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Sources and fate of freshwater exported in the East Greenland Current

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[1] Monitoring the sources and fate of freshwater in the East Greenland Current (EGC) is important, as this water has the potential to suppress deep convection in the Nordic and Labrador Seas if the outflow of freshwater from the Arctic Ocean increases in response to climate change. Here, hydrographic, oxygen isotope ratio and dissolved barium concentration sections across Denmark Strait collected in 1998 and 1999 are used to determine the freshwater composition of the EGC at these times. Comparison of meltwater fluxes at Denmark Strait and Fram Strait indicates a net melting of sea ice into the EGC between these two locations, with a significant proportion of sea ice drifting into the Nordic Seas or on to the East Greenland Shelf. We conclude that the phase of freshwater exiting the Arctic Ocean through Fram Strait is important in determining its possible impact on deep water formation in the Nordic and Labrador Seas. **Citation:** Dodd, P. A., K. J. Heywood, M. P. Meredith, A. C. Naveira-Garabato, A. D. Marca, and K. K. Falkner (2009), Sources and fate of freshwater exported in the East Greenland Current, *Geophys. Res. Lett.*, *36*, L19608, doi:10.1029/2009GL039663.

1. Introduction

[2] The East Greenland Current (EGC) transports between 50% and 75% of liquid freshwater and sea ice exported from the Arctic Ocean [*Aagaard and Carmack*, 1989; *Serreze et al.*, 2006]. The majority of this freshwater is thought to remain in the EGC as it flows southward along the East Greenland Shelf [*Nilsson et al.*, 2008] ultimately reaching the Labrador Sea via the West Greenland Current (WGC) and the Labrador Current. An unquantified fraction enters the deep basins of the Nordic Seas.

[3] Estimates of the liquid freshwater flux through Fram Strait vary between 63 and 95 mSv [*Meredith et al.*, 2001; *Holfort and Hansen*, 2004; *Dickson et al.*, 2007] while an additional 70 to 92 mSv is carried as sea ice [*Vinje*, 2001; *Widell et al.*, 2003; *Kwok et al.*, 2004; *Dickson et al.*, 2007]. The fate of this freshwater south of Fram Strait is not well known due to a lack of long term observations in the presence of significant interannual variability in transport. The large density difference between Polar Surface Water in the EGC and adjacent waters in the Nordic Seas [*Rudels et al.*, 2002] suggests that little liquid freshwater is lost from the surface of the EGC as a result of lateral mixing. The only directly observed sinks of freshwater from the EGC are the Jan Mayen and East Iceland Currents which collectively remove ~15 mSv of freshwater [*Jonsson*, 2003]. However, a significant proportion of freshwater may drift into the Nordic Seas as sea ice.

[4] Of primary concern are the relative proportions of freshwater entering the Labrador and Greenland Seas. A number of modeling studies [e.g., *Stouffer et al.*, 2006] suggest that variations in the supply of freshwater to the central Greenland and Labrador seas may modulate the rate of deep convection in those locations with consequences for the global thermohaline circulation.

[5] Here we use oxygen isotope ratio and dissolved barium concentration measurements to quantify the proportions of liquid freshwater passing through Denmark Strait originating from Eurasian rivers, North American rivers and melting sea ice. We infer the loss of each freshwater fraction from the EGC and comment on the implications of these losses for deep convection and dense water production in the Labrador and Nordic Seas.

2. Methods

[6] Samples were collected from 5–7 October 1998 and from 23–25 August 1999 (Figure 1h). Current velocities were determined by referencing geostrophic shear profiles to acoustic Doppler current profiler (ADCP) profiles. Referenced geostrophic profiles are used in preference to ADCP profiles, which tend to contain short-term ageostrophic components, and are less representative of the long term flow fields. Tidal currents were removed from ADCP profiles using the AOTIM-5 barotropic tidal model [*Padman and Erofeeva*, 2004].

[7] Proportions of sea ice meltwater and meteoric water were determined along sections following the procedure established by *Bauch et al.* [1995] and *Meredith et al.* [2001] using the following three-endmember balance:

$$f_i + f_m + f_a = 1 \qquad (1)$$

$$f_i S_i + f_m S_m + f_a S_a = S \qquad (2)$$

$$f_i \delta_i + f_m \delta_m + f_a \delta_a = \delta \qquad (3)$$

where $f_{i,m,a}$ are the derived fractions of sea ice meltwater, meteoric water and Arctic seawater respectively; $S_{i,m,a}$ are the assigned salinities of sea ice meltwater, meteoric water and Arctic seawater respectively; and $\delta_{i,m,a}$ are the assigned δ^{18}O values. Along the 1998 section, the three endmember balance was extended to determine the proportions of meteoric water derived from North American run-off and

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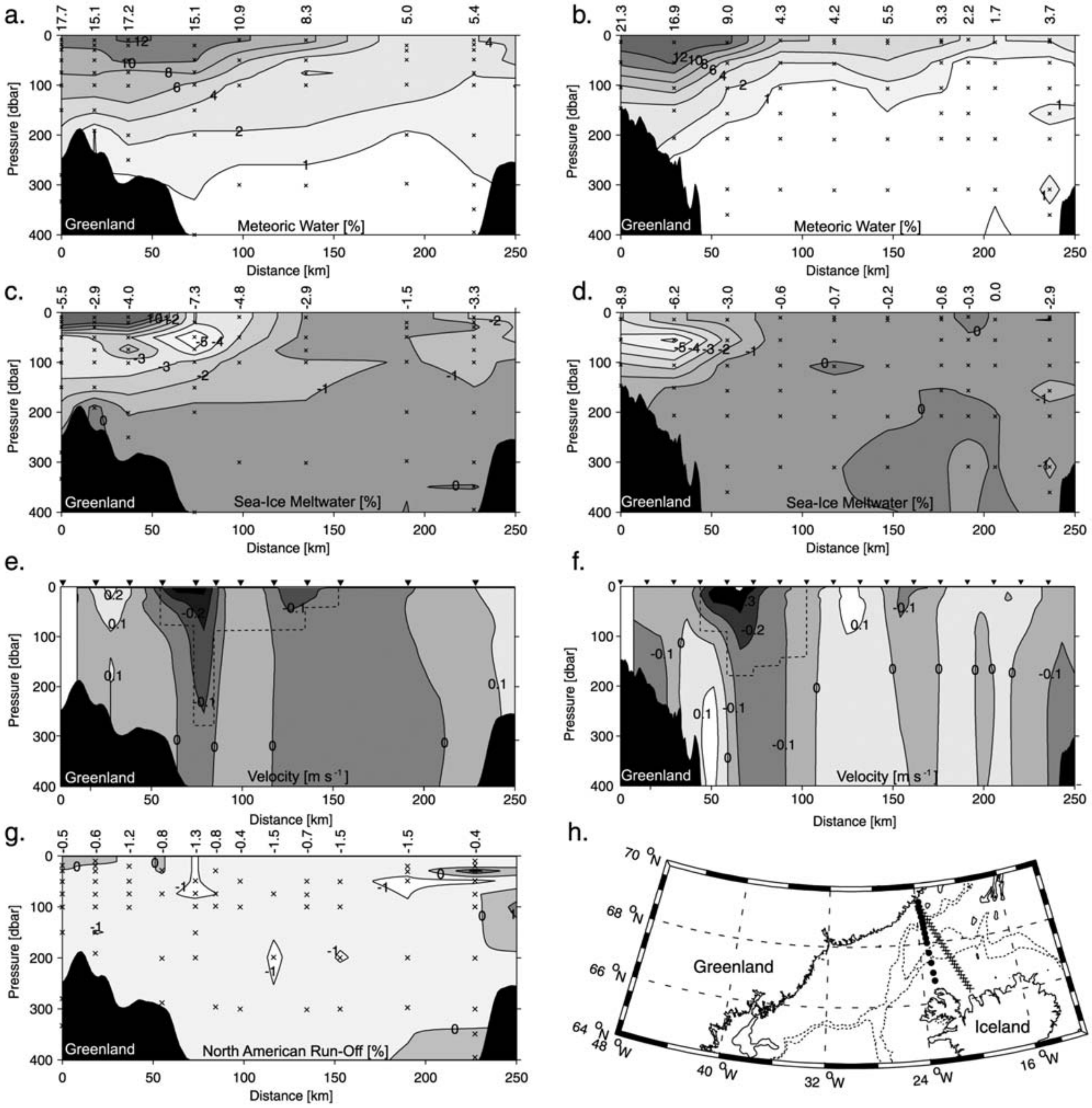

Figure 1. Freshwater concentration and velocity sections across Denmark Strait. Meteoric water in (a) 1998 and (b) 1999; sea ice meltwater in (c) 1998 and (d) 1999; Cross-sectional velocity fields in (e) 1998 and (f) 1999; (g) North American river water concentration in 1998; (h) Location of CTD casts in 1998 (circles) and 1999 (crosses). Numbers above plots indicate column inventories (in meters) above 200 db. Cross-sectional velocity fields are determined from ADCP-referenced geostrophic shear profiles. Triangles indicate the location of CTD casts Figures 1e and 1f, while the EGC is enclosed by a dashed line.

Eurasian run-off following the approach of *Taylor et al.* [2003]:

$$f_i + f_m + f_e + f_a = 1 \tag{4}$$

$$f_i S_i + f_m S_m + f_e S_e + f_a S_a = S \tag{5}$$

$$f_i \delta_i + f_m \delta_m + f_e \delta_e + f_a \delta_a = \delta \tag{6}$$

$$f_i Ba_i + f_m Ba_m + f_e Ba_e + f_a Ba_a = Ba \tag{7}$$

where $f_{i,m,e,a}$ are the derived fractions of sea ice meltwater, Eurasian run-off, North American run-off and Arctic seawater. $S_{i,m,e,a}$; $\delta_{i,m,e,a}$; $Ba_{i,m,e,a}$ represent the assigned salinity, δ^{18}O and dissolved barium concentration of each endmember. Values assigned to endmembers (Table 1) follow *Bauch et al.* [1995] and *Taylor et al.* [2003] in order to allow direct comparison with these studies and with *Meredith et al.* [2001] who use the same values. Whilst there are recent indications that barium may behave in a non-conservative way as sea ice retreats in the Arctic

Table 1. Endmembers for the Identification of Freshwater and Arctic Seawater Fractions at Denmark Strait With Estimated Uncertainties[a]

Water mass	Salinity [Uncertainty]	$\delta^{18}O$ [Uncertainty]	Ba (nmol L^{-1}) [Uncertainty]
Meteoric water	0 [0]	−21 [3]	-
Eurasian runoff	0 [0]	−21 [3]	120 [50]
N. American runoff	0 [0]	−21 [3]	520 [50]
Sea ice meltwater	3 [1.5]	surface + 2.1 [2]	5.4 [5]
Arctic seawater	34.94 [0]	0.3 [0.1]	57 [5]

[a] The term meteoric water describes any water that has fallen as precipitation including snow, run off and glacial meltwater.

[*Abrahamsen et al.*, 2009], the data we use were collected prior to the large decreases in Arctic sea ice. During the period, and on the large scales we are investigating, barium has been demonstrated to be a useful quantitative tracer [*Taylor et al.*, 2003].

[8] We note that Pacific water inflow via the Bering Strait and across the Arctic can contribute significantly to the freshwater composition of the EGC [e.g., *Taylor et al.*, 2003; *Jones et al.*, 2008; *Sutherland et al.*, 2009]. It is not the intention of this paper to examine this freshwater component individually, which would require other tracers, and which would enable our derived Arctic seawater prevalances to be decomposed into Atlantic and Pacific seawater contributions. Instead, we restrict our investigation to the meteoric water and sea ice melt components of the EGC freshwater balance.

3. Observations

[9] High concentrations of meteoric water were found in the core of the EGC over the East Greenland shelf break, exceeding 11% in both 1998 and 1999 (Figures 1a and 1b). Sea ice meltwater concentrations (Figures 1c and 1d) were negative in the upper part of the EGC indicating a net formation of sea ice from this water, rather than a net input of sea ice meltwater. In both 1998 and 1999 a sea ice meltwater concentration minimum of −5 to −6% occurred at a depth of 50 m underneath the core of the EGC. Within the core of the EGC sea ice meltwater concentrations were higher due to input from melting sea ice drifting southwards in the current. In 1998 sea ice meltwater concentrations were also positive at the surface over the East Greenland shelf break, probably as a result of in-situ melting.

[10] No significant concentrations of North American river water were observed at Denmark Strait in 1998 (Figure 1g). Small negative concentrations of North American run-off are attributed to small inaccuracies in endmember properties; we estimate the precision of the North American run-off field to be about 1%. The observed run-off was entirely of Eurasian origin. (Note, however, that the fraction of Eurasian run-off derived from the mass balance equations probably includes a limited amount of Greenlandic run-off and direct precipitation, which cannot be distinguished separately without additional tracers).

[11] Fractional transports within the EGC were estimated by integrating the product of freshwater fractions and cross-sectional velocities, as determined from ADCP referenced geostrophic shear profiles (Figures 1e and 1f). Integrations were performed over a region surrounding the core of the EGC in which the southward velocity exceeded 15% of the core velocity and in which the potential density was less than 27.70 kg m^{-3}. These integration regions are enclosed by dashed lines in Figures 1e and 1f. There was no evidence of the East Greenland Coastal Current (EGCC) between the EGC and western end of the 1998 or 1999 sections, both of which extended to within 20 km of the Greenlandic coast.

[12] Table 2 lists our estimates of the net and fractional freshwater fluxes through Denmark Strait and associated uncertainties. Note that the meteoric water fluxes are larger than the net freshwater fluxes. This is a consequence of the freshening effect of the meteoric water input to the ocean being offset partially by the salinifying effect of sea ice formation (brine rejection), with the net freshwater flux being quantified as the sum of the fluxes associated with these two components.

4. Discussion and Conclusions

[13] The meteoric water transports we determine in 1998 and 1999 are equivalent, within the estimated errors, the smaller transport in 1998 being mostly attributable to differences in the velocity field, rather than meteoric water concentrations. *Meredith et al.* [2001] estimated the meteoric water transport through Fram Strait to be 60 mSv during August–September 1998, which suggests that meteoric water was broadly conserved in the EGC between Fram Strait and Denmark Strait in 1998, neglecting any seasonal variability. This is consistent with the observations of *Rudels et al.* [2002] who conclude that liquid freshwater in the EGC should be broadly conserved downstream as strong horizontal density gradients prevent it from mixing readily into the Greenland or Iceland Gyres.

[14] The absence of North American run-off at Denmark Strait in October 1998 was consistent with the observations of *Taylor et al.* [2003] who concurrently observed a similar absence at Fram Strait. Assuming a separation distance of 1600 km and a mean velocity of 0.1 m s^{-1}, the water sampled at Denmark Strait in this study would have previously passed through Fram Strait in March 1998. The consistency with *Taylor et al.*'s [2003] observations thus suggests that there is little seasonal variability in the concentration of North American run-off in the EGC.

[15] Sea ice meltwater transports of approximately 20 mSv determined at Denmark Strait in both 1998 and 1999 imply a net formation of sea ice from the Arctic seawater endmember rather than a net addition of sea ice meltwater. Because of divergence between sea ice and the water from which it formed, it is not possible to infer a solid sea ice flux from a negative sea ice meltwater flux. However, comparison of the 20 mSv fluxes estimated in this study with the August–September 1998 flux of 30 mSv estimated by *Meredith et al.* [2001] at Fram Strait implies that 10 mSv

Table 2. Transports of Volume, Freshwater, Meteoric Water and Sea Ice Meltwater in the EGC at Denmark Strait[a]

	Volume [Sv]	Net Freshwater [mSv]	Meteoric Water [mSv]	Sea Ice Meltwater [mSv]
1998	−0.8 ± 0.3	−43 ± 9	−60 ± 15	20 ± 7
1999	−1.5 ± 0.1	−60 ± 3	−77 ± 4	17 ± 1

[a] Negative values indicate southward transports. Net freshwater fluxes are calculated relative to a reference salinity of 34.9.

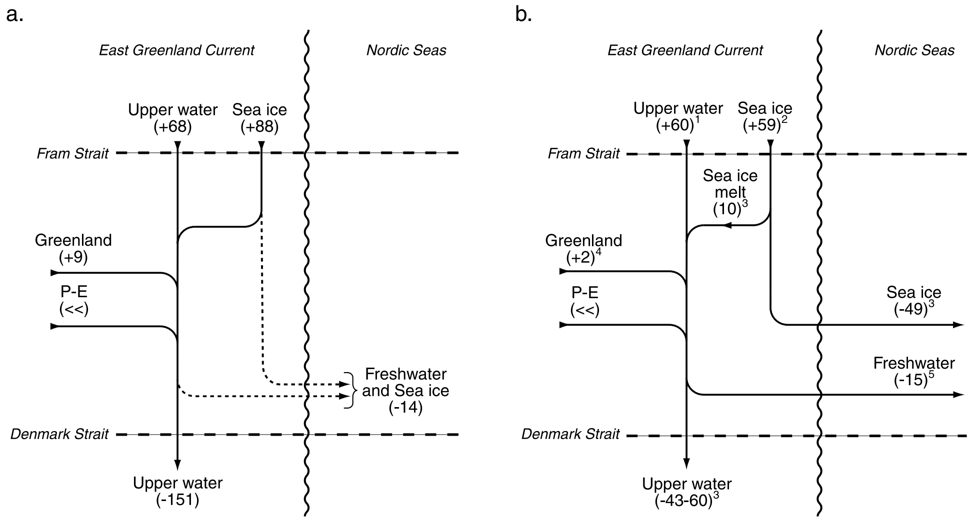

Figure 2. (a) The freshwater budget of the EGC, in mSv relative to 35.2, as implied by *Dickson et al.*'s [2007] freshwater budget for the Nordic Seas. (b) An updated freshwater budget for the EGC, in mSv relative to 34.9, including the observations of this study. Superscripts indicate the sources of flux estimates: ^{1}[*Rabe et al.*, 2009] (their solution a); ^{2}[*Kwok et al.*, 2004]; ^{3}this study; ^{4}[*Rignot and Kanagaratnam*, 2006]; ^{5}[*Jonsson*, 2003].

of sea ice melted into the EGC between Fram Strait and Denmark Strait.

[16] Sea ice meltwater and meteoric water transport estimates are influenced by short term variability in the southward velocity of the EGC, while the ratio of sea ice meltwater to meteoric water concentrations is a more robust parameter. The sea ice meltwater to meteoric water ratio was found to be about −1:2 at Fram Strait in 1995 [*Bauch et al.*, 1995] and in 1997 and 1998 [*Meredith et al.*, 2001]. We estimate a ratio of −1:3 at Denmark Strait in both 1998 and 1999 which is consistent with our estimate of a net melting of 10 mSv of sea ice into the EGC.

[17] Monthly composite special sensor microwave/imager (SSM/I) satellite images of Denmark Strait [*Cavalieri et al.*, 1999] for July, August and September 1999 reveal that there was no solid sea ice present along the track of the 1999 section at these times. Considering the 1998–1999 solid sea ice flux through Fram Strait of 59 mSv [*Kwok et al.*, 2004], minus a melting of 10 mSv into the EGC (this study) leaves a balance of approximately 49 mSv of sea ice or sea ice meltwater unaccounted for. This sea ice presumably either drifts out of the EGC and enters the Nordic Seas, or accumulates over the East Greenland Shelf during summer. Monthly composite SSM/I images of Denmark Strait show a sea ice concentration of <5% for October 1998, but it is unclear whether any sea ice was present when the tracer section was completed between 5th and 7th October 1998.

[18] A loss of solid sea ice from the EGC is supported by the net freshwater flux estimates at Denmark Strait determined in this study, which are generally similar to or lower than estimates further north.

[19] *Dickson et al.* [2007] construct a freshwater budget for the Nordic Seas relative to a reference salinity of 35.2. In their budget 165 mSv of freshwater enters the surface of the Nordic Seas via the EGC (88 mSv sea ice through Fram Strait, 68 mSv surface freshwater through Fram Strait and 9 mSv of Greenlandic input). The budget is balanced to ensure there is no accumulation of freshwater in the Nordic Seas by assuming an upper outflow of 151 mSv through Denmark Strait plus 29 mSv into the Barents Sea. The loss of 14 mSv of freshwater from the EGC between Fram and Denmark Straits implied by *Dickson et al.* [2007] is consistent with the observations of this study and feasible transports of freshwater in the Jan Mayen and East Icelandic Currents [*Jonsson*, 2007].

[20] Figure 2a shows the freshwater budget of the EGC implied by *Dickson et al.*'s [2007] freshwater budget for the Nordic Seas. Figure 2b shows a similar freshwater budget based on the observations of this study. Note that our budget is relative to a reference salinity of 34.9, while that of *Dickson et al.* [2007] is relative to a salinity of 35.2. The 151 mSv surface outflow through Denmark Strait assumed by *Dickson et al.* [2007] is large relative to recent summer observations of the liquid freshwater flux [e.g., *Sutherland and Pickart*, 2008], although the differing reference salinities prohibit precise comparison. In contrast to *Dickson et al.* [2007] we suggest that a significant volume of sea ice drifts out of the EGC into the Nordic Seas, rather than passing through Denmark Strait. A surface outflow of 57 mSv through Denmark Strait would be required to balance the budget that we propose, which is in good agreement with the 43–60 mSv that we observe. We emphasize that our freshwater budget figures are derived from measurements specific to the 1998–1999 period and to the summer season. The significant transport of sea ice though Denmark Strait in winter explains some of the discrepancy between our budget and the budget of *Dickson et al.* [2007]. The latter is derived from longer term freshwater flux estimates and therefore more closely approximates the annual mean circulation.

[21] Nonetheless, the 49 mSv flux of freshwater to the Nordic Seas we estimate may play an important role in modulating convection in that location. An intercomparison of several standardized experiments, where freshwater was applied to the North Atlantic in dynamical models [*Stouffer et al.*, 2006] suggests that a flux of 100 mSv applied continuously to the north Atlantic between 50 and 70 N

would be sufficient to significantly perturb the Atlantic meridional overturning circulation (AMOC). The 49 mSv leakage of sea ice into Nordic Seas that we estimate is of the same order of magnitude as the 100 mSv applied to the north Atlantic in the aforementioned model experiments. In another study, *Vellinga* [2004] fitted a line to a series of HadCM3 model runs which suggests each additional 1 Sv of freshwater added to the north Atlantic should reduce the AMOC by 1.1 ± 0.2 Sv per decade at 48 N. However, in the same study, Vellinga notes that freshwater applied directly to deep convection sites in Nordic Seas produced a larger change in the AMOC at 48 N then predicted by the trend line.

[22] Sea ice meltwater, North American run-off and Eurasian run-off tend to follow different paths within the Arctic Ocean. However, we suggest that after passing through Fram Strait, the phase of freshwater is more important in determining its fate than its origin. Our results support the idea that a significant proportion of sea ice drifts into the Nordic Seas while liquid freshwater is largely retained in the EGC.

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