Unprecedented decline of Arctic sea ice outflow in 2018

Hiroshi Sumata (✉ hiroshi.sumata@npolar.no)

Norwegian Polar Institute <https://orcid.org/0000-0002-2832-2875>

Laura de Steur

Norwegian Polar Institute

Sebastian Gerland

Norwegian Polar Institute

Dmitry Divine

Norwegian Polar Institute

Olga Pavlova

Norwegian Polar Institute

Article

Keywords: Sea Ice Export, Climate and Deep Water Formation, Anomalous Atmospheric Circulation, Freshwater Cycle, Ice Thinning

Posted Date: May 12th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-376386/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Nature Communications on April 1st, 2022.
See the published version at <https://doi.org/10.1038/s41467-022-29470-7>.

Unprecedented decline of Arctic sea ice outflow in 2018

Hiroshi Sumata^{1*}, Laura de Steur¹, Sebastian Gerland¹, Dmitry Divine¹, Olga Pavlova¹

¹Norwegian Polar Institute, Fram Centre, Tromsø, Norway

* Correspondence to: Hiroshi Sumata (hiroshi.sumata@npolar.no)

Abstract

Fram Strait is the major gateway connecting the Arctic Ocean and North Atlantic Ocean, where nearly 90% of the sea ice export from the Arctic Ocean takes place. The exported sea ice is a large source of freshwater to the Nordic Seas and Subpolar North Atlantic, thereby preconditioning European climate and deep water formation in the downstream North Atlantic Ocean. Here we show that in 2018, the ice export through Fram Strait showed an unprecedented decline since the early 1990s. The 2018 ice export was reduced to less than 40% relative to that between 2000 and 2017, and amounted to just 25% of the 1990s. The minimum export was attributed to regional sea ice-ocean processes driven by an anomalous atmospheric circulation over the Atlantic sector of the Arctic. The anomalous circulation caused a stagnation of southward sea ice drift, causing a sudden drop of sea ice thickness north of the Fram Strait due to local heat supply from the ocean. The result indicates that a drastic change of the freshwater cycle and its environmental consequences happen not only through ongoing Arctic-wide ice thinning, but also by regional scale atmospheric anomalies in the Atlantic sector on annual timescales.

41 **Introductory paragraph**

42

43 Sea ice export through the Fram Strait plays a central role in the freshwater cycle connecting the Arctic and
44 subarctic regions in the Northern Hemisphere^{1, 2}. Since the Arctic Ocean gathers 11% of the global river
45 discharge into 3% area of the global ocean³, sea ice export, together with low salinity seawater carried by
46 ocean currents, returns excess of the freshwater inputs toward lower latitudes⁴. The freshwater export mainly
47 occurs in the Atlantic sector of the Arctic, thereby setting up surface stratification of the neighboring Nordic
48 Seas and further downstream. The freshwater delivered to the Nordic Seas preconditions the physical
49 environment for marine ecosystems^{5, 6}, European weather and climate⁷, and modulates the rate of deep water
50 formation in the downstream North Atlantic Ocean with implications for climate on a global scale^{8, 9, 10}.

51

52 Sea ice export through Fram Strait accounts for approximately 90% of the total sea ice outflow from the
53 Arctic^{11, 12}. In the 20th century, the amount of ice export was equivalent to the liquid freshwater transport in
54 the East Greenland Current (EGC). The sea ice export, however, has shown a reduction in the last decades,
55 mainly attributed to a reduction of mean ice thickness in Fram Strait, which is close to 15% per decade in the
56 last two decades¹³. Climate simulations point to a continued decline in the coming decades with direct
57 consequences for the hydrological cycle in the Arctic and Subarctic regions^{14, 15}.

58

59 Sea ice export and liquid freshwater export with the EGC in the western half of Fram Strait extends
60 approximately from the Prime Meridian to the continental shelf of East Greenland with strong seasonal
61 fluctuations^{16, 17} (Figure 1). In the eastern half of the strait, the West Spitsbergen Current (WSC) carries warm
62 and saline Atlantic Water (AW) northward along the eastern coast of Svalbard. The major part of AW enters
63 the Eurasian Basin through the Barents Sea and through the Svalbard and Yermack Pass branches north of
64 Svalbard, while a significant portion of AW spreads west northwestward within and north of the Fram Strait
65 where it meets the EGC^{18, 19, 20}.

66

67 Sea ice in Fram Strait is originally formed upstream in the Arctic Ocean. The major part of this ice originates
68 from the Siberian shelves (i.e., the Laptev Sea, the East Siberian Sea and to some extent the Chukchi Sea)
69 and the southern perimeter of the perennial sea ice cover in the central Arctic^{21, 22}. The ice floes experience
70 seasonal thickening and thinning during their advective pathway toward the Fram Strait. The transpolar drift
71 stream, driven by an anticyclonic wind field centered in the Canada Basin, is the main driver transporting ice
72 floes from the Siberian shelves to Fram Strait. Ice floes in Fram Strait continue their southward motion along
73 with the EGC, partially driven by northerly wind associated with a sea level pressure (SLP) gradient between
74 Greenland and the Barents Sea^{23, 24}. A perennial difference of surface temperature between northern
75 Greenland and the Barents Sea maintains a pressure gradient, setting up northerly winds and resulting in
76 southward sea ice motion through Fram Strait year-round, though most prominent in winter²⁵.

77

78 Here we report a strong decline in sea ice export through Fram Strait in 2018, unprecedented since
79 observations started in the 1990s, and evidenced by ice thickness measurements from Upward Looking
80 Sonar (ULS) combined with satellite remote sensing observations. The cause of this decline is found through
81 an analysis combining backward trajectories of ice floes, remote sensing products and atmospheric reanalysis
82 data.

83

84

85 **Sea ice volume transport through Fram Strait**

86

87 Sea ice volume export is calculated from ice thickness, an areal fraction of sea ice (sea ice concentration) and
88 ice drift speed. Passive microwave satellite observations have provided the fraction of sea ice and ice drift
89 speed covering the entire Arctic and Subarctic for all seasons since 1979^{26, 27}, whereas ice thickness estimates
90 from satellites are still limited to the freezing season due to properties of ice surface in the melting season²⁸.
91 Upward Looking Sonar (ULS) installed underneath sea ice, however, can provide accurate, near-continuous
92 measurements of ice thickness covering all seasons^{21, 25}. The Fram Strait Arctic Outflow Observatory (AOO)
93 maintained by the Norwegian Polar Institute has been monitoring ice thickness and ocean properties in the
94 EGC at about 79°N in the western Fram Strait since the early 1990s. An array of four ocean moorings at
95 ~3.25°W, 4°W, 5°W and 6.5°W has been equipped with ULSs covering the main tongue of sea ice in the
96 EGC. The observatory has provided a reference of the long-term variations and changes of the freshwater
97 and sea ice export from the Arctic Ocean to the Nordic Seas^{13, 29}.

98

99 In 2018, the ULS array recorded an unprecedented decline of ice draft (from which ice thickness is
100 calculated) since the comprehensive measurements started in 1990. A sudden drop of ice thickness was
101 recorded by all four ULSs starting already in August 2017, lasting until the end of the record in August 2018
102 (Figure 2). Here we refer to ‘annual mean’ as the average from September to August in order to cover the full
103 seasonal cycle of sea ice from freezing in autumn to melting in summer. The decline in 2018 was
104 accompanied by a reduction of sea ice concentration particularly evident in the eastern part of the EGC
105 (Figure 2, green lines). The measured drop in the ice thickness, together with the reduction of ice
106 concentration, resulted in a large reduction of sea ice volume in Fram Strait. The reduction of annual mean
107 effective ice thickness (this is the thickness weighted for ice concentration across the array) was 0.74 m
108 relative to the preceding year (see numbers embedded in Figure 2), corresponding to a reduction of ice
109 volume by 55% .

110

111 As a direct consequence of the large reduction in ice volume, annual sea ice volume transport reached a
112 record minimum in 2018 since the observations started (Figure 3c). The annual volume transport in 2018 was
113 just 590 km³ yr⁻¹, implying a reduction of 60% relative to the 2000 – 2017 period and 75% relative to the
114 1990s. (Table 1). The minimum fell below the second minimum recorded in 2013 by 36%, indicating the
115 anomalous situation in 2018 is exceptional. The decline was amplified by a concurrent slowdown of ice drift

116 speed (Figure 3b). Southward sea ice motion was particularly low from January to July in 2018 (66% slower
117 than 1990 – 2018 average), resulting in the weakest annual mean drift speed since 1992. The weak drift was
118 found to be co-responsible for the observed thickness decline through atmospheric conditions, as we will
119 show in the following sections.

120

121

122 **Origin and modification of sea ice north of Fram Strait**

123

124 To investigate the cause of the ice thickness decline in Fram Strait, we constructed backward trajectories of
125 sea ice floes in Fram Strait. The temporal evolution of ice thickness is examined along with ice drift
126 trajectory back in time, together with concurrent thermodynamic forcing on the ice floes (see method
127 section). Figure 4a shows backward trajectories of ice floes which arrived in Fram Strait in May in each year
128 from 2011 to 2017 and 2018. The trajectories describe the origins and pathways of the ice floes (lines in
129 Figure 4a) along with their locations three months before arrival to the strait (diamonds in Figure 4a). The
130 ice floes in 2018 did not show very different pathways compared to those of the preceding years 2011-2017,
131 indicating that neither the origins nor pathways were the cause of the anomalous thickness in 2018. Figure 4b
132 shows the temporal evolution of ice thickness along the trajectories shown in Figure 4a. When looking at the
133 thickness of sea ice upstream more than one year prior to arriving to Fram Strait in 2018, the sea ice was
134 notably thicker than the ice in 2011-2017 (Figure 4b preceding months from -30 to -13). Thickness of the sea
135 ice arriving in Fram Strait in 2018, however, started to decline rapidly three months before arriving to the
136 strait (Figure 4b preceding months -3 to -1). This was unusual compared with the thickness evolutions of the
137 preceding years that exhibited further thickening during this period in mid-winter (February – March)
138 (orange vs. blue lines in Figure 4b at preceding months from -3 to -2).

139

140 Associated with the 2018 trajectories, we find anomalously warm atmospheric conditions during the
141 preceding winter months (Oct. 2017 – Feb. 2018 or preceding months -8 to -3) at the locations where the ice
142 pack were then, before arriving to Fram Strait (Figure 4c). The warm conditions showed a relative maximum
143 in February 2018, coinciding with the start of the anomalous sea ice thinning in 2018 (Figure 4b). In
144 February 2018, monthly mean 2 m air temperatures along the trajectories were nearly 10 degrees higher than
145 the average of the preceding years 2011-2017. While these warm conditions likely have decelerated further
146 thickening of the ice floes in comparison with the preceding years, it is unlikely that the atmospheric heat
147 supply caused the drastic thinning of the ice floes during February - April 2018. The highest monthly mean 2
148 m air temperature in this period was still below -10 °C, i.e., well below the freezing point of sea water.

149

150 The other prominent difference associated with the trajectories in 2018 relative to 2011-2017, is the location
151 of the ice floes three months before arriving at the strait (diamonds in Figure 4a and Figure 4d). In 2018, the
152 ice floes stayed in an area north of Fram Strait about 200 – 300 km closer to that compared to the ice floes in
153 2011 – 2017. This area north of Fram Strait is characterized by a strong heat supply from the underlying AW

154 to sea ice^{30, 31, 32}. The trajectory analysis shows that the ice floes were thinning rapidly between 82°N (~ 300
155 km north of Fram Strait) and the mooring array at ~79°N (Figure S1 – S6, summarized in Table S1). In 2011
156 – 2017, ice floes reached this area approximately one month before the arrival at the strait and experienced a
157 substantial melting (Table S1). According to the ice thickness changes along the 2011-2017 trajectories, the
158 average melt rate during the last month before arriving at the strait is 0.8 cm day⁻¹ in winter (December to
159 February) and 1.7 cm day⁻¹ in early spring (March – April) (Table S2), which is consistent with the melt rates
160 of 0.3 – 9 cm day⁻¹ in spring obtained from in-situ measurements north of Fram Strait³³. In 2018, the sea ice
161 reached the area south of 82°N already three months before arriving at Fram Strait, allowing for the ice floes
162 to be exposed to strong heat supply from the ocean two to three times longer than in the preceding years. The
163 additional reduction in ice thickness associated with this longer residence time is estimated to be 20 – 50 cm
164 in winter and 50 – 100 cm in spring. These numbers quantitatively explain the acceleration in thickness
165 decline observed in winter 2018 (Figure 4b and Figures S1 – S6).

166

167

168 **Anomalous sea level pressure pattern in 2018**

169

170 The longer residence time of the ice floes in the northern vicinity of Fram Strait was a consequence of slow
171 and stagnant ice motion from autumn 2017 to summer 2018. The stagnation was caused by a repeated
172 reversal of the SLP gradient across the strait and associated changes in prevailing wind direction during this
173 period (Figure 5c and d). An east – west dipole SLP anomaly repeatedly emerged in the Atlantic sector of the
174 Arctic Ocean, most prominent in February 2018 (Figure 5a, b). This pattern has also been recognized for the
175 unusual emergence of the polynya north of Greenland in 2018^{34, 35}. The spatial pattern of these dipole
176 anomalies is characterized by a high pressure center in the Barents Sea and a low pressure center over the
177 Canadian Archipelago and Greenland.

178

179 These anomaly patterns are different from the ‘Arctic dipole anomaly’ in its location of the center of
180 anomalies. The Arctic dipole anomaly is a characteristic pressure anomaly pattern over the Arctic region,
181 having its one of the centers of anomaly in Kara Sea and Laptev Sea³⁶. The Arctic dipole anomaly was
182 reported to influence the sea ice export through Fram Strait in winter³⁷. The SLP anomalies occurred in the
183 2017 – 2018 period has more direct impact on the ice export compared to the Arctic dipole anomaly pattern,
184 since they were situated such that Fram Strait was sandwiched between the anomaly centers. The reversals of
185 zonal SLP gradient across Fram Strait led to concurrent southerly winds that reduced, and even halted,
186 southward sea ice motion in Fram Strait (Figure 5d, Figure S3-S6 bottom panels). The spatial pattern of the
187 anomalies are very similar to the earlier reported SLP anomaly pattern associated with variations in sea ice
188 motion in Fram Strait²⁴ (i.e. the second leading empirical orthogonal function (EOF) mode of daily SLP in
189 the Atlantic sector (45 – 90°N, 90°W – 90°E)). Though the EOF mode was derived from daily SLP analysis,
190 the 2018 dipolar anomalies emerged repeatedly on a monthly time scale with a slightly different spatial
191 pattern (Figure S7).

192

193 The southerly wind events reduced the annual mean southward motion of sea ice to Fram Strait significantly
194 and resulted in enhanced ice melt due to the longer residence time north of the strait where AW meets the
195 transpolar drift stream. At the same time, the southerly winds carried warm air masses to the area north of
196 Fram Strait, leading to an anomalous warm air temperatures in this area, which also had a negative impact on
197 ice growth in winter (Figure 5e).

198

199

200 **Discussions and wider implications**

201

202 This unprecedented reduction of sea ice export by nearly 60% relative to 2000-2017 and 75% relative to the
203 1990s average, raises an important question regarding potential impact on the freshwater cycle in the
204 Northern Hemisphere: where has the sea ice melt water gone? Since the sea ice export through Fram Strait
205 has supplied roughly a half of the freshwater export from the Arctic Ocean to the Subpolar North Atlantic in
206 the 20th century, such a drastic reduction may have a large impact on hydrography and climate both in the
207 Arctic Ocean and downstream North Atlantic Ocean. Has the melt water remained in the Arctic Ocean and
208 strengthened the ocean stratification, or has it increased the liquid freshwater export with the EGC toward
209 lower latitudes? We may expect that the liquid freshwater transport has increased during this time, or at least
210 that outflowing Polar Water was fresher after winter 2017- 2018. However, it is hard to identify surface
211 freshening by sea ice melt by the ocean moorings in Fram Strait as the upper instruments are 25 to 50 m
212 below the surface. Ongoing analysis from the ocean observations from the Fram Strait AOO, as well as
213 intensive monitoring efforts at observational arrays further south (e.g., OSNAP³⁸, RAPID-MOCHA³⁹) are
214 necessary to quantify the downstream impact of the event.

215

216 It is also important to identify potential impact of the event on the sea ice mass balance of the Arctic Ocean.
217 Since the analysis showed that a substantial part of the ice melt has occurred in the northern vicinity of Fram
218 Strait, the record low ice export does not necessarily slow down the long-term decline of ice volume in the
219 Arctic Ocean. However, if the melt water remained in the surface of the Eurasian Basin and strengthened
220 insulation of sea ice from the underlying warm AW, it may have a long-term effect both in sea ice and ocean
221 circulation. A ceaseless monitoring effort of both sea ice and ocean in the Atlantic sector of the Arctic Ocean
222 is necessary to clarify both short-term and long-term impact of the event.

223

224 The effect of a preconditioned environment and potential recurrences of such events in a changing climate
225 also need to be investigated. Oceanic heat transport into the Arctic Ocean is increasing^{40, 41}, ice thickness in
226 the Arctic Ocean is declining⁴², and mobility of sea ice is increasing in a number of regions⁴³; these might
227 have preconditioned the 2018 ice export decline while the effects of each component needs to be clarified.
228 The cause of the repeated appearance of dipole SLP anomaly like in 2018 and the likelihood of recurrences
229 in the future also need further investigation. A relation between the most prominent anomaly in February

230 2018 and a sudden stratospheric warming has been pointed out³⁴, whereas the cause of the repeated
231 occurrence of similar patterns in 2017 – 2018, its relation to dominant atmospheric patterns such as North
232 Atlantic Oscillation or North Atlantic blocking activity, and potential occurrence in a changing climate are
233 still unclear. Interactions and feedbacks between these components in the freshwater cycle and resulting
234 impacts on ocean ecosystem and European climate are ongoing challenges.

235

236

237

238 **Methods**

239

240 **Data**

241

242 Ice thickness data were obtained from Upward Looking Sonars (ULSs) and Ice Profiling Sonars (IPSs)
243 moored in the East Greenland Current in Fram Strait. Four ULS/IPSs are zonally aligned at 79° N from 1990
244 to 2001 and at 78.8° N from 2002 to 2018 with two temporal gaps in 1996 and 2008 and with several spatial
245 gaps in between. Zonal positions (names) of the moorings are 3° W (F11), 4° W (F12), 5° W (F13), and 6.5 –
246 7.0° W (F14), respectively (Figure S8). Locations and temporal coverages of the ULS/IPSs array until 2014
247 were described in a past literature¹³. After 2014, four IPSs were continuously operated except for two data
248 gaps (missing F13 in 2014 and F12 in 2015). Though the zonal locations of the moorings have slightly
249 changed from year to year, the changes are taken into account in the zonal interpolation procedure of the ice
250 volume transport calculation.

251

252 The ULS and IPS measure the underwater fraction of sea ice (sea ice draft) by recording travel times of
253 sound reflected at the bottom of floating sea ice⁴⁴. The raw data were processed to ice draft data by ASL
254 Environmental Science Inc., following standard procedures^{44, 45} including screening of erroneous records (e.g
255 despiking, sound speed corrections)⁴⁶. The ice draft is converted to ice thickness by an average ratio of
256 thickness to draft in Fram Strait, 1.136, derived from on-site drilling measurements⁴⁷. Ice draft measurement
257 interval varies with the instruments used and their respective settings. From 1990 to 2005, ULSs (ES300)
258 were used to obtain the draft data, measurement intervals of which vary from 60 to 600 seconds, though in
259 most cases an interval of 240 seconds was employed. After 2006, IPSs (IPS4 and IPS5) were used to
260 measure the ice draft. The measurement interval of IPS4 and IPS5 was set to two seconds, though an interval
261 of one second was applied in some IPSs from 2014 to 2016.

262

263 Daily mean ice draft and thickness are calculated by averaging the original data except for open water
264 fraction. Hence the daily mean thickness exhibits a spiky time series when the area is largely occupied by
265 open water (Figure 2 blue lines). Effective ice thickness is then calculated by taking the fraction of open
266 water (sea ice concentration) into account. Hence the effective thickness corresponds to ice volume averaged
267 over the daily period. Monthly mean ice thickness and effective ice thickness are calculated by the daily

268 thickness and effective thickness (Figure 3a). Temporal coverage of each daily data gives weight in this mean
269 calculation. The monthly mean effective ice thickness is used for the volume flux calculation.

270

271 We also apply altimetry based sea ice thickness products from remote sensing for the backward trajectory
272 analysis and validation of interannual variation of the ULS/IPS thickness time series in the freezing season
273 (Figure 3a, green line). The remote sensing products give thickness estimates with a basin-wide spatial
274 coverage, though their temporal coverages are limited in the freezing season from October to April. It has
275 been pointed out that the products differ in their absolute magnitude though they agree in the spatial
276 distribution and basin-scale gradients^{48, 49}. To take into account the uncertainty of the thickness estimates
277 from remote sensing, we apply three different thickness products for the trajectory analysis independently
278 and use the mean and standard deviation of the results of the three applications as a measure of thickness
279 estimates along the trajectories. The used products are, the weekly Arctic sea-ice thickness derived from
280 CryoSat and SMOS using an optimal interpolation scheme (hereafter AWI CS2smos product)²⁸, Arctic sea
281 ice and physical oceanography derived from CryoSat-2 Baseline-C Level 1b waveform observations
282 (hereafter Univ. Bristol thickness product)⁵⁰, and CryoSat Operational Polar Monitoring Product (hereafter
283 NERC-CPOM thickness product)⁵¹. These three products provide ice thickness estimates based on CryoSat-2
284 radar altimeter measurements⁵² combined with different thickness retrieval algorithms⁴⁹. Two of the products
285 (AWI CS2smos and Univ. Bristol) in addition merged ice thickness estimates from Soil Moisture and Ocean
286 Salinity satellite (SMOS) to exploit its advantage in thin sea ice area⁵³. The time period of the products used
287 in this study is from 2010 to 2018. Ice thickness estimates by Envisat⁵⁴ are also used for validation of
288 interannual variation of the ULS/IPS time series in the period 2002 – 2010 for winter months (Figure 3a,
289 green line).

290

291 Sea ice drift products derived from satellite remote sensing are used to calculate ice volume flux at the Fram
292 Strait section and backward trajectories of ice floes. Polar Pathfinder Daily 25 km EASE-Grid Sea Ice
293 Motion Vectors, version 4.1²⁷ (hereafter NSIDCv4 ice drift) is used for both the volume flux and the
294 trajectory calculation. The product serves the longest temporal coverage (1979 – 2018) among available drift
295 products by a combination of ice motion estimates derived from various sensors and tracks of ice tethered
296 buoys, which suits both the volume flux and trajectory calculation for a long-range (Figure 3b). Other drift
297 products are also employed for a validation purpose, though they have temporal gaps and temporal coverages
298 are limited in recent years. To construct a seamless time series, we combine three different basin-wide
299 products; OSI-405⁵⁵ and the sea ice motion estimates by Kimura⁵⁶ (hereafter Kimura ice drift), and the Polar
300 Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors, version 2^{57, 58} (hereafter NSIDCv2 ice drift). The
301 three products are combined to take their full advantage: OSI-405 is employed if data are available,
302 KIMURA is used for deriving ice drift for summer months, and NSIDCv2 ice drift is used to fill temporal
303 gaps of the two products. Due to the combination of the products in different quality, the merged drift has
304 artificial temporal variations in basin-averaged drift speed⁵⁹. Hence we carefully apply the merged ice drift
305 for partial validation of NSIDCv4 ice drift time series after 2002 (Figure 3b, orange line).

306

307 Sea ice concentration is taken from the Global Sea Ice Concentration Climate Data Records of the
308 EUMETSAT OSI SAF²⁶ (OSI-409 version 1.2 for a period from January 1990 to April 2015, and OSI-430
309 version 1.2 for a period after April 2015). The products contain robust uncertainty estimates as well as the
310 sea ice concentration estimates. The sea ice concentration and its uncertainty are used to calculate sea ice
311 volume flux at the Fram Strait section and to provide a termination condition of the backward trajectory
312 calculation.

313

314 Atmospheric data are taken from European Center for Medium-Range Weather Forecasts Reanalysis v5⁶⁰
315 (ERA5). Daily and monthly mean 2 m air temperature, sea level pressure, and 10 m wind are used in the
316 analyses.

317

318

319 **Sea ice volume transport in Fram Strait**

320

321 The Fram Strait section is discretized in 0.2 degrees (4.32 km at 78.8° N) zonal segments for the sea ice
322 volume transport calculation. The volume transport at a segment is given by

323

$$324 \quad f(T, A, V) = T(x) \cdot A(x) \cdot V(x) \quad , \quad (1)$$

325

326 where T , A , and V are sea ice thickness, ice concentration, and ice drift velocity perpendicular to the section
327 at location x , respectively. Sea ice concentration and ice drift speed at each segment are linearly interpolated
328 from monthly mean values at the nearest data points. Monthly mean sea ice concentration is calculated from
329 the daily sea ice concentration of OSI-409 and OSI-430, while monthly mean sea ice drift speed is calculated
330 from daily values of NSIDCv4. Sea ice thickness at each segment is calculated from a linear interpolation of
331 thickness between nearest mooring sites if the segment is located in the range of the mooring array ($6.5^\circ \text{ W} <$
332 $x < 3.0^\circ \text{ W}$). The validity of the interpolation is supported by high correlations of monthly mean values of ice
333 thickness (0.64 – 0.94) and effective ice thickness (0.81 – 0.95) between the mooring sites (Figure S9). If the
334 segment is located outside the mooring array ($x < 6.5^\circ \text{ W}$ or $x > 3.0^\circ \text{ W}$), an extrapolation is applied. The
335 extrapolated thickness is calculated from ice thickness at the outermost mooring site and a mean zonal
336 gradient of ice thickness in the Fram Strait section. Monthly mean values of the zonal (spatial) gradient, α are
337 estimated from the ice thickness gradient between the four mooring sites for all observations between 2010
338 to 2018 (Figure S10).

339

340 The total sea ice volume transport in Fram Strait, F , is given by a zonal integration of (1),

341

$$342 \quad F = \int_{x_w}^{x_E} T(x) \cdot A(x) \cdot V(x) dx \quad . \quad (2)$$

343

The western edge of the integration, x_w , is set to 13° W, where sea ice does not move throughout year¹⁶, while the eastern edge x_e varies in time depending on sea ice extent. The time series of the monthly mean sea ice volume transport estimate is shown in Figure 3c, together with volume transport estimates obtained from different combinations of ice thickness and drift speed estimates (Envisat/CS2smos ice thickness, ice drift from the combination of three products). Though the magnitude of peaks in each year differs between the different estimates, they generally agree with the interannual variation of annual volume transport and the drastic reduction in 2018.

Uncertainty estimates of the sea ice volume transport

Uncertainty of the monthly mean sea ice volume transport at each zonal segment, Δf , is calculated by the following formula,

$$\Delta f \simeq |f| \left(\left| \frac{\Delta T}{T} \right| + \left| \frac{\Delta A}{A} \right| + \left| \frac{\Delta V}{V} \right| \right), \quad (3)$$

where ΔT , ΔA , and ΔV , are uncertainty estimates of monthly mean values of ice thickness, ice concentration, and ice drift speed, respectively. The formula assumes that ΔT , ΔA , and ΔV are small compared to T , A , and V , respectively, and they are independent variables. Eq. (3) takes into account systematic errors in addition to random errors⁶¹. A constant value of error estimates is used for sea ice concentration (2.37% on a monthly basis, based on the smearing uncertainty of daily sea ice concentration). The uncertainty of sea ice drift speed is given by an empirical error function formula⁶², which takes into account an increase of uncertainty in higher drift speed and lower sea ice concentration. The uncertainty of the monthly mean ice thickness ΔT is estimated based on the accuracies of respective instruments^{44, 21}, with an assumption of no systematic bias and negligible influence of snow depth variation (Table S2). The high sampling rate of ULS/IPS combined with the fast and variable sea ice motion in Fram Strait gives a thickness estimate representing a larger spatial area compared with slow and stagnant sea ice motion area. The extrapolation of ice thickness outside the zonal range of the mooring array ($x < x_{F14}$, $x > x_{F11}$) introduces an additional uncertainty associated with the uncertainty of the zonal gradient of thickness,

$$\frac{\Delta T(x)}{|T(x)|} = \frac{\Delta T(x_{F14}) + \Delta \alpha \cdot (x_{F14} - x)}{|T(x_{F14}) + \alpha \cdot (x_{F14} - x)|} \quad (x < x_{F14}), \quad (4)$$

$$\frac{\Delta T(x)}{|T(x)|} = \frac{\Delta T(x_{F11}) + \Delta \alpha \cdot (x - x_{F11})}{|T(x_{F11}) + \alpha \cdot (x - x_{F11})|} \quad (x > x_{F11}), \quad (5)$$

where x_{F14} and x_{F11} are locations of the westernmost and the easternmost mooring site F14 and F11, respectively. The standard error of the zonal gradient, $\Delta\alpha$, is given by the standard deviation of the zonal gradient between the mooring sites in the 2010 – 2018 period (Figure S10). The uncertainty of the monthly mean ice volume flux is given by

$$\Delta F = \int_{x_w}^{x_e} |T(x) \cdot A(x) \cdot V(x)| \left(\left| \frac{\Delta T(x)}{|T(x)|} + \frac{\Delta A}{|A(x)|} + \frac{\Delta V(A(x), |V(x)|)}{|V(x)|} \right| \right) dx \quad (6)$$

The largest source of the uncertainty comes from the zonal extrapolation of ice thickness (49 – 73%), while ice concentration (drift speed) contributes to 13 – 24 (13 – 26) % of the total uncertainty. Uncertainty of annual volume flux in different periods is summarized in Table 1.

Backward sea ice trajectory analysis.

Backward trajectories of sea ice floes are calculated by the daily sea ice motion vectors from NSIDCv4 (Figure S11). Pseudo ice floes initially settled at the Fram Strait section (8 floes distributed from 0° to 10° W at 0° W, 1.5° W, 3.0° W, 4.0° W, 5.0° W, 6.5° W, 8.0° W, 10.0° W) are advected by the daily sea ice motion vectors backward in time for 4 years. Ice drift vector at each floe position is calculated by interpolation of daily data at surrounding data points with a Gaussian-type weighting (e-folding scale of 25 km). If no ice drift data is available within 25 km distance from an ice floe position or sea ice concentration at the floe position is lower than 15%, the trajectory calculation is terminated. The ice concentration at an ice floe position is calculated from an interpolation of daily sea ice concentration (OSI-409/OSI-430) with a Gaussian-type weighting (e-folding scale of 12.5 km). The backward calculations start on the 15th of each month from 1990 to 2018. Trajectory data starting from 2011 to 2018 are combined with sea ice thickness estimates from CS2smos products to examine the evolution of ice thickness along the trajectories.

Uncertainty of daily position of pseudo ice floes is assessed by comparisons with buoy tracks obtained from the International Arctic Buoy Program (IABP)⁶³. We used 83 buoy tracks that arrived in Fram Strait in the period from 2000 to 2018 and calculated corresponding pseudo buoy tracks backward in time. The comparisons show that the backward trajectory calculation has approximately 100 km (230 km) error after three months (one year) calculation back in time and the error can be reasonably approximated by a linear function of backtracking days (Figure S12). The error function is used to quantify the uncertainty of physical quantities on the trajectories associated with the position error. A Gaussian kernel, the e-folding scale of which is given by the position error, is applied to estimate temporal evolution of sea ice thickness and 2 m air temperature along the trajectories.

CS2/CS2smos ice thickness products from three different institutes (AWI CS2smos, Univ. Bristol, and NERC-CPOM) are independently applied to estimate temporal evolutions of ice thickness along the trajectories. Mean positions of the ice floes in each month are calculated by averaging positions of surviving floes on the 15th of a month, and the Gaussian kernel is applied to estimate ice thickness for the position. The temporal evolutions of ice thickness are obtained in monthly intervals except for the melting season (May to September) (Figure 4b and Figure S1 – S6 top pannels). The history of atmospheric forcing on ice floes is reconstructed by the evolution of 2 m air temperature along the trajectories. The 2 m air temperature is taken from ERA5 with the same averaging procedure with ice thickness (Figure 4c).

Data availability

The ice draft data from Fram Strait AOO are available at the Norwegian Polar Data Centre at <https://doi.org/10.21334/npolar.2021.5b717274>. The Altimetry-based sea ice thickness estimates are available at ftp://ftp.awi.de/sea_ice/product/cryosat2_smos/ (AWI CS2smos product), <https://data.bas.ac.uk/full-record.php?id=GB/NERC/BAS/PDC/01257> (Univ. Bristol product), <http://www.cpom.ucl.ac.uk/csopr/seaice.php> (NERC-CPOM product), and <https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-ice-thickness?tab=form> (Envisat). The ice drift data are available at <https://nsidc.org/data/NSIDC-0116/versions/4> (NSIDCv4), <https://nsidc.org/data/NSIDC-0116/versions/2> (NSIDCv2), ftp://osisaf.met.no/archive/ice/drift_lr/merged/ (OSI-405), <https://ads.nipr.ac.jp/vishop/> (KIMURA). The sea ice concentration data are available at <ftp://osisaf.met.no/reprocessed/ice/conc/v2p0/> (OSI-409, superseded by OSI-450) and <ftp://osisaf.met.no/reprocessed/ice/conc-cont-reproc/v1p2/> (OSI-430). ERA5 reanalysis product is available at <https://cds.climate.copernicus.eu#!/home>.

Code availability

The backward trajectory code is available on request.

Acknowledgements

This study has been made possible through the long-term observations from the Fram Strait Arctic Outflow Observatory maintained by the Norwegian Polar Institute. This work was supported by the Norwegian Research Council through the FRIPRO program (grant 286971, project FreshArc).

Author Contributions

450 HS conducted all the data analysis in this study, synthesized all inputs, and wrote the paper with significant
451 inputs from LdS. LdS organized and implemented the research project of freshwater and sea ice export
452 through Fram Strait. SG developed sea ice part of the project with DD. OP put the idea of the backward
453 trajectory analysis. DD pointed out effect of southerly wind and necessity of melt rate analysis of sea ice.
454 LdS contributed to formulate oceanic effect on sea ice. All the authors contributed to shape and polish ideas,
455 and to finalize the paper.

456

457 **Competing interests**

458 The authors declare no competing interests.

459

460

461 **References**

462

- 463 1. Peterson, B. J. et al. Trajectory shifts in the Arctic and subarctic freshwater cycle. *Science* **313**, 1061–1066
464 (2006).
- 465 2. Carmack, E. C. et al. Freshwater and its role in the Arctic Marine System: Sources, disposition, storage,
466 export, and physical and biogeochemical consequences in the Arctic and global oceans. *J. Geophys. Res.*
467 *Biogeosciences* **121** (3) 675 – 717 (2015) .
- 468 3. Dai, A., and Trenberth, K. E. Estimates of freshwater discharge from continents: Latitudinal and seasonal
469 variations. *J. Hydrometeorol.* **3**, 660–687 (2002).
- 470 4. Foukal, N. P., Gelderloos, R. and Pickart, R. S. A continuous pathway of freshwater along the East
471 Greenland shelf. *Science Advances* **6** (43) eabc424 (2020).
- 472 5. Greene, C. H. and Pershing, P. J. Climate drives sea change. *Science* **315**, 1084–1085 (2007).
- 473 6. Haug, T. et al. Future harvest of living resources in the Arctic Ocean north of the Nordic and Barents Seas:
474 A review of possibilities and constraints. *Fisheries Research* **188**, 38 – 57 (2017).
- 475 7. Woollings, T., Gregory, J. M., Pinto, J. G., Reyers, M. and Brayshaw, D. J. Response of the North Atlantic
476 storm track to climate change shaped by ocean–atmosphere coupling. *Nature Geoscience* **5**, 313 – 317
477 (2012).
- 478 8. Lazier, J. R. N. Oceanographic conditions at Ocean Weather Ship Bravo, 1964 – 1974. *Atmosphere-Ocean*
479 **18** (3) 227 – 238 (1980).
- 480 9. Dickson, R. R., Meincke, J., Malmberg, S.-A. and Lee, A. J. The “great salinity anomaly” in the Northern
481 North Atlantic 1968–1982. *Prog. Oceanogr.* **20**, 103–151 (1988).
- 482 10. Rahmstorf, S. et al. Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation.
483 *Nature Climate Change*, **5**, 475 – 480 (2015).
- 484 11. Serreze, M. C. et al. The large-scale freshwater cycle of the Arctic. *J. Geophys. Res.* **111**, C11010 (2006).
- 485 12. Haine, T. W. N. et al. Arctic freshwater export: Status, mechanisms, and prospects. *Global Planet.*
486 *Change* **125**, 13– 35 (2015).

- 487 13. Spreen, G. et al. Arctic sea ice volume export through Fram Strait from 1992 to 2014. *J. Geophys. Res.*
488 *Oceans* **125**, e2019JC016039 (2020).
- 489 14. Holland, M. M., Finnis, J., Barrett, A. P. and Serreze, M. C. Projected changes in Arctic Ocean
490 freshwater budgets. *J. Geophys. Res.* **112**, G04S55 (2007).
- 491 15. Jahn, A., & Laiho, R. Forced changes in the Arctic freshwater budget emerge in the early 21st century.
492 *Geophys. Res. Lett.* **47**, e2020GL088854. (2020).
- 493 16. Muckenhuber, S. and Sandven S. Sea ice drift data for Fram Strait derived from a feature-tracking
494 algorithm applied on Sentinel-1 SAR imagery. *Data in Brief* **18**, 1410 – 1415 (2018).
- 495 17. Aagaard, K., and Coachman, L. K. The East Greenland Current North of Denmark Strait, Part II. *Arctic*
496 **21**, 267 – 290 (1968)
- 497 18. Hattermann, T., Isachsen, P. E., von Appen, W.-J., Albrechtsen, J. and Sundfjord, A. Eddy-driven
498 recirculation of Atlantic Water in Fram Strait. *Geophys. Res. Lett.* **43**, 3406–3414 (2016).
- 499 19. von Appen, W.-J., Schauer, U., Hattermann, T. and Beszczynska-Möller, A. Seasonal Cycle of Mesoscale
500 Instability of the West Spitsbergen Current. *J. Phys. Oceanogr.* **46**, 1231 – 1254 (2016).
- 501 20. Athanase, M. et al. New hydrographic measurements of the upper Arctic western Eurasian Basin in 2017
502 reveal fresher mixed layer and shallower warm layer than 2005–2012 climatology. *J. Geophys. Res.*
503 *Oceans* **124**, 1091–1114 (2019).
- 504 21. Hansen, E. et al. Thinning of Arctic sea ice observed in Fram Strait: 1990–2011, *J. Geophys. Res.*
505 *Oceans* **118**, 5202–5221 (2013).
- 506 22. Krumpen, T. et al. Arctic warming interrupts the Transpolar Drift and affects longrange transport of sea
507 ice and ice-rafted matter. *Scientific Report* **9** 5459 (2019).
- 508 23. Widell, K., Osterhus, S. and Gamelsrød, T. Sea ice velocity in the Fram Strait monitored by moored
509 instruments. *Geophys. Res. Lett.* doi:10.1029/2003GL018119 (2003).
- 510 24. Tsukernik, M., Deser, C., Alexander, M. Tomas, R. Atmospheric forcing of Fram Strait sea ice export: a
511 closer look. *Clim. Dyn.* **35**, 1349–1360 (2010).
- 512 25. Vinje, T. Fram Strait Ice Fluxes and Atmospheric Circulation: 1950 – 2000. *J. Clim.* **14**, 3508 – 3517
513 (2001).
- 514 26. Lavergne, T. et al. Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate
515 data records. *The Cryosphere* **13**, 49-78 (2019).
- 516 27. Tschudi, M. A., Meier, W. N. and Stewart, J. S. An ehancement to sea ice motion and age products at the
517 National Snow and Ice Data Center (NSIDC). *The Cryosphere* **14**, 1519 – 1536 (2020).
- 518 28. Ricker, R. et al. A weekly Arctic sea-ice thickness data record from merged CryoSat-2 and SMOS
519 satellite data. *The Cryosphere* **11**, 1607-1623 (2017).
- 520 29. de Steur, L., Peralta-Ferriz, C. and Pavlova, O. Freshwater export in the East Greenland Current
521 freshens the North Atlantic. *Geophys. Res. Lett.* **45**, 13,359–13,366 (2018)

522 30. Fer, I., Peterson, A. K., Randelhoff, A. and Meyer, A. One-dimensional evolution of the upper water
523 column in the Atlantic sector of the Arctic Ocean in winter. *J. Geophys. Res. Oceans* **122**, 1665–1682
524 (2017).

525 31. Peterson, A. K., Fer, I., McPhee, M. G. and Randelhoff, A. Turbulent heat and momentum fluxes in the
526 upper ocean under Arctic sea ice. *J. Geophys. Res. Oceans* doi:10.1002/2016JC012283 (2017).

527 32. Duarte, P. et al. Warm Atlantic water explains observed sea ice melt rates north of Svalbard. *J. Geophys.*
528 *Res. Oceans* **125**, e2019JC015662 (2020).

529 33. Sirevaag, A. and Fer, I. Early Spring Oceanic Heat Fluxes and Mixing Observed from Drift Stations
530 North of Svalbard. *J. Phys. Oceanogr.* **39**, 3049 – 3069 (2009).

531 34. Moore, G. W. K., Schweiger, A., Zhang, J. and Steele, M. What caused the remarkable February 2018
532 North Greenland Polynya? *Geophys. Res. Lett.* **45**, 13,342 – 13, 350 (2018).

533 35. Ludwig, V. et al. The 2018 North Greenland Polynya observed by a newly introduced merged optical and
534 passive microwave sea-ice concentration dataset. *The Cryosphere* **13**, 2051 – 2073 (2019).

535 36. Wu, B., Wang, J. and Walsh, J. E. Dipole Anomaly in the Winter Arctic Atmosphere and Its Association
536 with Sea Ice Motion. *J. Clim.* **19**, 210 – 225, (2006).

537 37. Watanabe, E., Wang, J., Sumi, A. and Hasumi, H. Arctic dipole anomaly and its contribution to sea ice
538 export from the Arctic Ocean in the 20th century. *Geophys. Res. Lett.* **33**, L23703 (2006).

539 38. Lozier, M. S. et al. A sea change in our view of overturning in the subpolar North Atlantic. *Science* **363**,
540 516 – 521 (2019).

541 39. Cunningham, S. A. et al. Temporal variability of the Atlantic meridional overturning circulation
542 at 26.51N. *Science* **317**, 935–938 (2007).

543 40. Polyakov, I. V. et al. Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic
544 Ocean. *Science* **356**, 285-291 (2017).

545 41. Tsubouchi, T. et al. Increased ocean heat transport into the Nordic Seas and Arctic Ocean over the period
546 1993–2016. *Nat. Clim. Chang.* **11**, 21–26 (2021).

547 42. Kwok, R. Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability
548 (1958 – 2018). *Environ. Res. Lett.* **13**, 105005 (2018).

549 43. Spreen, G., Kwok, R., Menemenlis, D. Trends in Arctic sea ice drift and role of wind forcing: 1992 –
550 2009. *Geophys. Res. Lett.* **38**, L19501, doi:10.1029/2011GL048970 (2011).

551 44. Melling, H., Johnston, P. H. and Riedel, D. D. Measurements of the Underside Topography of Sea Ice by
552 Moored Subsea Sonar. *J. Atmos. Oceanic Technol.* **12**, 589 – 602 (1995) .

553 45. Fissel, D.B., Marko, J.R. and Melling, H. Advances in upward looking sonar technology for studying the
554 processes of change in Arctic Ocean ice climate. *Journal of Operational Oceanography*, 1, 9-18 (2008).

555 46. ASL Environmental Sciences Inc., Data Processing and analysis of ice keel depths, Fram Strait, 2006-
556 2007. *Report for Norsk Polarinstitut, Tromsø, Norway by ASL Environmental Sciences Inc.*, Victoria,
557 B.C. Canada (2009).

558 47. Vinje, T., and Finnekåsa, Ø. The ice transport through Fram Strait, *Norsk Polarinstitutt Skr.*, **186**, 1 - 41
559 (1986).

560 48. Bunzel, F., Notz, D., and Pedersen, L. T. Retrievals of Arctic sea-ice volume and its trend significantly
561 affected by interannual snow variability. *Geophys. Res. Lett.* **45**, 11,751–11,759 (2018).

562 49. Sallila, H., Farrell, S. L., McCurry, J. and Rinne, E. Assessment of contemporary satellite sea ice
563 thickness products for Arctic sea ice. *The Cryosphere* **13**, 1187 – 1213 (2019).

564 50. Landy, J. C., Petty, A. A., Tsamados, M., & Stroeve, J. C. Sea ice roughness overlooked as a key source
565 of uncertainty in CryoSat-2 ice freeboard retrievals. *J. Geophys. Res. Oceans* **125**, e2019JC015820.
566 (2020).

567 51. Laxon, S. W. et al. CryoSat-2 estimates of Arctic sea ice thickness and volume. *Geophys. Res. Lett.* **40**,
568 732-737 (2013).

569 52. Wingham, D. J. et al. CryoSat: A mission to determine the fluctuations in Earth's land and marine ice
570 fields. *Advances in Space Research* **37**, 841 – 871 (2006).

571 53. Kaleschke, L., Tian-Kunze, X., Maaß, N., Makynen, M., and Drusch, M. Sea ice thickness retrieval from
572 SMOS brightness temperatures during the Arctic freeze-up period. *Geophys. Res. Lett.* **39**, L05501
573 (2012).

574 54. Hendricks, S., Paul, S., and Rinne, E. ESA Sea Ice Climate Change Initiative (Sea_Ice_cci): Northern
575 hemisphere sea ice thickness from the Envisat satellite on a monthly grid (L3C), v2.0. Centre for
576 Environmental Data Analysis. doi:10.5285/f4c34f4f0f1d4d0da06d771f6972f180 (2018).

577 55. Lavergne, T., Eastwood, S., Teffah, Z., Schyberg, H. and Breivik, L.-A. Sea ice motion from low-
578 resolution satellite sensors: An alternative method and its validation in the Arctic. *J. Geophys. Res.* **115**,
579 C10032 (2010).

580 56. Kimura, N., Nishimura, A., Tanaka, Y. and Yamaguchi, H. Influence of winter sea-ice motion on summer
581 ice cover in the Arctic. *Polar Res.*, **32**, 20193 (2013).

582 57. Tschudi, M. A., Fowler, C., Maslanik, J. A. and Stroeve, J. Tracking the movement and changing surface
583 characteristics of Arctic sea ice. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, **3**, 536–540 (2010).

584 58. Fowler, C., Emery, W. and Tschudi, M. Polar pathfinder daily 25 km EASE-Grid sea ice motion vectors,
585 version 2. (Daily and Mean Gridded Field), NASA DAAC, National Snow and Ice Data Center, Boulder,
586 CO, accessed 23 February 2016, <https://nsidc.org/data/nsidc-0116> (2013).

587 59. Sumata, H., Kauker, F., Karcher, M. and Gerdes, R. Simultaneous Parameter Optimization of an Arctic
588 Sea Ice-Ocean Model by a Genetic Algorithm. *Mon. Wea. Rev.* **147**, 1899 – 1926 (2019).

589 60. Hersbach, H. et al. The ERA5 global reanalysis, *Q. J. R. Meteorol. Soc.* **146**, 1999 – 2049 (2020).

590 61. Ku, H. H. Notes on the Use of Propagation of Error Formulas, *Journal of RESEARCH of the National*
591 *Bureau of Standards – C. Engineering and Instrumentation*, **70C** (4), Oct.-Dec., 263 – 273 (1966).

592 62. Sumata, H., Gerdes, R., Kauker, F. and Karcher, M. Empirical error functions for monthly mean Arctic
593 sea-ice drift. *J. Geophys. Res. Oceans* doi:10.1002/2015JC011151 (2015).

594 63. Rigor, I. G., Wallace, J. M. and Colony, R. L. Response of Sea Ice to the Arctic Oscillation. *J. Clim.* **15**,
595 2648 – 2663 (2002).
596
597

Figure 1. Sketch of the Arctic Ocean and subarctic seas with sea ice drift pattern and ocean currents through Fram Strait. BS: Barents Sea, CB: Canada Basin, EB: Eurasian Basin, EGC: East Greenland Current (thick black arrow), ESS: East Siberian Shelf, FS: Fram Strait (thick magenta line), GL: Greenland, KS: Kara Sea, LS: Laptev Sea, NS: Nordic Seas, SB: Svalbard, TDS: Transpolar drift stream (thick sky blue arrow), WSC: West Spitsbergen Current (thick orange arrow). The background color shows mean sea ice concentration in winter (January – March, 1980 – 2018 mean), and small blue arrows show annual mean sea ice drift field in 1980 – 2018.

Figure2. Time series of observed sea ice properties at (a) eastern most site F11 and (b) western most site F14 of the Fram Strait Arctic Outflow Observatory for 2016 – 2018 period. The black lines depict annual mean effective ice thickness in each year, the period and value of which are shown by a double arrow and a number. The annual mean values are defined by an average from October of preceding year to September of the year.

Figure 3. Time series of (a) ice thickness, (b) southward ice drift speed and (c) southward ice volume transport at the Fram Strait section. Estimates from different data sources are shown in different color. Annual mean values are calculated from averages from October of preceding year to September of the year to represent a seasonal cycles of sea ice formation and melt. See method section for detail. AWI CS2smos product is used in the thickness time series in (a) and southward volume transport in (c).

Table 1. Estimates of southward annual sea ice volume flux at the Fram Strait section.

Period [year]	Volume flux [$\text{km}^3 \text{ yr}^{-1}$]	
	Mean $\pm$ uncertainty	$\pm$ std. dev.
1990 - 1999	2450 ± 650	± 760
2000 - 2009	1760 ± 470	± 410
2010 - 2017	1390 ± 430	± 270
2018	590 ± 260	—

Figure 4. (a) Backward trajectories of sea ice floes which arrived at Fram Strait in May, 2011 – 2017 and 2018, and reconstructions of (b) ice thickness, (c) 2 m air temperature, and (d) latitude along the trajectories back in time. The magenta line in panel (a) shows Fram Strait. The right edge of the panels (b) - (d) denotes arrivals of the ice floes at Fram Strait, while the left edge denotes 2.5 year (30 months) before the arrival. Corresponding months are shown at the top of the panels (b) – (d). The ice thickness in panel (b) shows an average of independent reconstructions by three different ice thickness products (AWI CS2smos, Univ. Bristol, and NERC-CPOM) derived from CS2smos/CS2. The 2m air temperature in panel (c) is obtained from ERA5. See method section for a description.

Figure 5. Spatial pattern and time series of sea level pressure anomaly, wind field and 2 m air temperature over the Fram Strait area from European Center for Medium-Range Weather Forecasts Reanalysis v5 (ERA5). (a) Sea level pressure anomaly in February, 2018 relative to 1990 – 2018 mean, (b) wind and pressure field in February, 2018, time series of (c) sea level pressure difference between the Barents Sea and Greenland, (d) 10 m meridional wind over the Fram Strait area, and (e) 2 m air temperature anomaly in the north of Fram Strait. The pressure difference is calculated from the averages in the two black polygons shown in panel a), used in Tsukernik et al. (2010)²⁴. The 10 m meridional wind and 2 m air temperature anomaly are calculated by an average in the green polygon and the blue sector in panel a. The gray shades shown in panels (c), (d) and (e) depict positive pressure difference (Barents Sea – Greenland) larger than 5 hPa on monthly basis.

Supplementary material

Figure S1. The same with Figure 5b, c, and d, but for reconstructions for ice floes arrived at Fram Strait in January, 2011 – 2017 and 2018.

Figure S2. The same with Figure 5b, c, and d, but for reconstructions for ice floes arrived at Fram Strait in February, 2011 – 2017 and 2018.

Figure S3. The same with Figure 5b, c, and d, but for reconstructions for ice floes arrived at Fram Strait in March, 2011 – 2017 and 2018.

Figure S4. The same with Figure 5b, c, and d, but for reconstructions for ice floes arrived at Fram Strait in April, 2011 – 2017 and 2018.

Figure S5. The same with Figure 5b, c, and d, but for reconstructions for ice floes arrived at Fram Strait in June, 2011 – 2017 and 2018.

Figure S6. The same with Figure 5b, c, and d, but for reconstructions for ice floes arrived at Fram Strait in July, 2011 – 2017 and 2018.

Table S1. Mean ice floe positions and thickness before arrival in Fram Strait (2011 - 2017)

Arrival in Fram Strait	Latitude [°N]		Ice thickness [m]			Ice thickness change [m]	
	Two months before arrival	One month before arrival	Two months before arrival	One month before arrival	In Fram Strait	Preceding two months	Preceding one month
Nov.	82.6	81.4	---	1.30	1.17	---	-0.13
Dec.	83.6	81.7	1.47	1.60	1.30	-0.17	-0.30
Jan.	83.3	81.3	1.77	1.68	1.45	-0.32	-0.23
Feb.	82.7	80.7	1.87	1.75	1.53	-0.34	-0.22
Mar.	82.9	81.3	2.01	1.95	1.58	-0.43	-0.37
Apr.	83.9	81.9	2.22	2.29	1.63	-0.59	-0.66
May	83.4	80.8	2.46	2.18	---	---	---
Jun.	81.8	80.1	2.34	---	---	---	---

The positions of ice floes are estimated from backward trajectory analysis, while ice thickness estimates in each location in each month are obtained from averages of three ice thickness products derived from CS2 and SMOS (AWI, University Bristol and NERC CPOM). See Method section for description.

Table S2. Mean melt rate of ice floes for one month before arrival at Fram Strait (2011 - 2017)

Arrival in Fram Strait	Mean meltelt rate [cm day ⁻¹]
Nov.	0.43
Dec.	0.97
Jan.	0.77
Feb.	0.73
Mar.	1.2
Apr.	2.2

The melt rate is calculated from ice thickness change along the trajectories of ice floes.

Figure S7. Spatial patterns of four SLP anomaly events from 2017 autumn to 2018 summer in ERA5: (a) September 2017, (b) February 2018, (c) May 2018, and (d) July 2018. The anomalies are defined by difference of monthly mean values from 1980 – 2018 monthly mean climatology.

Figure S8. Sketch of the Fram Strait Arctic Outflow Observatory in the East Greenland Current in Fram Strait. ULS/IPSSs were implemented at the top of F11 - F14 moorings.

Figure S9. Autocorrelation of (a) ice thickness and (b) effective ice thickness at the Fram Strait zonal section calculated from combinations of ULS/IPs (orange plus makers) and EnviSat/CS2smos (blue line). The correlations are calculated from the monthly mean ice thickness time series from 1990 to 2018 for ULS/IPs, while from 2002 to 2018 for ULS/IPs. Note that the correlations of EnviSat/CS2smos are obtained from freezing months (Oct. - Apr.). The AWI product is used for the CS2smos correlation.

Figure S10. Seasonal cycle of zonal gradient of ice thickness in Fram Strait. The gradient is calculated from ice thickness difference between western and eastern most sites during the period of 2010 – 2018. The monthly mean values of the thickness are used to calculate the gradient.

Table S2. Uncertainty of monthly mean sea ice thickness at the Fram Strait section

Period [year]	instruments	Accuracy* [m]	Sampling interval [sec]	Uncertainty of monthly mean ice thickness [m]
1990 – 1991	ES300	0.2	480	2.7×10^{-3}
1991 – 2003	ES300	0.2	240	1.9×10^{-3}
2003 – 2006	ES300	0.2	120	1.3×10^{-3}
2007 – 2018	IPS4, 5	0.1	2	0.088×10^{-3}

Figure S11. An example of sea ice trajectories of pseudo ice floes which arrived in Fram Strait from October 2017 to September 2018. Blue, green, orange and red lines correspond to pseudo ice floes arrived in Fram Strait in October, November, December (OND), January, February, March (JFM), April, May, June (AMJ), and July, August, September (JAS), respectively. The back markers (triangles, crosses, squares) denote positions of the floes 6 month, 1 year and 2 years before arrival at Fram Strait. The gray thin lines show all trajectories from 1990 to 2018. Note that the number of JAS trajectories is much less than other seasons because the trajectory calculation cannot be initiated due to low sea ice concentration in Fram Strait in 2018 summer.

Figure S12. Evolution of position errors of backward trajectory calculation. Trajectories of 83 pseudo buoys initially located in Fram Strait are calculated by NSIDCv4 daily sea ice motion vectors backward in time. The pseudo buoy trajectories are compared with tracks of real buoys to calculate the position errors. The real buoy data were selected from International Arctic Buoy Program (83 buoy track which arrived in Fram Strait in the period from 2010 to 2018). The dashed black line is a fitted linear function which is used as an influence radius when calculating physical properties (2m air temperature and ice thickness) along the backward trajectories.