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## Journal Article

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# 1 **Sea-ice transport driving Southern Ocean salinity and its recent trends**

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11 **Recent salinity changes in the Southern Ocean<sup>1-7</sup> are among the most prominent signals**  
12 **in the global ocean, yet their underlying causes have not been firmly established<sup>1,3,4,6</sup>.**  
13 **Here, we propose that trends in northward transport of Antarctic sea ice are a major**  
14 **contributor to these changes. Using satellite observations supplemented by sea-ice**  
15 **reconstructions, we estimate that the wind-driven<sup>8,9</sup> northward freshwater transport by**  
16 **sea ice increased by  $20\pm 10\%$  between 1982 and 2008. The strongest and most robust**  
17 **increase occurred in the Pacific sector coinciding with the largest observed salinity**  
18 **changes<sup>4,5</sup>. We estimate that the additional freshwater for the entire northern sea-ice edge**  
19 **entails a freshening rate of  $-0.02\pm 0.01$  g kg<sup>-1</sup> per decade in open ocean surface and**  
20 **intermediate waters, similar to the observed freshening<sup>1-5</sup>. The enhanced rejection of salt**  
21 **near the coast of Antarctica associated with stronger sea-ice export counteracts regionally**  
22 **the freshening of continental shelf<sup>2,10,11</sup> and newly formed bottom waters<sup>6</sup> due to the**  
23 **increasing addition of glacial meltwater<sup>12</sup>. Although the data sources underlying our**  
24 **results have substantial uncertainties, regional analyses<sup>13</sup> and independent data from an**  
25 **atmospheric reanalysis support our conclusions. Our finding that northward sea-ice**  
26 **freshwater transport is a key determinant of the Southern Ocean salinity distribution also**  
27 **in the mean state further underpins the importance of the sea-ice induced freshwater flux.**  
28 **Through its influence on the ocean's density structure<sup>14</sup>, this process has critical**  
29 **consequences for the global climate by affecting the deep-to-surface ocean exchange of**  
30 **heat, carbon, and nutrients<sup>14-17</sup>.**

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34 Observations of salinity in the Southern Ocean over the last decades have revealed a substantial,  
35 wide-spread freshening in both coastal<sup>10,18</sup> and open ocean surface waters<sup>2,5</sup> as well as in the  
36 water masses sourced from these regions<sup>1,3,4,6</sup>. In particular, Antarctic Intermediate Water  
37 (AAIW) and Subantarctic Mode Water (SAMW) freshened at a rate between  $-0.01$  and  $-0.03$   
38  $\text{g kg}^{-1}$  per decade during the second half of the 20<sup>th</sup> century<sup>1,3,4</sup>. In the Pacific and Indian Ocean  
39 sectors, continental shelf waters and Antarctic Bottom Water (AABW) also freshened  
40 substantially<sup>2,6,10</sup>, while in the Atlantic this freshening was smaller<sup>6,18</sup>. These salinity changes  
41 have been attributed to increased surface freshwater fluxes, stemming either from enhanced  
42 Antarctic glacial melt<sup>2,6,10-12</sup> or from increased atmospheric freshwater fluxes, as a result of an  
43 excess of precipitation over evaporation<sup>1,5</sup>. Glacial meltwater<sup>12</sup> most likely freshened coastal  
44 waters in the Amundsen and Ross Seas<sup>2,10,11</sup>, but the freshening signal in AABW, which is  
45 formed in this region, is much smaller than expected<sup>6</sup>. In contrast, in the open Southern Ocean,  
46 increases in the atmospheric freshwater flux as simulated by global climate models appear to  
47 be largely insufficient to explain the recent freshening of AAIW<sup>1,4</sup>.

48 Changes in northward sea-ice transport could possibly contribute to the wide-spread salinity  
49 changes in the Southern Ocean<sup>8</sup>. This process acts as a lateral conveyor of freshwater by  
50 extracting freshwater from the coastal regions around Antarctica where sea ice forms and  
51 releasing it at the northern sea-ice edge where sea ice melts<sup>19-21</sup> (Figure 1a). Despite substantial  
52 wind-driven changes in sea-ice drift over the last few decades<sup>8,9</sup>, this contribution has not been  
53 quantified yet. Here, we suggest that surface freshwater fluxes induced by a stronger northward  
54 sea-ice transport are a major cause for the observed salinity changes in recent decades. The  
55 large contribution of freshwater transport by sea ice to the salinity trends is corroborated by our  
56 finding that this process plays a key role for the climatological mean salinity distribution.

57 Our conclusions are based on basin-scale estimates of annual net sea-ice-ocean freshwater  
58 fluxes and annual northward transport of freshwater by sea ice over the period 1982 through  
59 2008. Further evidence in support is provided by our assessment of atmospheric reanalysis  
60 data<sup>22</sup> and results from another regional study<sup>13</sup>. We derived the sea-ice related freshwater  
61 fluxes by combining sea-ice concentration, drift, and thickness data and by using a mass-  
62 balance approach of the sea-ice volume divergence and local change (Methods). The analysed  
63 sea-ice concentration stems from satellite observations<sup>23</sup> (Extended Data Figure 1) and its  
64 thickness from a combination of satellite data<sup>24</sup> and a model-based sea-ice reconstruction that  
65 assimilates satellite data<sup>25</sup> (Extended Data Figure 2). The sea-ice volume divergence was  
66 computed from satellite-based sea-ice drift vectors<sup>26</sup> (Extended Data Figures 3-4) and sea-ice  
67 volume. From the resulting sea-ice volume budget, we finally estimated the freshwater  
68 equivalents of local annual sea-ice-ocean fluxes due to freezing and melting and annual lateral  
69 sea-ice transport (Methods).

70 Uncertainties in these derived freshwater flux products are substantial (Methods). A major  
71 challenge arises from the need to combine sea-ice drift estimates from different satellites in  
72 order to estimate trends. We addressed potential inhomogeneities and biases by vigorous data  
73 quality control, several corrections, and considering different time periods (Methods). A second  
74 challenge is associated with the relatively limited number of observations of sea-ice thickness.  
75 These uncertainties plus the observationally constrained range of the other input quantities  
76 entered our error estimates of the final freshwater flux product (Extended Data Tables 1-2). In  
77 the Atlantic sector, uncertainties associated with the mean sea-ice thickness distribution  
78 dominate the uncertainty, while in the Pacific sector, uncertainties are mostly caused by  
79 uncertainties in sea-ice drift.

80 Our analysis reveals large trends in the meridional sea-ice freshwater transport in the Southern

81 Ocean between 1982 and 2008 (Figures 1b and 2c) affecting the regional sea-ice-ocean  
82 freshwater fluxes (Figure 2d). The annual northward sea-ice freshwater transport of  $130\pm 30$   
83 mSv (1 milli-Sverdrup =  $10^3 \text{ m}^3 \text{ s}^{-1} \approx 31.6 \text{ Gt yr}^{-1}$ ; Figure 2a; Extended Data Table 1) from the  
84 coastal to the open ocean region strengthened by  $+9\pm 5$  mSv per decade (Extended Data Table  
85 2). Here, the coastal ocean refers to the region between the Antarctic coast and the zero sea-ice-  
86 ocean freshwater flux line, and the open ocean is the region between the zero sea-ice-ocean  
87 freshwater flux line and the sea-ice edge (Figure 2b). The increased northward transport caused,  
88 on average, an additional extraction of freshwater from the coastal ocean of  $-40\pm 20 \text{ mm yr}^{-1}$   
89 per decade and an increased addition to the open ocean region of  $+20\pm 10 \text{ mm yr}^{-1}$  per decade.

90 The overall intensification occurred primarily in the Pacific sector where we find a vigorous  
91 northward freshwater transport trend of  $+14\pm 5$  mSv per decade. The trends in this sector are  
92 the most robust ones (Extended Data Table 3). Over the whole period, this change in the Pacific  
93 sector corresponds to an increase of about 30% with respect to the climatological mean in the  
94 entire Southern Ocean (Extended Data Table 1). Largest trends occurred locally in the high-  
95 latitude Ross Sea (Figure 2d), where our estimated trends agree well with a previous study<sup>13</sup>  
96 (Methods). The increase in the Pacific sector is partly compensated for by small decreases in  
97 the Atlantic and Indian Ocean sectors. We reach similar conclusions when we consider only  
98 the satellite data from 1992 through 2004, i.e., the period when they are least affected by  
99 potential inhomogeneities (Extended Data Table 3).

100 The reason for the observed northward sea-ice freshwater transport and its recent trends is the  
101 strong southerly winds over the Ross and Weddell Seas, which persistently blow cold air from  
102 Antarctica over the ocean, pushing sea ice northward<sup>9</sup>. The winds over the Ross Sea  
103 considerably strengthened in recent decades, possibly due to a combination of natural, multi-  
104 decadal variability, changes in greenhouse gases, and stratospheric ozone depletion<sup>9</sup>. These  
105 changes in southerly winds induced regional changes in northward sea-ice drift<sup>8,9</sup>, which are  
106 responsible for the sea-ice freshwater transport trends (Methods). This relation between the  
107 atmospheric circulation and sea-ice drift changes enabled us to independently estimate the sea-  
108 ice drift anomalies using sea-surface pressure gradients along latitude bands from atmospheric  
109 reanalysis data<sup>22</sup> (Methods). Comparing the resulting northward sea-ice transport anomalies to  
110 the satellite-based estimates across the same latitude bands, results in a similar overall trend  
111 (Figure 3). Thus, this alternative approach not only corroborates our estimated long-term trend,  
112 but it also suggests that any remaining inhomogeneities in the sea-ice drift data due to changes  
113 in the satellite instruments are comparably small after applying multiple corrections (Methods).

114 To assess how the changing sea-ice-ocean freshwater flux (Figure 2d) affected the salinity in  
115 the Southern Ocean, we assumed that the additional freshwater in the open ocean region entered  
116 AAIW and SAMW formed from upwelling Circumpolar Deep Waters (CDW)<sup>27,28</sup> (Methods).  
117 We find that our freshwater flux trends imply a freshening at a rate of  $-0.02\pm 0.01 \text{ g kg}^{-1}$  per  
118 decade in the surface waters that are transported northward and form AAIW and SAMW  
119 (Figure 1b). Thus, the sea-ice freshwater flux trend could account for a substantial fraction of  
120 the observed long-term freshening in these water masses<sup>1,3,4</sup>. The strong sea-ice-ocean  
121 freshwater flux trends in the Pacific sector (Figure 2d) spatially coincide with the region of  
122 largest observed surface freshening<sup>2,5</sup> (Extended Data Figure 7) and can explain also the  
123 stronger freshening of the Pacific AAIW as compared to that of the Atlantic<sup>1,4</sup>. A more  
124 quantitative attribution of the observed salinity trends to the freshwater transport trends is  
125 beyond the scope of our study because the observed freshening trends stem from different time  
126 periods, and have strong regional variations and large uncertainties themselves<sup>1,3,4</sup>. However,  
127 our data show that changes in northward sea-ice freshwater transport induce salinity changes  
128 of comparable magnitude to the observed trends.

129 Our estimates in coastal regions (Figure 2d) also help to explain the observed salinity changes  
130 in AABW<sup>6</sup>, which is sourced from this region. Additional glacial meltwater from West  
131 Antarctica<sup>12</sup> strongly freshened the continental shelf in the Ross and Amundsen Seas over  
132 recent decades<sup>2,10,11</sup> (Figure 1b). However, the observed freshening in Pacific and Indian Ocean  
133 AABW was found to be much smaller than expected by this additional glacial meltwater<sup>6</sup>. Our  
134 data suggests that the freshening induced by the increasing glacial meltwater is substantially  
135 reduced by a salinification from an increased sea-ice to ocean salt flux over the continental shelf  
136 in the Pacific sector. This salt flux trend corresponds to a freshwater equivalent of  $-10\pm 3$  mSv  
137 per decade, resulting from an increasing northward sea-ice export from this region of enhanced  
138 sea-ice formation (Figure 2c-d). In contrast, over the continental shelf in the Atlantic sector,  
139 our data suggests a decreasing sea-ice to ocean salt flux, corresponding to a freshwater  
140 equivalent of  $+6\pm 3$  mSv per decade, which may have contributed to the observed freshening of  
141 the newly formed Atlantic AABW<sup>6</sup> and the north-western continental shelf waters<sup>18</sup>.

142 The large contribution of trends in sea-ice freshwater transport to recent salinity changes in the  
143 Southern Ocean is in line with the dominant role that sea ice plays for the surface freshwater  
144 budget in the seasonal sea-ice zone<sup>29</sup> and for the global overturning circulation<sup>19-21,27</sup> in the  
145 mean state. The freshwater equivalent of the total Southern Ocean sea-ice melting flux (Figure  
146 4a) is as large as  $460\pm 100$  mSv (Extended Data Table 1). On an annual basis, the vast majority  
147 of this melting flux is supported by the freezing of seawater of  $-410\pm 110$  mSv, with the  
148 remaining flux arising from snow-ice formation<sup>30</sup> (Methods; Figure 4b). Most of the sea ice is  
149 produced in the coastal region ( $-320\pm 70$  mSv), but only about 60% of the sea ice also melts  
150 there. The rest, i.e.,  $130\pm 30$  mSv is being exported to the open ocean (Figure 4c). These mean  
151 estimates agree well with an independent study carried out in parallel to this study<sup>27</sup>, which is  
152 based on the assimilation of Southern Ocean salinity and temperature observations (Methods).

153 The process of northward freshwater transport by sea ice effectively removes freshwater from  
154 waters entering the lower oceanic overturning cell, in particular AABW, and adds it to the upper  
155 circulation cell, especially AAIW (Figure 1a). Hereby, the salinity difference between these  
156 two water masses and thus the meridional and vertical salinity gradients increase. In steady  
157 state, the northward sea-ice freshwater transport of  $130\pm 30$  mSv implies a salinity modification  
158 of  $+0.15\pm 0.06$  g kg<sup>-1</sup> and  $-0.33\pm 0.09$  g kg<sup>-1</sup> in waters entering the lower and upper cell,  
159 respectively (Methods). The latter suggests that sea-ice freshwater transport accounts for the  
160 majority of the salinity difference between upwelling CDW and the exiting AAIW. We  
161 estimated that the salinification from sea ice in waters entering the lower circulation cell is  
162 compensated for by glacial meltwater and by an excess precipitation over evaporation in this  
163 region at about equal parts, agreeing with the very small salinity difference between CDW and  
164 AABW (Methods).

165 Because salinity dominates the density structure in polar oceans<sup>14</sup>, our findings imply that sea-  
166 ice transport is a key factor for the vertical and meridional density gradients in the Southern  
167 Ocean and their recent changes (Figure 1). This interpretation is consistent with the observation  
168 that large areas of the upper Southern Ocean not only freshened but also stratified in recent  
169 decades<sup>7</sup>. Increased stratification potentially hampers the mixing of deeper, warmer, and  
170 carbon-rich waters into the surface layer and thus could increase the net uptake of CO<sub>2</sub><sup>14,16,17</sup>.  
171 Consequently, our results suggest that Antarctic sea-ice freshwater transport, through its  
172 influence on ocean stratification and the carbon cycle, is more important for changes in global  
173 climate<sup>14,15</sup> than has been appreciated previously. This implication of our findings for the  
174 climate system stresses the urge to better constrain spatial patterns as well as temporal  
175 variations of sea-ice-ocean fluxes by reducing uncertainties in observations of drift, thickness,  
176 and snow cover of Antarctic sea ice.

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262 **Author contributions.** F.A.H., M.M., and I.F. conceived the study. F.A.H. assembled the data  
263 and performed the analyses. F.A.H. and N. G. wrote the manuscript. M.M., I.F., and S.K.  
264 assisted during the writing process. S.K. assisted in the quality and uncertainty assessment. All  
265 authors developed the methods and interpreted the results. N.G. and M.M. supervised this study.

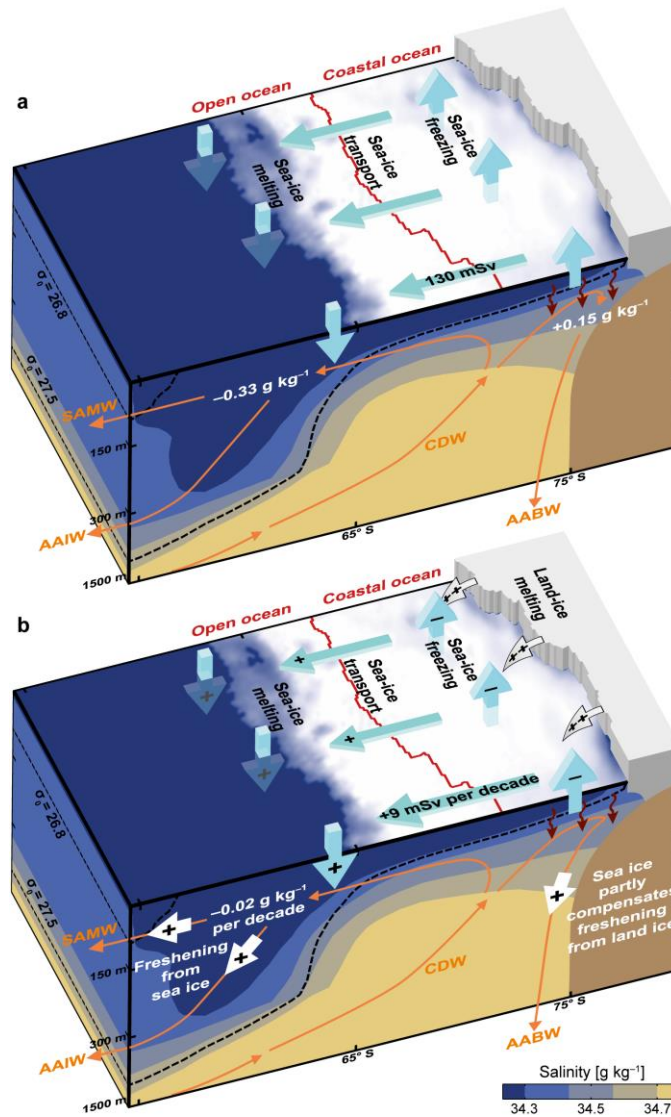
266 **Data deposition.** Sea-ice freshwater fluxes leading to the main conclusions are publicly  
267 available (<http://dx.doi.org/10.16904/8>). Other presented data is available from the  
268 corresponding author upon request.

269 **Code availability.** Climate Data Operators (CDO; version 1.6.8) used for part of the analysis  
270 are publicly available (<http://www.mpimet.mpg.de/cdo>). Other analytical scripts are available  
271 upon request from the corresponding author.

272 **Competing financial interests.** The authors declare no competing financial interests.

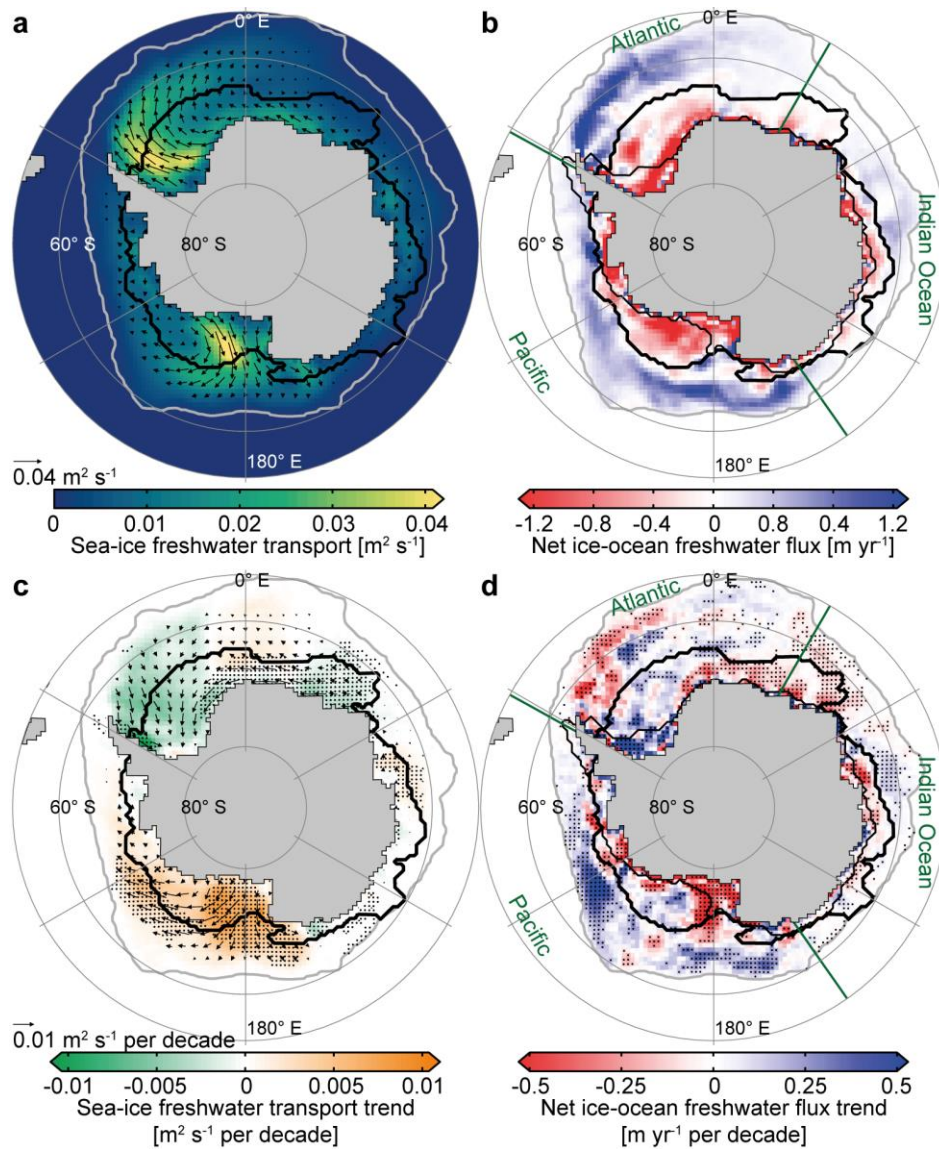
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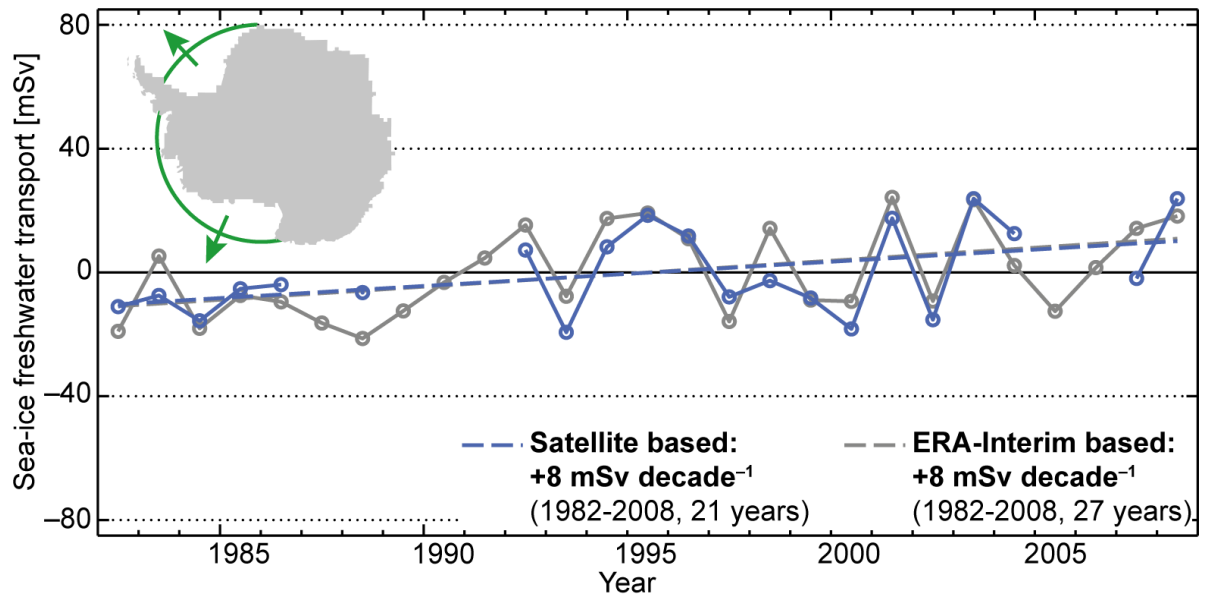
275

276 **Figure 1 | Effect of northward sea-ice freshwater transport on Southern Ocean salinity.**  
 277 Schematic cross-section illustrating the effect of northward sea-ice freshwater transport (blue  
 278 arrows) on (a) mean ocean salinity and (b) on the trends over the period 1982 through 2008  
 279 (Methods). The red line separates the open and coastal ocean regions. The increasing sea-ice  
 280 transport freshened the open ocean and, by leaving the salt behind in the coastal region (red  
 281 curved arrows), compensated for part of the freshening by enhanced glacial meltwater input  
 282 (grey arrows). White arrows indicate the freshening effect from both sea ice and land ice.  
 283 Positive fluxes are defined downward or northward. The background shows mean salinity (in  
 284 colour) and density (dashed black lines) separating Circumpolar Deep Water (CDW) from  
 285 Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW). Orange arrows:  
 286 ocean circulation; AABW: Antarctic Bottom Water.



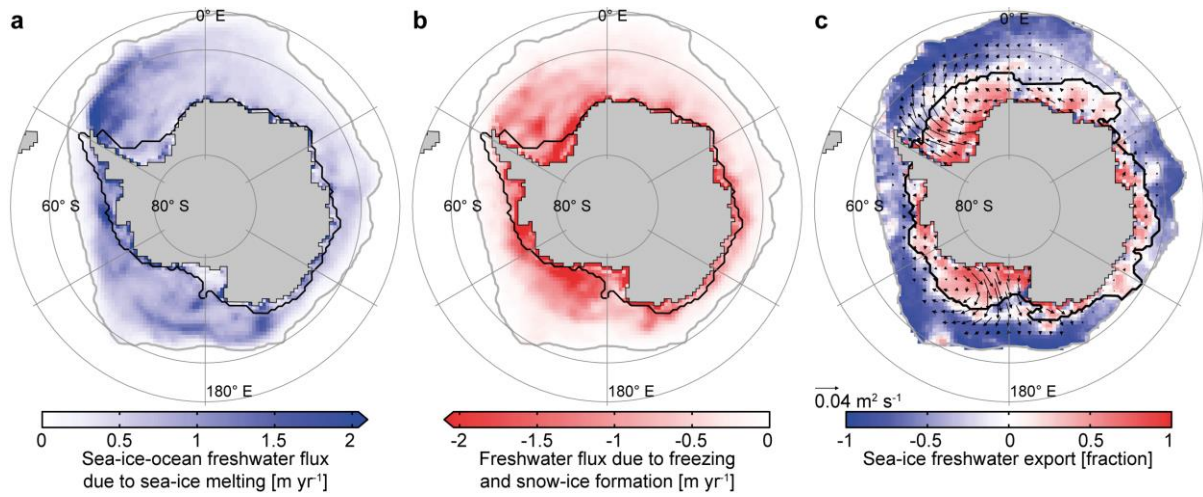
287

288 **Figure 2 | Mean state and trends of net annual freshwater fluxes associated with sea ice**  
 289 **over the period 1982 through 2008. a,** Mean sea ice induced freshwater transport. **b,** Mean  
 290 net sea-ice-ocean freshwater flux. **c, d,** Linear trends of northward sea-ice freshwater transport  
 291 (c) and net sea-ice-ocean freshwater flux from freezing and melting (d). Stippled trends are  
 292 significant at the 90% level (Methods). Arrows: (a) mean and (c) trend of the annual transport  
 293 vectors; thick black lines: zero sea-ice-ocean freshwater flux line dividing the coastal from the  
 294 open ocean regions; thin black lines: continental shelf (1000-m isobath); grey lines: sea-ice  
 295 edge (1% sea-ice concentration); green lines: basin boundaries.



296

297 **Figure 3 | Time series of annual northward sea-ice freshwater transport anomalies across**  
 298 **latitude bands.** The underlying sea-ice drift data are based on two independent data sources,  
 299 i.e., the corrected NSIDC satellite data (blue; only consistent years) and zonal sea-level pressure  
 300 gradients from ERA-Interim data (grey; Methods). Dashed lines show the respective linear  
 301 regressions. Inserted map shows the latitude bands in the Atlantic (69.5° S) and Pacific (71° S)  
 302 sectors.



303

304 **Figure 4 | Mean annual sea-ice related freshwater fluxes associated with melting, freezing,**  
 305 **and transport over the period 1982 through 2008. a, Sea-ice-ocean freshwater flux due to**  
 306 **melting. b, Freshwater flux associated with freezing and snow-ice formation. c, Fraction of**  
 307 **freshwater exported relative to local freezing flux (red) and imported relative to the local**  
 308 **melting flux (blue) due to sea-ice induced freshwater transport (arrows). Black and grey lines**  
 309 **as in Figure 2.**

310

## 311 **Methods**

312 **Data.** Satellite-derived sea-ice concentration stems from the Climate Data Record (CDR;  
313 version 2; 1980 to 2009; <http://dx.doi.org/10.7265/N55M63M1>)<sup>23</sup> that comprises data from the  
314 NASA Team algorithm (NTA)<sup>31</sup> and the Bootstrap algorithm (BA; version 2)<sup>32</sup>, as well as a  
315 merged data set. Sea-ice thickness data stems from a reconstruction with the ocean-sea-ice  
316 model NEMO-LIM2 (1980 to 2009)<sup>25</sup>, from the laser altimeter ICESat-1 (2003 to 2008;  
317 <http://seaice.gsfc.nasa.gov>)<sup>24</sup>, as well as from ship-based observations (ASPeCt; 1980 to 2005;  
318 <http://aspect.antarctica.gov.au>)<sup>33</sup>. Satellite-derived sea-ice drift stems from the National Snow  
319 and Ice Data Center (NSIDC, version 2; 1980 to 2009, <http://nsidc.org/data/nsidc-0116>)<sup>26</sup> and  
320 is corrected by drifting buoy data (1989 to 2005)<sup>34</sup>. We used an alternative sea-ice drift product  
321 for the uncertainty estimation (Kwok et al.; 1992 to 2003; <http://rkwok.jpl.nasa.gov>)<sup>35,36</sup>.  
322 Additionally, we used daily atmospheric sea-level pressure, surface air temperature, and 10-m  
323 wind speed from the ERA-Interim reanalysis (1980 to 2009, <http://apps.ecmwf.int>)<sup>22</sup>. We  
324 provide a detailed description of the data processing in the corresponding sections below.

325 **Sea-ice concentration.** We used all three sea-ice concentration products available from the  
326 CDR<sup>23</sup> (data section). If any of the grid points in either the merged, NTA, or BA product shows  
327 0% sea-ice concentration, all products are set to 0% sea-ice concentration. We used a first order  
328 conservative remapping method from the Climate Data Operators (CDO, version 1.6.8)<sup>37</sup> to  
329 interpolate the sea-ice concentration to the sea-ice drift grid. The BA performs superior  
330 compared to the NTA around Antarctica as the NTA underestimates sea-ice concentrations by  
331 10% or more<sup>23,38</sup> (Extended Data Figures 1a-b). Therefore, we primarily used the BA product.  
332 However, BA potentially underestimates sea-ice concentration in presence of thin sea ice and  
333 leads<sup>23,38</sup>. Therefore, we used the merged product that should be more accurate in these  
334 regions<sup>23</sup> to estimate the uncertainties. Generally, sea-ice concentration is the best constrained  
335 of the three sea-ice variables. Its contribution to the climatological mean flux uncertainty is  
336 below 1% (Extended Data Table 1). To obtain the uncertainty in the freshwater flux trends, we  
337 additionally used the NTA because differences in the Antarctic sea-ice area trends between the  
338 BA and NTA have been reported<sup>39</sup>. Differences between the BA and NTA sea-ice concentration  
339 trends range from 10% to 20% relative to the actual trend (Extended Data Figures 1c-d). The  
340 associated uncertainties in the spatially integrated sea-ice freshwater flux trends are about 10%  
341 (Extended Data Table 2).

342 **Sea-ice thickness.** Sea-ice thickness data spanning our entire analysis period do not exist,  
343 mostly owing to challenges in remote sensing of Antarctic sea-ice thickness<sup>40</sup>. Therefore, we  
344 used a sea-ice thickness reconstruction<sup>25</sup> (data section) from a model that assimilated the  
345 observed sea-ice concentration. Through the assimilation, the model constrained air-sea heat  
346 fluxes, improving the spatial and temporal variability of sea-ice thickness. The model did not  
347 assimilate sea-ice thickness observations themselves. Sea-ice thickness, as we use it here, is not  
348 weighted with sea-ice concentration and does not include the snow layer.

349 The reconstruction overestimates the sea-ice thickness in the central Weddell and Ross Seas  
350 and underestimates it in some coastal regions compared to the ICESat-1<sup>24</sup> and ASPeCt<sup>33</sup> data  
351 sets (data section; Extended Data Figure 2). To compare the different sea-ice thickness data  
352 sets, we interpolated the reconstruction, ICESat-1, and ASPeCt data to the sea-ice drift grid  
353 using CDO<sup>37</sup> distance-weighted averaging. For our best estimate of the sea-ice freshwater  
354 fluxes, we applied a weighted bias correction to the reconstruction using the spatially gridded  
355 version of the ICESat-1 data (see below). Both the ICESat-1 and ASPeCt data sets are  
356 potentially biased low, particularly in areas with thick or deformed sea ice<sup>33,40-42</sup>, where we  
357 found the largest differences between these two data sets and the uncorrected reconstruction.

358 Thus, the thicker sea ice in the Weddell Sea in the uncorrected reconstruction might yet be  
359 realistic, especially when considering alternative ICESat-1 derived estimates for this  
360 region<sup>40,43,44</sup>. To capture the full uncertainty range associated with the mean sea-ice thickness  
361 distribution, we used the difference between the uncorrected reconstruction and the ICESat-1  
362 data. Uncertainties in sea-ice thickness dominate the climatological freshwater flux  
363 uncertainties in the Atlantic and Indian Ocean sectors, ranging from 10% to 35%, and are also  
364 substantial in all other regions and for the overall trends (Extended Data Tables 1-2).

365 For the correction of the mean sea-ice thickness distribution, we first calculated relative  
366 differences to ICESat-1 whenever data were available. Then, we averaged all differences that  
367 were within two standard deviations over time. We applied this average, relative bias correction  
368 map to the data at each time step. To ensure that local extremes were not exaggerated, we used  
369 weights. Weights were one for a sea-ice thickness of 1.2 m, i.e., the full bias correction was  
370 applied, and decreased to zero for sea-ice thicknesses of 0.2 m and 2.2 m, i.e., no bias correction  
371 was applied. We derived these thresholds empirically to reduce biases with respect to the non-  
372 gridded ICESat-1 and ASPeCt data (Extended Data Figure 2). Trends in the reconstruction  
373 remain largely unaffected by the bias correction (comparing Extended Data Figure 2a and the  
374 original trend<sup>25</sup>).

375 Local extremes in the sea-ice thickness reconstruction, caused by ridging events, are most likely  
376 inconsistent with the observed sea-ice drift and would lead to unrealistic short-term variations  
377 in our final fluxes. However, when considering net annual melting and freezing fluxes and  
378 averages over large areas these variations cancel. To reduce the noise in our data set, we filtered  
379 extremes with a daily sea-ice thickness anomaly larger than 2 m with respect to the  
380 climatological seasonal cycle, representing only 0.1% of all data points. These and other  
381 missing grid points (in total 2.6%) were interpolated by averaging the neighbouring grid points.  
382 We also calculated our sea-ice freshwater fluxes based on the unfiltered data and included these  
383 fluxes in our uncertainty estimate.

384 Snow-ice formation due to flooding and refreezing<sup>30,45</sup> is part of the estimated sea-ice thickness.  
385 As snow-ice forms partly from the atmospheric freshwater flux and not from the ocean alone,  
386 it could lead to an overestimation of the total ocean to sea-ice freshwater flux due to freezing.  
387 The amount of snow-ice formation is highly uncertain<sup>30,45</sup> but within the uncertainty of the sea-  
388 ice thickness. To account for this process, we reduced the freezing fluxes according to snow-  
389 ice formation estimates from the reviewed literature<sup>30</sup>. In the Atlantic, Indian Ocean, and Pacific  
390 sectors, we applied approximate snow-ice formation rates of  $8\pm 8\%$ ,  $15\pm 15\%$ , and  $12\pm 12\%$  of  
391 the freezing flux, respectively<sup>30</sup>. In the entire Southern Ocean, the amount of snow that is  
392 transformed to ice would thus amount to about 50 mSv, or about 35% of the suggested  
393 atmospheric freshwater flux onto Antarctic sea ice<sup>27</sup>.

394 Trends in sea-ice thickness (Extended Data Figure 2a) are highly uncertain but broadly agree  
395 among different modelling studies<sup>25,46,47</sup>. To show that our results are robust with respect to the  
396 less certain trends or short-term variations in sea-ice thickness, we compared our estimated  
397 transport trends across the latitude bands (3) with a sensitivity analysis, where we kept the sea-  
398 ice thickness constant. The resulting transport trends across the latitude bands of about  $-6$  mSv  
399 per decade in the Atlantic sector and about  $+11$  mSv per decade in the Pacific sector are still  
400 within our estimated uncertainty (Extended Data Table 2). Most of the sea-ice thickness trends  
401 (Extended Data Figure 2a) occur either north (Pacific sector) or south (Atlantic sector) of the  
402 zero freshwater flux line or latitude bands. Thus, the trend in sea-ice thickness does not  
403 considerably affect the northward sea-ice freshwater transport trend. However, the mean sea-

404 ice thickness uncertainty at the zero freshwater flux line is the largest contributor to the overall  
405 northward sea-ice freshwater transport trend (Extended Data Table 2).

406 **Sea-ice drift.** We used the gridded version of the NSIDC<sup>26</sup> (data section) sea-ice drift data set.  
407 In the Antarctic, it is based on five passive microwave sensors<sup>48,49</sup> and the Advanced Very High  
408 Resolution Radiometer (AVHRR)<sup>50</sup> data (Extended Data Figure 4). Two studies validated this  
409 data set with buoy data in the Weddell Sea (1989 through 2005)<sup>34</sup> and around East Antarctica  
410 (1985 to 1997)<sup>51</sup>. There is a very high correlation between the buoy and the satellite data on  
411 large temporal and spatial scales (i.e., monthly and regional) and a strongly reduced agreement  
412 on smaller scales (i.e., daily and local)<sup>34,51</sup>. The satellite-derived sea-ice drift underestimates  
413 the sea-ice velocity given by the buoys by 34.5%<sup>34</sup>, i.e., faster drift velocities have a larger  
414 bias<sup>52</sup>. The bias is smaller for the meridional (26.3%) than for the zonal drift<sup>34</sup>. We here  
415 corrected for these low biases by multiplying the drift velocity with the correction factor (1.357)  
416 that corresponds to the meridional drift bias<sup>34</sup>. We argue that the meridional component of the  
417 bias is the better estimate in the central sea-ice region, which is the key region for our results.  
418 Here, the drift is mainly meridional. The larger biases are observed in the swift, mostly zonal  
419 drift along the sea-ice edge causing the larger zonal biases. The spatial dependence of the bias  
420 and our correction imply that larger biases and uncertainties remain in our final product around  
421 the sea-ice edge.

422 We further processed this bias-corrected drift data. First, we removed all data flagged as bad in  
423 the product. Second, we removed any data with sea-ice concentrations below 50%, closer than  
424 75 km to the coast<sup>34</sup>, or with a spurious, exact value of zero. Our results are not sensitive to this  
425 filtering but it reduces the spatial and temporal noise. After these modifications, about 75% of  
426 all grid cells covered by sea ice had an associated drift vector.

427 We compared both the original and the bias-corrected data to a partly independent product by  
428 Kwok et al.<sup>35,36</sup> (data section). We interpolated these data onto our grid using CDO<sup>37</sup> distance  
429 weighted averaging and applied the same 21-day running mean as for the NSIDC sea-ice drift  
430 data. We compared sea-ice drift vectors whenever both data sets were available and sea-ice  
431 concentrations were larger than 50%. Extended Data Figure 3 shows the meridional drift  
432 components prior (a) and after applying the bias correction factor from the buoy data (b). We  
433 find that the agreement between the two data sets is much higher after the corrections.  
434 Compared to the original NSIDC sea-ice drift data set, the largest improvement occurs in the  
435 slope: 1.06 compared to 1.55. Root-mean-square differences and the linear correlation  
436 coefficient remain identical and the absolute bias is reduced by 0.2 km/day. Correlation  
437 coefficients between the two data sets are 0.8 for both the zonal and meridional drift component.  
438 The spatial patterns of the mean annual sea-ice drift speed (Extended Data Figure 3c-e)  
439 illustrate the improvement in agreement between the two data sets after the application of the  
440 bias correction but confirm that considerable differences remain at the sea-ice edge. These  
441 differences lead to a relatively high root-mean-square difference of the annual mean sea-ice  
442 drift speed in these regions (Extended Data Figure 3f). However, in the central sea-ice pack–  
443 the region that is crucial for our results–the root-mean-square differences are much smaller.

444 Our bias-corrected sea-ice drift speeds are typically slightly lower (about 9% to 19%) than those  
445 by Kwok et al. but considerably higher than in the uncorrected NSIDC data (about 26%, see  
446 above). We used these differences between the data sets to estimate the uncertainties induced  
447 by sea-ice drift on the final product ( $\Delta u$  in Extended Data Tables 1-2): First, we re-computed  
448 all fluxes by correcting the original NSIDC data with correction factors derived from the Kwok  
449 et al. data (1.82 or 45% for the zonal drift, and 1.55 or 35% for the meridional drift) instead of  
450 the buoy-derived correction factor. This way, we also accounted for an uncertainty in the drift

451 direction. Then, we averaged the deviations between our best estimate and the Kwok et al. based  
 452 estimate with those between our best estimate and using the uncorrected and unfiltered NSIDC  
 453 data. Uncertainties from sea-ice drift in the freshwater fluxes are about 20%. They considerably  
 454 contribute to the final freshwater flux uncertainty and our trend uncertainties in all regions.

455 **Sea-ice-ocean freshwater flux.** We estimated annual net sea-ice-ocean freshwater fluxes over  
 456 the period 1982 through 2008 by calculating the local sea-ice volume change and divergence<sup>8,53</sup>.  
 457 From this, we derived, through a mass balance, the local freshwater fluxes  $F$  ( $\text{m}^3 \text{s}^{-1}$ ) from the  
 458 sea ice to the ocean due to freezing and melting on a daily basis:

$$F = -C_{fw} \left( \frac{\partial(A c h)}{\partial t} + \nabla \cdot (A c h \vec{u}) \right). \quad (1)$$

459 The four variables  $c$ ,  $h$ ,  $\vec{u}$ , and  $A$  denote the sea-ice concentration, thickness, drift velocity, and  
 460 grid-cell area, respectively. The factor  $C_{fw}$  converts the sea-ice volume flux to a freshwater  
 461 equivalent<sup>54</sup>:

$$C_{fw} = \frac{\rho_{ice}(1 - s_{ice}/s_{sw})}{\rho_{fw}}. \quad (2)$$

462 Here,  $\rho_{ice}$ ,  $s_{ice}$ ,  $s_{sw}$ , and  $\rho_{fw}$  are sea-ice density ( $925 \text{ kg m}^{-3}$ )<sup>55</sup>, sea-ice salinity ( $6 \text{ g kg}^{-1}$ )<sup>56</sup>,  
 463 reference seawater salinity ( $34.7 \text{ g kg}^{-1}$ )<sup>28</sup>, and freshwater density ( $1000 \text{ kg m}^{-3}$ ), respectively.

464 Annual sea-ice freshwater fluxes were computed from the daily fluxes from March to February  
 465 of the next year (i.e., March 1982 to February 2009), which corresponds to the annual freezing  
 466 and melting cycle of sea ice in the Southern Ocean<sup>53</sup>. Remaining imbalances between, e.g., the  
 467 open and coastal ocean of the Atlantic sector (Extended Data Tables 1-2) are due to multiyear  
 468 sea ice in the coastal region. We performed all calculations on the grid of the sea-ice drift data<sup>26</sup>  
 469 and averaged all data products over three by three grid boxes resulting in a nominal resolution  
 470 of 75 km. To obtain the zero freshwater flux contour line, we averaged the climatological fluxes  
 471 over nine by nine grid boxes. To estimate melting and freezing fluxes, we separately summed  
 472 up positive and negative daily fluxes over a year (Figures 4a-b). As temporal fluctuations  
 473 accumulate when only adding positive or negative values, noise can lead to an overestimation  
 474 of these fluxes. Therefore, each of the sea-ice variables ( $c$ ,  $h$ , and  $\vec{u}$ ) were low-pass filtered  
 475 using a 21-day running mean.

476 **Sea-ice freshwater transport.** The total northward sea-ice volume transport ( $\text{m}^3 \text{s}^{-1}$ ) between  
 477 the coastal and open ocean region equals the spatial integral of the divergence term in (1) in  
 478 either of the two regions (Gauss's Theorem). We chose the open ocean region since there is  
 479 considerable zonal exchange between the Indian Ocean and Atlantic sectors (Figure 2a) in the  
 480 coastal region, influencing the sector based estimates. In the open ocean, this effect is  
 481 negligible. We used this approach for the reported transport estimates (Extended Data Tables  
 482 1-3 and Extended Data Figures 5a-c).

483 To demonstrate that our main findings are robust on a basin-scale, and not influenced by small  
 484 scale noise and local uncertainties, we also calculated the northward sea-ice freshwater  
 485 transport across the latitude bands  $69.5^\circ \text{ S}$  in the Atlantic sector and  $71^\circ \text{ S}$  in the Pacific sector  
 486 (Figure 3). To this end, we averaged sea-ice concentration, thickness, and meridional drift ( $c_n$ ,



487  $h_n$ , and  $v_n$ ) in  $1^\circ$  longitude segments ( $n$ ) along these latitudes and calculated the local freshwater  
 488 transport  $T_n$  ( $\text{m}^3 \text{s}^{-1}$ ):

$$T_n = C_{fw} c_n h_n v_n \Delta l_n. \quad (3)$$

489 Here  $\Delta l_n$  denotes the length of the latitude increment  $n$  along the boundary and  $C_{fw}$  is defined in  
 490 (2). Both sectors together show an annual northward freshwater transport of  $100 \pm 30$  mSv with  
 491 an increase of  $8 \pm 5$  mSv per decade over the period 1982 to 2008 (Extended Data Figure 5d and  
 492 Figure 3). This compares well with the mean ( $120 \pm 30$  mSv) and trend ( $9 \pm 5$  mSv per decade)  
 493 of our spatially integrated sea-ice-ocean fluxes in the Pacific and Atlantic (Extended Data  
 494 Figures 5b-c).

495 We calculated the spatial pattern of the sea-ice freshwater transport  $\vec{f}$  ( $\text{m}^2 \text{s}^{-1}$ ) as displayed in  
 496 Figures 2a and c through:

$$\vec{f} = C_{fw} c h \vec{u}. \quad (4)$$

497 **Time-series homogenisation.** Our analysis and earlier studies<sup>9,57</sup> revealed major temporal  
 498 inhomogeneities in the NSIDC sea-ice drift data set at the transitions between satellite sensors  
 499 (Extended Data Figure 4). We argue that these temporal inhomogeneities are linked to the  
 500 unavailability of the 85/91 GHz channels and sparser data coverage in the earlier years. The  
 501 drift speed before 1982 appears underestimated, which is to some extent mitigated by AVHRR  
 502 data thereafter. From 1982 to 1986, the drift speed is consistent but has a low bias. The drift  
 503 ramps up in 1987, when the 85 GHz channels became available, and decreases again between  
 504 1989 and 1991, when these channels degraded<sup>58</sup>. A final sudden decrease occurs from 2005 to  
 505 2006 when 85 GHz data were not used. We used wind speed data over the sea ice from ERA-  
 506 Interim<sup>22</sup> (data section) as an independent data source and scaled it to the sea-ice drift velocity  
 507 for comparison (Extended Data Figures 4b). The scaling factor stems from the consistent years  
 508 in the period 1988 to 2008 and varies in space and with season<sup>59,60</sup>. This analysis supports our  
 509 argument that the sea-ice drift speed is underestimated when the higher resolution 85/91 GHz  
 510 channels were not available. We note that the meridional drift seems less sensitive to these  
 511 inhomogeneities than the total drift, which might be related to a higher data availability in the  
 512 central sea-ice pack and is consistent with the lower biases found in the meridional sea-ice drift.

513 The spurious increase of the sea-ice velocity would affect our estimated trends if they were not  
 514 taken into account (Extended Data Figures 5-6). Thus, we corrected the annual divergence (1)  
 515 and lateral transport (3-4) for the sensor-related temporal inconsistencies as follows: We  
 516 excluded the inconsistent years 1980 and 1981, 1987, 1989 to 1991, 2005, and 2006 from the  
 517 analysis. To homogenise the years 1982 to 1986 with the years 1988 to 2008, i.e., remove the  
 518 spurious trend in 1987, we first calculated linear regression lines prior and after 1987 at each  
 519 grid point. Then, we added the differences between the end (1986) and start (1988) points of  
 520 the regression lines to all years prior to 1987, i.e., assuming a zero change in the year 1987.  
 521 Fitting regressions prior and past spurious jumps is a common procedure to homogenise climate  
 522 data<sup>61,62</sup>. Here, we used a linear regression that serves the purpose of computing long-term  
 523 trends in the time series.

524 To estimate the sensitivity of the trends in northwards sea-ice freshwater transport to  
525 uncertainties associated with the offset correction before 1987 (orange and green, Extended  
526 Data Figure 5), we performed a Monte Carlo analysis by varying the offset and estimating the  
527 resulting trends. We generated  $10^4$  normally distributed offsets around our best guess (about  
528  $19 \pm 5$  mSv for the entire Southern Ocean; Extended Data Table 3). The standard deviation of  
529 this distribution was chosen to match the offset uncertainty that arises from the root-mean-  
530 square errors of the trends in each of the two time intervals 1982 to 1986 and 1988 to 2008. For  
531 each of these generated offsets, we then estimated the trends and their significance (Extended  
532 Data Table 3). For both the entire Southern Ocean and the Pacific sector, all sampled offsets  
533 yield a positive northward sea-ice freshwater transport trend. All trends for the Pacific sector  
534 and 92% for the entire Southern Ocean are positive and at the same time significant. Thus, our  
535 trend results are insensitive to uncertainties in the applied homogenization at the 90%  
536 confidence level. The posterior uncertainty shows that the uncertainty associated with the offset  
537 has no noticeable effect on the total uncertainty range, i.e., is smaller than  $\pm 1$  mSv per decade.

538 **Uncertainty estimation.** Uncertainties of local (grid-point based) fluxes and time scales shorter  
539 than one year are probably large, due to potential inconsistencies between the data sets on such  
540 scales and an amplification of the uncertainties by the spatial and temporal differentiations in  
541 (1). Integrating these terms in space and time greatly reduces these uncertainties (Extended  
542 Data Tables 1-2). We estimated uncertainties in our product that are associated with the  
543 underlying input variables  $c$ ,  $h$ , and  $\bar{u}$  by using their observationally constrained range from  
544 different data sources, including the applied corrections and filtering as described in the  
545 corresponding sections. Additionally, we used an averaging period of 31 days, instead of 21  
546 days, and, for trends only, an estimate without a running-mean filter, to obtain uncertainty  
547 estimates associated with temporal noise ( $\Delta t$ ). The results confirmed that only the annual  
548 melting or freezing fluxes, but not the net annual fluxes, are sensitive to the low-pass filtering  
549 as in the latter product the noise is averaged out. The sensitivity of the spatially integrated values  
550 to variations of the zero freshwater flux line is estimated by varying the smoothing radius from  
551 two to six grid boxes ( $\Delta A$ ). The uncertainty associated with the constant conversion factor  
552 ( $\Delta C_{fw}$ ; equation 2) is about 5% when using a realistic range of values<sup>28,55,56</sup>. For the trends only,  
553 we computed the standard error of the slope from the variance of the residuals around the  
554 regression line ( $\Delta s_e$ )<sup>63</sup>. The total uncertainty for both the climatological mean and the trends  
555 was estimated by calculating the root-mean-square of the individual contributions. This analysis  
556 shows that in the Atlantic and Indian Ocean sectors both the uncertainties in the climatology  
557 and trends (Extended Data Tables 1-2) are dominated by uncertainties in the sea-ice thickness.  
558 In contrast, the uncertainty in sea-ice drift dominates the uncertainty in the Pacific sector. We  
559 tested the significance of the trends with a t-test, accounting for the fact that only 21 out of 27  
560 years were used and for a lag-one autocorrelation<sup>63</sup>. To indicate the significance of the trends  
561 at grid-point level (Figures 2c-d and Extended Data Figure 6), at which the data uncertainties  
562 are unknown, the local root-mean-square of the variance of the residuals was artificially  
563 increased by 40%, approximately corresponding to our data uncertainty estimate in Extended  
564 Data Table 2. The quality of our data directly at the coastline and around the sea-ice edge is  
565 reduced due to the limited quality and quantity of the underlying observations in these regions.

566 **Sea-ice freshwater flux evaluation.** A modelling study<sup>27</sup>, carried out in parallel to this study,  
567 calculated freshwater fluxes associated with sea-ice formation, melting, and transport in the  
568 Southern Ocean State Estimate (SOSE). This model assimilates a large amount of observational  
569 data and optimizes surface fluxes. They estimated an annual sea-ice-ocean freshwater flux due  
570 to sea-ice formation of  $-360$  mSv over the entire Southern Ocean, which is within our estimated  
571 range of  $-410 \pm 110$  mSv. Moreover, they estimated that the combined annual sea-ice-ocean  
572 freshwater flux due to sea-ice and snow melting is about 500 mSv. Thus, in their estimate a

573 total of 140 mSv of snow accumulated on the sea ice. Our estimates partly include snow  
574 accumulation on sea ice, because part of the sea-ice thickness results from snow-ice formation,  
575 which we estimated to be about  $-50$  mSv (section on sea-ice thickness). However, the snow  
576 layer on top of the sea ice is not included in our estimate of the freshwater flux due to sea-ice  
577 melting of  $460 \pm 100$  mSv. In that study<sup>27</sup>, the authors estimate that the lateral sea-ice freshwater  
578 transport from the density class of CDW to AAIW and SAMW amounts to 200 mSv in the  
579 period between 2005 and 2010. Their estimate slightly differs from our estimated transport from  
580 the coastal to the open ocean that ranges between about 140 mSv and 160 mSv in 2007 and  
581 2008 (Extended Data Figure 5). The reasons might be the slightly different regions and that  
582 their estimate also includes the transport of the snow layer on top of the sea ice.

583 Given the reduced confidence in the local fluxes (e.g. sea-ice production in coastal polynyas),  
584 it is reassuring that our data agree within our estimated range of uncertainty with previous  
585 estimates of mean fluxes for some larger coastal polynya regions<sup>64,65</sup>. Our confidence is higher  
586 for fluxes integrated over larger regions such as the high-latitude Ross and Weddell Seas  
587 (Extended Data Figure 5e). Here our estimates are in close agreement with previous studies as  
588 discussed in the following.

589 In the Ross Sea, we estimated that the northward transport from the coastal region across a flux  
590 gate between Land Bay and Cape Adare<sup>36</sup> (turquoise area in Extended Data Figure 5e) is  $23 \pm 5$   
591 mSv, increasing by about 30% (or  $+7 \pm 4$  mSv) per decade in the period 1992 to 2008. Based on  
592 the same passive microwave data but using a different algorithm for retrieving the sea-ice  
593 motion data, two studies<sup>36,66</sup> found a mean sea-ice area flux across this flux gate of about  $10^6$   
594 km<sup>2</sup> between March and November in the periods 1992 to 2003<sup>36</sup> and 1992 and 2008<sup>66</sup>,  
595 respectively. Using an approximated mean sea-ice thickness (0.6 m)<sup>13,66</sup> and the conversion  
596 factor (2), this corresponds to a mean northward freshwater transport of about 19 mSv. In close  
597 agreement with our estimate, these studies found an increase of 30% per decade (about +6 mSv  
598 per decade). Another study<sup>13</sup>, using sea-ice motion from the Advanced Microwave Scanning  
599 Radiometer-EOS (AMSR-E), estimated that the mean sea-ice area flux between April and  
600 October (2003 to 2008) across the same flux gate is about  $9.3 \times 10^5$  km<sup>2</sup> corresponding to a  
601 freshwater transport of about 23 mSv. Based on the same data but using an alternative  
602 approach<sup>67</sup>, they found that the total sea-ice production in all Ross Sea polynyas together was  
603 about 737 km<sup>3</sup> between April and October (2003 to 2008), corresponding to a sea-ice-ocean  
604 freshwater flux of  $-31$  mSv. This estimate is similar to the total production of about  $-36 \pm 7$  mSv  
605 south of the flux gate in our data set, because most of the sea-ice production of this region  
606 occurs in the polynyas<sup>13</sup>. Using passive microwave data, the same study<sup>13</sup> found an increase of  
607 the production in the Ross Sea polynyas of 28% per decade between 1992 and 2008. A  
608 modelling study<sup>68</sup> found a net annual sea-ice-ocean freshwater flux due to melting and freezing  
609 of  $-27$  mSv on the continental shelf in the Ross Sea, which is in agreement with our estimate  
610 of  $-23 \pm 5$  mSv. They also found a long-term (unquantified, see their Figure 9b) decrease of the  
611 net annual sea-ice-ocean freshwater flux over the Ross Sea continental shelf in the period 1963  
612 to 2000, which is qualitatively in line with our results.

613 In the Weddell Sea, the northward sea-ice area flux across a flux gate close to the 1000 m  
614 isobaths (blue area in Extended Data Figure 5e) has been found to be  $5.2 \times 10^5$  km<sup>2</sup> based on  
615 AMSR-E data between April and October (2003 to 2008)<sup>13</sup>. Using an approximated mean sea-  
616 ice thickness (0.75 m)<sup>13</sup> and the conversion factor (2), this corresponds to a mean northward  
617 freshwater transport of about 16 mSv. This agrees well with our estimate of an annual northward  
618 transport of  $16 \pm 4$  mSv for the same years and the same region. Similar to the Ross Sea, the  
619 production in the major polynyas of the Weddell Sea was estimated<sup>13</sup>. However, in the Weddell  
620 Sea, a large fraction of the sea-ice transported across the flux gate is not produced in the coastal

621 polynyas<sup>13</sup>, i.e., we cannot directly compare our large-scale estimate to the sea-ice production  
 622 in the polynyas. In the same study<sup>13</sup>, based on passive microwave data, they found a small, but  
 623 insignificant long-term decrease of the sea-ice production in the Weddell Sea polynyas between  
 624 1992 and 2008, which is qualitatively consistent with our findings in the Atlantic sector. For a  
 625 much larger area in the Weddell Sea, a modelling study<sup>69</sup> estimated an annual northward sea-  
 626 ice freshwater transport of about 34 mSv and another observational study<sup>70</sup>, mostly based on  
 627 moorings and wind speed, estimated that this flux is as large as about  $38 \pm 15$  mSv. These  
 628 estimates agree well with our finding of an annual northward freshwater transport of  $41 \pm 18$   
 629 mSv across the  $69.5^\circ$  S latitude band, which is approximately their considered transect.

630 **Sea-ice freshwater transport based on ERA-Interim data.** To support our findings, we  
 631 quantified changes in sea-ice motion induced by changes geostrophic winds<sup>59,60,70,71</sup> from daily  
 632 ERA-Interim<sup>22</sup> sea-level pressure and surface air temperature (data section). We averaged the  
 633 data over  $1^\circ$  longitudinal segments along the previously defined latitude bands (Figure 3),  
 634 computed 21-day running means, and smoothed the data spatially over 7 longitude bins. Then,  
 635 we calculated the sea-level pressure gradients along the latitude bands and used these together  
 636 with the atmospheric surface density to estimate geostrophic winds normal to the latitude  
 637 bands<sup>59,71</sup>. From these, we calculated the sea-ice drift speed using a drift-to-wind-speed ratio of  
 638 0.016, derived from drifting buoys in the central Weddell Sea<sup>59,71</sup>. This parameter is strongly  
 639 variable in space and time, which is a major uncertainty in the resulting sea-ice drift.  
 640 Nevertheless, it provides an average estimate for the mostly free drifting sea ice in the central  
 641 Antarctic sea-ice pack<sup>59,71</sup>.

642 The resulting northward sea-ice freshwater transport (3) is independent in terms of the sea-ice  
 643 drift but not in terms of the sea-ice concentration and thickness. We used anomalies (at each  $1^\circ$   
 644 increment) since the absolute values of the local transport are likely biased by local influences  
 645 of ocean currents and sea-ice properties. The resulting total annual anomalies of the northward  
 646 sea-ice freshwater transport agree well in terms of variability and long-term trend with the  
 647 transport anomalies based on the satellite sea-ice drift ( $+8$  mSv per decade; Figure 3). These  
 648 estimates do not suffer from the temporal inhomogeneities that we identified in the satellite sea-  
 649 ice drift data (section on time-series homogenisation).

650 **Sea-ice contribution to ocean salinity.** We determined the evolution of ocean salinity  $s$  (g  
 651  $\text{kg}^{-1}$ ) in response to a given surface freshwater flux  $F$  ( $\text{m}^3 \text{s}^{-1}$ ) from a combination of mass and  
 652 salt balances. The mass balance for a given, well-mixed ocean surface box of volume  $V$  and  
 653 density  $\rho$  reads:

$$\frac{d\rho V}{dt} = \rho_{in} Q_{in} + \rho_{fw} F - \rho Q_{out}, \quad (5)$$

654 where  $Q_{in}$  and  $Q_{out}$  ( $\text{m}^3 \text{s}^{-1}$ ) are the volume fluxes of seawater in or out of the box,  $\rho_{in}$  ( $\text{kg m}^{-3}$ )  
 655 is the respective density. In a steady state, the above equation (5) yields:

$$\rho_{in} Q_{in} = \rho Q_{out} - \rho_{fw} F. \quad (6)$$

656 The corresponding salt balance reads:

$$\rho V \frac{ds}{dt} = \rho_{in} Q_{in} s_{in} - \rho Q_{out} s, \quad (7)$$

657 We assumed the same constant source water salinity  $s_{in} = s_{sw}$  and freshwater density  $\rho_{fw}$  as in  
 658 (2), and used a constant reference density ( $\rho = 1027 \text{ kg m}^{-3}$ ). Moreover, we used the formation  
 659 rate of the modified water mass as the volume flux of seawater out of the surface box ( $Q_{out} =$   
 660  $Q$ ). Then, substituting (6) in (7) yields:

$$\rho V \frac{ds}{dt} = (\rho Q - \rho_{fw} F) s_{sw} - \rho Q s. \quad (8)$$

661 In a steady state, this results in an equation that describes the modified salinity  $s$ :

$$\rho Q s = (\rho Q - \rho_{fw} F) s_{sw}. \quad (9)$$

662 Using  $s = s_{sw} + \Delta s$ , where  $\Delta s$  is the salinity difference between the source and modified water  
663 masses, (9) reduces to:

$$\Delta s = -\frac{\rho_{fw} s_{sw} F}{\rho Q}. \quad (10)$$

664 We used net water-mass transformation rates ( $Q$ ) of 29 Sv between CDW and AABW and 13  
665 Sv between CDW and AAIW/SAMW<sup>28</sup>. Figure 1a illustrates the results and shows the zonal  
666 mean ocean salinity and density distribution<sup>72</sup> for comparison.

667 Assuming that  $+130 \pm 30$  mSv of freshwater enter CDW through northward sea-ice freshwater  
668 transport, the salinity modification (10) is  $-0.33 \pm 0.09$  g kg<sup>-1</sup>. The uncertainty includes a  $\pm 2$  Sv  
669 uncertainty in the water-mass formation rate. In observations, the salinity difference between  
670 CDW and AAIW and SAMW ranges from about  $-0.3$  to  $-0.5$  g/kg<sup>28</sup>. Thus, northward  
671 freshwater transport by sea-ice could explain the majority of the salinity modification,  
672 consistent with very recent findings<sup>27</sup> and a mixed-layer salinity budget<sup>73</sup>.

673 Similarly, we calculated the contribution of  $-130 \pm 30$  mSv of freshwater removed from coastal  
674 regions due to northward sea-ice transport to the salinity modification (10) between CDW and  
675 AABW, obtaining an increase of  $+0.15 \pm 0.06$  g kg<sup>-1</sup>. The uncertainty includes a  $\pm 7$  Sv  
676 uncertainty in AABW formation. However, observed salinity differences between the CDW  
677 and AABW are generally small or even of opposite sign<sup>74</sup>. This is the result of a compensating  
678 effect between a sea-ice driven salinification and a freshening from glacial and atmospheric  
679 freshwater. Freshwater fluxes from land ice through basal and iceberg melting are about  $+46 \pm 6$   
680 mSv and  $+42 \pm 5$  mSv, respectively<sup>75</sup>. Assuming that roughly 60% of the icebergs melt in the  
681 coastal regions<sup>76</sup>, a total of about  $+70$  mSv are added from the land ice to the coastal ocean,  
682 corresponding to a freshening of about  $-0.08$  g kg<sup>-1</sup> or a compensation of the sea-ice freshwater  
683 flux of about 55% in AABW. We estimated from the ERA-Interim atmospheric reanalysis  
684 data<sup>22</sup> that the net atmospheric freshwater flux in the coastal region is about  $+80$  mSv,  
685 corresponding to a freshening of about  $-0.09$  g kg<sup>-1</sup>. The resulting net salinity change in coastal  
686 waters from sea-ice, atmospheric, and land-ice freshwater fluxes is almost zero ( $-0.02$  g kg<sup>-1</sup>).  
687 Such a compensation of the freshwater fluxes in coastal regions was noticed previously<sup>69,77</sup>. We  
688 note that large regional variations of these fluxes have been reported<sup>75,78</sup>.

689 To estimate the temporal salinity changes at the surface and in newly formed AAIW and  
690 SAMW, we assumed a constant water-mass formation rate  $Q$ , and that the freshwater flux and  
691 ocean salinity consist of a climatological value plus a time-dependent perturbation ( $\bar{F} + F'$  and  
692  $\bar{s} + s'$ , respectively). Then, (8) yields:

$$\rho V \frac{ds'}{dt} = \rho Q s_{sw} - \rho_{fw} s_{sw} \bar{F} - \rho Q \bar{s} - \rho_{fw} s_{sw} F' - \rho Q s'. \quad (11)$$

693 As the climatological fluxes are in steady state, the first three terms on the right side in (11)  
694 cancel according to (9), resulting in:

$$\rho V \frac{ds'}{dt} = -\rho_{fw} s_{sw} F' - \rho Q s'. \quad (12)$$

695 We approximated the freshwater-flux perturbation by our estimated trend ( $F'=at$ ), and  
 696 rearranged the terms resulting in a first order linear differential equation:

$$\frac{ds'}{dt} + \frac{Q}{V} s' = -\frac{\rho_{fw} s_{sw} a}{\rho V} t. \quad (13)$$

697 Integration in time yields an expression for the time-dependent evolution of the salinity  
 698 perturbation:

$$s' = -\frac{\rho_{fw} s_{sw} a}{\rho Q} \left( t - \frac{V}{Q} + \frac{V}{Q} e^{-\frac{Q}{V}t} \right). \quad (14)$$

699 To obtain an estimate of the salinity trend at a given time  $t$ , we substituted (14) into (13):

$$\frac{ds'}{dt} = \frac{\rho_{fw} s_{sw} a}{\rho Q} \left( e^{-\frac{Q}{V}t} - 1 \right). \quad (15)$$

700 The equilibrium response of the system, i.e., the long-term trend after several years of  
 701 perturbation is:

$$\lim_{t \rightarrow \infty} \frac{ds'}{dt} = -\frac{\rho_{fw} s_{sw} a}{\rho Q}. \quad (16)$$

702 Using our estimated sea-ice freshwater transport trend of  $+9 \pm 5$  mSv per decade and a water-  
 703 mass formation rate as above, we obtained an equilibrium freshening rate of  $-0.023 \pm 0.014$  g  
 704  $\text{kg}^{-1}$  per decade (green in Extended Data Figure 7b), which is valid for sufficiently large  $Qt/V$ .

705 Extended Data Figure 7b (purple and blue; using 14) shows that if we assumed that the trend  
 706 started in 1982, there would be a delayed response lowering the mean salinity trend estimate  
 707 depending on  $V$ . We thus tested the sensitivity of the trend to  $V$ , which corresponds to the upper  
 708 150 m between the zero sea-ice-ocean freshwater flux line and the Subantarctic Front<sup>79</sup>  
 709 (Extended Data Figure 7a), which is the source region of AAIW. The circumpolar  $V$  of about  
 710  $5 \times 10^6$   $\text{km}^3$  results in a mean salinity trend (using 14) of  $-0.014 \pm 0.008$  g  $\text{kg}^{-1}$  per decade  
 711 between 1982 and 2008 (purple). However, AAIW formation does not occur in a circumpolar  
 712 belt but mostly in the south-eastern Pacific and north-western Atlantic, i.e., on either side of  
 713 Drake Passage<sup>80-84</sup>. Assuming that most of the water is modified in this region and further  
 714 downstream in the South Pacific<sup>80,82,84</sup>, we estimated a second, somewhat smaller  $V$  of about  
 715  $2 \times 10^6$   $\text{km}^3$  (blue). The sea-ice freshwater transport trend into this reference volume is about  
 716  $+8 \pm 5$  mSv per decade (Figures 2c-d), resulting in a mean salinity trend (using 14) of  
 717  $-0.018 \pm 0.010$  g  $\text{kg}^{-1}$  per decade (blue). Since a certain amount of freshwater is transported  
 718 eastward, out of this sector (blue), the mean trend of the delayed response lies somewhere in  
 719 between the estimates based on the two different reference volumes (blue and purple).

720 It is unlikely that the trend started exactly in 1982. Thus, the actual salinity response will fall  
 721 between our estimated delayed response and the equilibrium response. For the range of values

722 in the discussion above, the deviations of the freshening rate due to effects of delay and  
723 variations in reference volume are much smaller than the actual magnitude of the trend itself.  
724 We thus conclude that the overall mean freshening rate of newly formed AAIW and the surface  
725 waters advected northward across the Subantarctic Front into SAMW due to the changes in sea-  
726 ice freshwater transport is about  $-0.02 \pm 0.01 \text{ g kg}^{-1}$  per decade (Figure 1b).

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	Flux [mSv]	$\Delta t$ [mSv]	$\Delta A$ [mSv]	$\Delta c$ [mSv]	$\Delta h$ [mSv]	$\Delta u$ [mSv]	$\Delta C_{fw}$ [mSv]
<b>Southern Ocean:</b>							
Transport	+130 ±30	±0	±5	±0	±16	±25	±6
Net open ocean	+130 ±30	±0	±5	±0	±16	±25	±6
Net coastal ocean	-130 ±30	±0	±5	±0	±14	±26	±6
Net continental shelf	-60 ±20	±0	±0	±0	±8	±13	±3
Total melting	+460 ±100	±37	-	±1	±74	±49	±23
Total freezing	-410 ±110	±37	-	±1	±73	±50	±23
<b>Atlantic sector:</b>							
Transport	+60 ±20	±0	±1	±0	±13	±11	±3
Net open ocean	+60 ±20	±0	±1	±0	±13	±11	±3
Net coastal ocean	-50 ±20	±0	±1	±0	±14	±9	±3
Net continental shelf	-20 ±5	±0	±0	±0	±2	±4	±1
Total melting	+180 ±40	±13	-	±0	±25	±21	±9
Total freezing	-160 ±40	±13	-	±0	±25	±19	±9
<b>Indian Ocean sector:</b>							
Transport	+10 ±5	±0	±1	±0	±4	±2	±1
Net open ocean	+10 ±5	±0	±1	±0	±4	±2	±1
Net coastal ocean	-10 ±6	±0	±1	±0	±4	±4	±1
Net continental shelf	-10 ±4	±0	±0	±0	±3	±2	±0
Total melting	+70 ±30	±7	-	±0	±24	±5	±4
Total freezing	-70 ±30	±7	-	±0	±24	±6	±4
<b>Pacific sector:</b>							
Transport	+60 ±20	±0	±2	±0	±9	±12	±3
Net open ocean	+60 ±20	±0	±2	±0	±9	±12	±3
Net coastal ocean	-60 ±20	±0	±2	±0	±9	±13	±3
Net continental shelf	-30 ±9	±0	±0	±0	±6	±6	±2
Total melting	+200 ±50	±17	-	±0	±43	±23	±10
Total freezing	-180 ±60	±17	-	±0	±43	±24	±10

852

853 **Extended Data Table 1 | Mean and uncertainties of annual sea-ice freshwater fluxes over**  
854 **the period 1982 through 2008.** Positive numbers indicate a freshwater flux into the ocean or  
855 northward transport ( $1 \text{ mSv} = 10^3 \text{ m}^3 \text{ s}^{-1}$ ). The final uncertainty estimate (95% confidence level)  
856 stems from the uncertainties in the filtering of high-frequency temporal noise ( $\Delta t$ ), variations  
857 of the zero freshwater flux line ( $\Delta A$ ), sea-ice concentration ( $\Delta c$ ), sea-ice thickness ( $\Delta h$ ), sea-ice  
858 drift ( $\Delta u$ ), and the freshwater conversion factor ( $\Delta C_{fw}$ ), respectively. See Methods for details.  
859 See Figure 2 for definition of regions.

	Flux [mSv dec <sup>-1</sup> ]	$\Delta s_e$ [mSv dec <sup>-1</sup> ]	$\Delta t$ [mSv dec <sup>-1</sup> ]	$\Delta A$ [mSv dec <sup>-1</sup> ]	$\Delta c$ [mSv dec <sup>-1</sup> ]	$\Delta h$ [mSv dec <sup>-1</sup> ]	$\Delta u$ [mSv dec <sup>-1</sup> ]	$\Delta C_{fw}$ [mSv dec <sup>-1</sup> ]
<b>Southern Ocean:</b>								
Transport	<b>+9</b> ±5	±3.2	±0.3	±1.1	±0.8	±3.0	±1.9	±0.5
Net open ocean	<b>+10</b> ±5	±3.5	±0.4	±1.1	±0.8	±3.0	±2.0	±0.5
Net coastal ocean	<b>-10</b> ±5	±3.5	±0.2	±1.1	±0.7	±3.3	±1.1	±0.5
Net continental shelf	<b>-3</b> ±2	±1.8	±0.0	±0.0	±0.1	±0.8	±0.1	±0.1
<b>Atlantic sector:</b>								
Transport	-4 ±5	±4.3	±0.1	±0.7	±0.1	±1.4	±0.7	±0.2
Net open ocean	-4 ±5	±4.4	±0.1	±0.7	±0.1	±1.4	±0.7	±0.2
Net coastal ocean	+6 ±6	±5.7	±0.1	±0.7	±0.0	±0.6	±1.8	±0.3
Net continental shelf	<b>+6</b> ±3	±2.5	±0.0	±0.0	±0.0	±0.6	±1.6	±0.3
<b>Indian Ocean sector:</b>								
Transport	-1 ±1	±1.3	±0.0	±0.2	±0.1	±0.3	±0.2	±0.0
Net open ocean	-1 ±1	±1.3	±0.0	±0.2	±0.1	±0.3	±0.2	±0.0
Net coastal ocean	<b>-3</b> ±2	±0.9	±0.0	±0.2	±0.1	±1.1	±0.7	±0.1
Net continental shelf	<b>+2</b> ±1	±0.9	±0.1	±0.0	±0.1	±0.3	±0.4	±0.1
<b>Pacific sector:</b>								
Transport	<b>+14</b> ±5	±3.4	±0.2	±0.6	±0.7	±1.3	±2.8	±0.7
Net open ocean	<b>+14</b> ±5	±3.4	±0.3	±0.5	±0.7	±1.2	±2.9	±0.7
Net coastal ocean	<b>-13</b> ±5	±3.6	±0.2	±0.5	±0.6	±1.9	±2.3	±0.7
Net continental shelf	<b>-10</b> ±3	±2.6	±0.1	±0.0	±0.2	±1.2	±1.8	±0.5

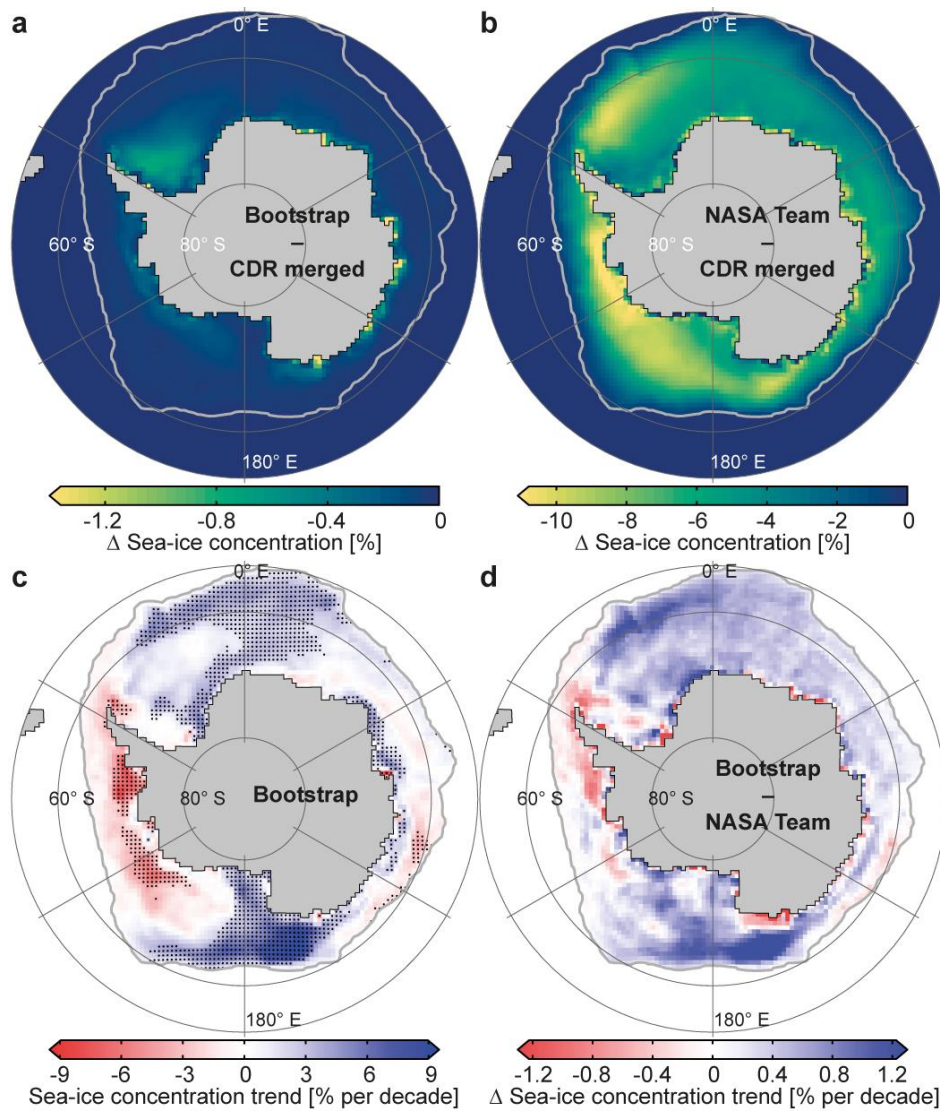
860

861 **Extended Data Table 2 | Decadal trends of annual sea-ice freshwater fluxes and their**  
862 **uncertainties over the period 1982 through 2008.** Positive numbers indicate a freshwater flux  
863 trend into the ocean or a northward transport trend (1 mSv dec<sup>-1</sup> = 10<sup>3</sup> m<sup>3</sup> s<sup>-1</sup> per decade). The  
864 final uncertainty estimate (95% confidence level) stems from the standard error of the slope of  
865 the regression line ( $\Delta s_e$ ), filtering of high-frequency temporal noise ( $\Delta t$ ), variations of the zero  
866 freshwater flux line ( $\Delta A$ ), sea-ice concentration ( $\Delta c$ ), sea-ice thickness ( $\Delta h$ ), sea-ice drift ( $\Delta u$ ),  
867 and the freshwater conversion factor ( $\Delta C_{fw}$ ), respectively. Bold numbers indicate a significance  
868 of at least a 90% confidence level. See Methods for details. See Figure 2 for definition of  
869 regions.

	Southern Ocean	Atlantic sector	Indian Ocean sector	Pacific sector
1992 – 2004: Flux trend [mSv dec <sup>-1</sup> ]	+4 ±9	-12 ±11	<b>-5 ±3</b>	<b>+21 ±10</b>
1992 – 2008: Flux trend [mSv dec <sup>-1</sup> ]	<b>+11 ±8</b>	-5 ±9	-2 ±2	<b>+17 ±8</b>
1982 – 2004: Flux trend [mSv dec <sup>-1</sup> ]	<b>+8 ±5</b>	-6 ±5	-1 ±1	<b>+15 ±6</b>
1982 – 2008: Flux trend [mSv dec <sup>-1</sup> ]	<b>+9 ±5</b>	-4 ±5	-1 ±1	<b>+14 ±5</b>
1982 – 2008 Monte Carlo analysis:				
Flux offset before 1987 [mSv]	+19 ±5	+13 ±7	+3 ±2	+4 ±5
Probability for trend of same sign [%]	100	92	78	100
Probability for significant trend of same sign [%]	92	26	9	100
Posterior trend uncertainty [mSv dec <sup>-1</sup> ]	±5	±6	±2	±5

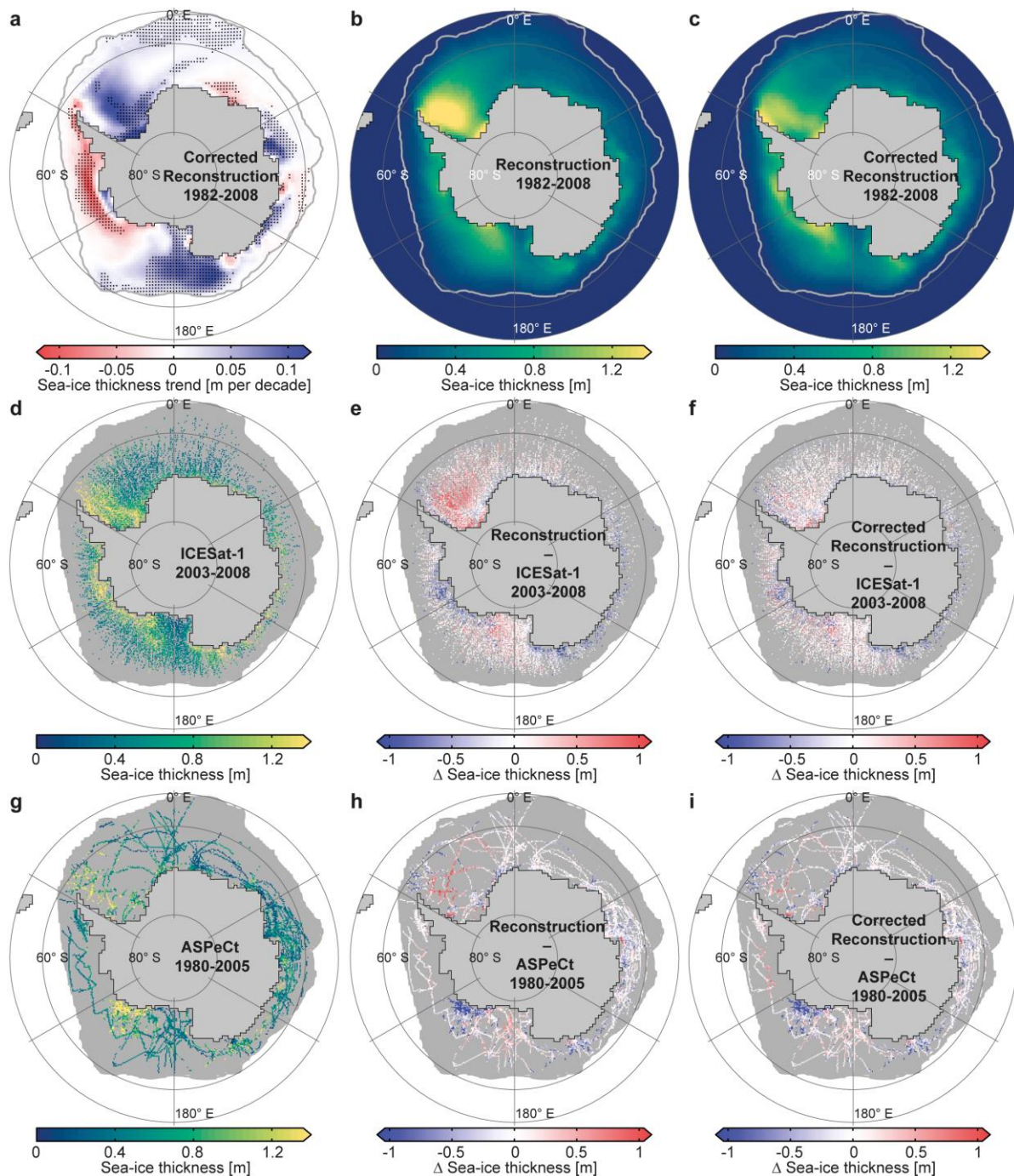
870

871 **Extended Data Table 3 | Sensitivity of northward sea-ice freshwater transport trend to**  
872 **time periods and homogenisation.** Positive numbers indicate a northward freshwater transport  
873 trend (1 mSv dec<sup>-1</sup> = 10<sup>3</sup> m<sup>3</sup> s<sup>-1</sup> per decade). Bold numbers indicate a significance of the trend  
874 of at least a 90% confidence level. The Monte Carlo analysis is performed for 10<sup>4</sup> normally  
875 distributed sample offsets. Uncertainties (95% confidence level) stem from the standard error  
876 of the slope of the regression line and the data uncertainty. See Methods for details. See Figure  
877 2 for definition of regions.



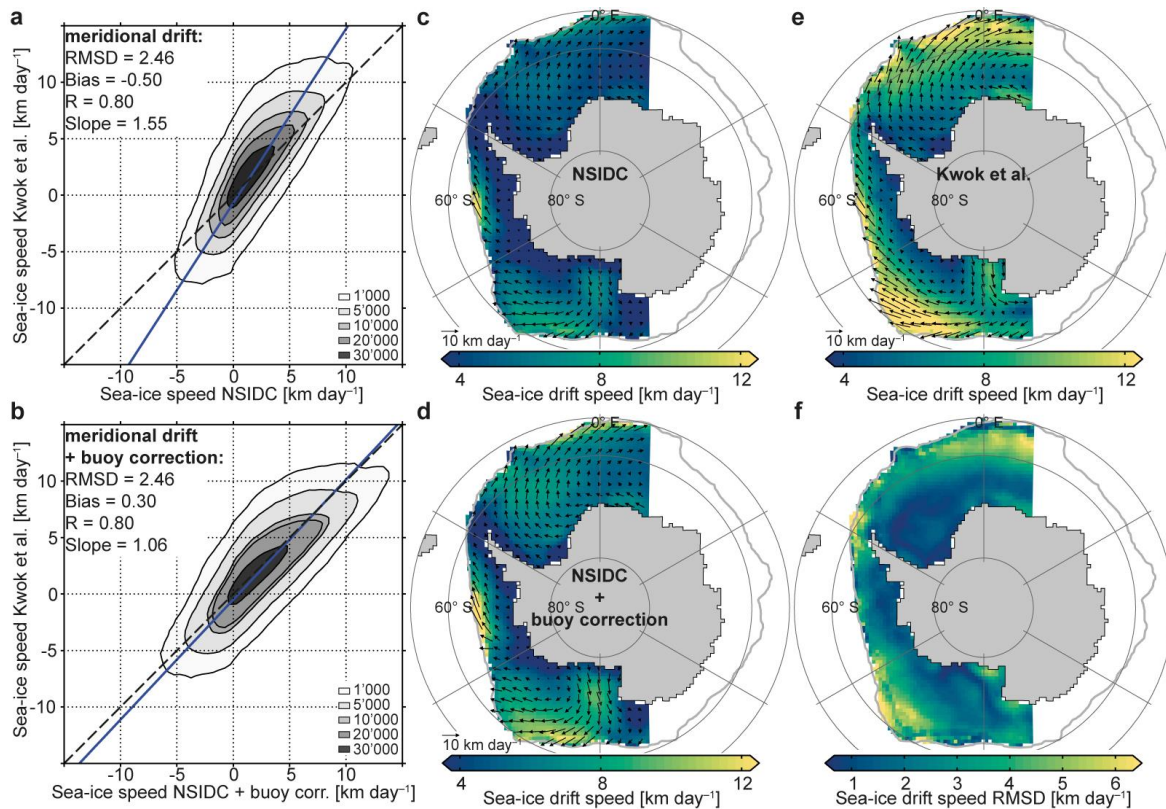
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879 **Extended Data Figure 1 | Uncertainties and trends in Antarctic sea-ice concentration over**  
 880 **the period 1982 through 2008. a, Bootstrap (BA) minus CDR merged data. b, NASA Team**  
 881 **(NTA) minus CDR merged data. c, Decadal trends of the BA sea-ice concentration. Stippled**  
 882 **trends are statistically significant (at least 90% level). d, Decadal trends of Bootstrap minus**  
 883 **NASA Team data. The thick grey line marks the mean sea-ice edge (1% sea-ice concentration).**  
 884 **See Methods for details.**



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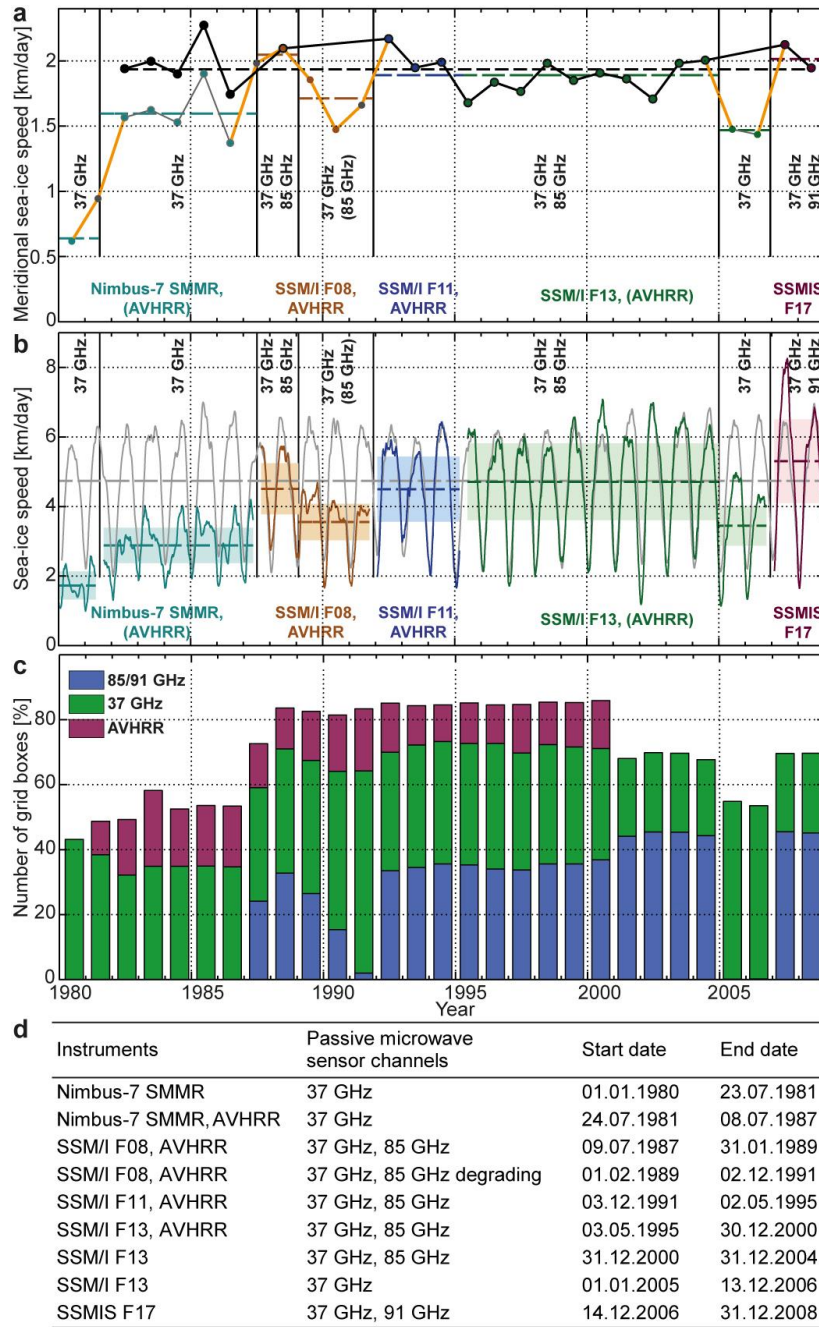
886 **Extended Data Figure 2 | Mean, trend, and uncertainty of Antarctic sea-ice thickness.** **a,**  
 887 Decadal trends of the corrected reconstruction (1982-2008). Stippled trends are statistically  
 888 significant (at least 90% level). **b,** Mean of the reconstruction (1982-2008). **c,** Mean of the  
 889 corrected reconstruction (1982-2008). **d,** Mean of the non-gridded ICESat-1 data (2003-2008,  
 890 13 campaigns). **e,** Reconstruction minus non-gridded ICESat-1 data (2003-2008). **f,** Corrected  
 891 reconstruction minus non-gridded ICESat-1 data (2003-2008). **g,** Mean of the ASPeCt data  
 892 (1980-2005). **h,** Reconstruction minus ASPeCt data (1980-2005). **i,** Corrected reconstructions  
 893 minus ASPeCt data (1980-2005). The thick grey line marks the mean sea-ice edge (1% sea-ice  
 894 concentration). Differences are based on data when both respective products were available.  
 895 Data points without data in the sea-ice covered region are grey shaded in d-i. See Methods for  
 896 details.



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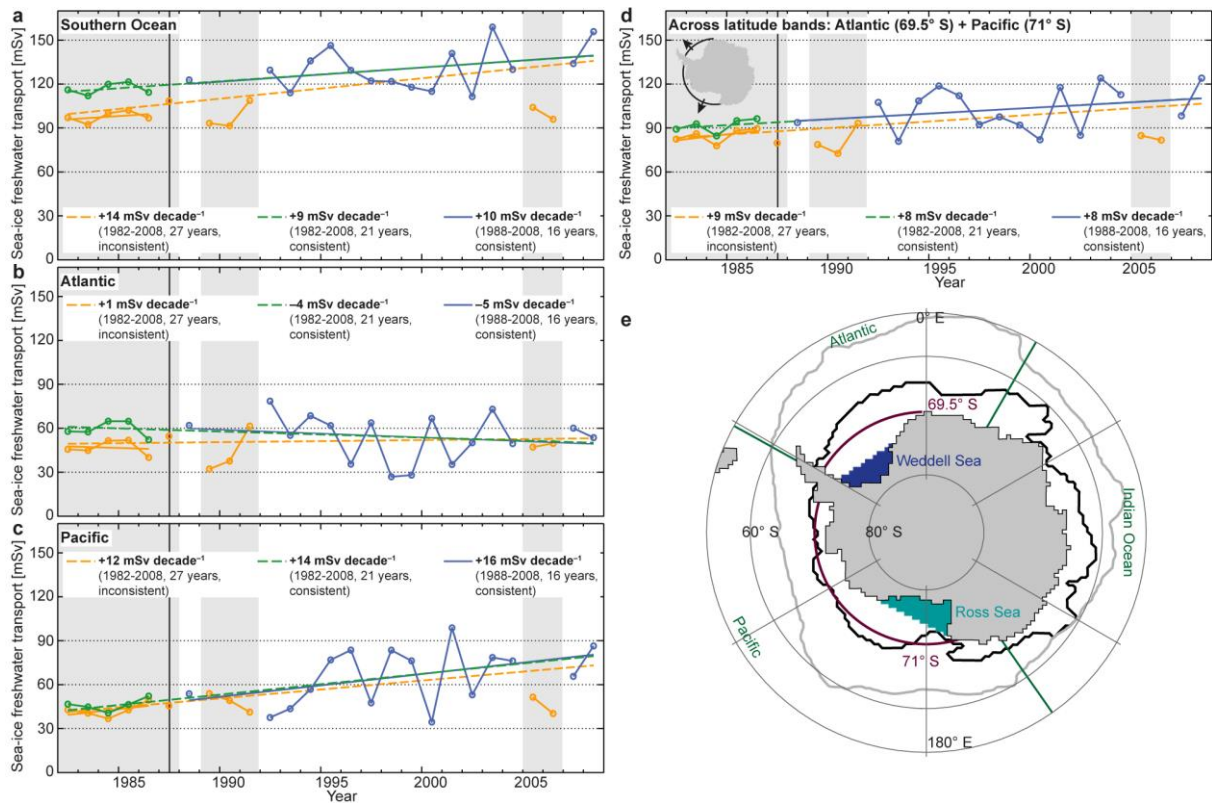
898 **Extended Data Figure 3 | Sea-ice drift speed comparison between the NSIDC and Kwok**  
 899 **et al. data for the period 1992 to 2003. a-b**, Low-pass filtered, 21-day running mean, (a)  
 900 original and (b) bias-corrected daily meridional NSIDC sea-ice drift speed compared to the  
 901 low-pass filtered daily meridional Kwok et al. data. Contours mark the number of grid boxes  
 902 and the blue line marks the fitted least squares linear regression line. **c-e**, Mean sea-ice drift  
 903 speed of the (c) original and (d) bias-corrected NSIDC, and (e) Kwok et al. sea-ice drift speed.  
 904 Arrows denote the drift vectors. **f**, Root-mean-square differences between the annual mean bias-  
 905 corrected NSIDC and Kwok et al. sea-ice drift speed. The thick grey line in c-f marks the mean  
 906 sea-ice edge (1% sea-ice concentration). Data points were compared when both data sets were  
 907 available. See Methods for details.





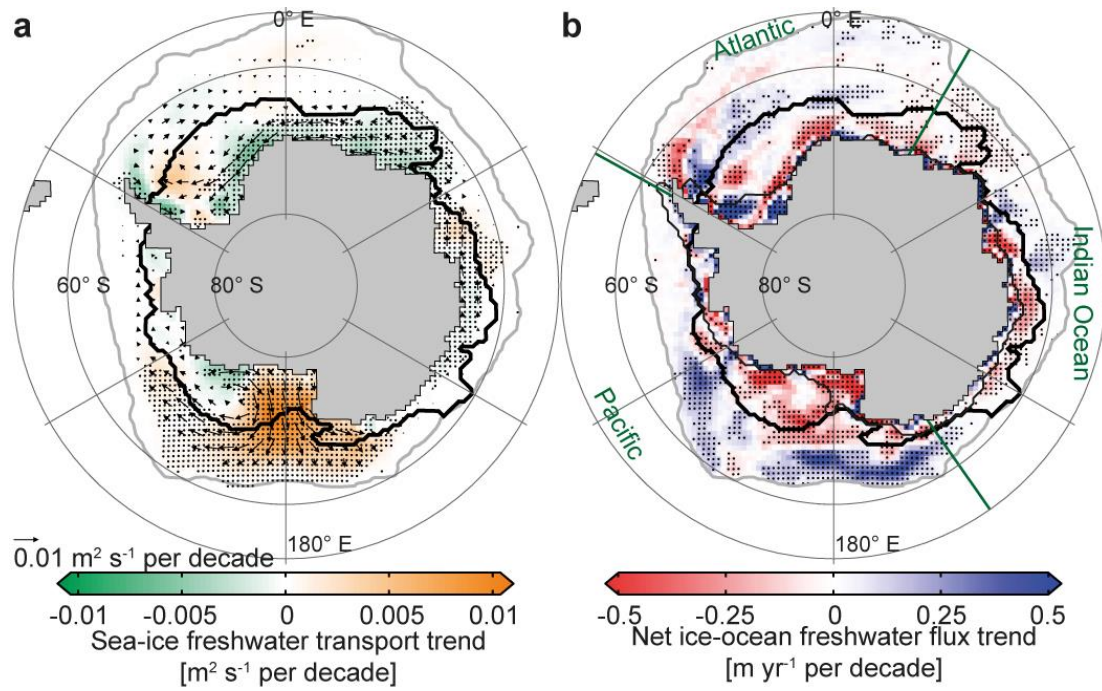
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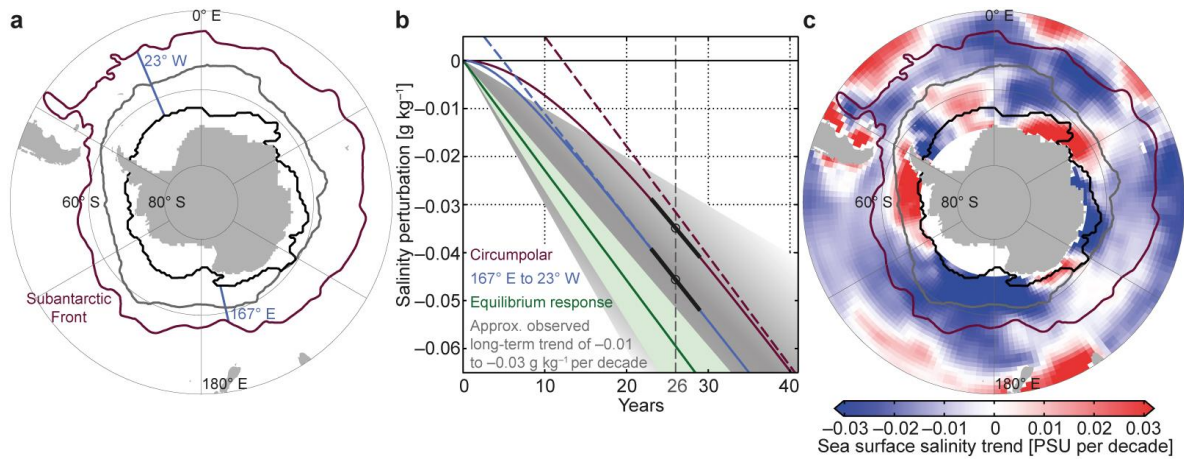
909 **Extended Data Figure 4 | Temporal inhomogeneities in the NSIDC satellite sea-ice drift**  
 910 **data. a**, Annual mean meridional sea-ice drift speed averaged over the entire sea-ice area (sea-  
 911 ice concentration >50%). Thick orange lines: spurious trends due to changes in underlying data;  
 912 black: data corrected for inconsistencies and used in this study (1982 to 2008). **b**, Low-pass  
 913 filtered (91-day running mean) sea-ice drift speed averaged over the entire sea-ice area (sea-ice  
 914 concentration >50%). Grey: reduced wind speed from ERA-Interim using a reduction factor  
 915 from the period 1988 to 2008. (a-b) In colour: uncorrected data for each respective underlying  
 916 satellite instrument combination; dashed lines: mean over the respective period; black vertical  
 917 lines: periods of the same underlying channels. Text denotes the sensors and the frequency of  
 918 the microwave radiometer channels used. **c**, Fraction of sea-ice covered grid boxes with at least  
 919 one drift vector observation in a 21-day window and a 75 by 75 km grid box using the non-  
 920 gridded NSIDC drift data. Colours indicate the contribution of each sensor and channel. **d**,  
 921 Different combinations of instruments and passive microwave sensor channels and the related  
 922 periods underlying the NSIDC sea-ice drift data. See Methods for details.



923

924 **Extended Data Figure 5 | Time series and regions of annual northward sea-ice freshwater**  
 925 **transport.** Transport from the coastal ocean to the open ocean region in the (a) Southern Ocean  
 926 (b) Atlantic sector (c) Pacific sector. d, Across latitude bands in the Atlantic (69.5° S) and  
 927 Pacific (71° S) sectors. Orange: not accounting for inhomogeneities; blue: homogeneous years  
 928 only; green: homogenised time series. Corrected or removed years are shaded in grey. Straight  
 929 lines show the linear regressions for the periods 1982 to 2008 (dashed orange and green), 1982  
 930 to 1986 (solid orange), and 1988 to 2008 (homogeneous years only; solid blue). See Methods  
 931 for details. e, Regions used for evaluation of the sea-ice freshwater fluxes. Turquoise shading:  
 932 area south of the coastal Ross Sea flux gate<sup>13,36,66</sup>; dark blue shading: area south of the coastal  
 933 Weddell Sea flux gate<sup>13</sup>; purple lines: 69.5° S latitude band in the Atlantic sector and 71° S  
 934 latitude band in the Pacific sector; black line: smoothed mean zero sea-ice-ocean freshwater  
 935 flux line dividing the coastal and open ocean regions (see Methods); thick grey line: mean sea-  
 936 ice edge (1% sea-ice concentration); green lines: basin boundaries.





946

947 **Extended Data Figure 7 | Contribution of sea-ice freshwater flux trends to ocean salinity.**

948 **a**, Map showing the regions used for the estimation of salinity changes due to sea-ice freshwater  
 949 fluxes. Blue lines: sector important for AAIW formation (167° E to 23° W); purple line:  
 950 Subantarctic Front<sup>79</sup>; black line: smoothed mean zero freshwater flux line dividing the coastal  
 951 and open ocean regions; thick grey line: mean sea-ice edge (1% sea-ice concentration). **b**,  
 952 Salinity response to a freshwater flux perturbation using the long-term equilibrium response  
 953 (green) and using a delayed response starting in 1982 for a circumpolar reference volume  
 954 ( $5 \times 10^6 \text{ km}^3$ ; purple), or for the region of most AAIW formation ( $2 \times 10^6 \text{ km}^3$ ; blue). See Methods  
 955 for details. Dashed lines: respective asymptotic equilibrium response; black lines: respective  
 956 current trends; grey shading: approximate observed long-term trend in AAIW<sup>1,3,4</sup>. **c**, Observed  
 957 long-term sea-surface salinity trends (data from P. Durack & S. Wijffels,  
 958 <http://www.cmar.csiro.au/oceanchange>; 1950 to 2000)<sup>5,85</sup>.