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Causes for Atlantic Freshwater Content Variability in the GECCO3 Ocean Synthesis

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Key Points:

- The net freshwater transport across the meridional boundaries dominates the freshwater content variations in mid and high latitudes
- The importance of surface freshwater flux variations increases toward the tropics and on multi-decadal time scales
- Subpolar changes are mainly gyre driven, while overturning and especially the shallow overturning cells contribute more at lower latitudes

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Abstract Regional freshwater content (FWC) changes are studied over the period 1961–2018 using the GECCO3 ocean synthesis. In four dynamically distinct regions of the Atlantic, the study identifies causes for FWC variability with a focus on interannual and decadal time-scale changes. Results show that in each region, it is a combination of the surface freshwater flux and the net freshwater transport across the region's boundaries that act jointly in changing the respective FWC. Surface flux mainly contributes to the FWC variability on multi-decadal time scales. The impact of surface flux also increases toward the tropics. On shorter time scales, it is especially horizontal transport fluctuations, leading to FWC changes in mid and high latitudes. Going from north to the south, the transport across a single meridional boundary becomes less correlated with the FWC changes but the net transport across both boundaries plays an increasingly important role. Moreover, the subpolar box is mainly gyre driven, which differs from the other two, essentially overturning driven, North Atlantic boxes. In the tropical Atlantic, the shallow overturning cell and the deep overturning contribute about equal amounts to the freshwater variations.

Plain Language Summary Causes for freshwater content (FWC) variability in the Atlantic Ocean are analyzed for four study areas over the period 1961–2018 based on a model simulation (GECCO3 ocean synthesis). Targeting relatively long time scales, interannual, decadal to multi-decadal FWC changes are separated into the contributions from variations of the freshwater input/output through the ocean surface and from freshwater transport (FWT) variations related to the ocean circulation changes. Surface freshwater flux is more influential on multi-decadal time scales, and its impact increases toward the tropics. On shorter time scales, the oceanic FWT across the boundaries of the region dominates the FWC changes in mid and high latitudes. The transport variability in the subpolar region is mainly driven by the horizontal circulation, while transports resulting from vertical salinity differences are more important at lower latitudes. Moreover, in the tropics transports related to shallow salinity differences are not negligible on interannual time scales.

1. Introduction

Associated with changes in the global water cycle are variations of the freshwater content (FWC) in the ocean (e.g., Schmitt, 2008). Particularly in the Atlantic Ocean and the Arctic, associated salinity changes are of great importance for driving fluctuations in ocean dynamics as well as for climate variability and change (Häkkinen & Proshutinsky, 2004; Jahn et al., 2010; Köberle & Gerdes, 2007; Köhl & Serra, 2014). As an example, the large freshwater export from the Arctic through the passages of the Canadian Arctic Archipelago enters the North Atlantic, changes the seawater density and thereby plays a role in the large-scale thermohaline circulation (Dickson et al., 2002). With a coarse resolution ocean model Rahmstorf (1996) demonstrated that an important contributor to the Atlantic meridional overturning circulation (AMOC) stability is the salinity balance among the surface freshwater flux, the freshwater transport (FWT) by the overturning circulation and the freshwater import by the gyre circulation in the South Atlantic. Moreover, long-term salinity variations also act as important contributors to regional sea level changes in the Atlantic, where halosteric sea level changes strongly compensate thermosteric changes (Antonov et al., 2002; Durack et al., 2014; Levitus et al., 2005). In the Arctic they actually drive multi-decadal to centennial sea level changes (Carson et al., 2015; Pardaens et al., 2011).

Geographically varying ocean salinity has long been considered as a result of a long-term balance between surface freshwater flux and ocean processes (Schmitt, 2008; Talley, 2002). Sea surface salinity (SSS) has been suggested to act as a rain gauge as well as an indicator of the global water cycle since it seems to be indicative of changes in surface freshwater flux (Lagerloef et al., 2010; Schmitt, 2008; Terray et al., 2012). Recent studies have confirmed that the link between the distributions of SSS and surface freshwater flux is region-dependent as well as timescale-dependent, highlighting the importance of the role of upper ocean dynamics (Qu et al., 2011; Vinogradova & Ponte, 2013; Yu, 2011). Large-scale climate modes such as the Atlantic Multidecadal Oscillation and the North Atlantic Oscillation (NAO) have been found to have pronounced effect on the SSS in the Atlantic (Friedman et al., 2017).

In contrast, details of subsurface salinity variations at mid and low latitudes in the Atlantic are less documented, and related change mechanisms are less known. A few existing studies reveal that large-scale and coherent long-term salinity changes in the Atlantic, particularly a deep freshening in the subpolar regions as well as a shallower and stronger increase in salinity at lower latitudes (Boyer et al., 2005; Curry et al., 2003; Durack & Wijffels, 2010; Skliris et al., 2014). This feature was also reported by Boyer et al. (2007) in an analysis of FWC changes in the upper 2,000 m, revealing a decrease over the period 1955–2006 in the North Atlantic as a whole (0°−80°N) with a freshening from late 1960s to early 1990s in the subpolar North Atlantic and Nordic Seas (north of 50°N). Boyer et al. (2007) found that surface freshwater flux is an important contributor to FWC changes especially in the subpolar North Atlantic but not in other regions, implying the importance of ocean processes.

Besides surface freshwater flux, horizontal oceanic FWT convergence is a major factor driving regional FWC changes. Estimates of the Atlantic FWT have been provided based on observations as well as model simulations (Köhl, 2015; McDonagh et al., 2015; Talley, 2008; Valdivieso et al., 2014; Wijffels, 2001). Studies have demonstrated that the freshwater loss in the subtropical South Atlantic is balanced by the freshwater import through the wind-driven subtropical gyre and the fresh water in the high-latitude North Atlantic is transported southward via the flow of North Atlantic Deep Water (Rahmstorf, 1996; Talley, 2008). The southward meridional FWT throughout the Atlantic strengthens under global warming (Skliris et al., 2020). Additionally, the FWT by the overturning circulation has been underscored and suggested as an indicator of the AMOC bi-stability (de Vries and Weber, 2005; Hawkins et al., 2011; Rahmstorf, 1996).

Ocean synthesis data has been recently used to study FWC changes in the North Atlantic. For instance, Jackson et al. (2019) demonstrated that they consistently show more saline conditions over the period 1995–2015 in the upper 500 m of the subtropics and Tesdal and Haine (2020) analyzed changes in FWC within the subpolar North Atlantic Ocean from 1992 to 2015 based on the ECCOv4 reanalysis. They found that the subpolar North Atlantic Ocean has undergone a decade of salinification followed by ongoing freshening, which Robson et al. (2016) have already seen before and attributed to a weakening salt transport associated with variability in the AMOC. Studies have also revealed that the driving mechanism is largely dependent on the region, the study period and the time scales (e.g., Boyer et al., 2007; Tesdal & Haine, 2020), and that ocean synthesis data can be promising tools to improve the understanding of the variability and its driving force for those observation-sparse periods and regions (Jackson et al., 2019). Therefore, in this paper, we focus on the temporal variation of FWT over the longer period of the past nearly 60 years and more importantly its role in changing the FWC in different sub-regions in the Atlantic.

In the following, we analyze variations in Atlantic FWC and transport within the German contribution to the Estimating the Circulation and Climate of the Ocean (GECCO) ocean state estimate. The primary objective is to address the main mechanisms causing the interannual to decadal variations of FWC changes in four regions over the past nearly 60 years.

The structure of the remaining paper is as follows. The model data and the methods will be introduced in Section 2. The results are divided into two parts: Section 3 presents variabilities of FWC and FWT; in Section 4, regional freshwater budgets are discussed regarding the variations of surface freshwater flux and FWT with a focus on detecting the main driving force for the FWC changes. Concluding remarks can be found in Section 5.

2. Data and Methods

2.1. GECCO3

The latest version of the GECCO ocean synthesis, GECCO3, is used to study regional FWC variability in the Atlantic Ocean over the period 1961–2018. Same as the previous versions, GECCO3 is also based on the Massachusetts Institute of Technology general circulation model (Adcroft et al., 2002) but has an increased resolution. GECCO3 is configured with a horizontal resolution of 0.4°, following the higher-resolution version of the earth

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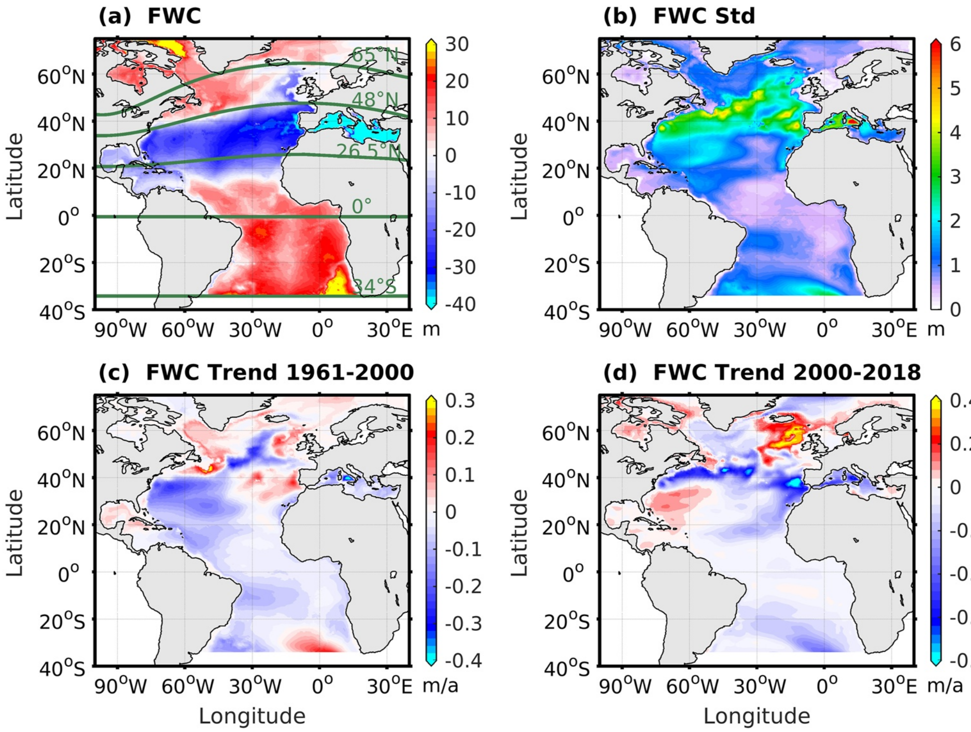

Figure 1. (a) Time mean and (b) standard deviation of the freshwater content (FWC) in the Atlantic. The dark green curves in panel (a) define the boundaries of each box used for calculating the freshwater budget. Linear trends of the FWC (c) before and (d) after 2000.

system model developed at the Max Planck Institute for Meteorology (MPI-ESM) (Jungclaus et al., 2013). It has 40 vertical levels with increasing thicknesses from 12 m in the upper layers to 600 m in the deeper layer expressing full-depth ocean floor topography. For the parameter estimation, the prior of the atmospheric state is taken from the 6-hourly National Centers for Environmental Prediction Reanalysis 1 data (Kalnay et al., 1996) and is further modified during the assimilation procedure to minimize the difference to the data. Fluxes are derived via bulk formulas (Large & Yaeger, 2004) and freshwater forcing in the model is represented as virtual salt flux. Additionally, surface relaxation with a time-scale of 60 days to the climatological salinity from World Ocean Atlas 2018 is used. The sensitivity to the SSS relaxation is tested by two versions of the synthesis with different relaxation time scales in Köhl (2020). As for the assimilation, GECCO3 uses the adjoint method and one single assimilation window to cover the full period 1948–2018. The impact of assimilation is evaluated with available independent estimates, such as global heat content, meridional heat and freshwater transports and AMOC transports (Köhl, 2020). The estimates demonstrate improvements of the new version with lower model-data differences as well as the stability of FWT to the freshwater flux perturbations. The GECCO3 synthesis and the evaluation with assimilated and independent data are described in detail in Köhl (2020). The synthesis is available at https://icdc.cen.uni-hamburg.de/en/gecco3.html.

Using the monthly mean GECCO3 output, we analyze the relative contributions of surface freshwater flux and ocean FWT to the FWC variability in the following four regions of the Atlantic Ocean (Figure 1a): the subpolar North Atlantic (48°N−65°N), the subtropical North Atlantic (26.5°N−48°N), the tropical North Atlantic (0°−26.5°N), and the tropical South Atlantic (34°S−0°).

2.2. Methods

At each horizontal model grid point, the FWC is calculated according to

$$\mathrm{FWC}(x, y, t) = \int_{-D}^{0} F_a dz, \tag{1}$$

where the freshwater anomaly, F_a, is given by

$$F_a = 1 - S/S_0. \tag{2}$$

Here, D is the ocean depth, S is the seawater salinity, and S_0 is the reference salinity (35 psu) chosen to be the same as the model used to convert freshwater fluxes into virtual salt flux. The sensitivity to the reference values is of concern if there is substantial net volume transport across the section where freshwater transports are evaluated or if large ranges of reference values are useful to be considered across different sections. This is for instance true in the context of the transports through various passages connecting the Atlantic and Arctic Ocean (Schauer & Losch, 2019). In our calculation, the net volume transport though a section is much smaller than the compensated components of the transports, and the range of salinity values averaged over the sections is around 1% only. Therefore, the choice of reference value does not matter much and would only lead to a few percent difference.

To split the meridional freshwater transport (FWT) into components resulting from the overturning circulation (FWT_{ot}) and from the gyre circulation (FWT_{gy}), a well-established decomposition regarding the zonal mean and the deviations from the zonal mean (Böning & Bryan, 1996) is applied according to

$$\mathrm{FWT} = \mathrm{FWT_{ot}} + \mathrm{FWT_{gy}} \tag{3}$$

$$= \int_{-D}^{0}\int_{E}^{W}\left(\overline{v}\,\overline{F_a} + v'F_a'\right)dx\,dz. \tag{4}$$

The overbar represents the zonal mean and the prime symbolizes the deviation from the zonal mean. The combination of the overturning component ($\overline{v}\,\overline{F_a}$) and gyre component ($v'F_a'$) represents the total FWT. For simplicity the decomposition is done in depth space, which particularly in the subpolar Atlantic can lead to quite different results than a decomposition in density space (Jackson et al., 2022; Köhl, 2015).

The FWC tendency (ΔFWC) is defined as the anomaly of one particular month (t) relative to the former month ($t - 1$):

$$\Delta\mathrm{FWC}(t) = \int_{S}^{N}\int_{E}^{W}\mathrm{FWC}(x,y,t)\,dx\,dy - \int_{S}^{N}\int_{E}^{W}\mathrm{FWC}(x,y,t-1)\,dx\,dy). \tag{5}$$

Thus, a positive (negative) value of ΔFWC means that the seawater gets fresher (saltier) relative to the former time step. The freshwater budget is expressed as

$$\Delta\mathrm{FWC} = \mathrm{SF} + (-\mathrm{Tn}) + \mathrm{Ts} + r. \tag{6}$$

For the freshwater budget analysis, three components are considered to contribute to the FWC change (ΔFWC) in each box, including the surface flux into the ocean (SF), the southward FWT across the northern boundary (−Tn) and the northward FWT across the southern boundary (Ts). In addition, r denotes the residual resulting from the resolved eddy fluxes not represented by the monthly means, isopycnal and numerical mixing. Note that the contribution from the Gent and McWilliams (1990) (GM) parametrization of eddy tracer advection is included in the transport estimates and not part of the residual. In general, small and nearly constant residuals indicate that it is possible to close the regional freshwater budget with the considered fluxes since the major contributions to the variability are captured. Fluxes entering the box should increase the FWC in the box. Thus, a minus sign is added to Tn because a positive FWT at the northern boundary is directed out of the box and reduces the FWC in the box. The convergence and divergence of the transports across the boundaries are defined as the net transport

$$\mathrm{Tnet} = (-\mathrm{Tn}) + \mathrm{Ts}. \tag{7}$$

3. Freshwater Content and Freshwater Transport

3.1. Freshwater Content Variability

The time mean and standard deviation of the FWC in the Atlantic over the period 1961–2018 are shown in Figure 1. The FWC in the subtropical and subpolar North Atlantic has lower values but higher variability than in the tropical regions (Figures 1a and 1b). South of 10°N, FWC is higher but shows lower variability.

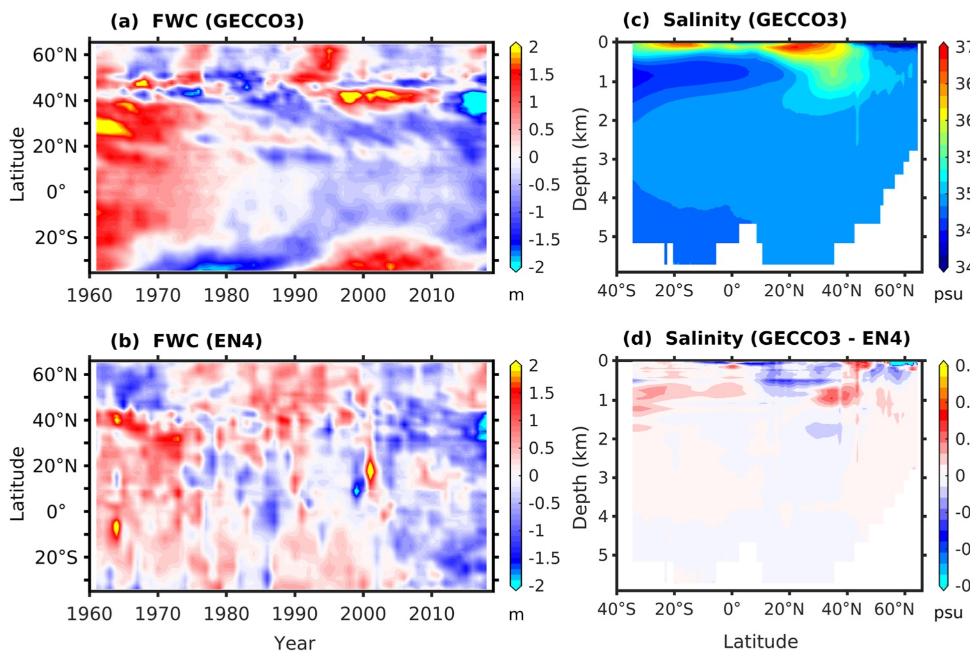

Figure 2. Hovmöller diagrams of the annual zonal-mean freshwater content in the layer 0–2,000 m of (a) GECCO3 in comparison to (b) EN4.2.2. (c) Time mean of the zonal-mean salinity of GECCO3 and (d) the difference between GECCO3 and EN4.2.2. Panels (c), (d) are shown in the latitude-depth plane, and the Mediterranean Sea has been excluded.

Boyer et al. (2007) showed an increase in FWC in the subpolar North Atlantic between the late 1960s and the early 1990s, which was followed by a relatively weak decline until 2006. The freshening period was found to be well correlated with the variations of surface freshwater flux, but the correlation does not hold for salinification period and other regions. Similarly, Tesdal and Haine (2020) reported this decadal cycle of freshening and salinification in the subpolar North Atlantic from 1992 to 2015 and attributed this variability to advective convergence. To validate GECCO3, the reversal of the FWC trends around the year 2000 is also shown here by the linear trends before and after 2000 (Figures 1c and 1d). Accordingly, the subpolar gyre gets fresher before 2000, and the trend reverses afterward. In contrast, the subtropical gyre gets saltier before 2000 and fresher afterward. While previous studies have elaborated mechanisms for the subpolar region, it is of interest to study contributors to this variability in other regions.

A comparison of anomalies of the zonal-mean FWC in the top 2,000 m with an observation-based estimate derived from the EN4.2.2 objective analysis (Good et al., 2013) (Figures 2a and 2b) reveals a broad agreement between both on the multi-decadal time scale, but many differences on interannual time scales. There is a basin-wide decrease of FWC south of roughly 45°N in both estimates, which is noticeable during the first two and the last decade. Variabilities in the subpolar gyre are somewhat out of phase between the estimates of GECCO3 and EN4.2.2. GECCO3 shows a maximum during early 1990s, while EN4.2.2 shows a longer-term increase from 1960 with a peak around 1990, yet both show a weak maximum at the end of the run. The largest decline in the 2000s is peaking at 40°N in both estimates, however the variability slightly further north is characterized by an increase until the 1990s in EN4.2.2 while GECCO3 shows decadal variability. However, after mid 1990 they agree well. In comparison to the EN4.2.2 based estimate, GECCO3 is more dominated by decadal variability and shows less interannual variability. A high FWC signal, appearing in the 1960s at 40°N in both products, propagates over the following 50 years slowly to 20°N. In EN4.2.2, the propagation speed appears to be higher, and due to superimposed variability, the propagation is only visible until the mid-1980s. A pronounced 50-year oscillation at the southern boundary (34°S) is only visible in GECCO3. The pattern correlation is 0.44, and typically around 0.6 except for the southern boundary and the region around 47°N.

Recent studies have discussed the importance of the salinity bias in the southern Atlantic to the freshwater transports and further to AMOC bi-stability analyses (Haines et al., 2022; Mecking et al., 2017; Mignac et al., 2019). For validation, the zonal-mean salinity of GECCO3 is shown with the difference against the estimate from EN4.2.2

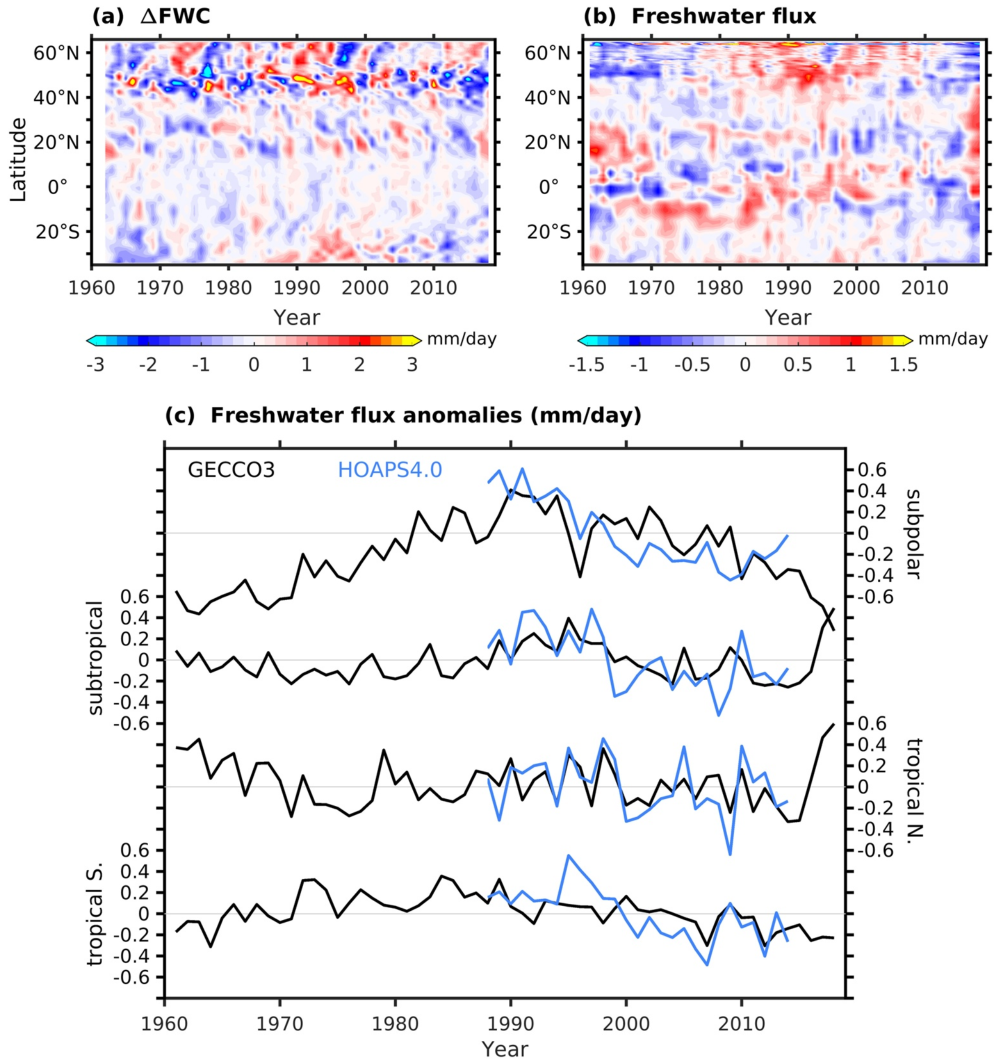

Figure 3. Hovmöller diagrams of the annual zonal-mean (a) freshwater content changes in comparison to (b) surface freshwater flux (mm/day). (c) The annual time series of the freshwater flux anomalies in the four sub-regions from GECCO3 over 1961–2018 (black) and HOAPS 4.0 over 1988–2014 (blue). For (b) and (c), positive denotes the freshwater into the ocean.

(Figures 2c and 2d). The salinity minimum of the Antarctic Intermediate Water (AAIW) of GECCO3 appears around 1,000 m, which well reproduces the position of the AAIW salinity minimum shown in observation-based estimates (e.g., Curry et al., 2003; Mecking et al., 2017). In contrast, Haines et al. (2022) found that models with northward overturning related FWT at 34°S tend to have shallow AAIW layer with salinity minimum between 300 and 600 m. Further comparison with EN4.2.2 shows that the GECCO3 ocean is fresher in the upper 200 m of about 0.3 psu between 20°N and 20°S. South of 20°S, the bias is almost positive up to around 0.2 psu and relatively uniform in the vertical structure, which is very different from the salinity bias from CMIP5 models reported by Mecking et al. (2017) and Haines et al. (2022), showing a vertical difference with too fresh surface water (up to 0.8 psu) and too saline lower water (up to 0.4 psu).

The annual mean of the zonal-mean FWC changes (ΔFWC) and the surface freshwater flux are shown in Figures 3a and 3b. The FWC changes mainly on interannual time scale; the reversal of freshening and salinification in the subpolar region and south of 20°S is also shown. Surface flux changes appear on longer time scales and cannot fully explain the variation of FWC. To further validate the surface flux of GECCO3, the annual time series of the freshwater flux over the four sub-regions are shown in Figure 3c with the satellite-based observation HOAPS 4.0 (Andersson et al., 2017), covering the years 1988–2014. The results reveal a broad agreement between these

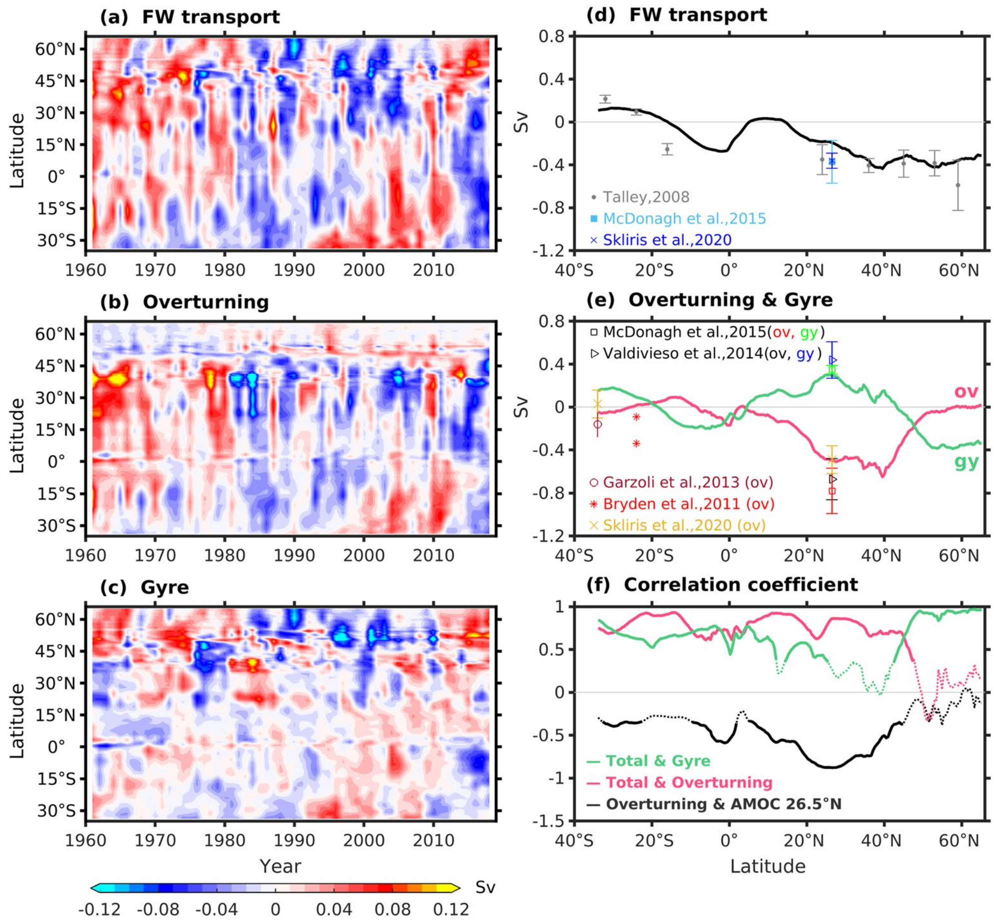

Figure 4. Hovmöller diagrams of the annual northward freshwater transport (FWT) anomalies shown as (a) total, (b) overturning component and (c) gyre component. (d) Mean meridional FWT and (e) its overturning (red) and gyre (green) components. For comparison, estimates from previous studies are marked with different symbols accordingly. (f) Correlation coefficients between total and gyre component (green), total and overturning component (red), as well as overturning component and the Atlantic meridional overturning circulation at 26.5°N (black). The correlation coefficients are calculated after detrending and shown in bold where significant at 99% confidence level.

two estimates with a correlation around 0.6, which comes mostly from the long-term changes. Misfits exist in the year-to-year variations especially for the subpolar North Atlantic and the tropical South Atlantic. For the subtropical and tropical North Atlantic, the curves match well with slightly less variability in GECCO3.

3.2. Freshwater Transport Variability

As the surface flux cannot fully explain the variation of FWC, we analyze in the following the FWT in detail and attempt to understand the processes that are responsible for changing the FWC with a focus on interannual and decadal time scales.

Variations of FWT in terms of the total, the overturning component and the gyre component are shown in Figures 4a–4c, respectively. The interannual transport variability is in general the dominant signal, superimposed with decadal variability. The overturning component south of 45°N accounts for most of the variations of the total transport there (e.g., the dominance of the overturning component at 26.5°N) as expected and verified by observation (McDonagh et al., 2015). North of 45°N, the gyre component shows strong coherence with the total transport, which agrees with the FWT at 50°N shown by Jackson et al. (2019). These features are reflected in the green and red curves in Figure 4f, which show the correlations between the total transport and the two components at each latitude.

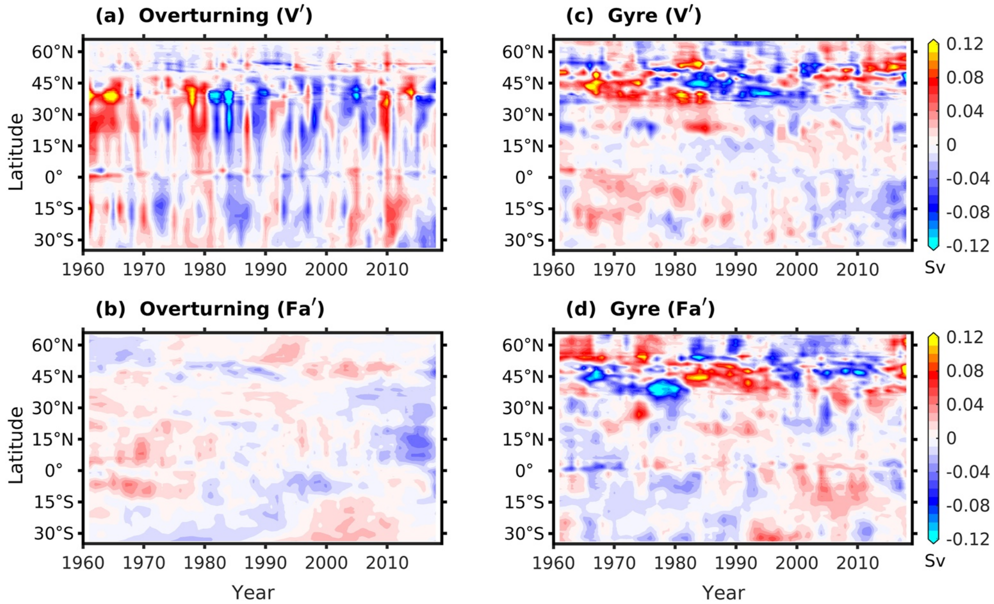

Figure 5. Hovmöller diagrams of the decomposition of the overturning and gyre components into the contributions from velocity variations and salinity variations, shown as (a) Overturning (V′), (b) Overturning (Fa′), (c) Gyre (V′) and (d) Gyre (Fa′).

The time-mean FWT in the Atlantic (Figure 4d) is shown together with its overturning and gyre components (Figure 4e), in comparison to observational estimates (Bryden et al., 2011; Garzoli et al., 2013; McDonagh et al., 2015; Talley, 2008), estimates based on ocean synthesis (Valdivieso et al., 2014) and estimates from CMIP5 models (Skliris et al., 2020). Freshwater transport between 20°S and 26.5°N is underestimated in GECCO3, which is similar to other estimates reported before (e.g., see Figure 1 of Mignac et al. (2019)). The underestimation also holds for the overturning component, which do not reach the values from observations (e.g., −0.78 ± 0.21 Sv at 26.5°N (McDonagh et al., 2015) or the range from −0.09 to −0.34 Sv at 24°S (Bryden et al., 2011)) but is in the ranges of the estimates based on ocean synthesis (Valdivieso et al., 2014) and CMIP5 models (Skliris et al., 2020). The gyre component is near the lower range from the observation (e.g., 0.35 ± 0.04 Sv at 26.5°N (McDonagh et al., 2015)) and reanalyzes (e.g., 0.44 ± 0.17 Sv at 26.5°N (Valdivieso et al., 2014)).

As shown in Figure 4f, for the southern Atlantic the dominance of the overturning component still holds around 20°S but fades further southward, while the gyre component gradually takes control especially at 34°S. This is different from Mignac et al. (2019) who found that the gyre freshwater transports dominate the freshwater transports throughout the South Atlantic. This could be relevant to the fresher water in the upper 200 m between 20°N and 20°S shown in Figure 2d. As for the transport at 34°S, the overturning component is −0.045 Sv, which is close to the observational estimate in the range from −0.28 to −0.05 Sv (Garzoli et al., 2013) and therefore suggests consistency with the current AMOC state (Mecking et al., 2017).

A decomposition of the overturning and gyre components into the contributions from velocity variations and salinity variations (Figure 5) reveals that the overturning component is mostly controlled by velocity variations. Its variability is dominated by the interannual time scale and is highest around the latitude of 40°N (Figures 5a and 5b). The variability of contributions from salinity and velocity variability to the gyre component is high north of 40°N and is mainly dominated by decadal and multi-decadal signals (Figures 5c and 5d). The contributions from velocity variations and salinity variations of the gyre component are highly anti-correlated at the latitudes between 40°N and 50°N.

4. Freshwater Budgets

In the following, we will analyze the freshwater budget of the four defined regions in the Atlantic (Figure 1a) and identify the main mechanisms causing interannual to decadal variations of FWC change in each region over the period 1961–2018. Note that budget calculations are performed for regions delimited by grid lines and that north

Table 1
The Correlation Coefficients of the Freshwater Content Change and the Contribution Components (SF, Tnet, −Tn, and Ts) as Well as the Correlation Coefficients of the Net Transport (Tnet) and the Transports Across the Boundaries (−Tn and Ts) in the Boxes From North to the South

Box	ΔFWC and SF	ΔFWC and Tnet	ΔFWC and −Tn	ΔFWC and Ts	Tnet and −Tn	Tnet and Ts
48°N−65°N	0.52	0.91	0.77	0.69	0.67	0.87
26.5°N−48°N	0.63	0.85	0.66	0.47	0.74	0.60
0°−26.5°N	0.71	0.62	0.46	0.24*	0.77	0.36*
34°S−0°	0.72	0.77	0.39	0.60	0.52	0.76

Note. The correlation coefficients higher than 0.6 are indicated with the light gray background color, and the ones that are statistically insignificant at the level of 95% are marked with an asterisk.

of 20°N, there is about a 10° difference between east and west in latitude due to the curvature of the grid lines (dark green curves in Figure 1a). All fluxes into a box are denoted positive. For the FWT analysis, northward is indicated as positive. A 3-year running mean is applied to all time series to focus the analysis on interannual to decadal time scales. The correlation coefficients of the components in the boxes from north to south are summarized in Table 1. The correlation coefficients are calculated based on the annual time series and after removing the linear trend. Correlation coefficients exceeding 0.6 are indicated with the light gray background color, and the ones that are statistically insignificant at the 95%-level are marked with an asterisk.

4.1. Subpolar North Atlantic

In the subpolar North Atlantic (48°N−65°N), freshwater inputs through the surface and across the northern boundary are balanced by the freshwater output through the southern boundary (Figure 6a). The surface flux variability is relatively small and more relevant for long-term variations. It is noticeable that there is a positive trend in ΔFWC prior to 1990 followed by a negative trend subsequently, which correlates with the long-term variation of the surface flux. This supports the analyses of the FWC trends (Figures 1c and 1d) that the subpolar gyre gets fresher before 2000 and saltier afterward, consistent with previous observations (e.g., Boyer et al., 2007; Tesdal & Haine, 2020). The correlation coefficients (Table 1) of ΔFWC and the transports further confirm the finding by Tesdal and Haine (2020), which highlights the importance of advective convergence. The net FWT, which is dominated by the transport across the southern boundary ($r = 0.87$), represents the main contribution to the variations of ΔFWC ($r = 0.91$).

Transports anomalies across 65°N and 48°N are decomposed into the gyre and overturning components and further into the contributions of salinity variations and velocity variations (Figure 7). Note that for the secondary

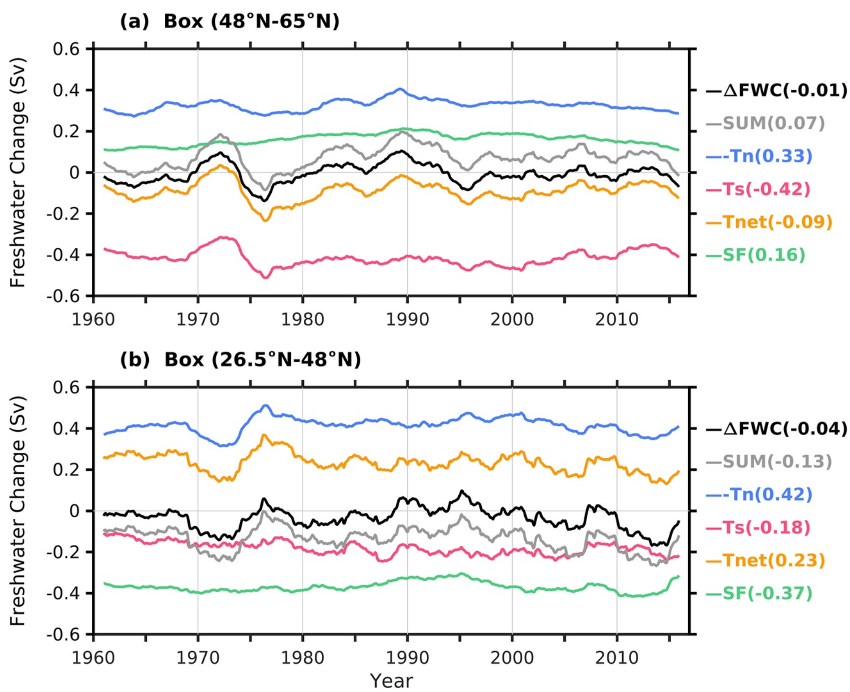

Figure 6. Freshwater budget analysis of (a) the subpolar North Atlantic box (48°N−65°N) and (b) the subtropical North Atlantic box (26.5°N−48°N), shown as time series of the freshwater content changes (ΔFWC, black), the contributions of the freshwater transports across the northern boundary (−Tn, blue) and the southern boundary (Ts, red), the net transport (Tnet, orange), the surface freshwater flux (SF, green) and the sum of Tnet and SF (SUM, gray). The mean value of each component is given in brackets. Fluxes into the box are denoted as positive. The time series are all smoothed with a 3-year running mean.

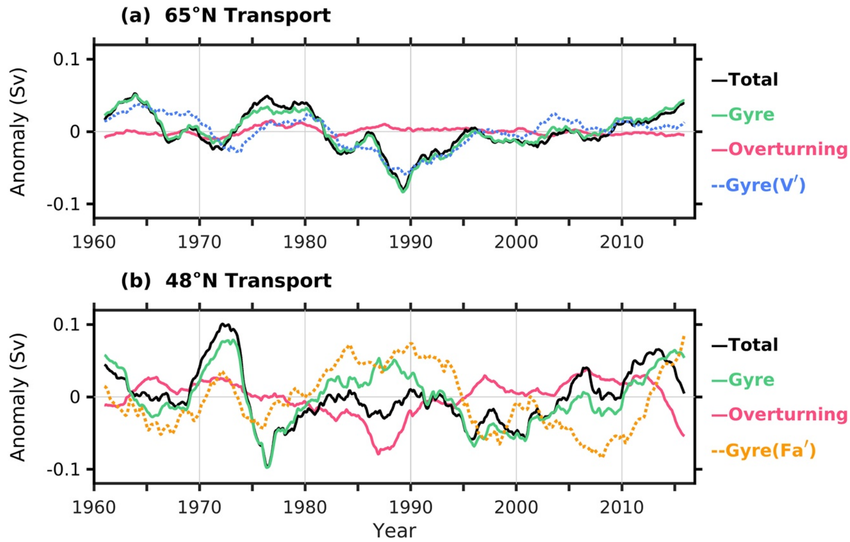

Figure 7. The anomalies of the freshwater transports at the boundaries (a) 65°N and (b) 48°N. The decomposition of the gyre component (green) and overturning component (red) are shown in every subplots with solid curves. The further decomposition to the contributions of salinity variations (orange) and velocity variations (blue) are shown with dashed curves, and only the most relevant ones are shown. Northward is denoted as positive for the transport analysis.

decomposition, only the most relevant components are shown in the figure for clarity. At 65°N and 48°N, the transports are dominated by the gyre components, which is also shown by the correlation coefficients along theses latitudes (Figure 4f). This is especially true at 65°N, where the variability of the overturning component is very small (Figure 7a). The gyre component is governed by velocity variations at 65°N, while the contribution from salinity variations is more important for the gyre component at 48°N.

4.2. Subtropical North Atlantic

In the subtropical North Atlantic (26.5°N−48°N), the variability of the surface flux is relatively small, which is similar to the subpolar box (green curves in Figure 6). Values of ΔFWC are mostly negative during the entire study period caused by the large surface freshwater loss in the subtropical region and the southward FWT leaving the region at the southern boundary. This is consistent with previous finding showing a decrease in FWC in the North Atlantic (e.g., Boyer et al., 2007). The net transport is strongly correlated with variations of the FWC change in this box ($r = 0.85$), which is driven by the transport across the northern boundary ($r = 0.74$).

4.3. Tropical Atlantic

The ΔFWC of the tropical North Atlantic box (0°−26.5°N) are varying around zero but are mostly negative during the entire study period (Figure 8a). There is more southward transport leaving the region across the southern boundary than the transport input across the northern boundary, which is mostly balanced by the positive surface freshwater input in the region. None of the transports across lateral boundaries shows high correlation with ΔFWC ($r = 0.46$ and 0.24, respectively). However, the convergence and divergence of them show considerable impact on the ΔFWC variations ($r = 0.62$), which is smaller than the correlation between ΔFWC and the surface flux ($r = 0.71$). In addition, the net transport convergence is dominated by the transport across 26.5°N ($r = 0.77$), while the transport across 0° shows less interannual variability.

As shown in Figure 4, the overturning component contributes significantly south of 45°N; different from 48°N, the transport at 26.5°N (Figure 9a) is thus mainly controlled by the overturning component, in agreement with the observational estimates (e.g., McDonagh et al., 2015). As expected, significant negative correlation ($r = -0.88$) is also shown between the overturning component and the AMOC at 26.5°N (black curve in Figure 4f). The general agreement between the AMOC of GECCO3 and the RAPID in situ observation has been demonstrated in Köhl (2020). In comparison to McDonagh et al. (2015) the FWT shows a similar decline from 2004 to 2010

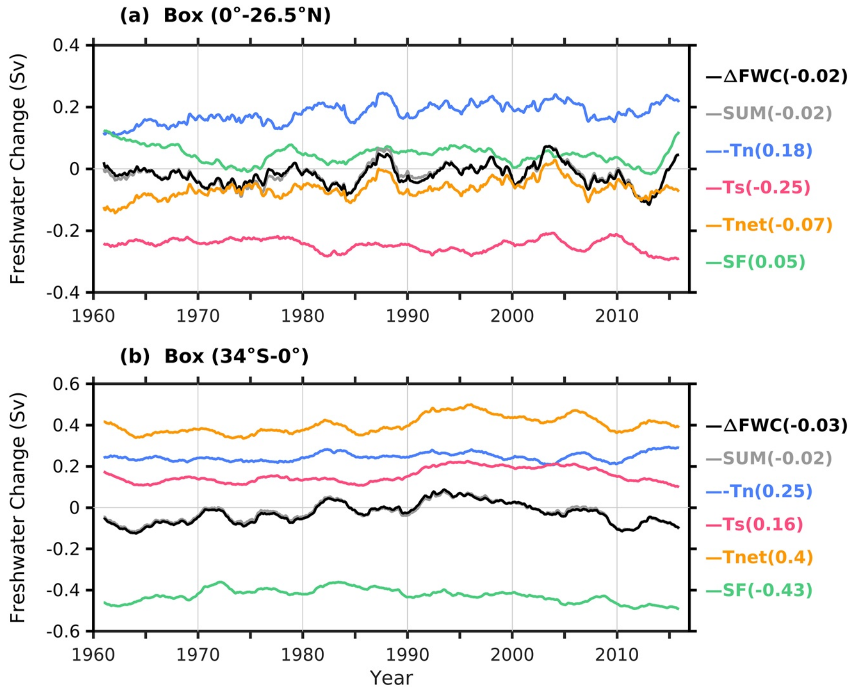

Figure 8. Freshwater budget analysis same as Figure 6 but for (a) the tropical North Atlantic box (0°−26.5°N) and (b) the tropical South Atlantic box (34°S−0°).

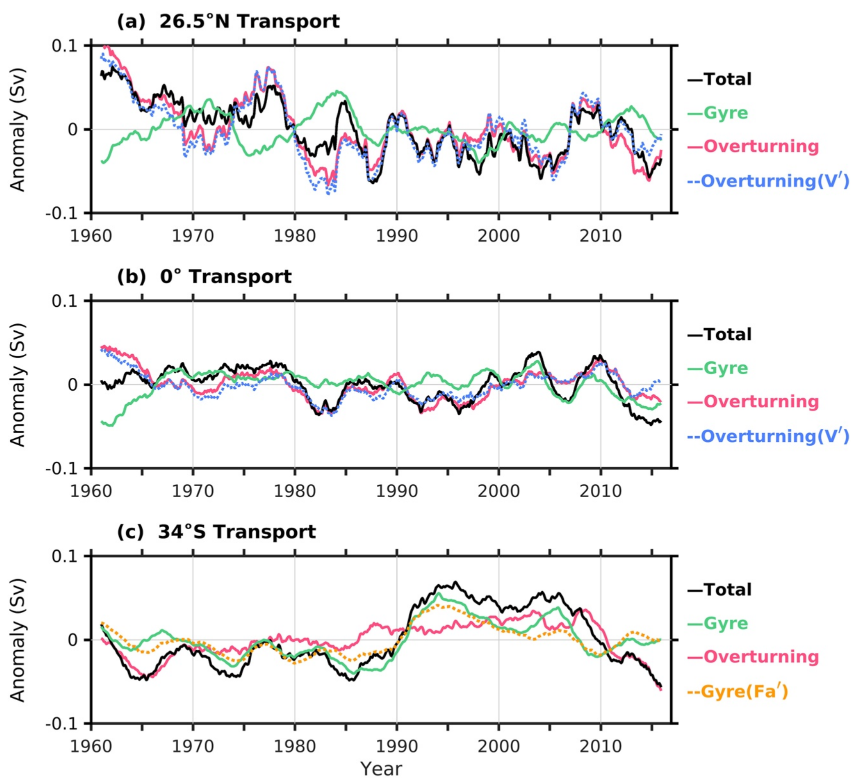

Figure 9. The anomalies of the freshwater transports same as Figure 7 but for the boundaries (a) 26.5°N, (b) 0° and (c) 34°S.

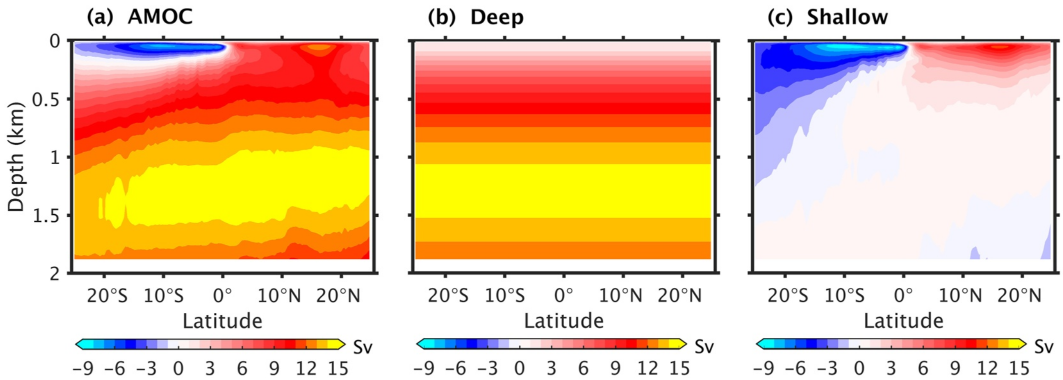

Figure 10. The time-mean meridional overturning streamfunction over the upper 2,000 m of the tropical Atlantic Ocean, shown as (a) the Atlantic meridional overturning circulation and the decomposition of (b) the deep circulation and (c) the shallow overturning cells.

but recovers afterward, while the observational estimate keeps declining throughout analysis period until 2013. In addition, the decomposition of the overturning component indicates that the primary contribution to its variation comes from velocity variations (V') (dashed-blue curve in Figure 9a), as also noted in Haines et al. (2022) for CMIP5 models. The transport at 0° (Figure 9b) is mainly affected by variations of the overturning component with less contribution from the gyre component due to its smaller variability. Furthermore, the overturning component and the gyre component are dominated by velocity variations and salinity variations, respectively (the further decomposition of the gyre component is not shown here).

The freshwater budget analysis of the tropical South Atlantic box (34°S−0°; Figure 8b) shows values of ΔFWC are around zero but mostly negative before the beginning of the 1980s and after 2002. For this region, the only source of freshwater loss comes from the surface flux. Similar to the subtropical North Atlantic box, also in this box transports across both boundaries converge over the entire study period. Specially, only in this box the transport across the southern boundary at 34°S is northward, which means adding fresh water into the region. This is consistent with observational estimate (Garzoli et al., 2013), and also suggests that the current AMOC is in a bi-stable regime. The respective freshwater convergence is balanced through a freshwater loss from the surface, and the net transport presents considerable impact on the variation of ΔFWC ($r = 0.77$).

Variations of the net transport are mostly controlled by the southern boundary transport ($r = 0.76$). Freshwater transport at 34°S is predominantly governed by the gyre component typically by the contribution from salinity variations (Figure 9c). It is again consistent with the finding from Mignac et al. (2019) who showed the dominate role of the gyre component at 34°S and its sensitivity to the salinity distribution.

4.4. Importance of the Shallow Overturning Cells

The shallow subtropical cells (STCs) are mainly wind-driven circulations and considered important in the tropical and subtropical oceans (Lu et al., 1998; McCreary & Lu, 1994). The STCs have impact on heat and water exchanges between tropical and subtropical oceans, and are suggested to play a role in climate variability (Schott et al., 2004). It is intriguing to determine the STCs contributions associated with the overturning circulation to variations in FWT.

For this purpose, we show the decomposition of the meridional overturning streamfunction in the upper tropical Atlantic Ocean between 25°S and 25°N (Figure 10). Only one closed shallow overturning cell can be detected south of the equator. The northern cell is more complicated because of the superimposed cross-equatorial meridional mean flow, which relates to the deep overturning circulation. To separate the superimposed meridional mean flow from the shallow overturning cells and to show the structure of the shallow overturning cells, a decomposition is applied. This can be done under the assumption that the deep meridional overturning circulation follows depth levels in the upper layers above 2,000 m, the deep circulation can then be represented by the meridional average (Figure 10b), and the shallow overturning cells are denoted by the deviation from the meridional average (Figure 10c). For the deep overturning the transport in the upper layer comprises roughly the top 1,200 m, and

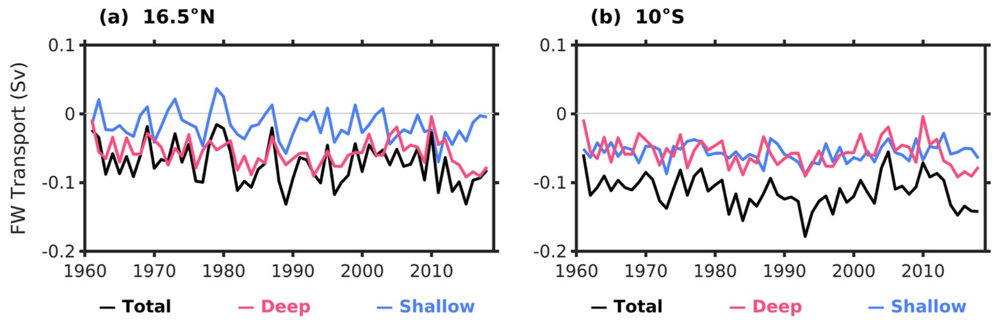

Figure 11. Annual time series of the northward freshwater transport as total (black) and the contributions from the deep overturning circulation (red) and the shallow overturning cells (blue), shown as the transports (a) at 16.5°N for the northern cell and (b) at 10°S for the southern cell.

the deep transport is below 1,200 m. For the shallow overturning contribution from the top layer comprises only the top 50 m and most of the deep return flow is between 50 and 1,000 m. As shown in Figure 10c, the centers of the shallow overturning cells lie around the depth of 50 m at 16.5°N for the northern cell and at 10°S for the southern cell.

Using the same method, the freshwater transports in the upper 2,000 m at 16.5°N and 10°S can also be decomposed into the contributions from the deep overturning circulation and the shallow overturning cells (Figure 11). For the northern cell (16.5°N), the contributions from the deep circulation accounts for the majority of the total transport. The deep circulation and the shallow overturning cell are equally important for the variations of the FWT ($r = 0.68$ and 0.72, respectively). For the southern overturning cell (10°S), transports related to the deep circulation and the shallow cells are both southward, and the total FWT correlates better with the deep overturning contribution ($r = 0.83$) than with the shallow overturning cell contribution ($r = 0.54$).

As suggested by Figure 4, the meridional FWT in the tropical Atlantic is highly related to its overturning component ($r = 0.9$ and 0.73 for 16.5°N and 10°S, respectively), which traditionally represents the FWT associated with the AMOC. This analysis helps to clarify the influence of different parts of the AMOC and highlights the importance of the shallow overturning cells in the tropical and subtropical regions especially for case studies. Due to its potential to indicate the FWT by the shallow overturning cells, further investigation regarding the role of shallow overturning cell strength would be worthwhile.

5. Concluding Remarks

This study aims to analyze variations of FWT and surface freshwater flux, with a focus on their roles in determining regional FWC variability on interannual and decadal time scales. To this end, four study areas in the Atlantic Ocean have been evaluated with respect to their freshwater fluctuations using the GECCO3 ocean synthesis for the period 1961–2018. As an update of the GECCO ocean synthesis, GECCO3 is configured with higher resolution taken from the higher-resolution version of MPI-ESM to provide compatible initial conditions for coupled climate models. Switching back to one single assimilation window avoids the 4-year cycle problem associated with the adjustments within each assimilation window in GECCO2, which also leads to better performance with respect to variability. The estimates in Köhl (2020) and in this study show better agreement with the assimilated and independent data sets, which can be partly attributed to the introduction of the large amount of Argo data in the early 2000s. Misfits still exist in salinity and surface freshwater flux in comparison with EN4.2.2 and HOAPS 4.0. In general, estimates from GECCO3 show less variability on interannual time scale. Moreover, underestimation appears in the FWT in the tropical regions in GECCO3, comparing to the estimates from observations (Bryden et al., 2011; Garzoli et al., 2013; McDonagh et al., 2015; Talley, 2008).

The FWC analysis reveals a similar decadal cycle of freshening and salinification identified before by Tesdal and Haine (2020). As the impact from surface flux is slow and more effective on longer time scales, we emphasis the importance of FWT. To understand the Atlantic FWT variability, a decomposition analysis is used to separate the transports of the overturning and gyre circulation, and further to identify the contributions from velocity variations and salinity variations. In general, the overturning component predominates the total FWT variations south of 45°N, while the gyre component plays a role around the equator and north of 45°N. The further decomposition indicates that the overturning component is governed by velocity variations, while the variability of salinity variations is relatively slow and small. This supports the findings of Haines et al. (2022) that the velocity dominates the overturning component in all studied CMIP5 models and across all timescales. For the gyre component, the contributions from velocity variations and salinity variations are rather anti-correlated along the latitudes, especially between 40°N and 50°N. The dominance of the salinity variations for the gyre component there may explain why the strength of the subpolar gyre does not control the salinity in the eastern subpolar gyre (Foukal & Lozier, 2017).

The close link between the FWT and the overturning in the region south of 45°N also indicates a close link to the NAO, as the relation between NAO and AMOC is well established (e.g., Buckley & Marshall, 2016; Eden & Willebrand, 2001; Köhl, 2015), which however was not further explored here. Moreover, the current state of reduced overturning (Smeed et al., 2018), which is about to come to an end (Moat et al., 2020), would imply persistently reduced southward FWT during the recent years. However, based on the GECCO3 results, the southward transport at 26.5°N and further south have already been no longer below the long-term mean since 2014.

The freshwater budget analysis of the North Atlantic suggests that the net FWT across the meridional boundaries dominates the variations of FWC changes. Going from north to the south, transport across a single meridional boundary becomes less correlated with FWC changes. The net transport across the boundaries, however, plays an important role in changing the FWC in these regions. Moreover, the subpolar box is mainly gyre driven, which differs from the other two, essentially overturning driven, North Atlantic boxes.

For the tropical regions, the absolute dominance of the net transport to the FWC changes weakens, as the contribution from the surface flux is relatively enhanced. Different from the North Atlantic boxes, the southern tropical box (34°S−0°) is the only box where the transports across both boundaries converges over the entire study period due to the northward FWT at 34°S. The variations of the transport convergence are governed by the transport at 34°S, where the gyre component prevails and is determined by salinity variability. Prior studies about the FWT at 34°S especially the overturning component of it and the relationship with the AMOC bi-stability have emphasized the importance of salinity bias in model simulations (Haines et al., 2022; Mecking et al., 2017; Mignac et al., 2019). It needs to be dealt with caution, because it is critical to the FWT at 34°S and can potentially lead to misrepresentation of AMOC stability.

Although our analysis points to the need to consider the variability of the net FWT across both boundaries in FWC analysis of the Atlantic Ocean, it does not rule out the effects of surface flux, as it is always a combined effect of the surface flux and the net FWT in changing the respective FWC in the sub-regions. For the tropical regions, where the transports are mainly overturning driven, we emphasize the importance of the shallow overturning cells in the FWT analysis.

Data Availability Statement

The GECCO3 data can be obtained via https://icdc.cen.uni-hamburg.de/en/gecco3.html, the EN4.2.2 objective analysis is available at https://www.metoffice.gov.uk/hadobs/en4/download-en4-2-2.html and HOAPS 4.0 data was retrieved from https://www.cen.uni-hamburg.de/en/icdc/data/atmosphere/hoaps.html.

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