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2 **Rapid circulation of warm subtropical waters in a major**  
3 **glacial fjord in East Greenland**

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16 **The recent rapid increase in mass loss from the Greenland Ice Sheet<sup>1,2</sup> is primarily**  
17 **attributed to an acceleration of outlet glaciers<sup>3-5</sup>. One possible cause is increased**  
18 **melting at the ice/ocean interface<sup>6,7</sup> driven by the synchronous warming<sup>8-10</sup> of**  
19 **subtropical waters offshore of Greenland. This hypothesis is largely untested,**  
20 **however, because of the lack of observations from Greenland' s glacial fjords and**  
21 **our limited understanding of their dynamics. Here, we present new ship-based and**  
22 **moored oceanographic data, collected in Sermilik Fjord, a large glacial fjord in East**  
23 **Greenland, showing that subtropical waters are present throughout the fjord and**  
24 **are continuously replenished via a wind-driven exchange with the shelf, where they**  
25 **occur year-round. The temperature and rapid renewal of these waters suggest that,**  
26 **at present, they drive enhanced submarine melting at the terminus. Key controls on**  
27 **the melting rate are the volume and properties of subtropical waters on the shelf**  
28 **and the patterns of the along-shore winds, suggesting the glaciers' acceleration**  
29 **was triggered by a combination of atmospheric and oceanic changes. These**  
30 **measurements provide evidence of rapid advective pathway for the transmission of**  
31 **oceanic variability to the ice-sheet margins and highlight an important process that**  
32 **is missing from prognostic ice-sheet models.**

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36           The Greenland Ice Sheet's contribution to sea level rise more than doubled in the  
37 last decade<sup>1,2</sup>, predominantly due to the acceleration of outlet glaciers flowing into deep  
38 fjords in western and southeastern Greenland<sup>3,4,5</sup>. The glacier speed-up occurred  
39 approximately at the same time as a warming trend began in the subpolar North Atlantic  
40 Ocean, adjacent to Greenland's southeastern and western sectors<sup>8-10</sup>, giving rise to the  
41 hypothesis that glacier acceleration was triggered by ocean warming<sup>11-13</sup>. The proposed  
42 mechanism involves enhanced melting at the front of the glacier, driven by increased  
43 ocean heat transport, which leads to ice thinning, ungrounding of the terminus and ice  
44 flow acceleration<sup>6,7</sup>.

45  
46           A lack of measurements from Greenland's glacial fjords, however, makes it  
47 difficult to test this hypothesis. First, the warming waters belong to the Irminger Current  
48 (IC), a topographically-steered branch of the North Atlantic Current (NAC), which  
49 carries warm, subtropical water (STW) into the subpolar basin (Figure 1a). This water is  
50 trapped offshore over the continental slope, while cold, fresh polar water (PW),  
51 transported by the East and West Greenland Currents (EGC and WGC; Figure 1a)  
52 dominates the shelf adjacent to the fjords<sup>14</sup>. Evidence that STW reaches Greenland's  
53 fjords is limited to a few summer profiles from Jakobshavn<sup>12</sup> and Kangerdlugssuaq<sup>15</sup>  
54 fjords and there is no direct evidence that it comes into contact with glaciers. The lack of  
55 adequate fjord measurements from the period prior to the glaciers' acceleration, in  
56 particular, means that we need to rely on our understanding of the processes which  
57 control the properties and circulation within the fjords (and hence the heat transport to the

58 glaciers' termini) in order to infer past conditions and assess the ocean's role in triggering  
59 the acceleration of Greenland's glaciers. At present, the mechanisms governing the  
60 circulation of STW on the shelf and inside Greenland's glacial fjords are unknown.

61

62 The 100 km long Sermilik Fjord (66° N, 38° W) connects Helheim Glacier with  
63 the Irminger Sea (Figure 1b). In 2003, Helheim Glacier retreated several kilometers and  
64 almost doubled its flow speed<sup>3,4</sup>. Warm STW has recently been observed outside the fjord  
65 on the shelf<sup>6</sup> but there are no records of ocean properties within the fjord itself. We  
66 collected thirty-eight temperature and salinity profiles, together with bathymetric and  
67 current data, in and just offshore of Sermilik Fjord during two surveys in July and  
68 September, 2008 (Figure 1b). Additional data were collected by several moored  
69 instruments (Figure 1b; see Methods Summary).

70

71 Sermilik is a U-shaped glacial trough which is deeper (900 m at the mouth) than  
72 most of the adjacent shelf (300-400 m). No sill was found in our surveys. Instead we  
73 identified a 700 m deep channel extending from the mouth (Figure 1b) towards a deep  
74 trough that stretches across the entire shelf (Figure 1a). In September, this 20 km wide  
75 channel was mostly filled with warm (4.2 °C) STW which, assuming geostrophy and no  
76 flow at the bottom, was flowing towards the fjord. Slightly cooler STW (3.5-4 °C) was  
77 present in large volumes inside the fjord from a depth of 200-300 m to the bottom at all  
78 surveyed locations (Figure 2 a-c). A 10-20 m thick layer of glacial meltwater (GM) and a  
79 100-150 m thick layer of PW were found above STW throughout the fjord (Figure 2 a-c).

80 Property changes within the fjord were mostly in the along-fjord direction with limited  
81 across-fjord variation (consistent with a narrow fjord not strongly influenced by rotation).

82

83 The same three water masses were present in the fjord during both surveys but  
84 with different characteristics in the upper 300-400 m (Figure 2). In particular, the PW  
85 layer was noticeably thinner and warmer in September, which increased the mean  
86 temperature of the upper 400 m from 0.5 to 2 °C. This warming is too large to be driven  
87 by local heating (it requires a surface heat flux of 470 W/m<sup>2</sup> for July and August which is  
88 three times larger than that estimated for the same period from the National Center for  
89 Environmental Prediction Renalysis<sup>17</sup> for the region outside the fjord, shown in Figure  
90 3c) and, also, surface fluxes would not penetrate deep in this highly stratified  
91 environment. Thus, the change must result from the advection of warmer waters into the  
92 fjord, as confirmed by the presence of different water masses in the upper layers in July  
93 and in September (Figure 2a-c). To investigate whether changes in the fjord are  
94 consistent with those occurring outside the fjord, we reconstructed the seasonal variation  
95 of temperature on the shelf using data collected by 19 Hooded seals (*Cystophora cristata*)  
96 tagged with satellite-linked temperature-depth recorders<sup>18</sup> (5269 dives from 2004 to  
97 2008<sup>19</sup>) (Figure 3). These data reveal that STW (subsurface waters warmer than 3.5 °C)  
98 are present on the shelf year round and, also, that the shelf waters warm from July to  
99 December. Both the trend and the magnitude of the warming (the shelf's upper 400 m  
100 also warm by ~1.5 °C from July to September) support the conclusion that changes in the  
101 fjord are a result of advection from the shelf. (The shelf temperatures are warmer than

102 those in the fjord because they represent a spatial average across the shelf, including  
103 regions close to undiluted STW on the slope.)

104

105 The rapid flushing of the upper waters of the fjord indicates a vigorous  
106 circulation. We investigate its nature by first considering an estuarine-type circulation,  
107 driven by a large melt water input at the head, consisting of a fresh outflow at the surface  
108 balanced by a saltier, subsurface inflow (see Supplementary Figure 1a). The magnitude of  
109 the estuarine circulation and the related flushing time are estimated from the observed  
110 vertical property distribution and by applying conservation of mass and salt. Assuming  
111 the circulation is limited to the upper 300 m, the ‘fastest’ estimated flushing time is ~2  
112 years (see Supplementary Methods), indicating that the observed summertime changes  
113 cannot be attributed to this type of circulation alone.

114

115 A second type of circulation common in narrow, deep fjords<sup>20</sup> is an ‘intermediary  
116 circulation’<sup>21</sup> driven by pressure gradients which arise between the fjord and the coastal  
117 region. It is associated with strongly sheared flows and an exchange of properties that  
118 persist until the fjord (the smaller volume) has equilibrated to the coastal region. Several  
119 pieces of evidence indicate that such a circulation may dominate in Sermilik Fjord. First,  
120 we observed large, strongly-sheared currents in the upper 100-200 m during both surveys  
121 (Figure 2e and g). These currents are more vigorous than the expected 10-15 cm/s tidal  
122 currents, which would arise from a barotropic tide in a 800 m deep channel and a tidal  
123 range of 1.5 m (the maximum range measured by a tide-gauge deployed in the fjord from

124 July-September 2008). Second, the observed currents must, by continuity, have  
125 compensating outgoing currents at depth, otherwise they would raise sea-level in the  
126 fjord by several meters within one hour which is inconsistent with the tide-gauge data.

127

128 Intermediary circulations can be driven by any forcing which results in fjord/shelf  
129 gradients<sup>20</sup> but our observations indicate along-shore winds as the dominant driver in  
130 Sermilik Fjord. Northeasterly wind events, for example, will initially ‘pile-up’ water and  
131 depress the halocline at the mouth of the fjord driving an inflow in the upper layer and at  
132 outflow at depth which, in turn, raises sea-level and depresses the halocline in the fjord.  
133 Once the winds subside, and the shelf relaxes back to the pre-event state, the fjord  
134 responds with the reverse circulation pattern (see Supplementary Figure 1).

135

136 Several along-shore wind events, which occurred during our surveys and mooring  
137 occupations, allow us to test the wind-driven intermediary-circulation hypothesis. Both  
138 surveys were conducted during or immediately after strong northeasterly (see Figure 3c  
139 for direction) wind events (Figure 4a) and the observed velocities and shear are consistent  
140 with the expected response. Clear evidence for depression of the halocline at the mouth  
141 of the fjord (Figure 2d) was found in the first survey, which took place during a wind  
142 event. Assuming the observed velocities were sustained, the upper 300 m of the fjord  
143 would be renewed within 4 days. Also, data collected by two summer moorings (see  
144 Figure 1b for location, and Methods Summary for a description) show qualitatively that  
145 northeasterly wind events are associated with a temporary downward displacement (by

146 50-100 m) of the isotherms (Figure 4b) and a temporary freshening at 25 m and 180-200  
147 m (Figure 4c), consistent with the response described above. While the summer mooring  
148 records are too short to establish statistical significance, an 8 month record of pressure,  
149 temperature and salinity from a third mooring reveals that anomalies in all three fields are  
150 significantly correlated with along-shore wind events, and of the sign expected for a  
151 wind-forced intermediary circulation (see Supplementary Figure 2). We conclude that  
152 along-shore wind events, which are intense and frequent along Greenland's eastern  
153 coast<sup>22</sup>, control the renewal rate of waters in Sermilik Fjord and cause the fjord to track  
154 sub-seasonal changes on the shelf.

155

156         The presence of large volumes of STW in Sermilik Fjord during the summer, their  
157 renewal rate and observations that these waters are found on the shelf year-round, suggest  
158 that STW are also present in the fjord year-round. Their temperature, circulation and  
159 along-fjord retention of heat indicate that significant submarine melting is occurring at  
160 Helheim Glacier, which has an estimated terminus depth of 700 m<sup>23</sup>. Key controls to the  
161 rate of melting are the volume and properties of STW on the shelf as well as the along-  
162 shore winds. Since the characteristics of Sermilik Fjord and of the nearby shelf/slope  
163 region, including the along-shore winds<sup>22</sup> and deep channels<sup>24</sup> stretching across the shelf,  
164 are common to glacial fjords in southeastern and western Greenland, it is likely that these  
165 results can be generalized to other glacial fjords in this region – which contains the  
166 majority of the accelerating glaciers<sup>1</sup>.

167



168           The data presented here are limited to the period that followed Greenland's  
169 glaciers' accelerations and, thus, cannot provide direct evidence on the ocean's role in  
170 triggering the acceleration. Nonetheless, our results offer several new insights to this  
171 issue. First, the presence and renewal of STW in Sermilik Fjord provides evidence of a  
172 fast and direct pathway connecting the subpolar North Atlantic Ocean to glacial fjords  
173 along Greenland's southeast and west coasts. This supports the proposed hypothesis that  
174 changes in the North Atlantic might have impacted Greenland's glaciers within one  
175 year<sup>12</sup>. Second, our findings indicate that either changes in the volume and properties of  
176 STW on the shelf and/or changes in the intensity and number of transiting storms<sup>25</sup> would  
177 affect melting at the tidewater margins of outlet glaciers. Both mechanisms are plausible  
178 (and likely connected) given the pronounced changes in the N. Atlantic's ocean and  
179 atmosphere which began in the mid-1990s<sup>26,27</sup>. Thus, our findings support increased  
180 submarine melting as a trigger for the glacier acceleration but indicate a combination of  
181 atmospheric and oceanic changes as the likely driver.

182 **Methods Summary**

183 Measurements in Sermilik Fjord were conducted from a locally-chartered 24 foot vessel.  
184 Conductivity, temperature and depth (CTD) profiles were collected using a 6 Hz XR-620  
185 RBR sensor to 800 m in July and to 600 m in September. Four to six CTD profiles were  
186 collected across sections 1, 2, 3 and one at station A between July 4-6 and again between  
187 August 31-September 3, when sections S and 4 (Figure 1b) were added. Cross-  
188 instrument and pre- and post-deployment calibrations were carried out. Underway  
189 velocity data were collected using a vessel-mounted 300 kHz RDI Acoustic Doppler  
190 Current Profiler, combined with continuous vessel tracking by Global Position System,  
191 across section 2 in July and across sections 2 and 3 in September. Bathymetric data were  
192 obtained using a 320 Knudsen 12 kHz Echosounder.

193 Two moorings were deployed at depths of 25 and 180 m from July to September  
194 and a third mooring was deployed at 35 m from September 2008 to August 2009 (Figure  
195 1b). All three moorings carried a Seabird SBE 37-SM CTD recorder approximately 1 m  
196 above the bottom. In addition, the deeper mooring carried a thermistor string consisting  
197 of 10 Starmon Mini Temperature Recorders, spaced 10 m apart from the bottom to 100 m  
198 off the bottom. An RBR DR1050 depth recorder located above the uppermost recorder  
199 provided a measure of mooring tilt. The deep mooring was hit by ice three times and  
200 eventually displaced to a depth of 220m. The 35 m mooring was also hit by ice and  
201 displaced several times until it settled at 65 m at the end of December (where it stayed  
202 until it was recovered). All three moorings were located within 300 m of each other and  
203 displacements were less than 100 m.

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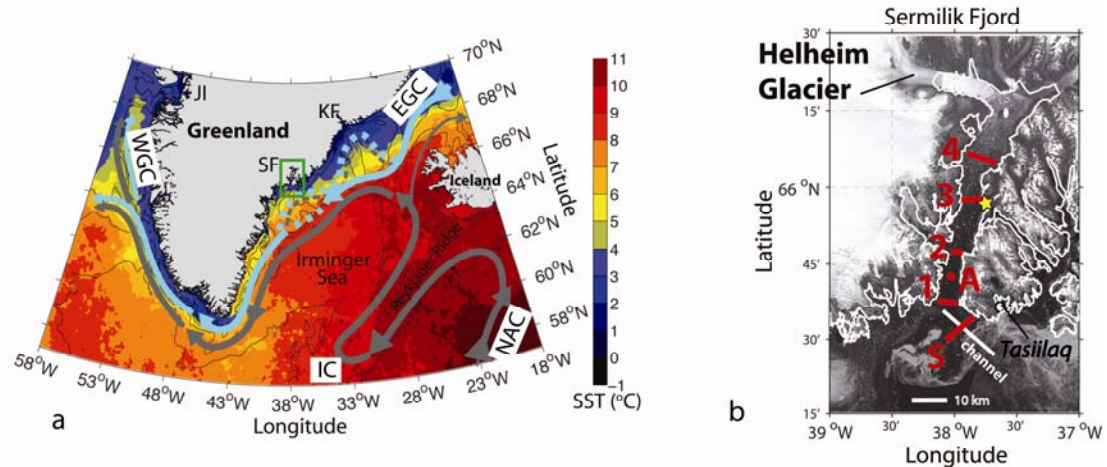
274 **Supplementary Information** accompanies the paper on [www.nature.com/nature](http://www.nature.com/nature).

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283 **Authors' Contributions** FS and GSH conceived the study, F.S., D. A. S., L. A. S. and G. S. H.  
284 participated in the collection of oceanographic data in Sermilik Fjord, and F.S. and D. A. S. were  
285 responsible for the analysis. M. O. H., G. B. S. and A. R. A. were responsible for the capture of the seals  
286 and deployment of the transmitter and F.D. for processing the data from the seals. .

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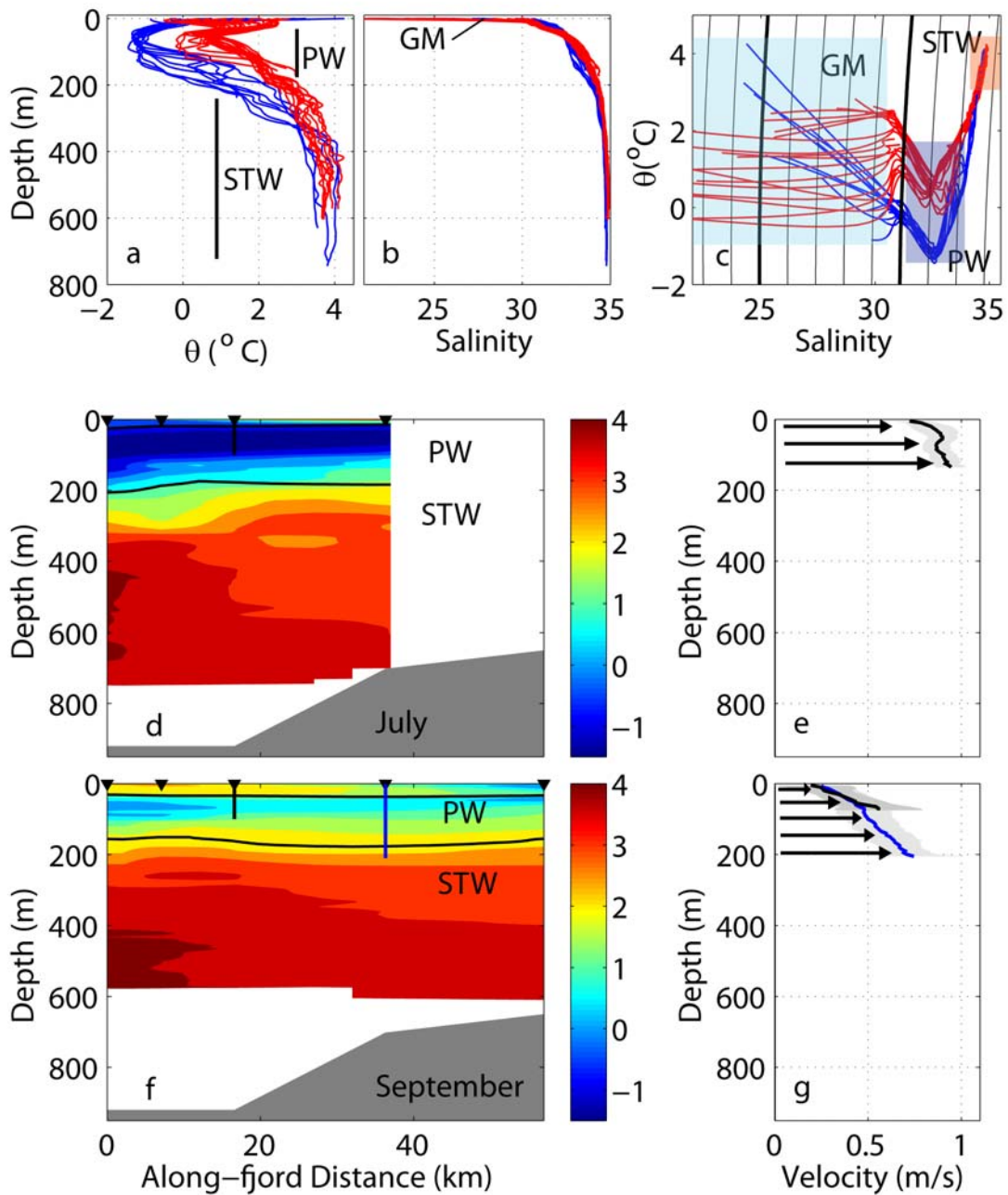
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291 **Figure 1** a) Currents around Greenland overlaid on the 2003 mean sea-surface  
 292 temperature from the Advanced Very High Resolution Radiometer (filled  
 293 contours). Bathymetric contours (100, 500, 1000, 2000, 3000 m) are overlaid in  
 294 black. PW transported by the EGC and WGC is in blue (dashed paths indicate  
 295 multiple branches) and STW transported by the NAC and IC in gray. Sermilik  
 296 Fjord (SF, green box), Kangerdlugssuaq Fjord (KF) and Jakobshavn Isbrae (JI)  
 297 are indicated. b) Landsat mosaic of Sermilik Fjord. Sections (1-4, S) plus station  
 298 A occupied in the 2008 surveys are indicated in red, moorings' locations by the  
 299 yellow star.

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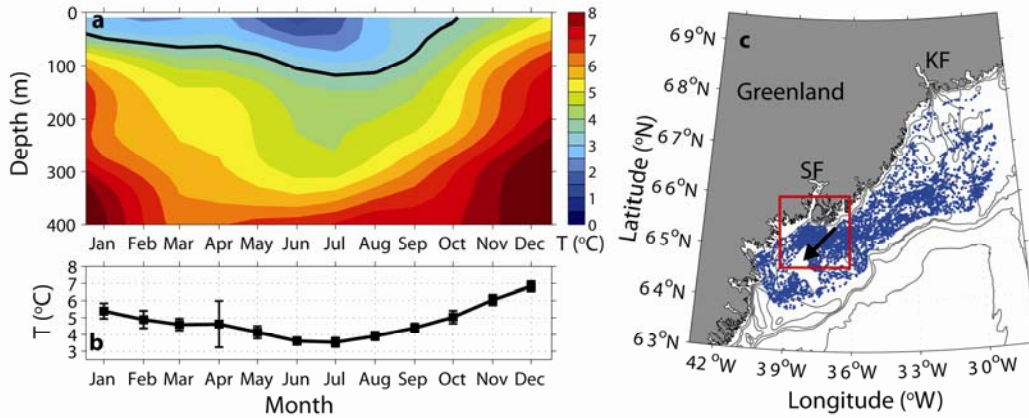
302 **Figure 2.** Measurements in Sermilik Fjord in summer 2008 and the 3  
 303 watermasses, GM, PW and STW. **a)** Potential temperature in July (blue) and



304 September (red); **b)** Salinity (colors as a). **c)** Potential temperature versus salinity  
305 (colors as a). Potential density contours are overlaid in black (thick lines are  
306  $\sigma_{\theta}=20$  and  $25 \text{ kg/m}^3$ ) **d)** and **f)** Potential temperature distribution in the along-fjord  
307 direction ( $x=0$  is the mouth) from across-section averages, in July and  
308 September, respectively. The 31.5 and 34 isohalines are overlaid to separate the  
309 3 layers. Top triangles indicate section location and vertical bars the velocity  
310 sections. Bathymetry is shaded in gray. **e)** and **g)** Along-fjord velocity averaged  
311 across-fjord at the sections indicated in d) and f) respectively, positive is towards  
312 the head of the fjord. Shading indicates the standard deviation across the  
313 section; arrows indicate direction of flow.

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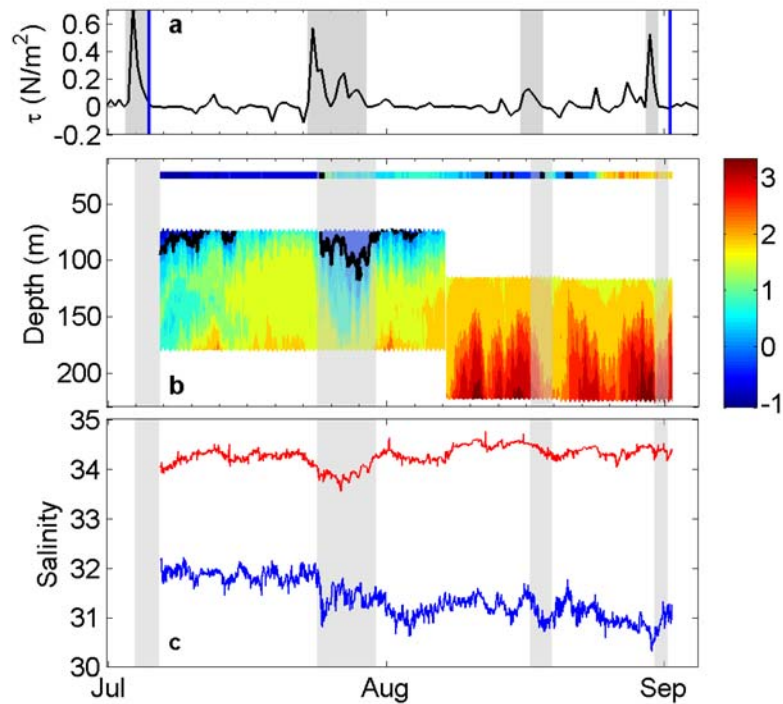


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317 **Figure 3** Seasonal temperature variation on the East Greenland Shelf from  
 318 tagged Hooded seals. a) monthly and spatially averaged temperature profiles  
 319 versus depth (solid line is 3.5°C and approximately separates the PW from the  
 320 STW). b) mean monthly temperature averaged over the upper 400m (vertical  
 321 bars indicate standard error). c) locations of the 5269 seal dives. Both the winds  
 322 and the heat fluxes referred to in the text were averaged over the red box shown.  
 323 The direction of the northeasterly winds (oriented at 54°) is shown by the black  
 324 arrow.

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328 **Figure 4.** Along-shore winds in Sermilik Fjord. a) Northeasterly wind stress  
 329 outside of Sermilik Fjord from Quikscat. Wind events are shaded (see  
 330 Supplementary Methods). Blue lines show when the velocity data was collected.  
 331 b) Potential temperature from the two summer moorings. Data from the 11  
 332 temperature recorders was vertically interpolated. The deep mooring was hit by  
 333 ice and relocated 40 m deeper in early August. Wind-events as in a) but lagged  
 334 by one day (see Supplementary Methods) c) Salinity from the two moorings at 25  
 335 m (blue) and at 180-200 m (red). Shaded regions as in b).

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## 340 **Supplementary Methods**

### 341 **Estuarine Circulation**

342 We estimate the magnitude of the estuarine circulation in the fjord by assuming a simple  
343 two-layer system with an outflowing fresh plume and an inflowing saltier layer  
344 (Supplementary Figure 1a). Using relations for the conservation of mass and salt<sup>28</sup>, the  
345 fjord's flushing time ( $T_f$ ) due to an estuarine circulation is:

$$346 \quad T_f = \frac{(h_{out} + h_{in})WL}{S_{in}R} (S_{in} - S_{out}),$$

347 where  $W$  is the width of the fjord (8 km),  $L$  the length (100 km),  $R$  the rate of melt water  
348 input,  $h$  the layer thickness,  $S$  the salinity, and subscripts 'in/out' refer to the inflowing  
349 deep, salty layer and the outflowing fresh layer, respectively. If we assume the estuarine  
350 circulation is confined to the upper 300m (the layer over which we observed the most  
351 pronounced changes), data from the two surveys yield the following estimates:  $h_{out} \sim 10$ -  
352  $20$  m,  $h_{in} \sim 280$ m,  $S_{in} \sim 33$ - $33.3$ ,  $S_{out} \sim 28$ - $29.5$ .

353 To estimate meltwater input,  $R$ , we first consider Helheim Glacier, the dominant source  
354 of meltwater for Sermilik Fjord. Measurements of exposed stake heights on Helheim  
355 Glacier (GSH and LAS, unpublished data) yield surface melt rates of  $\sim 4$  m/yr at 100 m  
356 asl and  $\sim 2$  m/yr at 700 asl. We use a simple linear scaling to apply these estimates to the  
357 glacierized area surrounding the upper portion of Sermilik Fjord using a digital elevation  
358 model<sup>3</sup> to obtain a liquid water runoff of  $\sim 5$  Gt/yr. An unknown amount of liquid water is  
359 generated by submarine melting at the tidewater terminus of Helheim Glacier and by  
360 icebergs in the fjord which, for the purposes of this calculation, we assume is equal to the

361 terrestrial runoff. This yields a net value for  $R$  (~10 Gt/yr) which is probably an  
362 underestimate because we neglected 1) snow-melt runoff from the non-glacierized land-  
363 surface and 2) meltwater from other portions of the ice sheet bordering the fjord as well  
364 as local glaciers. To account for this and, in general, to minimize the flushing time  
365 estimate, we more than double our estimated fresh water input and use  $R \sim 25$  Gt/yr = 25  
366 km<sup>3</sup>/yr.

367 Using these values, the estimated flushing time of the upper 300 m is > 2 yr, with a mean  
368 inflow velocity of 0.1 cm/s and an outflow velocity of 2 cm/s. It would take more than 5  
369 years to flush the entire fjord (assuming a mean depth of 700 m). We emphasize that the  
370 purpose of this simple calculation is to maximize the magnitude of the estuarine  
371 circulation (and minimize the flushing time); even taking the maximum range of input  
372 values yields a flushing time that is an order of magnitude slower than that implied from  
373 our field observations. This suggests that, while still contributing to the net circulation  
374 within the fjord, the meltwater driven estuarine circulation is not the dominant  
375 mechanism for water mass renewal inside the fjord.

376

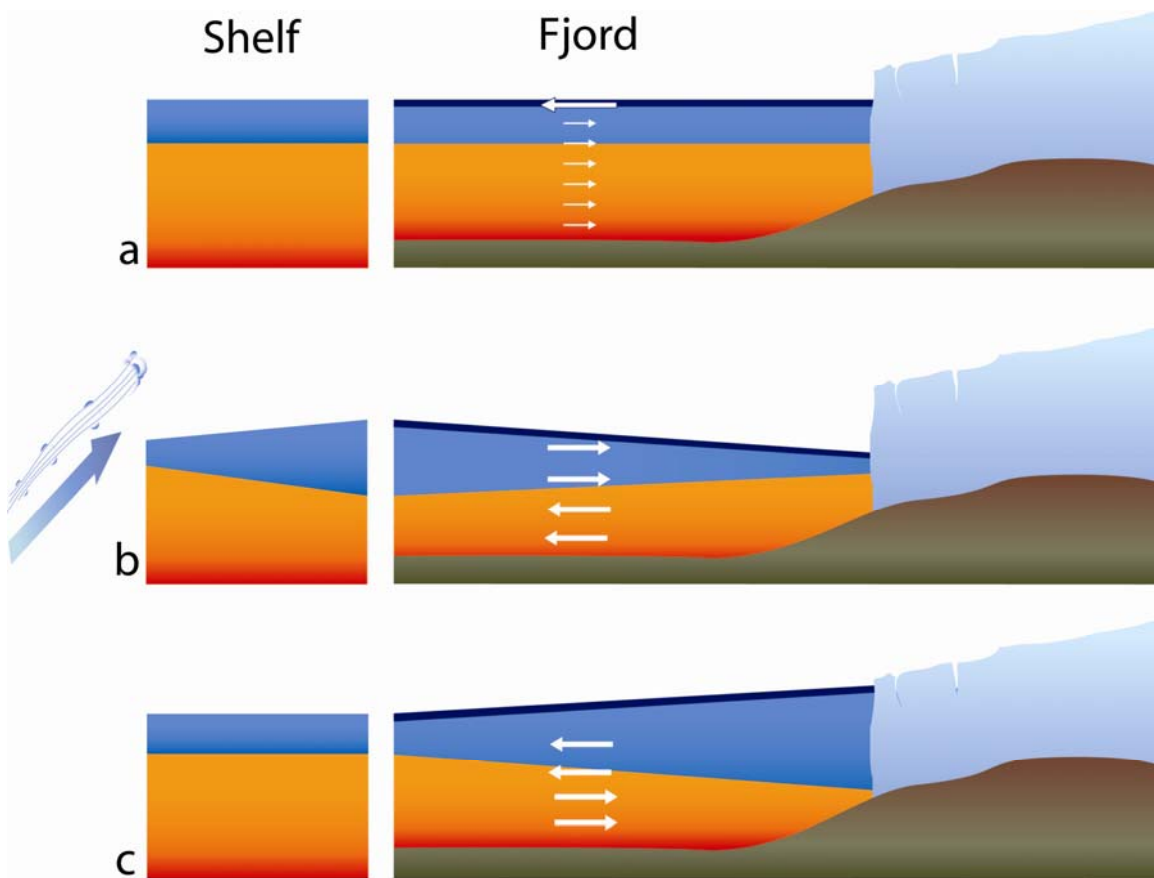
### 377 **Along-shore Winds**

378 12 hourly wind velocity (at 10 m) data are obtained from NASA's Quick Scatterometer  
379 (QuikSCAT; <http://podaac.jpl.nasa.gov>). Winds in the coastal region outside of Sermilik  
380 Fjord are derived by averaging across a region bounded by 36-39° W and 64.5-66° N (see  
381 Figure 3c). This region is large enough to ensure that data coverage is always available  
382 and minimizes the effect of data gaps that commonly occur in the proximity of the coast.

383 We note that the winds over the shelf have relatively large spatial coherence and that our  
384 results are not overly sensitive to the exact ‘region’ used for averaging. Positive along-  
385 shore winds are oriented at  $54^\circ$  (see Figure 3c). The wind-stress is obtained using the  
386 Large and Pond formulation<sup>29</sup> (Figure 4a and Supplementary Figure 2a). Wind events are  
387 defined as along-shore wind events whose magnitude exceeds  $0.1 \text{ N m}^{-2}$  and whose  
388 duration is longer than 1 day.

389

### 390 Intermediary Circulation



391

392 **Supplemental Figure 1** Circulation in Sermilik Fjord a) Classic estuarine  
393 circulation in the absence of wind-forcing: a fast outflowing glacial meltwater plume and

394 a weaker compensating inflow at depth. Wind-driven circulation: b) Northeasterly winds  
395 'pile-up' water and depress the halocline at the mouth driving an inflow in the upper  
396 layer and outflow at depth. c) After the wind ceases and the shelf region returns to pre-  
397 event conditions and the fjord relaxes through the reverse circulation.

398

### 399 **Analysis of the 8-month mooring record**

400 The third mooring, carrying a single CTD recorder was deployed in early  
401 September 2008 and recovered in mid-August 2009 (see Methods Summary). Its initial  
402 location coincided with that of the shallow summer mooring but, after having been hit  
403 and displaced by ice several times, the mooring settled at 65 m at the end of December,  
404 40 m deeper than its original depth. Spatially, the mooring was displaced less than 100 m  
405 from its original location. To remove any bias due to displacement, we restrict this  
406 analysis to data from December 28, 2008 to August 20, 2009 when the mooring remained  
407 at one location (and depth). Post-recovery calibrations did not show any sensor drift. The  
408 mooring recorded temperature (T), salinity (S) and pressure (P) every half hour  
409 throughout its deployment. These data were filtered with a 40 hour Hanning window to  
410 remove tidal and other high frequency noise (Supplementary Figure 2 b-d). To quantify  
411 the fjord's response to along-shore wind events, which have time-scales on the order of  
412 several days, we removed long term variations (such as seasonal) from the records by  
413 subtracting a 30-day low-pass filtered time series (also using a 30-day Hanning window).  
414 The resulting time series of anomalies are shown in Supplementary Figure 2e. The along  
415 shore wind stress outside of the fjord for the same period is shown in Supplementary  
416 Figure 2a. An anomaly time series for the wind is obtained in the same way as for the



417 ocean variables, Supplementary Figure 2e.

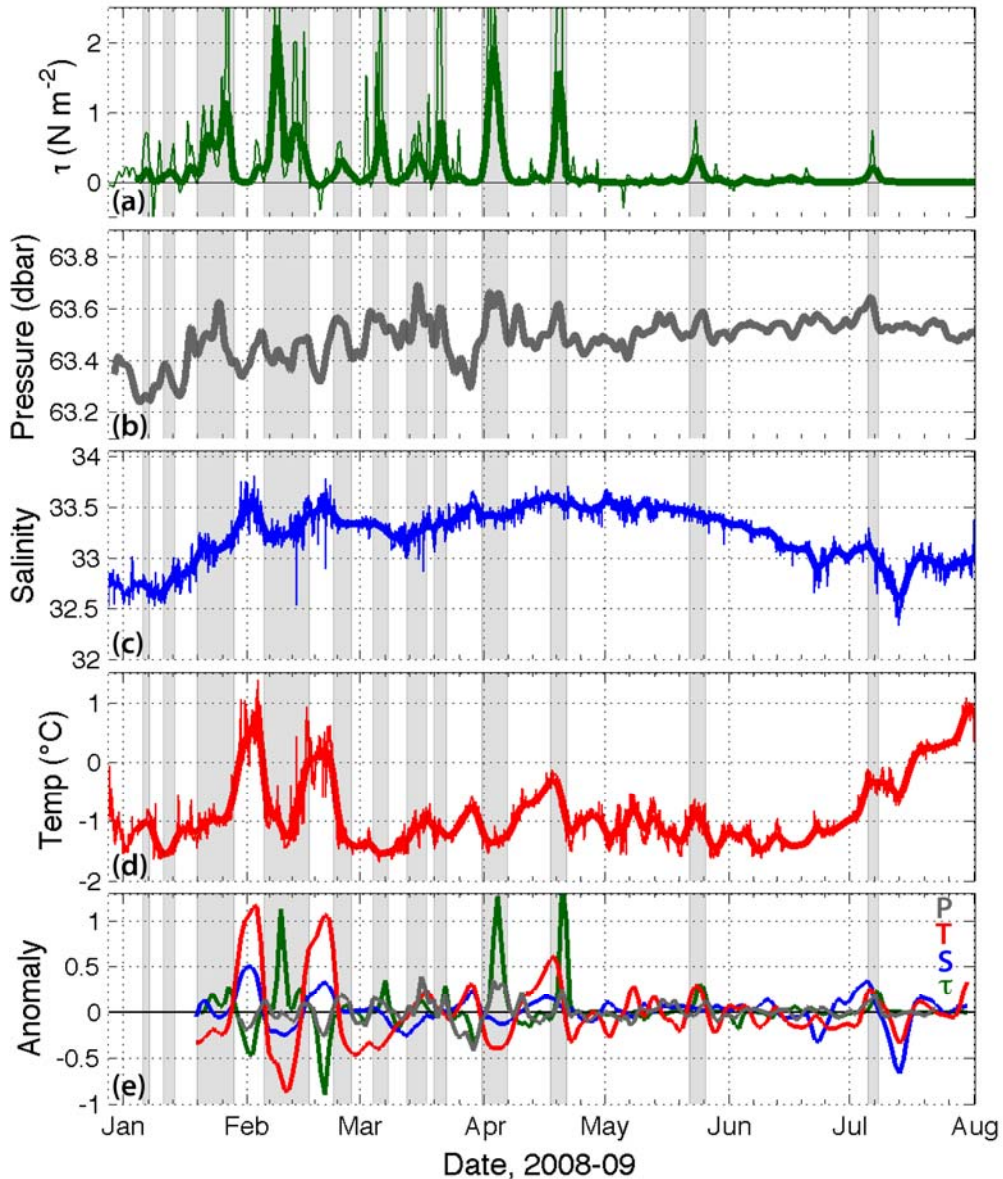
418 Visual inspection of the curves in Supplementary Figure 2 shows that positive  
419 wind stress anomalies are associated with positive pressure (equivalent to positive sea-  
420 surface height), negative salinity, and negative temperature anomalies. This is the  
421 expected response for a northeasterly wind event described in the text and Supplementary  
422 Figure 1 b and c. A simple regression of the anomaly time series for the fjord's properties  
423 on the wind stress anomaly time series reveals that all three are significantly correlated at  
424 the 99% level using 64 degrees of freedom (193 day long record with a 3-day  
425 decorrelation time scale), Supplementary Table 1. The correlation is largest for the  
426 pressure record which is representative of sea-surface height variability and at zero lag.  
427 (Mooring blow down is negligible given the length of the mooring, less than 1 m, and,  
428 also, it cannot account for negative pressure anomalies.) This is consistent with a rapid  
429 barotropic adjustment of the fjord. Maximum correlations with temperature and salinity  
430 are found at 1 day lag consistently with the slower baroclinic response.

431  
432 **Supplementary Table 1.** Correlations of variables from the long mooring record with  
433 the alongshore wind stress.

<b>Variable</b>	<b>R</b>	<b>Lag</b>	<b>Significant</b>
Salinity	-0.33	1 day	$p < 0.01$
Temperature	-0.46	1 day	$p < 0.01$
Pressure	0.53	0	$p < 0.01$

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436 Finally, it is evident from Supplementary Figure 2 that the wind-driven intermediary  
437 circulations do not account for all of the variability at this depth. Departures from this  
438 correlation are expected to occur and, we argue, are not inconsistent with the conclusions  
439 of this study – that the wind-driven intermediary circulation is the dominant but not the

440 only forcing of the fjord's variability. Indeed, the mooring discussed here is shallow  
441 enough that one cannot rule out the impact of local air-sea fluxes both during the  
442 wintertime period (as sea-ice forms in the fjord) and during the summer (when summer  
443 heating may be mixed down). The latter may explain the warming observed in late  
444 summer when there appear to be few or no wind-events. Second, and as noted in the main  
445 text, intermediary circulations will arise from any mechanism that generates a fjord/shelf  
446 pressure gradient (e.g. coastally trapped waves or eddies). Indeed on intermediary-  
447 circulation-like event occurs in mid-July but it is not associated with a wind-event  
448 (Supplementary Figure 2).



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**Supplementary Figure 2.** (a) Time series of the alongcoast windstress,  $\tau$  ( $\text{N m}^{-2}$ ), outside Sermilik Fjord measured by the QuikSCAT scatterometer (see Supplementary Methods). The light line is the original data and the heavy line is the 40-hr low-passed time-series. Shading highlights downwelling ( $\tau > 0$ ) wind. (b) The 40-hr low-pass filtered pressure record from the shallow mooring. (c) Same as in *b*, but for salinity. (d) Same as in *b*, but for temperature. (e) Time series of pressure (P), temperature (T), salinity (S), and wind stress ( $\tau$ ) anomalies. The wind stress and pressure anomalies have been shifted one day to correspond with the maximum correlations found with T and S. The  $\tau$ , S, and P anomalies are scaled by a factor of 2 to help visualization. Units are the same as in panels a) to d).

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