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Author Response to Editor and Reviewers for MS No.: tc-2016-79:
"Fram Strait sea ice export variability and September Arctic sea ice extent over the last 80 years", by L. H. Smedsrud et al.

Dear Editor. Thank you for your helpful comments, and the chance to resubmit the paper in a substantially changed version. We have indeed followed your suggestions as outlined below, and our response here is given **using bold text**. The new text in the manuscript is shown **using red bold font**, and this version is included at the end of our response letter, on page 13 onwards. We certainly agree that "no particular record is the truth" and that the errors "are not well defined", but have done our best to improve the description and discussion as suggested. In short we have:

1) Better described the uncertainty both in the SAR based and "mSLP" based time series.

2) Extended the discussion about the large-scale atmospheric forcing incorporating the two papers of Hilmer and Jung (2000) and Wu at al (2006).

3) More carefully estimated and discussed uncertainties of our mSLP based time series, including using the long-term changes in sea ice concentration from Walsh et al (2015).

4) Tightened and re-written much of the discussion of the link to the following September SIE, and instead cited the newly published Williams et al (2016) paper.

Lars H. Smedsrud, Mari H. Halvorsen, Julienne C. Stroeve, Rong Zhang and Kjell Kloster.

Editors Comments:

Both reviewers express concerns about the presentation of uncertainty in your manuscript. In response to reviewer 2 could you please discuss how the uncertainty in ice drift estimate impacts the area flux estimate. Yes, I agree the variance is not the same as the error estimate, however it is very hard from your current text and figures to gauge the signal to noise ratio. In the context of the trends and whether you can identify periods of variability that are longer than the interannual variability this variance does impact the length of time series you need to draw conclusions. Your manuscript could be clarified in this respect, which would of course make the paper more readable and accessible. For example, you discuss in detail the difference in trends between various different analyses, but do not put this into the context of if these differences are statistically insignificant. You do discuss the point that the last 30 years is impacted by several high export years at the end of the time series, and I think you can do a better job of putting this into context. The fact that your SLP based export estimate differs from previous work needs to be considered in the context of no particular record being the truth and all having errors that are not well defined.

The uncertainty of the SAR based (2004 – 2014) time series have now been better described in section 2.1. This is the main difference between our new results and previous estimates of the area export. The uncertainties for the mSLP based time series are more difficult to describe, but we have now used the Walsh et al (2015) data to come up with a good estimate in section 4.

There are several previous works linking the Fram Strait export or the Arctic sea ice pack state and ice motion to the Dipole Anomaly. Please consider the work of Jia Wang's group for example.

We have added the Wu et al. (2006) paper, which is also a substantial paper on the AD link to export into the discussion in section 4.3. We did previously already cite the Wang et al (2009) paper.

Your choice of calling March to August Spring is a little unusual in my mind. I understand that you choose this time period based on the assumption all ice that grows in open water created by the export between these times will melt out in summer. This is a highly simplified model and does not account for ridging, but then again the albedo feedback will amplify the melt so you are not really looking at export from March-August as a linear indicator of open water in summer. Did you choose to split the time series periods in March as this is the 6 month split that gives you the best fit of the export to end of summer ice extent?

The split from March to August was done at the start of the analysis, based on the timing of the maximum extent. It is thus based on simple physics and conveniently splits the year into two halves. Export anomalies from September – February should have a qualitatively different effect. We agree that it is a highly simplified model to estimate the open water created by the export, but this was the basis for the previous section 4.5. Section 4.5 and 4.6 and 4.8 have now all been merged and compacted into one, the new section 4.5.

I am having trouble wrapping my head around how the over 80% variance in ice export explained by cross strait pressure gradient and assumed seasonal cycle on ocean currents (at a time when the time series is also experiencing larger export), and the 22-55% covariance of the export proxy and following September sea ice extent allow you to make strong statements about causality.

We agree that our previous discussion was suggesting this link without substantial evidence, but it has now been confirmed for the 1993-2014 period by Williams et al. (2016). What we add additionally in the new version is a discussion of the longer term period between 1935 and 2014.

While the proxy record is defendable, I am not sure what contribution export has to ice extent based on the correlations. Does the proxy perform as well earlier in the time series, how much of the reduction in correlation is due to decreased covariance of the three station pressure with ice drift? In fact, the shorter time period is influenced by specific high export years, and you show that the last 7 years of the record are where this happens and influences trends. If you were to chose a similar short time series bracketing the years identified by for example Son Ngheim et al. (2007) as high transpolar ice drift and export (e.g. 2005-2007) would you get increased correlation based on this particular event? It does not look so from my quick scan of your figures, and the ice export at Fram Strait lagged (by a year) the transpolar drift event that the 2007 minimum was related to. It appears to me that the only time when the export explained a significant portion of the September ice extent has been in recent years (2011-2014). Is this the case? I agree with reviewer 1 that you should tightening your manuscript to not overstate results.

We have substantially modified the discussion on the link to the following September SIE, and base some of it on the new Williams et al, (2016) paper now. See the new section 4.5. It is indeed correct that for individual years other factors like ridging probably have a much larger role, and we have included the new Hutchings and Perovich (2015) paper discussing the 2007 event in special. It remains clear that the link appears stronger in recent years, but we do find a modest influence in the long-term, which is physically sound in our view and backed up by the correlations.

Specific Points

Abstract line 18 and 20: Missing squared from your area dimensions. Also at page 12, lines 20 and 21. Check throughout please.
We have checked throughout that the sea ice area export values are given as, for ex. 300,000 km^2.

Page 2, line 32 "FShas" -> "FS has"
Corrected now.

line 25-26 "should be considerably more accurate that 10%". Did you not actually estimate this? I think you just need to reconsider your grammar here.
The description of the accuracy has been improved, and is now stated in cm/s.

page 5 line 16-19 You have noted an increased ice drift in winter. Echoing reviewer 1, there is increased open water in summer and potentially changes to surface roughness of the ice. This will impact stress transfer between the wind and ocean, and increased wind stress transfer to the ocean might also lead to increased currents. This is an example of speculative discussion where you could strengthen the manuscript by focusing on your key result (the time series) and a more rounded acknowledgement of its limitations.

page 16 line 25: There is a missing word
“export” added.

Please check all your references are listed. I could not find Krumpen et al. (2016) for example.
All references have been checked and updated now.

Reviewer 1 Comments:

The manuscript discusses the Fram Strait sea ice area export over the last 80 years, i.e., from 1935 to 2014. Large variability but no longterm trend is found. However, during the last decade according to the presented time series, ice area export increase. The authors, based on comparisons between spring ice export anomalies and summer minima, conclude that the increased ice export is partially responsible for the accelerated decline in Arctic sea ice extent. The variability and long term trends of the Arctic sea ice export and its connection to changes of the sea ice area within the Arctic Basin is an interesting and important topic.

For the manuscript at hand I had many problems reviewing it because it (a) discusses and mixes very different datasets and methods, and (b) draws very bold and far reaching conclusions based on quite simplified assumptions not taking the complexity of the coupled ocean-sea ice-atmosphere system enough into account:

- the authors construct a Fram Strait sea ice area flux proxy time series based on the across Strait air pressure gradient between Greenland and Svalbard. A regression between a high resolution SAR based ice area flux time series for 2004-2014 and the pressure gradient is performed. The regression coefficients (including a seasonal cycle adjustment) are used to reconstruct the sea ice area flux based on pressure observations alone. No sea ice observations are used before 2004 but only the air pressure. This fact was not initially clear to me as a reader from the methods section and I only understood it from the side note on page 9. Before the authors mention a new longterm sea ice extent time series (Walsh et al., 2015) but in the end they do not use it. This means that the time series before 2014 does not include any variability due to the changing sea ice area within Fram Strait. While Fram Strait is one of the areas in the Arctic with the smaller sea ice decrease during the satellite era it still shows a significant decrease. The time series presented here does not account for any such changes before 2004. These issues or other limits of the proxy time series are not discussed in the manuscript. On the contrary the authors never call it a proxy time series. These facts should be clearly mentioned already at the beginning of the document.

We have now re-written both the abstract and the methods section, and make it absolutely clear from the start that we rely on the SLP values to construct our 80 year long time series. Previously we tried first to focus on the recent high export years (2004 – 2014), but we agree that it is more clear now.

While our method is not standard we have clearly stated what we did in section 2.3. The term “proxy” is usually used for paleo observations like different organisms found in sediment cores that in some way reflect for example surface temperature. The physical relationship between SLP and ice drift is strong and qualitatively very different to this use of the word. We thus used the term “mSLP based” to describe our ice export estimates prior to 2004. This term was used in section 3.1 for example. Note that also “observations” of sea ice cover are some kind of “proxy” in the way that what is really measured by the satellite is radiation, and the uncertainties are in this case also difficult to properly nail down.

The fact that we use observed surface pressure is now made clear also in the abstract, so we think this and the other revisions done should make this clear.

- the Walsh et al. sea ice extent time series covering the complete 1935-2014 period is used for comparisons between ice export and ice extent in the manuscript. For a revised version of the manuscript this dataset should be combined with the air pressure data to add some ice extent variability to the ice export time series, which should make it more realistic. It is unclear to me why this was not done. The Walsh et al. ice extent dataset is prominently introduced as a new and improved time series.

Yes - we used the new Walsh et al (2015) data set primarily to evaluate effects of sea ice export, because we wanted to investigate September SIE variability in relation to ice export. It is not straight-forward to combine it with the SLP observations to make a new and more 'realistic' ice export because it only provides a mid-month ice concentration field, and many of the winter months have values based on spatial and temporal interpolation. For 2004 – 2014 we use ice concentration for the same days as the SAR imagery. We have now analyzed sea ice extent and ice concentration (Figure 1 and 2), and used that as a basis for new estimates of uncertainty.

- the 2004 to 2014 part of the time series is based on ice area flux estimates based on manually derived sea ice drift from high resolution SAR imagery. This should give very good estimates of the ice area export. I still would have appreciated some discussion of potential uncertainties due to the manual extraction by a human analyst or how they were mitigated. For example, were the number and the spatial distribution of the manually derived ice drift vectors constant for the complete time series? It is my understanding that this time series was build up over many years. Can we assume that the quality is constant over time? The stated uncertainty of +-3 km for an individual ice drift vector is actual much higher than what I would have expected. The grid cell size of the SAR data is about 100m. Adding some uncertainty caused by geolocation variability and identifying the exact same point in two images I still would have expected an uncertainty on the order of 500m or better like for example reported for the Radarsat RGPS data.

The SAR time series has images every three days for the 2004 – 2014 period, and have been manually derived by the same person, Kjell Kloster, for all that time. The details are described in a report; Kloster and Sandven (2014). Although it is manually derived, having the same person doing it should lead to a constant quality over time. An independent test of a SAR image pair by the University of Tasmania (Petra Heil, personal comm. 2012) showed that a computer image tracker could re-produce about 60% of the velocity vectors, but gave basically the same vectors for those that were picked up. We have added a better description of the uncertainties in section 2.1 now.

- the authors then merge the air pressure proxy time series with the SAR based time series. The complete air pressure based ice export time series is not shown. In my opinion that should not be done. The two time series have very different error bars and characteristics. The air pressure gradient is the only information we have got to estimate the ice export before 1979 when the satellite data start. This is argument enough to use the air pressure as a proxy to derive and discuss the ice export variability.

But again, it then also should be clearly stated what kind of time series is discussed in the manuscript. There is quite some focus on the 2004-2014 SAR dataset but the authors state themselves that this time period is too short to discuss significant trends. On page 7 the trends for the 1935-2014 air pressure time series alone are given and it is argued that these statistics are very similar to the merged time series. I would argue the other way around: use a consistent time series, i.e., the air pressure proxy ice export, for the complete period. This will avoid any biases, changes in statistics etc. due to the merging process in 2004.

We agree that this is an important question, and it is exactly why we discussed this merging in three different paragraphs (Page 7, line 23 – 29, Page 8, line 13 – 33). We did however end up on the opposite conclusion that the best thing was to present the "best possible" merged time series. The trends would be very similar if we should follow this suggestion and plot that in Fig. 2 instead. Analyzing ice concentrations from Walsh et al (2015) for 1935 onwards we find small and not significant trends for most months. The two figures below shows this clearly.

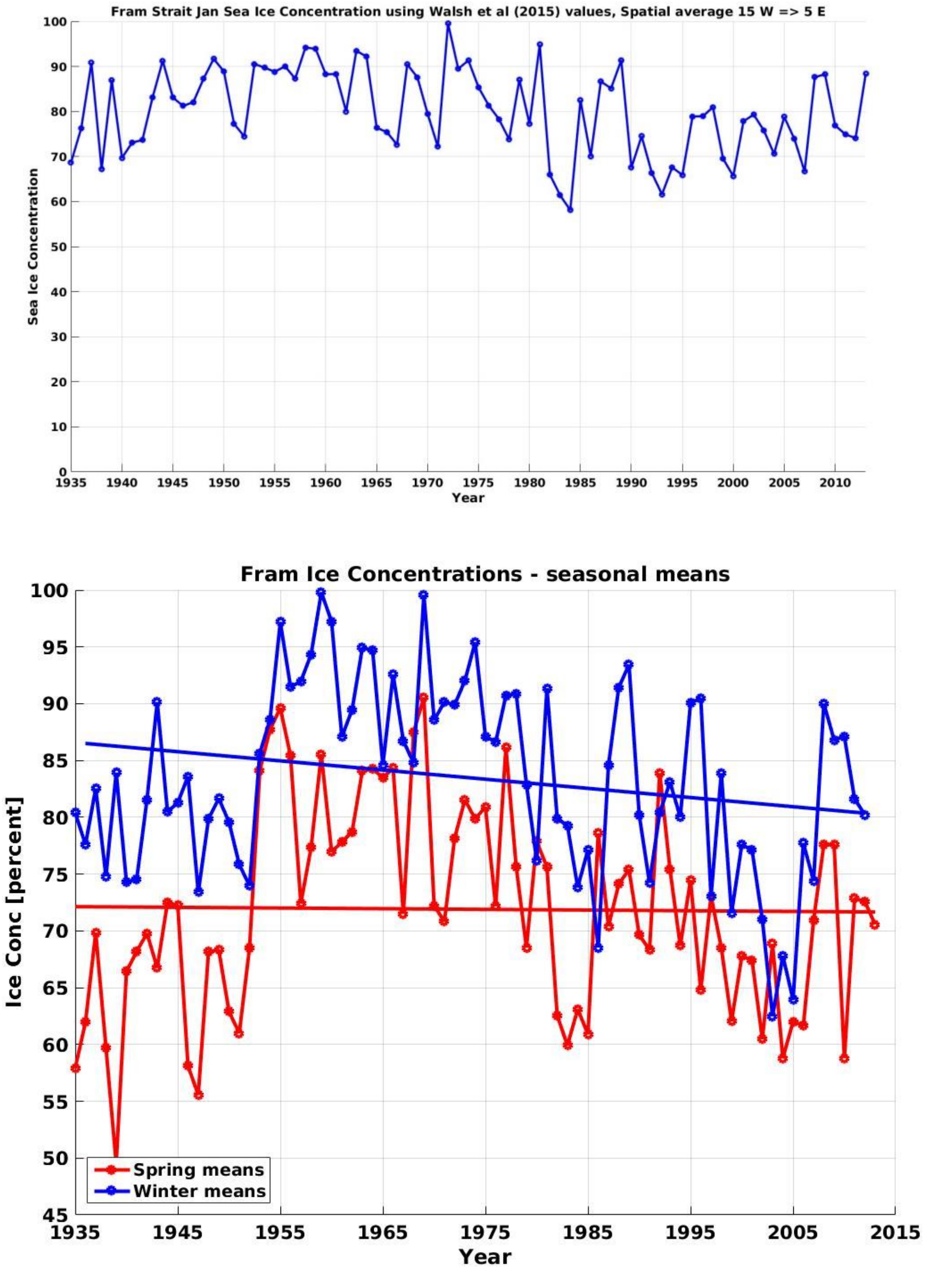

Figure 1: Sea ice concentrations in the Fram Strait from the Walsh et al. (2015) data. Spatial average between 15W and 5 E. a) Mid-month sea ice concentration for January between 1935 and 2013. b) Seasonal means for 1935 – 2013. The spring trend is – 0.1 %/decade, and the winter trend is -0.9 %/decade, but they are not significantly different from zero (p>0.05).

Figure 2 shows the similarity of the seasonal cycle between the adapted air pressure and SAR ice export time series. This is nice and shows good agreement but also differences for some months. For the reader it would be important to also see the two time series together for the complete 2004-2014 period. If the complete discussion in the manuscript would be changed to the air pressure only time series (see my last point) the SAR derived time series could be added to Fig. 4 for comparison.

We understand the importance of checking the agreement between the mSLP based and SAR based values. Fig. 4 in Smedsrud (2011) shows such a comparison for 2004 – 2010. The updated values are similar, and we found no particular reason to include them as a separate figure here. From visual inspection of Fig. 4 here it should be clear that there are no significant differences in the merged values on either side of 2004.

- The manuscript mentions that their ice export estimates for the last 30 years do not agree with estimates from passive microwave radiometers (e.g. Kwok et al., 2013). Actually, these satellite data based time series do not find a trend in ice export, which is opposite to the trend found here from the air pressure data. The authors attribute this difference to the low resolution of the satellite data and that it will not correctly track all ice in Fram Strait (p. 12). That is one possible explanation but the authors do not demonstrate this failure but hypothesis it. That is okay because the satellite data is not the topic of their study. But then the authors should be more critical also towards their own time series and list factors, which could explain the difference to the satellite data. For example: there is an increase in the across pressure gradient during the last 30 years. As this is the only data used in the proxy ice export time series presented here this directly results in a positive ice export trend.

However, there are other factors, which influence Fram Strait ice export and could or have changed during the last decades and therefore counteract the increased pressure gradient:

(i) the ice area in Fram Strait (FS) shows a negative trend reducing the ice area export, which is not accounted for here.

(ii) the surface winds in FS are not only determined by the pressure gradient but have a strong contribution from thermal wind (THW) forcing (van Angelen et al., 2011). If the THW forcing would have been reduced during the last decades that would counteract the increased pressure gradient

(iii) the ice surface drag (surface roughness) could have changed, i.e., the atmosphere to ice energy transfer function can have changed. This could also be caused by a change of internal ice stress, i.e., how lose or compact the ice in FS is.

(iv) the ocean forcing can have changed

I don’t know if these factors can explain the difference to the satellite ice export time series but they should be discussed. Also in the summary it should be mentioned that all conclusion drawn here are based on the air pressure time series presented but that for other available ice export estimates one would get to complete opposite conclusions.

The reviewer states an important point, and we have not tried to “minimize” the sea ice export variability not related to SLP. We agree that there are a number of physical parameters that could have changed over these 80 years, and we have added a better discussion of these points in the new version. All four points are valid, and i) have been quantified based on the Walsh et al (2015) data in Fig. 1 above. We have further extended the discussion of uncertainties based on the Walsh et al. (2015) data below in figure 2. While there is no way to acquire more detailed observations, the Walsh et al (2015) data does provide a simple guide to uncertainties in some of these parameters. The 10-20% variability in March ice concentration translates into a variability of about 10% in sea ice export.

We also agree that the stronger thermal wind forcing during winter (van Angelen et al. 2011) is another explanation for the larger export during winter than estimated by the mSLP. We previously discussed this seasonal difference and attributed it to a

stronger East Greenland Current (EGC, page 5 line 10 – 28). It is also consistent with a stronger thermal wind, and this has now been added. Note that the simulations of van Angelen et al. (2011) did not include an ocean model, so the thermal wind could well explain the stronger current during winter.

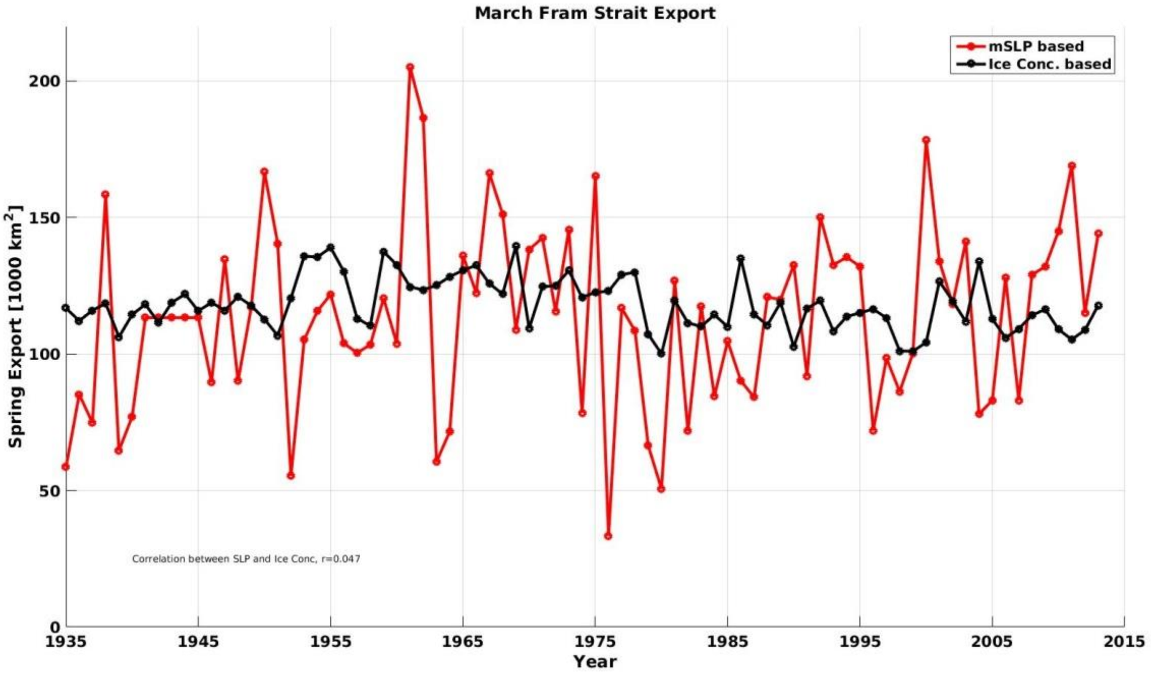

Figure 2: The Fram Strait Ice Area Export in March. The red line shows the SAR + mSLP based time series, while the black line shows the effect of variations in March sea ice concentration, using the mean March Export of 113,000 km².

For iii) the main influence on roughness is probably sea ice concentration as discussed above for the Walsh et al. (2015) data of, and changes thickness. It is likely that before 2004 ice was thicker and moved less effectively for a given mSLP gradient as found by Kwok et al (2013). This would lead to smaller values of ice export prior to 2004, and would thus increase the trend onwards from 1979. Our results remain different from for example Fig. 7 of Kwok et al (2013) that finds a positive trend for summer ice area export (June – September), but not for the annual values. Likewise is a change in ocean forcing iv) possible, but not observations are available to discuss such a change.

The main difference from Kwok et al (2013) is the 2004 – 2014 time period when we have higher export values. In this period we use the observed passive microwave sea ice concentration. This is in short why we wanted to present the “best possible” time series and not the “mSLP based” time series as suggested above.

- In section 4 from 4.2 onwards the sea ice area export time series and the Walsh et al. sea ice extent time series are used to draw quite far reaching conclusion about the influence of the sea ice export increase they find on the recent decrease in Arctic sea ice area. They make the in my view oversimplified assumption that every spring ice export anomaly directly relates to a loss in ice area for the summer sea ice extent. There are many other factors which will influence this relationship, e.g., if the ice gets compressed or more spread out in the Arctic Basin and many more feedbacks the authors are well aware of. One would need a coupled Arctic regional climate model to make more robust conclusions about such relationship. I actually like such simplified speculations in the way of: “If we would assume the ice export anomalies to directly relate to anomalies in Arctic summer ice area this would mean . . .” But here they are presented as hard results and in a very broad way. I recommend to remove most of the discussion related to this in section 4 and concentrate on the new 80 year ice export time series at hand. Some of these hypothetical consequences can then be briefly mentioned at the end of the discussion.

We understand the reviewers point. Specified simulations using a regional climate model could be performed for another way of estimating the effects of the sea ice export variability. Such model simulations are complicated, and have not been performed. Using a dynamical sea ice drift model Williams et al (2016) have actually performed experiments using coastal divergence and Fram Strait export, and find a similar level of influence on the September SIE. We are indeed aware of many other factors influencing September SIE variability, and only stated that between 18% - 22% is caused by the export, apart from in the last 10 years. Our understanding is also based on the long control run from the coupled GFDL model. In a previous version of this paper (Halvorsen at al 2015, The Cryospere Discussions) these model results were included in more detail, and backed up our understanding. They were subsequently removed due to a previous reviewer’s suggestion.

We have rewritten the discussion, removed the speculative parts, and added more text about the link in simulations between September SIE and FS ice export in section 4.6.

The 80 year long air pressure based FS ice export time series by itself merits publication. Some information about the actual sea ice variability from the Walsh et al. dataset should be added. Errors and uncertainties have to be discussed more upfront and also in relation to other published but much shorter ice area export estimates. The mainly speculative discussion about consequences should be reduced and declared more clearly.

Thank you for your interest in the export itself. We agree, but also found that more people are interested in the export if the plausible consequences are also discussed. This is what we attempted to do here.

Minor comments:

p7, l18: for 2011-2013 the export exceeds 1mil sq km.
Corrected.

p8, 3.2: is there a reason for choosing the period 1979-2014 beside that it maximizes the trend found in an on longterm average trend less time series?

The period 1979 – 2014 is when the “high quality passive microwave” sea ice concentration data is available, so our confidence in September SIE is higher for this period than earlier.

p8, l19: in 2011 and 2012 the spring and winter exports are of similar magnitude but not in 2013 and 2014. Exports were on more similar magnitude during the 1940-50s. The reduction in seasonal cycle therefore is only temporarily.
Yes, corrected. We were thinking of the smoothed values here.

p9, l3: I cannot see that Kwok, 2009 uses reanalysis data. They use satellite data.
Kwok (2009) used reanalysis data during the summer months, when the passive microwave data does not allow for “proper” feature tracking. We now cite the new van Angelen et al (2011) instead, that use re-analysis as boundary conditions.

p10, l13-14: In Fig 4 the 1995 export is larger than in 2012. That was also correctly stated before.
The difference comes from the use of calendar year. The Fig. 4 values use 1.September – 31. August.

p11: see also Kwok et al., 2013 for a detailed discussion of AO and ice circulation.
We have included both Hillmer and Jung (2000) for the NAO. In addition, the work by Wu et al (2006), which come to similar conclusions to ours on the AD link, has been included in the discussion in section 4.3.

p11: the purpose and conclusions from 4.3 regarding this manuscript remain a bit unclear to me. Better motivate or remove.

A discussion of the large-scale atmospheric circulation was requested by previous reviewers and reviewer 2. This also relates to the comparison with the long-term variability simulations by Zhang (2015).

p13, l8-9: this is a very strong assumption (no feedbacks considered) and makes all conclusions based on this more hypothesis and speculations. Not a problem but should be clearly called that then and not presented the same way as the results based on the export time series. Could be more like an outlook section.

p13, l26-31: again speculative; the correlation of -0.43 is modest as you correctly say.

Section 4.5 has been substantially revised. The new section 4.5 is a much condensed version of the previous section 4.5, 4.6 and 4.8.

p14, 4.6: here you estimate the influence of one feedback. But there are many others. See e.g. the influence of ice convergence along the CAA contributing to the 2012 minimum. As a fully coupled system I am not sure one can simply separate feedbacks and sum them up again in the end. All feedbacks will interact with each other, there are many non-linear responses. A coupled GCM would be a better approach to evaluate this.

We do agree that dedicated regional simulations could potentially be valuable. What we have at hand are the long runs of the GFDL coupled GCM, which largely confirms that the AD is linked to the export, and further that the export is linked to the September SIE. The other factors that are correctly mentioned here were shortly mentioned on Page 15 (line 21-23). The old section 4.6 was condensed into just one sentence in the new section 4.5.

p15, 4.7: here you look at a GCM but only in relation to AD. Does the GFDL model show high correlations between spring export and summer ice area minima?

A detailed analysis of the GFDL simulations was requested removed by another previous reviewer. Some of this text has been added back now in the new section 4.6 and this perhaps explains partly why this discussion seemed more speculative than it really was.

<u>Reviewer 2 Comments:</u>

This paper attempts to extend the time series of Fram Strait (FS) ice export back to 1935. My primary concern with this paper is the accumulated errors in their regression of ice velocities going back to 1935. Given these uncertainties, I don't think they can make any definitive conclusions based on the extrapolated time series. Details on this concern and other comments are provided below. I suggest rejection of this paper.

1) Standard error about the regression line for equation 1.
The authors state a standard error of the regression line of 3.4 cm/s. Ice velocities are typically 12 cm/s. The error adds up to an ice export uncertainty of +/- 250000 kmˆ2, which is also the variance about the mean of 883000 kmˆ2. Given this uncertainty, it is hard to trust any conclusions drawn on their extrapolated time series, which is foundation of this paper.

The standard error is a statistical estimate of uncertainty, and describes the scatter around the regression line. The scatter is caused by the other factors influencing sea ice drift other than the geostrophic wind, and will be close to normally distributed around the regression line. The method is the same as used in Smedsrud et al (2011), but with 5 years of extended data. The uncertainty will further decrease when averaging into seasons is performed, because some months have slightly higher speed than the regression predicts, and some will have lower. So it is not correct to "add up" the uncertainty as suggested by the reviewer here.

The new study be van Angelen et al. 2011 also find that the SLP gradient is a very useful estimate of Fram Strait Export. Uncertainties for 1935 - 2004 have now been estimated using the Walsh et al (2015) data on ice concentration.

2) Fram Strait SLP Gradient
I think the linear interpolation to estimate pressure to 78N after 1958 is probably OK since the stations are close, but prior to 1958, the southern station may be too far?
The authors need to substantiate the use of the 3 weather stations on Greenland to interpolate SLP at 78N and estimate the across strait pressure gradient. One way to do this is to compare the estimated SLP at 78N based on the regression from Nord to Danmarkshavn, and Nord to Tasillaq during a period when they have data from all 3 stations.

Equation 1 should also be evaluated based on the 2 estimates of dp/dx across the strait to see how much difference the use of the different stations make.

We did perform correlations between the stations as described on page 4, line 11-18. There is relative lower but significant correlation (r=0.77 instead of r =0.93) between Nord and Tasiilaq, and there are no other alternative observations available prior to 1958, so this is the best data we have. The SLP pattern tends to follow the Greenland coast quite well (Fig. 4c in Hilmer & Jung (2000) for example), and what matters here is the East-west SLP gradient, which should be robust. No particular change in variability is visible in Figure 4 before and after 1958.

3) The authors should cite Hilmer and Jung, 2000 "Evidence for a recent change in the link between the North Atlantic Oscillation and Arctic sea ice export", in any discussion of Fram Strait ice flux. I think this is the definitive paper on the topic. Given that HJ cover the period going back to 1958, and many of the authors own papers discuss the period after this to the present. This paper would really have to substantiate their estimates for export prior to 1958 to make an acceptable contribution to the literature.

Thank you for pointing out this paper, it has been cited in the updated version. We find that some of our conclusions are consistent with their results. Prior to 1978 Hilmer

and Jung (2000) used simulations with quite a coarse resolution numerical model driven by another set of simulations (NCEP reanalysis) that are now known to have several issues in the Arctic. We therefore have more confidence in our own results for the early time period, as they are directly based on observations. Note that both the “missing” link between NAO and winter export, and a (not discussed) long term trend 1958 – 1997 is qualitatively consistent with our results. We used the AO index in our discussion (page 11) instead of the NAO, as it is a better index for the Arctic large scale atmospheric circulation and is also highly correlated with the NAO.

Fram Strait sea ice export variability and September Arctic sea ice extent over the last 80 years

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This version shows the new text after review marked using red bold font.

Abstract. **A new long-term data record of Fram Strait sea ice area export from 1935 to 2014 is developed using a combination of satellite radar images and station observations of surface pressure across Fram Strait. This data record shows that the long-term annual mean export is about 880,000 km², representing 10 % of the sea-ice covered area inside the basin. The time series has large inter-annual and multi-decadal variability, but no long term trend. However, during the last decades, the amount of ice exported has increased**, with several years having annual ice exports that exceed 1 million km². **This increase is a result of faster southward ice drift speeds due to stronger southward geostrophic winds**, largely explained by increasing surface pressure over Greenland. Evaluating the trend onwards from 1979 reveals an increase in annual ice export of about +6% per decade, with spring and summer showing larger changes in ice export (+11% per decade) compared to autumn and winter (+2.6 % per decade). During winter, increased ice export results in growth of new and relatively thin ice inside the basin, while during summer or spring, export contributes directly to open water further north that enhances the ice-albedo feedback **in** summer, both in turn leading to reduced summer sea ice extent. **During periods with low export in spring and summer, such as from 1950 to 1970, mid-September sea ice extent was consistently higher. Our results further strengthen suggested links between** export anomalies and the following September sea ice for the recent decade, **and support a moderate influence in general**.

1 Introduction

Along with expectations for a warming planet, the spatial extent of the Arctic sea ice cover has declined. This is especially apparent during the last two decades as the Arctic sea ice cover has become both thinner and smaller in extent (**Lindsay and Schweiger, 2015;** Comiso 2012; Stroeve et al., 2012). In September 2012, the lowest September sea ice extent (SIE) since the satellite record started in 1979 occurred. The 2012 minimum was 16 % lower than in 2007, and 44 % below the 1981-2010 average minimum. While the ice recovered somewhat after 2012, **including this summer, the 10** lowest September sea ice extents have all occurred in the **last 10 years**. A number of processes have been suggested to explain the ice loss, but both observations and simulations from global climate models point to **an increasing influence of warming from** greenhouse gas forcing as a **dominant** driver of the observed sea ice loss (Stroeve and Notz, 2015; Kay et al., 2011). Natural variability has also played a role, including increased poleward transport of heat in both the ocean and atmosphere (Graversen et al 2011, Zhang 2015), an increase in **downwelling** longwave radiation due to cloud cover (Francis et al., 2005)

and changes in atmospheric circulation that enhance ice export out of the Arctic (Nghiem et al., 2007; Smedsrud et al., 2011). Yet, despite the large number of existing studies, the role and influence of natural variability remains unclear, especially on longer time-scales **than the current satellite data record.**

Historically, about 10 % of the Arctic sea ice area is exported through Fram Strait (FS) annually (Fig. 1), and the ice export through the other Arctic gateways are an order of magnitude smaller (Kwok 2009). Because quite thick ice is lost by this export through FS (Hansen et al., 2013), a larger than normal ice export will decrease the remaining mean thickness within the Arctic Basin. An influence of export anomalies on Arctic sea ice thickness was previously suggested by Rigor et al. (2002) using buoy data. A similar conclusion was reached using model simulations from climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Langehaug et al., 2013). Recently Fučkar et al. (2015) found that much of the Northern Hemisphere sea ice thickness variability could be explained by changes in sea ice motion related to wind forcing.

Several studies have suggested that sea ice drift speeds are increasing, both within the Arctic Basin (Hakkinen et al., 2008; Rampal et al., 2009), and also in FS (Rampal et al., 2009, Smedsrud et al., 2011). Positive trends were also found in the annual FS ice area export by Widell et al. (2003) (4 % per decade from 1950 - 2000) and Smedsrud et al. (2011) (5 % per decade from 1957 - 2010). Using the available NSIDC sea ice drift data, Krumpen et al (2016) recently found a much higher trend for 1980-2012 (37.6 % per decade), but noted that the large positive trend seemed “unrealistic”. However, contrary to these studies, Kwok et al. (2013) found a small negative trend in annual FS ice area export between 1982 and 2009, but with positive trends for 2001 – 2009 for both annual (October - September) and summer (June - September). Spreen et al. (2009) did not observe any significant change in FS ice volume export for the period 2003 – 2008 for observed winter means (October – April). Thus, there remains some uncertainty exactly how export through FS has changed and how it has influenced the long-term decline in the summer ice cover.

The Arctic seasonal maximum sea ice cover generally occurs in late February or early March (Zwally and Gloersen 2008), though it has also been observed to occur as late as early April (e.g. on April 2 in 2010; **https://nsidc.org/arcticseaicenews/2010/04**). Changes in ice export through FS between March and August could therefore influence the following September SIE by fostering development of open water within the icepack that in turn enhances the ice-albedo feedback during the melt season (Smedsrud et al., 2011; Kwok and Cunningham 2010). Such an influence has recently been examined between 1993 and 2012 by Williams et al. (2016) in combination with coastal divergence. **This study suggested that Fram Strait ice area export is a good predictor for the September sea ice extent because it represents the sum of ice export from the peripheral seas and the net pack ice divergence. This study expands on the work by Williams et al. (2016) by estimating the FS ice area export over a much longer time-period, from 1935 to 2014. In this study,** we evaluate the long-term mean, variability and trends over this 80 year record, and further examine the influence of the long-term FS export on a new time-series of September SIE, also covering the years 1935-2014 (Walsh et al. 2015).

2 Data and Methods

In this study we rely on a combination of ice drift speeds estimated from Envisat Advanced Synthetic Aperture Radar (ASAR) WideSwath and Radarsat-2 ScanSAR (from 2012) images and monthly mean sea level pressure differences across Fram Strait to construct a long-term data record of FS ice export.

2.1 Ice Drift observations: 2004-2014

We use observed sea ice drift speeds onwards from February 2004 and updated through December 2014, calculated by recognizing displacement vectors manually on ASAR WideSwath and Radarsat-2 ScanSAR images captured 3 days apart (Kloster and Sandven 2014). **These images were resampled from 50-100 m to 300-500m pixels in order to reduce the SAR speckle noise, greatly improving feature recognition and tracking accuracy over the 3 day time interval.** Displacement vectors that cross 79°N were linearly interpolated to bins (1° longitude, each 21 km) from 15°W to 5°E (Fig. 3).

For most 3 days image pairs, displacement vectors with **an accuracy of ±2 km and spacing of 30 – 50 km were calculated using the known satellite orbit and one reference point. Drifting platforms and buoys were used to estimate uncertainties, indicating values better than ±3%.** This accuracy is considered sufficient because subsequent averaging or addition in time/space of many unbiased vectors will generally result in improved accuracy. We only used monthly mean cross-strait ice drift speed values, defined as the spatial-temporal mean southward speed of all ice crossing 79°N (Fig. 1) between the fast ice edge and the pack ice edge at 50 % sea ice concentration. On the western side of the strait, a linear interpolation from zero motion in the stable fast ice to the first measured motion vector was made. It was assumed that ice displacement to the east of the last measured vector is constant near the ice edge. The monthly mean speed value results from the averaging of about 50 individual, unbiased displacement vectors, thus the calculated mean speed value should have an accuracy better than **±0.1 cm/s.**

Using the mean drift speeds as derived above, corresponding FS ice area export along 79°N was calculated as the product of sea ice drift and passive microwave sea ice concentration (Kloster and Sandven 2014). **The combined uncertainty of the passive microwave sea ice concentration and ice speed is about ±5% in the 3-day fluxes. We use values summarized over a month or season here (cumulative values) and the uncertainty for these values are further reduced because uncertainties become lower with a larger number of samples. A spring ice area export value of 500,000 km^2 is the sum of 60 3-day values from March 1 to August 31, and has an estimated uncertainty better than ± 5,000 km^2.** From here on, ice area export will be referred to as ice export.

2.2 Sea Level Pressure observations: 1935-2014

To extend the time-period, observed monthly mean Sea Level Pressure (mSLP) values were used onwards from 1935 to estimate ice export prior to the ASAR data starting in February 2004. The cross-strait difference along 78°N was calculated between 18°W and 15°E based on monthly mSLP observations from Longyearbyen (Fig. 3, Svalbard Airport, Norwegian Meteorological Institute, http://eklima.met.no) and from weighted averages of monthly mSLP from two nearby stations on the Greenland side at 18°W; Danmarkshavn and Nord (Fig. 3, Danish Meteorological Institute, Cappelen 2014). mSLP is available from Danmarkshavn and Nord back to 1958. For the 1935-1958 period, a linear regression between Nord and Tasiilaq further south was performed.

The mSLP observations were then used to calculate cross-strait geostrophic winds following (Thorndike and Colony 1982). Because mSLP from Danmarkshavn and Nord correlated well (r=0.93), we derived a linearly interpolated value at 78°N,18°W directly using these stations onwards from 1958. For the period 1935-1958, interpolated values between station Nord and Tasiilaq were used, which have a somewhat lower correlation (r=0.77). Our method assumes that wind and ocean drag are the dominant forces acting on the sea ice, consistent with geostrophic winds explaining more than 70 % of the variance of ice drift speed in the Arctic Ocean (Thorndike and Colony 1982). In the FS, winds have also been found to be the dominant force acting on sea ice (Widell et al., 2003), and the cross strait pressure difference in SLP well represents the ice drift on a daily time-scale (Tsukernik et al., 2009). **On the other hand, van Angelen et al. (2011) simulated local Fram Strait surface winds and found them more related to thermal wind forcing than larger scale forcing. Nevertheless, they found that ice export for individual years from 1979 to 2007 was better explained by large-scale forcing because thermal winds were mostly constant between years.**

2.3 Blended Ice Drift and Export: 1935-2014

We next evaluate the relationship between the observed SAR ice drift speed and the geostrophic wind since 2004 **to verify the use of mSLP to extend the record prior to 2004.** A linear regression between monthly mean ice drift speed and geostrophic wind **from 2004 to 2014** (r=0.77, with 95 % confidence interval [0.68, 0.83]) reveals that the ice in FS generally drifts at a speed that is 1.6 % of the geostrophic wind speed (Eq. 1). The constant contribution resulting from the linear regression represents the speed of the ice given no local wind forcing, and is 6.7 cm/s (eq.1). In other words, the value of 6.7 cm/s represents the mean ocean current, though nonlinear components of ice drift, including forces from variations in ocean currents or internal ice stress may also represent parts of this constant (Thorndike and Colony 1982). It is important to note however, it is not the locally wind-driven, ocean current. Both the mean drift speed and the mean ocean current are comparable to previous studies (Widell et al., 2003; Smedsrud et al., 2011; Thorndike and Colony 1982). The standard error of the regression is 3.4 cm/s.

$$V_{ice} = 0.016 \times V_g + 0.067 \ \ [\text{m/s}]. \qquad (1)$$

If sea ice concentration does not change systematically inside the ice pack locally, we expect a similar relationship between mSLP and sea ice export. This was indeed what we found, with a correlation between the cross-strait mSLP and ice export of r=0.73.

The annual cycle of mSLP-based ice speed and export is similar to earlier estimates, with higher speeds during winter, and weaker during summer (Kwok 2009). The annual mean speed is close to 12 cm/s (Fig. 2), which is a spatially averaged value between 15°W and 5°W, and a temporal average for the years 2004-2014.

However, a clear seasonal difference is observed between the SAR ice speed and the mSLP-estimated ice speed (Fig. 2). Previously it was assumed that the mean ocean current would be constant throughout the year (Kwok 2009; Smedsrud et al., 2011), e.g. 6.7 cm/s from eq. 1. However, based on the 10 years of detailed SAR velocities, we instead find it is necessary to account for the seasonality of the mean ocean current in order to match the mSLP-derived ice drift with the SAR data. The suggested seasonal change is a mean winter current (December – April) of 9.5 cm/s, and a mean summer current of 3.9 cm/s (June – October). The East Greenland Current (EGC) thus appears 2.8 cm/s stronger than the mean during winter, and 2.8 cm/s weaker during summer. Note that this seasonal difference cannot be explained by a seasonally varying internal ice stress, because ice is thicker and denser during winter, which would result in a larger ice stress and therefore weaker ice drift speed for a similar wind speed.

An increase in the EGC would be consistent with generally stronger winds in the North Atlantic region during winter, **and also stronger thermal forcing (van Angelen et al., 2011)**. This suggests that the EGC is responding to the larger scale wind-forcing as well as to the local winds. Generally, the entire circulation along the continental slope of the Arctic Basin - Nordic Seas is driven by the wind-stress curl north of the Greenland-Scotland ridge (Isachsen et al., 2003). Two recent studies confirm that the EGC is stronger during winter, and **may** respond to the large-scale wind stress curl in the Nordic Seas **or the stronger thermal forcing during winter**. It is thus likely that this increase is causing the additional winter export (Fig. 2). de Steur et al. (2014) analyzed mooring data along 79°N between 1997 and 2009, and found that surface currents were below 5 cm/s during summer and 10-15 cm/s during winter, also varying in the east-west direction. Daniault et al. (2011) found a maximum in the flow in January and a minimum in July for the years 1992-2009 based on satellite radar altimetry data at 60°N, and that the vertical distribution remained constant over this time period.

The above studies support a bias-correction for the constant EGC speed in eq. 1 to increase (decrease) the mSLP-based winter (summer) ice speeds. Thus, assuming a stronger EGC during winter, and weaker during summer, we added the seasonal difference to the time-series of mSLP-based ice speed. This means that in eq. 1, we add 2.8 cm/s to the constant 6.7 cm/s for the months December through April, and subtract 2.8 cm/s from the constant 6.7 cm/s for June through October, while May and November remained unchanged. This bias corrected mSLP-based ice speed better matches the SAR observations (Fig. 2), with a correlation of r=0.88. The same correction was also applied for the calculated ice export, representing a decrease in summer values of 23,800 km² and increase in winter values of 22,400 km² accordingly (not shown). The seasonal correction further improves the correlations between observed and mSLP-based ice export (r=0.87). In other words, we expect our bias-corrected mSLP based time-series from 1935 to 2004 to explain about 80 % of the “true” ice drift and export variability. **Using high resolution wind simulation, van Angelen et al. (2011) found a similar correlation (r=0.85) between annual export and surface wind for 1979 – 2007. Our described seasonal correction is also consistent with their simulated stronger thermal forcing during winter that would set up a sea surface gradient and drive a related stronger barotropic ocean current.**

Taking into account the seasonally varying EGC and thermal wind explained above, in addition to the monthly varying geostrophic winds based on observed mSLP, we calculate monthly mean ice export prior to 2004 and blend them with the SAR-based observed ice export from 2004 to 2014. This generates an 80-year long record of monthly mean FS ice export.

2.4 Sea Ice Extent

Finally, a newly blended historical and modern record of sea ice concentrations is now available from the National Snow and Ice Data Center (NSIDC), the “Gridded monthly sea ice extent and concentration, 1850 onwards” (Walsh et al., 2015). This data set is an improvement upon an earlier historical record from Chapman and Walsh (1991), and provides mid-month sea ice concentrations on a 0.25 x 0.25 degrees grid **(Walsh et al., 2016).** A total of 16 different sources of information were used to construct ice cover information back to 1850. Prior to the modern satellite data record, which began in October 1978 from a series of successive passive microwave sensors (e.g. the Scanning Multichannel Microwave Radiometer (SMMR) and several Special Sensor Microwave/Imager (SSM/I) and SSMIS sensors), observations come from earlier satellite missions, aircraft and ship observations, compilations by naval oceanographers, ice charts from national ice services, and whaling log records, among others. For many regions and time-periods several sources of sea ice data and weighting was applied **(Walsh et al., 2016)**. The monthly files are intended to represent ice on the 15th or 16th of each month using the NASA Team sea ice algorithm. Using this data set, the ice extent is defined as the area covered by ice of greater than 15 % ice concentration.

Initial evaluation of the data set indicated a problem with inconsistencies in the land mask applied throughout the entire time-period. This was fixed and led to a slight reduction in the overall sea ice extent prior to the satellite data record. To evaluate how ice export influences changes in sea ice cover within the Arctic basin, we use an Arctic Ocean Domain mask as defined in Serreze et al. (2007) and compute sea ice extent within this domain only (Fig. 1). For the September SIE time-series this mainly excluded the Greenland Sea downstream of the FS ice export, where we expect high export to contribute to a larger ice cover.

The mid-month sea ice concentration from Walsh et al. (2015) along 79°N is used to estimate uncertainties in the 80-year long record of monthly mean FS ice export in section 4. Importantly monthly and seasonally trends in ice concentration are small or non-existing within Fram Strait (15°W to 5°E). Additionally, correlations between sea ice concentrations and export are close to zero, suggesting no systematic influence of the geostrophic winds on the sea ice concentration.

3 Results

3.1 Long-term (1935-2014) Annual Mean Ice Export Variability and Trends

Figure 3 shows that the temporal mean ice drift speed is quite constant spatially across the FS eastward of 5°W, and that the speed decreases westward towards the Greenland coast. Velocities are clearly strongest during winter with mean speeds above 20 cm/s, decreasing to less than 10 cm/s during summer eastward of 5°W. FS ice drift is in the south-southwesterly direction steered by the Greenland Coast. The ice export occurs mostly between 5°W and the Greenwich Meridian. The export is limited on the western side by the decreasing ice speed, reaching zero at 16°W, where stationary land fast ice is usually found. On the eastern side the ice export is limited by zero concentration varying from 5°W to 5°E (not shown).

The 1935-2014 long-term annual FS sea ice export, defined as September 1 to August 31, is on average 883,000 km², and ranges from 0.6 to 1.2 million km² (Fig. 4). Winter export is defined as September through February and has a long-term mean of 528,000 km². We define spring export as March through August, and the mean value is 354,000 km². Note that the 1935-2014 long-term annual mean ice export of 883,000 km² is 25 % higher than previously found by Kwok (2009) using data from 1979 to 2007, but similar to values from Thorndike and Colony (1984), Widell et al. (2003) for 1950-2000 and Smedsrud et al. (2011) for the period 1957 to 2011.

The consequences of the export variability are discussed later, here we just note that since 2006, ice export has remained higher than the long-term mean (Fig. 4), and that for 2011-2013, the annual export exceeded 1 million km². In addition, there are a number of notable export events in the 80-year time series. Note that there are no mSLP values observed during WWII, so the seemingly constant values from 1940 to 1945 are set identical to the long term mean annual values. The lowest annual export occurred in 1946 with only 599,000 km² exported, and the highest export with 1,206,000 km² was in 1995.

The annual and seasonal trends appear robust, and no systematic difference appears by merging the mSLP based values prior to 2004 with the SAR-based values since 2004. This was **confirmed** by comparing trends for the merged time series (1935-2014) with those based on the observed mSLP only (1935-2014). For example, the mSLP-based annual trend is 0.2 versus 0.3 % per decade for the merged values, while for winter the values are 1.1 versus 1.6 % per decade, and spring -0.8 versus -1.3 % per decade. These long-term trends are small and not significantly different from zero (p =0.2), and are therefore not included in Fig. 4. We also searched for specific cycles, or frequencies, in the new 80-year time series. Apart from the obvious annual cycle (Fig. 2) we could not find any special peaks in calculated spectrums of the annual, winter or spring export (not shown). The smoothed time series appeared similar for cut-off frequencies representing cycles above 10 years, so we chose to show a 20-year cut-off (or frequency of 0.05 cycles/year) in Fig. 4. Overall the variations are similar for the annual and spring export values, while there is less long-term variability in the winter export. For the smoothed series there is a distinct peak in annual and spring export between 1951 and 1954. After 1954, there is a decrease in annual and spring export until the mid 1980’s, and an overall increase onwards to 2014. Thus, there is a hint of a long-term multidecadal oscillation with a period around 70-years.

3.2 Recent (1979-2014) Ice Export Variability and Trends

The increasing exports onwards from the 1980’s create statistically significant positive trends for both the annual and seasonal values **over the modern satellite data record, and the time-period for which large declines in sea ice have been observed.** For example, from 1979 to 2014 we find a positive trend in annual export of +5.9 % (p=0.025) per decade (Fig. 4). This trend is consistent with a general increase in ice drift speed observed well inside the deep Arctic Basin (Fig. 1, Spreen et al., 2011, Rampal et al., 2009), but the small number of buoys exiting in FS have precluded estimating trends there. The positive trend in annual ice export from 1979 to 2014 is largely driven by higher ice export during spring: the winter ice export trend is +3.0 % (p=0.213) per decade, while the spring export trend is +11.1 % (p=0.011) per decade (Fig. 4).

The increasing spring export since 1979 may have important **implications for the sea ice cover**, and we therefore analyze this time-period further to make sure no biases are introduced by using the blended mSLP + SAR export fields. Trends are found to be similar between the merged (mSLP + SAR) and mSLP based time-series, with a positive trend in spring export of 13.1 % (±6.8) per decade from the mSLP only based estimates, and a trend of 11.1 % (±8.1) per decade using the merged time-series. These trends are not significantly different at the 95 % confidence level. Note that around 1980, the spring export was approximately half of the winter export. The robust trend in spring export since 1980 has resulted in a smaller seasonal difference, and **for 2011 and 2012**, the export in winter and spring **were** of similar magnitude (Fig. 4). The recent high values could perhaps be surprising, were it not for the longer time-series where a similar high spring export is evident in the 1950’s.

We also do not find a “shift” in the trends after 2004 when the SAR values are used. For example, the spring 1979 - 2003 trend is +9.1 % (±11.3) per decade, almost as high as the 11.1 % for the 1979-2014 period. So the spring export is the main cause of increased annual export before and after 2003, and the differences are not significant at the 95 % confidence level. Due to the few years and large variability, the **~20 year trends are generally** not significantly different from zero (p>0.05). The annual trend for 1979 – 2003 is 3.8 % (p=0.36), compared to 5.9 % for 1979-2014, and for winter 0.8 % (p=0.84), compared to 2.6 % for 1979 – 2014. This indicates that the export trends since 1979 are related to a gradual increase in mSLP across FS over most of this period. The increased spring ice export is due to stronger geostrophic winds, driven by an increase of 0.53 hPa per decade in mSLP over Greenland between 1979 and 2014. The increase in SLP is strongest in June – August, and covers the larger part of Greenland (not shown). The mSLP trend on the Svalbard side is a slightly lower and negative trend, is strongest in March – May, and covers the larger part of the Barents Sea (not shown).

4 Discussion

In this study we use station mSLP data, rather than values derived from atmospheric reanalysis data sets **and simulations** (Smedsrud et al., 2011, Widell et al., 2003; **van Angelen et al., 2011**), because we discovered unexplained systematic differences between NCEP reanalysis mSLP fields and observed mSLP within the FS in recent years. Despite the wide use of reanalysis data sets, they are heavily influenced by the numerical model used to simulate the fields, and they are therefore regarded as less accurate than the station data used in this study.

Prior to 2004 we do not utilize observations of cross-strait variations in the width of the ice covered area, ice speed or ice concentrations, but base our ice export values solely on the regression equation found between observed mSLP from Longyearbyen, station Nord, Danmarkshavn and Tasiilaq (Fig. 3) and observed SAR ice export. **The new Walsh et al (2015) mid-month sea ice concentration provided a possibility to estimate the uncertainty, but this data is mostly based on** sea ice extent **estimates before 1979**. Using the observed mSLP values is therefore the only consistent way to calculate ice export over the last 80-years. **There are possible systematic contributions to the overall uncertainty from a number of factors, like sea ice roughness, the ocean current, the thermal wind, and the sea ice thickness and concentration. Our best estimate for the uncertainty in the seasonal spring and winter means is about 10%, i.e. 354,000 km² ± 35,000 km² for spring, and 528,000 km² ± 52,000 km². This is based on the seasonal mean ice concentration between 15°W and 5°E along 79°N in the Walsh et al (2015) data, showing winter concentration of 83% with std. ±11%, and spring concentration close to 72% with std. ±9% (not shown). There is no long-term trend in sea ice concentration for the spring months. For the winter months there is a small, but not significant trend (-0.9 % per decade) cause by higher values prior to 1979 when the Walsh et al. (2015) data are based on very few observations.**

4.1 Long-term variability of September SIE

The mid-September SIE time series shows two stages, a modest increase from 1935 until around 1965, and then a monotonic decrease over the last 50 years (Fig. 5). There is a "break-point" around the mid 1990's when the September SIE loss accelerates as has been noted earlier (Stroeve et al., 2012). From the mid 1960's until the mid 1990's the loss in SIE is small. The minimum SIE value pre-dating 1995 occurs in 1952, and the last two minima in 2007 and 2012 are also clearly visible (Fig. 5). The overall mid-September SIE maximum occurred in 1963.

Evaluating 30-year trends for successive 30-year periods, along with the standard errors shows distinct periods of ice loss and ice gain (Fig. 6). From the 1950s to 1967, trends are positive and then become negative. The long-term 1935-1990 trend is essentially 0, in stark contrast to the 1991 to 2013 trend, which is strongly negative. The last 7 consecutive 30-year trends are significantly different from trend periods before 1990 (Fig. 6), **and thus the September ice loss since the 1990s is unprecedented as far back as 1850 (Walsh et al., 2016).**

4.2 Effects of long-term variability and trends in ice export

Our ice export values are largely consistent with previous studies on FS ice export for the recent decades (Kwok et al., 2013; Spreen et al., 2009; Smedsrud et al., 2011). The year-to-year variability is of the same order, and the maximum and minimum values are also similar. The largest difference to the Smedsrud et al. (2011) export values is that the time series is updated to 2014 and now extends back to 1935. In addition, there is no overall long-term linear trend in annual export.

The effect of sea ice drift variability on the Arctic sea ice cover in general has been recognized for a long time (Thorndike and Colony 1982). Rigor et al (2002) used drifting buoy data from 1979 to 1998, and found a systematic change between the 1980's and 1990's driven by the large scale atmospheric forcing. During the 1980's the Beaufort gyre was large, the ice stayed inside the Arctic Basin for several years, and FS sea ice export was low, contributing to a thicker ice cover. In the 1990's the Beaufort gyre weakened, ice drift was more directly from the Siberian coast to FS, and the FS sea ice export was higher. Our results are consistent with Rigor et al. (2002) in that the annual export was lower during the 1980's (810,000 km²) than during the 1990's (890,000 km²). The overall maximum annual export in a calendar year occurred in 2012 with a value of 1,176,000 km², but the second largest calendar year export occurred in 1995 (1,131,000 km²). Note that these values are a little different from those plotted in Figure 2, which show the winter + spring export from September 1 through August 31.

One suggested mechanism for the rapid decline in summer Arctic SIE is that a larger winter export could create a larger fraction of thin first year ice that is more prone to melting out the following summer. In addition, first year ice is smoother than thick and old ice, and may allow for larger fractions of melt ponds during summer (Landy et al., 2015). Schröder et al. (2014) found a strong correlation between such simulated spring melt pond fraction and September Arctic SIE. However, in this study we find that the correlation between winter ice export and the following September SIE is modest (r=-0.26 between 1979-2014.). Thus, the small increase in winter ice export over the last 35 years (2.6 % per decade) suggests that summer ice loss is not particularly sensitive to winter sea ice export. Because the winter export is larger than the spring export (Fig. 2) there has generally been a clear connection between annual and winter export anomalies. Yet while there is little change in winter export, there has been a notable increase in the spring export, i.e. after the Arctic seasonal maximum SIE occurs in late February or early March. In fact in recent years, the spring export has been almost as large as the winter export (Fig. 4). **An increase in summer ice export (June-September) for 2000-2010 was already noted by Kwok et al (2013), and here we show that this is part of a longer trend.** We turn our attention towards the increasing spring export in section 4.5, but first examine the cause of the variability in the larger atmospheric circulation.

4.3 Influence of large-scale atmospheric circulation

Rigor et al. (2002) concluded that annual FS export correlated well with the Arctic Oscillation (AO) index during the 1980's and 1990's, and found a 10 % increase of FS export with an AO index of +1. The response was most apparent for the winter (DJF) AO index and the winter ice export. Examining our longer time series, this relationship does not appear stationary in time, and since 2000, the AO index has fluctuated around zero, while the FS export has remained at anomalously high levels. The maximum DJF AO value occurred in 1989, not related to a peak in the annual FS export. Over the 80 year time-series we find that the winter AO index is not a good indicator of winter FS ice export, the correlation is as low as *r=0.19* (using DJF AO, and winter export (SONDJF), and only increases to *r=0.22* if the winter AO index is also calculated for SONDJF. This is not surprising because the AO spatial pattern does not exhibit strong pressure gradients in the FS (not shown). **The lack of a consistent long-term relationship between FS export and the AO index is consistent with Hilmer and Jung (2000). They found no correlation between the winter North Atlantic Oscillation index (NAO, which closely resembles the AO), and winter FS ice export for the period 1958 – 1977, but higher correlations for 1978-1997, again consistent with Rigor et al. (2002).**

Other studies have suggested FS export is more strongly linked to a SLP dipole pattern than the AO (Tsukernik et al., 2009). They found that on a daily time scale, the atmospheric circulation pattern responsible for the **export anomalies from 1979 to 2006 was** a dipole between the Barents Sea (low pressure) and Greenland (high pressure). The ice motion was maximized at 0-lag, persisted year-round, and over time scales of 10–60 days. This SLP dipole pattern emerged from the second empirical orthogonal function (EOF) of daily SLP anomalies in both winter and summer, with maximum correlation east and west of the FS. An implication of this result is to use station based observed cross-strait SLP pressure gradient like we have done here.

The observed cross-strait SLP gradient, the dipole pattern analyzed by Tsukernik et al. (2009) and the Arctic Dipole (AD) are similar expressions of varying strength of the southerly winds in FS **(Wu et al., 2006)**. The AD has been suggested previously as a major driver of the record low Arctic summer SIE in 2007 (Wang et al., 2009) and was defined as the second leading mode (PC2) of spring (April-July) SLP anomalies within the Arctic Circle. **In this study, we define** a positive AD pattern as having a positive SLP anomaly over Greenland and a negative SLP anomaly over the Kara and Laptev Seas, a pattern which enhances transpolar ice drift. We calculate the AD index onwards from 1948 using the NCEP/NCAR reanalysis data, for which data are not available before 1948. The observed AD index and spring export correlates ($r_{AD-FS\ ice\ export} = 0.45$) over the longer period 1948-2014 (Fig. 7), **as well as over the shorter satellite data record** ($r_{AD-FS\ ice\ export} = 0.44$ for 1979-2014). **These correlations suggest the** AD explains part of the FS ice export variability, but that the cross-strait SLP gradient remains the best predictor of the local wind forcing and therefore FS sea ice drift. **These results substantiate the results of Wu et al. (2006) that found a similar link for FS ice motion and the AD using**

buoy data from 1979 – 1998. In future projections, high rates of summer Arctic sea ice loss are also associated with enhanced transpolar drift and FS ice export driven by changing sea level pressure patterns (Wettstein et al., 2014). Wettstein at al. (2014) found co-varying atmospheric circulation patterns resembling the AD, with maximum amplitude between April and July.

4.4 High annual export during the last decade

Our updated time series shows large annual values of Arctic sea ice export during the last decade. The same SAR-based export values used here were previously used by Smedsrud et al. (2011) for 2004 – 2010, but 2011, 2012 and 2013 had un-reported annual exports above 1 million km² (Fig. 4). A comparison between SAR-based and passive microwave-based drift speeds gave mostly similar values for both methods since 2007, but indicated some high export events that are only detected using the SAR-based drift speeds (Smedsrud et al., 2011). This is likely the major explanation for the difference between previous passive microwave-based export values (Kwok 2009) and our results. **Note that Kwok et al. (2013) does find a positive trend for annual export for 2001 – 2009, and the values are lower.** We believe that the cause of the differences primarily results from the coarse resolution of the passive satellite observations missing some high-speed export events during winter. We speculate that high sea-ice concentrations in the FS make it difficult to track individual sea ice floes using the coarser resolution passive microwave images **as done by Kwok et al. (2013)**.

The Arctic Basin covers an area of about 7.8 million km², and has been fully ice covered from November through May since 1979. The annual ice export during the 1980's (~800,000 km²) was 10 % of this winter ice covered area. However, during the last seven years (2007-2014) the mean annual ice export increased to nearly 1 million km², representing 13 % of this area. This is the relative ice export, or the large-scale divergence of the Arctic Basin sea ice cover; the export divided by the area covered by sea ice.

If the sea ice cover decreases and the export remains constant, the divergence, or the relative export, increases too. The observed increase in export represents a 30 % increase in the relative area export, but with a smaller annual mean ice covered area inside the Arctic Basin the increase rises to about 40 %. This value is based on using a 1 million km² in export and a mean annual ice covered area inside the Arctic Basin of 7.0 million km² for the last 7 years (2007 – 2014). Such an increase in export is expected to contribute towards both a thinner and smaller Arctic ice cover in general (Langehaug et al.., 2013), because older and thicker sea ice than the Arctic Basin average is transported southward through FS. During winter, the open water anomalies created within the basin quickly refreeze, and thus, an impact of the modestly increased winter ice export since 1979 has likely been towards a thinner ice cover (Lindsay and Schweiger 2015). This is consistent with Fučkar et al. (2015) who found that a reduction of the FS winter export related to their Canadian-Siberian Dipole cluster explains a thickening over most of the Arctic Basin between 0.2 – 0.5 m. This cluster is the one with the largest change in FS export and explains 28.6 % of the variability, while the other two clusters mostly describe divergence within the Basin. **Williams et al. (2016) recently found a clear link between FS area export anomalies and September SIE (r=0.72) for the years 1993-2014, and that export anomalies from February until June contributed to the following September SIE. We therefore proceed with a discussion of the spring export that has increased since 1979.**

4.5 Consequences of spring Fram Strait ice export anomalies

The later in the season the export anomaly occurs, the stronger effect one might expect on the September minimum SIE. But working against this, is the overall decrease in export from March towards August (Fig. 2). However, even if there is some re-growth in March, April and May, from increased spring export, the newly formed ice will be thin and have a thin snow cover, and therefore likely melt more easily and deform later the same season. The transition from winter and re-freezing, to summer and positive ice-albedo feedback, occurs gradually later in the year as one moves north, but melting will prevail over most of the Arctic Basin onwards from May (Markus et al., 2009). **Williams et al. (2016) found that FS export anomalies are a better predictor for the September SIE than coastal divergence between 1993 and 2014. This was caused by the ice export being a good estimate also for the net perennial pack ice divergence. Our results confirm their findings for the last two decades, but we also find a more moderate link for the entire 80 year period. For the recent ten years (2004-2014) when our ice export values are directly observed by SAR the de-trended anti-correlation is** $r_{FS\ ice\ export-Sept\ SIE} = -0.74$ **(Table 1), similar to Williams et al. (2016). For the last 20 years we get a more modest influence (r=-0.47), and for the entire 80 year period we get r=-0.43 (Table 1). The explained general variance is thus in the range 15-20 %.**

The increase in spring FS ice export from the 1980's – 2010 was on the order of 200,000 km^2 (Fig. 4). Meanwhile the September SIE decreased by about 2.0 million km^2 (Fig. 5). It is thus a similar magnitude of influence, about 10 %, between the direct change in spring FS ice export compared to the anomalies in September SIE themselves, as found based on the anti-correlations in Table 1.

Any perturbations in Arctic sea ice cover may be further enhanced by positive feedback mechanisms. **Two strong positive feedbacks that enhance summer ice loss are** the ice-albedo feedback (Perovich et al., 2007) and **the smaller resistance of thinner ice to wind driven ridging** (Rampal et al.., 2009, **Hutchings and Perovich 2015**). Since 1979 melt onset **also** begins about 10 days earlier than it used to inside the Arctic Basin**, allowing for earlier development of open water** (Stroeve et al., 2014). Using observed solar forcing from the North Pole stations (Björk and Söderkvist 2002) and representative change in surface albedo and open water area (Perovich et al., 2007), **we estimate that an additional ice area exported during spring (March – August) of 200,000 km^2 can lead to melting of about 400,000 km^2 of a 1.5 m thick sea ice cover (Zygmuntowska et al., 2014). The ice-albedo feedback thus has the potential to increase initial open water areas to a total of 600,000 km^2, or explain about 25 % of the total 2.5 million km^2 loss of September SIE since the 1980's.**

4.6 Other drivers of September Sea Ice Extent variability

Finally, a large number of processes have likely contributed to the September SIE variability over the last 80 years. Among these are advection of heat towards the Arctic in the ocean and the atmosphere, sea ice divergence within the Arctic Ocean, increased greenhouse gases of the atmosphere, and also changes in sea ice export. From the above discussion the influence from ice export appears to be generally between 10-20 %. For individual years like 2007, sea ice divergence is found to be an important factor (Hutchings and Perovich, 2015), while the influence from atmospheric and oceanic heat transport is further discussed below.

Using coupled climate model simulations, Zhang (2015) identified the northward Atlantic heat transport, Pacific heat transport, and the spring Arctic Dipole as the main predictors of low-frequency variability of summer Arctic SIE. The study focused on variability longer than 30 years, and used a 3,600-year segment of the pre-industrial control simulation from the Geophysical Fluid Dynamics Laboratory (GFDL) Coupled Model version 2.1 (CM2.1). The influence of oceanic heat transport is smaller for the year-to-year variability that we focus on in this paper, leaving the AD as one of the main causes of simulated summer Arctic SIE variability at the inter-annual time scale.

Using the same 3600-year long GFDL CM2.1 control simulation, we find that the simulated spring FS ice export is indeed significantly **inversely correlated with the September SIE (*r =-0.34*) and positively correlated with** the AD index (*r=0.63*, not shown). **This is similar to the inverse correlation found between the observed de-trended spring FS ice export and September SIE over the 80 years from 1935 to 2014 (*r* = *-0.43*, Table 1) and supports a general level of influence from the spring FS ice export of around 10% on the observed September SIE loss. The** link between the AD and spring FS ice export appears stronger in model simulations than for the available observations ($r_{AD-FS\ ice\ export} = 0.45$) between 1948 and 2014.

The simulations in Zhang (2015) suggested the AD to be one of the main drivers of low frequency summer Arctic SIE. Here we would like to estimate how much of this AD influence can be explained by FS ice export at the inter-annual time scale from observed correlations since 1979. In this period $r_{AD\ -Sept\ SIE} = -0.53$. We roughly estimate that 45 % of this correlation is caused indirectly by the FS spring export variability, because; $r = r_{AD-FS\ ice\ export} \times r_{FS\ ice\ export-Sept\ SIE} = 0.44 \times -0.54 = -0.24$, and (-0.24) ⁄ (-0.53) = 0.45. The FS spring export and the AD therefore have roughly equal contributions to September SIE variability in addition to the common mechanism being stronger northerly geostrophic winds driving higher spring export. The additional direct AD influence on summer Arctic SIE is probably due to **ridging** inside the Arctic Basin, and atmospheric advection of heat and moisture (Graversen et al., 2011). The FS export influence independent from the AD is plainly export variability not driven by AD.

We also examined a forced historical simulation for the 20th century combined with a forced 21th century projection under the Coupled Model Intercomparison Project phase 3 (CMIP3) A1B scenario using the GFDL model. Such a simulation is forced with changes in all external forcings such as anthropogenic greenhouse gases and aerosols. In these simulations we found no significant trend in simulated spring FS ice export between 1979 and 2013. This is consistent with the 1935-2014 long-term trend being close to zero, and further suggests that the atmospherically driven FS ice export increase since 1979 (Fig. 4) is mostly due to natural variability.

5 Conclusions

A new and updated time-series of Fram Strait ice area export from 1935-2014 was presented in this study. The new time-series was constructed using high resolution radar satellite imagery of sea ice drift across 79°N from 2004 - 2014, regressed on the observed cross-strait surface pressure difference back to 1935. The overall **long-term** mean annual export is 883,000 km^2, and there are no significant trends over this 80-year **record**. Winter export (September - February) carries about 60 % of the annual **export**, while the spring export (March - August) carries the remaining 40 %.

The pressure difference from observed sea level pressure across the Fram Strait on Svalbard and Greenland directly explains 53 % of the variance in the observed ice export for 2004 - 2014. The best fit between ice drift and geostrophic winds results in a seasonal difference of ~3 cm/s, suggesting that the East Greenland Current, carrying a large part of the export, flows faster during winter and slower during summer, consistent with generally stronger large-scale **or thermal** wind forcing. The ice export based on observed sea level pressure, including a seasonal variation in the underlying current, explains almost 80 % of the observed ice export variance.

While there is no long-term trend in export from 1935 to 2014, we do find positive and robust trends in sea ice area export over the last 35 years. This increase in export is created by stronger geostrophic winds, largely due to an observed increase in the surface pressure on Greenland, creating a positive trend of +6 % per decade for annual mean ice area export since 1979 (Fig. 4). The trend is mostly explained by the high trends for spring and summer months (March-August), when ice export has a robust trend of +11 % per decade.

Despite not explaining all of the variance in ice export, the surface pressure based time series suggest about 18% of the observed variance in September sea ice extent is explained by spring ice export through Fram Strait between 1935 and 2014. We have confidence in this result because it is a physical process, and the results are similar to simulations partially explaining the correlation between the observed Arctic Dipole anomalies and the September SIE (Zhang 2015). This is simply the wind forcing (Arctic Dipole) driving the ice export, again leading to anomalies in September SIE.

Onwards from the 1990's, the influence of Fram Strait spring ice area export **appears to increase, consistent with the results from Williams et al (2016).** Between 1993 and 2014, 22 % of the observed variance in mid-September sea ice extent is explained by the spring ice export, increasing to 55 % for the last 10 years (Table 1). To reach such a level of influence, feedbacks **or other processes like ridging inside the basin and related coastal divergence have likely contributed and may have been correlated with the export anomalies (Williams et al. 2016)**. Positive feedback mechanisms enhancing summer SIE anomalies are the ice-albedo feedback and increased deformation of thinner ice (Perovich et al., 2007; Rampal et al., 2009). During the last 10-20 years, the Arctic sea ice cover has decreased quite rapidly, and the contributions from natural variability and greenhouse gas forcing are still being debated. We calculated an important driver of Arctic sea ice variability for the last 80 years, and found that over this time scale there is no systematic increase in sea ice area exported southwards out of the Arctic Ocean in the Fram Strait. This is consistent with available historical simulations stating that we do not expect any systematic ice export change related to global warming (Langehaug et al., 2013). This is also consistent with studies stating that there is little systematic change in the Arctic large-scale circulation (Vihma 2014).

The Arctic ice cover is now thinner and more mobile than before, and over the last three decades the September ice cover seems to have acquired an increased coupling to the Fram Strait spring sea ice area export. The increased export over the last 35 years appears to be linked to natural variability on multi-decadal time-scales because there is no trend over the last 80 years. Such a long-term variability has been found in Northern Hemisphere surface air temperature and temperature of inflowing Atlantic Water to the Barents Sea (Smedsrud et al., 2013). Consequently we speculate that there is potential for a partial recovery of the September SIE in the next decade or two, when, or if, the spring ice export decreases back to the long-term mean level of the last 80 years.

Author contribution: M. H. Halvorsen did most of the calculations of sea ice export based on the sea level pressure data, J. Stroeve calculated and plotted sea ice extent variations and helped re-focus the manuscript, R. Zhang contributed with analysing the Arctic Dipole time series and simulated sea ice export, and K. Kloster analysed the original SAR images and calculated monthly mean ice speed and export. L. H. Smedsrud prepared the manuscript with contributions from all co-authors and made most of the figures.

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Table 1. Correlations over time between Fram Strait Spring Export and mid-September Sea Ice Extent ($r_{FS\ ice\ export-Sept\ SIE}$)

	1935-2014	1979-2014	1993-2014	2004-2014
Export and extent	-0.23	-0.55	-0.49	-0.72
De-trended values	-0.43	-0.39	-0.47	-0.74

Figures and Captions:

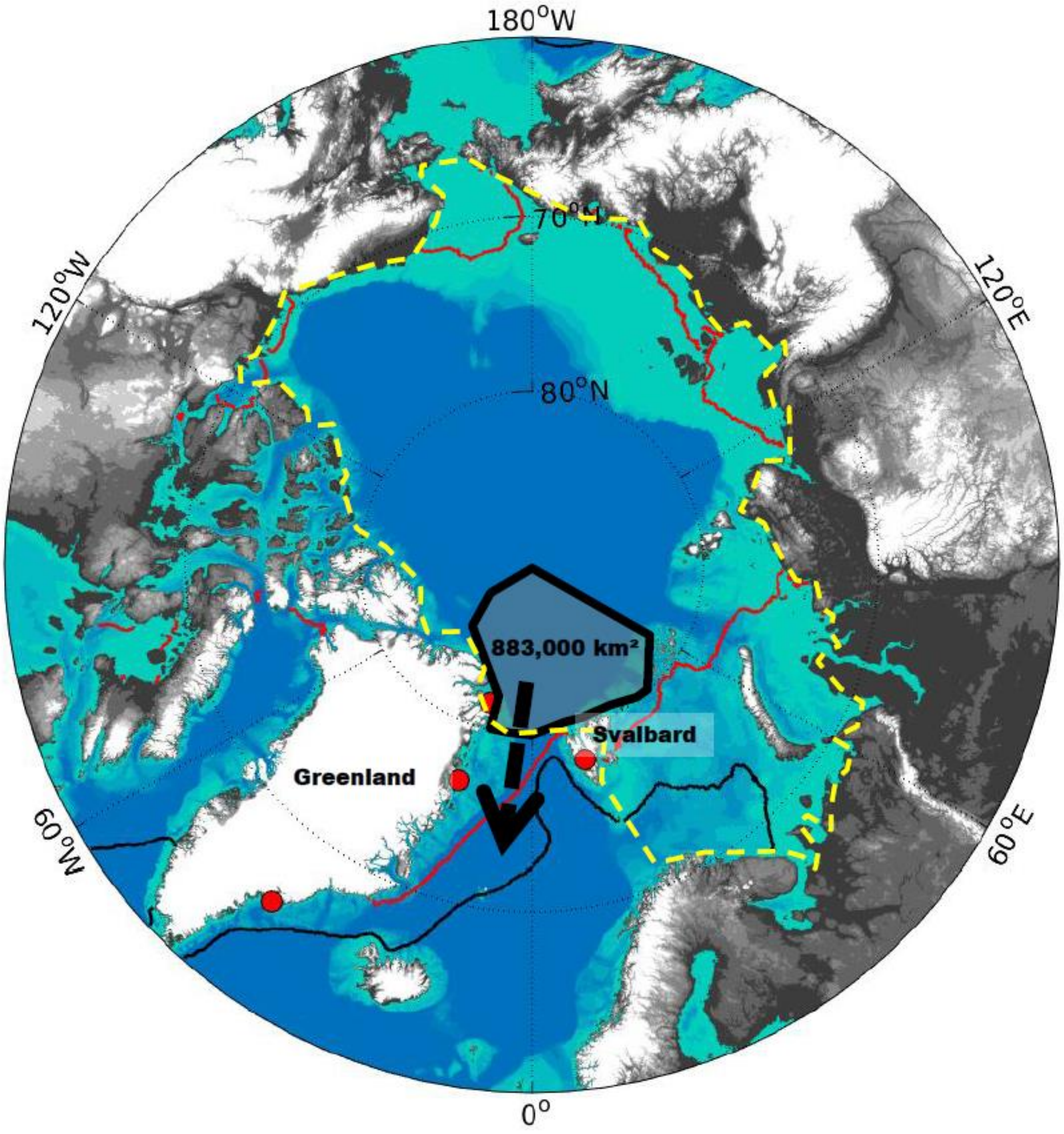

Figure 1: The Arctic Ocean and surrounding shelf and land areas. The large black arrow shows location of Fram Strait, and the red circles positions of the meteorological stations with Sea Level Pressure observations. The 1935 to 2014 mean positions of the mid-month Sea Ice Extent is plotted for September (red) and March (black). The 1935-2014 mean annually exported sea ice area (883,000 km²) is illustrated by the polygon. The outer extent of the Arctic Ocean Domain is drawn using the yellow dashed line.

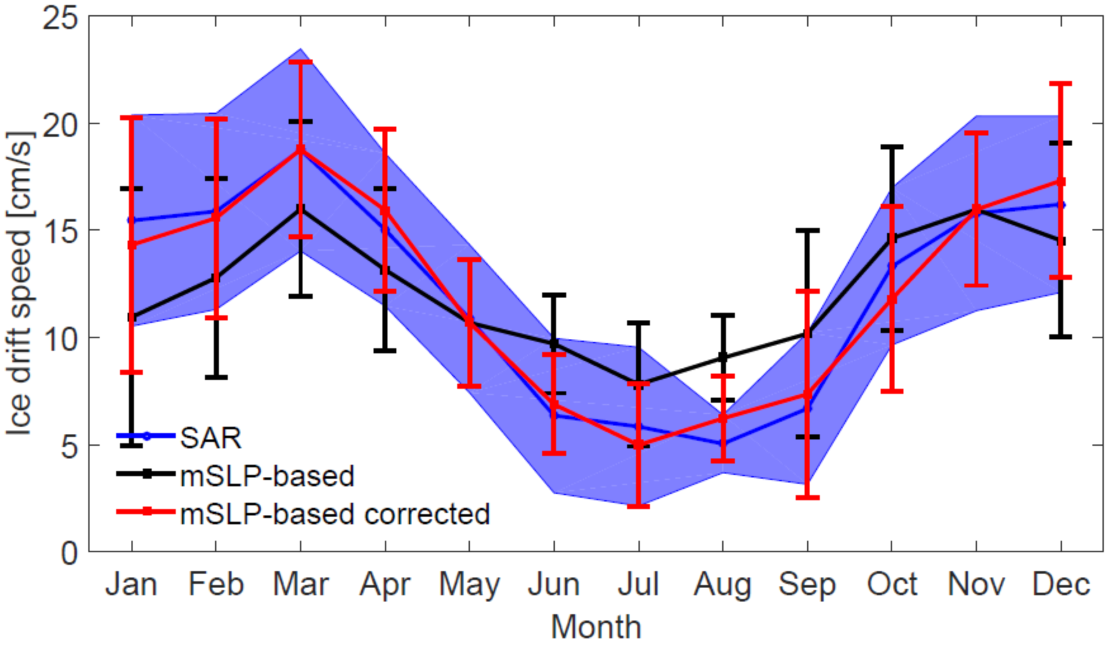

Figure 2: Annual cycle of monthly mean southward ice drift speed in Fram Strait between 2004 and 2014. Observed ice drift speed (SAR) are shown in blue, and our pressure based ice drift speed in black. The corrected ice drift speed is shown in red. Standard deviations of observed ice drift speed are shaded in purple, and of calculated ice drift speed as vertical, coloured lines.

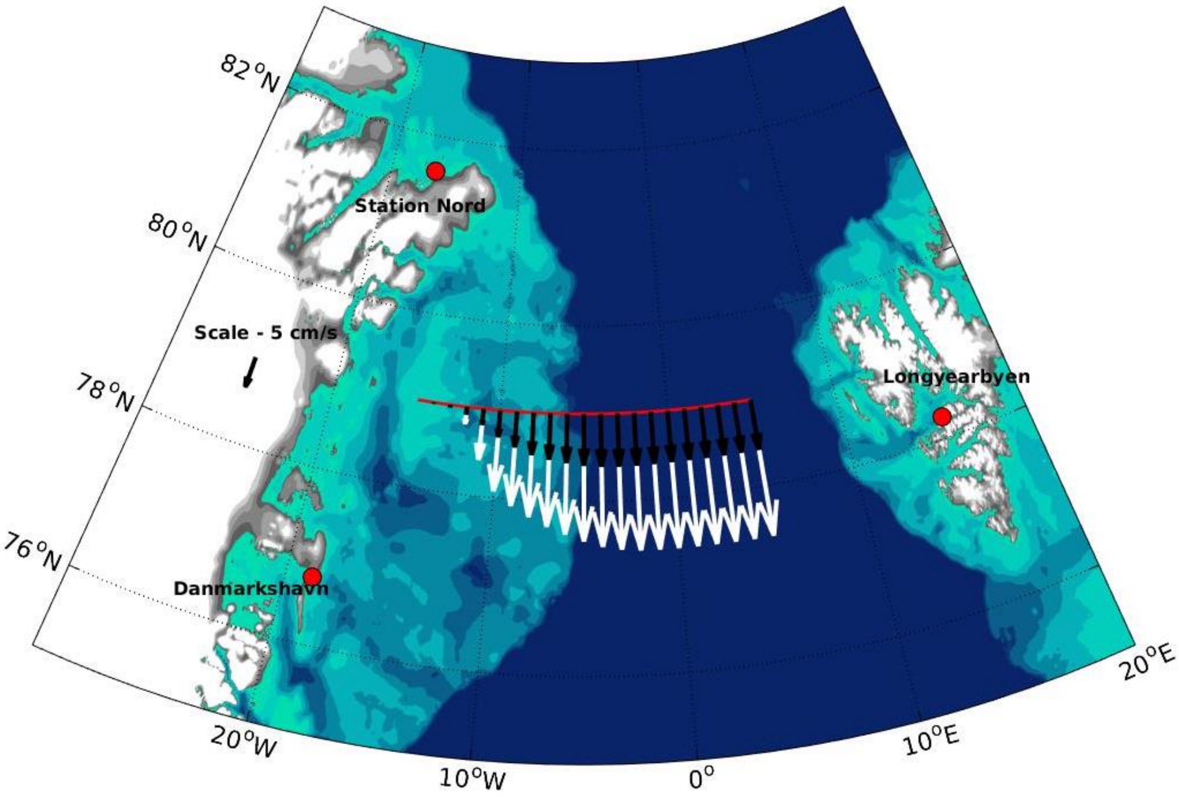

Figure 3: The Fram Strait between Greenland (left) and Svalbard (right) with summer (black arrows) and winter (white arrows) mean sea ice drift speed. Southward ice drift across 79°N (red line) from February 2004 to December 2013 were interpolated to 1° bins based on SAR imagery. Summer speeds are June – September means, while winter speeds are December - March means. Shades of blue show ocean bathymetry in 100 m steps down to 500 m depth. Red circles show locations for surface pressure observations on Svalbard (Longyearbyen) and Greenland (Station Nord and Danmarkshavn). Pressure observations were interpolated between the Greenland stations to calculate the mean pressure gradient along 78.25°N. Before 1958 pressure observations from Danmarkshavn are lacking, so observations from Tasiilaq (65.60°N, 37.63°W) were used, further south along the Greenland coast (Fig. 1).

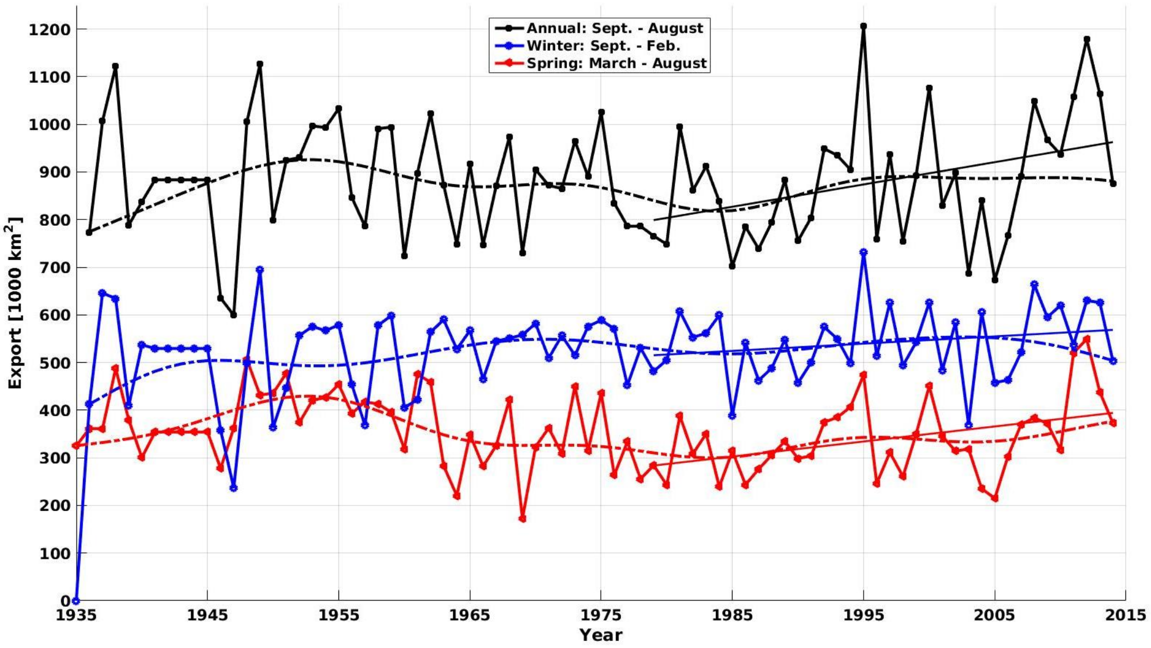

Figure 4: Southward ice area export in Fram Strait. Ice export from 1935 - 2003 is based on the relationship between observed mean sea level pressure and observed ice export by SAR, and ice export from 2004 - 2014 are solely observations by SAR. Annual values (black) are averaged for September 1st through August 31st. Winter export is September 1st - February 28th. (blue) and Spring is March 1 st - August 31 st. (red). Values are plotted half way through the respective period. Smoothed time-series are included produced by filtering with a 20 year cutoff 8-order Butterworth filter (dashed lines), and linear trends are plotted onwards from 1979. The long-term (1935-2014) trends are not included because they are not significantly different from zero.

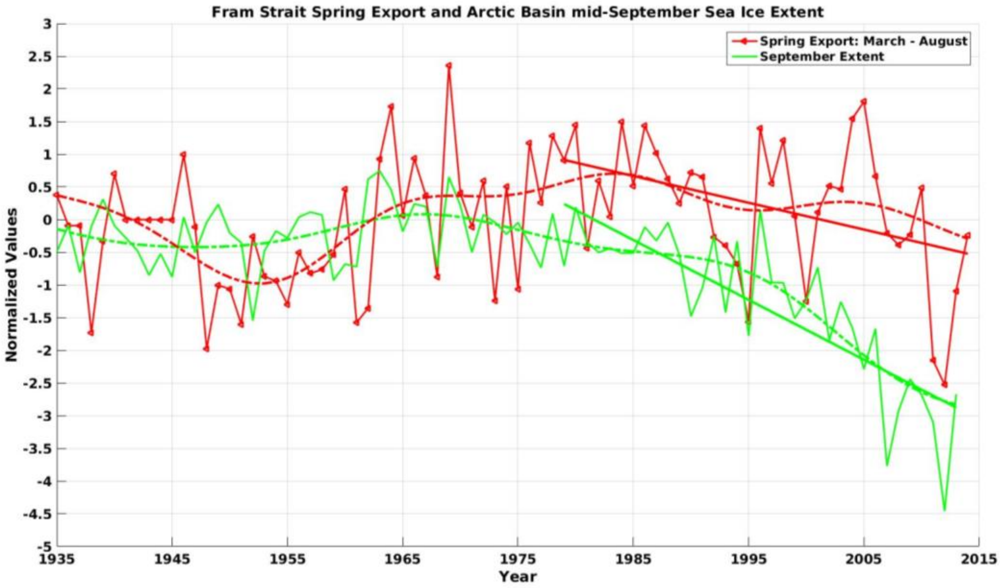

Figure 5: Spring Fram Strait ice area export (red) and mid-September Arctic SIE (green). The ice export is averaged for March 1st through August 31st. Both time-series have been normalized by subtracting the mean and dividing with the standard deviation. The ice export is here plotted with negative values as high southward export for easier comparison. Smoothed time-series are included produced by filtering with a 20 year cutoff 8-order Butterworth filter. The 1979 - 2014 trends in ice export and mid-September SIE is shown as solid straight lines. SIE values are obtained from Walsh et al., (2015).

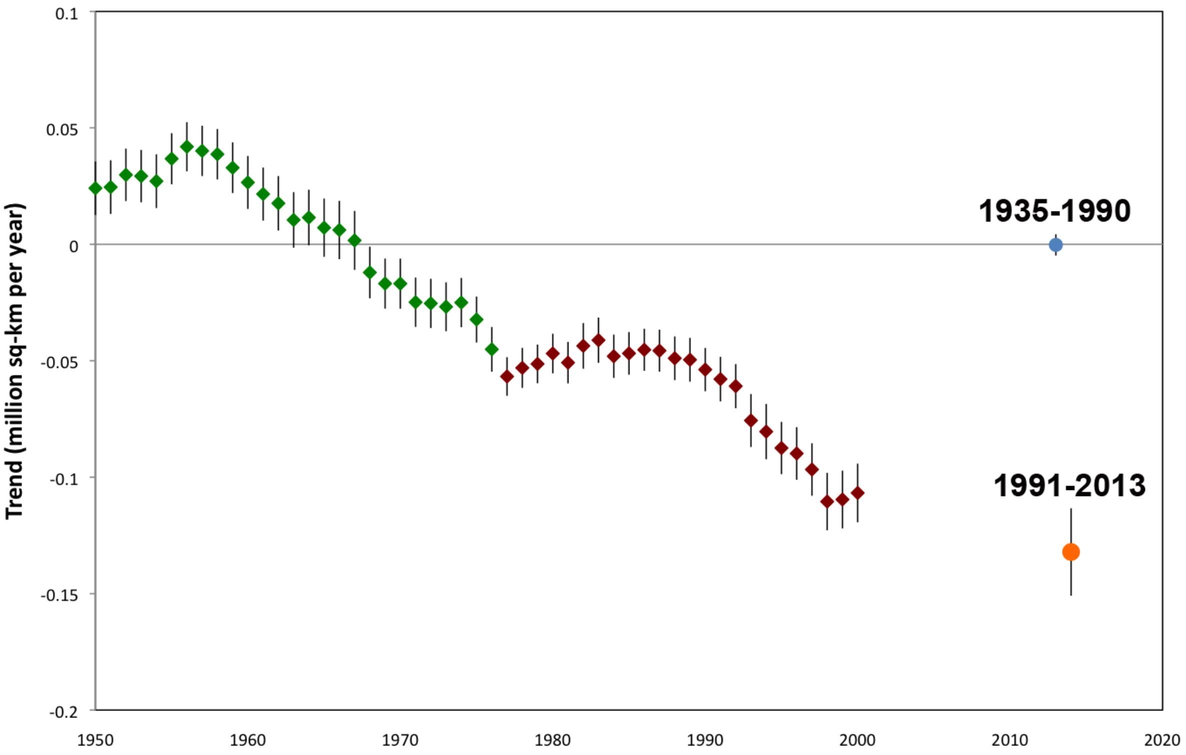

Figure 6: Consecutive 30-year trends of mid-September SIE in the Arctic Basin. The first green symbol shows the 30 year trend between 1935 and 1964, and is plotted at the center year in 1950. The next value in 1951 shows the trend for 1936 to 1965, and so on. The last green symbol in 1975 is for the 1961 to 1990 trend. The red symbols show trends after 1990, ending with the 1984 to 2013 trend. The blue symbol shows that the 1935 to 1990 trend was zero, and the orange symbol shows the trend from 1991 to 2013. SIE values are obtained from Walsh et al., (2015).

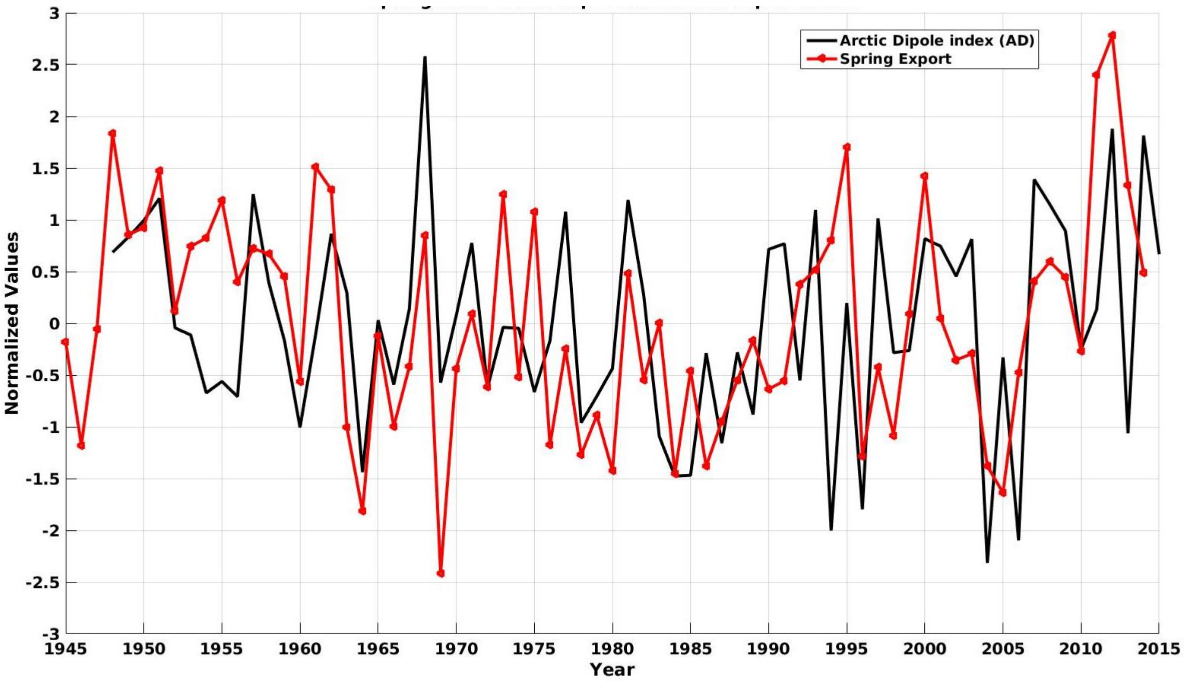

Figure 7. : Fram Strait Spring export (March-August) and April-July Arctic Dipole (NCEP/NCAR reanalysis) anomalies from 1948 – 2014. Both time series are de-trended and normalized by their standard deviations, 0.817 million km^2 and 28.8 hPa, respectively. The correlation between them is $r_{AD-FS\ ice\ export} = 0.45$ for the entire period, and similar for 1979-2014 ($r_{AD-FS\ ice\ export} = 0.44$).