



Assessment of the seasonal cycle in Atlantic density flux

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Abstract. An analysis of the seasonal/sub-seasonal cycles of density flux is now possible thanks to advances in satellite oceanography. The kinematic density flux framework, developed to infer the buoyancy-driven ocean circulation using high-resolution satellite datasets, was applied at 1/4° resolution to monthly maps of satellite-derived Sea Surface Salinity, Temperature, and Currents (SSS, SST and SSC) over 2011-2020. Combining them with a blended satellite/in-situ Mixed Layer Depth (MLD) dataset, we derived density flux estimates throughout the Atlantic. We also performed a harmonic analysis to the density flux estimates, to diagnose the contribution of thermal and haline processes to density flux. We find that the subtropics and mid-latitude annual cycle explains 70-80% of the variability in net density flux. With the addition of a semi-annual cycle, the explained variance reaches 80-85%, suggesting density flux is sensitive to other atmospheric/oceanic processes with higher/lower temporal frequencies. Haline processes dominate density flux variability in the Denmark Strait, and parts of the Labrador and Norwegian Seas—all crucial areas for the Atlantic Meridional Overturning Circulation. The subpolar North Atlantic density flux is primarily governed by haline variability, with freshwater forcing driving most monthly extremes and exhibiting a quasi-symmetric pattern of alternating positive and negative events. Anomalous thermal contributions and localized salinification in December 2020 mark a striking departure from prior years, raising the question of whether this signals a regime shift or a singular event.

1 Introduction

Surface density flux is a fundamental driver of oceanic buoyancy exchange, governing the formation and transformation of water masses that shape large-scale circulation patterns (Groeskamp et al., 2019). Density flux refers to mass changes over a volume of the ocean (such as the mixed layer). The water mass transformation results from density flux integrated over outcropping isopycnals, and thus represents a volume transport through specific density surfaces (Speer and Tziperman, 1992). The convergence of water mass transformation between isopycnals results in a ventilation of the ocean below the mixed layer (ML)—this process is termed the water mass formation. This, in turn, directly affects the strength and stability of key ocean circulation systems, including the Atlantic Meridional Overturning Circulation (AMOC) (Estrella-Perez et al., 2020; Weijer et al., 2019; Li et al., 2021; Fu et al., 2023). Therefore, accurate surface density flux estimates, now achievable through high-resolution satellite observations, can provide valuable insight into the processes of water mass transformation and formation.

Traditional thermodynamic methods estimate surface density flux using direct air-sea flux measurements, requiring accurate estimates of heat and freshwater fluxes (Speer and Tziperman, 1992; Tziperman, 1986; Walin, 1982). However, these estimates



are often subject to uncertainties due to sparse in situ observations, biases in reanalysis datasets and coarse spatial resolutions (Cerovečki et al., 2011-12; Brunke et al., 2011), which limit their ability to capture mesoscale and sub-mesoscale processes. Additionally, thermodynamic approaches do not account for lateral mixing within ML (Speer and Tziperman, 1992), which can cause discrepancies between expected and observed rates of water mass formation (Iudicone et al. (2008); Marshall and Schott (1999)).

Marshall et al. (1999) and Iudicone et al. (2008) developed methods to diagnose water mass evolution via the kinematics of density. Specifically, by incorporating local density changes and advection rather than relying on direct flux estimates, this approach resolves the contributions of air-sea interactions, the effects of lateral mixing and ML variability on ML density change. However, the full capabilities of this kinematic approach could only be realised with the widespread availability of high-resolution satellite observations. Within this setting, Piracha et al. (2023) leveraged high-resolution satellite observations of sea surface salinity, temperature and currents (SSS, SST and SSC, respectively) along with ML depth (MLD) estimates to obtain more complete estimates of surface density flux. However, due to the use of sea surface datasets, the authors assumed homogeneous scalar properties over ML, which can result in more intense surface density fluxes, in part, due to the neglect of the depth penetrative effect of short-wave solar radiation (Iudicone et al., 2008; Piracha et al., 2023).

Especially for SSS, inter-comparisons between satellite and in-situ interpolated data products have highlighted a limitation in the latter to fully capture small-scale SSS variability (Yu et al., 2021). This suggests that accurately accounting for the effect of small-scale SSS processes on surface density flux is crucial, especially as freshwater fluxes play an important role in deep water formation in the sub-polar North Atlantic (Doherty et al. (2021)). Furthermore, high-latitude and tropical oceans in particular are found to be particularly sensitive to freshwater fluxes, whose influence has been shown to impact the Atlantic Thermohaline Circulation. Thus, the contribution of SSS to surface density flux would be especially relevant for ocean circulation studies.

To this end, we estimate monthly maps of surface density flux at a $\frac{1}{4}^\circ$ grid resolution over a 10-year period (2011–2020) using satellite observations. We further assess surface density flux seasonality and perform a harmonic decomposition to isolate contributions from annual and semi-annual cycles. In addition, by analysing the spatial and temporal distribution of surface density flux anomalies over the subpolar North Atlantic, we identify regions where density gains/losses are intensifying/weakening, thereby providing insights into the effect of a changing climate on surface density fluxes. These results offer an improved perspective on oceanic buoyancy exchange and its role in modulating large-scale circulation.

The manuscript is structured as follows: Section 2 describes the datasets used in this study. Section 3 details the methodology for the density flux estimation and the harmonic analysis framework. Section 4 presents the main results, while Section 5 discusses their implications for water mass formation and AMOC variability.

2 Datasets

All datasets provide global coverage over ice-free regions and are derived from satellite observations, with the exception of MLD. The datasets are interpolated from their native spatial resolutions to a uniform $\frac{1}{4}^\circ$ grid using a Gaussian inverse-distance weighted interpolation method, as in Piracha et al. (2023). Additionally, all variables are aggregated to a monthly temporal



60 resolution. The study period is defined as 2011–2020 to align with the temporal coverage of the selected SSS product used in this analysis.

2.1 Satellite datasets

The SSS data employed for this study are derived from observations acquired by the European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) mission. Specifically, we employ the Level 4 (L4) SSS product processed by the Barcelona Expert Center (BEC) (Olmedo et al., 2020a). This product is generated using a multi-fractal fusion technique, which integrates
65 $\frac{1}{4}^\circ$ Level 3 (L3) SSS maps (Olmedo et al., 2017) with 0.05° sea surface temperature (SST) maps from the Operational Sea Surface Temperature and Sea-Ice Analysis (OSTIA) system to produce a L4 SSS product at a resolution of 0.05° (Olmedo et al., 2016). The 10-year (2011–2020) temporal series employed in this study is publicly available at <https://bec.icm.csic.es/ocean-global-sss/>.

70 The OSTIA Level 4 SST product, provided by the UK Met Office, is produced using objective analysis techniques applied to a combination of satellite and in situ observations, along with sea ice information from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). These global SST maps are generated daily at a 0.05° spatial resolution (Donlon et al., 2012). The datasets were accessed via the Copernicus Marine Environmental Monitoring Service (CMEMS) (<ftp://nrt.cmems-du.eu>).

75 Sea surface current vector (SSC) data are obtained from the Data Unification and Altimeter Combination System (DUACS), which provides gridded altimetric products. These datasets exhibit root-mean-square (RMS) differences of approximately 15 cm/s when compared to in situ measurements from Atlantic Oceanographic and Meteorological Laboratory (AOML) drifters (Taburet and Pujol, 2018).

2.2 In-situ/Satellite blended dataset

80 The MLD dataset used in this study is obtained from the Multi-Observation Global Ocean ARMOR3D L4 product. MLD is estimated using a density threshold method, which corresponds to the temperature change induced by a 0.2°C cooling from a reference depth of 10 m (Greiner et al., 2021).

The ARMOR3D product employs a two-step approach to blend satellite-based surface observations with in situ measurements (Guinehut et al., 2004):

- 85 1. Linear regression is applied between satellite sea level anomaly (SLA) and SSS/SST to generate synthetic salinity and temperature profiles extending to a depth of 1500 m.
2. Optimal interpolation is then used to merge these satellite-derived profiles with in situ salinity and temperature observations, effectively correcting the large-scale bias in the synthetic fields.



3 Methodology

90 3.1 Kinematic density flux

The kinematic density flux formulation originates from the evolution equation of an oceanic scalar, which describes scalar variability as a result of surface forcing, mesoscale eddy turbulence, advection, and interior oceanic processes such as double diffusion and salt fingering. As outlined in Piracha et al. (2023), the inclusion of MLD introduces an additional term in kinematic density flux, which accounts for vertical entrainment across the ML base as well as the induction of fluid into the ML
95 through interactions between ML spatial gradients and the background horizontal velocity field. The kinematic density flux (f_ρ) can then be expressed as:

$$f_\rho = \frac{D\rho}{Dt} \cdot h = \rho \left(\beta \frac{DS}{Dt} - \alpha \frac{D\theta}{Dt} \right) \cdot h \quad (1)$$

where ρ represents density, and α and β are the thermal expansion and haline contraction coefficients, respectively, which relate temperature and salinity variations to their corresponding effects on density; and h is MLD and t is time. In the following
100 equations, θ and S denote SST and SSS, respectively. To estimate the material derivative, SSC is needed. These consist of an eastward and northward component, as we neglect the vertical velocity which is one-two orders of magnitude smaller.

For practical purposes, we use satellite-based SSS, SST, and SSC, alongside the gridded MLD product, to compute equation 1. Specific details on how to numerically approximate this equation can be found in section 3.2.2 of Piracha et al. (2023).

In this work, we focus on analysing the seasonality of density flux and seek to understand the relative contributions of
105 thermal forcing (f_θ ; equation 2) and haline forcing (f_S ; equation 3) to the net density flux as follows:

$$f_\theta = -\rho\alpha \left(\frac{D\theta}{Dt} \cdot h \right) \quad (2)$$

$$f_S = \rho\beta \left(\frac{DS}{Dt} \cdot h \right) \quad (3)$$

3.2 Anomalies

We calculate monthly anomalies of density fluxes over the subpolar North Atlantic, defined as the region spanning from 40°N
110 to 70°N and from 70°W to 30°E. To compute these anomalies, we subtract the 10-year average density flux from each month's observed value. The 10-year average, $\overline{f_{2011-2020}}$, is computed from the mean of the monthly density flux maps over the period 2011-2020 for the month in question (e.g. 10 maps for January corresponding to the 10 year January average). The anomaly for each month is then determined by the following equation:

$$f(m)_{\text{anom}} = f(m) - \overline{f_{2011-2020}(m \bmod 12)}, \quad \forall m \in \{1, \dots, 120\}, \quad f(m) \quad (4)$$



115 Where:

1. $f(m)$ represents the observed density flux for month m of the 120 months considered in this study,
2. $\overline{f_{2011-2020}}(m \bmod 12)$ is the 10-year mean density flux for the corresponding month of the calendar year (notice that $m \bmod 12$ is between 1 and 12),
3. $f(m)_{\text{anom}}$ is the resulting anomaly for each month.

120 This approach allows us to isolate seasonal and interannual variations in density flux, providing a clearer understanding of the underlying temporal dynamics. We compute the anomalies separately for each month, ensuring that the seasonal cycle is preserved and that variations specific to each month are captured. These monthly anomalies are then analysed to assess spatial and temporal patterns in the subpolar North Atlantic density fluxes.

3.3 Harmonic Analysis

125 To extract seasonal information from the data, we apply a harmonic analysis that involves fitting a cosine function to the temporal series. This analysis includes a 12-month period to capture the annual cycle and a 6-month period for the semi-annual cycle. We use least-squares regression to fit these functions and determine the optimal amplitude and phase values of the periodic function. The amplitude represents the maximum value for either the annual or semi-annual cycle, while the phase indicates the specific time (month) when the maximum of the cycle occurs. The mathematical formulation is therefore:

$$\begin{aligned} y(t) &= \bar{y} + \mathcal{A}_0 \cos(\omega_0 t + \phi_0) + \mathcal{A}_1 \cos(\omega_1 t + \phi_1) \\ \omega_0 &= \frac{2\pi}{12} \\ \omega_1 &= \frac{2\pi}{6} \end{aligned} \tag{5}$$

In this formulation, ω_0 and ω_1 represent the annual and semi-annual frequencies, respectively, while $\mathcal{A}_0$ and $\mathcal{A}_1$ are the annual and semi-annual amplitudes, respectively. The terms ϕ_0 and ϕ_1 correspond to the annual and semi-annual phases, respectively, and $\bar{y}$ denotes the average value of the temporal series $y(t)$.

135 To evaluate the relative contributions of the annual and semi-annual frequencies to the overall data, we follow the methodology outlined in Yu et al. (2021), where an R^2 statistics is used to quantify the proportion of variance explained by each frequency.

$$R^2 = \left(1 - \frac{\sigma^2(s(t) - y_i(t))}{\sigma^2(s(t))} \right) \tag{6}$$

140 Here, $s(t)$ represents the temporal series (such as SSS, SST, density flux, and its thermal and haline components in our study), and σ is the standard deviation operator. The term $y_i(t)$ refers to either the annual or semi-annual mode derived from the harmonic analysis.



4 Results

4.1 Annual and seasonal averages

The 2011–2020 mean and seasonal averages of the density flux driving dense water formation in the Atlantic Ocean are shown, respectively in Figures 1 and 2. These fields are decomposed into net, thermal, and haline contributions. Their spatial
145 distributions reflect key oceanographic processes, including air-sea fluxes, freshwater input from rivers, and interactions with mesoscale dynamics, ML variability, and sea-ice formation/melting.

The overall density flux pattern in Figure 1a shows strong positive density flux at mid-to-high latitudes, with buoyancy gain in the tropics. The subtropical gyres exhibit widespread positive density fluxes, particularly in the North Atlantic, reflecting dominant cooling-driven densification over the subtropical gyres (Figure 1b). This imbalance towards densification over the
150 subtropical gyres is the main formation mechanism of mode waters McCartney (1977, 1982); Hanawa and Talley (2001). In contrast, the subpolar North Atlantic and Southern Ocean display significant haline-driven dense water formation, pointing to the impact of salinity variations from sea-ice processes and the import/export of freshwater from the Arctic (Figure 1c).

In the subtropical gyres, the dominant control on density flux is surface heat loss, particularly in the North Atlantic, shown as strong thermally driven densification (Figure 1b). These areas correspond to regions of strong latent and sensible heat loss
155 associated with air-sea interactions during winter, especially along the Gulf Stream (Figure 2a, b).

The subpolar North Atlantic exhibits a striking contrast, where haline-driven processes dominate net density flux (Figure 1c). The Labrador Sea and areas influenced by the East Greenland Current display significant haline contributions to density flux. This reflects freshwater import from the Arctic, possibly via the Fram strait and subsequent transport via the East Greenland Current. The Beaufort gyre and freshwater export via the Davis strait may also play a lesser role on the haline density flux
160 dominance in the Labrador sea. This is consistent with observations of stronger haline contribution to density flux in the Greenland and Labrador seas (Figure 1c)—especially visible during winter and autumn (figure 2c, l).

A similar pattern emerges in the Southern Ocean, where haline processes dominate south of the Sub-Antarctic Front, likely due to the formation/melting of sea-ice. The thermal contribution is less significant here, but strong wind-driven upwelling also influences density flux via freshwater dynamics, particularly along the Antarctic Circumpolar Current (ACC) (Figure 1c).
165 This signal can be further shown as thermally driven densification (i.e. cooling) along with haline driven density losses (i.e. freshening) in Spring (Figure 2e, f) and the opposite in autumn (Figure 2k, l).

Tropical and equatorial regions exhibit mean negative density flux (Figure 1a), reflecting strong precipitation and riverine freshwater input. The Amazon and Congo River outflows contribute significant freshwater to the equatorial Atlantic, leading to strong buoyancy forcings that reduces density flux (Figure 1c). This pattern is evident in all seasonal panels (Figure 2, right-
170 most column) but is strongest in spring (Figure 2f), when precipitation and runoff reach their peak. Equatorial currents and countercurrents further distribute freshwater laterally, due to the interplay between precipitation, evaporation and atmospheric heat transport via Intertropical Convergence Zone (ITCZ) dynamics. This is seen best in Figure (Figure 2, right-most column), showing seasonal changes of haline-driven density flux (equatorial dynamics here are governed by the dynamics of the ITCZ,



the riverine freshwater input and the subsequent advection via the equatorial currents and countercurrents). All in all, leading to haline processes being the dominant control on tropical and equatorial density flux dynamics.

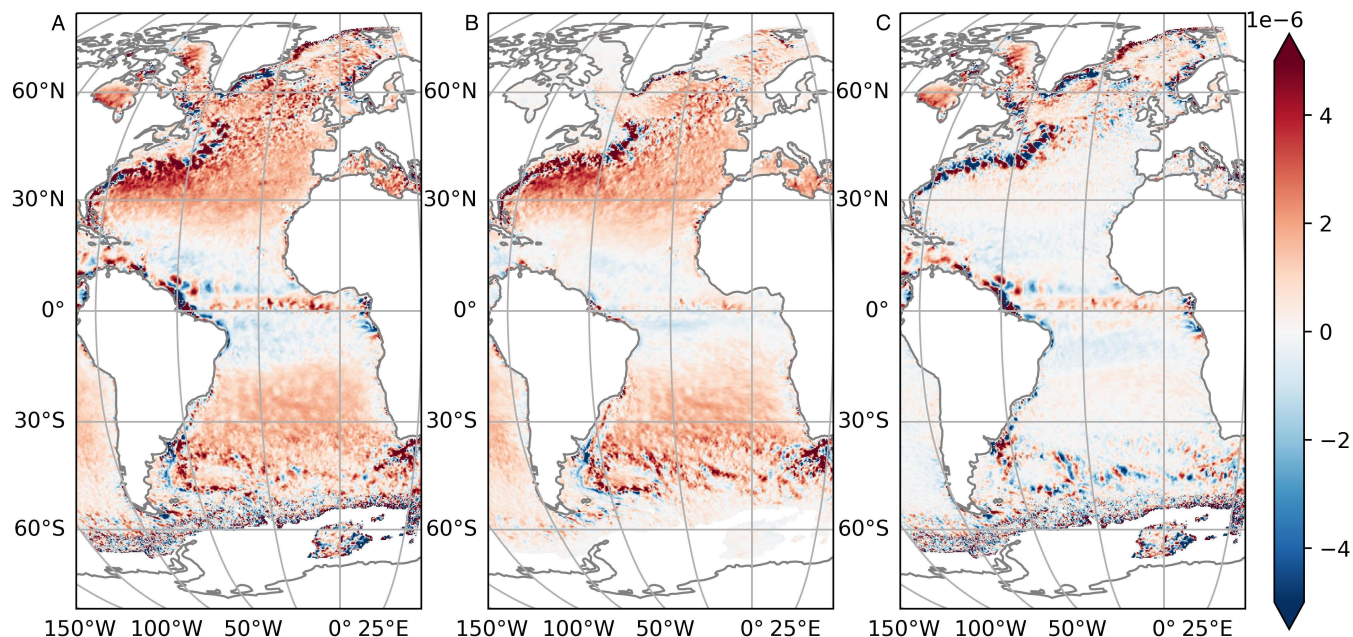


Figure 1. 2011-2020 averages of net (A), thermal (B) and haline (C) components of the density flux. The units are $\text{kg m}^{-2} \text{s}^{-1}$

4.2 Annual cycle

The spatial distribution of the annual harmonic amplitude of density flux (Figure 3a) is shaped by air-sea interaction processes and ocean circulation dynamics, which determine the strength of seasonal density changes. The highest amplitudes are observed in the Gulf Stream and North Atlantic Current systems, where strong winter heat loss leads to significant buoyancy removal, followed by summer re-stratification. The phase distribution (Figure 3d) in these regions indicates that the maximum density flux occurs in boreal autumn, coinciding with the period of strongest surface cooling and evaporation, as well as the associated rapid deepening of ML. In contrast, the South Atlantic generally exhibits weaker annual variability, with more pronounced signals in the western boundary currents and subtropical gyre, where seasonal variations in convection modulate the density flux. The equatorial Atlantic has low total density flux amplitudes, yet it still displays a seasonal cycle controlled by the migration of the ITCZ.

The amplitude of the annual harmonic of the thermal component (Figure 3b) closely mirrors that of the total density flux structure (Figure 3a) in the mid-latitudes and subtropical regions, where the rapid cooling from the end of autumn dominates the seasonal cycle. The strongest thermal amplitudes are found in the Gulf Stream extension, North Atlantic Current, and subtropical gyres, where intense autumn/winter cooling drives large seasonal density changes. The South Atlantic exhibits a



190 similar thermal pattern, with high-amplitude signals concentrated in the western boundary currents (e.g., the Brazil Current) and in regions where evaporation exceeds precipitation.

In the subpolar gyre, the amplitude of the haline component of the annual harmonic (Figure 3c) is extremely weak. This contrasts with mid-latitude and subtropical regions, where the thermal component drives strong seasonal density fluxes. The total density flux in the subpolar gyre also exhibits a weak annual harmonic amplitude (Figure 3a), further confirming that
195 while salinity is the primary driver of seasonal density changes in this region, its effect is spread over timescales other than the annual cycle. This weak haline seasonality is linked to the complex interplay of freshwater processes, including seasonal ice melt, precipitation, and advection of fresher waters from the Arctic, which introduce variability that is not necessarily synchronized with a strong annual periodicity.

The phase of the haline component (Figure 3f) is more spatially variable than that of the thermal component, particularly
200 in the subpolar North Atlantic, where freshwater fluxes from precipitation, ice melt, and Arctic inflows modulate the seasonal density cycle. Unlike the thermal-driven seasonal cycle, which follows a smooth winter peak, the haline phase structure is more erratic, reflecting the irregular timing of freshwater input and redistribution. Notably, in the subpolar gyre, the haline-driven density flux reaches its seasonal peak before significant wintertime convection begins, suggesting that low-frequency salinity variations play a preconditioning role in deep water formation, rather than exhibiting a strong annual cycle like the thermal
205 component.

We chose not to present the semi-annual harmonic of the density flux cycle independently, as its standalone amplitude and contribution to overall variance were comparatively small and exhibited high spatial and seasonal variability. Instead, we focused on showing the variance explained by the annual harmonic and by the combination of both annual and semi-annual harmonics. This approach allows us to highlight the dominant temporal scale of variability while still capturing the aggregate
210 influence of shorter-period fluctuations, thereby providing a clearer and more concise representation of the primary forcing patterns in surface density flux dynamics.

4.3 Explained variance by the annual and semi-annual cycles

The explained variance of the annual and semi-annual harmonics offers a quantitative measure of how much of the total density flux variability is captured by dominant seasonal modes. Across much of the Atlantic, these two harmonics account
215 for approximately 80% of the variance, particularly in the subtropics, where seasonal heat loss primarily drives water mass transformation. These high explained variances are observed in the western boundary currents and the subtropical gyre (80%), both dominated by thermal processes (Figure 1), which themselves show a pronounced seasonal cycle in the subtropics (Figure 2).

In contrast, the subpolar Atlantic displays low explained variance in total density flux variability (Figure 5a), where the
220 annual and semi-annual harmonics together account for less than 10% of the total variance. This differs from the thermal component, where seasonal harmonics explain 20–80% of its variability (Figure 5b). The haline component, however, exhibits similarly low explained variance, via these two seasonal harmonics, to the total density flux in the subpolar Atlantic (Figure 5a), indicating that this region is more sensitive to haline variability than to seasonal thermal changes.



This breakdown between thermal and haline contributions reinforces the dominant role of heat fluxes in shaping the seasonal cycle of density flux across most of the Atlantic basin. In particular, the thermal component accounts for the majority of variance in regions experiencing strong wintertime cooling (Figure 2). However, in the subpolar Atlantic, the haline component plays a disproportionately large role—evident in the weak seasonality of total density flux—highlighting the importance of freshwater forcing in this region. Similar haline dominance is observed in localized regions such as the ITCZ, major river outflows, and areas with strong evaporation–precipitation gradients, where seasonal freshwater anomalies significantly impact density flux.

4.4 Extreme events in density flux

The time series of thermal, haline, and net density flux anomalies (Figure 5) reveals a persistent dominance of haline-driven variability across the subpolar North Atlantic, indicating that salinity variations play a primary role in modulating ocean buoyancy fluxes in the region. In contrast, thermal anomalies exhibit a more subdued role, suggesting that temperature fluctuations contribute less significantly to density flux variability in the colder subpolar latitudes, where seasonal and interannual temperature ranges are relatively constrained.

Unlike previous years, where thermal anomalies remained relatively weak or counteracted haline signals, December 2020 exhibits an atypical scenario in which thermal flux anomalies contribute strongly to anomalous density flux events. This shift is particularly striking given that throughout much of the record, haline variability dominated the density flux signal.

The time series of density flux anomalies reveals an intriguing pattern of variability, with significant positive and negative events occurring at comparable frequencies. By applying a threshold of $\pm 2.5 \times 10^{-6} \text{ kg, m}^{-2}, \text{ s}^{-1}$, it is observed that nearly every positive anomaly exceeding this magnitude has a corresponding negative anomaly of nearly equal strength, either preceding or following it. This alternating pattern suggests a quasi-symmetric oscillation in the subpolar density flux anomalies that may not have been fully appreciated in previous studies.

4.4.1 Spatial Patterns

The spatial distributions of the December density flux anomalies from 2017 to 2020 (figure 6) highlight the evolving dominance of haline forcing across the subpolar gyre, with a notable shift in 2020. In previous years, negative haline anomalies—indicative of freshening—were widespread across the gyre, acting as the primary driver of density flux variability. This pattern continued in 2020, where most of the subpolar gyre remains dominated by strong negative haline-driven anomalies, reinforcing the persistent influence of anomalous freshwater forcing over the region.

However, a key departure from previous years is observed in December 2020. While broad freshening continues over the subpolar gyre, positive haline anomalies (salinification) emerge and strengthen around key deep water formation sites, including the East Greenland Sea, the Iceland-Scotland Ridge, and the Labrador Sea. This positive anomaly in salinity is particularly notable compared to prior years, where these regions primarily exhibited negative haline-driven anomalies.



5 Summary and Conclusions

255 This study highlights the critical role of freshwater dynamics in modulating the North Atlantic density flux. The observed sensitivity of density flux to freshwater perturbations suggests a potential weakening mechanism in high-latitude regions crucial for deep water formation. The findings align with previous studies indicating that North Atlantic salinity anomalies —driven by riverine input, precipitation, and Arctic outflows— precondition deep water formation sites, thereby reducing convection and slowing the AMOC (Johnson et al., 2019; Stommel, 1961).

260 In contrast to annual and semi-annual cycles, which together do not explain the total variability in Atlantic surface density flux, large-scale ocean circulation in the Atlantic has been shown to be sensitive to multi-decadal climatic oscillations such as the Atlantic Multidecadal Oscillation (Dima et al., 2022). This suggests that low frequency modes of variability are crucial in understanding the total surface density flux variability.

The use of satellite-derived density flux measurements represents a significant advancement in oceanographic studies, and
265 a fresh perspective on ocean circulation. Traditionally, water mass transformation and overturning circulation have relied on in-situ hydrographic measurements or numerical models, both of which have spatial and temporal limitations. By leveraging satellite-based observations, this study provides an unprecedented view of surface buoyancy fluxes and their drivers, acting as a stepping stone towards understanding variability in large-scale ocean circulation.

As density flux is a key variable in estimating water mass formation, this study lays the foundation for satellite-based
270 monitoring of global water mass evolution. The continuous monitoring of density variations and surface buoyancy changes via satellites could improve climate prediction models and pave the way for a dedicated satellite observing system aimed at tracking global water masses.

The findings also emphasize the critical role of freshwater variability in density flux anomalies and reinforces the need for improved salinity observations in regions like the Southern Ocean, where satellite-derived SSS products are currently limited.
275 The development of Southern Ocean-specific SSS products will be crucial for improving global assessments of freshwater-driven variability (González Gambau et al., 2023).

Further, the study emphasizes the need for integrating numerical models with satellite observations to resolve the underlying mechanisms governing density flux variability. By coupling ocean-atmosphere models with satellite-derived density fluxes, future studies could develop powerful tools for understanding the response of the oceans under a warming climate.

280 In conclusion, this study provides the first satellite-based assessment of Atlantic density flux variability, showing the sensitivity to freshwater dynamics in the subpolar North Atlantic, and the potential to monitor long-term water mass evolution. This work could inform the design of an observing system dedicated to tracking global ocean circulation from the perspective of water masses.

As part of the ongoing Arctic-Flow project (www.arctic-flow.net), we aim to deliver high-resolution, satellite-constrained
285 estimates of surface density fluxes across the Nordic Seas, a critical region for deep water formation and the Atlantic Meridional Overturning Circulation (AMOC). Our approach leverages rigorously screened and dynamically consistent input datasets—including sea surface temperature, salinity, and velocity fields—to compute kinematic density fluxes with unprecedented accuracy. The



resulting products will be validated against in situ observations from the Nordic Seas, providing a physically robust benchmark to assess and track seasonal and interannual changes in water mass transformation. The analyses and findings presented here
290 advance the Arctic-Flow project's broader goal of constraining the role of Arctic and subpolar processes in modulating the AMOC strength and long-term stability.

Appendix A

A1 Calculation of uncertainties

The diagnosed variability in surface density flux is found to be significant relative to the uncertainties inherent in the input
295 satellite products. To support this conclusion, we quantified the uncertainties associated with the key surface variables used in the analysis, allowing us to evaluate the signal-to-noise ratio across both space and time.

Uncertainties in OSTIA sea surface temperature (SST) are represented as analysis errors, derived by comparing the main SST field with a parallel product that isolates the contribution of observational measurements. (McLaren et al., 2019) found that the standard deviation between drifter buoys and OSTIA SSTs was 0.35, whilst against Argo it was 0.4. Despite the dependence
300 between drifter boy and Argo datasets, the validation against the two agree over the period 2003-2019. The two fields—satellite-derived SST and observational-only SST are then combined to obtain a grid-point-level error estimate (McLaren et al., 2019).

Uncertainty in sea surface salinity (SSS) was quantified using the triple collocation method, which jointly compares three independent SSS datasets (typically including satellite observations, in situ measurements, and model-derived estimates) to
305 isolate and calibrate their individual errors. This technique enables the estimation of spatially resolved uncertainties consistent with the scales accessible by satellite products (Olmedo et al., 2020b; González-Gambau et al., 2020).

As SSS and SST are originally provided at a spatial resolution of $1/20^\circ$ and at daily temporal frequency, their uncertainties were adjusted to match the $1/4^\circ$ and monthly scale of the analysis. This was achieved by dividing the uncertainty fields by a factor of 5 for the spatial upscaling and by the square root of the number of days in each month for the temporal averaging.
310 Uncertainties in sea surface current (SSC) and mixed layer depth (MLD) were not included in this estimate, allowing the analysis to isolate the impact of SST and SSS uncertainties on surface density fluxes. Final uncertainty values were normalized relative to the annual harmonic amplitude of each variable to provide a scale-aware assessment of signal significance (Fig. A1).



315 *Data availability.* Daily level 4 SMOS Sea Surface Salinity data is available from the BEC ftp server (becftp.icm.csic.es) at a $\frac{1}{20}^{\circ}$ resolution with global coverage in ice-free regions (Olmedo et al., 2020a).

Daily level 4 OSTIA Sea Surface Temperature data is available from the ftp servers of the Copernicus Marine Environmental Monitoring Service (CMEMS; ftp://nrt.cmems-du.eu) at a $\frac{1}{20}^{\circ}$ resolution with global coverage in ice-free region (M. Worsfold and Martin, 2020).

320 Monthly Sea Surface Current data is available from the ftp servers of the Copernicus Marine Environmental Monitoring Service (CMEMS; ftp://nrt.cmems-du.eu) at $\frac{1}{4}^{\circ}$ resolution with global coverage in ice-free region (Marie-Isabelle Pujol and team, 2023).

Monthly in-situ/satellite blended MLD data is available from the ftp servers of the Copernicus Marine Environmental Monitoring Service (CMEMS; ftp://nrt.cmems-du.eu) at $\frac{1}{4}^{\circ}$ with global coverage in ice-free region.

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325 conducted the experiments. M. Portabella and E. Olmedo provided constant discussions and gave crucial help in analysing and interpreting the results. A. Turiel supervised the study and reviewed the final manuscript.

Competing interests. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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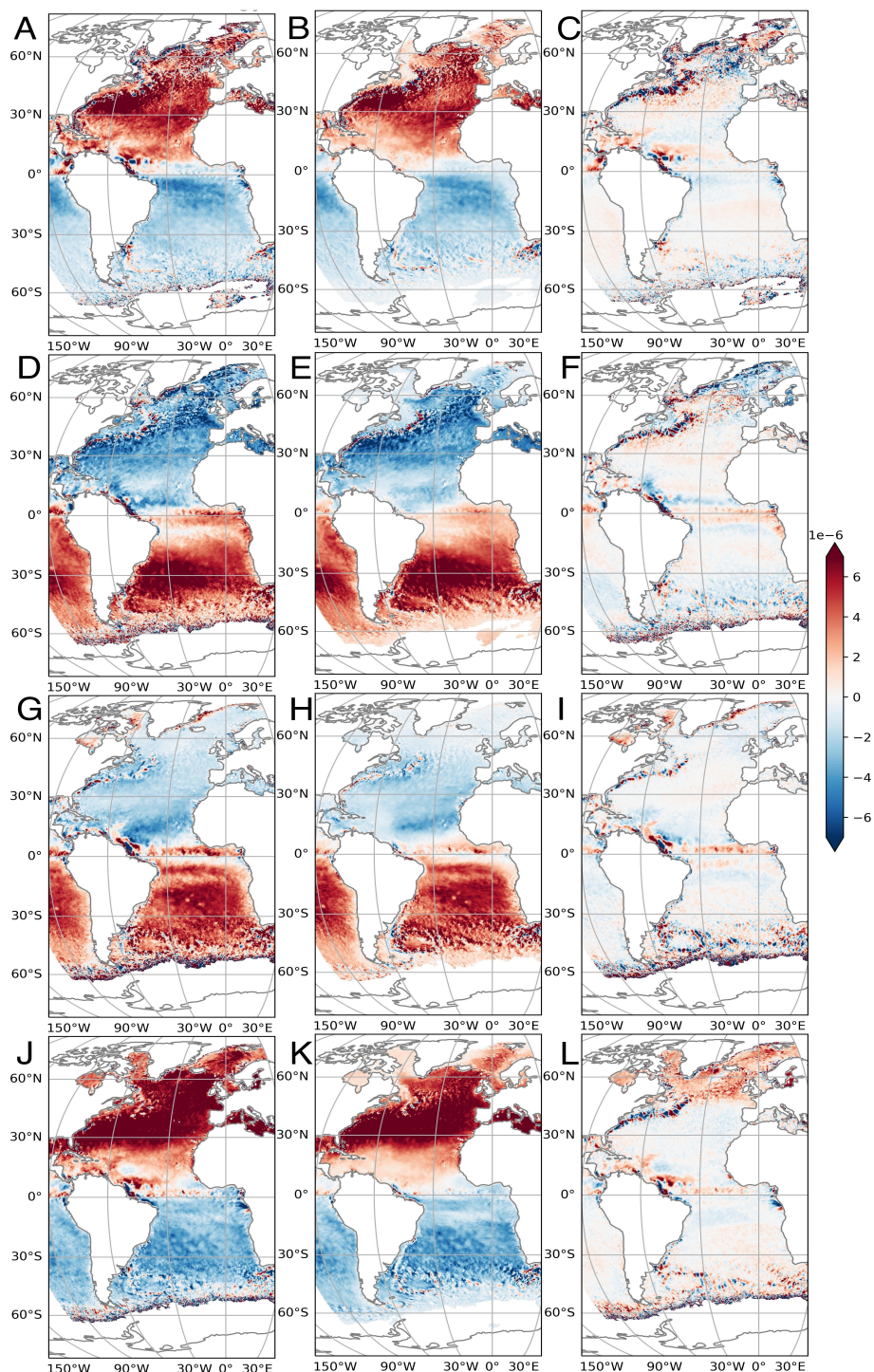


Figure 2. 2011-2020 averages of DJF (first row), MAM (second row), JJA (third row), SON (bottom row) net (left column), thermal (middle column) and haline (right column) components of the density flux. The units are $kgm^{-2}s^{-1}$

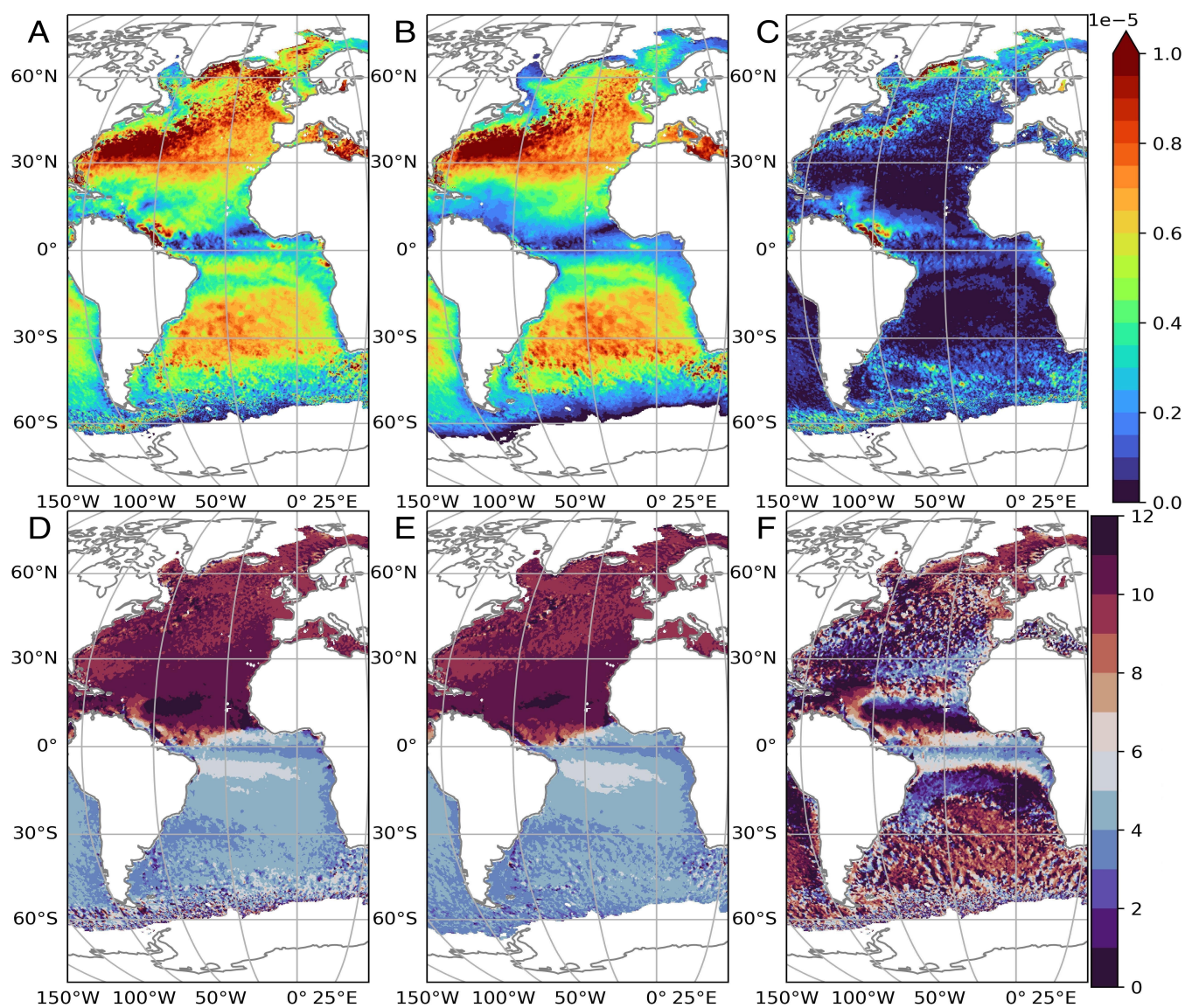


Figure 3. The annual harmonic amplitude (top row) and phase (bottom row) for density flux (left column), and its thermal (middle column) and haline (right column) components. The units for the top and bottom rows are $\text{kg m}^{-2} \text{s}^{-1}$ and months, respectively.

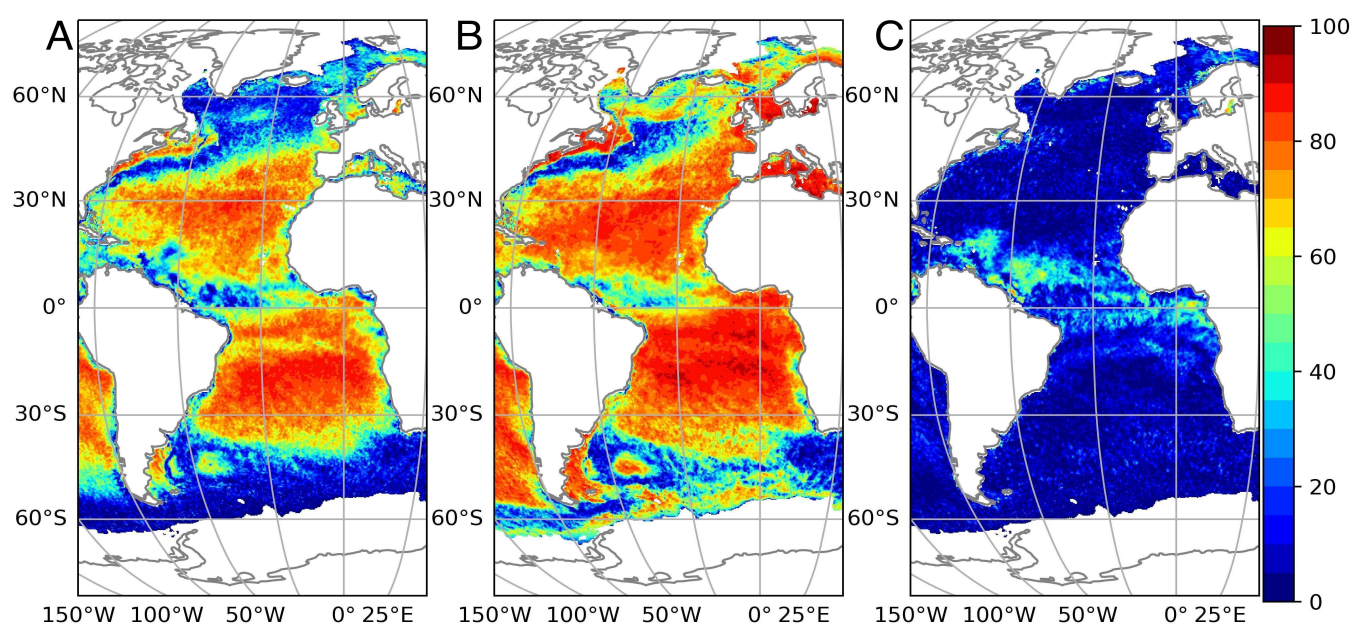


Figure 4. The variance in density flux (a), and its thermal (b) and haline (c) components explained by both the annual and semi-annual harmonics (expressed as a percentage).

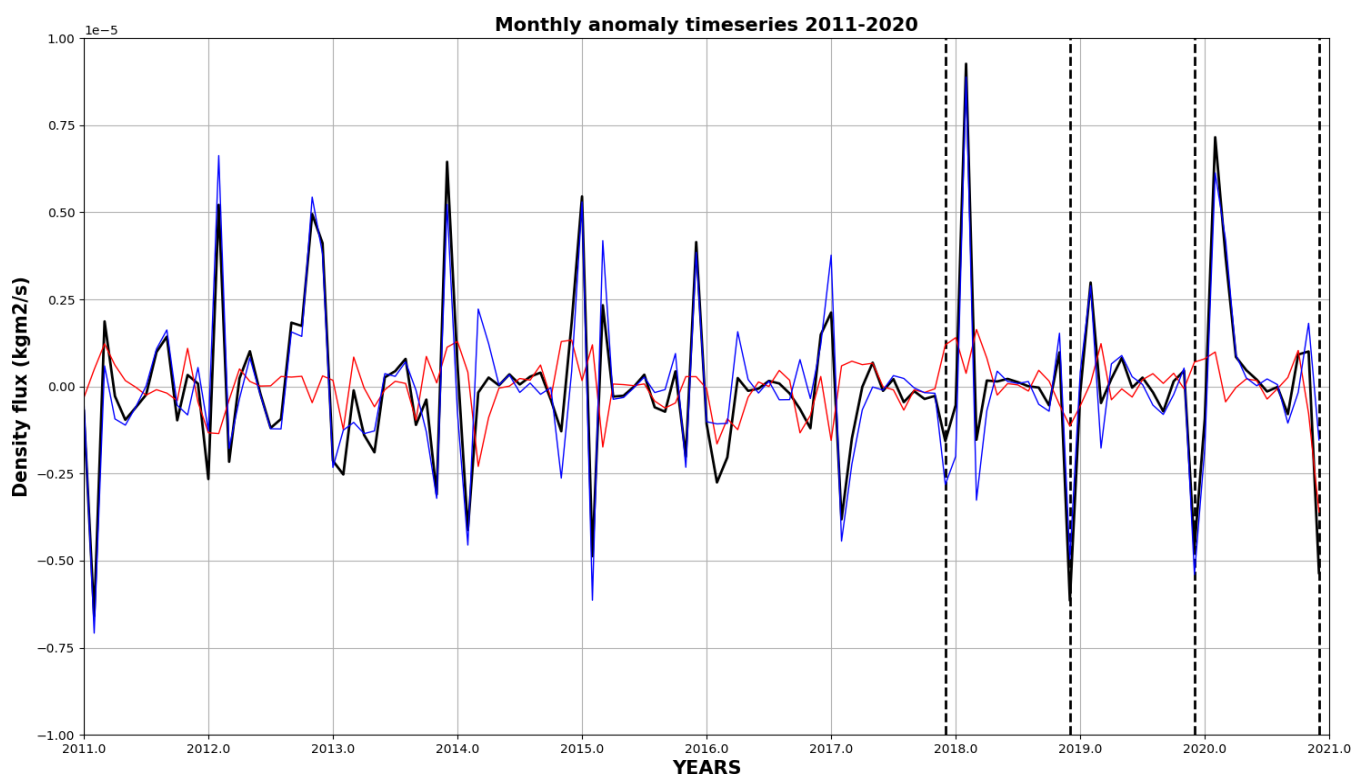


Figure 5. Time series of monthly anomalies in density flux relative to the 2011-2020 mean averaged over the sub-polar gyre, divided into net (Thick solid black line), thermal (thin solid red line) and haline (thin solid blue line) components. The four black dashed lines represent the anomalies of the last four Decembers (2017-18-19-20) comprising significant lightning events in density flux.

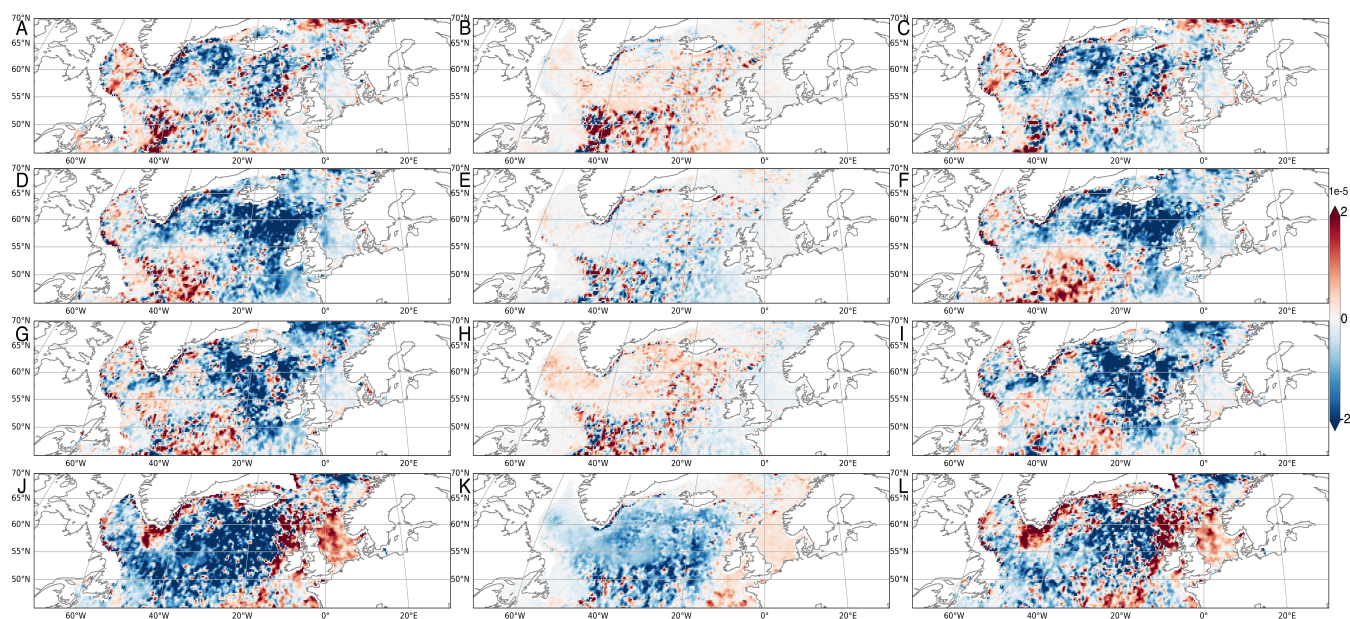


Figure 6. spatial patterns of the monthly anomalies marked by the four black dashed lines in figure 5. Those anomalies are mapped along the rows (top-down: 2017-18-19-20). We subsequently divide density flux contributions into thermal and haline components (the columns from left to right, respectively).

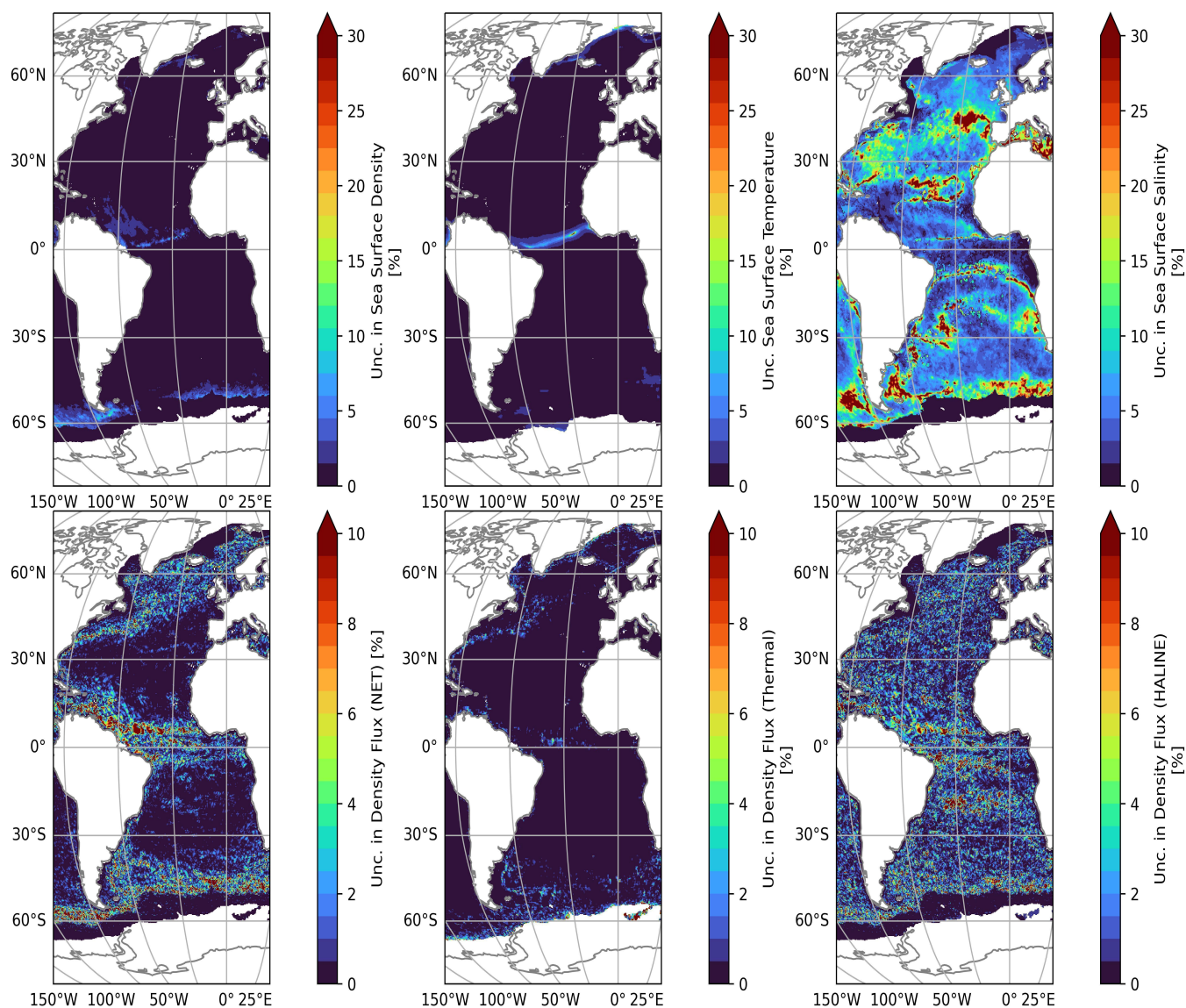


Fig. A1. Uncertainty in Sea Surface Density (a), Temperature (b) and Salinity (c) along with net (d), thermal (e) and haline (f) components of the density flux expressed as a percentage of their respective annual cycles as calculated using a harmonic analysis.