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RESEARCH ARTICLE

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Key Points:

- We investigate cross-shelf exchanges east of Greenland with a new data set of drifters deployed at the shelfbreak in 2019, 2020, and 2021
- Drifters, altimetry, and an atmospheric reanalysis, indicate enhanced cross-shelf exchanges at the Blosseville Basin and Cape Farewell
- Winds, eddies, and local topography drive small scale and intermittent export east of Greenland, and can enhance mixing near the shelf

Supporting Information:

Supporting Information may be found in the online version of this article.

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Cross-Shelf Exchanges Between the East Greenland Shelf and Interior Seas

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Abstract Increasing freshwater fluxes from the Greenland ice sheet and the Arctic to the Subpolar North Atlantic could cause a freshening of deep convection regions and affect the overturning circulation. However, freshwater pathways from the Greenland shelf to interior seas and deep convection regions are not fully understood. We investigate exchanges of liquid freshwater between the east Greenland shelf and neighboring seas using drifter data from five deployments carried out at different latitudes along the east Greenland shelf in 2019, 2020, and 2021, as well as satellite data and an atmospheric reanalysis. We compute Ekman transport from winds and geostrophic velocity from satellite altimetry at the shelfbreak and identify the Blosseville Basin and Cape Farewell as areas favorable to cross-shelf exchanges. We further investigate exchange processes in these regions using drifter data. In the Blosseville Basin, drifters are brought off-shelf toward the Iceland Sea and into the interior of the Basin. As they are advected downstream, they re-enter the shelf and are driven toward the coast. At Cape Farewell, the wind appears to be the main driver, although on one occasion we found evidence of an eddy turning drifters away from the shelf. The drifters brought off-shelf at Cape Farewell mostly continue around Eirik Ridge, where they re-enter the West Greenland Current. Overall, the identified export over the east Greenland shelf is limited, small scale, and intermittent, thus unlikely to flux large amount of liquid freshwater into the interior, though exchange processes could enhance mixing in the near-shelf region.

Plain Language Summary Climate change is expected to lead to a faster melt of the Greenland ice sheet. This may have a large effect on the ocean circulation due to its location near areas where strong winter cooling by the atmosphere turns warm ocean surface waters into cold, dense deep waters. As light fresh meltwater from Greenland enters these regions, winter cooling may not be strong enough anymore to make these waters dense enough to take part in the deep ocean circulation. In this study, we investigate tracks from drifting ocean instruments deployed near Greenland, as well as satellite data, to study where, and how much, freshwater could enter these deep water formation areas. We find two locations along the east Greenland shelf, at 60° and 68°N, where strong winds and ocean eddies can steer freshwater offshore, These processes are intermittent and only lead to small amounts of freshwater brought to areas where deep waters are formed.

1. Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is a key element of the climate system, redistributing heat, and freshwater across the oceans (Buckley & Marshall, 2016). Anthropogenic climate change is predicted to lead to a weakening of the overturning circulation in the coming century (Collins et al., 2019; Weijer et al., 2020), which would have important consequences on global and regional climate (Jackson et al., 2015; Zhang et al., 2019).

Increasing upper ocean stratification in the Subpolar North Atlantic (SPNA) could lead to a weakening of deep convection and affect the AMOC. In particular, input of freshwater from the Arctic (Haine et al., 2015) and Greenland (Bamber et al., 2018; Shepherd et al., 2020) is predicted to increase in the coming decades. If this additional freshwater enters interior seas of the SPNA, it could impact the stratification of deep convection regions (Aagaard & Carmack, 1989; Bakker et al., 2016; Manabe & Stouffer, 1995; Weijer et al., 2019). However, model studies disagree on the timescale at which additional freshwater input could have a significant impact on the AMOC and whether it is already visible (Böning et al., 2016; Dukhovskoy et al., 2019; Yang et al., 2016). There are still uncertainties on the exact pathways freshwater from Greenland and the Arctic would follow to enter the deep convection regions (Dukhovskoy et al., 2016). While recent observations suggested that overturning east of Greenland dominates the total overturning in the SPNA (Li et al., 2021; Lozier et al., 2019; Petit et al., 2020), studies of the impact of additional freshwater input on deep convection

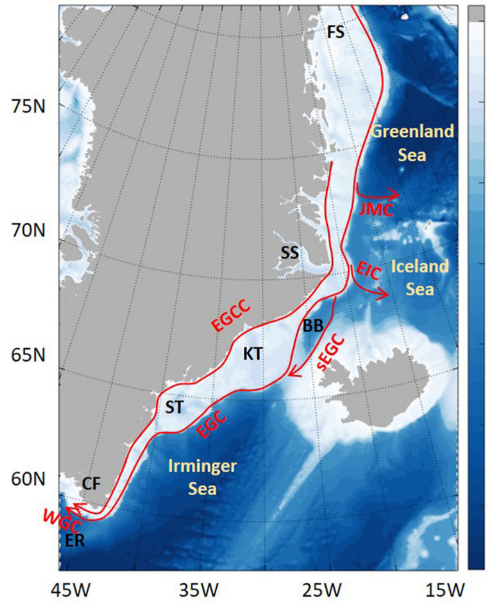

Figure 1. Bathymetry and overview of the circulation over the East Greenland shelf. EGC: East Greenland Current; EGCC: East Greenland Coastal Current; sEGC: Separated East Greenland Current; JMC: Jan Mayen Current; EIC: East Icelandic Current; WGC: West Greenland Current. FS: Fram Strait. SS: Scoresby Sund. BB: Blosseville Basin. KT: Kangerdlussuaq Trough. ST: Sermilik Trough. DS: Denmark Strait. CF: Cape Farewell. ER: Eirik Ridge. Bathymetry is retrieved from the ETOPO2022 60 arc-seconds data set (NOAA National Centers for Environmental Information, 2022).

and deep water formation mostly focused on the Labrador sea so far (e.g., Pennelly et al., 2019; Yang et al., 2016). In summer, shallow freshwater layers are seen over the deep convection region in the Irminger Sea (Sterl & de Jong, 2022). In winter, this layer is mixed down the water column by convective mixing, which reaches down to 400 m even in weak winters (M. F. de Jong et al., 2012). The re-formation of a new freshwater layer over a few months in spring (Sterl & de Jong, 2022) suggests that it is fed by local sources. This restratification process in the Irminger Sea and the possibility of additional freshwater inhibiting convection in the Irminger and Nordic Seas, underline the need for a better understanding of freshwater pathways east of Greenland.

The East Greenland Current (EGC) transports fresh polar surface waters coming from the Arctic and from Greenland runoff (Rudels et al., 2002) southwards over the shelf (Figure 1). The main branch of the EGC flows alongside the shelfbreak from Fram Strait to Cape Farewell (Håvik, Pickart, et al., 2017; Sutherland & Pickart, 2008). A fresher branch, referred to as East Greenland Coastal Current (EGCC) flows alongside the coast (Bacon et al., 2014; Foukal et al., 2020; Håvik, Pickart, et al., 2017). The fresh surface waters in the EGCC and EGC are isolated from the warmer, more saline interior seas, by a strong hydrographic front at the shelfbreak. Over most of the east Greenland shelf, strong and consistent barrier winds driven by the steep topography of Greenland constrain the surface waters further toward the coast by driving onshore Ekman transport (Moore & Renfrew, 2005).

North of Denmark Strait, three permanent circulation features are known to contribute to export from the EGC into the Nordic Seas. The Jan Mayen Current is situated at the Jan Mayen fracture zone (Bourke et al., 1992) and diverts shelf waters into the Greenland Sea. The East Icelandic Current branches off from the EGC at the latitude of Scoresby Sund into the southern Iceland sea (Casanova-Masjoan et al., 2020; Jónsson, 2007). The Jan Mayen and East Icelandic Current are estimated to only divert a small fraction of the total freshwater transport of the EGC toward the Nordic Seas (Håvik, Pickart, et al., 2017; Macrander et al., 2014). At the entrance of the Blosseville Basin, the EGC branches off and forms the separated EGC, that flows alongside the slope at the base of the Iceland shelf, diverting up to 37% of freshwater away from the shelfbreak (De Steur et al., 2017; Håvik, Våge, et al., 2017; Våge et al., 2013). Two hypotheses were proposed to explain the formation of this separated branch: Baroclinic instabilities at the northern end of Blosseville Basin, characterized by a sharp bend in the bathymetry, could lead to the shedding of eddies that coalesce on the other side of the basin, forming the separated branch (Håvik, Pickart, et al., 2017; Håvik, Våge, et al., 2017; Våge et al., 2013). Alternatively, the branch could be part of an anticyclonic gyre caused by negative wind stress curl over the Blosseville Basin (Harden et al., 2016).

South of Denmark Strait, only limited export toward the Irminger Sea has been identified (Duyck & De Jong, 2021; Pennelly et al., 2019). Deep troughs along the shelf, notably the Kangerdlussuaq and Sermilik troughs, lead to exchanges between the shelfbreak and coastal current. Part of the shelfbreak EGC flows inside these troughs and either rejoins the shelfbreak current downstream or joins the EGCC (Duyck & De Jong, 2021; Sutherland & Cenedese, 2009; Sutherland & Pickart, 2008). At Cape Farewell, northeasterly winds are less dominant than over the rest of the shelf and alternate with westerly winds. Strong westerly events, or Tip Jets (Moore, 2003; Moore & Renfrew, 2005) could drive freshwater off the shelf at Cape Farewell (Duyck et al., 2022), possibly impacting convection close to the shelfbreak or just south of Eirik Ridge (M. F. de Jong et al., 2012; Piron et al., 2016, 2017).

The study presented here investigates exchanges between the east Greenland shelf and neighboring seas, as well as processes responsible for these exchanges. It uses a new drifter data set, as well as atmospheric reanalysis data and satellite observations. Section 2 describes the drifter deployments and the other data sets used. In Section 3 we identify the main areas of cross-shelf exchange along the east Greenland shelf, and investigate processes that could lead to exchanges in the Blosseville Basin and at Cape Farewell. Section 4 discusses the importance of the identified exchange processes for freshwater export east of Greenland.

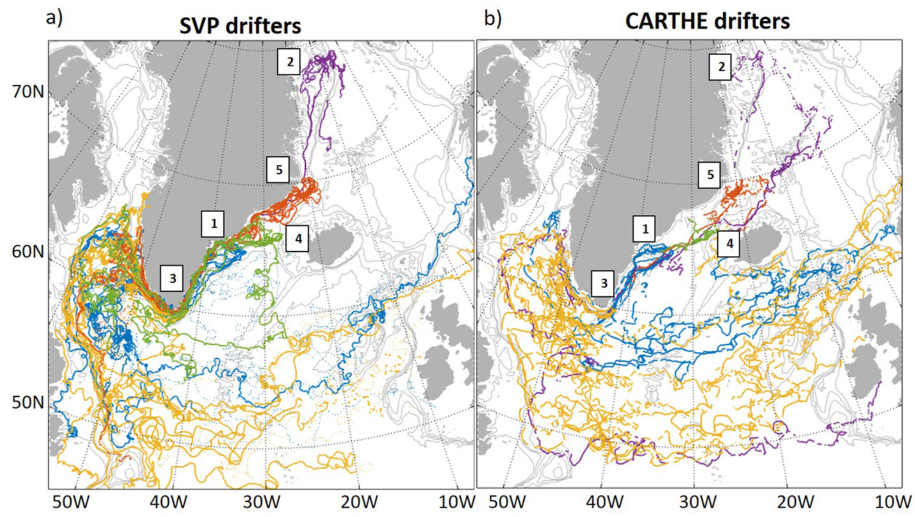

Figure 2. Trajectories of Surface Velocity Program (left) and Consortium for Advanced Research for the Transport of Hydrocarbon in the Environment (right) drifters per deployment. 1: Sermilik (blue), 2: Fram Strait (purple), 3: Cape Farewell (yellow), 4: Denmark Strait (green), and 5: Scoresby Sund (red). Bathymetric contours are shown at 2,000, 1,000, 500, and 200 m.

2. Materials and Methods

2.1. Drifter Data Sets

In this study, we use the final drifter data set of the East Greenland Current Drifter Investigation of Freshwater Transport (EGC-DrIFT) project. As part of this project, 120 drifters were deployed at the east Greenland shelf, over 5 deployments, spread over 3 years, 2019, 2020, and 2021 (Figure 2). Each deployment consisted of two types of surface drifters: Surface Velocity Program (SVP) and CARTHE drifters.

SVP drifters are spherical buoys fitted with a holey sock drogue that anchors the drifter at 15 m depth (Lumpkin et al., 2017). We deployed SVP drifters fitted with a temperature sensor (named SVP-T in the following) and SVP drifters fitted with both temperature and conductivity sensors (SVP-S). The drifters transmitted measurements and GPS positions via Iridium at 3-hourly intervals for SVP-T drifters and 1-hourly interval for SVP-S drifters. CARTHE drifters (named after the Consortium for Advanced Research for the Transport of Hydrocarbon in the Environment, Novelli et al., 2017) are smaller drifters, made of a floating torus sitting low above water and a solid drogue that anchors them at 40 cm. They transmit GPS position at 3-hourly interval. These two types of drifters, anchored at different depth, were deployed in pairs to describe the behavior of different water layers.

The EGC-DrIFT data set was processed as follows: We first removed duplicate positions, erroneous positions (null or out of bounds coordinates) as well as repeated message dates. We then used a speed criterion to detect spikes in GPS positions. We removed temperature and conductivity values outside of range (Conductivity below 1 or above 50 S m^{-1}, and sea surface temperature (SST) below −2°C or over 20°). We removed remaining spikes in temperature and conductivity manually. Hydrographic properties, such as absolute salinity and density were derived from measurements using the TEOS-10 toolbox (McDougall & Barker, 2011), and drifter velocities were computed and filtered with a 25-hr centered Butterworth filter to remove tidal and inertial motions (as in Koszalka et al. (2011)). We then interpolated the drifter trajectories on a 3 hr timestep, from August 2019 to November 2022, where data gaps are shorter than 12 hr. We evaluated the presence of a drogue on SVP drifters using the GPS time to first fix (for SVP-T drifters) or a combination of this parameter and the submergence parameter (SVP-S). Both parameters exhibit drastic changes when the drifter drogue is lost as the buoy is not dragged underwater as frequently (Lumpkin & Johnson, 2013). The trajectory of undrogued drifters is more directly impacted by wind slippage and Stokes drift (Poulain et al., 2009), so it is essential to know when drifters lose their drogues to analyze their behavior. In the following, only drogued SVP drifters are considered, unless specified otherwise.

In the following paragraphs, we describe the drifter deployments and provide a short description of the trajectories. The five deployments are summarized in Table 1, and the resulting trajectories are shown in Figure 2. The different regions mentioned are shown Figure 1.

Table 1
Summary of Drifter Deployments as Part of the EGC-DrIFT Project

	Deployment date	CARTHEs	SVP-T	SVP-S
Sermilik	August 2019	15	7	8
Fram Strait	September 2019	15	8	7
Cape Farewell	July 2020	15	7	8
Denmark Strait	August 2021	5	2	3
Scoresby Sund	August 2021	10	6	4

The first deployment took place on 14 August 2019, just upstream of Sermilik Trough. Fifteen CARTHE drifters, seven SVP-T and eight SVP-S drifters were deployed along two lines at the shelfbreak. Five of the CARTHE drifters were exported off the shelf east of Greenland, most of them at Cape Farewell, while all SVP drifters continued on the west Greenland shelf after rounding Cape Farewell. This first deployment and its results were described in Duyck and De Jong (2021).

The second deployment took place in Fram Strait, from 2 to 13 September 2019. Fifteen CARTHE, eight SVP-T and seven SVP-S drifters were deployed along one line at 78.8°N. Deployment positions were adjusted to avoid an area of the shelf where sea ice was encountered. Unfortunately, many of these drifters were steered into sea ice shortly after deployment. This resulted in more than half of the drifters ceasing to work within the first 2 weeks. Of the drifters that continued working, two SVP and two CARTHE drifters exited the shelf at the latitude of Fram Strait, and a third SVP drifter was exported toward the Greenland Sea at the latitude of Jan Mayen.

The third deployment took place on 20 July 2020 at Cape Farewell, with 15 CARTHEs, 7 SVP-T, and 8 SVP-S drifters deployed across the shelfbreak at 60°N. The drifters deployed the most onshore remained on the shelf, while the others exited the shelf, and re-entered it west of Greenland. Part of them entered an eddy off Eirik Ridge. Eventually all SVP and CARTHE drifters were transported west of Greenland.

The fourth deployment took place just south of Denmark Strait on 27 July 2021, with five CARTHE, two SVP-T and three SVP-S drifters. The CARTHE drifters stopped working within the first month and a half, and none of them reached Cape Farewell. All the SVP drifters rounded Cape Farewell, and one was exported into the Labrador Sea just west of Cape Farewell instead of continuing into the West Greenland Current (WGC).

The fifth deployment took place near Scoresby Sund on 3 and 4 August 2021, along two lines at 69.65° and 69.95°N. Ten CARTHE, six SVP-T, and four SVP-S drifters were deployed. Similarly as for the Denmark Strait deployment, most CARTHEs did not survive past the first month. Both the CARTHE and SVP drifters showed important cross-shelf exchanges between Scoresby Sund and the southern Blosseville Basin, but all the SVP drifters re-entered the shelf and rounded Cape Farewell into the WGC. Two CARTHE drifters were exported into the Iceland Sea and did not re-enter the shelf.

Overall, the majority of the drifters deployed at the east Greenland shelfbreak remained on the shelf or in the shelfbreak current on the eastern side of Greenland. Most SVP drifters were driven further toward the coast as they were advected downstream. After rounding Cape Farewell, some were exported into the Labrador Sea. The trajectories from CARTHE drifters are similar, but CARTHEs tended to remain at the shelfbreak and were more frequently exported east of Greenland than SVP drifters. Both CARTHE and SVP drifter trajectories indicate exchanges at the shelfbreak, with drifters exiting and re-entering the shelf instead of being exported into interior seas. With the EGC-DrIFT data set, we added 15,000 drogued drifter days in the area, and improved coverage especially close to the coast alongside the southern east and west Greenland shelf, as well as between Kangerdlussuaq Trough and Scoresby Sund, where there was little drifter data before (Figure S1 in Supporting Information S1). The life duration of each drifter depended on the type of drifter and the deployment area, ranging from a few hours to more than 2 years. A summary of all drifters deployed, their life duration and drogue off date can be found in Figure S2 and Table S1 in Supporting Information S1.

Additionally, we used drifter trajectories from the Global Drifter Program 6-hour interpolated data set (GDP, Centurioni et al., 2019; Lumpkin & Centurioni, 2019), from July 1993 to July 2022. There are only sparse data north of Denmark Strait in the GDP and EGC-DrIFT data sets, therefore we also included SVP drifters from the International Arctic Buoy Program data set (IABP, Rigor et al., 2002). There are caveats with using drifters from this data set as most of them were deployed on sea-ice and no information on drogue status is available. To detect when drifters are on ice, we used a temperature threshold of −1.8°C following the IABP recommendation. We only use parts of trajectories identified as being in water in the following. We included the IABP drifters in the study because they add crucial information in areas where data are scarce, while keeping in mind that some of the IABP drifters may be undrogued. Figure S3 in Supporting Information S1 shows the mean circulation computed with and without the IABP data set. The IABP drifter data were processed to remove spikes in the positions and measurements in the same way as the EGC-DrIFT data set, and were interpolated on a 6-hourly timestep from January 1993 to November 2022.

2.2. Other Data Sets

To complement results from drifters, we used sea level anomaly, geostrophic velocities and eddy kinetic energy derived from the Copernicus Marine Service global satellite altimetry product in delayed time SEALEVEL_GLO_PHY_L4_MY_008_047. This merged satellite altimetry product has a 0.25° resolution and is available from 1993 to 2021. It merges data from all available altimeter missions. Only a minority of satellites collect data up to 81°N, most of them only collecting data up to 66°N. Grid cells with ice coverage >15% are set to NaN, and we did not consider areas covered with ice more than 50% of the time, which excludes the inshore Greenland shelf north of 76°N.

We retrieved satellite SST from the GHRSST Level 4 MUR Global Foundation SST Analysis (JPL MUR MEaSUREs Project, 2015), a data blend of microwave, infrared, ice fraction and in situ measurements, with a very high resolution (1 km) in cloudless conditions (Chin et al., 2017). We used MUR data from 1 August to 30 September 2021 and verified that MUR data along drifter tracks correlates well with drifter temperature measurements (mean correlation of 0.95).

We retrieved the wind speed and wind angle at 10 m from the Copernicus Climate Data Store Arctic Regional Reanalysis on single levels (CARRA, Schyberg et al., 2020) atmospheric reanalysis. We computed the zonal and meridional wind velocities from these variables. We selected CARRA data from 1998 to 2022 with a 6-hr temporal resolution. The reanalysis has a 2.5 km spatial resolution. We identified Tip Jets and strong northeasterly wind events in the data set using the method described in Duyck et al. (2022). We identified Tip Jets as westerly winds (mean wind direction toward the 45°–135° quadrant with respect to north) with a mean speed over 17 m s^{-1}, that persist for at least 12 hr. For moderate westerlies, the threshold was lowered to 8 m s^{-1}. Strong and moderate north-easterlies were defined with the same threshold, and mean wind direction toward the 180°–270° quadrant with respect to north.

2.3. Computations of Transports and Export Across the East Greenland Shelfbreak

The east Greenland shelf is on average 200–400 m deep, with some deeper troughs cutting across the shelf, that can reach 1,000 m depth. A strong bathymetric slope delimitates the continental shelf and deep ocean, with the ocean floor falling from 400 to 2,000 m deep over a few kilometers. In the following, we use the 600 m isobath as a boundary for the shelf to identify cross shelf fluxes and refer to that boundary as "shelfbreak." This isobath was retrieved from Fram Strait to Cape Farewell from the ETOPO2022 60 arc-seconds data set, and smoothed with a 50 km window. We divided the shelfbreak into 31 100 km-long sections and computed the number of shelfbreak crossings by drogued SVP drifters within these sections. Sections of the shelfbreak where more offshore than inshore crossings occur indicate areas of possible freshwater export. However, drifters are sometimes exported at one section and re-imported in the following section. Thus, these numbers are indicative of exchange areas rather than a quantitative estimate of export.

We computed Ekman transport at the shelfbreak to estimate potential wind-driven export in different areas of the shelf. Ekman transport was computed for each time step from wind stress as per Equations 1 and 2, interpolated on the shelfbreak and rotated according to the local shelf angle to obtain Ekman transport across the shelfbreak (T_{ek_sh}, Equation 3).

$$\begin{cases} \tau_x = \rho_{air} C_d u \sqrt{u^2 + v^2} \\ \tau_y = \rho_{air} C_d v \sqrt{u^2 + v^2} \end{cases}, \quad (1)$$

with τ_x, τ_y the meridional and zonal wind stress, u and v the zonal and meridional wind components at 10 m, $\rho_{air} = 1.2$ kg m^{-3} the air density, and C_d the wind drag defined non-linearly according to Trenberth et al. (1990).

$$\begin{cases} T_{x\_ek} = \dfrac{\tau_y}{f\,\rho} \\ T_{y\_ek} = \dfrac{-\tau_x}{f\,\rho} \end{cases}, \quad (2)$$

$$T_{ek\_sh} = \cos(\theta_{sh})T_{y\_ek} - \sin(\theta_{sh})T_{x\_ek}, \tag{3}$$

With T_{x_ek} and T_{y_ek} the zonal and meridional Ekman transports, f the Coriolis parameter at 70°N retrieved from TEOS 10 GSW oceanographic toolbox (McDougall & Barker, 2011), $\rho = 1{,}027$ kg m^{-3} the water density, and θ_{sh} the local angle of the shelfbreak, computed anticlockwise from the x axis, so that in the rotated frame, axes are along shelf southwards, and across shelf offshore.

We similarly computed geostrophic velocities across the shelfbreak at each time step to identify areas most favorable to export. Geostrophic velocities from satellite altimetry (u_g and v_g) were interpolated at the shelfbreak and rotated to obtain geostrophic velocity across the shelfbreak (v_{g_sh}, Equation 4).

$$v_{g\_sh} = \cos(\theta_{sh})v_g - \sin(\theta_{sh})\mathrm{u}_g \tag{4}$$

3. Results

3.1. Overview of the East Greenland Circulation and Possible Exchange Areas

The EGC-DrIFT data set provides new insight close to the southeast Greenland coast and in areas with scarce drifter density, such as the Blosseville Basin, but the data are concentrated in specific time periods, mostly in summer. In the following, we use data from the EGC-DrIFT, GDP and IABP data sets, as well as geostrophic velocities from dynamic topography and surface winds from the CARRA reanalysis to identify potential regions of enhanced export at the east Greenland shelfbreak.

The data coverage and mean circulation inferred from the three drifter data sets are shown Figure 3a. South of Denmark Strait, the drifter-derived circulation agrees well with geostrophic velocities derived from dynamic topography (Figure 3c). In the Denmark Strait area (Figure 3b), the available drifter data mostly originate from our 2021 deployment (Figure S1 in Supporting Information S1). This concentration in time results in some differences between the two. North of Scoresby Sund, the drifter data density is very sparse. Only the shelfbreak EGC is well sampled there.

Over most of the shelfbreak, the geostrophic velocities are strongly directed along the shelf. At the Blosseville Basin and Cape Farewell, both the drifter-derived and geostrophic mean circulation show shelf waters being driven off-shelf, the first one as shelf waters flow through Blosseville Basin, the second one as they are driven over Eirik Ridge. On the contrary, deep troughs like the Sermilik and Kangerdlussuaq troughs, contribute to constraining freshwater on the shelf by driving part of the shelfbreak current toward the coast. Data coverage is too sparse to investigate exchanges upstream of Scoresby Sund.

The computation of drifter crossings at the shelfbreak shows four areas that display more drifter export than import, which indicates possible export of fresh shelf waters toward the interior (Figures 4a and 4b): At 75°N, north of Scoresby Sund, south of Sermilik Trough, and at Cape Farewell. As noted before, the scarcity of data north of Scoresby Sund limits our insight into possible export in the northern part of the east Greenland shelf. The export region just south of Sermilik Trough corresponds to a bend in the shelf. The strongest net export is observed at Cape Farewell. At some of the sections we observe a lot of exchanges, but no net export of drifters. It is unknown what this means in terms of freshwater exchange.

The mean across-shelf geostrophic velocity is oriented offshore over most of the shelfbreak, except for a few areas that correspond to bends in the topography (Figure 4c). The section of the shelfbreak with the strongest mean offshore geostrophic velocity is the southeast shelf, from downstream of Sermilik Trough to Cape Farewell. Eddy kinetic energy derived from satellite altimetry indicate the Denmark Strait sill as the most energetic area, followed by the shelfbreak region from just upstream to just west of Cape Farewell. Eddies in these areas could contribute to freshwater exchanges with interior seas.

Between 74° and 60°N the wind is predominantly north-easterly and along-shelf. This drives inshore Ekman transport (Figure 4d). A few regions stand out where winds are more often favorable to export. At Cape Farewell, north-easterlies alternate with localized westerly winds, including Tip Jets. Winds are favorable for export about 50% of the time. Two other regions show weaker mean on-shelf transport than the rest of the shelf: Between 74° and 76°N, the dominant northerly winds are not along-shelf, which leads to a lesser onshore transport than over

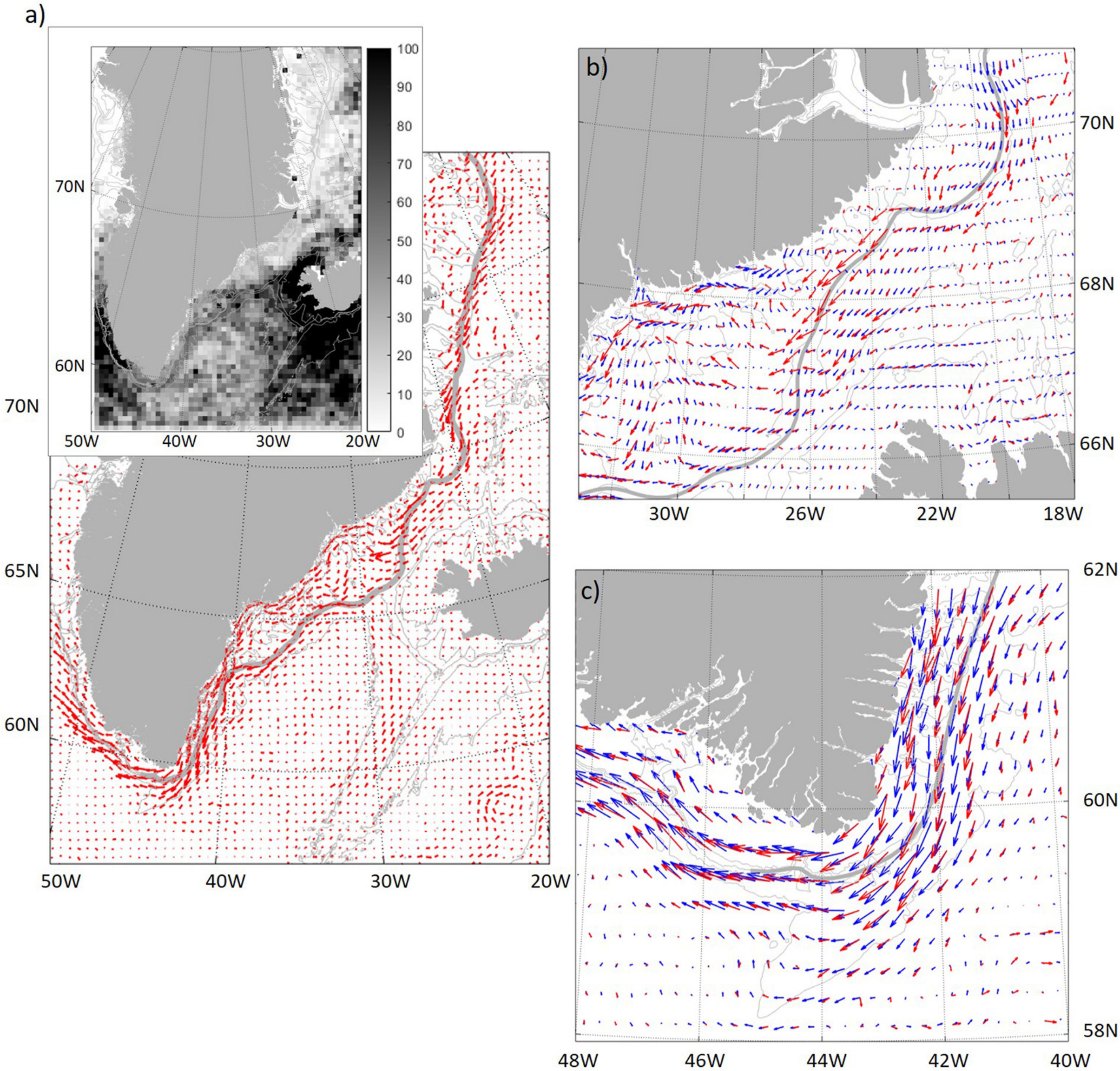

Figure 3. Mean circulation from drifters and altimetry-derived geostrophic velocities (a). Number of drifter day per bins and mean surface circulation computed using the East Greenland Current Drifter Investigation of Freshwater Transport, International Arctic Buoy Program data set, and Global Drifter Program 6-hour interpolated data set drifter data sets; (b). Mean surface circulation from drifters (red) and mean geostrophic velocity (blue) upstream of Denmark Strait; (c). Same at Cape Farewell. To obtain the circulation map, we compute mean drifter velocities in 30 × 30 km bins using the jlab 2dstats function (Lilly, 2021). Only bins with more than 5 drifter days are shown. Bathymetry in gray at −2,000, −1,000, −500, and −200 m. The thick gray line represents the shelfbreak.

the rest of the shelf. At Sermilik Trough, the weaker inshore Ekman transport could be associated to wind variability and to the sharp bend of the shelfbreak.

In the following, we investigate the local circulation and processes driving exchanges in the Blosseville Basin, and Cape Farewell regions, two areas highlighted as potential enhanced export regions.

3.2. Exchange Processes in the Blosseville Basin

One of the areas identified as favorable to cross-shelf exchanges and potential freshwater export in the previous section is the Blosseville Basin and Denmark Strait region, where drifters were brought on and off the shelf. This is consistent with existing studies, that identified a bifurcation of the EGC just upstream of Blosseville Basin (Våge et al., 2013) and described eddies at the shelfbreak and in the basin (Håvik, Våge, et al., 2017).

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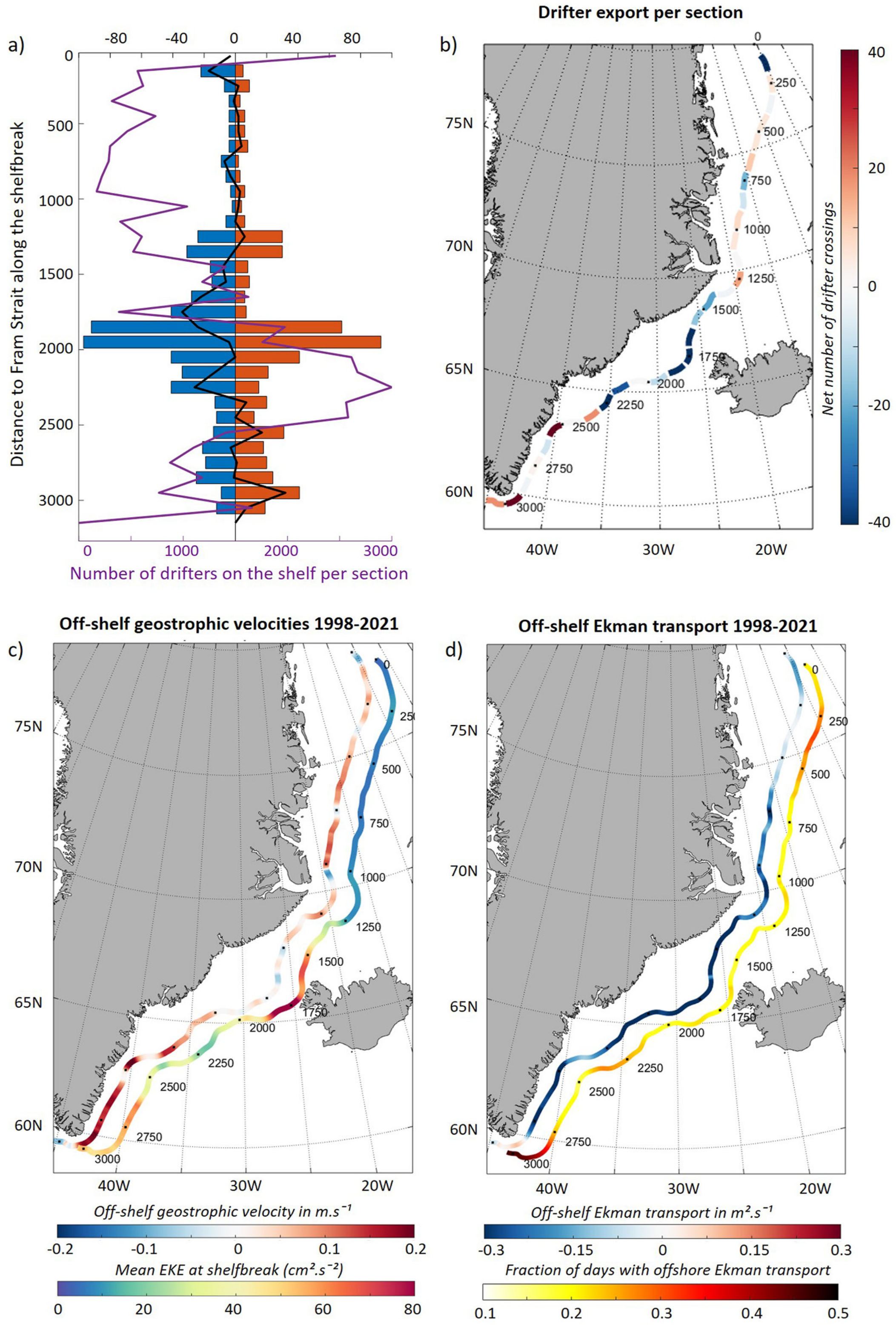

Figure 4.

Exchanges between the shelf and the interior in this region are illustrated by the drifters deployed at Scoresby Sund and Denmark Strait in summer 2021. The drifters that were deployed at Scoresby Sund separated into four groups with distinct behaviors after they were deployed (Figure 5a).

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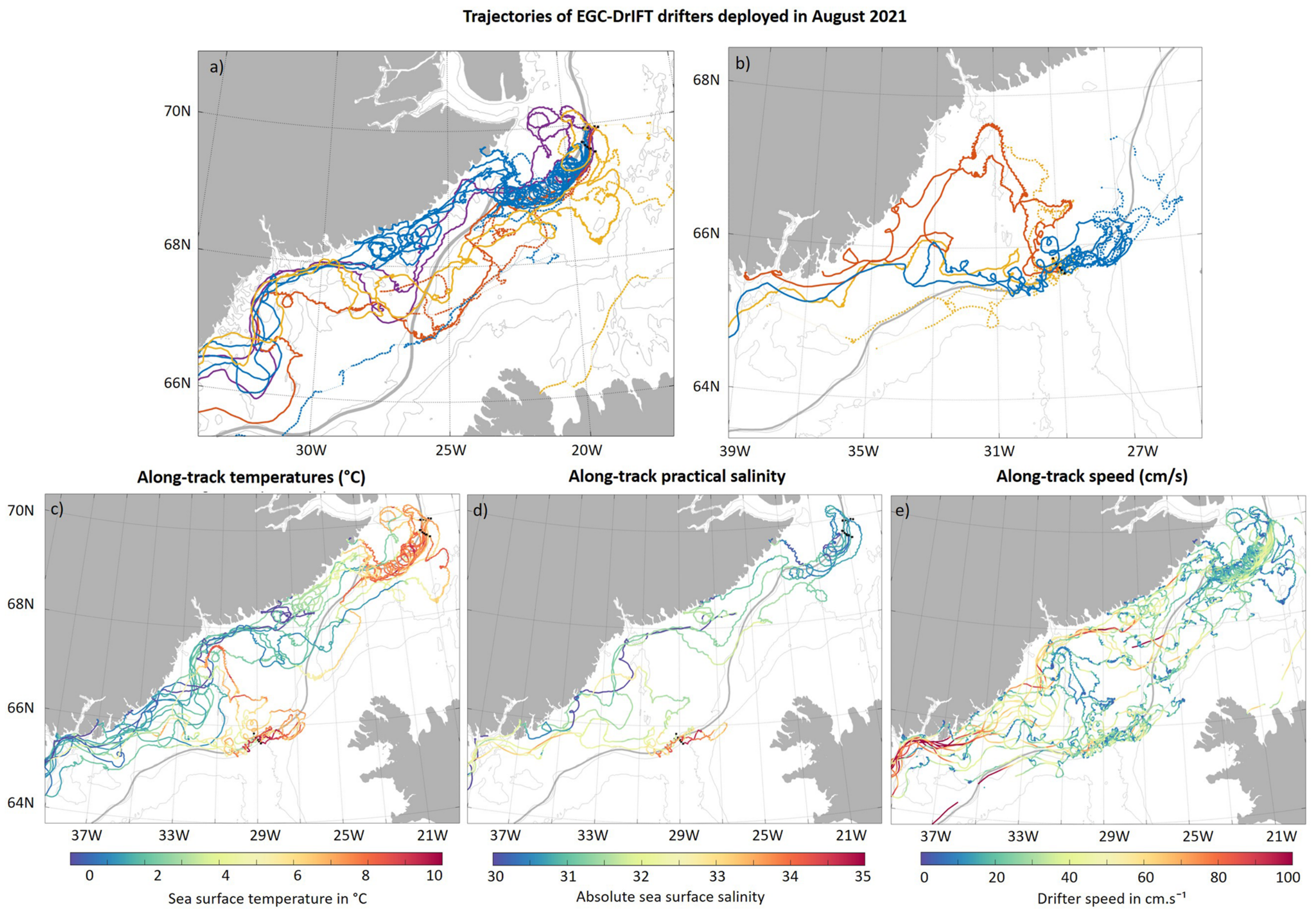

Figure 5. Trajectories and properties of drifters deployed at Scoresby Sund and Denmark Strait. (a) Trajectories from drifters deployed at Scoresby Sund. See text for explanation of colors. (b) Same for drifters deployed at Denmark Strait. (c) Temperatures along trajectories as measured by Surface Velocity Program (SVP) drifters. (d) Salinity along trajectories as measured by SVP-B drifters. (e) Velocities from SVP and Consortium for Advanced Research for the Transport of Hydrocarbon in the Environment drifters. Bathymetry in gray at −2,000, −1,000, −500, and −200 m. The thick gray line represents the shelfbreak.

1. A first group, consisting of five SVP (in blue) and five CARTHE drifters (in blue, dashed line) deployed inshore of the shelfbreak, were apparently deployed in a warm and fresh eddy (Figures 5c and 5d). The drifters remained in the eddy between 15 and 25 days and exited the eddy as it reached Blosseville Basin at 67.5°N. After leaving the eddy, one of the CARTHE drifters crossed to the Iceland side of the Blosseville Basin. The SVP drifters were pushed back on the shelf and two SVP drifters ran aground on the Greenland coast while the rest were advected downstream along the coast while continuing to show eddying behavior. They entered the core of the EGCC as they approached Kangerdlussuaq trough (Figure 5e).
2. A second group, consisting of one SVP (in red) and three CARTHE drifters (red, dashed line) deployed at the northern line, initially followed the shelfbreak without entering the eddy. The three CARTHE drifters exited the Greenland shelf just south of Scoresby Sund, were advected across the Blosseville Basin and back on the shelf at Denmark strait. The SVP drifter followed the shelfbreak to ∼68.5°N, turned toward Iceland, followed the east side of the Blosseville Basin south to Denmark Strait and re-entered the east Greenland shelf at ∼67°N. That drifter also measured rapid SST changes, cooling down as it crossed from the shelfbreak into the Blosseville Basin, and cooling further as it re-entered the shelf downstream.

Figure 4. (a) Number of drifter crossings per section of the shelfbreak. The purple line shows the number of drifter days on the shelf per section, and the black line shows the net number of offshore crossings (offshore-inshore). (b) Net number of offshore crossings (off-shore crossings—onshore crossings) per shelfbreak section. (c) Mean geostrophic transport across the shelfbreak (positive is offshore) and mean eddy kinetic energy at the shelfbreak, 1998–2021. The mean eddy kinetic energy is not shown at the geographic location of the shelf, but next to it, to allow for comparisons with the mean geostrophic transport; (d) Mean Ekman transport across the shelfbreak and fraction of days with offshore Ekman transport, 1998–2021. Similarly as for (c), the fraction of days is shown next to the mean Ekman transport rather than at the geographic location of the shelf.

3. A third group, consisting of two SVP (in yellow) and two CARTHE drifters (yellow, dashed line), deployed offshore of the shelfbreak at the southern line, exited the shelfbreak at Scoresby Sund (Figure 5a). The two SVP drifters were exported off-shelf at the latitude of Scoresby Sund, were advected south into the Blosseville Basin, and reentered the shelf close to the Denmark Strait sill. The two CARTHE drifters remained off the Greenland shelf after being exported.
4. The remaining two SVP drifters (in purple) were driven toward the coast shortly after deployment and were advected downstream over the shelf before entering the EGCC as they approached Kangerdlussuaq Trough.

The drifters deployed at Denmark Strait can similarly be categorized in three groups (Figure 5b): (a) A first group, consisting of the three SVP (in blue) and three CARTHE drifters (blue, dashed line) deployed most offshore, first headed northwards into the strait. They then headed back southwards, entered the shelf, drifted toward the coast and entered the EGCC at Sermilik Trough. (b) A second group, consisting of one SVP (in yellow) and the two CARTHE drifters (yellow, dashed line) deployed most inshore, were immediately advected southwards along the shelfbreak. The SVP drifter was driven into the EGCC at the level of Sermilik Trough. (c) A third group, consisting of the remaining two SVP (in red) and one CARTHE drifter (red, dashed line), was steered into the Kangerdlussuaq Trough toward the coast where they entered the EGCC.

The drifter tracks show exchanges in the Blosseville Basin area. SVP drifters exported at the Blosseville Basin all re-entered the shelf as they reached Denmark Strait and were driven into the EGCC at Kangerdlussuaq Trough. A few CARTHE drifters did not join the EGCC, but they all stopped transmitting within the first 2 weeks after deployment. We now further investigate the conditions in the Blosseville Basin that led to the exchange.

From mid-June to early September 2021, the winds over Scoresby Sund, the shelf, and the Blosseville Basin, were mostly south-westerly, which is unusual, as winds in the regions are normally predominantly north-easterly, including in the summer (Figure 6c). This resulted in an anticyclonic circulation in the basin and a cyclonic circulation over the shelf (Figure 6a). This circulation was strongest in the first part of August, at the time of deployment. From mid-August, strong north-easterly winds started dominating again (Figure 6d) and the anticyclonic circulation in the Blosseville Basin disappeared. This caused the geostrophic velocities to be intensified at the coast (Figure 6b), concurrently with an acceleration of the drifters (Figure 5e). The change in wind conditions and circulation was reflected in SST.

Figure 7 shows satellite SST over the same period, together with drifter trajectories. The along-track temperature measured by SVP drifters is close to the satellite SST. We observe a rapid cooling (by 4°C) of the shelf waters and the Blosseville Basin between the end of August and early September, concurrently with the strengthening of northeasterly winds and the associated change in dynamic topography. The colder waters first appear at the shelf, maybe coming from upstream, and then extend toward the Iceland Sea and into the Blosseville Basin. South of the Blosseville Basin, the SST and drifter trajectories shows the impact of the deep Kangerdlussaq Trough on exchanges between the shelf and warmer waters at the sheflbreak, with warmer interior waters entering the trough and drifters being steered around it.

3.3. Cape Farewell

Cape Farewell is another area identified as favorable to cross shelf exchanges and potential freshwater export. In that region, strong westerly wind events (Tip Jets) could contribute to local off-shelf freshwater export (Duyck & De Jong, 2021; Duyck et al., 2022). Moreover, both geostrophic velocities and the combined drifter data set suggest that the EGC moves away from the shelfbreak as it is steered around Eirik Ridge (Figure 3c).

This is illustrated by the drifters deployed at Cape Farewell in July 2020 (Figure 8a). After deployment, the drifters separated in three groups. (a) The first group consists of the nine SVP (in blue) and 13 CARTHE drifters (blue, dashed line) deployed most offshore. They meandered closer and further from the shelfbreak while traveling around Cape Farewell. They arrived at 46°W seven days after deployment. (b) A second group, consisting of five SVP drifters (in red) were driven off-shelf over Eirik Ridge, where they appear to have been trapped in an eddy. The eddy moved west along the shelfbreak and the SVPs entered the WGC at different points of the shelfbreak. It took these drifters 15 days longer to arrive at 46°W. CARTHEs deployed together with the SVP drifters from this second group did not enter the eddy and are in group one. (c) The inshore group, consisting of two CARTHEs (in yellow, dashed line) and one SVP (yellow) remained on the shelf, were advected toward the WGC as they arrived west of Greenland, and headed back toward the coast. This is similar to trajectories of drifters originating from the EGCC described by Duyck and De Jong (2021).

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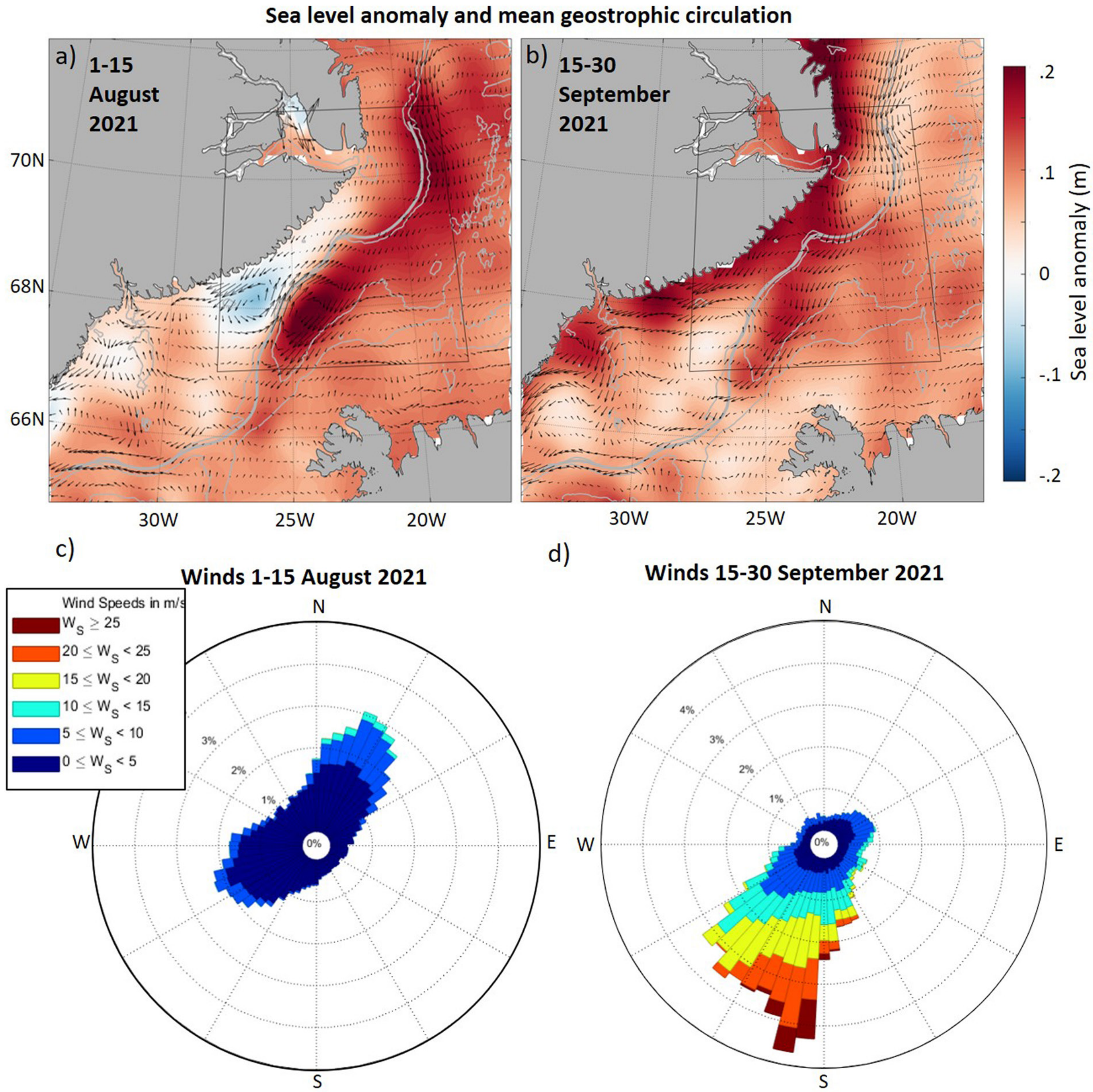

Figure 6. (a) Mean sea level anomaly and mean geostrophic velocities from 1 to 15 August 2021 (left) and 15 to 30 September 2021 (right). Bathymetry in gray at −2,000, −1,000, −500, −200 m. The thick gray line represents the shelfbreak; (b) Wind polar plot for winds in the area delimited in panels (a, b), for the same time periods. The wind angle corresponds to the direction winds flow toward.

Temperature and salinity along the tracks show a sharp transition in water properties between drifters deployed at the shelfbreak and off-shelf (Figures 8c and 8d). As they enter the eddy, drifters from the second group measure much warmer (from 4° to 7°) and saline (33.5–34.9) waters, similar to the offshore group.

The deployment at Cape Farewell in 2020 took place at a time when winds were northeasterly (Figure 8b) and therefore not favorable to export. Drifters crossing the shelfbreak east of Cape Farewell suggest that even as winds could be an important driver of export at Cape Farewell, they are not the only one. The eddy sampled by the drifters is an indication that eddy activity could play a role in mixing shelf waters into interior waters. This cannot be explored further with this data.

We can further investigate the role played by winds at Cape Farewell. Using the combined (EGC-Drift, GDP, IABP) drifter data set, we look at drifter advection during specific wind events identified in the CARRA

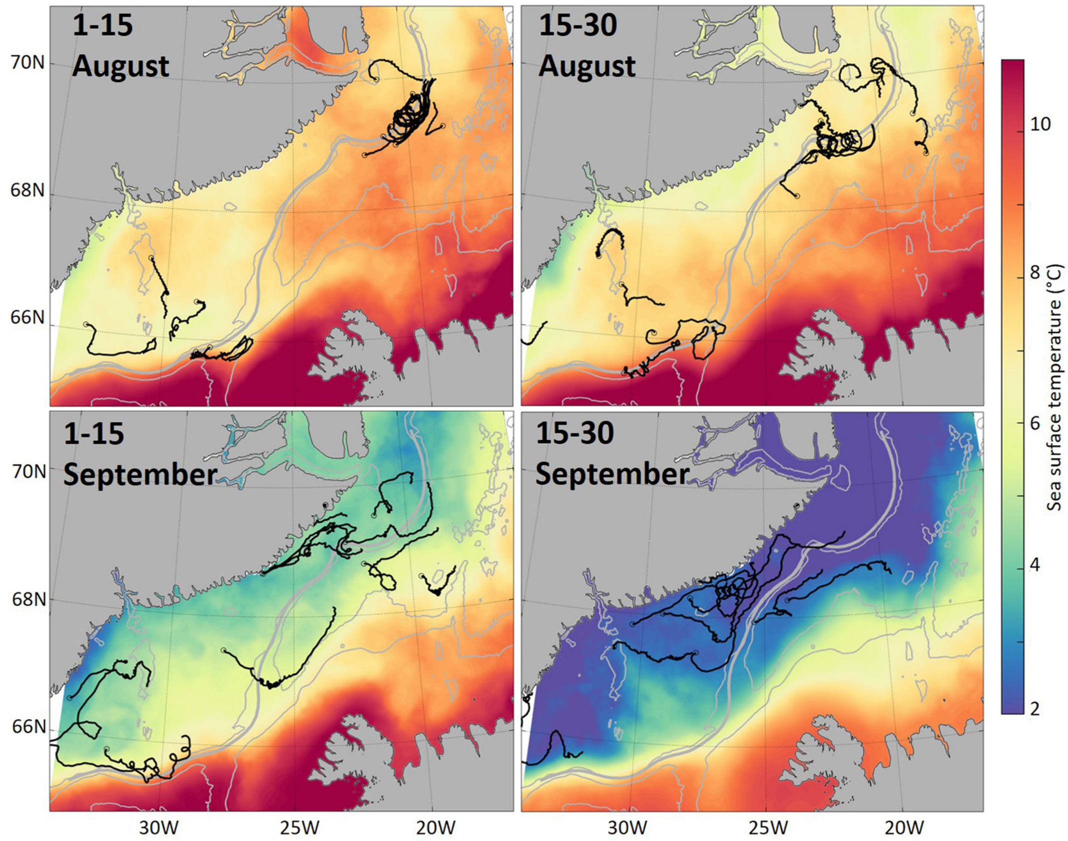

Figure 7. Mean sea surface temperature from MUR per 15 days and drifter trajectories during the corresponding time period. Bathymetry in gray at −2,000, −1,000, −500, and −200 m. The thick gray line corresponds to the shelfbreak.

reanalysis. We identify strong northeasterlies and Tip Jets (defined in Section 2.2) using time series of spatially averaged wind direction and speed at Cape Farewell (see box Figure 9a) from 1998 to 2022. We select trajectories from drifters from 1 before to 1 day after the peak of these Tip Jet and strong north-easterly events. Figure 9a shows these composites for drifters from the GDP (blue), the IABP (red), and EGC-DrIFT (green) data sets. The pale colors indicate undrogued drifters, which are more sensitive to wind. We find twice more drifters in the area during strong northeasterlies than during Tip Jets, due to seasonal differences in occurrences of these wind events and drifter coverage. The effect of the wind is most clearly visible off the shelf, outside of the influence of the strong EGC. During northeasterlies, tracks are directly along the shelf. During Tip Jets, tracks are directed to the east. In both cases, undrogued drifters from the GDP data set show a stronger response to the wind direction.

We extend the analysis to moderate westerlies and northeasterlies (defined in Section 2.2), that have also been shown to be of importance by Duyck et al. (2022). We compute the mean circulation from drifters during these two types of events. During northeasterlies (blue), we find a slightly stronger EGC. During westerlies (red), we see stronger steering toward the shelf edge upstream of Eirik Ridge and offshelf at Eirik Ridge (Figure 9b).

At Cape Farewell winds, eddies, but also the topographically steered mean circulation contribute to enhancing the potential for surface waters from the shelf mixing with interior waters. We however observe only limited freshwater export as most of the drifters that arrive at Cape Farewell round the Cape and continue into the WGC, even if they were driven off-shelf east of Greenland.

4. Discussion and Conclusions

The data presented here highlight two areas of exchange, the Blosseville Basin and Cape Farewell, and point toward winds and eddies as exchange processes. Over most of the rest of the shelf, northeasterly winds and deep troughs constrain the flow to the EGC and EGCC. Scarce drifter coverage north of 71°N hinders investigation

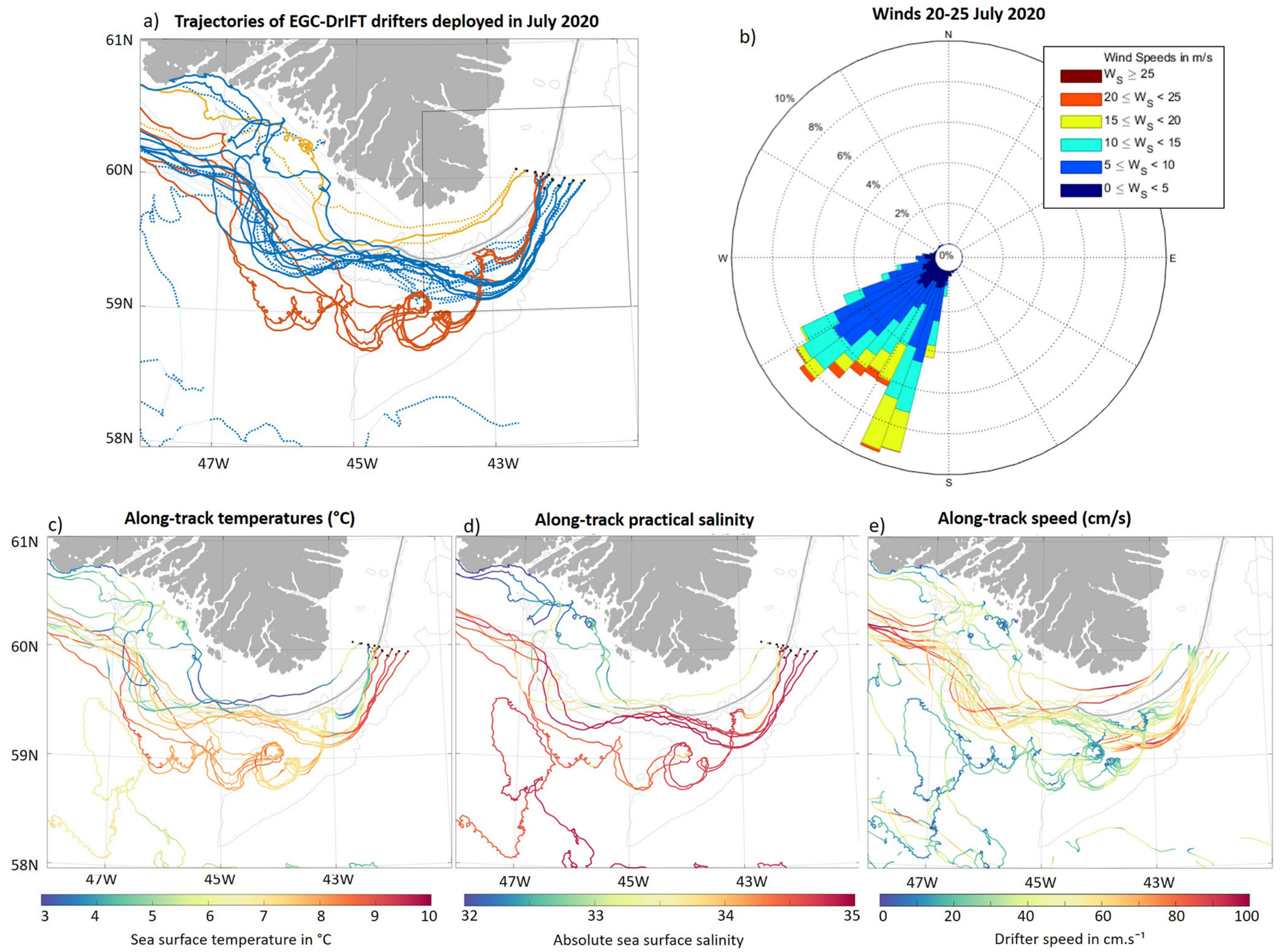

Figure 8. Trajectories and properties of drifters deployed at Cape Farewell in 2020. (a) Trajectories of Surface Velocity Program and Consortium for Advanced Research for the Transport of Hydrocarbon in the Environment (CARTHE) drifters colored as described in the text. Faded colors correspond to CARTHEs. (b) Wind polar plot showing the direction winds flow toward, for the area shown in black in (a) from 25 to 30 July 2020, in the week after deployment. (c) Along track temperatures, (d) Along track salinity. (e) Along track speed. Bathymetry in gray at −2,000, −1,000, −500, and −200 m. The thick gray line represents the shelfbreak.

on the northern part of the shelf. The export of fresh surface waters from the northern Greenland shelf into the Nordic Seas could be of particular importance to the formation of the dense waters that form the overflow waters in the AMOC lower limb (Chafik & Rossby, 2019; Huang et al., 2020). Observations along the shelf (Dickson et al., 2007; Håvik, Pickart, et al., 2017) suggest that some of the fresh surface waters are exported away from the shelf between Fram Strait and Denmark Strait, while other studies suggest only limited export (Dukhovskoy et al., 2019). Dodd et al. (2009) argue that a majority of the export is due to sea ice. Using CARRA, we show that winds over the northern part of the shelf are less constraining than in other areas, which could allow for enhanced export, in particular of sea ice. Further studies are necessary to quantify liquid and solid freshwater export of the Greenland shelf north of 71°N.

At Scoresby Sund, the EGC-DrIFT drifters were initially in an eddy, until they reached Blosseville Basin. Part of them were then advected on the shelf while the rest crossed the basin (Figure 5a). The mean circulation derived from all drifters shows the shelfbreak EGC and separated EGC flowing on both sides of the basin (Figure 3b). During the EGC-DrIFT deployment, winds were predominantly southwesterly, causing an anticyclonic circulation in the Blosseville Basin. By September, the winds were northeasterly and the anticyclone disappeared. This change was associated with inflow of colder waters, which extended toward Iceland. This is consistent with Håvik and Våge (2018) who argued that upwelling favorable winds (that lead to offshore Ekman transport) are associated with an extension of lighter waters over the Greenland slope in the Blosseville Basin area. There are

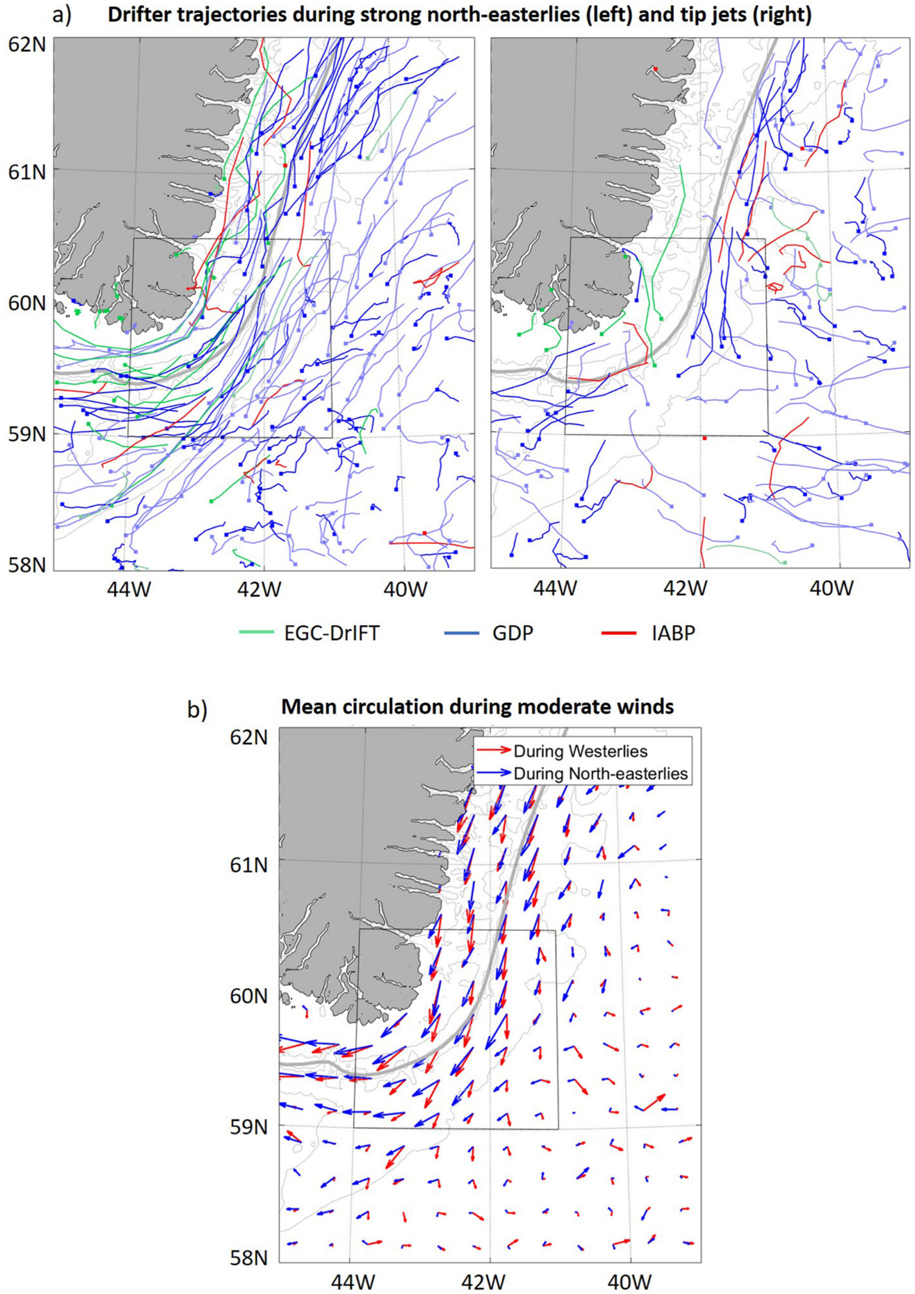

Figure 9. Impact of wind events on drifters at Cape Farewell. (a) Trajectories of drifters from 1 day before to 1 day after peak Tip Jet (left) and strong north-easterlies events. The direction of trajectories is represented by a large dot at the end of the segment. (b) Binned circulation of drifters from the combined data set during westerly and north-easterly events. Bathymetry in gray at −2,000, −1,000, −500, and −200 m. The thick gray line represents the shelfbreak.

two hypotheses for the formation of the separated EGC (Våge et al., 2013). It could result from the shedding of eddies just upstream of Blosseville Basin that coalesce at the base of the Iceland shelf (De Steur et al., 2017; Håvik, Våge, et al., 2017). Alternatively, it could result from negative wind stress curl over the basin creating an anticyclone, of which the shelfbreak EGC is the return branch (Harden et al., 2016). These hypotheses are not mutually exclusive and our results offer support for both.

At Cape Farewell, we show that surface water can be brought offshore due to wind, eddy, and topography driven processes. Westerly winds at Cape Farewell have a strong impact on local circulation (Figure 9b) and facilitate export as Duyck et al. (2022) suggested using a high-resolution model. The mean circulation in that area is slightly offshore of the shelfbreak as it is steered by Eirik Ridge (Figure 3c). Additionally, eddies could contribute to export or mixing. Nearly all SVP drifters that left the east Greenland shelf at Cape Farewell re-entered it on the western side of Greenland. However, this does not preclude export of freshwater as mixing and loss of freshwater may occur along the way. A quantitative measure of export along the east Greenland shelf cannot be determined as this would require high quality salinity fields in the Greenland shelf region. Current salinity satellite products are not accurate at high latitude, near land or near ice (Vinogradova et al., 2019). Salinity data from Argo are sparce and limited to regions deeper than 2 km. An estimate derived from changes in salinity, or freshwater storage, in the region is difficult because of the large uncertainties on precipitation and evaporation. Our analysis suggests that export of liquid freshwater between Scoresby Sund and Cape Farewell is likely to be small.

Export off the west Greenland shelf is known to be larger. There it is driven both by eddies and winds (Chanut et al., 2008; Hátún et al., 2007; Schulze Chretien & Frajka-Williams, 2018). In the EGC-DrIFT data set, 13 of the 34 SVP drifters that arrived west of Greenland were exported in the Labrador Sea, five of which were originally in the EGCC (Figure 2). This indicates exchange between the coastal current and the shelfbreak current as they round Cape Farewell, as also shown by Lin et al. (2018). Previous studies showed that most of the freshwater exported in the Labrador Sea originated from the EGC, instead of glaciers from southeast Greenland (Luo et al., 2016) or from the Canadian Arctic Archipelago (Wang et al., 2018). Exchanges between the coast and shelfbreak at Cape Farewell influence the freshwater distribution over the west Greenland shelf and are therefore important for freshwater export west of Greenland.

On a longer timescale, if additional freshwater is exported into the Labrador Sea, it will influence other regions of the SPNA. A freshening of the Labrador Sea would indirectly impact the Irminger Sea. However, a freshwater anomaly at the surface of the Labrador Sea must be advected to the Irminger Sea quickly to remain at the surface, as freshwater is mixing down and diluted over a layer of several hundred meters thick through fall and winter (Dukhovskoy et al., 2019), after which it will affect intermediate levels of the Irminger Sea hydrography (M. F. de Jong et al., 2012; Lavender et al., 2005). The EGC-DrIFT deployments (Figure 2), as well as GDP data, suggest there is no short and fast route from the west Greenland shelf to the central Irminger Sea. The freshwater anomaly that formed off the Labrador shelf in 2012 (Holliday et al., 2020) traveled around the subpolar gyre, was further strengthened at the surface by precipitation, and was seen to arrive in the eastern Irminger Sea in 2016 (Biló et al., 2022; F. M. de Jong et al., 2020). In general, the seasonal appearance of a fresh layer suggests more regular and nearby sources. We did not find evidence of a clear advective pathway from the east Greenland shelf in this study.

Exchanges between the southeast Greenland shelf and interior seas are driven by winds, eddies and topographic steering. These processes are small scale, intermittent and highly localized. It is likely the eddies and topographic effect enhance mixing of freshwater into the water column in the near shelf region, but it seems less likely that these will export large volumes of freshwater into the interior. Wind events, if sustained long or often enough, may export larger amounts and would be found in a shallow layer (Duyck et al., 2022). However, strong freshwater years (Oltmanns et al., 2018; Sterl & de Jong, 2022) were preceded by low Tip Jet winters. Nor did precipitation fully explain the interannual variability in freshwater stratification (Sterl & de Jong, 2022). Further study into the interannual variability of local wind, ice and precipitation driven freshwater fluxes will be needed to explain the large changes in freshwater stratification seen in some summers.

Data Availability Statement

The EGC-DrIFT data set is available from Duyck and De Jong (2023). The IABP data set can be retrieved from the IABP website (https://iabp.apl.uw.edu/, Rigor et al., 2002), and the GDP data set is available from Lumpkin and Centurioni (2019). This research made use of the EU Copernicus Marine Service Information altimetry product (Copernicus Marine Service, 2022), the MUR satellite sea surface temperature data set (JPL MUR MEaSUREs Project. 2015), the CARRA atmospheric reanalysis from the Copernicus Climate Data Store (Schyberg et al., 2020) and the ETOPO2022 bathymetry (NOAA National Centers for Environmental Information, 2022), as well as the jlab software (Lilly, 2021).

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References

Aagaard, K., & Carmack, E. C. (1989). The role of sea ice and other fresh water in the Arctic circulation. *Journal of Geophysical Research*, *94*(C10), 14485. https://doi.org/10.1029/JC094iC10p14485

Bacon, S., Marshall, A., Holliday, N. P., Aksenov, Y., & Dye, S. R. (2014). Seasonal variability of the East Greenland coastal current. *Journal of Geophysical Research: Oceans*, *119*(6), 3967–3987. https://doi.org/10.1002/2013JC009279

Bakker, P., Schmittner, A., Lenaerts, J. T. M., Abe-Ouchi, A., Bi, D., van den Broeke, M. R., et al. (2016). Fate of the Atlantic meridional overturning circulation: Strong decline under continued warming and Greenland melting. *Geophysical Research Letters*, *43*(23), 12252–12260. https://doi.org/10.1002/2016GL070457

Bamber, J. L., Tedstone, A. J., King, M. D., Howat, I. M., Enderlin, E. M., van den Broeke, M. R., & Noel, B. (2018). Land ice freshwater budget of the Arctic and North Atlantic Oceans: 1. Data, methods, and results. *Journal of Geophysical Research: Oceans*, *123*(3), 1827–1837. https://doi.org/10.1002/2017JC013605

Biló, T. C., Straneo, F., Holte, J., & Le Bras, I. A. (2022). Arrival of new great salinity anomaly weakens convection in the Irminger Sea. *Geophysical Research Letters*, *49*(11), e2022GL098857. https://doi.org/10.1029/2022GL098857

Böning, C. W., Behrens, E., Biastoch, A., Getzlaff, K., & Bamber, J. L. (2016). Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean. *Nature Geoscience*, *9*(7), 523–527. https://doi.org/10.1038/ngeo2740

Bourke, R. H., Paquette, R. G., & Blythe, R. F. (1992). The Jan Mayen current of the Greenland Sea. *Journal of Geophysical Research*, *97*(C5), 7241–7250. https://doi.org/10.1029/92JC00150

Buckley, M. W., & Marshall, J. (2016). Observations, inferences, and mechanisms of the Atlantic meridional overturning circulation: A review. *Reviews of Geophysics*, *54*(1), 5–63. https://doi.org/10.1002/2015RG000493

Casanova-Masjoan, M., Pérez-Hernández, M. D., Pickart, R. S., Valdimarsson, H., Ólafsdóttir, S. R., Macrander, A., et al. (2020). Along-stream, seasonal and interannual variability of the North Icelandic Irminger current and East Icelandic current around Iceland. *Journal of Geophysical Research: Oceans*, *125*(9), e2020JC016283. https://doi.org/10.1029/2020JC016283

Centurioni, L. R., Turton, J., Lumpkin, R., Braasch, L., Brassington, G., Chao, Y., et al. (2019). Global *in situ* observations of essential climate and ocean variables at the air–sea interface. *Frontiers in Marine Science*, *6*, 419. https://doi.org/10.3389/fmars.2019.00419

Chafik, L., & Rossby, T. (2019). Volume, heat, and freshwater divergences in the subpolar North Atlantic suggest the Nordic Seas as key to the state of the meridional overturning circulation. *Geophysical Research Letters*, *46*(9), 4799–4808. https://doi.org/10.1029/2019GL082110

Chanut, J., Barnier, B., Large, W., Debreu, L., Penduff, T., Molines, J. M., & Mathiot, P. (2008). Mesoscale eddies in the Labrador Sea and their contribution to convection and restratification. *Journal of Physical Oceanography*, *38*(8), 1617–1643. https://doi.org/10.1175/2008JPO3485.1

Chin, T. M., Vazquez-Cuervo, J., & Armstrong, E. M. (2017). A multi-scale high-resolution analysis of global sea surface temperature. *Remote Sensing of Environment*, *200*, 154–169. https://doi.org/10.1016/j.rse.2017.07.029

Collins, M., Sutherland, M., Bouwer, L., Cheong, S. M., Frolicher, T., DesCombes, H. J., et al., (2019). Extremes, abrupt changes and managing risks. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, et al. (Eds.). *IPCC special report on the ocean and cryosphere in a changing climate* (pp. 589–655).

Copernicus Marine Service. (2022). Global Ocean gridded L 4 sea surface heights and derived variables reprocessed 1993 ongoing [Dataset]. https://doi.org/10.48670/moi-00148

de Jong, F. M., Steur, L., Fried, N., Bol, R., & Kritsotalakis, S. (2020). Year-round measurements of the Irminger current: Variability of a two-core current system observed in 2014–2016. *Journal of Geophysical Research: Oceans*, *125*, e2020JC016193. https://doi.org/10.1029/2020JC016193

de Jong, M. F., Van Aken, H. M., Våge, K., & Pickart, R. S. (2012). Convective mixing in the central Irminger Sea: 2002-2010. *Deep-Sea Research Part I Oceanographic Research Papers*, *63*, 36–51. https://doi.org/10.1016/j.dsr.2012.01.003

De Steur, L., Pickart, R. S., Macrander, A., Våge, K., Harden, B., Jónsson, S., et al. (2017). Liquid freshwater transport estimates from the East Greenland Current based on continuous measurements north of Denmark Strait. *Journal of Geophysical Research: Oceans*, *122*(1), 93–109. https://doi.org/10.1002/2016JC012106

Dickson, R., Rudels, B., Dye, S., Karcher, M., Meincke, J., & Yashayaev, I. (2007). Current estimates of freshwater flux through Arctic and subarctic seas. *Progress in Oceanography*, *73*(3–4), 210–230. https://doi.org/10.1016/j.pocean.2006.12.003

Dodd, P. A., Heywood, K. J., Meredith, M. P., Naveira-Garabato, A. C., Marca, A. D., & Falkner, K. K. (2009). Sources and fate of freshwater exported in the East Greenland Current. *Geophysical Research Letters*, *36*(19), L19608. https://doi.org/10.1029/2009GL039663

Dukhovskoy, D. S., Myers, P. G., Platov, G., Timmermans, M.-L., Curry, B., Proshutinsky, A., et al. (2016). Greenland freshwater pathways in the sub-Arctic Seas from model experiments with passive tracers. *Journal of Geophysical Research: Oceans*, *121*(1), 877–907. https://doi.org/10.1002/2015JC011290

Dukhovskoy, D. S., Yashayaev, I., Proshutinsky, A., Bamber, J. L., Bashmachnikov, I. L., Chassignet, E. P., et al. (2019). Role of Greenland freshwater anomaly in the recent freshening of the subpolar North Atlantic. *Journal of Geophysical Research: Oceans*, *124*(5), 3333–3360. https://doi.org/10.1029/2018JC014686

Duyck, E., & De Jong, M. F. (2021). Circulation over the South-East Greenland Shelf and potential for liquid freshwater export: A drifter study. *Geophysical Research Letters*, *48*(5), e2020JB020886. https://doi.org/10.1029/2020GL091948

Duyck, E., & De Jong, M. F. (2023). Full EGC-DrIFT 6h interpolated dataset [Dataset]. NIOZ. https://doi.org/10.25850/nioz/7b.b.ff

Duyck, E., Gelderloos, R., & de Jong, M. F. (2022). Wind-driven freshwater export at Cape Farewell. *Journal of Geophysical Research: Oceans*, *127*(5), e2021JC018309. https://doi.org/10.1029/2021JC018309

Foukal, N. P., Gelderloos, R., & Pickart, R. S. (2020). A continuous pathway for fresh water along the East Greenland shelf. *Science Advances*, *6*(43), eabc4254. https://doi.org/10.1126/sciadv.abc4254

Haine, T. W. N., Curry, B., Gerdes, R., Hansen, E., Karcher, M., Lee, C., et al. (2015). Arctic freshwater export: Status, mechanisms, and prospects. *Global and Planetary Change*, *125*, 13–35. https://doi.org/10.1016/j.gloplacha.2014.11.013

Harden, B. E., Pickart, R. S., Valdimarsson, H., Våge, K., de Steur, L., Richards, C., et al. (2016). Upstream sources of the Denmark Strait Overflow: Observations from a high-resolution mooring array. *Deep Sea Research Part I: Oceanographic Research Papers*, *112*, 94–112. https://doi.org/10.1016/j.dsr.2016.02.007

Hátún, H., Eriksen, C. C., & Rhines, P. B. (2007). Buoyant eddies entering the Labrador Sea observed with gliders and altimetry. *Journal of Physical Oceanography*, *37*(12), 2838–2854. https://doi.org/10.1175/2007JPO3567.1

Håvik, L., Pickart, R. S., Våge, K., Torres, D., Thurnherr, A. M., Beszczynska-Möller, A., et al. (2017). Evolution of the East Greenland current from Fram Strait to Denmark strait: Synoptic measurements from summer 2012. *Journal of Geophysical Research: Oceans*, *122*(3), 1974–1994. https://doi.org/10.1002/2016JC012228

Håvik, L., & Våge, K. (2018). Wind-driven coastal upwelling and downwelling in the shelfbreak East Greenland Current. *Journal of Geophysical Research: Oceans*, *123*(9), 6106–6115. https://doi.org/10.1029/2018JC014273

Håvik, L., Våge, K., Pickart, R. S., Harden, B., von Appen, W.-J., Jónsson, S., & Østerhus, S. (2017). Structure and variability of the shelfbreak east Greenland Current north of Denmark Strait. *Journal of Physical Oceanography*, *47*(10), 2631–2646. https://doi.org/10.1175/JPO-D-17-0062.1

Holliday, P. N., Bersch, M., Berx, B., Chafik, L., Cunningham, S., Florindo-López, C., et al. (2020). Ocean circulation causes the largest freshening event for 120 years in eastern Subpolar North Atlantic. *Nature Communications*, *11*(1), 585. https://doi.org/10.1038/s41467-020-14474-y

Huang, J., Pickart, R. S., Huang, R. X., Lin, P., Brakstad, A., & Xu, F. (2020). Sources and upstream pathways of the densest overflow water in the Nordic Seas. *Nature Communications*, *11*(1), 5389. https://doi.org/10.1038/s41467-020-19050-y

Jackson, L. C., Kahana, R., Graham, T., Ringer, M. A., Woollings, T., Mecking, J. V., & Wood, R. A. (2015). Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Climate Dynamics*, *45*(11–12), 3299–3316. https://doi.org/10.1007/s00382-015-2540-2

Jónsson, S. (2007). Volume flux and fresh water transport associated with the East Icelandic Current. *Progress in Oceanography*, *73*(3–4), 231–241. https://doi.org/10.1016/j.pocean.2006.11.003

JPL MUR MEaSUREs Project. (2015). GHRSST level 4 MUR global foundation sea surface temperature analysis. Ver. 4.1 [Dataset]. PO.DAAC. https://doi.org/10.5067/GHGMR-4FJ04

Koszalka, I., LaCasce, J. H., Andersson, M., Orvik, K. A., & Mauritzen, C. (2011). Surface circulation in the Nordic Seas from clustered drifters. *Deep Sea Research Part I: Oceanographic Research Papers*, *58*(4), 468–485. https://doi.org/10.1016/j.dsr.2011.01.007

Lavender, K. L., Owens, W. B., & Davis, R. E. (2005). The mid-depth circulation of the subpolar North Atlantic Ocean as measured by subsurface floats. *Deep Sea Research Part I: Oceanographic Research Papers*, *52*(5), 767–785. https://doi.org/10.1016/j.dsr.2004.12.007

Li, F., Lozier, M. S., Bacon, S., Bower, A., Cunningham, S. A., de Jong, M. F., et al. (2021). Subpolar North Atlantic western boundary density anomalies and the meridional overturning circulation. *Nature Communications*, *12*(1), 3002. https://doi.org/10.1038/s41467-021-23350-2

Lilly, J. M. (2021). jLab: A data analysis package for Matlab, v.1.7.1 [Software]. https://doi.org/10.5281/zenodo.4547006

Lin, P., Pickart, R. S., Torres, D. J., & Pacini, A. (2018). Evolution of the freshwater coastal current at the southern tip of Greenland. *Journal of Physical Oceanography*, *48*(9), 2127–2140. https://doi.org/10.1175/JPO-D-18-0035.1

Lozier, M. S., Li, F., Bacon, S., Bahr, F., Bower, A. S., Cunningham, S. A., et al. (2019). A sea change in our view of overturning in the subpolar North Atlantic. *Science*, *363*(6426), 516–521. https://doi.org/10.1126/science.aau6592

Lumpkin, R., & Centurioni, L. (2019). Global Drifter Program quality-controlled 6-hour interpolated data from ocean surface drifting buoys [Dataset]. NOAA National Centers for Environmental Information. https://doi.org/10.25921/7ntx-z961

Lumpkin, R., & Johnson, G. C. (2013). Global ocean surface velocities from drifters: Mean, variance, El Nino–Southern Oscillation response, and seasonal cycle. *Journal of Geophysical Research: Oceans*, *118*(6), 2992–3006. https://doi.org/10.1002/jgrc.20210

Lumpkin, R., Özgökmen, T., & Centurioni, L. (2017). Advances in the application of surface drifters. *Annual Review of Marine Science*, *9*(1), 59–81. https://doi.org/10.1146/annurev-marine-010816-060641

Luo, H., Castelao, R. M., Rennermalm, A. K., Tedesco, M., Bracco, A., Yager, P. L., & Mote, T. L. (2016). Oceanic transport of surface meltwater from the southern Greenland ice sheet. *Nature Geoscience*, *9*(7), 528–532. https://doi.org/10.1038/ngeo2708

Macrander, A., Valdimarsson, H., & Jónsson, S. (2014). Improved transport estimate of the East Icelandic current 2002–2012. *Journal of Geophysical Research: Oceans*, *119*(6), 3407–3424. https://doi.org/10.1002/2013JC009517

Manabe, S., & Stouffer, R. (1995). Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean. *Nature*, *378*(6553), 165–167. https://doi.org/10.1038/378165a0

McDougall, T. J., & Barker, P. M. (2011). *Getting started with TEOS-10 and the Gibbs Seawater (GSW) oceanographic toolbox* (p. 28). SCOR/IAPSO.

Moore, G. W. K. (2003). Gale force winds over the Irminger Sea to the east of Cape Farewell, Greenland. *Geophysical Research Letters*, *30*(17), 1894. https://doi.org/10.1029/2003GL018012

Moore, G. W. K., & Renfrew, I. A. (2005). Tip jets and barrier winds: A QuikSCAT climatology of high wind speed events around Greenland. *Journal of Climate*, *18*(18), 3713–3725. https://doi.org/10.1175/JCLI3455.1

NOAA National Centers for Environmental Information. (2022). ETOPO 2022 15 arc-second global relief model [Dataset]. NOAA National Centers for Environmental Information. https://doi.org/10.25921/fd45-gt74

Novelli, G., Guigand, C. M., Cousin, C., Ryan, E. H., Laxague, N. J. M., Dai, H., et al. (2017). A biodegradable surface drifter for ocean sampling on a massive scale. *Journal of Atmospheric and Oceanic Technology*, *34*(11), 2509–2532. https://doi.org/10.1175/JTECH-D-17-0055.1

Oltmanns, M., Karstensen, J., & Fischer, J. (2018). Increased risk of a shutdown of ocean convection posed by warm North Atlantic summers. *Nature Climate Change*, *8*(4), 300–304. https://doi.org/10.1038/s41558-018-0105-1

Pennelly, C., Hu, X., & Myers, P. G. (2019). Cross-isobath freshwater exchange within the North Atlantic subpolar gyre. *Journal of Geophysical Research: Oceans*, *124*(10), 6831–6853. https://doi.org/10.1029/2019JC015144

Petit, T., Lozier, M. S., Josey, S. A., & Cunningham, S. A. (2020). A new paradigm for Atlantic Ocean deep water formation. *Geophysical Research Letters*, *47*(22), e2020GL091028. https://doi.org/10.1029/2020GL091028

Piron, A., Thierry, V., Mercier, H., & Caniaux, G. (2016). Argo float observations of basin-scale deep convection in the Irminger Sea during winter 2011–2012. *Deep-Sea Research, Part A: Oceanographic Research Papers I*, *109*, 76–90. https://doi.org/10.1016/j.dsr.2015.12.012

Piron, A., Thierry, V., Mercier, H., & Caniaux, G. (2017). Gyre-scale deep convection in the subpolar North Atlantic Ocean during winter 2014–2015. *Geophysical Research Letters*, *44*(3), 1439–1447. https://doi.org/10.1002/2016GL071895

Poulain, P. M., Gerin, R., Mauri, E., & Pennel, R. (2009). Wind effects on drogued and undrogued drifters in the eastern Mediterranean. *Journal of Atmospheric and Oceanic Technology*, *26*(6), 1144–1156. https://doi.org/10.1175/2008JTECHO618.1

Rigor, I. G., Wallace, J. M., & Colony, R. L. (2002). Response of sea ice to the Arctic oscillation. *Journal of Climate*, *15*(18), 2648–2663. https://doi.org/10.1175/1520-0442(2002)015<2648:ROSITT>2.0.CO;2

Rudels, B., Fahrbach, E., Meincke, J., Budéus, G., & Eriksson, P. (2002). The East Greenland current and its contribution to the Denmark strait overflow. *ICES Journal of Marine Science*, *59*(6), 1133–1154. https://doi.org/10.1006/jmsc.2002.1284

Schulze Chretien, L. M., & Frajka-Williams, E. (2018). Wind-driven transport of fresh shelf water into the upper 30m of the Labrador Sea. *Ocean Science*, *14*(5), 1247–1264. https://doi.org/10.5194/os-14-1247-2018

Schyberg, H., Yang, X., Køltzow, M. A. Ø., Amstrup, B., Bakketun, Å., Bazile, E., et al. (2020). Arctic regional reanalysis on single levels from 1991 to present [Dataset]. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.713858f6

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., et al. (2020). Mass balance of the Greenland ice sheet from 1992 to 2018. *Nature*, *579*(7798), 233–239. https://doi.org/10.1038/s41586-019-1855-2

Sterl, M. F., & de Jong, M. F. (2022). Restratification structure and processes in the Irminger Sea. *Journal of Geophysical Research: Oceans*, *127*, e2022JC019126. https://doi.org/10.1029/2022JC019126

Sutherland, D. A., & Cenedese, C. (2009). Laboratory experiments on the interaction of a buoyant coastal current with a Canyon: Application to the East Greenland current. *Journal of Physical Oceanography*, *39*(5), 1258–1271. https://doi.org/10.1175/2008jpo4028.1

Sutherland, D. A., & Pickart, R. S. (2008). The East Greenland coastal current: Structure, variability, and forcing. *Progress in Oceanography*, *78*(1), 58–77. https://doi.org/10.1016/j.pocean.2007.09.006

Trenberth, K. E., Large, W. G., & Olson, J. G. (1990). The mean annual cycle in global ocean wind stress. *Journal of Physical Oceanography*, *20*(11), 1742–1760. https://doi.org/10.1175/1520-0485(1990)020<1742:TMACIG>2.0.CO;2

Våge, K., Pickart, R. S., Spall, M. A., Moore, G., Valdimarsson, H., Torres, D. J., et al. (2013). Revised circulation scheme north of the Denmark Strait. *Deep-Sea Research I*, *79*, 20–39. https://doi.org/10.1016/j.dsr.2013.05.007

Vinogradova, N., Lee, T., Boutin, J., Drushka, K., Fournier, S., Sabia, R., et al. (2019). Satellite salinity observing system: Recent discoveries and the way forward. *Frontiers in Marine Science*, *243*, 428925. https://doi.org/10.3389/fmars.2019.00243

Wang, H., Legg, S., & Hallberg, R. (2018). The effect of Arctic freshwater pathways on North Atlantic convection and the Atlantic meridional overturning circulation. *Journal of Climate*, *31*(13), 5165–5188. https://doi.org/10.1175/jcli-d-17-0629.1

Weijer, W., Cheng, W., Drijfhout, S. S., Fedorov, A. V., Hu, A., Jackson, L. C., et al. (2019). Stability of the Atlantic meridional overturning circulation: A review and synthesis. *Journal of Geophysical Research: Oceans*, *124*(8), 5336–5375. https://doi.org/10.1029/2019JC015083

Weijer, W., Cheng, W., Garuba, O. A., Hu, A., & Nadiga, B. T. (2020). CMIP6 models predict significant 21st century decline of the Atlantic meridional overturning circulation. *Geophysical Research Letters*, *47*(12), e2019GL086075. https://doi.org/10.1029/2019GL086075

Yang, Q., Dixon, T., Myers, P., Bonin, J., Chambers, D., van den Broeke, M. R., et al. (2016). Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic overturning circulation. *Nature Communications*, *7*(1), 10525. https://doi.org/10.1038/ncomms10525

Zhang, R., Sutton, R., Danabasoglu, G., Kwon, Y. O., Marsh, R., Yeager, S. G., et al. (2019). A review of the role of the Atlantic meridional overturning circulation in Atlantic multidecadal variability and associated climate impacts. *Reviews of Geophysics*, *57*(2), 316–375. https://doi.org/10.1029/2019rg000644