Dear reviewer 1 and 2,

we very much appreciate your valuable and helpful comments, which significantly contributed to an improved manuscript.

Your main concerns were

A) **The assumption of a zero snow thickness in summer**
B) **Neglecting atmospheric processes contributing to the observed gradient in along strait ice thickness**
C) **Missing uncertainties for both, area and volume flux estimates.**

Following your suggestion, we

1) discard the "no snow cover" assumption. Unfortunately, during airborne EM surveys no snow measurements were made, except during the *Polarstern* cruise in 2001 and 2004, where a mean snow or weathered ice thickness of 0.07 - 0.1 m has been observed. Therefore, and due to the general snow climatology of Arctic sea ice where snow completely melts in June and July leaving the ice surface bare in August and September (Maykut et al. 1971, Warren et al. 1999), we assume a 0.1 m thick layer of weathered ice or snow to contribute to the total ice thickness. The unknown interannual variability of snow thickness we believe to be equivalent to the averaged snow thickness uncertainty on multiyear ice for July and August (+- 5.0 cm) provided by Warren et al. (1999). Please see comments and text changes provided below.
2) We now have a closer look at the atmospheric component by taking into account net shortwave- and longwave radiation differences between northern and southern end of the EM profile. Our findings show that atmospheric contribution to ice melt may be indeed larger than initially assumed. Based on new calculations, there is no indication of a presence of warm Atlantic water, leading to enhanced bottom melt between 79 and 81°N. However, there are still many uncertainties associated to this calculation. E.g. the net radiation estimates may not be very accurate. In addition, it seems that the transit time of sea ice is underestimated due to uncertainties in motion data. Please see comments and text changes provided below.
3) We agree that the manuscript would benefit from a better quantification of uncertainties associated to area and volume fluxes. Because there are no buoy data available that could be used for a proper validation, we fully rely on estimates made by others.

   In the manuscript, we now take into account uncertainty estimates for NSIDC motion data provided by Fowler et al. (2013) and error estimates that were recently published by Sumata, et al. (2015, "*Uncertainty of Arctic summer ice drift assessed by high-resolution SAR data", J. Geophys. Res., 120, 5285-5301*). Based on values provided by Sumata et al. 2015, we number area flux uncertainties for summer outflow. In addition, we provide error estimates for volume flux calculations taking into account the interannual variability of snow thickness provided by Warren et al. (1999).

Answers to all comments are provided below. Please note that

red text refers to comments made by reviewer 1 or 2

black text indicates the answer to comments

blue text provides revised text in manuscript

Again, thanks for all feedback!

Best regards

Thomas Krumpen and co-authors

Reply to comments made by reviewer 1:

5175:25 “The underestimation of peak pressure ridge thickness is a result of footprint smoothing, an effect that is mass-conserving for mean thickness values on kilometer scale.” Why? Or, provide a reference?

There are publications (see below) that compare airborne EM data to ULS draft data and the results shows that the two retrieval methods give reasonably consistent results. Thus, the local underestimations of the airborne EM method must be mass-conserving. A reference is now given in the manuscript. There are also 3D forward modeling results of the EM method over deformed sea ice available that support this hypothesis, but there results are so far unpublished.

Reference:

Andrew R. Mahoney, Hajo Eicken, Yasushi Fukamachi, H. Ohshima, D. Shimizu, Chandra Kambhamettu, R. MV, Stefan Hendricks, Joshua Jones: Taking a Look at Both Sides of the Ice: Comparison of Ice Thickness and Drift Speed as Observed from Moored, Airborne and Shore-Based Instruments Near Barrow, Alaska.. Annals of Glaciology 01/2015; 56(69):363-372. DOI:10.3189/2015AoG69A56

Lindsay, R. and Schweiger, A.: Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations, The Cryosphere, 9, 269-283, doi:10.5194/tc-9-269-2015, 2015.

5176:13: “. . . Note that before calculating mean and modal thickness from the pdf’s, ice thinner than 0.15 m was excluded from the analysis, as we categorize this thickness category as open water bin due to the 10 cm noise of the EM sensor. . .” Is this thresholding really necessary if the noise was normally distributed?

It is true that the noise is normally distributed and that averaging signal noise will amount to a thickness of zero. But the purpose of the thresholding is to exclude open water areas and thin ice from the calculation of mean thicknesses altogether. In the manuscript the sentence was simplified and linkage to the EM noise removed to avoid confusion.

5176:18 Why 25 km? How many samples in 25 km?

We chose 25 km to make gradient computations comparable to observations made by Hansen et al. The four mooring sites for ULS observations carried out by Hansen at 79° N are 20 to 30 km apart from each other. This is now mentioned in the text. 25 km contain approximately 7000 samples.

5176:22 I don't quite buy the assumption that the snow biases are negligible – especially in July and early August. And, it depends on where you are along the strait – certainly not true in the northern bits. Are there field records from the Polarstern cruises that you can turn to for support of your statement?

We agree that assuming the snow cover to be close to zero may not be valid for August. Unfortunately, no snow thickness measurements were made in 2004 or in parallel to the airborne campaigns that took place after 2004. During *Polarstern* cruise in 2001, 0.1 m of snow or weathered ice thickness was observed. Therefore, and due to the general snow climatology of Arctic sea ice where snow completely melts in June and July leaving the ice surface bare in August and September (Maykut et al. 1971, Warren et al. 1999), we now assume a 0.1 m thick layer of weathered ice or snow to contribute to the total ice thickness. The uncertainty in snow thickness (interannual variability in snow cover for July/August) is equivalent to the averaged snow thickness uncertainty on multiyear ice provided by Warren et al. 1999 (+- 5 cm). Note that the snow layer is now subtracted before volume flux calculations are made (indicated in the manuscript). The uncertainty of volume fluxes is the product of area flux uncertainties and mean ice thickness plus/minus the snow thickness uncertainty.

Revised section on snow cover: Since per definition EM ice thickness measurements include the snow layer, interannual changes in ice thickness may not be solely related to changes in ice thickness, but also to changes in snow cover. During the presented EM surveys no snow measurements were made, except during the *Polarstern* cruise in 2001 and 2004, where a mean snow or weathered ice thickness of 0.07 - 0.1 m has been observed. Therefore, and due to the general snow climatology of Arctic sea ice where snow completely melts in June and July leaving the ice surface bare in August and September (Maykut et al. 1971, Warren et al. 1999), we assume a 0.1 m thick layer of weathered ice or snow to contribute to the total ice thickness. This assumption is also supported by snow or weathered layer observations in Fram Strait during the months of August and September by Renner et al. (2014). Variations may be due to episodic, short lasting events of new snow accumulation which typically melt within a few days during July and August. Below we assume the unknown interannual variability of snow thickness to be equivalent to the averaged snow thickness uncertainty on multiyear ice for July and August (+- 5.0 cm) provided by Warren et al. (1999).

Section 2.2.2 To be complete – just state the motion uncertainty for each product.

We now state the uncertainties taken from Rozman et al. (2011) and Krumpen et al. (2013) for the CERSAT (< 1 cm s-1) motion product and from Fowler et al. (2013) and Sumata et al. (2015) for NSIDC based motion estimates (between 1 – 2 cm sec-1). Note that these estimates are used later on to number uncertainties of provided area and volume fluxes.

Text changes (NSIDC motion data description): 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). In addition NCEP/NCAR winds are used as an ice drift estimator (1 % of wind speed, 20° turning angle) when no other data is available, which can happen more often during summer months. A description of the data set and the sea ice motion retrieval algorithm can be found in Folwer et al. 2013. According to the authors, the uncertainty of the drift product is 1 cm sec-1. However, with the progress of summer melting season, the error increases. By using SAR based ice drift as a reference, Sumata et al. (2015) estimated the uncertainties to range from 1.0 to 2.0 cm sec-1 between May and July, depending on drift speed and ice concentration.

Text changes (CERSAT motion data description): Following Rozman et al. (2011) and Krumpen 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 (less than 1 cm sec-1).

Section 2.2.3 The trajectories are rather coarse, so it is highly unlikely that one is tracking a “specific” floe – more like an “assemblage” floes.

Correct. The term is misleading. The low resolution of the drift product will enable us to track areas only, not a specific floe. This was corrected.

5179:31 So, U and V are zonal and meridional ice motion?

Correct. This is now better described the manuscript.

5180:12: I assume any mention of age is ‘age’ from the NSIDC dataset?

Yes, sea ice age information was obtained from the drift-age model of Maslanik et al. (2011) using NSIDC drift and concentration data. We better describe this in the text and in caption of Figure 3.

Figure 3 Caption: How is ice age determined from EM measurements? Do you mean age of the ice covered by the EM measurements?

Sorry, it's of course "covered", not observed. Age information is taken Maslanik et al. (2011). A reference is now provided in the caption of Fig. 3.

Figure 4 Caption: It is really ice plus whatever residual snow that is on the ice, isn't it? Should really re-iterate that snow depth is assumed to be zero in the caption. Also, the legend of the figure should be in a box. Otherwise, they look like data on the plot. It would also help to refer the reader to the locations in Fig. 1.

Yes, EM-thickness is ice thickness plus snow thickness. We now provide the definition of EM-ice thickness in the caption of Fig. 4 and 5 and the thickness of the snow layer. Note that the legend of the figure 4 was moved to a box and a reference to Fig. 1 was made. In addition, we now provide standard deviation for mean values. Please also see answer to your comment on snow thickness (5176:22)

Figure 5 and 6. It would be useful to plot, along with the mean, the standard deviation of the thickness estimates.

We agree. The standard deviation was added to Figure 6. However, instead of adding it to Figure 5, we decided to provide standard deviation in Figure 4, when thickness results are presented for the first time.

5184:1 80 days (between 81 to 79N) translate into less than 2 km/day or ~ 2 cm/s. It seems slow given the current moves faster than several cm/s. In fact, you should be able to find the surface current in other publications (perhaps a citation is in order).

The ice traveled a distance of almost 330 km (starting at 0°E and ending at 10°W; note that the EM-profile length is 290 km. Accidentally we wrote 220 km in the manuscript). Hence, the resultant ice drift is 4.8 cm sec-1. Taking into account that currents (reference is now provided in the text) contributes with almost 4.6 cm sec-1 to ice export, the velocity is indeed low. This points to an underestimation of transit time due to uncertainties in NSIDC motion information. Changes in the text were made accordingly. Please see also answer to next comment.

5184:2 You're assuming all that ocean heat goes to melting the ice? How about surface melt? Is there no surface melt in the Fram Strait?

We agree. Just looking at surface temperature may be indeed too simple. We now take into account net shortwave- and longwave radiation differences between northern and southern end of the profile. We found a difference of almost 12 Wm-2 which is close to the 16 Wm-2 that would be required to melt 38 cm of ice. Hence, there is no indication of a presence of warm Atlantic water, leading to enhanced bottom melt between 79 and 81°N. There are still many uncertainties associated to this calculation. E.g. the net radiation based on NCEP data might not be very accurate. In addition, it seems that the transit time of sea ice is underestimated due to uncertainties in motion data.

In the modified Section we better discuss impact of ocean and atmosphere on the observed gradient and weaken the conclusion we have drawn. Note that key sentences in the Abstract and Conclusion Section were adapted:

Revised along Strait gradient section: According to aerial photos taken during the flight, the ice cover was rather homogenous. Likewise, there is no gradient in ice concentration along the profile or changes in the frequency of open water occurrence. 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. The decrease in modal thickness is likely associated with oceanographic and atmospheric processes acting on the pack ice while drifting south: Differences in net short- and longwave radiation between 79 and 81°N and the presence of warm Atlantic water may lead to enhanced surface and bottom melt that could explain the observed gradient. A thinning of 0.38 m implies a heat flux of 16 Wm-2. Using the backtracking approach as described in Sect. 2.2.3, we estimated the transit time of sea ice between 81°N, 0°E and 79°N, 10°W to be around 80 days with an average ice drift velocity of 4.8 cm sec-1. The difference in net short- and longwave radiation between norther and southern end of the thickness profile amounts to 12 Wm-2 over 80 days (source: NCEP Reanalysis data). Consequently, the ocean contributes with 4 Wm-2 to sea ice melt, which is clearly within the range of observed ocean heat fluxes in the Arctic Basin (2-5 Wm-2, Fer et al. 2009), but lower than observed ocean heat flux in Fram Strait area (Sirevaag et al., 2009). Hence, there is little indication of a presence of warm Atlantic water, impacting enhanced bottom melt between 79 and 81°N. However, calculations may suffer from uncertainties in net short- and longwave radiation obtained from reanalysis data. In addition, we found the ice drift velocity taken from satellite motion information (4.8 cm sec-1) to be lower than ice drift velocity calculated based on geostrophic winds plus the contribution of the steady southwards flowing current below the sea ice. The average geostrophic wind velocity obtained from NCEP reanalysis data amounts to 2.6 m sec-1 between May 16 and August 4. This is equivalent to an ice drift of 3.6 cm sec-1, assuming the southward directed ice drift velocity to be 1.4 % of the geostrophic wind speed in Fram Strait (Smedsrud et al. 2011). According to the authors and observations made by Widdel et al. (2003), underlying currents contribute with additional 4.6 cm sec-1 to ice export out of Fram Strait. Hence, there is indication that transit time may be underestimated due uncertainties associated to

NSDIC motion information, which would result in an overestimation of atmospheric processes contributing to sea ice melt.

5185:9 It is difficult separate, in general, age and melt in this case. So, this is rather speculative.

Sentence was removed. Note that changes were made in Abstract and Conclusion section too. See also answer to comment P5184, L 10-13 by reviewer 2.

5187:7 Are there no drifting buoys in the area for the entire period?

There are a few buoys that left Fram Strait during summer month. However, the buoys provided via IABP are assimilated into the NSDIC motion product. Hence, they can't be used for validation, but we made this clearer in the manuscript. With respect to uncertainty of the NSIDC drift product we know refer to the study of Sumata et al. (2015). The authors compared different summer drift products based on passive microwave sensors to SAR based ice drift information (compare answer to 5187:24 and modified discussion on flux estimate uncertainties)

5187:24 The question is: what are the uncertainties of the SAR estimates and the NSIDC estimates of ice motion. Saying that it is difficult because of different methodology and different latitudes is a cop out. Why are the NSIDC-based sea ice motion estimates unrealistically low before 1995? Please provide a reference.

We agree that the manuscript would benefit from a better quantification of uncertainties associated to area and volume fluxes. Because there are no buoy data available that could be used for a proper validation, we fully rely on estimates made by others.

In the manuscript, we now take into account uncertainty estimates for NSIDC motion data provided by Fowler et al. (2013) and error estimates that were recently published by Sumata, et al. (2015, "*Uncertainty of Arctic summer ice drift assessed by high-resolution SAR data*", J. Geophys. Res., 120, 5285-5301). The authors investigate error statistics of two low resolution Eulerian ice drift products (NSIDC and a product provided by Kimura et al.) through a comparison with SAR derived ice drift. The accuracy of the SAR derived ice drift trajectories relative to buoy data is 320 m. The estimated uncertainty maps for the low resolution drift products show that the uncertainty of NSIDC motion estimates is increasing with the progress of summer melt. Between May and July, the uncertainties range from 1.0 to 2.0 cm sec-1, depending on sea ice concentration and drift speed.

Assuming the ice drift uncertainty to be around 1 cm sec-1 between October and April (Fowler et al. 2013) and between 1.0 and 2.0 cm sec-1 between May and September depending on sea ice concentration and drift speed (Sumata et al. 2015), we calculated errors associated to monthly area flux estimates. Based on the obtained area flux uncertainty, we also provide a volume flux uncertainty.

Following changes were made in the manuscript:

- Based on Fowler et al. 2013 and Sumata et al. 2015, we provide uncertainty estimates for monthly area fluxes. The uncertainties are introduced in chapter 2.2.2: Sea ice drift. See our answer to comment on your section 2.2.2
- How uncertainties are calculated is now explained in chapter 2.2.5: Ice area flux across Fram Strait: The corresponding uncertainties are calculated as the integral of the product between NSIDC drift uncertainties provided by Fowler et al. (2013) and Sumata et al. (2015) and ice concentration. Following Fowler et al. (2013), we assume the uncertainty of ice drift velocity to be within the range of 1.0 cm sec-1 during winter months (October – April). During summer months (May-September), uncertainty estimates provided by Sumata et al. (2015) are applied ranging from 1.0 – 2.0 cm sec-1, depending on ice drift velocity and ice concentration.
- Uncertainty estimates were added to Fig. 7 and 8. and are discussed in chapter 3.4: Summer sea ice area and volume flux
- In addition, we now provide in chapter 3.4 uncertainties for volume fluxes: The uncertainty is the product of area flux uncertainties and mean ice thickness.

  …and improved volume flux discussion….:

  The reliability of volume flux depends as well on the accuracy of sea ice motion information in summer as on the available ice and snow thickness information. Assuming that the sea ice thickness pdf's are accurate, and uncertainties related to interannual variability in snow cover are small (+- 5 cm), the biggest error in volume flux estimates arises from sea ice motion information.

  Due to the lack of sea ice motion observations obtained from drifting buoys in Fram Strait during summer months, we cannot evaluate the uncertainty of satellite-based sea ice motion information directly. Nevertheless, recent studies of Sumata et al. (2014) and Sumata et al. (2015) indicate that NSIDC ice motion information suffer from a general underestimation of drift during summer months and a generally reduced accuracy in the narrow Fram Strait. In particular, low drift velocities and ice concentration result in errors of up to 2.0 cm,sec-1. In this study we apply the uncertainty estimates provided by Sumata et al. (2015) for different drift speeds and ice concentration to evaluate reliability of our flux calculations. As an additional quality control we compare our results with area flux estimates from Kloster et al. (2011) and Smedsrud et al. (2011)….

- We cannot justify our statement that NSIDC-based sea ice motion estimates are unrealistically low before 1995. Therefore, the sentence was excluded.
- Following sentence was added to conclusion: 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. Because differences in model based sea ice volume fluxes across Fram Strait (Koenigk et al., 2008) are clearly larger than uncertainty associated to the combined use of satellite- and airborne estimates, our results are of practical use for model validation.

5188:20 I would dispute the use of the word “extensive”.

Removed in abstract, introduction and conclusion.

5189:6 Could you see in the data any localization of the thinner ice due to melt? Otherwise this is rather speculative.

We don’t quite understand the comment. In line 5189:5–6 we describe changes in mean thickness and fraction of ice thicker than 3 m. The pattern is somewhat similar to the observed changes in modal thickness. Nevertheless, we do not state that this is connected, although, to some extent, the shrinking tail of the ice thickness distribution as well as the decrease in modal ice thickness is certainly reflected in the mean thickness.

Reply to comments made by reviewer 2:

P5172, L 8: "…and the estimated age …" sentence needs to be rephrased.

Thanks. Sentence is indeed a little bit confusing. It was changed to:

The primary source of the surveyed sea ice leaving Fram Strait is the Laptev Sea and its age has decreased from 3 to 2 years between 1990 and 2012. The thickness data consistently also show a general thinning of sea ice 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.

P5172, L 9: "thinning" … of sea ice.

Thanks, changed….

P5172, L 13: "decrease" ... of what specifically?

…of sea ice thickness. Thanks for the hint. Corrected.

P5172, L 24: remove "annual"

Thanks, removed

P5176, L 3-4: It is not quite clear here, in how far the thickness pdf allows to draw conclusions about the boundary conditions of ice formation. What is meant by "boundary conditions"?

Boundary conditions refers to the dynamic and thermodynamic conditions during the ice formation. We agree that the term "boundary condition" alone is not very descriptive. Since we do not really look at processes during ice formation, we decided to skip the sentence completely.

P5176, L 23: I think the Warren et al. (1999) reference is not suitable for this statement.

See answer to next comment. We improved discussion on the absence of a snow cover and provide additional references.

P5176, L 25: I think that the "snow bias" deserves a more detailed discussion. How was the snow treated in the ground-based measurements? Were coincident snow thickness measurements conducted? Does aerial photography from the AEM measurements support the statement ". . .led to a significantly reduced snow cover or no snow cover at all."?

We agree that assuming the snow cover to be close to zero may not be valid for August. Unfortunately, no snow thickness measurements were made in 2004 or in parallel to the airborne campaigns that took place after 2004. During *Polarstern* cruise in 2001, 0.1 m of snow or weathered ice thickness was observed. Therefore, and due to the general snow climatology of Arctic sea ice where snow completely melts in June and July leaving the ice surface bare in August and September (Maykut et al. 1971, Warren et al. 1999), we now assume a 0.1 m thick layer of weathered ice or snow to contribute to the total ice thickness. The uncertainty in snow thickness (interannual variability in snow cover for July/August) is equivalent to the averaged snow thickness uncertainty on multiyear ice provided by Warren et al. 1999 (+- 5 cm). Note that the snow layer is now subtracted before volume flux calculations are made (indicated in the manuscript). The uncertainty of volume fluxes is the product of area flux uncertainties and mean ice thickness plus the snow thickness uncertainty.

Revised section on snow cover: Since per definition EM ice thickness measurements include the snow layer, interannual changes in ice thickness may not be solely related to changes in ice thickness, but also to changes in snow cover. During the presented EM surveys no snow measurements were made, except during the *Polarstern* cruise in 2001, where a mean snow or weathered ice thickness of 0.1 m has been observed. Therefore, and due to the general snow climatology of Arctic sea ice where snow completely melts in June and July leaving the ice surface bare in August and September (Maykut et al. 1971, Warren et al. 1999), we assume a 0.1 m thick layer of weathered ice or snow to contribute to the total ice thickness. This assumption is also supported by snow or weathered layer observations in Fram Strait during the months of August and September by Renner et al. (2014). Variations may be due to episodic, short lasting events of new snow accumulation which typically melt within a few days during July and August. Below we assume the unknown interannual variability of snow thickness to be equivalent to the averaged snow thickness uncertainty on multiyear ice for July and August (+- 5.0 cm) provided by Warren et al. (1999).

P5177, L 9: "interpretation" … I guess you mean "interpretation in a larger spatial context"?

Yes. We are using your formulation now: "The interpretation of EM thickness measurements in a larger spatial context…"

P5178, L 12-26: Please state more clearly why it is necessary to complement your preferred sea-ice drift data set (CERSAT) with the NSIDC data set. Does this approach raise inconsistency that is potentially problematic?

The CERSAT drift product is available between September and May only. Consequently, we need a bridge dataset for summer months (NSIDC). We make this clearer in the data description. The inconsistency is of course hard to estimate. However, we now provide uncertainties for the different products. The uncertainty for CERSAT product is thereby lower than for NSIDC motion data:

Revised drift data description: In this study, two different sets of ice drift products were used: The first data set, Polar Pathfinder Sea Ice Motion Vectors (Version 2), was chosen because of its 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 second dataset, sea ice motion provided by the Center for Satellite Exploitation and Research (CERSAT) at the Institut Francais de Recherche pour d'Exploitation de la Mer (IFREMER), shows a good performance on the Siberian shelf and was therefore used to complement the calculation of ice drift trajectories between September and May.

The Polar Pathfinder Sea Ice Motion 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, 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). In addition NCEP/NCAR winds are used as an ice drift estimator (1 % of wind speed, 20° turning angle) when no other data is available, which can happen more often during summer months. Adescription of the data set and the sea ice motion retrieval algorithm can be found in Folwer et al. 2013. According to the authors, the uncertainty of the drift product is 1 cm sec-1. However, with the progress of summer melting season, the error increases. By using SAR based ice drift as a reference, Sumata et al. (2015) estimated the uncertainties to range from 1.0 to 2.0 cm sec-1 between May and July, depending on drift speed and ice concentration.

In addition to NSIDC drift data, the tracking routine as described in Sect. 2.2.3 makes use of CERSAT motion estimates. Since a substantial part of Fram Strait sea ice originates from the Laptev Sea (Rigor et al.,1997), the calculation of drift trajectories requires a drift data set with good performance on the Siberian shelf. Following Rozman et al. (2011) and Krumpen 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 (less than 1 cm sec-1). 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 (Girard-Ardhuin et al., 2012). 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).

P5179, L 6: "… assumed to be melted". Since your following the ice backwards I guess you assume that it rather formed when before the <= 15% constraint applies?

Sorry, yes. “Melted” would apply if we would track forward. But even the term “formed” may be misleading here since we do not know for sure if an ice parcel was formed. We now state that we consider ice parcels to be lost when ice concentration is lower than 15 %:

… (a) the ice reaches a position next to a coastline, (b) the ice concentration at a specific location reaches a threshold value of (<= 15%) when ice parcels are considered lost, or (c) the tracking time exceeds four years.

P5181, L 17: “ … reduction in the deformation history” … needs to be explained in more detail.

The growth and decay of ridged ice is controlled by a number of factors acting on the ice along its way to the Fram Strait. This is nicely described and discussed by Hansen et al. (2013). First, it is likely that the loss of perennial ice and associated decrease in ice age contributes to a decrease in deformed ice, since younger ice likely contains less consolidated pressure ridges. In addition, temporal changes in wind stress (frequency of storms, etc.), sea ice thickness and availability of thin ice could affect deformation. Another important factor that could explain observed decrease in deformation is ocean heat, since melt rate is thickness dependent: A small increase in available heat affects ridges much more than surrounding level ice (Amundrud et al., 2006). It is likely that there is more heat made available since sea ice extent is decreasing and ice velocity accelerates leading to higher lead fractions. Additional heat is made available through pulses of warm Atlantic water entering the Fram Strait. It is however difficult to link changes in thickness with changing ocean heat directly. Nevertheless, because of thickness dependent melt rates it is likely that a decrease in deformation is much more reflected in deformed ice than in level ice.

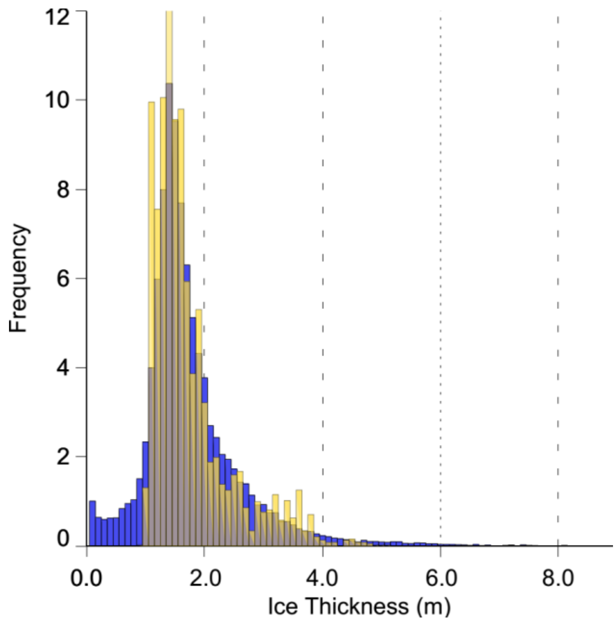
Revised section: Hence, the reduction of the deformed ice fraction points to a reduction in the deformation history in source areas and along pathways, mainly in the Laptev Sea and along the Transpolar Drift, which is in agreement with findings of Hansen et al. (2013). Following the authors, the decrease can be associated to changes in wind stress or a loss in perennial ice (decrease in ice age), since younger ice likely contains less consolidated pressure ridges. Another important factor that could explain observed decrease in deformation is ocean heat, since melt rate is thickness dependent and an increase in ocean heat affects ridges much more than surrounding level ice. The decrease in ice extent (Meier et al. 2014), and the speed up of ice drift along the pathways with the associated increase in lead fraction (Rampal et al. 2009) leads to an increased heat uptake which could in turn result in enhanced melt of deformed ice.

P5182, L 10-12: This statement needs some more explanation. For the reader it would be interesting to see the thickness PDFs for GEM and AEM, respectively.

Instead of referring to a dataset that is not shown in the manuscript, we now provide a reference to two publications that discuss comparability of both methods (see Fig. 3, Haas et al. 2006 and Haas et al. 2008).

The section was modified as follows: 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-based measurements is smaller than the footprint of airborne surveys which reduces footprint smoothing of pressure ridges. However, thickness distributions obtained by both methods in the same region have very similar shapes and modes (e.g. Haas et al. 2006, Haas et al. 2008), their Fig. 3), warranting their combination for this study. To further ensure compatibility with the AEM thicknesses, the GEM data have been regridded to the sampling interval of the airborne data and ice thinner than 0.15 m and open water has been excluded from the analysis of the AEM measurements. For our study we assume that mean thicknesses obtained with both method are comparable as well. We base this assumption on the high number of available GEM surveys and the general exclusion of thin ice thicknesses from the AEM data, which will be vastly underrepresented in the GEM data.

The Figure below shows a comparison of AEM and GEM thickness pdfs that were obtained last summer (June) north of Spitzbergen during the *Polarstern* cruise PS92. GEM measurements (shown in yellow) were made on June 18 on a large floe covering a distance of several kilometers. The AEM data (blue) were obtained during 3 flights two days before and after the GEM survey. The modal thickness of AEM measurements is equivalent to the GEM derived modal thickness (in this example = 1.4 m). The mean thickness differs slightly (1.8 m for AEM and 1.7 m for GEM).



P5183, L 20: What exactly do you mean by "equally distributed leads". Is it that the along-gradient floe size distribution can be assumed constant?

We refer to the frequency of open water/lead occurrence along the flight. It is not connected to floe size distribution, which we did not look at. Note that we could not find any gradient in ice concentration either. Please see revised text provided in answer to your next comment.

P5183, L 24: "air temperature is not the only driver for surface melt, gradients in short and longwave radiation might have an influence, especially if also gradients in the surface albedo are potentially present.

We agree. Just looking at surface temperature may be indeed too simple. We now take into account net shortwave- and longwave radiation differences between northern and southern end of the profile. We found a difference of almost 12 Wm-2 which is close to the 16 Wm-2 that would be required to melt 38 cm of ice. Hence, there is no indication of a presence of warm Atlantic water, leading to enhanced bottom melt between 79 and 81°N. There are still many uncertainties associated to this calculation. E.g. the net radiation based on NCEP data might not be very accurate. In addition, it seems that the transit time of sea ice is underestimated due to uncertainties in motion data.

In the modified Section we better discuss impact of ocean and atmosphere on the observed gradient and weaken the conclusion we have drawn. Note that key sentences in the Abstract and Conclusion Section were adapted:

Revised along Strait gradient section: According to aerial photos taken during the flight, the ice cover was rather homogenous. Likewise, there is no gradient in ice concentration along the profile or changes in the frequency of open water occurrence. 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. The decrease in modal thickness is likely associated with oceanographic and atmospheric processes acting on the pack ice while drifting south: Differences in net short- and longwave radiation between 79 and 81°N and the presence of warm Atlantic water may lead to enhanced surface and bottom melt that could explain the observed gradient. A thinning of 0.38 m implies a heat flux of 16 Wm-2. Using the backtracking approach as described in Sect. 2.2.3, we estimated the transit time of sea ice between 81°N, 0°E and 79°N, 10°W to be around 80 days with an average ice drift velocity of 4.8 cm sec-1. The difference in net short- and longwave radiation between norther and southern end of the thickness profile amounts to 12 Wm-2 over 80 days (source: NCEP Reanalysis data). Consequently, the ocean contributes with 4 Wm-2 to sea ice melt, which is clearly within the range of observed ocean heat fluxes in the Arctic Basin (2-5 Wm-2, Fer et al. 2009), but lower than observed ocean heat flux in Fram Strait area (Sirevaag et al., 2009). Hence, there is little indication of a presence of warm Atlantic water, impacting enhanced bottom melt between 79 and 81°N. However, calculations may suffer from uncertainties in net short- and longwave radiation obtained from reanalysis data. In addition, we found that the ice drift velocity of 4.8 cm sec-1 taken from satellite motion information to be lower than ice drift velocity calculated based on geostrophic winds plus the contribution of the steady southwards flowing current below the sea ice. The average geostrophic wind velocity obtained from NCEP reanalysis data amounts to 2.6 m sec-1 between May 16 and August 4. This is equivalent to an ice drift of 3.6 cm sec-1, assuming the southward directed ice drift velocity to be 1.4 % of the geostrophic wind speed in Fram Strait (Smedsrud et al. 2011). According to those authors and observations made by Widdel et al. (2003), underlying currents contribute with additional 4.6 cm sec-1 to ice export out of Fram Strait. Hence, there is indication that transit time may be underestimated due uncertainties associated to NSDIC motion information, which would result in an overestimation of atmospheric processes contributing to sea ice melt.

P5184, L 10-13: I think this is a rather strong statement given that this observation is still a snapshot, even if the profile is 170 km long.

Statement was weaken and the Marnela et al. reference removed. Revised text: The absence of a gradient in modal thickness indicates that enhanced bottom or surface melt due to atmospheric or oceanographic processes is limited to areas south of 80°N.

P5188, L 3: replace “trends in” by “trends is”.

Thanks

P5173, L 3: Is there also a reference for “a decrease of net ice growth rates”?

We now refer to Holland et al. (2010): The sea ice mass budget of the Arctic and its future change as simulated by coupled climate models, Climate Dynamics, 2010, 34, pp. 185 – 200, doi: 0.1007/s00382-008-0493-4

P5174, L 1: "intraannual" ... do you mean seasonal?

Yes. We replaced "intraanuual" by "seasonal".

Assuming that the sea-ice thickness PDFs are quite accurate, the flux estimates will still be very sensitive to uncertainties in sea-ice concentration. Especially an increase in areas with very thin ice - maybe associated with an increased lead fraction or a change in floe size distribution in Fram Strait – could introduce a bias that is promoted by the cut-off value for thin-ice thickness values that is applied here, potentially amplified by the fact that the PMW sea-ice concentrations might be too coarse to resolve these changes. This point merits some additional discussion in the context of volume flux estimates.

The frequency of thin ice classes (> 0.15 m ice thickness) is less than 1 % in sea ice thickness PDFs of the individual flights. Also we cannot see a change in thin ice fraction associated to an increased lead fraction over time. Note that the occurrence of thin ice with less than 15 cm may be also related to a smoothing effect near the edge of floes (50 m footprint of the EM-Bird) and not so much to the occurrence of refrozen leads (which would be unusual at the end of July anyway). But we do agree that flux estimates, both, area and volume, would benefit from uncertainty estimates. We do believe that uncertainties of motion estimates are the largest source of errors associated to area and volume flux estimates. Reviewer 1 asked us to better quantify these uncertainties. In the manuscript, we now take into account uncertainties estimates for NSIDC motion data provided by Fowler et al. (2013) and error estimates that were recently published by Sumata, et al. (2015, "*Uncertainty of Arctic summer ice drift assessed by high-resolution SAR data*", J. Geophys. Res., 120, 5285-5301). The authors investigate error statistics of two low resolution Eulerian ice drift products (NSIDC and a product provided by Kimura et al.) through a comparison with SAR derived ice drift. The estimated uncertainty maps for the low resolution drift products shows that the uncertainty of NSIDC motion estimates is increasing with the progress of summer melt. Between May and July, the uncertainties range from 1.0 to 2.0 cm sec-1, depending on sea ice concentration and drift speed.

Assuming the ice drift uncertainty to be around 1 cm sec-1 between October and April (Fowler et al. 2013) and between 1.0 and 2.0 cm sec-1 between May and September depending on sea ice concentration and drift speed (Sumata et al. 2015), we calculated errors associated to monthly area flux estimates. Based on the obtained area flux uncertainty, we also calculated a volume flux uncertainty. Changes that were made in the manuscript are listed in the answer 5187:24 (Reviewer 1).

Figure 4: It is quite hard to distinguish symbols in the legend from data points. The reader might think that it is data points for the year of 2009 (at least in my printout).

The legend was moved to a box. Note that we also provide standard deviation for mean thickness in Figure 4.

Figure 7: What is the difference between gray and black curves?

Added to Figure caption: The blue (formerly black) and red (formerly grey) line indicate monthly sea ice area transports across 79°N, 15°W and 79°N, 5°E based on SAR images (Kloster et al., 2011) and based on SLP gradients (Smedsrud et al., 2011).

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Recent summer sea ice thickness surveys in ~~the~~ Fram Strait and associated ice 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~~ A data set of ground-based and airborne electromagnetic ice thickness measurements collected during summer 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~~ primary source of the surveyed sea ice leaving Fram Strait is the Laptev Sea ~~, and the estimated age is consistent with a~~ and its age has decreased from 3 to 2 years between 1990 and 2012. The thickness data consistently also show a general thinning of sea ice 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 in sea ice thickness of 0.19 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~~ While satellite data show that monthly ice area export had positive trends since ~~2001, the mean fluxes during~~ 1980 (10.9×10^3 km^2 decade^{-1}), the summer (July and August) ~~are small (18~~ice area export is low with high uncertainties. The average volume export amounts to 16.78 ~~km^3), and long-term trends are uncertain due to the limited surveys available.~~ 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.

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~~ a rate of approximately 12.7 % decade^{-1} over the satellite record (Meier et al., 2014; Comiso and Hall, 2014, 1978–present) and its mean thickness has decreased by $0.58 \pm 0.07\,\mathrm{m\,decade}^{-1}$ over the period 2000–2012 (Lindsay and Schweiger, 2015). The thinning of sea ice is accompanied by an increase of ice drift velocity (Spreen et al., 2011), deformation (Rampal et al., 2009; Martin et al., 2014) and a decrease of net ice growth rates (Hollands, 2010) . 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. These strongly impact ocean processes further south.

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~~ a 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 ice in the west to thinner ice in the east. The high interannual and ~~intraannual~~ seasonal 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~~ EM measurements together with satellite based area flux estimates to calculate volume outflows for the periods when thickness surveys where 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 the Fram Strait region for eleven, one month long ICESat ~~observations~~ observation 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 estimates shall improve the understanding of interannual variability in summer sea ice outflow and complement existing winter volume flux calculations.

2 Data

2.1 EM ice thickness measurements

EM ice thickness measurements utilize the contrast of electrical conductivity between sea water and sea ice to determine the distance of the instrument to the ice–water interface (Haas et al., 2009). In 2001 during the RV *Polarstern* cruise (ARK-XVII/2), only ground-based EM (GEM) data were obtained using an instrument (Geonics EM31Mk2) pulled on a sledge across the ice (Haas, 2004). With GEM measurements, the distance to the ice–water interface corresponds to the ice plus snow thickness (hereafter referred to as EM ice thickness). After 2001, measurements were made with an airborne EM (AEM) system towed 12 to 20 m above the ice surface. Here, the distance to the uppermost snow surface is determined with a laser altimeter. The ice plus snow thickness is then calculated as the difference between the laser and EM derived distance (Haas et al., 2009). In 2004, AEM measurements were conducted with a helicopter operated from RV *Polarstern* (cruise ARK-XX/2) along triangular flight tracks with a side length of 40 to 80 km (Haas et al., 2008). In 2010, 2011 and 2012 AEM surveys were conducted with the *Polar 5* aircraft during the TIFAX (Thick Ice Feeding Arctic Export) campaigns operating from the Danish Station Nord in Nord-East Greenland (Haas et al., 2010). These airplane surveys allow the acquisition of hundreds of kilometers of data along straight flight lines. An overview of the flight tracks surveyed during the individual field campaigns is given in Fig. 1.

The accuracy of the EM measurements is on the order of ±0.1 m over level sea ice (Pfaffling et al., 2007). However the maximum thickness of pressure ridges can be underestimated by as much as 50 %. The underestimation of peak pressure ridge thickness is a result of footprint smoothing, an effect that is mass-conserving for mean thickness values on kilometer scale ~~. Thus, mean ice thickness values from AEM data are in general agreement with other sources (Lindsay and Schweiger, 2015) , such as ULS, though the probability density function (pdf) may differ slightly (Mahoney et al., 2014) . Still, the AEM thickness pdf enables us to determine the general thermodynamic and dynamic boundary conditions of ice formation (Thorndike et al., 1975; **?**) .~~ (Lindsay and Schweiger, 2015; Mahoney et al., 2014) . The thickness pdf's for all profiles presented in this paper were calculated from histograms with a bin width of 0.1 m. The most frequently occurring ice thickness, the mode of the distribution, represents level ice thickness and is the result of winter accretion and summer ablation. Because ridge thicknesses are in general underestimated in AEM data, the mode is most representative ~~for~~ of the ice thickness pdf. The fraction of dynamically deformed ice is represented by the length and the shape of the tail of the thickness distribution. In this study, the fraction of ice thicker than 3 m is used to give a relative estimate of the amount of deformed ice. The mean thickness is used to quantify the overall decline in sea ice thickness. Note that before calculating mean and modal thickness from the pdf's, ~~ice thinner~~ thin ice (less than 0.15 m~~was~~) and open water were excluded from the analysis~~, as we categorize this thickness category as open water bin due to the 10noise of the EM sensor~~. For the investigation of across and along Fram Strait thickness gradients, pdf's, mean and mode were calculated over a 25 km distance for meridional profiles (along Fram Strait) and zonal profiles (across Fram Strait). The distance is equivalent to the spacing between ULS observations of Hansen et al. (2013) at 79° N.

Since per definition EM ice thickness measurements include the snow layer, interannual changes in ice thickness may not be solely related to changes in ice thickness, but also to changes in snow cover. ~~However, even though snow thickness during EM surveys may not have been at its minimum, we believe that temperatures above freezing had certainly~~

~~led to a significantly reduced snow cover or no snow cover at all (Warren et al., 1999) . Hence,~~ During the presented EM surveys no snow measurements were made, except during the Polarstern cruises in 2001 and 2004, where a mean snow or weathered ice thickness of $0.07-0.1$ m has been observed. Therefore, and due to the general snow climatology of Arctic sea ice where snow completely melts in June and July leaving the ice surface bare in August and September (Maykut, 1971; Warren et al., 1999) , we assume a 0.1 m thick layer of weathered ice or snow to contribute to the total ice thickness. This assumption is also supported by snow or weathered layer observations in Fram Strait during the months of August and September by Renner et al. (2014) . Variations may be due to episodic, short lasting events of new snow accumulation which typically melt within a few days during July and August. Below we assume the ~~bias that arises from the unknown~~ unknown interannual variability of snow thickness to be ~~negligible~~equivalent to the averaged snow thickness uncertainty on multi-year ice for July and August ($\pm$ 5.0 cm) provided by Warren et al. (1999) .

The examination of interannual changes in the sea ice cover over a certain area requires continuous and overlapping measurements. Despite shortcomings due to logistical and meteorological challenges of air- and shipborne campaigns in the Arctic, we consider our data set to be sufficiently homogenous with respect to its temporal and spatial coverage. Nevertheless, to ensure a maximum degree of consistency and to limit bias due to warm Atlantic Water (Beszczynska-Moeller et al., 2012), only flights obtained between 82 and 85° N and 13° W and 20° E were selected (compare the red shaded area in Fig. 1). A summary of the survey flights obtained during individual campaigns is presented in Table 1 together with survey dates and length of EM-profiles. In addition, the modal and mean ice thickness, as well as fraction of ice ≥ 3 m and the open water fraction are given.

2.2 Satellite data

The interpretation of EM thickness measurements in a larger spatial context requires information about the age, drift history, and source areas of the surveyed ice. Below we describe the data set that was used to determine age and drift trajectories. In addition, we present the approach to quantify ice area fluxes through Fram Strait.

2.2.1 Sea ice concentration

Sea ice concentration data used in this study are obtained from the National Snow and Ice Data Center (NSIDC). The data set was derived using measurements from the Scanning Multichannel Microwave Radiometer (SMMR) aboard the Nimbus-7 satellite, from the Special Sensor Microwave/Imager (SSM/I) on the -F8, -F11, and -F13 satellites of the Defense Meteorological Satellite Program (DMSP), and from Microwave Imager/Sounder (SSMIS) aboard DMSP-F17. Sea ice concentration was calculated based on the Bootstrap algorithm (Comiso, 2000). Data are available on a daily basis at 25 km × 25 km spatial resolution.

2.2.2 Sea ice drift

Passive-microwave retrieved ice drift products are provided by different institutions and have been widely used in sea ice studies and for model assimilation (e.g. Miller et al., 2006; Kwok, 2009; Spreen et al., 2011; Sumata et al., 2014). In this study, two different 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 second data set, sea ice motion provided by the Center for Satellite Exploitation and Research (CERSAT) at the Institut Francais de Recherche pour d'Exploitation de la Mer (IFREMER), shows a good performance on the Siberian shelf (Krumpen et al., 2013) and was therefore used to complement the calculation of ice drift trajectories between September and May.

The Polar Pathfinder Sea Ice Motion 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, only until 2004) and buoy observations from the International Arctic Buoy Program (IABP). In addition NCEP/NCAR winds are used as an ice drift estimator (1% of wind speed, 20° turning angle) when no other data is available, which can happen more often during summer months. A description of the data set and the sea ice motion retrieval algorithm can be found in Fowler et al. (2013). According to the authors, the uncertainty of the drift product is 1.0 cm sec^{-1}. However, with the progress of summer melting season, the error increases. By using SAR based ice drift as a reference, Sumata et al. (2015) estimated the uncertainties to range from 1.0 to 2.0 cm sec^{-1} between May and July, depending on drift speed and ice concentration.

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~~CERSAT motion estimates. Since a substantial part of Fram Strait sea ice originates from the Laptev Sea (Rigor and Colony, 1997), the calculation of drift ~~trajecotories~~ trajectories requires a drift data set with good performance on the Siberian shelf. Following Rozman et al. (2011) and Krumpen 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 (less than 1.0 cm sec^{-1}). 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 (Girard-Ardhuin, 2012) . 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~~ ice area 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 ($\leq 15\,\%$) ~~were the ice is assumed to be melted~~when ice parcels are considered lost, 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 $25\,\mathrm{km} \times 25\,\mathrm{km}$ 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 meridional (V ~~and~~) and zonal (U ~~drifts~~) ice drift 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. The corresponding uncertainties are calculated as the integral of the product between NSIDC drift uncertainties provided by Fowler et al. (2013) and Sumata et al. (2015) and ice concentration. Following Fowler et al. (2013) , we assume the uncertainty of ice drift velocity to be within the range of 1.0 $\mathrm{cm\,sec^{-1}}$ during winter months (October April). During summer months (May–September), uncertainty estimates provided by Sumata et al. (2015) are applied ranging from 1.0 2.0 $\mathrm{cm\,sec^{-1}}$, depending on ice drift velocity and ice concentration. Transport (flux) rates are given in $\mathrm{km^2\,day^{-1}}$ or $\mathrm{month^{-1}}$. After removing the seasonal cycle, trends were calculated by linear regression, 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 (source: Maslanik et al., 2011) 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 and bias that may arise from year to year varying snow cover (± 5.0 cm, Warren et al., 1999). According to Fig. 4 the modal ice thickness has decreased over 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~~ and Hansen et al. (2014) . Following the authors, the decrease can be associated to changes in wind stress or a loss in perennial ice (decrease in ice age), since younger ice likely contains less consolidated pressure ridges. Another important factor that could explain observed decrease in deformation is ocean heat, since melt rate is thickness dependent and an increase in ocean heat affects ridges much more than surrounding level ice. The decrease in ice extent (Meier et al., 2014) , and the speed up of ice drift along the pathways with the associated increase in lead fraction (Rampal et al., 2009) leads to an increased heat uptake which could in turn result in enhanced melt of deformed ice. 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. This is in agreement with Hansen et al. (2014) who estimate that the contribution of thick, deformed ice towards the mean ice thickness is decreasing from about 70% in 2001 to about 50% in 2011.

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-based measurements is smaller than the footprint of airborne surveys which reduces footprint smoothing of pressure ridges. ~~To~~ However, thickness distributions obtained by both methods in the same region have very similar shapes and modes (e.g. Haas, 2006; Haas et al., 2008 , their Fig. 3), warranting their combination for this study. To further ensure compatibility with the AEM thicknesses, the GEM data have been regridded to the sampling interval of the airborne data and ice thinner than 0.15 m and open water has been excluded from the analysis of the AEM measurements (see Sect. 2.1). ~~Unfortunately, there are no temporally and spatially overlapping GEM and AEM measurements available in our data set that could be used for direct comparison. However, a comparison of simultaneous AEM and GEM ice thickness measurements made in the central Arctic in summer of 2011 and 2012 give confidence in the comparability of the modal thicknesses.~~ For our study we assume that ~~the mean is~~ mean thicknesses obtained with both method are comparable as well. We base this assumption on the high number of available GEM surveys and the general exclusion of thin ice thicknesses from the AEM data, which will be vastly underrepresented in the GEM data.

3.2 Comparsion to other observations

In Fig. 5 we compare our thickness measurements with thickness estimates made by Renner et al. (2014) and Hansen et al. (2013). By means of moored Upward Looking Sonars (ULS) positioned between 79° N, 7° W and 79° N, 3° W, Hansen et al. (2013) reconstructed a time series of sea ice thickness over 21 years (1990–2011). To enable a comparison with our observations, ULS thickness estimates in Fig. 5 are averaged August measurements, except for 2012 where averaged July measurements are used. Ice thickness measurements taken from Renner et al. (2014) were obtained with a GEM during cruises with RV *Lance* (Norwegian Polar Institute). Measurements cover the width of Fram Strait along approximately 79° N in September between 2003 and 2012. For details about data processing and handling we refer to Renner et al. (2014) and Hansen et al. (2013). A decrease in both, modal and mean thickness with a distinct reduction after 2004 is visible in all three data sets. According to the ULS observations, the mean and modal thickness in August is decreasing by 0.65 m and 0.41 m decade^{-1} between 1990 and 2012. GEM observations indicate an even more pronounced thinning of Fram Stait ice cover. A direct comparison of our observations 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~~ Along and ~~along~~ across 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, 0° E and covers a distance of ~~220~~290 km (south to 79° N~~).~~ , 10° W).

According to aerial photos taken during the flight, the ice cover ~~along the profile~~ was rather homogenous~~with equally distributed leads.~~ . Likewise, there is no gradient in ice concentration along the profile or changes in the frequency of open water occurrence. 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~~ The decrease in modal thickness is likely associated with oceanographic ~~processes: Mainly the presence of warm Atlantic water, leading to enhanced bottom melt between~~ and atmospheric processes acting on the pack ice while drifting south: Differences in net short- and longwave radiation between 79 and 81° ~~N. In August, when the along strait decrease in ice thickness was sampled, ice motion was low.~~ N and the presence of warm Atlantic water may lead to enhanced surface and bottom melt that could explain the observed gradient. A thinning of 0.38 m implies a heat flux of 16 W m^{-2}. Using the backtracking approach as described in Sect. 2.2.3, we estimated the transit time of sea ice between ~~79 and~~ 81° N, 0° E and 79° N, 10° W to be around 80 days ~~. If the thinning is produced by ocean heat fluxes this implies a mean ocean heat flux of 16~~with an average ice drift velocity of 4.8 cm sec^{-1}. The difference in net short- and longwave radiation between norther and southern end of the thickness profile amounts to 12 W m^{-2} ~~. This~~ over 80 days (source: NCEP Reanalysis data). Consequently, the ocean contributes with 4 W m^{-2} to sea ice melt, which is clearly within the range of observed ocean heat fluxes in the ~~area (Sirevaag, 2009) , but higher than observed Arctic Basin values in the range~~ Arctic Basin (2–5 W m^{-2} ~~(Fer, 2009) .~~ (Fer, 2009)), but lower than observed ocean heat flux in Fram Strait area (Sirevaag, 2009) . Hence, there is only little evidence of a presence of warm Atlantic water, impacting enhanced bottom melt between 79 and 81° N. However, calculations may suffer from uncertainties in net short- and longwave radiation obtained from reanalysis data. In addition, we found that the ice drift velocity of 4.8 cm sec^{-1} taken from satellite motion information is lower than ice drift velocity calculated based on geostrophic winds plus the contribution of the steady southwards flowing current below the sea ice. The average geostrophic wind velocity obtained from NCEP reanalysis data amounts to 2.6 m sec^{-1} between May 16 and August 4. This is equivalent to an ice drift of 3.6 cm sec^{-1}, assuming the southward directed ice drift velocity to be 1.4 % of the geostrophic wind speed in Fram Strait (Smedsrud et al., 2011) . According those authors and observations made by Widdel et al. (2003) , underlying currents contribute with additional 4.6 cm sec^{-1} to ice export out of Fram Strait. Hence, there is indication that transit time may be underestimated due to uncertainties associated to NSDIC motion information, which would result in an overestimation of atmospheric processes contributing to sea ice melt.

In 2012, a second 170 km long flight in upstream direction was performed. Measurements were a continuation of the transect made in 2011 and started at 80.5° N. The ice cover was again rather homogenous with a few leads. According to Fig. 2 ice was formed in the western Laptev Sea and transported via the Transpolar Drift towards Fram Strait. The absence of a gradient in modal thickness indicates that enhanced bottom or surface melt due to ~~presence of AW branches~~ atmospheric or oceanographic processes is limited to areas south of ≈ 80° N. ~~Marnela et al. (2013) found the recirculation to be weaker close to 80N than close to 78N, with strongest effects at 79N.~~

The ice thickness gradient across Fram Strait was investigated during two flights in 2010 (22 August) and 2012 (21 July). The long operating distance of *Polar 5* enabled us to obtain the first continuous profiles over closed ice pack north of 81° N. The across strait ice thickness profile is presented in Fig. 6b. Both transects show a negative trend in modal (0.02 m and 0.04 m $degree^{-1}$ longitude) and mean (0.03 m and 0.11 m $degree^{-1}$ longitude) ice thickness from West to East. The gradient in mean thickness is thereby more pronounced than the gradient in modal thickness. For sea ice at this latitude or higher, one can assume the impact of ~~warm water~~ oceanographic and atmospheric processes on the ice cover to be ~~small~~smaller. This assumption is supported by the absence of a gradient in modal ice thickness for sea ice upstream of 80.5° N ~~and hydrographic observations of Marnela et al. (2013)~~ discussed above. Hence, we assume the observed gradient to be mainly associated with differences in age and deformation of ice provided by the Transpolar Drift system. A comparison to Fig. 2 reveals that the ice that enters Fram Strait west of the prime meridian is indeed older and therefore most likely thicker than ice that enters through the eastern section. Note that the good agreement between the length of pathways and observed thickness gives us confidence in the performance of the tracking approach.

Earlier quantifications of across strait gradients were made by Hansen et al. (2013) and Renner et al. (2014) approximately 300 km further south at 79° N. Their estimates are based on interpolations between single point upward looking sonar measurements and on merged EM profiles obtained during different days. For this position, the authors reported a decline in across strait modal thickness of -0.1 to $-0.3\,\mathrm{m\,degree^{-1}}$ longitude (Renner et al., 2014) and $-0.23\,\mathrm{m\,degree^{-1}}$ longitude (Hansen et al., 2013). ~~It stands to reason that the stronger gradient observed at 79N can be explained by an increasing strength of the AW recirculation in downstream direction.~~

3.4 Summer sea ice area and volume fluxes

To quantify whether coupled sea ice ocean models are capable of reproducing Fram Strait sea ice volume fluxes correctly, validation data are required. Using satellite data, the volume flux in Fram Strait can be described as the product of southward directed sea ice motion, concentration and mean thickness. Information on ice drift and concentration is available on a year round basis. However, the availability of satellite based thickness data from ICESat or CryoSat-2 are restricted to winter months, which is why ice volume flux estimates for summer periods are scarce. In the following, we will therefore use the presented ~~AEM~~ EM measurements together with satellite based area flux estimates to calculate volume outflows for the periods when thickness surveys where made.

Because of its year round availability, ice area flux out of Fram Strait is calculated using NSIDC motion estimates together with NSIDC ice concentration information. Figure 7 shows the monthly ice area export across Fram Strait from 1980–2012 (~~orange line)~~ black line) together with the associated uncertainty estimates (grey). Note that the area flux is the sum of meridional and zonal components, with a positive sign referring to ice export, and a negative sign indicating ice import into the Arctic (see Sect. 2.2.5). The average monthly ice area flux amounts to $46 \times 10^3\,\mathrm{km}^2$ with a standard deviation of $38 \times 10^3\,\mathrm{km}^2$ and an uncertainty of $\pm 18 \times 10^3\,\mathrm{km}^2$. The monthly ice export shows a pronounced 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.

We present ~~an extensive~~ a 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 rather short and irregular spaced time series in mind, the EM data provide evidence of adata sets, 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 $0.19\,\mathrm{m\,degree}^{-1}$ latitude south of 81° N is likely associated with ~~the presence of recirculated warm Atlantic water~~atmospheric and oceanic processes, leading to enhanced surface and 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 and associated uncertainties. 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 area export is low compared to the annual values with high uncertainties. For the investigated months, the average volume export amounts to ~~17.77~~16.78 km^3 ~~($\pm$34.45)~~ with highest rates in August 2010 (~~64.83~~61.25 km^3) and lowest in August 2001 ($-$~~15.97~~15.35 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. Because differences in model based sea ice volume fluxes across Fram Strait (Koenigk et al., 2008) are clearly larger than uncertainty associated to the combined use of satellite- and airborne estimates, our results are of practical use for model validation. Therefore, airborne thickness surveys in Fram Strait should be continued and extended in the future.

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References

Beszczynska-Moeller, A., Fahrbach, E., Schauer, U., and Hansen, E.: Variability in Atlantic water temperature and transport at the entrance to the Arctic Ocean, 1997–2010, J. Mar. Sci., 69, 852–863, doi:10.1093/icesjms/fss056, 2012.

Comiso, J. C.: Bootstrap Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS, Tech. Rep., NASA National Snow and Ice Data Center, Boulder, CO, USA, doi:10.5067/J6JQLS9EJ5HU, 2000.

Comiso, J. C. and Hall, D. K.: Climate trends in the Arctic as observed from space, Interdiscipl. Rev.-Clim. Change, 5, 389–409, doi:10.1002/Wcc.277, 2014.

Fer, I.: Weak vertical diffusion allows maintenance of cold halocline in the central Arctic, Atmos. Ocean. Sci. Lett., 2, 148–152, 2009.

Fowler, C., Emery, W., and Tschudi, M.: Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors, Version 2, Daily and Mean Gridded Field, Tech. Rep., NASA DAAC at the National Snow and Ice Data Center, Boulder, CO, USA, 2013.

Girard-Ardhuin, F., Ezraty, R.: Enhanced Arctic sea ice drift estimation merging radiometer and scatterometer data, IEEE Trans. Geosci. Remote Sensing, 50, 7, doi:10.1109/TGRS.2012.2184124, 2012.

Haas, C.: Late summer sea ice thicness variability in the Arctic Transpolar Drift 1991–2001 derived from ground-based electromagentic soundings, Geophys. Res. Lett., 31, L09402, doi:10.1029/2003GL019394, 2004.

Haas, C., Hendricks, S., and Doble, M.: Comparison of the sea ice thickness distribution in the Lincoln Sea and adjacent Arctic Ocean in 2004 and 2005, Ann. Glaciol., 44, 247–252, doi:10.3189/172756406781811781, 2006.

Haas, C., Pfaffling, A., Hendricks, S., Rabenstein, L., Etienne, J. L., and Rigor, I.: Reduced ice thickness in Arctic Transpolar Drift favors rapid ice retreat, Geophys. Res. Lett., 35, L17501, doi:10.1029/2008GL034457, 2008.

Haas, C., Lobach, J., Hendricks, S., Rabenstein, L., and Pfaffling, A.: Helicopter-borne measurements of sea ice thickness, using a small and lightweight, digital EM system, J. Appl. Geophys., 67, 234–241, 2009.

Haas, C., Hendricks, S., Eicken, H., and Herber, A.: Synoptic airborne thickness surveys reveal state of Arctic sea ice cover, Geophys. Res. Lett., 37, L09501, doi:10.1029/2010GL042652, 2010.

Hansen, E., Gerland, S., Granskog, M. A., Pavlova, O., Renner, A. H., Haapala, J., Loyning, T. B., and Tschudi, M.: Thinning of Arctic sea ice observed in Fram Strait: 1990–2011, J. Geophys. Res., 118, 5202–5221, doi:10.1002/jgrc.20393, 2013.

Hansen, E., Ekeberg, O.-C., Gerland, S., Pavlova, O., Spreen, G., and Tschudi, M.: Variability in categories of Arctic sea ice in Fram Strait, J. Geophys. Res., 119, 7175–7189, doi:10.1002/2014JC010048, 2014.

Kloster, K. and Sandven, S.: Ice Motion and Ice Area Flux in Fram Strait at 79° N Using ASAR and Passive Microwave for February 2004–July 2010, Tech. report 322, Nansen Environmental and Remote Sensing Centre, Bergen, Norway, 2011.

Hollands, M.,Serreze, M., and Stroeve, J.: The sea ice mass budget of the Arctic and its future change as simulated by coupled climate models, Clim. Dynamics, 34, 2, 185–200, doi:10.1007/s00382-008-0493-4, 2010.

Koenigk, T.,Mikolajewicz, U.,Haak, H., Jungclaus, J., Dickson, R., Meincke, J., and Rhines, P.: Modelling the Sea Ice Export Through Fram Strait. Arctic–Subarctic Ocean Fluxes, Springer Netherlands, 171-191, 2008.

Krumpen, T., Janout, M., Hodges, K. I., Gerdes, R., Girard-Ardhuin, F., Hölemann, J. A., and Willmes, S.: Variability and trends in Laptev Sea ice outflow between 1992–2011, The Cryosphere, 7, 349–363, doi:10.5194/tc-7-349-2013, 2013.

Kwok, R.: Outflow of Arctic Ocean Sea Ice into the Greenland and Barents Seas: 1979–2007, J. Climate, 22, 2438–2457, doi:10.1175/2008JCLI2819.1, 2009.

Kwok, R., Spreen, G., and Pang, S.: Arctic sea ice circulation and drift speed: decadal trends and ocean currents, J. Geophys. Res., 118, 2408–2425, 2013.

Lindsay, R. and Schweiger, A.: Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations, The Cryosphere, 9, 269–283, doi:10.5194/tc-9-269-2015, 2015.

Mahoney, A., Eicken, H., Fukamachi, Y., Ohshima, H., Shimizu, D., Kambhamettu, C., Hendricks, S., and Jones, J.: Taking a look at both sides of the ice: comparison of ice thickness and drift speed as observed from moored, airborne and shore-based instruments near Barrow, Alaska, Ann. Glaciol., 69, 69A565, 2014.

Marnela, M., Rudels, B., Houssais, M.-N., Beszczynska-Möller, A., and Eriksson, P. B.: Recirculation in the Fram Strait and transports of water in and north of the Fram Strait derived from CTD data, Ocean Sci., 9, 499–519, doi:10.5194/os-9-499-2013, 2013.

Martin, T., Steele, M., and Zhang, J.: Seasonality and long-term trend of Arctic Ocean surface stress in a model, J. Geophys. Res., 119, 1723–1738, doi:10.1002/2013JC009425, 2014.

Maslanik, J. A., Stroeve, J., Fowler, C., and Emery, W.: Distribution and trends in Arctic sea ice age through spring 2011, Geophys. Res. Lett., 38, L13502, doi:10.1029/2011GL047735, 2011.

Maykut, G. A.~~: The Surface Heat and Mass Balance,the Geophysics of Sea Ice, Martinus Nijhoff Publ.~~, and Untersteiner, N.: Some results from a time-dependent thermodynamic model of sea ice, J. Geophys. Res., 76, 6, ~~Dordrecht, 1985.~~ 1550–1575, doi:10.1029/JC076i006p01550, 1971.

Meier, W. N., Hovelsrud, G. K., van Oort, B. E., Key, J. R., Kovacs, K. M., Michel, C., Haas, C., Granskog, M. A., Gerland, S., Perovich, D. K., Makshtas, A., and Reist, J. D.: Arctic sea ice in transformation: a review of recent observed changes and impacts on biology and human activity, Rev. Geophys., 52, 185–217, doi:10.1002/2013RG000431, 2014.

Miller, P. A., Laxon, S. W., Feltham, D. L., and Gresswell, J.: Optimization of a sea ice model using Basinwide observations of arctic sea ice thickness, extent, and velocity, J. Climate, 19, 1089–1108, doi:10.1175/JCLI3648.1, 2006.

Pfaffling, A., Haas, C., and Reid, J. E.: A direct helicopter EM sea ice thickness inversion, assessed with synthetic and field data, Geophysics, 72, F127–F137, 2007.

Rabenstein, L., Hendricks, S., Martin, T., Pfaffhuber, A., and Haas, C.: Thickness and surface properties of different sea ice regimes within the Arctic Trans Polar Drift: data from summers 2001, 2004 and 2007, J. Geophys. Res., 115, C12059, doi:10.1029/2009JC005846, 2010.

Rampal, P., Weiss, J., and Marsan, D.: Positive trend in the mean speed and deformation rate of Arctic sea ice, 1979–2007, J. Geophys. Res., 114, C05013, doi:10.1029/2008JC005066, 2009.

Renner, A. H., Gerland, S., Haas, C., Spreen, G., Beckers, J. F., Hansen, E., Nicolaus, M., and Goodwin, H.: Evidence of Arctic sea ice thinning from direct observation, Geophys. Res. Lett., 41, 5029–5036, doi:10.1002/2014GL060369, 2014.

Rigor, I. G. and Colony, R. L.: Sea-ice production and transport of pollutants in the Laptev Sea, 1997–1993, Sci. Total Environ., 202, 89–110, doi:10.1016/S0048-9697(97)00107-1, 1997.

Rozman, P., Hoelemann, J., Krumpen, T., Gerdes, R., Koeberle, C., Lavergne, T., and Adams, S.: Validating satellite derived and modelled sea-ice drift in the Laptev Sea with in situ measurements from the winter of 2007/08, Polar Res., 30, 67218, doi:10.3402/polar.v30i0.7218, 2011.

Sirevaag, A.: Turbulent exchange coefficients for the ice/ocean interface in case of rapid melting, Geophys. Res. Lett., 36, L0460, doi:10.1029/2008GL036587, 2009.

Smedsrud, L. H., Sirevaag, A., Kloster, K., Sorteberg, A., and Sandven, S.: Recent wind driven high sea ice area export in the Fram Strait contributes to Arctic sea ice decline, The Cryosphere, 5, 821–829, doi:10.5194/tc-5-821-2011, 2011.

Spreen, G., Kern, S., Stammer, D., and Hansen, E.: Fram Strait sea ice volume export estimated between 2003 and 2008 from satellite data, Geophys. Res. Lett., 36, L19502, doi:10.1029/2009GL039591, 2009.

Spreen, G., Kwok, R., and Menemenlis, D.: Trends in Arctic sea ice drift and tole of wind forcing: 1992–2009, Geophys. Res. Lett., 38, 1–14, doi:10.1029/2011GL048970, 2011.

Sumata, H., Lavergne, T., Girard-Ardhuin, F., Kimura, N., Tschudi, M., F., K., Karcher, M., and Gerdes, R.: An intercomparison of Arctic ice drift products to deduce uncertainty estimates, J. Geophys. Res., 119, 4887–4921, doi:10.1002/2013JC009724, 2014.

Sumata, H., Kwok, R., Gerdes, R., Kauker, F., Karcher, M.: Uncertainty of Arctic summer ice drift assessed by high-resolution SAR data, J. Geophys. Res., 120, 5285–5301, doi:10.1002/2015JC010810, 2015.

Thorndike, A. S., Rothrock, D. A., Maykut, G. A., and Colony, R.: The thickness distribution of sea ice, J. Geophys. Res., 80, 4501–4513, 1975.

Vavrus, S. J., Holland, M. M., Jahn, A., Bailey, D., and Blazey, B. A.: Twenty-first-century Arctic climate change in CCSM4, J. Climate, 25, 2696–2710, doi:10.1175/JCLI-D-11-00220.1, 2012.

Warren, S. G., Rigor, I. G., Untersteiner, N., F., R. V., Bryzgin, N. N., Aleksandrov, Y. I., and Colony, R.: Snow depth on Arctic sea ice, J. Climate, 12, 1814–1829, 1999.

Webster, M. A.,Rigor, I. G.,Nghiem, S. V., Kurtz, N. T., Farrell, S. L., Perovich, D. K., Sturm, M.: Interdecadal changes in snow depth on Arctic sea ice, J. Geophys. Res., 119, 53955406, doi:10.1002/2014JC009985, 2014.

Widdel, K, Oesterhus, S., Gammelsroed, T.:Sea ice velocity in the Fram Strait monitored by moored instruments, J. Geophys. Res. Lett., 30, doi:10.1029/2003GL018119, 2003.

Table 1. The table summarizes for the area of interest and individual campaigns the dates of observations, platform, total profile length, the ice thickness (mode and mean ±SE), as well as the fraction of ice thicker than 3 m and the open water fraction along profiles.

Campaign	Platform	Dates of data takes	Total profile length (km)	Ice thickness Modal/Mean ±SE (m)	Fraction of ice ≥ 3 m (%)	Open water fraction (%)
ARK-XVII/2, 2001 (Haas, 2004)	RV *Polarstern*	8–21 Aug 2001	50	$2.0/2.58 \pm 1.1$	26	–
ARK-XX/2, 2004 (Haas et al., 2008)	RV *Polarstern*	2–4, 6–12, 14 Aug 2004	2270	$2.2/2.59 \pm 1.3$	29	1.5
TIFAX 2010 (Haas et al., 2010)	*Polar 5*	19 and 22 Aug 2010	500	$1.7/1.81 \pm 0.8$	8	4.7
TIFAX 2011	*Polar 5*	2 and 4 Aug 2011	660	$1.6/1.89 \pm 1.1$	10	10.5
TIFAX 2012	*Polar 5*	19 and 21 Jul 2012	890	$1.4/2.17 \pm 1.4$	15	3

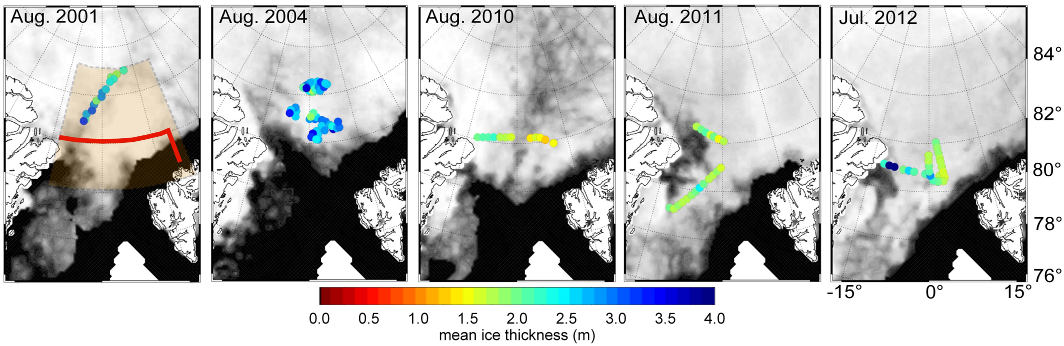

Figure 1. Overview of all EM ice thickness measurements obtained in the Fram Strait region during two cruises with the German ice-breaker RV *Polarstern* (August 2001 and 2004) and three surveys with the research aircraft *Polar-5* (August 2010 and 2011, July 2012). The color coding of the EM profiles 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~~ from the date of the first flight of each campaign, is plotted in the background going from 0% ice concentration in black to 100% in white. The thick red line in the left panel indicates the meridional and zonal gates through which satellite derived ice area fluxes were calculated.

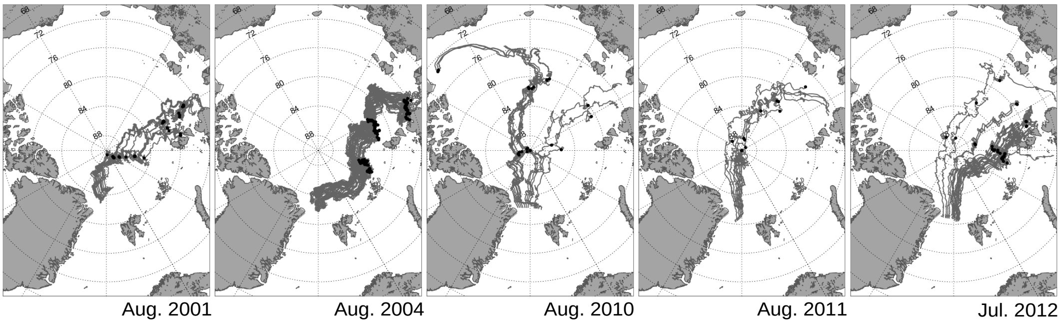

Figure 2. Backtracking of sampled sea ice using a combination of ice drift and concentration information. The start points of the trajectories (grey lines) are equivalent to the positions where EM measurements were obtained during the individual years. The black dots correspond to the position of particles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

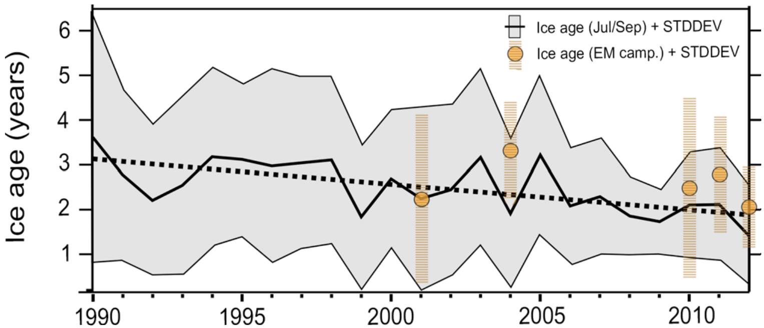

Figure 3. Comparison of age of sea ice ~~observed~~ covered by EM measurements and mean summer ice age in Fram Strait obtained from Maslanik et al. (2011) : The black line represents the average July–September ice age along the meridional and zonal gates through which satellite derived ice area fluxes were calculated (compare red line in Fig. 1). A trend line is added (dashed black line). The age of sea ice covered by EM measurements between 2001 and 2012 is indicated by orange circles. The grey shaded area and dashed bars correspond to the standard deviation of ice age for satellite and observational data, respectively.

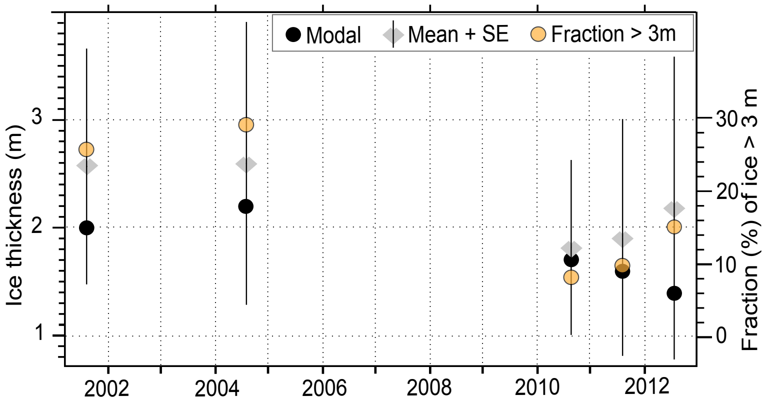

Figure 4. Mean (grey) plus standard deviation (black lines) and modal (black circles) EM ice thickness (~~left axis~~ice plus snow (0.1 m) thickness) obtained in the Fram Strait region between 2001 and ~~2012.~~ 2012 (left axis). The fraction of ice thicker than 3 m (right axis) is represented by orange circles. The locations of the performed survey flights is shown in Fig. 1.

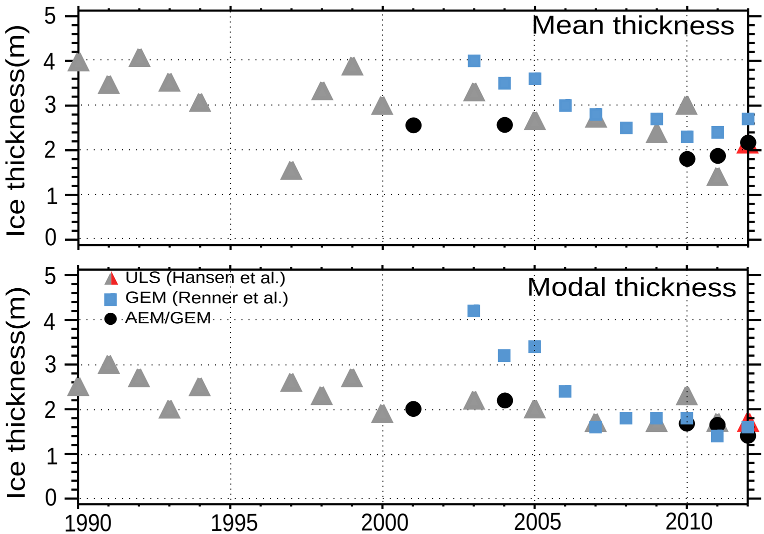

Figure 5. Comparison of mean (upper panel) and modal (lower panel) EM ice thicknesses (ice plus snow thickness) as obtained by ULS (source: Hansen et al., 2013), GEM (source: Renner et al., 2014) and GEM/AEM measurements in Fram Strait area. Grey/red triangles represent average August/July ULS measurements. The blue rectangles correspond to GEM measurements carried out between end of August and September. Black dots represent AEM/GEM measurements obtained during two cruises with RV *Polarstern* (August 2001 and 2004) and three surveys with the research aircraft *Polar-5* (August 2010 and 2011, July 2012).

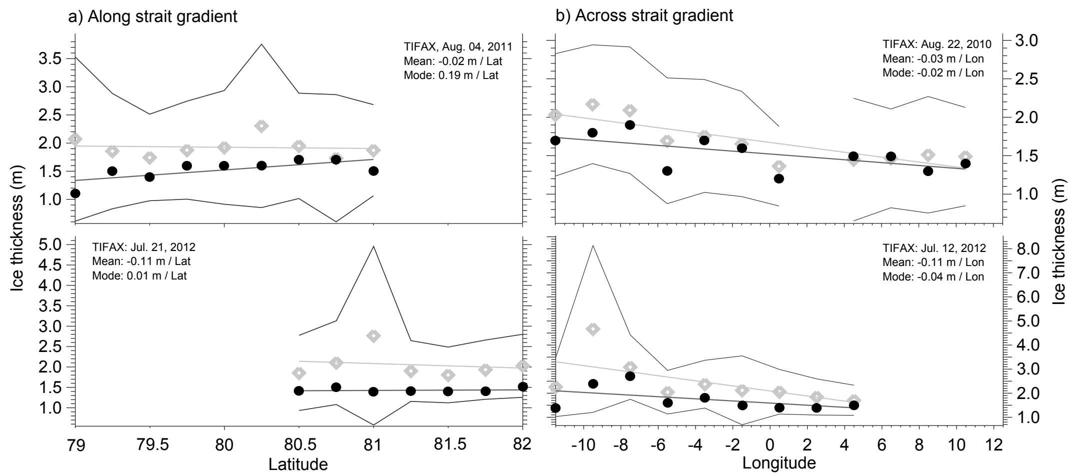

Figure 6. Across and along ~~strait~~ Fram Strait thickness ~~gradient~~gradients: **(a)** ~~shows the along~~ Along strait ~~gradient in ice thickness (m) for~~ flights made in August 2011 and 2012 between 10° W and 0° E. ~~The across~~ **(b)**: Across strait ~~gradient as obtained from two~~ flights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

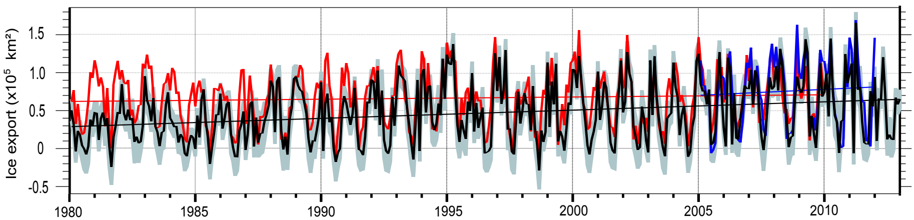

Figure 7. Monthly ice area export (given in $\times 10^3\,\mathrm{km}^2$) across Fram Strait. The ~~orange~~ black line presents area fluxes calculated from NSIDC drift and concentration information across the meridional and zonal gates (compare Fig. 1). In grey, the corresponding uncertainty estimates are given. The ~~black~~ blue and ~~grey~~ red line indicate monthly sea ice area transports across 79° N, 15° W and 79° N, 5° E ~~provided by Kloster and Sandven (2011)~~ based on SAR images (Kloster and Sandven, 2011) and ~~Smedsrud et al. (2011)~~ based on SLP gradients (Smedsrud et al., 2011) , respectively. Trend lines for individual flux estimates are plotted on top.

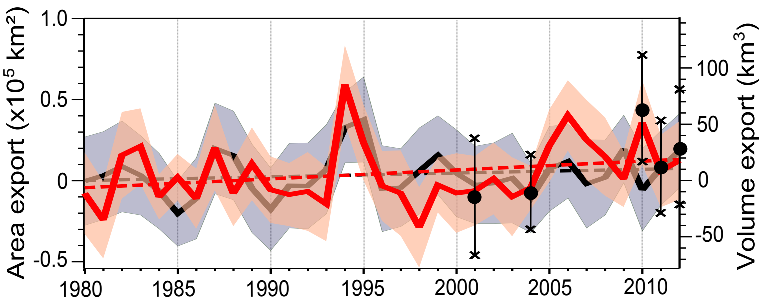

Figure 8. July (~~blue line~~black) and August (~~orange line~~red) ice area export across Fram Strait (given in $\times 10^3\,\mathrm{km}^2$), plotted on top of the corresponding uncertainty estimates (grey and light red). Area fluxes were calculated from NSIDC drift and concentration data. The associated volume flux for the years where ~~AEM~~ EM measurements are available is calculated as the product of NSIDC area flux estimates (August) and ~~AEM~~ EM mean thickness (black dots, ~~given in ,~~ right axis). The error bars indicate uncertainties of volume estimates. 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~~.