

Fram Strait sea ice thickness and summer export

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Recent summer sea ice thickness surveys in the Fram Strait and associated volume fluxes

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Abstract

Fram Strait is the main gateway for sea ice export out of the Arctic Ocean, and therefore observations there give insight into composition and properties of Arctic sea ice in general and how it varies over time. An extensive data set of ground-based and air-borne electromagnetic ice thickness measurements collected between 2001 and 2012 is presented here, including long transects well into the southern part of the Transpolar Drift obtained using fixed-wing aircrafts. The source area for the surveyed ice is primarily the Laptev Sea, and the estimated age is consistent with a decreased from 3 to 2 years between 1990 and 2012. The data consistently also show a general thinning for the last decade, with a decrease in modal thickness of second year and multiyear ice, and a decrease in mean thickness and fraction of ice thicker than 3 m. Local melting in the strait was investigated in two surveys performed in the downstream direction, showing a decrease of $0.19 \text{ m degree}^{-1}$ latitude south of 81° N probably driven by bottom melting from warm water of Atlantic origin. Further north variability in ice thickness is more related to differences in age and deformation. The thickness observations were combined with ice area export estimates to calculate summer volume fluxes of sea ice. This shows that it is possible to determine volume fluxes through Fram Strait during summer when satellite based sea ice thickness information is missing. While the ice area export based on satellite remote sensing shows positive trends since 2001, the mean fluxes during summer (July and August) are small (18 km^3), and long-term trends are uncertain due to the limited surveys available.

1 Introduction

Arctic sea ice extent and thickness have undergone dramatic changes in the past decades: Summer sea ice extent has declined at an annual rate of approximately $12.7\% \text{ decade}^{-1}$ over the satellite record (Meier et al., 2014; Comiso and Hall, 2014, 1978–present) and its mean thickness has decreased by $0.58 \pm 0.07 \text{ m decade}^{-1}$ over

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the period 2000–2012 (Lindsay and Schweiger, 2015). The thinning of sea ice is accompanied by an increase of ice drift velocity (Spren et al., 2011), deformation (Rampal et al., 2009; Martin et al., 2014) and a decrease of net ice growth rates. Climate model simulations indicate that ice extent and thickness will further decline through the 21st century in response to atmospheric greenhouse gas increases (Vavrus et al., 2012). The mass balance of Arctic sea ice is therefore determined not only by changes in the energy balance of the coupled ice–ocean–atmosphere system but also by the increasing influence of dynamic effects. One aspect of the mass balance of Arctic sea ice are changes of ice volume export rates through Fram Strait, the major sea ice outflow gate of the Arctic.

Trends in southern Fram Strait sea ice thickness were previously investigated by Hansen et al. (2013) and Renner et al. (2014). Based on a 21 year long time series (1990–2011) obtained from moored sonars, Hansen et al. (2013) showed that the ice thickness at 79° N decreased from an annual mean of 3.0 m during the 1990s to 2.2 m during 2008–2011. Renner et al. (2014) reported an even more pronounced thinning of Fram Strait ice cover. According to in-situ and airborne observations carried out at the end of the melt season, ice thickness decreased by over 50 % during 2003–2012. The first aim of this manuscript is to complement those recent findings by means of an extensive data set of electromagnetic (EM) ice thickness observations carried out during summer in northern Fram Strait and the southern part of the Nansen Basin. Measurements were obtained in the months of July and August of 2001, 2004 and 2010–2012 during two cruises of the German ice-breaker RV *Polarstern* and three airborne campaigns with the German DC3-T research aircraft *Polar-5*. An investigation of back trajectories of surveyed sea ice using satellite based sea ice motion data will allow us to examine the connection between thickness variability, ice age and source area.

A second objective of this paper is to investigate across- and along-Fram Strait gradients in sea ice thickness. According to ULS observations of Hansen et al. (2013), the ice thickness distribution in Fram Strait is characterized by a gradient from thicker

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ice in the west to thinner ice in the east. The high interannual and intraannual variability of this gradient is related to the thickness and age of ice that enters Fram Strait. Both vary substantially since ice originates from different regions and had a different dynamic and thermodynamic history on its way through the Arctic Ocean (Rabenstein et al., 2010). The long operating distance of *Polar 5* enabled us to obtain the first continuous ice thickness measurements across, but also along Fram Strait. Below, we compare across-strait gradients obtained from *Polar 5* surveys to gradients observed further south by Renner et al. (2014) and Hansen et al. (2013). Surveys performed in the downstream direction are used to investigate local melt, associated to atmospheric and oceanic processes acting on southward drifting sea ice.

A third objective of this manuscript is to use the presented AEM measurements together with satellite based area flux estimates to calculate volume outflows for the periods when thickness surveys were made. Whether sea ice volume loss through Fram Strait accelerates is currently under discussion. Following Smedsrud et al. (2011), the decrease in Fram Strait ice thickness is accompanied by an increase in ice area export out of Fram Strait. Those authors used geostrophic winds derived from reanalysis data to calculate the ice area export between Spitsbergen and Greenland and found it to be about 25% larger than during the 1960's. In contrast, other studies (Kwok, 2009; Kwok et al., 2013) did not observe any significant trend in ice area export for the past decades. Only a few studies exist that quantify Fram Strait volume fluxes using satellite data directly. By combining sea ice concentration and drift from passive microwave satellites and thickness derived from ICESat laser altimetry, Spreen et al. (2009) determined the sea ice volume flux in Fram Strait region for eleven, one month long ICESat observations periods in spring and late autumn. However, volume flux estimates with thickness information obtained from altimeter satellites missions such as ICESat or CryoSat-2 are restricted to the period between October and April. Hence, little is known about sea ice volume fluxes through Fram Strait in the summer months. An approximation of sea ice volume flux during summer by means of AEM thickness observations and satellite drift and concentration data is the first of its kind. These es-

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sets of ice drift products were used: The first data set, Polar Pathfinder Sea Ice Motion Vectors (Version 2), was chosen because of its good performance and year round availability. Below it is used to estimate transport rates out of Fram Strait, and to calculate ice drift trajectories during summer months (June–August). The product provided by the NSIDC contains daily gridded fields of sea ice motion on a 25 km Equal Area Scalable Earth grid (EASE) for the period between 1978 to 2012 (Fowler et al., 2013). The motion vectors (hereafter referred to as NSIDC) are obtained from a variety of satellite-based sensors such as the SMMR, SSM/I, AMSR-E and Advanced Very High Resolution Radiometer (AVHRR) and buoy observations from the International Arctic Buoy Program (IABP). A description of the data set and the sea ice motion retrieval algorithm can be found in Fowler et al. (2013).

In addition to NSIDC drift data, the tracking routine as described in Sect. 2.2.3 makes use of motion estimates provided by the Center for Satellite Exploitation and Research (CERSAT) at the Institut Francais de Recherche pour d'Exploitation de la Mer (IFREMER), France. Since a substantial part of Fram Strait sea ice originates from the Laptev Sea (Rigor and Colony, 1997), the calculation of drift trajectories requires a drift data set with good performance on the Siberian shelf. Following Rozman et al. (2011) and Krumpfen et al. (2013), a comparison of different drift products with high resolution satellite and in-situ drift data in the Laptev Sea have shown that the CERSAT motion data has the highest accuracy in this region. Hence, the ice drift data provided by CERSAT were used in the tracking approach, bridged with NSIDC data during summer months. The motion fields (hereafter referred to as CERSAT) are based on a combination of drift vectors estimated from scatterometer (SeaWinds/QuikSCAT and ASCAT/MetOp) and radiometer (SSM/I) data. They are available with a grid size of 62.5 km, using time intervals of 3 days for the period between September and May (1991 to present).

2.2.3 Sea ice pathways and source areas

To determine drift trajectories and source areas of sampled sea ice we tracked the surveyed ice backward over a period of four years using NSIDC and CERSAT ice drift and NSIDC ice concentration products. A specific floe is tracked backwards until: (a) the ice reaches a position next to a coastline, (b) the ice concentration at a specific location reaches a threshold value of ($\leq 15\%$) where the ice is assumed to be melted, or (c) the tracking time exceeds four years.

2.2.4 Ice age

Sea ice age information was obtained from the drift-age model of Maslanik et al. (2011). Ice age is retrieved by tracking sea ice from the formation until the melt or export using NSIDC ice concentration and drift data. The data set is available on a $25\text{ km} \times 25\text{ km}$ grid with a temporal resolution of one week for the period between January 1990 and August 2013. For more details we refer to Maslanik et al. (2011).

2.2.5 Ice area flux across Fram Strait

In Sect. 3.4 we relate recent changes observed in Fram Strait ice thickness to satellite based estimates of ice area flux. Ice area flux estimates out of Fram Strait are calculated using NSIDC motion estimates together with NSIDC ice concentration information. Flux estimates are made along a zonal gate positioned at 82° N , between 12° W and 20° E and a meridional gate that connects the eastern end of the zonal gate with Spitzbergen (80.6° N , 20° E , compare Fig. 1). The ice area flux at the meridional and zonal flux gates is the integral of the product between the V and U drifts and ice concentration. In the following, ice area flux across Fram Strait is referred to as the sum of the meridional and zonal ice fluxes. A positive (negative) sign refers to an export out of (import into) the Arctic Ocean. Transport (flux) rates are given in $\text{km}^2\text{ day}^{-1}$ or month^{-1} . After removing the seasonal cycle, trends were calculated by linear regres-

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sion, and significance at the 95 % confidence level (p) was determined with Student's t test.

3 Results and discussion

3.1 Fram Strait sea ice thickness, source area and age

To investigate pathways and source areas of the surveyed ice, we used the location of the survey lines as starting points for the backtracking algorithm. Figure 2 shows the trajectories of ice surveyed in the area of interest between 2001 and 2012. The analysis shows that the largest fraction of the ice originated in the Laptev Sea. It took approximately two to three years of drift with the Transpolar Drift until the ice was exported through Fram Strait. In contrast, the ice surveyed in 2010 west of the 0° meridian mostly originated from the Beaufort Gyre.

The average age of ice covered by EM measurements is shown in Fig. 3 together with the average age of Fram Strait sea ice in summer (July–September) exiting through the meridional and zonal flux gates (compare red line in Fig. 1). Fram Strait ice age is decreasing at a rate of 0.6 years per decade. This result is significant at the 95 % confidence level. The average age of the surveyed ice between 2001 and 2012 is 2.56 years. The youngest ice was observed in 2012 (2.1 years), and the oldest ice was observed in 2004 (3.3 years). Note that the surveyed ice had a slightly higher mean ice age than all ice of Fram Strait combined. However, the differences are within the standard deviation (SE) and therefore in reasonable agreement.

Figure 4 summarizes EM thickness data obtained between 2001 and 2012. Owing to the rather limited number of campaigns and the snapshot character of the surveys a trend analysis of the time series may be of limited value. Nevertheless, given the overlapping study regions and seasons and the large lengths of surveys, the EM data provide evidence of a changing Fram Strait sea ice cover that stands out of the interannual variability. According to Fig. 4 the modal ice thickness has decreased over

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the past 11 years, with a distinct reduction in ice thickness after 2004, when the mode dropped by 36 % from 2.2 m (2004) to 1.4 m (2012). Similar to observations in 2007 at the North Pole by Haas et al. (2008), the interannual variability in modal thickness can be explained to some degree by different age compositions. For instance, the higher modal thickness in 2004 is likely the consequence of predominantly older ice (compare Fig. 3). However, there is no evidence of a change in age composition of surveyed ice towards younger ice that could explain the overall decline in ice thickness. In fact, the age of surveyed ice in 2010 and 2012 does not differ much from 2001, but the modal thickness is significantly lower. Therefore, we assume that the decline in modal thickness observed in Fram Strait rather reflects the thinning of second-year and multiyear ice in the Laptev Sea (source area) and Transpolar Drift than decreasing age. The decrease in modal thickness is accompanied by a decrease in ridged ice (fraction of ice thicker than 3 m). Note that in 2001 and 2004, the fraction of deformed ice is twice as high as in 2010, 2011 or 2012. Similar to the modal ice thickness, some of the interannual variability may be related to a varying age composition, but the overall decline is independent of ice age. Hence, the reduction of the deformed ice fraction points to a reduction in the deformation history in source areas and along pathways, mainly in the Laptev Sea and along the Transpolar Drift, which is in agreement with findings of Hansen et al. (2013). The shrinking tail of the ice thickness distribution as well as the decrease in modal ice thickness is also reflected in the mean thickness. Figure 4 shows that during the past 11 years the mean thickness dropped by 16 % from 2.58 m in 2001 to 2.17 m in 2012. A slight increase in mean thickness takes place after 2010. The increase is related to an increase in the fraction of deformed ice between 2010 and 2012.

The comparison of AEM and GEM based observations may introduce an additional uncertainty and must be limited to a comparable range of the thickness distribution. Although GEM data were obtained on a daily basis at representative locations along the ship track, the ground-based thickness surveys of 2001 are limited to large floes and predominantly level ice thick enough to walk on. In addition, the footprint of ground-

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with ULS and GEM based data is however difficult. In contrast to the AEM data, the ULS measurements consist of monthly averaged records obtained at single points located approximately 300 km further south. Nevertheless, despite the different locations the agreement between ULS and AEM data for August 2010 and 2011 and July 2012 is high. This indicates that a few but long AEM profiles provide representative information on ice thickness distribution even in areas of highly variable ice age and thickness composition such as Fram Strait. For the last three years, the agreement between AEM data and GEM measurements obtained by Renner et al. (2014) is high, too. Nevertheless, taking into account that GEM measurements by Renner et al. (2014) were obtained approximately 1 month later (September), one would expect the GEM thickness measurements to be lower than ULS and AEM data. According to Renner et al. (2014), the positive offset is likely related to absence of thin ice classes in the observations and preferential sampling of the survey sites.

3.3 Across and along strait thickness gradients

The thinning due to atmospheric and oceanographic processes on southward moving sea ice was investigated during two ice thickness surveys performed in downstream direction. Figure 6a shows AEM profiles that were made in 4 August 2011 and 21 July 2012. The first profile started at 81° N and covers a distance of 220 km (south to 79° N). According to aerial photos taken during the flight, the ice cover along the profile was rather homogenous with equally distributed leads. The high spatial variability in mean thickness makes an identification of a thickness gradient impossible. However, the modal thickness shows a continuous decrease of 0.19 m degree⁻¹ latitude. NCEP Reanalysis data of the past 10 weeks before the flight do not show any along strait gradient in air temperatures that could explain the thinning in downstream direction. Hence, we believe the decrease in modal thickness is associated with oceanographic processes: Mainly the presence of warm Atlantic water, leading to enhanced bottom melt between 79 and 81° N. In August, when the along strait decrease in ice thickness was sampled, ice motion was low. Using the backtracking approach as described

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seasonal cycle with lowest fluxes in July and August and highest export rates between December and March. During summer, flux rates are significantly lower and can become even negative, such that ice is being imported from southern Fram Strait. The pronounced seasonal cycle and much of the interannual variability of ice area export are associated with changes in SLP gradients across the gate, because gradients are generally lower during summer months and higher during winter. In addition, sea ice concentration in Fram Strait is lower during summer months, which leads to reduced export rates between July and September. Overall we find a positive trend in monthly Fram Strait area flux of $10.9 \times 10^3 \text{ km}^2 \text{ decade}^{-1}$. The trend is significant at the 99 % confidence level. Following Smedsrud et al. (2011) the increase in ice export is the consequence of a positive trend in the local pressure gradient, related to intensification of cyclones over the Nordic Seas. According to that study the sea ice area export has increased about 25 % larger since 1960s. The increase in ice export occurred mostly during winter and is directly connected to higher southward ice drift velocities, due to stronger geostrophic winds.

The area export for July, August and September accounts for only 6.2 % of the annual fluxes. The months with the lowest net contributions are July and August (1.4 %). Ice area export rates for both months are shown in Fig. 8 (blue and orange lines). The net sea ice export during July and August is positive, but estimates show considerable interannual variability with the highest rates occurring in August of 1994, 2006 and 2010 and lowest in 1981 and 1998. The average August ice area flux amounts to $4.3 \times 10^3 \text{ km}^2$ with a standard deviation (SE) of $19 \times 10^3 \text{ km}^2$. The average July ice flux is a bit lower ($3.8 \times 10^3 \text{ km}^2 \pm 13 \times 10^3 \text{ km}^2$). Note that there is a positive trend in the August and July ice export of 5.5×10^3 and $2.3 \times 10^3 \text{ km}^2 \text{ decade}^{-1}$, respectively. The trend is however not statistically significant.

The associated volume fluxes for the years where GEM/AEM measurements are available is calculated as the product of area flux and mean GEM/AEM thickness (Fig. 8). Note that for 2012, where AEM measurements were made one month earlier, area transport rates for July (blue line) were used. Given the low area export in July

and August, the volume transport is low, too. For the investigated months, the average volume export amounts to 17.77 km^3 ($\pm 34.45 \text{ km}^3$) with highest rates in August 2010 (64.83 km^3) and lowest in August 2001 (-15.97 km^3).

The reliability of volume flux depends as well upon the accuracy of sea ice motion information in summer as on the available thickness information. Following Sumata et al. (2014), ice motion information taken from passive microwave data suffer from a general underestimation of drift during summer months and a generally reduced accuracy in the narrow Fram Strait. Due to the lack of sea ice motion observations from drifting buoys, we compare our results with area flux estimates from Kloster and Sandven (2011) and Smedsrud et al. (2011) (Fig. 7, red and grey line). Area flux calculations of Kloster and Sandven (2011) are based on ice concentration data and manually derived ice motion information from ENVISAT SAR images. SAR WideSwath image pairs were captured three days apart with uninterrupted year-round coverage from February 2004 to December 2011. Estimates were made across 79° N , 15° W and 79° N , 5° E . Note that at 79° N Fram Strait is relatively narrow and therefore only a limited number of images are needed to cover the entire passage. According to the authors, the monthly mean export uncertainties amount to 5%. Smedsrud et al. (2011) used the pressure difference (NCEP/NCAR reanalysis data) between 79° N , 25° W and 79° N , 5° E together with SAR based flux estimates of Kloster and Sandven (2011) to estimate the linear regression between geostrophic winds, sea ice drift speed and ice area export. The linear relationship was then used to reconstruct ice area export based on pressure differences for the period between 1957 and 2010.

A direct comparison of our area flux estimates with the findings of Smedsrud et al. (2011) and Kloster and Sandven (2011) is difficult, because area flux estimates are based on different methods and were made at different latitude gates. Thus, we cannot quantify an absolute uncertainty associated with the volume estimates above. However, a comparison of our findings with area export estimates of others reveals that the trend in NSIDC export rates is much higher ($37.6 \text{ \% decade}^{-1}$ for the period 1980–2012) than the trend found by Kloster and Sandven (2011) ($22.2 \text{ \% decade}^{-1}$ for the

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period 2004–2011, compare Fig. 7) or the trend reported by Smedsrud et al. (2011) ($4.7\% \text{ decade}^{-1}$ for the period 1980–2010). A discussion on causes of differences in observed trends is beyond the scope of this manuscript. However, it is likely that large differences are at least partially related to unrealistically low NSIDC-based sea ice motion estimates before 1995. Nevertheless, despite large differences in observed trends the concordance between our findings and estimates of Kloster and Sandven (2011) and Smedsrud et al. (2011) gives us confidence in our results. The agreement in seasonal variability indicates that there is a relative consistency between area fluxes: The correlation coefficient (r) between NSIDC based estimates and computations of Smedsrud et al. (2011) is 0.79 and between NSIDC area flux and SAR-based estimates 0.80. The agreement between SAR-, and SLP-based export rates are of the same order ($r = 0.82$). A comparison of absolute fluxes for the periods where NSIDC, NCEP/NCAR reanalysis data and SAR-based estimates are available (2004–2010) shows that our estimates are approximately 18 and 20 % lower than estimates of Smedsrud et al. (2011) and Kloster and Sandven (2011). If the intercomparison is limited to summer months only (July–September), NSIDC based export rates are within the range of SAR-based estimates ($27 \times 10^3 \text{ km}^2$ vs. $28 \times 10^3 \text{ km}^2$), whereas computations based on pressure differences are higher ($53 \times 10^3 \text{ km}^2$).

4 Conclusions

We present an extensive data set of ground-based and airborne electromagnetic (EM) ice thickness measurements covering Fram Strait and the southern part of the Transpolar Drift in summer between 2001 and 2012. The data set adds to existing ice thickness information, with the addition of long transects that can only be obtained by fixed-wing aircrafts.

An investigation of pathways and source areas of surveyed sea ice shows that the largest fraction of ice has been formed in the Laptev Sea. The average age of ice covered by EM measurements is between 2.1 and 3.3 years. Keeping limitations of the

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rather short and irregular spaced time series in mind, the EM data provide evidence of a changing Fram Strait sea ice cover. As seen also in other, independent datasets, the observed decrease in modal thickness between 2001 and 2012 likely reflects a thinning of second-year and multiyear ice cover leaving the Arctic Basin through Fram Strait.

The decrease in modal thickness is accompanied by a decrease in mean thickness and fraction of ice thicker than 3 m.

The thinning effect of atmospheric and oceanographic processes on southward moving sea ice was investigated during two ice thickness surveys performed in downstream direction. A decrease in modal thickness of $0.19 \text{ m degree}^{-1}$ latitude south of 81° N is likely associated with the presence of recirculated warm Atlantic water, leading to enhanced bottom melt. Further north, the impact of warm water advection on the ice cover is negligible. Here, variability in ice thickness is more likely related to differences in age and deformation of ice.

Together with satellite based area flux estimates, we used our thickness measurements to calculate volume fluxes during summer months. Ice area flux estimates are performed using satellite based ice concentration and drift data. In agreement with Smedsrud et al. (2011) we find a significant positive trend in monthly Fram Strait area flux. The summer (July and August) ice export is low compared to the annual values. For the investigated months, the average volume export amounts to 17.77 km^3 ($\pm 34.45 \text{ km}^3$) with highest rates in August 2010 (64.83 km^3) and lowest in August 2001 (-15.97 km^3). Naturally, the volume flux estimates are limited to the period when airborne thickness surveys are available. Nevertheless, we could show that the combination of satellite data and airborne observations can be used to determine volume fluxes through Fram Strait and as such, be used to bridge the lack of satellite based sea ice thickness information in summer. Therefore, airborne thickness surveys in Fram Strait should be continued and extended in the future.

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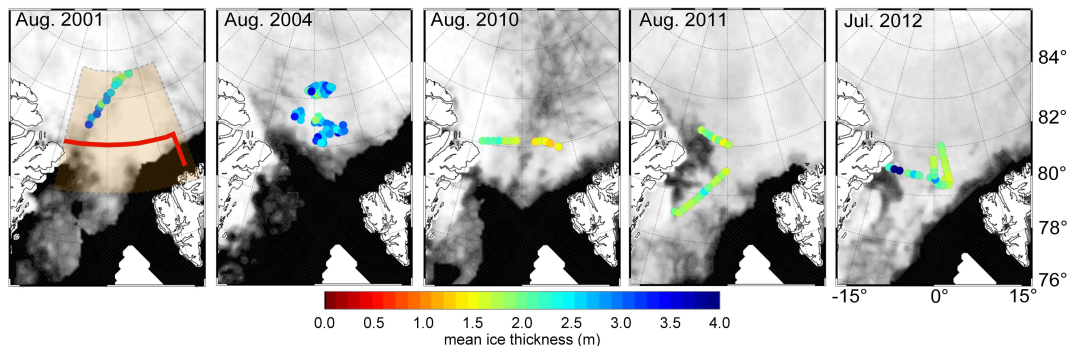


Figure 1. Overview of all EM ice thickness measurements obtained in the Fram Strait region during two cruises with the German ice-breaker RV *Polarstern* (August 2001 and 2004) and three surveys with the research aircraft *Polar-5* (August 2010 and 2011, July 2012). The color coding of the EM profiles corresponds to the mean ice thickness of 10 km sections. The light red shaded area marks the area of interest with the data acquisitions used in this analysis. Ice concentration at first flight of each campaign, is plotted in the background. The thick red line in the left panel indicates the meridional and zonal gates through which satellite derived ice area fluxes were calculated.

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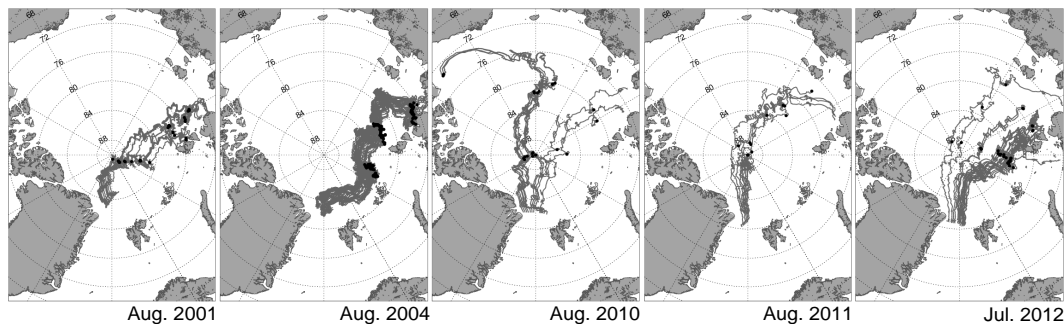


Figure 2. Backtracking of sampled sea ice using a combination of ice drift and concentration information. The start points of the trajectories (grey lines) are equivalent to the positions where EM measurements were obtained during the individual years. The black dots correspond to the position of particles on 21 September, when first-year ice becomes second-year ice, and second-year ice becomes multiyear ice.

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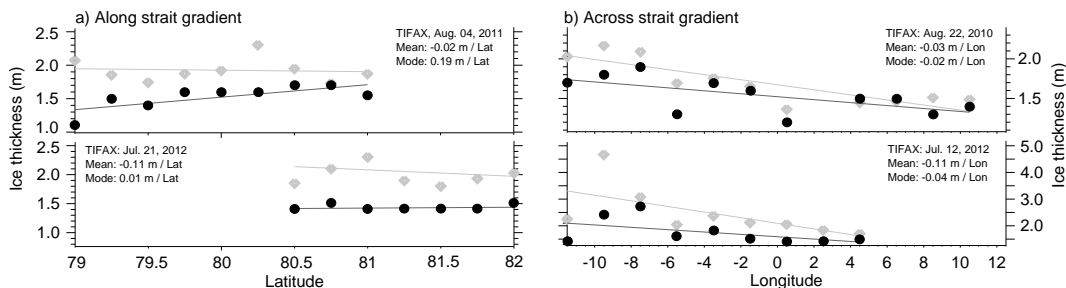


Figure 6. Across and along strait thickness gradient: **(a)** shows the along strait gradient in ice thickness (m) for flights made in August 2011 and 2012 between 10° W and 0° E. The across strait gradient as obtained from two flights in 2010 (at 81° N) and 2012 (at 82° N) is given in **(b)**. Grey rectangles correspond to the mean thickness, whereas black circles indicate modal thickness. The corresponding trend lines are plotted on top.

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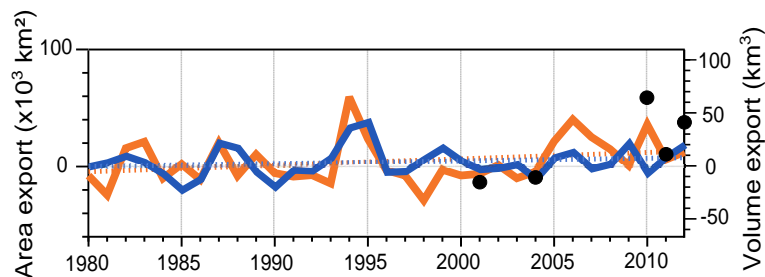


Figure 8. July (blue line) and August (orange line) ice area export across Fram Strait (given in $\times 10^3 \text{ km}^2$) calculated from NSIDC drift and concentration data. The associated volume flux for the years where AEM measurements are available is calculated as the product of NSIDC area flux estimates (August) and AEM mean thickness (black dots, given in km^3 , right axis). Note that for 2012, where AEM measurements were made one month earlier, area transport rates for July were used to number the corresponding volume flux.

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