The Complete Annual Record of Sea Ice Volume Export Through Fram Strait as Observed by Satellite from 2010-2022.

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Abstract

Fram Strait is the primary pathway for sea ice export from the Arctic Ocean, yet estimates of volume export are constrained by observations of ice thickness and drift. Using a new year-round CryoSat-2 ice thickness product we determine an average annual export of 1,712 ± 452 kmˆ3 from 2011-2022. 15% of the Arctic Oceans sea ice volume is exported annually, while 3.2% of the volume lost during the melt season is exported. Comparing high- and low-resolution ice drift products reveals the latter underestimate export by 30%. Comparing volume export between 82°N and 79°N reveals a high melt rate of 1 cm d-1, reducing export by 53%. September sea ice volume declines by 286 kmˆ3 for every 100 kmˆ3 exported during summer, highlighting how export amplifies the ice-albedo feedback. Our estimates of volume export provide new insight into Fram Straits role as a sea ice sink and freshwater source.

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Key Points

1. Year-round ice thickness data from CryoSat-2 closes the annual record of sea ice volume export through Fram Strait, with a mean of 1,712 km^3.
2. 15% of the Arctic Oceans sea ice volume is exported annually, while export accounts for only 3.2% of the melt season reduction in volume.
3. Comparing high- and low-resolution ice drift products reveals the latter underestimate export by 30%, affecting previous estimates.

Abstract:

Fram Strait is the primary pathway for sea ice export from the Arctic Ocean yet estimates of volume export are constrained by observations of ice thickness and drift. Using a new year-round CryoSat-2 ice thickness product we determine an average annual export of 1,712 ± 452 km^3 from 2011-2022. 15% of the Arctic Oceans sea ice volume is exported annually, while 3.2% of the volume lost during the melt season is exported. Comparing high- and low-resolution ice drift products reveals the latter underestimate export by 30%. Comparing volume export between 82°N and 79°N reveals a high melt rate of 1 cm d^{-1}, reducing export by 53%. September sea ice volume declines by 286 km^3 for every 100 km^3 exported during summer, highlighting how export amplifies the ice-albedo feedback. Our estimates of volume export provide new insight into Fram Straits role as a sea ice sink and freshwater source.

Plain Language Summary:

Sea ice in the Arctic Ocean is either lost through melt or export. Fram Strait is the primary pathway for sea ice export, yet t estimates of sea ice volume export are limited by the availability of ice thickness and drift data. Here we use a new year-round record of ice thickness from the satellite altimeter CryoSat-2 to refine the estimates of sea ice volume export from 2011 to 2022. Overall, we find that 1,712 km^3 or approximately 15% of the sea ice in the Arctic Ocean is exported annually. Calculating ice volume export at different locations reveals high melt rates in the area that thin the ice as it drifts south towards the north Atlantic Ocean. These estimates are not only key to understanding sea ice loss in the Arctic Ocean but also the supply of freshwater to the north Atlantic, where overturning is critical to the global climate.

1. Introduction:

Fram Strait is the primary pathway for sea ice export from the Arctic Ocean. As a result, it plays a significant role in both the ice mass balance of the Arctic Ocean and the delivery of freshwater to the North Atlantic, where it impacts the Atlantic meridional overturning circulation (Belkin et al., 1998; Ionita et al., 2016). Sea ice export through Fram Strait removes approximately 10% of the sea ice area (Smedsrud et al., 2017) and 14% of the sea ice volume in the Arctic Ocean annually (Spreen et al., 2020), while also comprising 25% of the total freshwater delivered to the North Atlantic (Lique et al., 2009). Sea ice is advected towards Fram Strait by the Transpolar Drift Stream (Figure 1A) while the sea level pressure gradient across the Strait dictates wind speeds, which drive ice drift and therefore ice flux through the Strait. This gradient drives a pronounced annual cycle in sea ice export from a peak in March to a minimum in August (Smedsrud et al., 2017; Spreen et al., 2020; Vinje et al., 1998). On average, between 706,000 and 880,000 km^2 of sea ice is exported through Fram Strait annually (Kwok, 2009; Smedsrud et al., 2017), however scaling this to sea ice volume export has been limited by the availability of ice thickness data.

Historically, sea ice volume export has been examined along a flux gate at 79°N where moored Upward Looking Sonars (ULS) have provided year-round observations of sea ice thickness since 1990 (Figure 1B). Initial estimates in the 1990s varied between 2,218 and 2,850 km^3 per year (Kwok, 2004; Kwok & Rothrock, 1999; Vinje et al., 1998). More recently, Spreen et al. (2020) determined an average annual volume export of 2,400 km^3 from 1992-2014 but found that a reduction in ice thickness (-15% per decade) has driven a reduction in sea ice volume export (-27% per decade). In particular, the ULS have revealed a reduction in the thickness of multi-year sea ice and presence of deformed ice in Fram Strait (Hansen et al., 2013), while there was a particular shift towards younger thinner ice passing through Fram Strait around 2007 (Babb et al., 2023; Sumata et al., 2023). Overall, annual average sea ice volume export, as estimated from the ULS, has declined from 2,450 km^3 in the 1990s, to 1,760 km^3 in the 2000s and 1,390 km^3 from 2010-2017, with a minimum of 590 km^3 in 2018 (Sumata et al., 2022). The disparity between the long-term negative trend in volume export and positive trend in area export (Smedsrud et al., 2017) highlights the importance of sea ice thickness observations.

While the ULS provide high resolution observations of ice thickness year-round, they are limited by their spatial coverage (7°W - 3°W; Figure 1B) and therefore require thickness to be extrapolated across the gate, which leads to significant uncertainty in volume flux estimates (i.e., 26% to 44%; Sumata et al., 2023). Conversely, satellite altimetry does not offer the high temporal resolution of a ULS but does provide complete coverage across the flux gate. Furthermore, the location of flux gates can be changed when using altimeters, which provides insight into local changes to the ice pack (i.e., melt) and can offer greater precision at higher latitudes where overpasses are more frequent (i.e., 82°N; Ricker et al., 2018). The limitation with altimeters is that historically they only provided estimates of thickness during winter (October to April), when the ice surface is cold. Using ICESat, Spreen et al., (2009) estimated an average winter export of 1,564 km^3 at 80°N from 2003-2008, though this estimate relied on ULS to fill gaps between the two ICESat observing periods (October-November and February-March). Using CryoSat-2, Ricker et al., (2018) estimated an average winter export of 1,711 km^3 at 82°N from 2010 to 2017. However, despite a majority of sea ice export occurring during winter, there was a summer gap in satellite estimates. Krumpen et al., (2016) used sparse airborne ice thickness surveys to estimate an average monthly export of 17 km^3 during July and August. However, there remains a gap during spring (May and June) when ice drift speeds remain modest, and a significant volume of sea ice may still be exported.

Here we use new year-round estimates of ice thickness from CryoSat-2 (Landy et al., 2022) in combination with a passive microwave ice drift product to close the annual record of sea ice volume export through Fram Strait from 2010-2022. We further refine estimates of volume export from 2016-2022 using high resolution observations of ice drift from spaceborne synthetic aperture radar (SAR) imagery. We discuss the consistency between published estimates of the volume flux, including the impact of selecting gates over the ULS array at 79°N or further north. Finally, we consider the role of sea ice volume export through Fram Strait in modulating the ice mass balance of the Arctic Ocean and the delivery of freshwater to the North Atlantic.

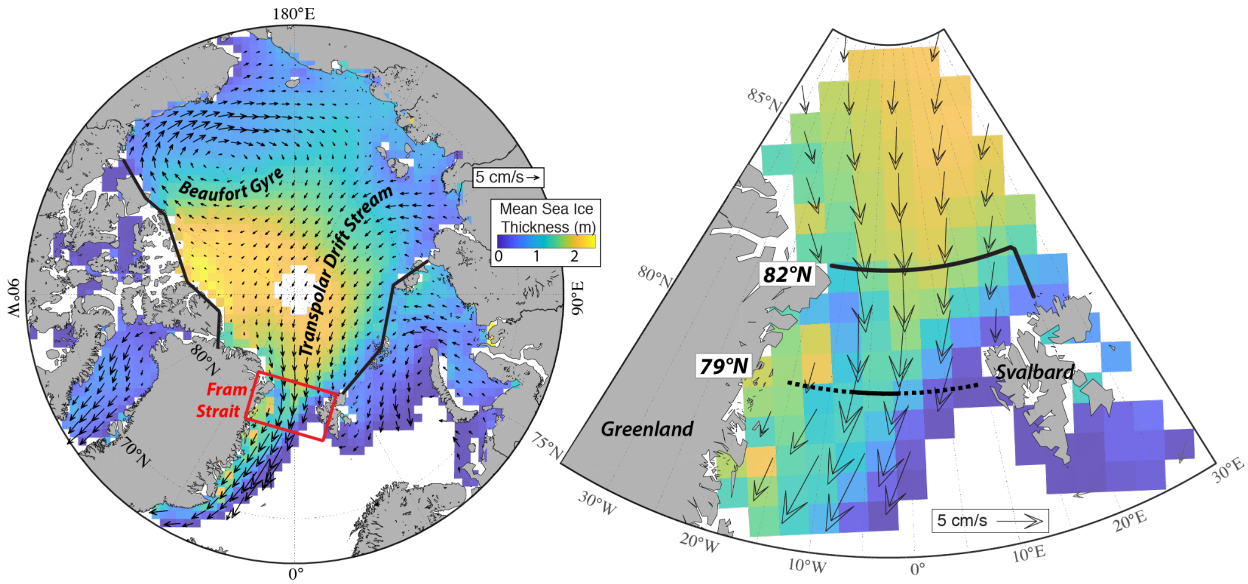

Figure 1: Mean fields of sea ice thickness and drift from 2010-2022 across the Arctic Ocean (left) and in the vicinity of Fram Strait (right) with the two gates at 82°N and 79°N presented. The Arctic Ocean for the ice mass balance analysis is defined by the black lines in the pan-Arctic map along with the Bering Strait and the chosen gate at Fram Strait. In the Fram Strait panel, the solid portion of the 79°N gate between 3° and 7°W is where the ULS are located.

2. Methods:

Sea ice volume flux (F) through Fram Strait ($km^3\ d^{-1}$) was calculated at 44 intervals (i) along the 82°N flux gate (Figure 1) previously used by Ricker et al., (2018). F was calculated using the following equation,

$$F_i = \sum_{i=1}^{n}(C_i\ H_i\ u_i\ \Delta x) \qquad (1)$$

where C is fractional sea ice concentration, H is ice thickness (km), u is ice drift speed normal to the gate ($km\ d^{-1}$) and Δx is the interval (15 km). Positive values of F indicate sea ice export from the Arctic Ocean, while negative values indicate ice import into the Arctic Ocean. C, H and u were interpolated from gridded products to each interval at each time step. F is summed annually from October to September.

Year-round fields of H from CryoSat-2 are provided at bimonthly intervals from October 2010 to July 2022 (Landy & Dawson, 2022). H is generally thinner in this product than the Alfred Wegener Institute (AWI) product used by Ricker et al., (2018) due to differences in radar echo re-tracking (described in Landy et al. (2020)), and snow loading. The AWI product uses a modified Warren (1999) snow climatology, whereas Landy and Dawson (2022) uses the Lagrangian snow evolution scheme SnowModel-LG (Liston et al., 2020; Stroeve et al., 2020). Validating their product against the ULS in Fram Strait, Landy et al. (2022) found a mean bias of +11 cm.

For the full CryoSat-2 record, F was calculated from fields of sea ice concentration (Cavalieri et al., 1996; updated 2023) and motion (Tschudi et al., 2019; updated 2023) derived from spaceborne passive microwave sensors. These estimates are referred to as F_{PMW}. For comparison to previous studies, F_{PMW} was also calculated at 79°N. Sea ice area flux (km^2) was calculated by solving F_{PMW} without H.

F was also calculated from 2016-2022 using high spatiotemporal resolution ice drift data (i.e., ~1 day, 200 m) derived from a combination of spaceborne SAR imagery (i.e., Sentinel-1, RADARSAT-2 and RADARSAT Constellation Mission) using the methodology of Komarov and Barber (2014) and ice concentration from daily ice charts from the National Ice Center (U.S. National Ice Center, 2023). These estimates are referred to as F_{SAR}. SAR resolves faster ice drift speeds than passive microwave drift products (Howell et al., 2022; Kwok et al., 1998; Smedsrud et al., 2017), which is important in Fram Strait where the fastest ice drift in the Arctic Ocean occurs (Figure 1).

Following Ricker et al., (2018) the uncertainty of F_{PMW} (σF_{PMW}) at each interval and time step, assuming uncorrelated errors between variables, is determined with the following equation,

$$\sigma F_{PMW} = L \sqrt{(H\, C\, \sigma_u)^2 + (H\, \sigma_C\, u)^2 + (\sigma_H\, C\, u)^2} \qquad (2)$$

where, σH, σC and σu are the uncertainties in thickness, concentration and drift respectively, and L is the length of the interval. σC is set at 5% (Ricker et al., 2018). σH is taken from the CryoSat-2 product (Landy and Dawson, 2022) and has a mean of 0.32 m. σu is taken from Sumata et al., (2014) and set at 0.873 km d^{-1} during winter (October-April) and 1.123 km d^{-1} during summer (May-September). The monthly uncertainty at 82°N peaks in March and April at 60 km^3 per month and is 17 km^3 during August and September. The average annual uncertainty at 82°N and 79°N is 452 km^3 and 176 km^3, which are equal to 26% and 21% of the average annual fluxes, respectively. The uncertainty in F_{SAR} is lower as the error in SAR-derived ice motion is estimated to be 0.43 km d^{-1} (Komarov & Barber, 2014).

Sea ice volume flux is scaled by 0.8 to estimate liquid freshwater flux relative to a reference salinity of 34.8 (Haine et al., 2015). The contribution of snow to the freshwater flux was calculated by replacing H in equation 1 with snow depth from SnowModel-LG and then using snow density from the model to calculate the liquid equivalent (km^3).

3. Results and Discussion:

3.1 Sea ice volume export at 82°N

3.1.1 Sea ice volume export

The biweekly record of F_{PMW} through Fram Strait is presented in Figure 2A. On average 72 km^3 of sea ice was exported biweekly, with a peak of 306 km^3 during late February 2012. F_{PMW} was only positive (import) during 22 biweekly periods (8%), most of which occurred between July and September, and all of which were below 20 km^3 and therefore in the range of the monthly uncertainty. Similar to the annual record in sea ice area export, the annual cycle in volume export shows a peak in March (305 km^3) and minimum in August (19 km^3; Figure 2B; Table 1). The reduction during spring and summer is gradual, so although F_{PMW} from July to September is very low (4% of the annual flux), F_{PMW} during May and June, which have not been captured by previous altimeter or airborne estimates, make a significant contribution (~15%) to the annual flux.

The monthly averages of F_{PMW} from winters 2010-2017 are 20% lower than those of Ricker et al., (2018) (orange in Figure 2B), which is expected given that our estimates of ice thickness are inherently thinner. Monthly averages of F_{PMW} from 2016-2022 are 27% lower than F_{SAR}, which is expected given that SAR detects faster ice drift speeds. These disparities highlight the importance of continuing to refine estimates of ice thickness and drift used to calculate volume fluxes. Furthermore, it provides important context on the interpretation of existing records of volume export derived from passive microwave drift products, which may underestimate volume export by nearly one-third.

Over the full CryoSat-2 record, F_{PMW} gives an average annual export of 1,712 km^3 through Fram Strait with a peak of 2,512 km^3 in 2015 and minimum of 907 km^3 in 2018 (Figure 2C; Table 1). From 2016-2021, F_{SAR} gives an average annual export of 2,360 km^3, with a peak of 2,914 km^3 in 2017 and minimum of 1,219 km^3 in 2018. Both datasets show a minimum in 2018 due to anomalously low export from February to May (Table 1), but also show a recovery in the years after, meaning 2018 did not provoke a step change in the volume flux but was rather an anomalously low year. There is no apparent linear trend in either F_{PMW} or F_{SAR}, although the records are too short for reliable climate signals to emerge. For comparison, F_{PMW} and F_{SAR} through Fram Strait are nearly seven- and ten-times greater, respectively, than the combined sea ice volume export through Nares Strait and the Canadian Arctic Archipelago (Howell et al., 2023).

Seasonally, 80% (76% in F_{SAR}) of the volume export occurs during winter (October-April) while the remaining 20% (24%) occurs during summer (May-September) and represents the gap that year-round observations of ice thickness can fill. On average 360 km^3 was exported during summer, with a peak of 633 km^3 in 2012 and minimum of 71 km^3 in 2018. Although the standard deviation of volume flux during winter is greater than summer (305 vs 149 km^3), the coefficient of variation for summer (44%) is double that for winter (22%), indicating volume export is twice as variable during summer compared to winter. Examining the contribution of concentration, drift, and thickness to the significant change in variance between summer and winter we find that it is primarily due to the seasonal change in ice drift. The coefficient of variation for ice drift increases from 79% in winter to 131% in summer, compared to a negligible change in the contribution of concentration from 35% in winter to 36% in summer, and a slight increase in the contribution of thickness from 55% in winter to 63% in summer. Similarly, Ricker et al., (2018) found that a majority of the variability in winter volume flux was due to variability in ice drift.

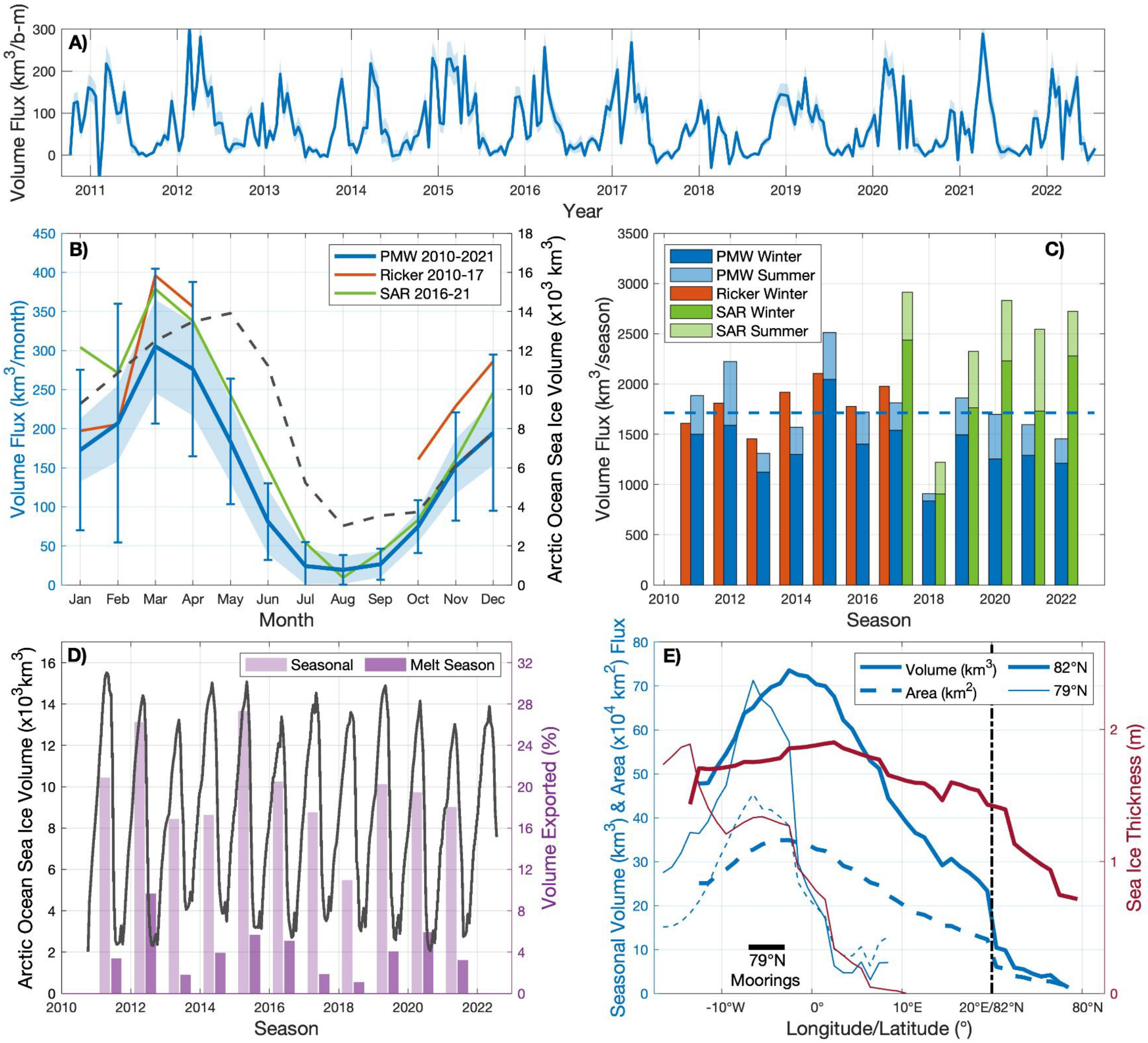

Figure 2: Sea ice volume export at 82°N. A) bi-weekly record of F_{PMW}. B) Monthly cycle of F_{PMW} (2010-2022; blue), F_{SAR} (2016-2022; green) and F from Ricker et al., (2018; 2010-2017; orange) with the monthly cycle of sea ice volume in the Arctic Ocean (gray dashed). The shading in A) and B) represent the uncertainty in F_{PMW}. The error bars in B) represent the standard deviation in monthly F_{PMW}. C) Annual F_{PMW} from 2011-2022 decomposed by winter (October to April) and summer (May to September) compared against winter fluxes from Ricker et al., (2018; orange) and year-round F_{SAR} (green). The dashed line in C) shows the mean annual F_{PMW}. D) bi-weekly record of sea ice volume in the Arctic Ocean and the proportion (%) exported through Fram Strait annually and each melt season. E) Across-Strait profile of the mean annual sea ice area and volume fluxes per year, and the mean ice thickness at each interval (1° longitude at 82°N or 15 km). In E) the thick lines denote data for 82°N, the thin lines denote data for the 79°N, the vertical dashed line denotes the switch from a zonal to meridional gate along the 82°N gate and the thick black line shows the longitudinal span of the 79°N mooring array.

Table 1: Monthly sea ice volume flux (km³) through Fram Strait (82°N) from October 2010 to July 2022. The monthly mean and annual sum are presented along their respective rows and columns. SAR estimates of sea ice volume flux are provided in brackets from February 2016 to July 2022.

Month	Year													
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Jan		295	54	75	32	151	85	358 (488)	206 (279)	244 (284)	118 (233)	152 (206)	300 (333)	**173 (304)**
Feb		-20	457	108	94	457	259 (42)	115 (266)	77 (17)	201 (193)	364 (723)	68 (78)	301 (582)	**207 (271)**
Mar		416	277	295	283	410	337 (194)	430 (474)	122 (125)	293 (400)	395 (740)	286 (399)	119 (318)	**305 (379)**
Apr		248	464	246	338	312	263 (93)	272 (412)	106 (117)	181 (234)	149 (269)	503 (727)	232 (510)	**276 (337)**
May		252	303	115	111	202	152 (130)	239 (251)	-19 (101)	205 (284)	206 (323)	222 (393)	212 (221)	**183 (243)**
Jun		101	149	41	40	164	54 (21)	47 (171)	70 (143)	102 (147)	153 (196)	36 (270)	16 (100)	**81 (150)**
Jul		19	95	27	1	63	39 (6)	-24 (36)	-9 (11)	5 (29)	34 (58)	23 (115)	17 (122)	**24 (54)**
Aug		3	34	8	62	8	48 (10)	10 (9)	4 (1)	13 (30)	6 (-1)	16 (6)		**19 (9)**
Sep		8	53	-3	56	30	29 (56)	-1 (11)	25 (58)	40 (73)	45 (27)	8 (28)		**27 (42)**
Oct	125	52	108	106	130	31	72 (101)	68 (58)	73 (149)	60 (47)	43 (39)	25 (104)		**75 (83)**
Nov	182	84	143	315	147	181	68 (166)	119 (110)	215 (201)	43 (74)	147 (104)	175 (306)		**152 (160)**
Dec	255	203	146	130	439	243	224 (530)	137 (199)	288 (300)	123 (141)	90 (180)	58 (126)		**195 (246)**
Sum		**1884**	**2223**	**1310**	**1570**	**2512**	**1722**	**1811 (2914)**	**907 (1219)**	**1861 (2326)**	**1696 (2832)**	**1594 (2545)**	**1455 (2722)**	

<u>3.1.2 Sea ice volume export and the Arctic Ocean ice mass balance</u>

Comparing the biweekly record of F_{PMW} and total sea ice volume within the Arctic Ocean (Figure 2D - boundaries in Figure 1A) we quantify the contribution of volume export through Fram Strait to the sea ice mass balance of the Arctic Ocean. Between 2011 and 2022, an average of 14.6% of the sea ice volume in the Arctic Ocean was exported through Fram Strait annually (Figure 2E). This is similar to the 14% reported by Spreen et al., (2020) using ULS data for export and PIOMAS for sea ice volume from 1992-2014 and implies that this proportion has been relatively stable over the last 30 years. This might be expected given that both sea ice volume in the Arctic Ocean and export through Fram Strait have declined at respective rates of -15% per decade (Kwok, 2018) and -27% per decade (Spreen et al., 2020). The proportion peaked at 21.8% in 2012, when volume export was the second highest of the study period and fell to a minimum of 7.4% in 2018. For comparison, over the same period 11% of the sea ice area in the Arctic Ocean was exported through Fram Strait annually, highlighting the higher-than-average thickness of ice passing through Fram Strait.

During summer, sea ice volume export through Fram Strait explained only 3.2% of the average 10,400 km^3 of sea ice lost from the Arctic Ocean between May and September (Figure 2B). For comparison, 5% of the reduction in sea ice area was due to export. Fram Strait has a lower impact on summer volume loss than area loss because volume and area are both lost from ice that melts out completely, while volume is also lost from ice that persists through September. The contribution of sea ice export to the loss of sea ice during summer peaked at 5.5% in 2012, when summer volume export peaked and contributed to the record sea ice minimum (Zhang et al., 2013), and was below 1% in 2018, when volume export was anomalously low (77 km^3). Interestingly, summer volume export was only 2% during 2013 and 2017, which were both years of recovery following years of record sea ice loss.

Overall, summer sea ice volume export is found to be significantly correlated with September sea ice volume in the Arctic Ocean (r = -0.68, $p < 0.05$), while the relationship between annual export and September volume was not significant. Based on this relationship, September sea ice volume declines by 286 km^3 for every 100 km^3 exported during summer, the relationship is not one-to-one as export amplifies other feedbacks that in turn drive ice melt (i.e., ice-albedo feedback). Given the high degree of uncertainty in volume flux estimates, we test the robustness of this relationship by running 1000 iterations with random uncertainties drawn from a normal distribution of the summer flux uncertainty ($\overline{\sigma F_S} = 148\,\mathrm{km}^3$) applied to summer estimates of volume export. The relationship remained significant in 80% of the iterations, suggesting a robust negative relationship between summer volume export and September volume. A similar test with the annual volume export and September sea ice volume resulted in a significant negative relationship in only 2.5% of the iterations, supporting our finding of no relationship between the two. This implies that years with higher winter sea ice export do not precondition the Arctics sea ice cover in spring for higher-than-normal melt and anomalously low September sea ice volume. High winter export may be offset by an enhanced negative thin ice-thermodynamic growth feedback (Stroeve et al., 2018).

<u>3.1.3 Across Strait profiles</u>

Satellite altimeters offer unique insight into the across-strait profile in ice thickness not captured by the ULS. Figure 2E shows the average across strait profiles in ice thickness, and the annual sea ice area and volume fluxes at 82°N and 79°N. At 82°N thickness is approximately 1.7 m near Greenland with a peak of 1.9 m around 2°E, a reduction towards 1.5 m across the zonal gate before falling below 0.7 m along the meridional gate. Sea ice area flux between 2010 and 2022 peaked at 3°W and fell off quickly across the zonal gate with minimal export across the meridional gate as the normal component of the ice drift in this area is minimal. As the compound of the ice thickness and area flux profiles, the sea ice volume flux peaked at 3°W and declined across the zonal gate with very little volume being exported across the meridional gate. Export peaks in this area because of the East Greenland Current driving greater ice drift speeds (Ricker et al., 2018; Figure 1).

3.2 Comparison between 82°N and 79°N and previous estimates.

F_{PMW} declined by 52% between 82°N and 79°N, with a slightly greater decrease during summer (58%) than winter (51%) (Figure 3). Reductions in both sea ice area flux (-36%) and thickness (-38%) drive the overall reduction in volume flux. The reduction in area flux is greater than the 10% reduction between 82°N and 79°N reported by Spreen et al., (2020), though their gates were oriented differently, and their study extended back to 1992, meaning that our observations could highlight a recent increase in the amount of sea ice area lost between these two gates. The reduction in area flux is primarily the result of a contraction of sea ice towards the Greenlandic coast (Figure 1B; 2E), however, this contraction does not represent ice convergence, as the ice thickness also declines between the gates. On average ice thickness declined by 0.20 m per degree-latitude between the gates, which was fairly consistent between winter (-0.20 m) and summer (-0.18 m) and agrees with the thinning rate of 0.19 m per degree-latitude observed during summer by Krumpen et al., (2016). Given that the gates are separated by 333 km and the average drift speed over the two gates throughout the CryoSat-2 period is 5.6 km d^{-1}, it takes an average of 59 days for the ice to drift from 82°N to 79°N. With an average thinning of 0.60 m between the gates over the full CryoSat-2 period, this equates to nearly 1 cm of melt per day throughout the year as the ice drifts between the two gates. Similarly, Sumata et al., (Duarte et al., 2020; Provost et al., 2017; Sirevaag & Fer, 2009; 2022) estimated high melt rates between 0.43 and 2.2 cm d^{-1}

immediately upstream of their flux gate at 79°N using altimetry-based estimates of ice thickness along backward trajectories of the ice passing by the ULS. These high melt rates highlight the influence of warm Atlantic water in Fram Strait driving rapid ice melt in the vicinity of Fram Strait (i.e., Duarte et al., 2020; Sirevaag and Fer, 2009; Provost et al., 2017).

Our estimates of F_{PMW} at 79°N are routinely lower than previous estimates at this gate (i.e., Kwok & Rothrock, 1999; Spreen et al., 2020; Sumata et al., 2022; Vinje et al., 1998). The difference with historic estimates from the 1990s is primarily due to the transition towards a younger, thinner ice pack passing through Fram Strait (i.e., Babb et al., 2023; Sumata et al., 2023). However, focusing on the period from 2010-2018, our estimates are 33% less than those from Sumata et al., (2022). This difference is likely to be caused by the high degree of uncertainty associated with extrapolating the across-Strait thickness profile from ULS that cover only 85 of the 588 km across the 79°N gate, which may overestimate ice thickness (Figure 2E). It may also be caused by CryoSat-2 underestimating the thickness of very thick and rough ice floes in Fram Strait; however, CryoSat-2 overestimated the ULS ice thickness by 11 cm when the observations were directly compared (Landy et al., 2022).

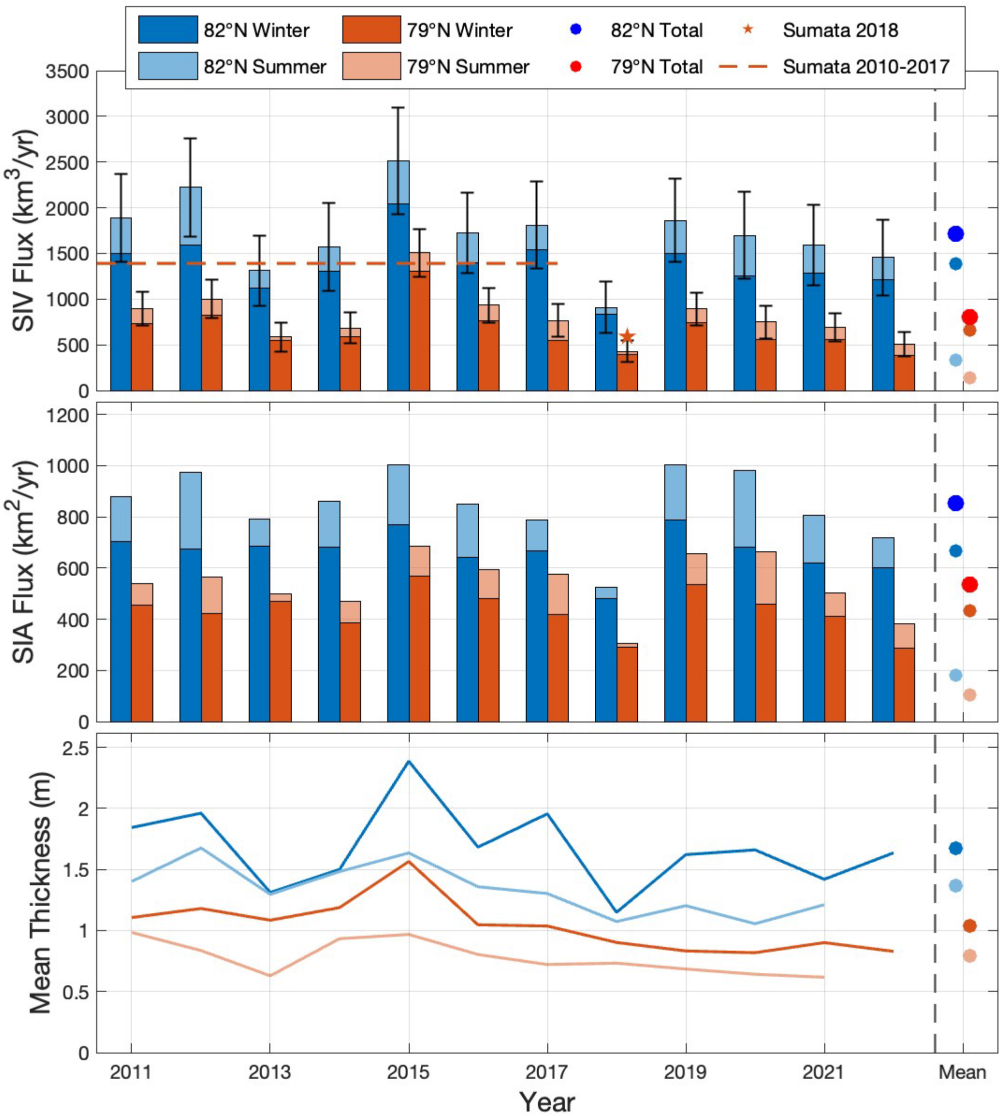

Figure 3: Annual sea ice volume (A) and area (B) fluxes and the mean annual ice thickness (C) for the 82°N and 79°N flux gates. The mean for the winter, summer and annual fluxes, along with the mean winter and summer thicknesses are presented on the far right of each plot. The error bars in A) represent the annual uncertainty in F_{PMW} at 82°N and 79°N. Estimates of sea ice volume flux at 79°N from Sumata et al., (2022) are provided in Panel A.

3.3 Freshwater Export Through Fram Strait.

In addition to serving as a sink for the ice mass balance of the Arctic Ocean, sea ice export through Fram Strait provides a large source of freshwater to the North Atlantic. For the sake of comparing the solid (sea ice and snow) and liquid components of the freshwater export through Fram Strait, we focus on the flux gate at 79°N where the moorings provide a long-term record of liquid freshwater export (Rabe et al., 2013; de Steur et al., 2009). Our estimates of F_{PMW} are equal to an annual average freshwater flux of 664 km^3 with an additional 17 km^3 of freshwater from snow, for a total solid freshwater flux of 681 km^3 yr^{-1} during the 2010s. This is considerably lower than previous freshwater budgets have estimated (2,300 km^3 yr^{-1} Serreze et al., 2006; 1900 km^3 yr^{-1} Haine et al., 2015), because these estimates have been based on historic observations of a thicker ice pack and were subject to the increased uncertainty of extrapolating ULS observations across the full 79°N gate (i.e., Vinje et al., 1998). The solid freshwater flux is only 21% of the liquid freshwater flux observed at the moorings (3,160 km^3; Rabe et al., 2013), though based on the increased melt rates between gates, we can estimate that up to 21% of this liquid freshwater flux is released as ice melts immediately upstream of 79°N. Furthermore, our estimate of solid freshwater flux through Fram Strait is double the estimated solid freshwater flux through Davis Strait (331 km^3 yr^{-1}; Curry et al., 2014), which is the other pathway for sea ice export into the North Atlantic. Together Fram and Davis Straits provide approximately 1,012 km^3 yr^{-1} of freshwater to the North Atlantic.

Given that there is no long-term trend in liquid freshwater flux through Fram Strait (Rabe et al., 2013), we suggest that the reduction in sea ice volume export (Spreen et al., 2020; Sumata et al., 2022) has led to an overall reduction in the total annual delivery of freshwater to the North Atlantic through Fram Strait. The magnitude of the total freshwater flux is projected to change under a warming climate, with reduced sea ice export but potentially enhanced liquid freshwater export through Fram Strait because of enhanced freshwater storage within the Arctic Ocean (Haine et al., 2015; Holland et al., 2007).

Conclusions:

A new year-round record of sea ice thickness from CryoSat-2 is used to complete the annual record of satellite-based estimates of Arctic sea ice volume export through Fram Strait. Using a passive microwave ice drift product over the full CryoSat-2 period (2010-2022), we find an average annual (October to September) export of 1,712 km^3 (±452 km^3) with 80% occurring during winter (October to April) and 20% during summer (May to September), the latter of which has not previously been captured by satellite altimeter-based studies. However, compared to volume export derived from high resolution observations of ice drift from SAR imagery, we find that passive microwave estimates underestimate volume export by nearly one-third, suggesting many previous records of volume export have underestimated the magnitude of sea ice export.

In terms of the ice mass balance of the Arctic Ocean, 14.6% of the Arctic Oceans sea ice volume is exported through Fram Strait annually, while 3.2% of the sea ice volume lost during the melt season is through export. We find a robust significant negative relationship between summer sea ice volume export and September sea ice volume in the Arctic Ocean, which declines by 286 km^3 for every 100 km^3 exported. Comparing sea ice volume export between the northerly gate at 82°N and the historic flux gate at 79°N, we find a 52% reduction. This highlights high melt rates in the vicinity of Fram Strait, with a year-round thinning of approximately 1 cm d^{-1} during the 60 days that it takes for ice to drift between the gates. Our estimates of volume export across 79°N are three to four times below previous estimates based on historic sea ice thickness observations, which highlights the long-term negative trend in ice thickness and therefore volume export through Fram Strait. We suggest the reduction in sea ice export is reducing the overall freshwater flux to the North Atlantic. Our estimated freshwater volume flux through 79°N is only 21% of the observed liquid freshwater flux across the same gate, though our results show that the same volume of freshwater may have been released through ice melt immediately upstream of the flux gate. Overall, we provide new estimates of sea ice volume flux through Fram Strait and its influence on the Arctic Oceans ice mass balance, its role as a source for freshwater to the North Atlantic, and importantly the uncertainty associated with previous estimates of this critical term.

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Data Availability Statement

The year-round record of sea ice thickness from CryoSat-2 is available from Landy and Dawson (2022). Daily fields of sea ice concentration and motion as observed by passive microwave satellites are available from Cavalieri et al., (1996) and Tschudi et al., (2019), respectively. We are in the process of packaging up the SAR ice motion data and adding it to the following ECCC repository https://crd-data-donnees-rdc.ec.gc.ca/CPS/products/IceFlux/.

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The Complete Annual Record of Sea Ice Volume Export through Fram Strait as Observed by Satellite from 2010-2022

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Key Points

1. Year-round ice thickness data from CryoSat-2 closes the annual record of sea ice volume export through Fram Strait, with a mean of 1,712 km^3.
2. 15% of the Arctic Oceans sea ice volume is exported annually, while export accounts for only 3.2% of the melt season reduction in volume.
3. Comparing high- and low-resolution ice drift products reveals the latter underestimate export by 30%, affecting previous estimates.

Abstract:

Fram Strait is the primary pathway for sea ice export from the Arctic Ocean yet estimates of volume export are constrained by observations of ice thickness and drift. Using a new year-round CryoSat-2 ice thickness product we determine an average annual export of 1,712 ± 452 km^3 from 2011-2022. 15% of the Arctic Oceans sea ice volume is exported annually, while 3.2% of the volume lost during the melt season is exported. Comparing high- and low-resolution ice drift products reveals the latter underestimate export by 30%. Comparing volume export between 82°N and 79°N reveals a high melt rate of 1 cm d^{-1}, reducing export by 53%. September sea ice volume declines by 286 km^3 for every 100 km^3 exported during summer, highlighting how export amplifies the ice-albedo feedback. Our estimates of volume export provide new insight into Fram Straits role as a sea ice sink and freshwater source.

Plain Language Summary:

Sea ice in the Arctic Ocean is either lost through melt or export. Fram Strait is the primary pathway for sea ice export, yet t estimates of sea ice volume export are limited by the availability of ice thickness and drift data. Here we use a new year-round record of ice thickness from the satellite altimeter CryoSat-2 to refine the estimates of sea ice volume export from 2011 to 2022. Overall, we find that 1,712 km^3 or approximately 15% of the sea ice in the Arctic Ocean is exported annually. Calculating ice volume export at different locations reveals high melt rates in the area that thin the ice as it drifts south towards the north Atlantic Ocean. These estimates are not only key to understanding sea ice loss in the Arctic Ocean but also the supply of freshwater to the north Atlantic, where overturning is critical to the global climate.

1. Introduction:

Fram Strait is the primary pathway for sea ice export from the Arctic Ocean. As a result, it plays a significant role in both the ice mass balance of the Arctic Ocean and the delivery of freshwater to the North Atlantic, where it impacts the Atlantic meridional overturning circulation (Belkin et al., 1998; Ionita et al., 2016). Sea ice export through Fram Strait removes approximately 10% of the sea ice area (Smedsrud et al., 2017) and 14% of the sea ice volume in the Arctic Ocean annually (Spreen et al., 2020), while also comprising 25% of the total freshwater delivered to the North Atlantic (Lique et al., 2009). Sea ice is advected towards Fram Strait by the Transpolar Drift Stream (Figure 1A) while the sea level pressure gradient across the Strait dictates wind speeds, which drive ice drift and therefore ice flux through the Strait. This gradient drives a pronounced annual cycle in sea ice export from a peak in March to a minimum in August (Smedsrud et al., 2017; Spreen et al., 2020; Vinje et al., 1998). On average, between 706,000 and 880,000 km^2 of sea ice is exported through Fram Strait annually (Kwok, 2009; Smedsrud et al., 2017), however scaling this to sea ice volume export has been limited by the availability of ice thickness data.

Historically, sea ice volume export has been examined along a flux gate at 79°N where moored Upward Looking Sonars (ULS) have provided year-round observations of sea ice thickness since 1990 (Figure 1B). Initial estimates in the 1990s varied between 2,218 and 2,850 km^3 per year (Kwok, 2004; Kwok & Rothrock, 1999; Vinje et al., 1998). More recently, Spreen et al. (2020) determined an average annual volume export of 2,400 km^3 from 1992-2014 but found that a reduction in ice thickness (-15% per decade) has driven a reduction in sea ice volume export (-27% per decade). In particular, the ULS have revealed a reduction in the thickness of multi-year sea ice and presence of deformed ice in Fram Strait (Hansen et al., 2013), while there was a particular shift towards younger thinner ice passing through Fram Strait around 2007 (Babb et al., 2023; Sumata et al., 2023). Overall, annual average sea ice volume export, as estimated from the ULS, has declined from 2,450 km^3 in the 1990s, to 1,760 km^3 in the 2000s and 1,390 km^3 from 2010-2017, with a minimum of 590 km^3 in 2018 (Sumata et al., 2022). The disparity between the long-term negative trend in volume export and positive trend in area export (Smedsrud et al., 2017) highlights the importance of sea ice thickness observations.

While the ULS provide high resolution observations of ice thickness year-round, they are limited by their spatial coverage (7°W - 3°W; Figure 1B) and therefore require thickness to be extrapolated across the gate, which leads to significant uncertainty in volume flux estimates (i.e., 26% to 44%; Sumata et al., 2023). Conversely, satellite altimetry does not offer the high temporal resolution of a ULS but does provide complete coverage across the flux gate. Furthermore, the location of flux gates can be changed when using altimeters, which provides insight into local changes to the ice pack (i.e., melt) and can offer greater precision at higher latitudes where overpasses are more frequent (i.e., 82°N; Ricker et al., 2018). The limitation with altimeters is that historically they only provided estimates of thickness during winter (October to April), when the ice surface is cold. Using ICESat, Spreen et al., (2009) estimated an average winter export of 1,564 km^3 at 80°N from 2003-2008, though this estimate relied on ULS to fill gaps between the two ICESat observing periods (October-November and February-March). Using CryoSat-2, Ricker et al., (2018) estimated an average winter export of 1,711 km^3 at 82°N from 2010 to 2017. However, despite a majority of sea ice export occurring during winter, there was a summer gap in satellite estimates. Krumpen et al., (2016) used sparse airborne ice thickness surveys to estimate an average monthly export of 17 km^3 during July and August. However, there remains a gap during spring (May and June) when ice drift speeds remain modest, and a significant volume of sea ice may still be exported.

Here we use new year-round estimates of ice thickness from CryoSat-2 (Landy et al., 2022) in combination with a passive microwave ice drift product to close the annual record of sea ice volume export through Fram Strait from 2010-2022. We further refine estimates of volume export from 2016-2022 using high resolution observations of ice drift from spaceborne synthetic aperture radar (SAR) imagery. We discuss the consistency between published estimates of the volume flux, including the impact of selecting gates over the ULS array at 79°N or further north. Finally, we consider the role of sea ice volume export through Fram Strait in modulating the ice mass balance of the Arctic Ocean and the delivery of freshwater to the North Atlantic.

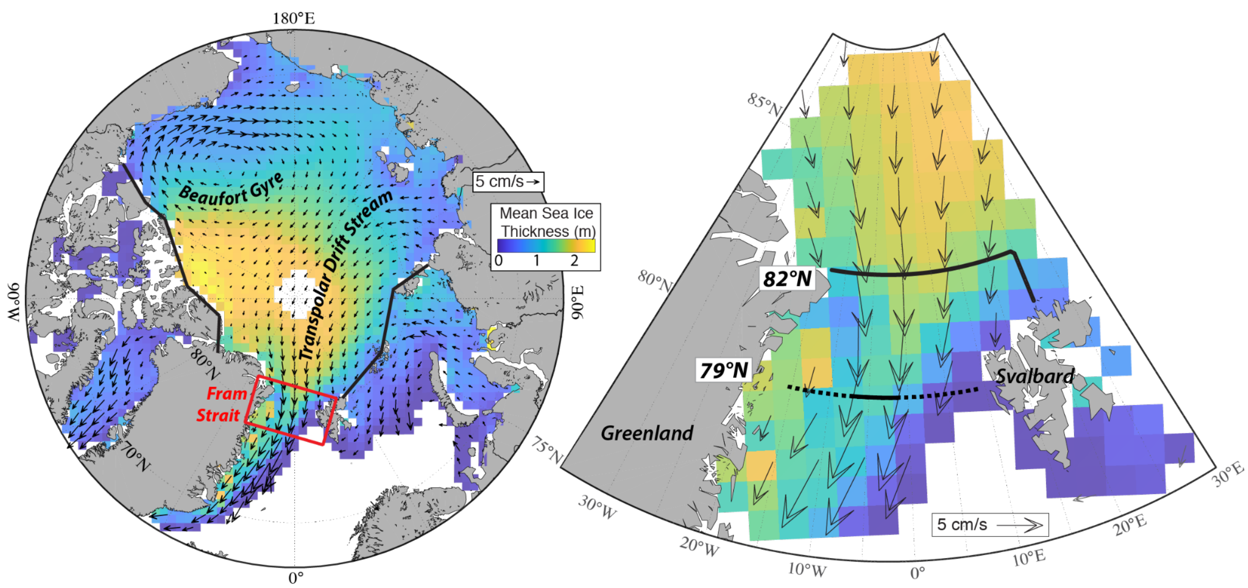

Figure 1: Mean fields of sea ice thickness and drift from 2010-2022 across the Arctic Ocean (left) and in the vicinity of Fram Strait (right) with the two gates at 82°N and 79°N presented. The Arctic Ocean for the ice mass balance analysis is defined by the black lines in the pan-Arctic map along with the Bering Strait and the chosen gate at Fram Strait. In the Fram Strait panel, the solid portion of the 79°N gate between 3° and 7°W is where the ULS are located.

2. Methods:

Sea ice volume flux (F) through Fram Strait (km^3 d^{-1}) was calculated at 44 intervals (i) along the 82°N flux gate (Figure 1) previously used by Ricker et al., (2018). F was calculated using the following equation,

$$F_i = \sum_{i=1}^{n}(C_i\, H_i\, u_i\, \Delta x) \qquad (1)$$

where C is fractional sea ice concentration, H is ice thickness (km), u is ice drift speed normal to the gate (km d^{-1}) and Δx is the interval (15 km). Positive values of F indicate sea ice export from the Arctic Ocean, while negative values indicate ice import into the Arctic Ocean. C, H and u were interpolated from gridded products to each interval at each time step. F is summed annually from October to September.

Year-round fields of H from CryoSat-2 are provided at bimonthly intervals from October 2010 to July 2022 (Landy & Dawson, 2022). H is generally thinner in this product than the Alfred Wegener Institute (AWI) product used by Ricker et al., (2018) due to differences in radar echo re-tracking (described in Landy et al. (2020)), and snow loading. The AWI product uses a modified Warren (1999) snow climatology, whereas Landy and Dawson (2022) uses the Lagrangian snow evolution scheme SnowModel-LG (Liston et al., 2020; Stroeve et al., 2020). Validating their product against the ULS in Fram Strait, Landy et al. (2022) found a mean bias of +11 cm.

For the full CryoSat-2 record, F was calculated from fields of sea ice concentration (Cavalieri et al., 1996; updated 2023) and motion (Tschudi et al., 2019; updated 2023) derived from spaceborne passive microwave sensors. These estimates are referred to as F_{PMW}. For comparison to previous studies, F_{PMW} was also calculated at 79°N. Sea ice area flux (km^2) was calculated by solving F_{PMW} without H.

F was also calculated from 2016-2022 using high spatiotemporal resolution ice drift data (i.e., ~1 day, 200 m) derived from a combination of spaceborne SAR imagery (i.e., Sentinel-1, RADARSAT-2 and RADARSAT Constellation Mission) using the methodology of Komarov and Barber (2014) and ice concentration from daily ice charts from the National Ice Center (U.S. National Ice Center, 2023). These estimates are referred to as F_{SAR}. SAR resolves faster ice drift speeds than passive microwave drift products (Howell et al., 2022; Kwok et al., 1998; Smedsrud et al., 2017), which is important in Fram Strait where the fastest ice drift in the Arctic Ocean occurs (Figure 1).

Following Ricker et al., (2018) the uncertainty of F_{PMW} (σF_{PMW}) at each interval and time step, assuming uncorrelated errors between variables, is determined with the following equation,

$$\sigma F_{PMW} = L\sqrt{(H\,C\,\sigma_u)^2 + (H\,\sigma_C\,u)^2 + (\sigma_H\,C\,u)^2} \qquad (2)$$

where, σH, σC and σu are the uncertainties in thickness, concentration and drift respectively, and L is the length of the interval. σC is set at 5% (Ricker et al., 2018). σH is taken from the CryoSat-2 product (Landy and Dawson, 2022) and has a mean of 0.32 m. σu is taken from Sumata et al., (2014) and set at 0.873 km d^{-1} during winter (October-April) and 1.123 km d^{-1} during summer (May-September). The monthly uncertainty at 82°N peaks in March and April at 60 km^3 per month and is 17 km^3 during August and September. The average annual uncertainty at 82°N and 79°N is 452 km^3 and 176 km^3, which are equal to 26% and 21% of the average annual fluxes, respectively. The uncertainty in F_{SAR} is lower as the error in SAR-derived ice motion is estimated to be 0.43 km d^{-1} (Komarov & Barber, 2014).

Sea ice volume flux is scaled by 0.8 to estimate liquid freshwater flux relative to a reference salinity of 34.8 (Haine et al., 2015). The contribution of snow to the freshwater flux was calculated by replacing H in equation 1 with snow depth from SnowModel-LG and then using snow density from the model to calculate the liquid equivalent (km^3).

3. Results and Discussion:

3.1 Sea ice volume export at 82°N

3.1.1 Sea ice volume export

The biweekly record of F_{PMW} through Fram Strait is presented in Figure 2A. On average 72 km^3 of sea ice was exported biweekly, with a peak of 306 km^3 during late February 2012. F_{PMW} was only positive (import) during 22 biweekly periods (8%), most of which occurred between July and September, and all of which were below 20 km^3 and therefore in the range of the monthly uncertainty. Similar to the annual record in sea ice area export, the annual cycle in volume export shows a peak in March (305 km^3) and minimum in August (19 km^3; Figure 2B; Table 1). The reduction during spring and summer is gradual, so although F_{PMW} from July to September is very low (4% of the annual flux), F_{PMW} during May and June, which have not been captured by previous altimeter or airborne estimates, make a significant contribution (~15%) to the annual flux.

The monthly averages of F_{PMW} from winters 2010-2017 are 20% lower than those of Ricker et al., (2018) (orange in Figure 2B), which is expected given that our estimates of ice thickness are inherently thinner. Monthly averages of F_{PMW} from 2016-2022 are 27% lower than F_{SAR}, which is expected given that SAR detects faster ice drift speeds. These disparities highlight the importance of continuing to refine estimates of ice thickness and drift used to calculate volume fluxes. Furthermore, it provides important context on the interpretation of existing records of volume export derived from passive microwave drift products, which may underestimate volume export by nearly one-third.

Over the full CryoSat-2 record, F_{PMW} gives an average annual export of 1,712 km^3 through Fram Strait with a peak of 2,512 km^3 in 2015 and minimum of 907 km^3 in 2018 (Figure 2C; Table 1). From 2016-2021, F_{SAR} gives an average annual export of 2,360 km^3, with a peak of 2,914 km^3 in 2017 and minimum of 1,219 km^3 in 2018. Both datasets show a minimum in 2018 due to anomalously low export from February to May (Table 1), but also show a recovery in the years after, meaning 2018 did not provoke a step change in the volume flux but was rather an anomalously low year. There is no apparent linear trend in either F_{PMW} or F_{SAR}, although the records are too short for reliable climate signals to emerge. For comparison, F_{PMW} and F_{SAR} through Fram Strait are nearly seven- and ten-times greater, respectively, than the combined sea ice volume export through Nares Strait and the Canadian Arctic Archipelago (Howell et al., 2023).

Seasonally, 80% (76% in F_{SAR}) of the volume export occurs during winter (October-April) while the remaining 20% (24%) occurs during summer (May-September) and represents the gap that year-round observations of ice thickness can fill. On average 360 km^3 was exported during summer, with a peak of 633 km^3 in 2012 and minimum of 71 km^3 in 2018. Although the standard deviation of volume flux during winter is greater than summer (305 vs 149 km^3), the coefficient of variation for summer (44%) is double that for winter (22%), indicating volume export is twice as variable during summer compared to winter. Examining the contribution of concentration, drift, and thickness to the significant change in variance between summer and winter we find that it is primarily due to the seasonal change in ice drift. The coefficient of variation for ice drift increases from 79% in winter to 131% in summer, compared to a negligible change in the contribution of concentration from 35% in winter to 36% in summer, and a slight increase in the contribution of thickness from 55% in winter to 63% in summer. Similarly, Ricker et al., (2018) found that a majority of the variability in winter volume flux was due to variability in ice drift.

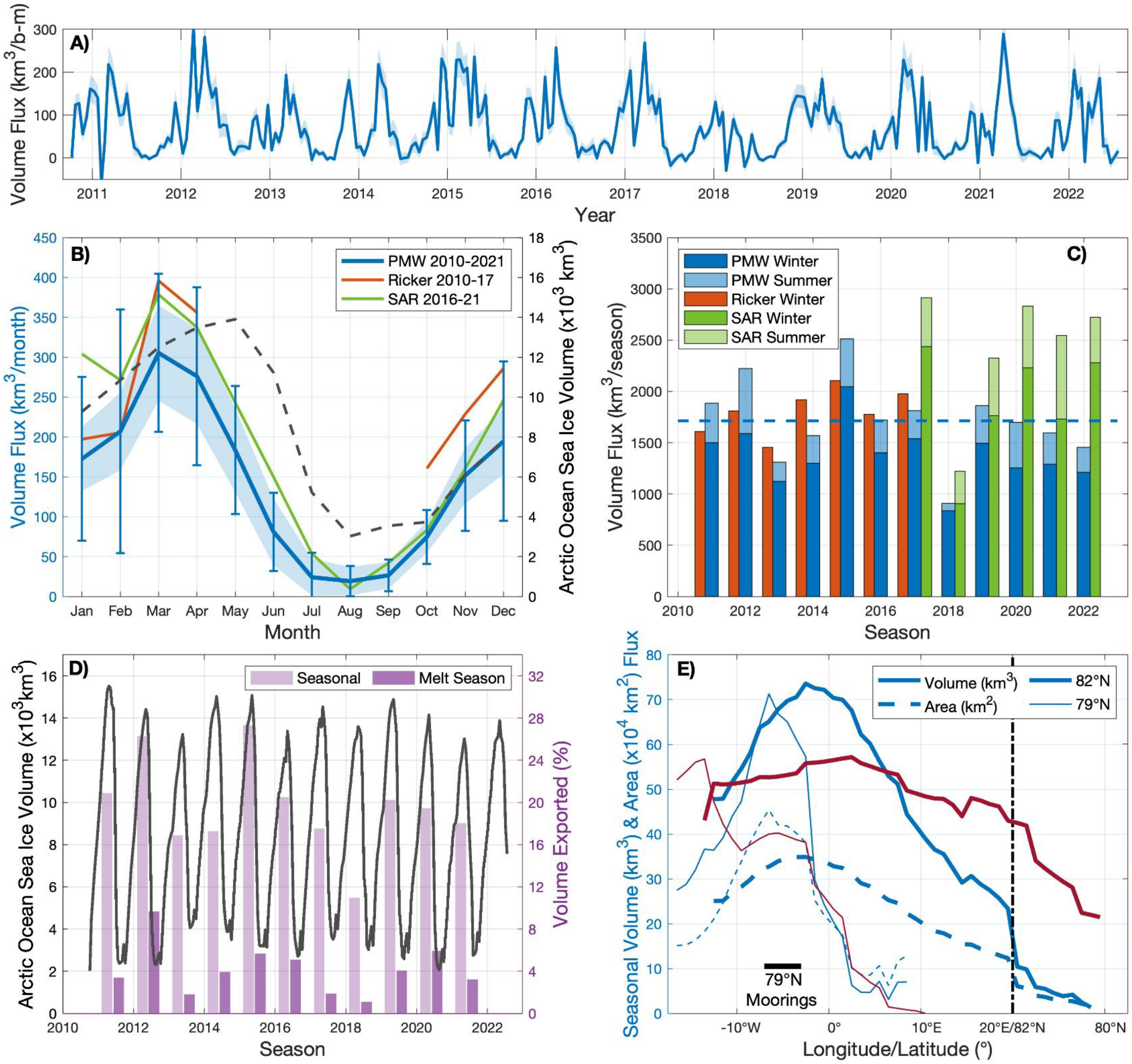

Figure 2: Sea ice volume export at 82°N. A) bi-weekly record of F_{PMW}. B) Monthly cycle of F_{PMW} (2010-2022; blue), F_{SAR} (2016-2022; green) and F from Ricker et al., (2018; 2010-2017; orange) with the monthly cycle of sea ice volume in the Arctic Ocean (gray dashed). The shading in A) and B) represent the uncertainty in F_{PMW}. The error bars in B) represent the standard deviation in monthly F_{PMW}. C) Annual F_{PMW} from 2011-2022 decomposed by winter (October to April) and summer (May to September) compared against winter fluxes from Ricker et al., (2018; orange) and year-round F_{SAR} (green). The dashed line in C) shows the mean annual F_{PMW}. D) bi-weekly record of sea ice volume in the Arctic Ocean and the proportion (%) exported through Fram Strait annually and each melt season. E) Across-Strait profile of the mean annual sea ice area and volume fluxes per year, and the mean ice thickness at each interval (1° longitude at 82°N or 15 km). In E) the thick lines denote data for 82°N, the thin lines denote data for the 79°N, the vertical dashed line denotes the switch from a zonal to meridional gate along the 82°N gate and the thick black line shows the longitudinal span of the 79°N mooring array.

Table 1: Monthly sea ice volume flux (km³) through Fram Strait (82°N) from October 2010 to July 2022. The monthly mean and annual sum are presented along their respective rows and columns. SAR estimates of sea ice volume flux are provided in brackets from February 2016 to July 2022.

Month	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Jan		295	54	75	32	151	85	358 (488)	206 (279)	244 (284)	118 (233)	152 (206)	300 (333)	**173 (304)**
Feb		-20	457	108	94	457	259 (42)	115 (266)	77 (17)	201 (193)	364 (723)	68 (78)	301 (582)	**207 (271)**
Mar		416	277	295	283	410	337 (194)	430 (474)	122 (125)	293 (400)	395 (740)	286 (399)	119 (318)	**305 (379)**
Apr		248	464	246	338	312	263 (93)	272 (412)	106 (117)	181 (234)	149 (269)	503 (727)	232 (510)	**276 (337)**
May		252	303	115	111	202	152 (130)	239 (251)	-19 (101)	205 (284)	206 (323)	222 (393)	212 (221)	**183 (243)**
Jun		101	149	41	40	164	54 (21)	47 (171)	70 (143)	102 (147)	153 (196)	36 (270)	16 (100)	**81 (150)**
Jul		19	95	27	1	63	39 (6)	-24 (36)	-9 (11)	5 (29)	34 (58)	23 (115)	17 (122)	**24 (54)**
Aug		3	34	8	62	8	48 (10)	10 (9)	4 (1)	13 (30)	6 (-1)	16 (6)		**19 (9)**
Sep		8	53	-3	56	30	29 (56)	-1 (11)	25 (58)	40 (73)	45 (27)	8 (28)		**27 (42)**
Oct	125	52	108	106	130	31	72 (101)	68 (58)	73 (149)	60 (47)	43 (39)	25 (104)		**75 (83)**
Nov	182	84	143	315	147	181	68 (166)	119 (110)	215 (201)	43 (74)	147 (104)	175 (306)		**152 (160)**
Dec	255	203	146	130	439	243	224 (530)	137 (199)	288 (300)	123 (141)	90 (180)	58 (126)		**195 (246)**
Sum		**1884**	**2223**	**1310**	**1570**	**2512**	**1722**	**1811 (2914)**	**907 (1219)**	**1861 (2326)**	**1696 (2832)**	**1594 (2545)**	**1455 (2722)**	

3.1.2 Sea ice volume export and the Arctic Ocean ice mass balance

Comparing the biweekly record of F_{PMW} and total sea ice volume within the Arctic Ocean (Figure 2D - boundaries in Figure 1A) we quantify the contribution of volume export through Fram Strait to the sea ice mass balance of the Arctic Ocean. Between 2011 and 2022, an average of 14.6% of the sea ice volume in the Arctic Ocean was exported through Fram Strait annually (Figure 2E). This is similar to the 14% reported by Spreen et al., (2020) using ULS data for export and PIOMAS for sea ice volume from 1992-2014 and implies that this proportion has been relatively stable over the last 30 years. This might be expected given that both sea ice volume in the Arctic Ocean and export through Fram Strait have declined at respective rates of -15% per decade (Kwok, 2018) and -27% per decade (Spreen et al., 2020). The proportion peaked at 21.8% in 2012, when volume export was the second highest of the study period and fell to a minimum of 7.4% in 2018. For comparison, over the same period 11% of the sea ice area in the Arctic Ocean was exported through Fram Strait annually, highlighting the higher-than-average thickness of ice passing through Fram Strait.

During summer, sea ice volume export through Fram Strait explained only 3.2% of the average 10,400 km^3 of sea ice lost from the Arctic Ocean between May and September (Figure 2B). For comparison, 5% of the reduction in sea ice area was due to export. Fram Strait has a lower impact on summer volume loss than area loss because volume and area are both lost from ice that melts out completely, while volume is also lost from ice that persists through September. The contribution of sea ice export to the loss of sea ice during summer peaked at 5.5% in 2012, when summer volume export peaked and contributed to the record sea ice minimum (Zhang et al., 2013), and was below 1% in 2018, when volume export was anomalously low (77 km^3). Interestingly, summer volume export was only 2% during 2013 and 2017, which were both years of recovery following years of record sea ice loss.

Overall, summer sea ice volume export is found to be significantly correlated with September sea ice volume in the Arctic Ocean (r = -0.68, $p < 0.05$), while the relationship between annual export and September volume was not significant. Based on this relationship, September sea ice volume declines by 286 km^3 for every 100 km^3 exported during summer, the relationship is not one-to-one as export amplifies other feedbacks that in turn drive ice melt (i.e., ice-albedo feedback). Given the high degree of uncertainty in volume flux estimates, we test the robustness of this relationship by running 1000 iterations with random uncertainties drawn from a normal distribution of the summer flux uncertainty ($\overline{\sigma F_S} = 148\,\mathrm{km}^3$) applied to summer estimates of volume export. The relationship remained significant in 80% of the iterations, suggesting a robust negative relationship between summer volume export and September volume. A similar test with the annual volume export and September sea ice volume resulted in a significant negative relationship in only 2.5% of the iterations, supporting our finding of no relationship between the two. This implies that years with higher winter sea ice export do not precondition the Arctics sea ice cover in spring for higher-than-normal melt and anomalously low September sea ice volume. High winter export may be offset by an enhanced negative thin ice-thermodynamic growth feedback (Stroeve et al., 2018).

3.1.3 Across Strait profiles

Satellite altimeters offer unique insight into the across-strait profile in ice thickness not captured by the ULS. Figure 2E shows the average across strait profiles in ice thickness, and the annual sea ice area and volume fluxes at 82°N and 79°N. At 82°N thickness is approximately 1.7 m near Greenland with a peak of 1.9 m around 2°E, a reduction towards 1.5 m across the zonal gate before falling below 0.7 m along the meridional gate. Sea ice area flux between 2010 and 2022 peaked at 3°W and fell off quickly across the zonal gate with minimal export across the meridional gate as the normal component of the ice drift in this area is minimal. As the compound of the ice thickness and area flux profiles, the sea ice volume flux peaked at 3°W and declined across the zonal gate with very little volume being exported across the meridional gate. Export peaks in this area because of the East Greenland Current driving greater ice drift speeds (Ricker et al., 2018; Figure 1).

3.2 Comparison between 82°N and 79°N and previous estimates.

F_{PMW} declined by 52% between 82°N and 79°N, with a slightly greater decrease during summer (58%) than winter (51%) (Figure 3). Reductions in both sea ice area flux (-36%) and thickness (-38%) drive the overall reduction in volume flux. The reduction in area flux is greater than the 10% reduction between 82°N and 79°N reported by Spreen et al., (2020), though their gates were oriented differently, and their study extended back to 1992, meaning that our observations could highlight a recent increase in the amount of sea ice area lost between these two gates. The reduction in area flux is primarily the result of a contraction of sea ice towards the Greenlandic coast (Figure 1B; 2E), however, this contraction does not represent ice convergence, as the ice thickness also declines between the gates. On average ice thickness declined by 0.20 m per degree-latitude between the gates, which was fairly consistent between winter (-0.20 m) and summer (-0.18 m) and agrees with the thinning rate of 0.19 m per degree-latitude observed during summer by Krumpen et al., (2016). Given that the gates are separated by 333 km and the average drift speed over the two gates throughout the CryoSat-2 period is 5.6 km d^{-1}, it takes an average of 59 days for the ice to drift from 82°N to 79°N. With an average thinning of 0.60 m between the gates over the full CryoSat-2 period, this equates to nearly 1 cm of melt per day throughout the year as the ice drifts between the two gates. Similarly, Sumata et al., (Duarte et al., 2020; Provost et al., 2017; Sirevaag & Fer, 2009; 2022) estimated high melt rates between 0.43 and 2.2 cm d^{-1}

immediately upstream of their flux gate at 79°N using altimetry-based estimates of ice thickness along backward trajectories of the ice passing by the ULS. These high melt rates highlight the influence of warm Atlantic water in Fram Strait driving rapid ice melt in the vicinity of Fram Strait (i.e., Duarte et al., 2020; Sirevaag and Fer, 2009; Provost et al., 2017).

Our estimates of F_{PMW} at 79°N are routinely lower than previous estimates at this gate (i.e., Kwok & Rothrock, 1999; Spreen et al., 2020; Sumata et al., 2022; Vinje et al., 1998). The difference with historic estimates from the 1990s is primarily due to the transition towards a younger, thinner ice pack passing through Fram Strait (i.e., Babb et al., 2023; Sumata et al., 2023). However, focusing on the period from 2010-2018, our estimates are 33% less than those from Sumata et al., (2022). This difference is likely to be caused by the high degree of uncertainty associated with extrapolating the across-Strait thickness profile from ULS that cover only 85 of the 588 km across the 79°N gate, which may overestimate ice thickness (Figure 2E). It may also be caused by CryoSat-2 underestimating the thickness of very thick and rough ice floes in Fram Strait; however, CryoSat-2 overestimated the ULS ice thickness by 11 cm when the observations were directly compared (Landy et al., 2022).

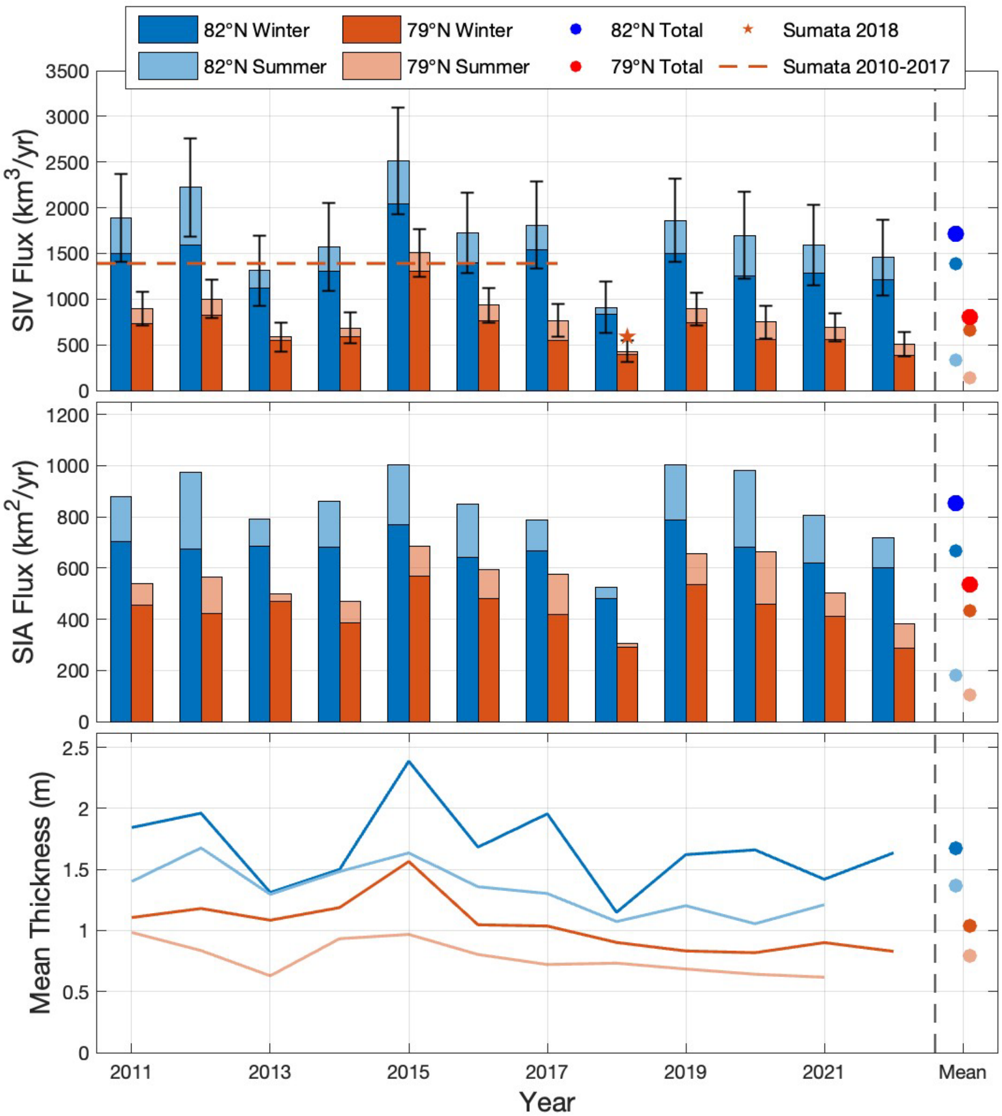

Figure 3: Annual sea ice volume (A) and area (B) fluxes and the mean annual ice thickness (C) for the 82°N and 79°N flux gates. The mean for the winter, summer and annual fluxes, along with the mean winter and summer thicknesses are presented on the far right of each plot. The error bars in A) represent the annual uncertainty in F_{PMW} at 82°N and 79°N. Estimates of sea ice volume flux at 79°N from Sumata et al., (2022) are provided in Panel A.

3.3 Freshwater Export Through Fram Strait.

In addition to serving as a sink for the ice mass balance of the Arctic Ocean, sea ice export through Fram Strait provides a large source of freshwater to the North Atlantic. For the sake of comparing the solid (sea ice and snow) and liquid components of the freshwater export through Fram Strait, we focus on the flux gate at 79°N where the moorings provide a long-term record of liquid freshwater export (Rabe et al., 2013; de Steur et al., 2009). Our estimates of F_{PMW} are equal to an annual average freshwater flux of 664 km^3 with an additional 17 km^3 of freshwater from snow, for a total solid freshwater flux of 681 km^3 yr^{-1} during the 2010s. This is considerably lower than previous freshwater budgets have estimated (2,300 km^3 yr^{-1} Serreze et al., 2006; 1900 km^3 yr^{-1} Haine et al., 2015), because these estimates have been based on historic observations of a thicker ice pack and were subject to the increased uncertainty of extrapolating ULS observations across the full 79°N gate (i.e., Vinje et al., 1998). The solid freshwater flux is only 21% of the liquid freshwater flux observed at the moorings (3,160 km^3; Rabe et al., 2013), though based on the increased melt rates between gates, we can estimate that up to 21% of this liquid freshwater flux is released as ice melts immediately upstream of 79°N. Furthermore, our estimate of solid freshwater flux through Fram Strait is double the estimated solid freshwater flux through Davis Strait (331 km^3 yr^{-1}; Curry et al., 2014), which is the other pathway for sea ice export into the North Atlantic. Together Fram and Davis Straits provide approximately 1,012 km^3 yr^{-1} of freshwater to the North Atlantic.

Given that there is no long-term trend in liquid freshwater flux through Fram Strait (Rabe et al., 2013), we suggest that the reduction in sea ice volume export (Spreen et al., 2020; Sumata et al., 2022) has led to an overall reduction in the total annual delivery of freshwater to the North Atlantic through Fram Strait. The magnitude of the total freshwater flux is projected to change under a warming climate, with reduced sea ice export but potentially enhanced liquid freshwater export through Fram Strait because of enhanced freshwater storage within the Arctic Ocean (Haine et al., 2015; Holland et al., 2007).

Conclusions:

A new year-round record of sea ice thickness from CryoSat-2 is used to complete the annual record of satellite-based estimates of Arctic sea ice volume export through Fram Strait. Using a passive microwave ice drift product over the full CryoSat-2 period (2010-2022), we find an average annual (October to September) export of 1,712 km^3 (±452 km^3) with 80% occurring during winter (October to April) and 20% during summer (May to September), the latter of which has not previously been captured by satellite altimeter-based studies. However, compared to volume export derived from high resolution observations of ice drift from SAR imagery, we find that passive microwave estimates underestimate volume export by nearly one-third, suggesting many previous records of volume export have underestimated the magnitude of sea ice export.

In terms of the ice mass balance of the Arctic Ocean, 14.6% of the Arctic Oceans sea ice volume is exported through Fram Strait annually, while 3.2% of the sea ice volume lost during the melt season is through export. We find a robust significant negative relationship between summer sea ice volume export and September sea ice volume in the Arctic Ocean, which declines by 286 km^3 for every 100 km^3 exported. Comparing sea ice volume export between the northerly gate at 82°N and the historic flux gate at 79°N, we find a 52% reduction. This highlights high melt rates in the vicinity of Fram Strait, with a year-round thinning of approximately 1 cm d^{-1} during the 60 days that it takes for ice to drift between the gates. Our estimates of volume export across 79°N are three to four times below previous estimates based on historic sea ice thickness observations, which highlights the long-term negative trend in ice thickness and therefore volume export through Fram Strait. We suggest the reduction in sea ice export is reducing the overall freshwater flux to the North Atlantic. Our estimated freshwater volume flux through 79°N is only 21% of the observed liquid freshwater flux across the same gate, though our results show that the same volume of freshwater may have been released through ice melt immediately upstream of the flux gate. Overall, we provide new estimates of sea ice volume flux through Fram Strait and its influence on the Arctic Oceans ice mass balance, its role as a source for freshwater to the North Atlantic, and importantly the uncertainty associated with previous estimates of this critical term.

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Data Availability Statement

The year-round record of sea ice thickness from CryoSat-2 is available from Landy and Dawson (2022). Daily fields of sea ice concentration and motion as observed by passive microwave satellites are available from Cavalieri et al., (1996) and Tschudi et al., (2019), respectively. We are in the process of packaging up the SAR ice motion data and adding it to the following ECCC repository https://crd-data-donnees-rdc.ec.gc.ca/CPS/products/IceFlux/.

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