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4 **Emerging impact of Greenland meltwater on deepwater formation in the North**
5 **Atlantic Ocean**

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26 **The Greenland Ice sheet has experienced increasing mass loss since the 1990s^{1,2}. The enhanced**
27 **freshwater flux due to both surface melt and outlet glacier discharge is assuming an increasingly**
28 **important role in the changing freshwater budget of the subarctic Atlantic³. The sustained and**
29 **increasing freshwater fluxes from Greenland to the surface ocean could lead to a suppression of deep**
30 **winter convection in the Labrador Sea, with potential ramifications for the strength of the Atlantic**
31 **meridional overturning circulation (AMOC)⁴⁻⁶. Here we assess the impact of the increases in the**
32 **freshwater fluxes, reconstructed with full spatial resolution³, using a global ocean circulation model**
33 **with a grid spacing fine enough to capture the small-scale, eddying transport processes in the subpolar**
34 **North Atlantic. Our simulations suggest that the invasion of meltwater from the West Greenland shelf**
35 **has initiated a gradual freshening trend at the surface of the Labrador Sea. While the freshening is still**
36 **smaller than the variability associated with the episodic ‘great salinity anomalies’, the accumulation of**
37 **meltwater may become large enough to progressively dampen the deep winter convection in the**
38 **coming years. We conclude that the freshwater anomaly has not yet had a significant impact on the**
39 **Atlantic meridional overturning circulation.**

40 The subpolar North Atlantic (Fig. 1a) plays an important role in the global climate system due to its
41 generation, by deep convection during winter, of North Atlantic Deep Water that feeds the deep limb of
42 the Atlantic meridional overturning circulation (AMOC). While annual formation rates vary strongly,
43 primarily due to the variability in atmospheric conditions⁷⁻⁹, a progressive anthropogenic freshening of
44 the surface waters bears the potential of a persistent weakening of convection intensities. Satellite
45 observations in conjunction with surface mass balance models provided detailed reconstructions of the
46 non-uniform distribution of Greenland ice-mass trends² and the corresponding freshwater discharge into
47 the ocean³. The meltwater fluxes show large increasing trends since the mid-1990s, particularly for the
48 south-eastern and western portions of the ice sheet, implying major additional sources of freshwater for

49 the subpolar North Atlantic¹⁰. Importantly, the ice mass loss has been increasing over time including the
50 most recent years¹¹.

51 The fate of this additional discharge is not well understood since a meltwater-related freshening trend is
52 difficult to distinguish from the strong decadal variability in the subarctic freshwater content^{12,13}.

53 According to ref. 3, the cumulative freshwater anomaly from the ice sheet as a whole amounted to 3200
54 km³ by 2010. From ocean observations it is not possible to infer how much of this input has been

55 retained in the subpolar North Atlantic, and in particular, how much of it has been invading the surface
56 waters of the Labrador Sea where it could impact the winter convection. The spreading of waters off the

57 Greenland shelf is intimately linked to mesoscale (~10-30 km) ocean transport processes; specifically, the
58 invasion of the interior Labrador Sea by low-salinity waters from the West Greenland Current (WGC)

59 system is governed by mesoscale eddies arising from an instability of the WGC at the steep bathymetry
60 off Cape Desolation^{14,15}. The eddy-induced flux is important for the stability of the near-surface waters¹⁶

61 and effectively confines the deep convection to the southwestern Labrador Sea¹⁷. Ocean model

62 studies^{18,19} with enhanced resolutions of 0.1° confirmed the key role of eddy processes in the oceanic

63 response to freshwater flux perturbations; however, the use of idealized flux scenarios in these studies,

64 with perturbations of 0.1-0.5 Sverdrups (Sv; 1 Sv = 10⁶ m³s⁻¹) which exceed the present flux anomalies by

65 an order of magnitude, prevents conclusions about the impact of the actual acceleration in the

66 Greenland melting.

67 We have assessed the fate and impact of the spatially non-uniform increase in the freshwater flux from

68 Greenland, based on a set of global ocean-sea ice models with increasing resolution devised to capture

69 the critical eddy processes in the subpolar North Atlantic. In the high-resolution case (Fig. 1a), the global

70 model mesh of 0.25° was refined to 0.05° in the North Atlantic between 32°N and 82°N (corresponding

71 to a mesh size of ~3 km in the Labrador Sea; Supplementary S1), providing an improved realism in the

72 simulation of the complex boundary current system²⁰. In particular, the model succeeds in generating a

73 wedge of enhanced mesoscale eddy activity in the north-eastern Labrador Sea originating off Cape
74 Desolation (Fig. 1b).

75 The impact of the increasing Greenland melting trend was determined by comparing a control simulation
76 forced with climatological coastal runoffs (CNTR) to a case (MELT) with a spatially non-uniform, linearly
77 increasing runoff-trend of $16.9 \text{ km}^3 \text{ yr}^{-2}$ following ref. 3, over a 30-year period beginning in 1990 (Fig. 1c).

78 The atmospheric forcing builds on a bulk formulation of air-sea fluxes with prescribed atmospheric data
79 for 1948-2007 developed for global ocean hindcast simulations^{21,22}. While the unknown future forcing
80 precludes a prediction of the inter-annually varying state of the ocean, we seek to assess the future
81 evolution of the individual impact of the meltwater, as given by the difference between MELT and CNTR,
82 by continuing both experiments for another 12 years with a repeated atmospheric forcing of the year
83 2007. The freshwater flux anomalies in MELT were extended by extrapolating the current trend³. Until
84 the end of this decade the cumulative runoff anomaly amounts to 7500 km^3 . However, less than half of
85 the additional meltwater, about 3000 km^3 , is accumulating in the subpolar North Atlantic (Fig. 1c) which
86 represents a relatively small addition to the large decadal changes in the total (0-2000m) freshwater
87 content recorded by refs. 12 and 13 (Fig. 1d). We note that the observed decadal variability is captured
88 by the hindcast simulation (CNTR), with a similar freshening trend during the 1970s and 1980s, and its
89 reversal thereafter.

90 The progression of the meltwater is illustrated by 'dyeing' the additional runoff, i.e., by computing the
91 fate of a dye released with the same source distribution as the freshwater off Greenland (Fig. 2;
92 Supplementary S2). In concurrence with previous studies^{18,19,24}, highest concentrations are evolving in
93 Baffin Bay, where the runoff from Northwest Greenland is superimposed by the northward flow of
94 meltwater by the WGC, and reinforced by a reduction in the southward volume transport through Davis
95 Strait (cf. ref. 24, 25). Farther south the spreading in the high-resolution model (Fig. 2a) differs from
96 lower resolution simulations in two main respects, as emphasized by the companion experiment using

97 the 0.25°-grid without refinement in the North Atlantic (Fig. 2b): one, in the emergence of a near-surface
98 route inshore of the Gulf Stream, providing an outlet for some fraction of the meltwater into the Mid-
99 Atlantic Bight; two, in the enhanced concentrations over the northern Labrador Sea, owing to the flux by
100 the WGC eddies (cf. ref. 10).

101 A first inference of the potential relevance of the meltwater signal for the convection intensity can be
102 obtained by contrasting the freshwater anomaly currently developing in the surface layer with the
103 historic episodes of surface freshening²⁶ around 1970 (known as the “Great Salinity Anomaly”, GSA70²⁷),
104 the mid-1980s and early 1990s²⁸ that were associated with pulses of enhanced sea ice export from the
105 Arctic Ocean along the shelf of East Greenland²⁹. Estimates of the freshwater discharges vary; however,
106 pertinent to the consideration here, the salinity record for the surface layer (0-300 m) of the Labrador
107 Sea suggests²⁷ that each of these events amounted to a freshwater anomaly of about 1700 km³ passing
108 the continental slope region off southwestern Greenland, consistent with an ice export anomaly through
109 Fram Strait of ~2300 km³ in the years preceding the GSA70²⁹. Our model simulation suggests that the
110 accumulation of meltwater in the Labrador Sea is by now reaching half that magnitude (Fig. 1c).

111 Meltwater-induced trends in the hydrography of the Labrador Sea occur in a rather gradual way (Fig. 3).
112 Throughout the simulation period, the decrease in the surface salinity remains small compared to the
113 inter-annual variability induced (until 2007) by the atmospheric forcing (Supplementary S3). However,
114 the signal is continuously increasing, towards the end of this decade reaching 0.3 in the WGC and 0.1
115 along the low-salinity wedge extending into the interior Labrador Sea (Figs. 3a,b). To assess the
116 significance of this emerging meltwater signal, it is instructive to contrast the current trend with the
117 surface salinity anomalies occurring during the great salinity anomalies. A manifestation of these events
118 can be seen on the West Greenland shelf where the salinity in CNTR dropped by about 1 (Supplementary
119 S3). The effects in the interior Labrador Sea were smaller, as shown by the record of the GSA70 by
120 former Ocean Weather Ship Bravo (OWS-B)⁸; its manifestation is also present in the model hindcast .

121 Obviously, the emerging salinity tendencies in MELT are still small compared to these strong,
122 intermittent freshening pulses.

123 While not yet of an amplitude comparable to these episodic events, the sustained accumulation of
124 meltwater may have begun to increase the near-surface stability enough to leave a first trace in the
125 intensity of the wintertime convection. Note that the great salinity anomalies, in spite of their similar
126 magnitudes, had considerably different impacts on the convection intensity³⁰: while the GSA70, in
127 conjunction with a series of mild winters, effectively shut down deep convection for three consecutive
128 years^{8,9}, there was no obvious impact of the last anomaly during the phase of harsh winters with very
129 strong convection in the early 1990s. While we thus cannot predict the absolute year-to-year evolution
130 of convection in the future (nor hindcast inter-annual variations beyond 2007), the difference between
131 MELT and CNTR does provide a useful means of isolating the meltwater effect (Fig. 3c; Supplementary
132 S4). Apart from a strong year-to-year variability, primarily reflecting the surface heat loss during winter
133 governed by the imposed atmospheric state, the main signal is the inter-decadal increase from the weak-
134 convection period during the late 1960s and 1970s to a period with maximum intensity during the late
135 1980s and early 1990s, and its subsequent slackening, in general accordance with previous accounts³⁰.

136 Compared to this strong background variability, the effect of the additional meltwater has remained
137 negligible until now; however, it progressively increases during the next years to nearly 30% of the range
138 of variability experienced during the previous decades. We note that the meltwater mainly affects the
139 formation of the dense class of LSW in the Labrador Sea, not the lighter, “upper” LSW formed also in the
140 Irminger Sea (Supplementary S4). A corresponding decline is seen in the depth of winter convection
141 which towards the end of the decade will be curbed by 200-500m (Fig. 3d). The strongest signals occur
142 along the main meltwater pathways: along the offshore edge of the western boundary current off the
143 Labrador continental slope, and in the interior northern Labrador Sea along the path of the WGC eddies.

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145 With an impact on the intensity of convection not emerging before the end of the decade, we cannot yet
146 expect a significant dynamical repercussion of the increased runoff. Accordingly, there is only a first hint
147 of a weak, but meridionally-coherent signal in the AMOC transport emerging towards the end of the
148 simulation period in the MELT-CNTR difference (Supplementary S4). This contrasts with the effect of an
149 idealized freshwater perturbation of larger magnitude. As demonstrated in a sensitivity experiment (I-
150 MELT), an instant increase to a constant flux of $3000 \text{ km}^3 \text{ yr}^{-1}$ (about 0.1 Sv) leads to a rapid dilution of
151 the surface waters (Supplementary S5), a cessation of deep convection after 6-8 years, followed by a
152 rapid slowdown of the AMOC by more than 5 Sv. At that point the accumulated runoff exceeds $\sim 20,000$
153 km^3 : under a continuation of the actual trend such a magnitude would be reached around 2040. This has
154 some bearing on the hypothesis⁶, that the increase in the ice-mass loss from Greenland could already
155 have begun to restrain the AMOC during the second half of the 20th-century: based on the present
156 simulations we argue that the accumulation of meltwater has not been large enough yet to affect the
157 freshwater budget of the subpolar North Atlantic, precluding a significant impact on the AMOC. Another
158 corollary of our simulations is, however, that the ongoing, and perhaps, accelerating melting-induced
159 freshening of the surface waters in the subpolar North Atlantic may begin to progressively affect the
160 deep water formation, and in turn the AMOC, before clear signals of trends in critical hydrographic
161 properties would become identifiable given the strong interannual variability in many of these fields.

162

163 **Methods**

164 Methods, including references, and statements of data and code availability are provided in the online
165 version of this paper.

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238

239 **Author Contributions**

240 All authors conceived the experiments. E. B. implemented the model and performed the experiments. E.
241 B., C. B., K.G. and A. B. analysed the results. C. B. wrote the paper with contributions by all co-authors.

242

243 **Competing financial interests**

244 The authors declare no competing financial interest.

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249 **Figure captions**

250 **Figure 1 | Circulation and freshwater content of the subpolar North Atlantic.** (a) Snapshot of surface
251 speed in the high-resolution model illustrating the vigorous eddy currents in the northwestern
252 Atlantic as simulated. (b) Mean depth of the March mixed layer (colours; m) and eddy kinetic energy
253 (EKE); c.i. $25 \text{ cm}^2\text{s}^{-2}$ ($100 \text{ cm}^2\text{s}^{-2}$) for EKE below (above) $100 \text{ cm}^2\text{s}^{-2}$. (c) Cumulated runoff perturbation
254 imposed in MELT using the rate of increase determined by ref. 3 until 2010 (light blue), and its
255 extrapolation through 2019 (dashed light blue), and the simulated freshwater content anomaly in the
256 subpolar North Atlantic (blue), and in the Labrador Sea only (green). (d) Variability of freshwater content
257 in the upper 2000 m of the North Atlantic between 50 - 80°N, derived from the ORAS4 ocean reanalysis
258 data discussed in ref. 23 (grey), and model simulations CNTR (black) and MELT (blue).

259 **Figure 2 | Fate of the additional Greenland runoff.** Distribution of vertically-integrated passive tracer
260 content in the last year of MELT (a) in the 0.05°-simulation (VIKING20); (b) same in the 0.25°-simulation
261 (ORCA025).

262 **Figure 3 | Trends in Labrador Sea surface salinity and convection intensity.** (a) Sea surface salinity
263 anomaly in the last year of MELT, black box indicating the site of OWS-B (see supplementary
264 information). (b) Meltwater-induced trends in sea surface salinity in the WGC (red box in a) and basin
265 interior (green box) as given by the difference MELT-CNTR. (c) Annual formation rate of Labrador Sea
266 Water (LSW), as given by the increase in the volume of the LSW density layer in the Labrador Sea during
267 the winter convection seasons, for CNTR (black) and MELT (blue). (d) Deviation of March mixed layer
268 depths in MELT from CNTR (average over years 2017-19), in m.

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