ocean heat content conditions in the SPNA as reflected by the second leading mode of sea-surface height (SSH) variability in the North Atlantic (Hátún and Chafik, 2018) (Figure 1b). However, we emphasize that this SSH-based metric primarily reflects large-scale ocean heat content rather than distinct ocean dynamics, as recently discussed by Chafik and Lozier (2025), and therefore does not clarify the underlying mechanisms driving shifts in Atlantic Water pathways. Furthermore, to confirm that the pathways of Atlantic Water to the North Sea vary depending on the prevailing ocean heat content conditions, we apply an Empirical Orthogonal Function (EOF) analysis on the Lagrangian tracks. This reveals a spatial dipole mode of variability between the Rockall Trough and Iceland Basin, reinforcing that the origin of Atlantic Water reaching the North Sea can vary depending on the large-scale oceanic conditions, although the dominant route to the North Sea in a time-mean sense based on particle counts is found to be the Rockall Trough (Figure 1d).

2 DATA AND METHODS

2.1 SATELLITE ALTIMETRY

This study utilizes daily velocities derived from satellite altimetry (Taburet *et al.*, 2019). The velocities result from applying the geostrophic equations to the absolute dynamic topography (ADT; sea level anomaly + mean dynamic topography). ADT is based on a two-satellite altimeter constellation, and the associated velocity fields are purely geostrophic, without the Ekman component. Since our focus is on the large-scale upper-ocean circulation and the transport of Atlantic Water from the NAC to the North Sea–occurring below the Ekman layer–the influence of Ekman transport is expected to be minimal. Wunsch (1997) demonstrated that altimetry-derived velocity fields primarily capture the first baroclinic mode, representing the motion of the main pycnocline. Advecting particles using these fields should thus adequately reflect upper-ocean circulation changes.

2.2 TRACMASS AND LAGRANGIAN TRAJECTORIES

We analyze Lagrangian trajectories in the 2-dimensional daily velocity field derived from satellite altimetry. The trajectories are calculated using the Lagrangian tracking tool TRACMASS (Döös *et al.*, 2017). TRACMASS calculates a virtual area flux from the two-dimensional velocities,

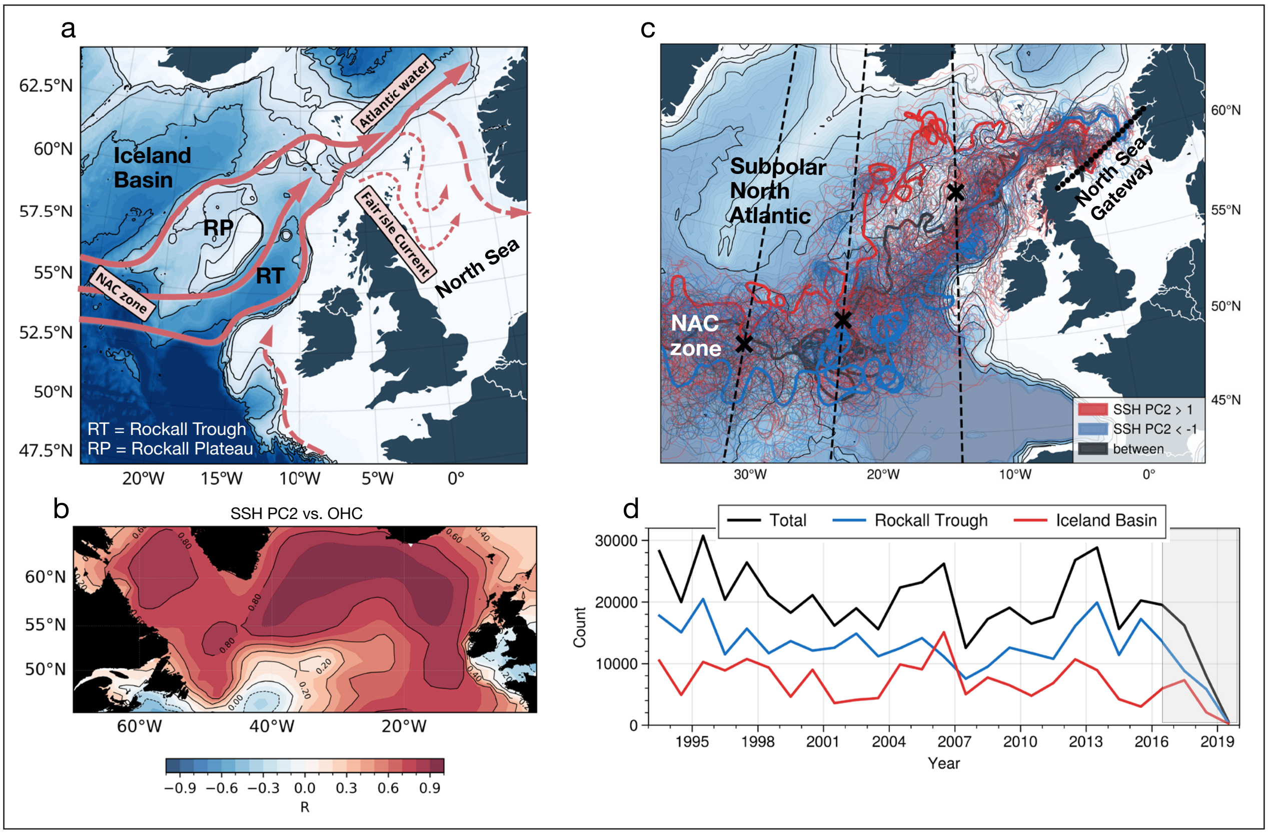

Figure 1 (a) Schematic of Atlantic Water pathways in the eastern SPNA toward the North Sea gateway (circles in panel c). **(b)** Spatial correlation between annually averaged SSH PC2 (1993–2019) and ocean heat content (OHC; 0–700 m) variability from the EN4 dataset (Good *et al.*, 2013). OHC has been deseasonalized and detrended before the analysis. **(c)** Spaghetti plot of backward trajectories initialized at the North Sea gateway and backtracked to the NAC zone (panel a). Thin solid trajectories show multiple examples of particle pathways under varying SPNA conditions indicated by SSH PC2 phases: warm (SSH PC2 > 1; red), cold (SSH PC2 < –1; blue), and neutral (–1 < SSH PC2 < 1; gray). Thick solid lines represent one representative trajectory for each SSH PC2 phase, illustrating the full path from the NAC zone to the North Sea gateway. Dashed meridional sections with crosses indicate locations used for diagnosing Lagrangian transport in Figure 4. **(d)** Annual mean particle count reaching the easternmost meridional section at 14°W (black line). The thick black cross at 58°N (panel c) marks the approximate boundary separating particles originating from the Iceland Basin (red line) and the Rockall Trough (blue line). The drop in particle count during the final years of the time series is due to an edge effect, as trajectories require sufficient time to reach the meridional sections. This period is highlighted with a gray box.

assuming unitary depth. Trajectories are seeded at the North Sea gateway, defined as a diagonal transect between Scotland and southern Norway (Figure 1c), and are subsequently tracked backward in time. The temporal and spatial seeding density is determined by the instantaneous transport at the seeding location, meaning that more trajectories are seeded during the periods of higher transport. As a result, both the total transport and the transport assigned to individual trajectories vary dynamically. In TRACMASS, this is controlled using nqua = 2 and partquant = 50, which sets the maximum transport per trajectory to 50 m^2/s. Furthermore, trajectories are followed for up to 7 years, or until they reach a domain boundary encapsulating our research area (Figure 1c). Using the trajectories, we first calculate the spatial patterns of the transports for 12 months preceding seeding, and then derive their anomalies relative to the corresponding long-term mean (Figure 2). To perform the principal component analysis (PCA; Figure 3), we standardize the anomalies by local variance, exclude any locations where fewer than one trajectory passed per year, and apply a spatial coarsening to a 2° resolution before the calculations.

2.3 PROCESSING OF LAGRANGIAN TRAJECTORIES

Particle positions are calculated for a fixed travel time of 12 months. Daily trajectories for each month of seeding between 1993 and 2019 are grouped, and months with less than 1 year of travel are discarded. Furthermore, only parcels that cross the 900 m isobath are taken into account, a measure to ensure approximately that parcels must originate from the North Atlantic proper. The particle locations are then summed over while weighted by each trajectory's initial area transport at a horizontal resolution equal to the input data of 0.25° longitude and latitude. The gridded data are subsequently averaged annually and over 1.25° longitude and latitude. The concept of the origin presented here is similar to that of Jones *et al.* (2020). From the gridded annual mean area-transport origin time series, hereafter referred to as origin, the areas that have less than one particle passing

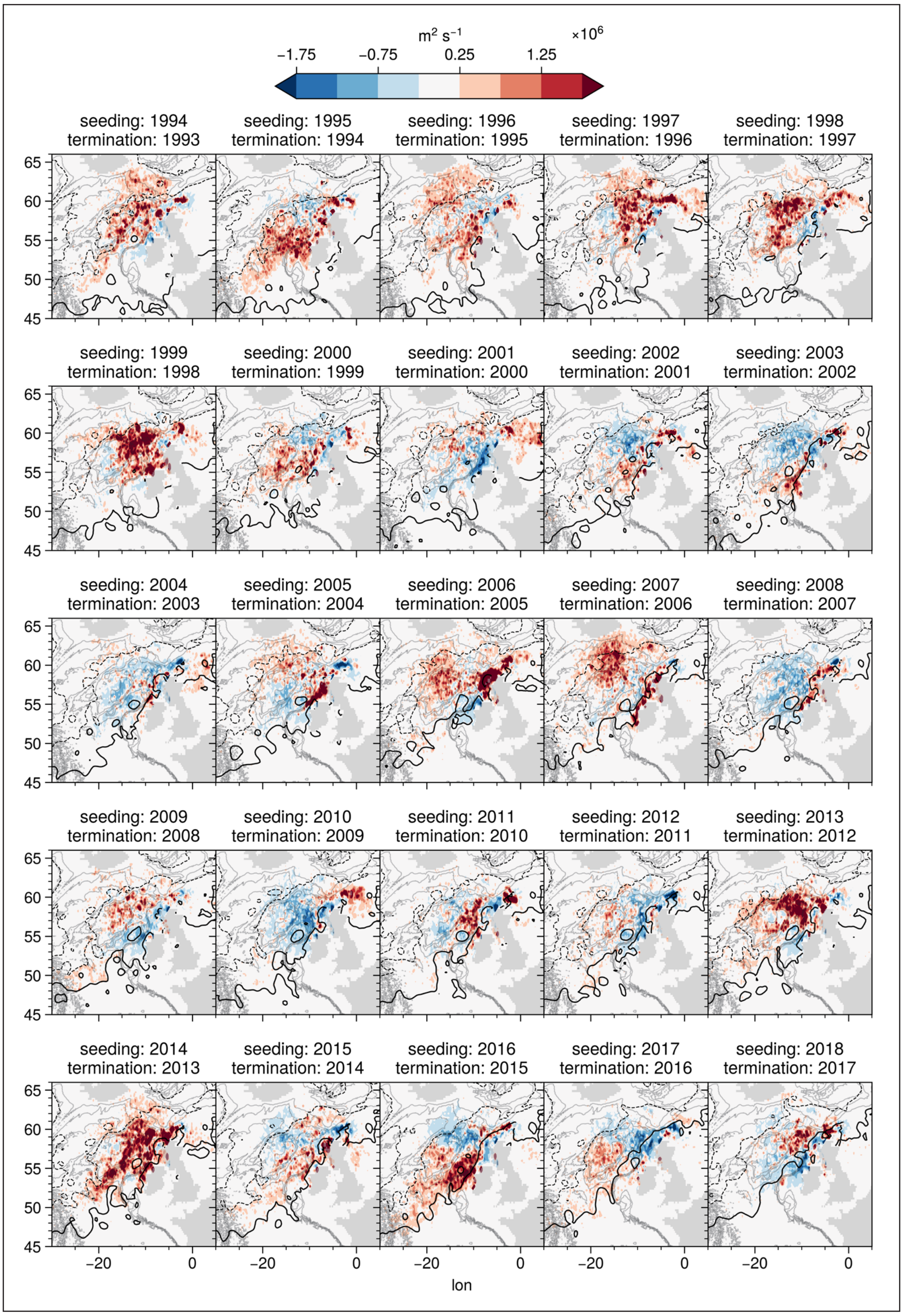

Figure 2 Anomalies of annual parcel transport 12 months before seeding overlaid with ADT contours at –0.4,–0.2, 0, 0.2, and 0.4 m. ADT is averaged using a 2-year pyramid-shaped weighting scheme. Annually, the total transport varies from 68% (seeding 2010, termination 2009) of the long-term mean up to 147% (seeding 2014, termination 2013). This results in years with same sign anomalies throughout. Percentages refer to the total transport relative to the time mean, for example, 68%/147% indicates a year with 32%/47% less/more transport than the time mean.

per year are removed. A moving average is applied with a window size of 14 months. Finally, a PCA is performed on the normalized anomalies of the cleaned origin time series.

It is worth mentioning that we also performed a PCA analysis on the trajectories on the shelf region, but the results were inconclusive, likely due to the limitations of gridded altimetry products in accurately resolving velocity fields in shallow and shelf regions where ageostrophic processes are significant. In addition, the mean dynamic topography is often poorly resolved over shelf regions, leading to unrealistic or weak velocities and thus reducing the reliability of altimetry-derived estimates in these areas. Given these challenges, the influence of on-shelf water on the inflow to the North Sea remains an open question for future research (see also Marsh *et al.* (2017)).

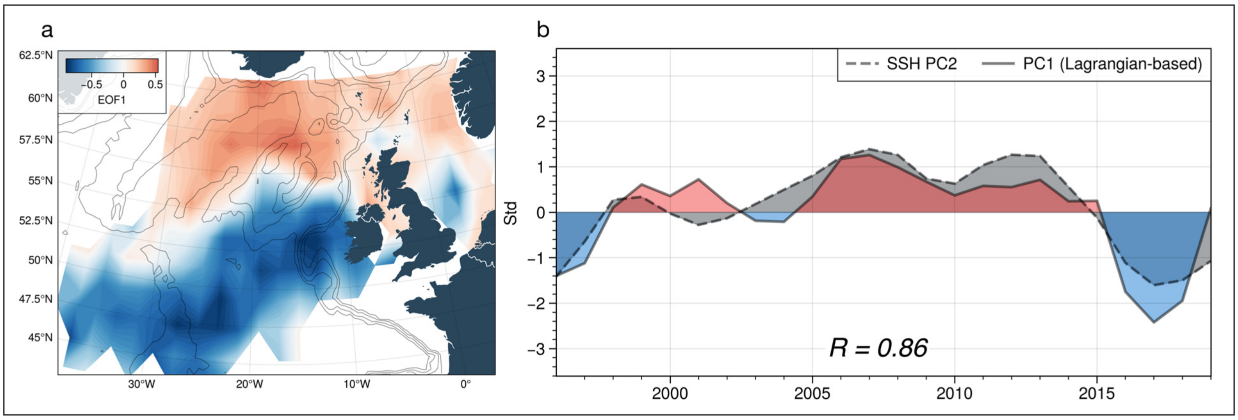

Figure 3 (a) The first leading mode of variability (EOF1) based on the Lagrangian trajectories. The analysis is performed on the anomalies of annual parcel transports 12 months before seeding. **(b)** Three-year rolling average of the first principal component of the Lagrangian trajectories (solid line with red-blue shading) overlaid with SSH PC2 (dashed line with gray shading). The correlation coefficient between the two time series is 0.86.

3 RESULTS

3.1 VARIABLE PATHWAYS OF ATLANTIC WATER TOWARD THE NORTH SEA

To expand on the initial Lagrangian analysis shown in Figure 1c, we now examine annual binned backward-tracked trajectories (Figure 2). Whereas Figure 1c demonstrates example pathways from the NAC zone to the North Sea gateway under varying SPNA conditions, Figure 2 further highlights their interannual variability. This analysis provides insight into the origin of waters, represented as Lagrangian volume transport anomalies, 1 year before reaching the North Sea gateway.

For instance, particles seeded in 1994 and stopped in 1993–a year characterized by anomalously cold SPNA conditions–exhibit a spatial pattern where the Lagrangian transport, which is proportional to particle density, is anomalously high in the northern Iceland Basin and Rockall Trough. The highest transport values align with the NAC path east of the Rockall Plateau (Houpert *et al.*, 2020), reinforcing the dominant role of this current in supplying water to the North Sea gateway. In addition, an increased number of trajectories follow the continental slope, suggesting an intensified shelf-edge current transport pathway during this period.

As shown in Figure 2, Atlantic Water pathways toward the North Sea exhibit considerable complexity and variability, with the relative contributions from the Iceland Basin and Rockall Trough shifting on interannual and multi-year timescales. Rather than following a single dominant route, the inflow draws on both source regions, with the predominant pathway evolving over time. These variations may reflect upstream changes in the SPNA along the NAC zone, driven by large-scale forcing mechanisms, as discussed by Chafik *et al.* (2023). Notably, the warming in the mid-2000s and cooling in the early 2010s coincide with shifts in pathway preference, indicating a strong link between SPNA thermal conditions and shifting currents. The drivers of these slow multi-year shifts are addressed in the Discussion section.

3.2 A DIPOLE MODE OF VARIABILITY IN ATLANTIC WATER PATHWAYS TOWARD THE NORTH SEA

Figure 3a presents an EOF analysis applied to the annual mean origins of the particles (Figure 2) to support the two main pathways discussed. The leading EOF mode, accounting for 19.2% of the variance, reveals a northwest-southeast dipole pattern between the Rockall Trough and the Iceland Basin, indicating that Atlantic Water inflow to the North Sea oscillates between these two pathways rather than following a single dominant route. Periods of increased transport from the Rockall Trough coincide with reduced transport from the Iceland Basin and vice versa, similar to the hypothesis of Houpert *et al.* (2020). The co-variability of this dipole pattern with SSH PC2 reflects a strong link between shifting Atlantic Water pathways and ocean heat content changes in the SPNA, as shown in Figure 3b. The latter compares the first principal component of the Lagrangian-based EOF with SSH PC2. The strong correlation ($R = 0.86$, $R^2 = 0.74$) suggests that approximately 74% of the variance in Atlantic Water transport variability toward the North Sea can be explained by SPNA thermal conditions, particularly on timescales longer than 3 years.

In summary, during negative phases of SSH PC2, characterized by anomalously cold conditions in the SPNA, Atlantic Water toward the North Sea predominantly originates from the Rockall Trough, with a reduction in transport from the Iceland Basin. In contrast, during positive phases, waters shift north of the Rockall Plateau, suggesting that the Iceland Basin route is favored under warmer conditions. This analysis confirms that SSH PC2, which mainly reflects the thermal conditions of the SPNA (Figure 1b), is closely linked to shifts in Atlantic Water pathways toward the North Sea. However, it does not elucidate the underlying processes driving shifts in waters between the Rockall Trough and the Iceland Basin (see Chafik and Lozier (2025) for further discussion), nor does it tell us whether this redistribution results from shifts in the NAC zone, aspects that are further explored in the following section and expanded upon in the Discussion section.

3.3 NAC SHIFTS AND ATLANTIC WATER PATHWAYS TOWARD THE NORTH SEA

In this section, we analyze the meridional organization of the flow at three longitudinal sections (14°W, 24°W, and 32°W; cf. Figures 1c and 4). Specifically, we calculate the Lagrangian transport at these sections and differentiate between anomalously positive and negative SSH PC2 periods. The goal is to understand which NAC branches are activated when transporting Atlantic Water toward the North Sea during these contrasting SPNA states.

At the easternmost section (14°W), transport anomalies reveal a distinct north-south migration of the NAC associated with contrasting phases of SSH PC2. During positive SSH PC2 periods (red bars), enhanced transport is observed north of 58°N, indicating a preference for a more northern pathway that directs Atlantic Water toward the North Sea. Conversely, during negative SSH PC2 periods (blue bars), transport anomalies dominate south of 58°N within the Rockall Trough, indicating a southerly shift in the NAC pathway. This migration highlights how contrasting SSH PC2 phases influence the routing of Atlantic Water at this section, with positive SSH PC2 favoring a northerly path and negative SSH PC2 favoring a southerly path via the Rockall Trough.

At the westernmost section (32°W), transport anomalies similarly reflect a north-south migration of the NAC. Positive SSH PC2 periods are associated with a northward shift, routing the flow of Atlantic Water into the Iceland Basin. In contrast, during negative SSH PC2 phases, the NAC migrates southward, diverting Atlantic Water along a more southerly route toward the Rockall Trough. The results provide a coherent picture of the NAC's north-south migration in the SPNA under contrasting SSH PC2 phases, highlighting its impact on the pathways via which Atlantic Water reaches the North Sea.

At the central section (24°W), however, transport anomalies during negative SSH PC2 phases exhibit a pronounced double-branch structure of the NAC, likely corresponding to its northern and southern branches (see, e.g., Daniault *et al.* (2016)). The southern branch appears to feed the slope current (cf. Figure 4c), consistent with Zhou and Nøst (2013) and Marsh *et al.* (2017), while the northern branch transports water into the eastern and interior Rockall Trough, in agreement with Houpert *et al.* (2020). During positive SSH PC2 phases, the central branch of the NAC dominates, with the center of mass of the associated trajectories likely following the eastern boundary of the Iceland Basin (along the western slope of the Rockall Plateau; cf. Figure 2) before connecting to the 14°W section.

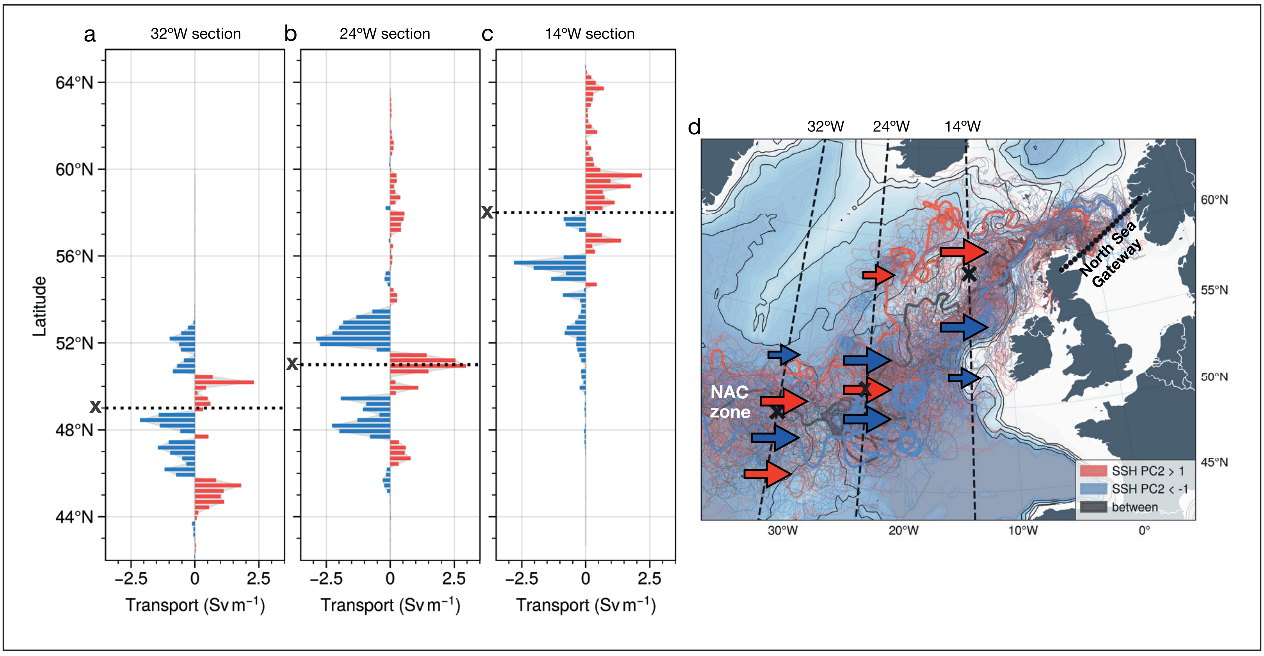

Figure 4 (a) Composite difference of Lagrangian transport at the easternmost meridional section, calculated as the difference between periods of anomalously positive SSH PC2 (>1 std) and anomalously negative SSH PC2 (<–1 std). **(b–c)** Same as (a), but for the central and westernmost meridional sections, respectively. Dashed lines and crosses on the y-axes indicate the approximate central position of the main flow (see panel d). **(d)** Schematic representation of transport anomalies, shown as arrows, at the three longitudinal sections (panels a–c) associated with contrasting SPNA periods, as indicated by SSH PC2 phases. These anomalies are overlaid on the trajectory pathways from Figure 1c. The positions of the crosses correspond to those indicated on the y-axes in panels (a–c).

4 DISCUSSION AND CONCLUSIONS

Our Lagrangian approach reveals distinct geographical shifts of Atlantic Water pathways between the Rockall Trough and Iceland Basin toward the North Sea. These shifts in particle trajectories and the associated dipole-like pattern are consistent with the reorganization of large-scale pathways under varying hydrographic conditions in the SPNA (Chafik *et al.*, 2023, 2019; Desbruyères *et al.*, 2021). Following periods of strong North Atlantic Oscillation, increased water mass transformation (Lozier, 2023), and southward spreading of deep density anomalies along the western boundary (Chafik *et al.*, 2023; Jackson *et al.*, 2016), the mid-latitude meridional heat transport intensifies. This process leads to a strengthening and northwestward shift of the NAC, as observed during the recent subpolar warming since 2016 (Chafik *et al.*, 2023; Desbruyères *et al.*, 2021). As a result, there is anomalous advection of waters into the Iceland Basin, as suggested by the Iceland Basin Lagrangian tracks. Conversely, decreased mid-latitude meridional heat transport is associated with a weakened NAC and its southeastward migration, causing waters to shift southward before following the Rockall Trough route. The timing of the abrupt reduction in Rockall Trough transport in January 2017 from OSNAP reported by Houpert *et al.* (2020) aligns closely with the onset of SPNA warming, highlighting a likely connection to the large-scale shifts in NAC pathways. It is these processes that we believe drive the variability in water masses reaching the North Sea, thereby influencing its hydrographic conditions on multi-year timescales.

A key consideration regarding our use of SSH PC2 is its interpretation and inherent limitations. In a recent study, Chafik and Lozier (2025) demonstrated that SSH PC2 (also referred to as the gyre index) primarily reflects variability in upper-ocean heat content rather than distinct ocean circulation dynamics. SSH PC2 should therefore be considered a proxy for thermal variability in the SPNA rather than an indicator of specific circulation changes (see also Foukal and Lozier (2017)). Despite this limitation, SSH PC2 remains a useful indicator of shifts in the pathways of Atlantic Water toward the North Sea, as shown in Figure 3. The strong correlation (R = 0.86) between SSH PC2 and the first principal component of the Lagrangian trajectories emphasizes its effectiveness in capturing this variability. However, it is important to recognize that SSH PC2 alone does not reveal the physical processes driving these pathway shifts, such as changes in the NAC position or the redistribution of transport between the Rockall Trough and the Iceland Basin. At this stage, we cannot confidently attribute shifting pathways and transport changes to variations in subpolar gyre strength, including its expansion or contraction, and we caution against such an interpretation despite its suggestion in previous studies (see Chafik and Lozier (2025), van der Molen and Pätsch (2022), and references therein). With this in mind, we propose that observations of overturning in the SPNA, such as those provided by OSNAP (Lozier *et al.*, 2019), may be invaluable not only for predicting Atlantic Water pathways and the associated North Sea conditions several years in advance but also for gaining insights into the processes that initiate and sustain the chain of events described above.

A particular aspect not yet discussed in relation to the transport anomalies shown in Figure 4 is the actual number of particles north and south of the crosses at the three sections and how they vary with time. While the 14°W section indicates that the Rockall Trough dominates in terms of the total number of particles in a time-mean sense (Figure 1c), this is not the case at the other sections. Notably, at both the central (24°W) and westernmost(32°W) sections, the number of particles north and south of the crosses (cf. Figure 1c) are anticorrelated over time. This observation not only highlights the north-south shifts of the NAC but also indicates that, away from the Rockall Trough, the relative contributions from the two basins along the NAC pathways vary temporally. This implies that the dominance of the Rockall Trough in a time-mean sense at 14°W may result from leakage of water across the Rockall Plateau into the Rockall Trough, which in turn influences the particle distribution and the observed transport patterns.

NAC shifts are crucial in determining which routes water will take to reach the North Sea. It is therefore imperative that the structure of the NAC pathway is accurately represented in climate models, which is a well-known challenge (see, e.g., Jackson *et al.* (2023)). Studies have shown that only high-resolution models are capable of adequately representing the spatial structure of the NAC (e.g., Marzocchi *et al.* (2015)). Equally important is the accurate representation of the boundary currents, specifically in the region near the Grand Banks (Talandier *et al.*, 2014), which is key in the interaction and the connectivity between the subpolar region and subtropics (Buckley and Marshall, 2016). This interaction is critical for driving upper limb transport anomalies and the associated supply of heat and salt into the eastern SPNA and the North Sea.

DATA ACCESSIBILITY STATEMENT

The TRACMASS code is available via GitHub at the following link: https://github.com/TRACMASS/tracmass. The satellite altimetry data are available from the Copernicus Marine Environment Monitoring Service (CMEMS) and accessed in the following link: https://data.marine.copernicus.eu/product/SEALEVEL_GLO_PHY_L4_MY_008_047/description. The EN4 data of the metoffice were obtained from https://www.metoffice.gov.uk/hadobs/en4/download-en4-2-1.html.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

Conceptualization and methodology: All authors. Formal analysis: Ezra Eisbrenner. Writing of the original draft: Léon Chafik with input from Ezra Eisbrenner and Kristofer Döös.

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