Dear reviewer 1,

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

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.