We are grateful to the two reviewers for their comments and have made all suggested revisions accordingly. We also addressed the comment of Dr. Fyke and corrected our reference mistake. Below please find responses to all reviewer's comments. Our responses are highlighted in yellow. The tracked changes version of the paper follow,

Interactive comment on **"Investigating the Local Scale Influence of Sea Ice on Greenland Surface Melt"** ***by*** **Julienne C. Stroeve et al.**

Anonymous Referee #1

Received and published: 5 June 2017

June 5, 2017

I have read the manuscript "Investigating the local influence of sea ice on Greenland surface melt" by J.C. Stroeve et al. This work evaluates statistical and physical links between Arctic sea ice conditions and subsequent melt events observed over the Greenland Ice Sheet. Through a statistical framework, the authors find strong covariability between Baffin Bay and Davis Strait melt and freeze onset and ice sheet melt occurrence within close spatial proximity to the aforementioned oceanic regions. The physical associations presented between local sea ice cover and the ice sheet appear to substantiate the author's statistical findings. In particular, composite turbulent flux and wind field analyses show transport of warm, moist air from the ocean (evident in early melt years) onto the ice sheet that subsequently enhance glacial melt, especially at lower elevations around the western and southern margins.

Overall, this manuscript is well-written and concise and I believe the quality of analyses presented are consistent with manuscripts published in The Cryosphere. This paper would make a contribution to the growing body of local/regional sea ice-ice sheet inter- actions within a rapidly changing North Atlantic Arctic environment. I would recommend acceptance pending the completion of a relatively small number of revisions, which I have detailed below by line numbers in the submitted manuscript.

Minor Comments:

Line 56: Add ". . .and mid-tropospheric height" after SLP to reflect coincident mid-level circulation changes in the Arctic. Papers such as Bezeau et al (2015) Int J Clim (doi:10.1002/joc.4000) could also be cited here.
Thank you for bringing this new reference to our attention. We have made the suggested additions.

Line 60: Relevant recent work by Ballinger et al. (2017) Clim Dyn (doi:10.1007/s00382-017-3583-3) similarly notes poleward advection of warm air masses delays autumn freeze onset in Baffin Bay, and impacts Greenland coastal temperature signals, and would appropriately fit here.
Thank you for bringing this new reference to our attention. We have added the citation.

Line 129: Do MAR 850 hPa winds, which use ERA products, compare more favorably relative to observations than MERRA low-level winds? As 500 hPa geopotential height and 10m winds are obtained from MERRA it would seem appropriate to use a similar product for 850 hPa winds.
We had at one point used 10 m and 850 hPa winds in Fig. 11 but did not keep them in the

end. It looks like we forgot to remove that from the data section so this becomes a non-issue. However, we used 10 m wind in Fig. 12 from MERRA-2.

Lines 132-133: Clarify whether MAR output for 2002 is forced by ERA-40 and ERA-I or just one of these datasets.
It is forced by ERA-40 from 1979-2002 and by ERA-I from 2002 to 2015.

Line 158: List the threshold of statistical significance used throughout the paper.
Done

Line 193: Change "didn't" to "did not"
Done

Lines 195-198: The authors should explicitly state what advantages SVD offers beyond more traditional bivariate correlation between two data fields? Such justification would be helpful given that simple and partial correlation techniques are also utilized in the paper.
The advantage of singular value decomposition is that it is able to maximum the covariance between the two fields to explicitly show the structure of the covariability, and also provides subsequent orthogonal modes of covariability (not as relevant for this paper since we only show the leading mode) that are by definition unrelated to the leading mode.

Line 239: Should this be Eq. 1? I do not see a second equation listed in the manuscript.
Thank you, this was a typo now corrected.

Line 241-242: When compositing by anomalous melt and freeze years using a +/-1 sigma threshold, it appears that only 3 early melt and 4 late melt onset are considered (as mentioned in Fig 12). If the sigma threshold is relaxed to increase sample size (perhaps to +/-0.75 sigma) does this substantially alter lower tropospheric wind patterns?
The 1σ threshold gives a different number of years for each region. In Figure 12 we just show the Baffin Bay region which does have only a few years with 1s differences in MO. If we relax to 0.75σ, the number of years anomalous in the AIRS time-period did not change. Ideally, we need a longer time-series of data from AIRS to look at including even more anomalous years in the composite.

Line 280: Change "hPA" to "hPa."
Done

Table 3: Does simple correlation reference a specific technique (i.e. Pearson's or Spearman's)? Clarify this in the caption and table.
This was a Pearson's correlation, this has now been added to the table caption.

Figures 9a/b: Graphic is somewhat confusing with time series plots stacked directly on top of each other. I would suggest that panels be clearly separated into a two-panel plot (labeled as a-d for instance) with y axis labeled accordingly on the correlation time series.

We have changed the figures accordingly to make them Figures A-D. Here are the captions for each:

Figure 9.

a) Baffin Bay SIC region latent heat flux (W/m2) from early minus late MO years (black line) and Baffin Bay GrIS region specific humidity (g/kg) from early minus late MO years (red line).

b) Week Lag-1week lagged running correlations (between 0.5 and 1.0) for early MO years latent heat flux from Baffin Bay and specific humidity from GrIS (blue line) and late MO latent heat flux from Baffin Bay and specific humidity GrIS years (green line).

c) Baffin Bay SIC region sensible heat flux (W/m2) from early minus late MO years (black line) and Baffin Bay GrIS region air temperature (K) from early minus late MO years (red line).

d) Week Lag-1week lagged running correlations (between 0.5 and 1.0) for early MO years sensible heat flux from Baffin Bay and air temperature from GrIS (blue line) and late MO sensible heat flux from Baffin Bay and air temperature GrIS years (green line).

In a-d) Dotted vertical lines represent the aver early MO date for Baffin Bay (dotted blue), and average late MO date for Baffin Bay (dotted blue, red highlight), average early MO date from GrIS (dotted green), and average late MO date form GrIS (dotted green, orange highlight).

Figure 12: Are these winds from AIRS or MERRA? The manuscript explicitly mentions use of MERRA 10m winds (line 160), but not from AIRS.

Correct, these winds are from MERRA2 in Figure 12. The reason why we do not use AIRS in this figure is because AIRS does not produce a wind product and there are no other satellite based wind products in the Arctic to our knowledge.

New Caption: Figure 12. Wind vectors and speeds at 10 meters from MERRA2 during 4 early melt years over Baffin Bay (top panel) and 3 late sea ice melt years (bottom panel). Smaller figures superimposed on the wind maps show the sea ice concentration (%) for that day.

Interactive comment on "Investigating the Local Scale Influence of Sea Ice on Greenland Surface Melt" by Julienne C. Stroeve et al. Anonymous Referee #2

Received and published: 4 July 2017

General comments

The study documents a statistical investigation and possible dynamical explanations of the covariance between sea ice concentration and the surface melt of Greenland Ice Sheet. The purpose is to demonstrate the impact of local changes of sea ice around Greenland on the ice sheet surface mass balance. The manuscript is well structured and the conclusions are clear based on the results of the analyses. The topic is interesting and relevant within the scope of The Cryosphere, and thus, with the changes suggested below, it should be acceptable for publication.

Specific comments

L254: you stated that the leading SVD mode explains 62% covariance between SIC C1 TCD and GrIS melt water production in June. This number might be misleading if there is only a very small amount of covariance between these two fields. In this case, the 'normalized squared covariance' (NSC) should be included as well (see details in Wallace et al., 1993 Journal of Climate).

The SVD was the first step for that particular analysis because it showed us the actual regions where we could be seeing a causal relationship based the locations of (maybe somewhat confusingly) significant correlations in the heterogeneous correlation maps. From there, we isolated two regions, Baffin Bay and Beaufort Sea, and did a similar analysis using partial correlation. Correlation is limited because you can't have two fields, so I took the spatial average of Baffin and Beaufort and correlated (and partial-correlated) that time series with the time series of melt at each grid point in Greenland.

Thank you for pointing out these references to the NSC. We added reference in the methods to the NSC: The normalized squared covariance (NSC) associated with each pair of spatial patterns indicates the total strength of this relationship [*Wallace et al*. 1993], with values greater than approximately 0.10 considered to indicate a significant relationship [*Riaz et al*. 2017].

We further calculated this normalized squared covariance as suggested. The NSC between 500 hPa heights and melt is:
June: 0.191
July: 0.111
August: 0.093

For sea ice and melt, NSC is:
June: 0.099
July: 0.081
August: 0.066

So there generally is a significant coupling between the ice sheet melt and height fields as we expect, but it is less significant between ice sheet melt and sea ice, which is more important. We were already thinking that this relationship is rather tenuous, and this is just further support for that idea. We additionally added the NSC values to Figure 3.

There is very little information employing NSC, and how hard a threshold of 0.10 is, but we do believe that the reviewer's comment on 482-492 is justified then and the fact that we lose much of the correlation between sea ice/ice melt after removing the GBI warrants mention of this 0.099 value to say that the coupling between these two fields is relatively weak. We added a statement in the Discussion to highlight this result:
This explanation is supported by the relatively weak value of NSC for June GrIS melt and SIC, which nearly doubles to 0.191 in the SVD analysis of 500 hPa geopotential heights instead of SIC.

L262: Figure 3(i) does not show any significant HC values, so it should not be included in this sentence.
That is correct and it is a relic of the old figures, so we removed reference to Fig. 3i.

L482-492: after you remove the impact of Greenland Blocking, the Baffin Bay SIC influence becomes much smaller. This may be because the overall coupling between the SIC and GrIS surface melt is not significant. Thus, the additional calculation of NSC mentioned above will probably help you to interpret the results.
See our response to previous comment.

L543-552: you wanted to show that during the early MO years over the sic ice, the wind is blowing from the open water areas onto the GrIS, but the plots in Figure 12 are exactly the opposite. For example, the figures in upper panel, the winds are offshore along the west coast of Greenland in all three cases.
That was a typo on our part, this has now been corrected. The winds do indeed show onshore flow along the west coast of Greenland during early MO years. The figures have been made larger so that this is seen easier.

Figure4: can you please tell more details of how you calculated the linear trends? Which method you used to do the significant test? In the legend, you should also specify which confidence level you used.
Done, linear trends were computed using least square regression and evaluated using a student T-test at 95% confidence.

Figure5: maybe you can indicate the weeks with significant trends on different lines?
We feel this will make the figure too cluttered as it is a busy figure already. The figure is more for illustration, showing how trends vary as a function of time of year for the different sectors around Greenland.

Figure6: please specify the confidence level you used. Maybe use ‘a, b and c’ to mark the figures in order to be consistent with other figures? Or, it should be ‘left, middle and right’, but not ‘top, middle and bottom’.
Yes thank you, this has been corrected.

Figure 12: please specify what is the parameter shown with blue and red colors. I guess it's SIC, and if so, you should give a separated color bar as well. Please make the color bars and the wind vectors bigger and clearer. The readers can hardly see them.

We made the figures larger and added the SIC color bar.

Investigating the Local Scale Influence of Sea Ice on Greenland Surface Melt

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Abstract

Rapid decline in Arctic sea ice cover in the 21st century may have wide-reaching effects on the Arctic climate system, including the Greenland ice sheet mass balance. Here, we investigate whether local changes in sea ice around the Greenland ice sheet have had an impact on Greenland surface melt. Specifically, we investigate the relationship between sea ice concentration, the timing of melt onset and open water fraction surrounding Greenland with ice sheet surface melt using a combination of remote sensing observations, and outputs from a reanalysis model and a regional climate model for the period 1979 - 2015. Statistical analysis points to covariability between Greenland ice sheet surface melt and sea ice within Baffin Bay and Davis Strait. While some of this covariance can be explained by simultaneous influence of atmospheric circulation anomalies on both the sea ice cover and Greenland melt, within Baffin Bay we find a modest correlation between detrended melt onset over sea ice and the adjacent ice sheet melt onset. This correlation appears to be related to increased transfer of sensible and latent heat fluxes from the ocean to the atmosphere in early sea ice melt years, increasing temperatures and humidity over the ice sheet that in turn initiate ice sheet melt.

1. Introduction

The shrinking sea ice cover is one of the most striking features of Arctic climate change [e.g. *Stroeve et al*., 2012; *Serreze et al*., 2007]. Since the late 1970s, the sea ice extent (SIE) has declined by more than 40% in September, with smaller, yet statistically significant negative trends in other months. These negative trends have been linked to the observed increases in atmospheric CO_2, with the prospect of the Arctic Ocean becoming seasonally ice free before the middle of this century if current emission rates continue [*Notz and Stroeve*, 2016]. At the same time, the Greenland ice sheet (GrIS) has experienced increased summer melt [e.g. *Tedesco et al*., 2011; *Fettweis et al*., 2011] and an increasingly negative mass balance [*Khan et al*., 2015]. While earlier studies found GrIS mass loss to be balanced by ice discharge and ice melt [*van den Broeke et al*., 2009], newer evidence shows surface melting is now contributing 84% to the mass loss since 2009 [*Enderlin et al*., 2014]. It has further been suggested that surface melting will dominate Greenland's contribution to sea level rise throughout the rest of this century [*Enderlin et al*., 2014; *Fyke et al.,* 2014a]. Similar to the sea ice environment, an anthropogenic signal has been identified in the observed changes of GrIS surface mass balance (SMB) [*Fyke et al*., 2014b].

While both the GrIS and sea ice environments are responding to anthropogenic warming [*Hanna et al*., 2008], changes in atmospheric circulation patterns that favor increased sea ice loss and GrIS melt have also played a role. Analysis of summer (JJA) sea level pressure (SLP) mid-tropospheric reveal statistically significant increases over Greenland and north of the Canadian Arctic Archipelago coupled with significant negative trends over northern Eurasia and Canada from 1979 to 2014 [*Serreze et al.*, 2016; *Bezeau et al., 2014*], dominated by a clear shift in the last decade (2005 to 2014) towards large positive SLP anomalies over the central Arctic Ocean and Greenland. This pattern favors both summer sea ice loss [e.g. *Wang et al.,* 2009; *Ogi and Wallace*, 2007] as well as Greenland surface melt [*Hanna et al*. 2013*; Mioduszewski et al.,* 2016; *Ballinger et al*., 2017]. Additionally, advection of warm and humid air masses appears to be the primary factor initiating sea ice melt onset [*Boisvert and Stroeve*, 2015; *Mortin et al*., 2016]. Anomalous GrIS melting also appears to coincide with increasing water vapor transport to the ice sheet [*Mattingly et al*., 2016]. Thus, it is not surprising that there is a strong inverse correlation between GrIS melt intensity (defined by *Tedesco et al.,* 2007) and the pan-Arctic September SIE (r = -0.83 from 1979 to 2015) [**Figure 1**]. Detrended data reveal a substantially weaker inverse relationship (r = -0.27), yet the year-to-year variability between September SIE and GrIS melt remains highly correlated (r = -0.69). This would suggest that atmospheric processes fostering a high melt year also tend to foster more summer sea ice loss and vice versa.

What about local-scale feedbacks? Changes in sea ice have strong local-scale influences on the Arctic climate through enhanced transfer of heat and moisture between the ocean and atmosphere, resulting in amplified Arctic warming [e.g. *Serreze et al*., 2009; *Screen and Simmonds*, 2010]. This is mostly manifested during the cold season, as warming of the ocean mixed layer during summer results in increased sensible and latent heat transfer from the ocean to the atmosphere [*Boisvert et al.*, 2015]. Other studies have linked sea ice loss to atmospheric warming in surrounding areas during other times of the year as well [*Comiso et al*., 2002; *Hanna et al.,* 2004; *Bhatt et al*., 2010, *Serreze et al*., 2011]. Sea ice loss is additionally tied to increased tropospheric moisture, precipitation, cloud cover, surface temperature, and decreased static stability [*Deser et al.,* 2000*; Rinke et*

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al., 2006; *Francis et al.,* 2009*; Serreze et al., 2*009*; Kay et al.,* 2011*; Screen and Simmonds,* 2010*; Stroeve et al.,* 2011*; Overland and Wang,* 2010*; Cassano et al.,* 2014]. Water vapor or moisture increases surface melting through its role in cloud formation and as a greenhouse gas, results in increased downward longwave radiation and precipitation [*Bennartz et al*., 2013, *Doyle et al.,* 2015, *van Tricht et al*., 2016].

This study examines whether or not local changes in the sea ice environment around Greenland are already impacting GrIS meltwater production and therefore SMB variations. First, we identify regions of SIC and GrIS melt covariability by applying the singular value decomposition method. We hypothesize that regions of covariability will have consistent trends in sea ice cover and melt production, as well as consistent trends in spring melt onset and fall freeze up. As a second step, this hypothesis is examined with a spatial analysis of trends for the entire study domain. Third, we investigate if a plausible mechanism for local scale influence between SIC and GrIS is present. Specifically, we hypothesize that the mechanism for the local scale influence is controlled by positive turbulent fluxes from the SIC regions. Therefore, anomalous turbulent fluxes should be larger in years with early sea ice melt onset than in later years in regions of covariability. In turn, these turbulent heat fluxes should result in increased specific humidity and near surface temperature over the GrIS, which should be reflected in positive net longwave radiation anomalies. Finally, a detailed analysis, restricted to the region with evidence of local scale influence, is performed. In this analysis, we examine the hypotheses that the timing of turbulent heat flux anomaly perturbations over reduced sea ice areas proceeds changes in GrIS humidity and temperature, and that wind patterns in early melt onset years are favorable for turbulent heat flux transport from the ocean to the ice sheet. Finally, correlation and partial correlation analysis is used to examine the influence of large scale atmospheric circulation (here represented by the Greenland Blocking Index).

2. Data

2.1 Sea Ice and Ice Sheet Data

Sea ice and Greenland melt extent/area calculations rely on algorithms applied to satellite passive microwave data from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR: 1978-1987) and the DMSP Special Sensor Microwave/Imagers (SSM/I and SSMIS: 1987-present). Specifically, we use several sea ice metrics derived from the NASA Team SIC algorithm [*Cavalieri et al*., 1996, updated 2008] and distributed by the National Snow and Ice Data Center (NSIDC). The data set spans October 1978 to present, providing daily (or every other day during the SMMR era) SIC estimates. Using the SIC, we additionally calculate the open water fraction (OWF) as well as the length of the ice-free season, defined as the number of days each year with ice concentration less than 15% [see *Parkinson*, 2014].

Changes in the timing of melt onset (MO) and freeze-up (FO), in addition to total melt season length over sea ice, are computed following *Markus et al.* [2009]. This study uses an updated version of the algorithm that bias corrects for intersensor calibration issues found between the F17 and F13 sensor and evaluates early melt onset (EMO), corresponding to the first day of MO, the continuous MO and the continuous FO.

GrIS melt extent is an estimate of the daily spatial extent of wet snow using the *Mote et al.* [2014] algorithm and distributed by NSIDC. From the binary melt/no melt classification, GrIS MO and FO dates were calculated for each pixel and each year from

1979 to 2015. We defined the start of the MO and FO as the first occurrence of a 5-day continuous melt or freeze-up period. Melt duration was calculated as the number of days between MO and FO. EMO was also determined and defined as the first time a spurious melt event lasting at least one day was recorded.

Besides mapping the GrIS melt extent and timing of MO and FO, we use meltwater production and 850 hPa wind as simulated by Modèle Atmosphérique Régional (MAR) v3.2 regional climate model [*Tedesco et al.,* 2013]. MAR is a three-dimensional coupled atmosphere-land surface model that uses reanalysis data at its lateral boundaries. In this study, MAR is forced with data from ERA-40 for the period 1979–2002 and ERA-Interim for the period 2002–2015 and outputs are produced on a polar stereographic projection with an approximate grid cell size of 25 x 25 km to match the passive microwave-derived fields. MAR's atmospheric model is coupled to the 1-D Surface Vegetation Atmosphere Transfer scheme, SISVAT [*Gallée and Schayes*, 1994; *De Ridder and Gallée*, 1998], which simulates surface properties and the exchange of mass and energy. SISVAT incorporates a snow model based on the CROCUS snowpack model [*Brun et al.*, 1992]. MAR has been validated through comparison with ground measurements [e.g. *Lefebre et al.,* 2003; *Gallée et al.,* 2005*; Lefebre et al.,* 2005], satellite data [e.g. *Fettweis et al.,* 2005, 2011*; Tedesco et al.,* 2011, *Alexander et al., 2014*], and applied to simulate long-term changes in the GrIS SMB and surface melt extent [*Fettweis et al.,* 2005, 2011*; Tedesco et al.,* 2008, 2011; *Tedesco and Fettweis, 2012*]. Data are freely available from an online repository [*Tedesco et al.*, 2015].

Meltwater production was used for grid cells classified by MAR as greater than 99% ice sheet to mask the tundra region of Greenland. In addition, meltwater production values of less than 1 mm day^{-1} in all grid cells were recoded to zero to account for MAR's scaled output. This threshold could be considered a conservative approximation of the occurrence of surface melt [*Fettweis et al., 2011, Figure 2*]. Finally, grid cells were masked in the interior ice sheet where mean monthly meltwater production does not exceed 1 mm day^{-1} to account for spurious correlations arising from a very limited number of dates that result in nonzero mean monthly values of meltwater production.

Trends for each pixel (or regional averages) are only computed if at least 30 years of valid data are found at that pixel. This ensures statistics are not biased by changes in spatial extent of the sea ice or Greenland melt. However, Greenland melt has been observed to extend to higher elevations in recent years, and in 2012 nearly the entire ice sheet experienced melt events [e.g. *Nghiem et al*., 2012]. Regional means are area-weighted. Trends are computed using linear-least squares and statistical significance is evaluated with a student T-test at the 95 and 99% levels.

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2.2 Atmospheric Data

Geopotential heights at 500 hPa and hourly 10 m wind speeds were obtained from NASA's Modern Era Retrospective-Analysis for Research and Applications (MERRA) products [*Bosilovich et al.*, 2011; *Cullather and Bosilovich*, 2011a, 2011b; *Rienecker et al.*, 2011]. MERRA is run on a 1/2° latitude by 2/3° longitude global grid with 72 hybrid-sigma vertical levels to produce analyses from 1979 to present. MERRA has been evaluated extensively since its release [*Cullather and Bosilovich*, 2011b; *Kennedy et al.*, 2011; *Reichle et al.*, 2011] and has compared favorably with other reanalysis products in the Arctic [*Zib et al.*, 2012; *Cullather and Bosilovich*, 2011; *Lindsay et al.*, 2014].

We also utilize atmospheric variables from NASA's Atmospheric Infrared Sounder (AIRS), designed specifically to map atmospheric water vapor content. This instrument has been used in several recent studies to document atmospheric changes and impacts on sea ice in the Arctic [e.g. *Boisvert and Stroeve*, 2015; *Stroeve et al*., 2014; *Serreze et al*., 2016]. While the data record is rather short (begins in September 2002), it provides twice daily global coverage at 1-degree spatial resolution of several key atmospheric variables, including skin and air temperature, precipitable water, cloud fraction and specific humidity. In this study we utilize the Level 3 Version 6 skin temperatures, 1000 hPa air temperature, effective cloud fraction, near surface specific humidity and total precipitable water. Additional variables derived from AIRS data products include the moisture flux [*Boisvert et al*., 2013; 2015], turbulent sensible heat flux and downwelling longwave radiation [*Boisvert et al.,* 2016].

3. Methods

3.1. Region of Interest and Study periods

For local assessment of sea ice changes and corresponding ice sheet changes, we define 5 sea ice and 5 adjacent ice sheet regions. Since we are examining the potential influence of the ocean on the ice sheet, it makes sense for the ocean regions selected to define the ice sheet boundaries, rather than the other way around. The definition of the sea ice boundaries comes from the International Hydrographic Organization, and we define 5 sea ice regions: Baffin Bay, David Strait, Lincoln Sea, Greenland Sea and the North Atlantic together with associated Greenland regions [**Figure 2**]. For the ice sheet, each region is defined along a topographical divide. While there are many local topographical divides, only those regions that matched the ocean delineations were selected.

We use two study periods. First, we do analysis from 1979 to 2015 when analyzing sea ice, melt extent and MAR model outputs. Second, AIRS data analysis is applied from 2003 to 2015 since a full year of data collection did not begin until 2003.

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3.2 Relationship between SIC and GrIS melt

To investigate covariability between summer SIC, GrIS melt water production, and 500 hPa geopotential heights, singular value decomposition (SVD) was applied to two fields at a time to produce pairs of coupled spatial patterns that explain their maximum mean squared temporal covariance [*Bretherton et al*., 1992]. The advantage of SVD is that it is able to maximize the covariance between the two fields to explicitly show the structure of the covariability.

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The temporal evolution of each pair's corresponding pattern in the two datasets is represented by the pair's associated expansion coefficients (EC), where subscripts GrIS, SIC and 500 denote the EC for ice sheet melt, sea ice concentration, and 500 hPa heights, respectively. These ECs were used to calculate heterogeneous correlation (HC) maps, which show the correlation coefficients between each EC and the opposing data field. The normalized squared covariance (NSC) associated with each pair of spatial patterns indicates the total strength of this relationship [*Wallace et al*. 1993], with values greater than approximately 0.10 considered to indicate a significant relationship [*Riaz et al*. 2017]. SVD has widely been used to investigate coupled modes of variability, including relationships between Arctic sea ice and snow cover [*Ghatak et al.*, 2010], and Arctic sea ice and atmospheric variables [*Stroeve et al.*, 2008].

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To further investigate how SIC in these regions is related to GrIS melt, SIC for both regions was spatially aggregated, de-trended and correlated with de-trended time series of GrIS meltwater production and the Greenland Blocking Index (GBI), respectively [*NOAA*, 2015]. The GBI is defined as the 500 hPa geopotential height field averaged between 20° – 80° W, 60° – 80° N [*Fang*, 2004; *Hanna et al.*, 2013], and is used as a metric for large-scale atmospheric circulation patterns over Greenland. To remove the influence of the GBI on both SIC and GrIS melt, we performed a partial correlation analysis of SIC in each region and GrIS meltwater production after the trends in GBI were removed [e.g. *Cohen et al.*, 2003].

3.3 Energy Balance

Following *Koenig et al.* [2014], the net heat flux into the atmosphere (F_{net}) emitted from the ocean is defined by:

$$F_{net} = Q_h + Q_e + LW - SW \quad (1)$$

where SW is the downward shortwave radiative flux at the surface, LW is the net upward longwave radiation, Q_h is the sensible heat flux, or heat transferred from the surface to the atmosphere by turbulent motion and dry convection, and Q_e is the latent heat flux, or heat extracted from the surface by evaporation. If the sum of the four right-hand side terms is positive, there is a net flow of heat from the surface to the atmosphere and vice versa.

Previous studies have looked at the strong seasonality in F_{net} over the Arctic Ocean [e.g. *Serreze et al*., 2007], with strong downward fluxes in summer and large upward fluxes in January associated with heat gain and loss, respectively, in the subsurface column. Updated trends from NCEP/NCAR reanalysis confirm that F_{net} trends are small in winter (January to April), except in the Barents Sea as a result of reduced sea ice and increased oceanic heat flux [*Ornaheim et al*., 2016] and also within Baffin Bay, again a result of less winter ice cover. Thus, in these two regions there is a transfer of heat from the ocean to the atmosphere during the winter months, which may spread over the sea ice areas and limit winter ice growth. In summer however (May to August), the direction is generally reversed with large heat fluxes from the atmosphere going towards the surface.

In this study we focus on how early sea ice retreat, as indicated by early melt onset during the transition from winter to summer, impacts the heat and moisture fluxes over early formed open water areas, and whether or not this is sufficient to impact Greenland melt. Towards this end, we composite the turbulent fluxes in Eq. 1 for low and high sea ice years, specific to each individual region analyzed using the AIRS data, with positive fluxes showing energy transfer from the surface to the atmosphere. We use the criteria of anomalies in melt onset exceeding 1 standard deviation (1σ) for each region when compositing. All data are detrended by subtracting the linear trend before computing the composites.

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4. Results

We begin with an assessment of the large-scale relationship between SIC and Greenland melt and its spatial covariability (4.1). This is followed by an analysis of changes in the sea ice cover surrounding Greenland, both in terms of SIC and OWF (4.2), followed by analysis of the timing of sea ice MO onset and FO, and its relationship with Greenland MO (4.3). Finally, turbulent heat and moisture flux changes composited for early and late melt onset years are examined (4.4) and large-scale influences are examined in section 4.5.

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4.1 Relationship between Sea Ice and Greenland Melt

The leading SVD mode explains the majority of the mean spatial covariance between monthly GrIS meltwater production and SIC in June and July (62%, 73%, respectively) and less than half (42%) in August. However, NSC values of 0.099 in June and only 0.081 and 0.066 in July and August, respectively, provide weak overall support for a significant relationship between SIC and GrIS meltwater production. HC maps reveal opposing sign of the correlations between the map pairs [**Figure 3**: columns 1 and 2; and columns 3 and 4] indicating an anticorrelation, meaning that increased ice sheet melt extent covaries with decreased sea ice area (it is irrelevant in the HC maps which is positive and which is negative). Specifically, the covariability of GrIS meltwater production and SIC, expressed as correlations on an HC map, show that sea ice and ice sheet melt strongly covary in two general regions, namely Baffin Bay/Davis Strait in June, and a large part of Beaufort Sea in June and July [**Figure 3(a) and (e)**]. In June, SIC in both the Baffin Bay/Davis Strait and the Beaufort Sea regions have strong correlations with EC_{GrIS}, $|r| > 0.70$), and GrIS meltwater production is highly correlated with EC_{SIC} for the majority of the unmasked ice sheet surface [**Figure 3b**]. The strong correlation in the Beaufort Sea persists in July but not in Baffin Bay/Davis Strait, and neither exhibits a significant correlation in August [**Figure 3(e) and (i)**]. At the same time, GrIS meltwater production correlations with EC_{SIC} are less expansive over the ice sheet in July and August, particularly in southern Greenland [**Figure 3(f) and (j)**].

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In the second SVD analysis of 500 hPa geopotential heights and GrIS melt water production, the leading SVD mode explains the majority of mean spatial covariance of the two variables in June and July (79% and 60%, respectively), but less than half in August (37%), which are similar values to the leading SVD mode for GrIS melt and SIC [**Figure 3(c), (g) and (k)**]. An NSC value of 0.191 indicates a significant relationship between GrIS melt and SIC in June, with more of a marginally significant relationship in July and August given NSC values of 0.111 and 0.093, respectively. The HC maps show a strong tendency for positive height anomalies centered on the Greenland side of the Arctic, though this area shrinks in July and August [**Figure 3(c), (g) and (k)**]. As before, this spatial pattern covaries with GrIS melt water production over most of the ice sheet in June, but is somewhat more restricted in extent in July and August. While SIC and GrIS melt extent covary regionally, large parts of the same areas of the GrIS melt extent region also covary with 500 hPa geopotential height fields. The similar spatial patterns in GrIS melt covariability with SIC and 500 hPa geopotential height fields suggest that the large-scale circulation may be a dominant explanation for the SIC – GrIS melt covariabilty. Before this possibility is examined more closely, we analyze trends in SIC and GrIS melt patterns and timing.

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4.2 Changes in the Sea Ice Cover around Greenland

The above analysis suggests a local-scale influence from SIC on GrIS melt within Baffin Bay and Davis Strait during June. This region of high SIC-GrIS covariability has experienced a sharp drop in SIC since 1979 [**Figure 4**]. In Baffin Bay and Davis Strait, SIC trends are negative in all seasons, and are particularly large in winter (DJF), spring (MAM) and summer (JJA) [**Figure 4a-d**]. In contrast, SIC trends in the East Greenland Sea are mixed, which may in part explain the lack of covariability within this region. Adjacent to the Greenland's east coast, positive SIC trends occur throughout winter and spring. Further east, reductions in SIC are confined to the area where the Odden used to form (c.f. Figure

2). During summer and fall, negative SIC anomalies persist along eastern GrIS, though they remain smaller than on the western side. North in the Lincoln Sea region, there is essentially no change in SIC year-round except for slight negative trends in summer.

Negative SIC trends have resulted in longer open water periods surrounding Greenland [**Figure 4e**]. Trends in annual open water days are mostly positive everywhere, the exceptions being the Lincoln Sea, which remains ice-covered year around, and the southern part of Davis Strait towards the Labrador Sea, a region where ice has expanded during recent winters. In some locations within Baffin Bay and the East Greenland Sea the number of open water days has increased by as much as 30 to 40 days per decade, but regionally averaged trends are generally on the order of 2 weeks per decade.

The strength of the OWF trends and exact timing of when these trends peak around the GrIS reveal large spatial differences [**Figure 5**]. The largest OWF trends occur in Baffin Bay during week 26 (third week of June), and are on the order of 10% dec^{-1}, with a secondary peak during week 44 (end of October). Further south in Davis Strait, OWF are positive throughout winter and into July (~5% dec^{-1}), reflecting both earlier ice retreat and later winter ice formation, with the largest trends during week 52 (6% dec^{-1}). East of Greenland, positive OWF trends are found throughout the year in the Greenland Sea, but are considerably weaker than found in Baffin Bay and Davis Strait. Finally, Lincoln Sea OWF trends are mostly negative (except in June and August), though trends are generally less than 1% dec^{-1}, and are not statistically significant. For comparison the Arctic Ocean OWF trends are also shown, showing peak OWF trends around week 38 (mid-September), reflecting the timing of the pan-Arctic sea ice minimum.

4.3 Changes in the Melt Season

We next examine if there is a link between the timing of EMO, MO, and FO over sea ice and over GrIS. The link between MO and the timing of ice retreat has already been established, with correlations between the detrended melt onset and detrended ice retreat dates greater than 0.4 [See Figure S10, *Stroeve et al.,* 2016].

Climatological regional mean values of EMO, MO, FO show that melt begins earlier and freeze-up happens later over the sea ice than it does on the ice sheet, and can be largely explained by temperature dependencies on elevation [**Table 1]**. In western Greenland, the continuous MO period for sea ice begins about 9 days earlier than on the ice sheet in the Baffin Bay region, and 15 days earlier in the Davis Strait region, whereas ice sheet FO occurs on average in early to mid-September, compared to the end of October (Baffin Bay) to the end of November (Davis Strait) over the adjacent sea ice. Similarly, in the Greenland Sea region, MO begins around 20 days earlier over the sea ice than on the ice sheet and FO happens about a month later. In contrast, the Lincoln Sea region exhibits similar timing in both MO and FO, which may be explained by the fact that this is the smallest region, and also the region furthest north where most melting will only occur at lowest GrIS elevations. Since there is little sea ice in the North Atlantic (e.g. regionally the open water season lasts for 360 days), MO and FO dates are not meaningful, but generally show values similar to as that observed in Davis Strait.

EMO, MO and FO trends for SIC and GrIS are of the same sign, indicating an overall lengthening of the melt season over the last 37 years in both environments [**Figure 6**]. Baffin Bay experiences the largest trends towards earlier MO and later FO, with regionally averaged trends of -8.3 and +7.8 days dec^{-1}, respectively, statistically significant at 99% confidence [**Table 2**]. This has led to an increase in the melt season length on the order of 16 days per decade. GrIS trends in the same region are typically smaller, especially in regards to the timing of freeze-up (4.6 days dec^{-1}) and melt season duration (11.1 days dec^{-1}). In contrast, larger statistically significant trends in both MO and FO are seen over the Davis Strait GrIS region, leading to a lengthening of the melt season that is larger than over the adjacent sea ice (18.7 days dec^{-1} compared 11.7 days dec^{-1}).

On Greenland's eastern side, similar ice sheet/sea ice MO trends are observed, but sea ice FO trends are smaller, and not statistically significant. The exception is the North Atlantic region, which exhibits large positive FO trends of 8.9 days dec^{-1}, resulting in an overall increase in melt season duration of 16.3 days dec^{-1}. However, given the low frequency of sea ice in this region, caution is warranted when interpreting these trends since ocean dynamics play a large role in the year-to-year variability in these values. Nevertheless, the largest trends in melt season duration over the eastern GrIS are also found in the North Atlantic sector (22.1 days dec^{-1}), primarily a result of earlier MO. The Greenland Sea GrIS sector also exhibits large trends in melt duration (14.4 days dec^{-1}), but earlier MO and later FO play a nearly equal role here. Interestingly, the Lincoln Sea GrIS region also displays large trends in melt season duration (12.7 days dec^{-1}), considerably larger than seen over the adjacent sea ice (5.5 days dec^{-1}). While the climatological mean timing of MO and FO is broadly similar over both the sea ice and the GrIS in the Lincoln Sea GrIS region, there has been a trend towards much later freeze-up (6.8 days dec^{-1}).

Finally, we examine whether there is synchronicity in the timing of melt onset and freeze-up between the sea ice and the ice sheet. In the Baffin Bay sector, the correlations between the sea ice and ice sheet MO and FO (respectively) exceed $0.6; p=0.001$. High correlations ($r>0.6$) are also seen in the Lincoln Sea sector and for EMO in the Greenland Sea sector ($r=0.6; p=0.001$). Correlations are reduced when MO, FO and EMO records are detrended, yet remain significant in the Baffin Bay and Lincoln Sea regions: detrended correlations for sea ice and the ice sheet EMO, FO and melt season duration exceed $r=0.5, p=0.001$ in Baffin Bay as well as the Lincoln Sea in regards to the MO, $p=0.002$. Elsewhere, no significant relationship is found.

4.4 Impact of sea ice changes on surface energy fluxes

Next we examine the relationship between early and late MO and variations in atmospheric moisture and heat fluxes using lag-correlation and composites for early and late MO years. We begin with an assessment of the differences in the strength of turbulent fluxes between early and late MO years. All months are shown to allow for both an assessment of what drives early MO over sea ice as well as to determine how early sea ice MO influences the overlying atmosphere [**Figure 7**].

On average, the transfer of latent heat flux occurs from the ocean to the atmosphere year-round in all regions, except the Lincoln Sea in Sep-May, and Baffin Bay in Dec-Feb. In Baffin Bay and Lincoln Sea, latent heat flux transferred to the atmosphere is small until the sea ice begins to break up and melt in the summer and moisture is released from the previously ice-covered ocean. Latent heat fluxes are directed into the atmosphere year-round in Davis Strait and Greenland Sea due to large areas of ice-free ocean that persists throughout the year.

Sensible heat flux is generally directed towards the surface for regions that are 100% sea ice covered during the cold season months (e.g. Baffin Bay and the Lincoln Sea) and then switches towards the atmosphere as the sea ice retreats in summer (Baffin Bay only). Regions that have large fractions of open water year-round generally have a net sensible heat flux transfer towards the atmosphere year-round, though some exceptions occur. Greenland Sea and Davis Strait exhibit sensible heat flux to the atmosphere in early spring and late fall (October-December) when the ice-free ocean surface is much warmer than the overlying air; due to the higher heat capacity of water, the opposite is true for ice-covered regions.

A larger amount of sensible and latent heat flux tends to enter the atmosphere in the spring during early MO years in all regions. However, the Baffin Bay region is the only region with a majority of positive fluxes throughout the year. When melt happens early in Baffin Bay, the additional sensible and latent heat fluxes result in ~14 Wm^{-2} entering the atmosphere in spring (March-June) and ~25 Wm^{-2} in autumn (September-December) due to a later FO. In contrast to Baffin Bay, turbulent flux anomalies in early MO years from Davis Strait and Lincoln Sea show no strong consistent pattern and switch between positive anomalies throughout the year. Compared to Baffin Bay, Davis Strait, which is further south, has larger latent heat fluxes entering the atmosphere between February-August during years with earlier MO, whereas sensible heat flux into the atmosphere is only larger during early MO years in February, April and November, reflecting both early MO (April) and later FO (November). Over the Lincoln Sea there are no fluxes of heat or moisture into the atmosphere during the late fall, winter and early spring due to the solid sea ice pack. However, by June there is an additional ~12 W m^{-2} of turbulent flux energy transferred to the atmosphere during early melt years. This generates smaller turbulent fluxes in July due to warmer air temperatures than when melting has just begun in late MO years. The early MO year turbulent flux anomalies from Greenland Sea are different from the other three regions, as there is more heat and moisture entering the atmosphere in January, March, October and December during early MO years.

Sensible and latent heat fluxes transfer heat and moisture into the local atmosphere and can cause the temperature and humidity to increase, which in turn should produce larger downwelling longwave flux at the surface due to the greenhouse feedback effect. Thus one would expect to see a larger net longwave flux (downwelling – upwelling) at the surface during early MO years when the local atmosphere contains more heat and moisture. We see evidence of this occurring until roughly July as there is more net longwave directed towards the surface of the ice sheet in most regions when the sea ice melts earlier **[Figure 8]**. In August the surface net longwave flux turns largely negative during early MO years, partly because the warmer ice sheet results in dominance of upwelling radiation fluxes, and partly because there is less of an influence of early season conditions.

The increase in heat and moisture into the atmosphere from the surrounding ocean in early MO versus late MO years and subsequent increase in energy at the ice sheet surface is shown in more detail for Baffin Bay in **Figures 9(a)** and **(d).** In April and May (day 1 to 61 in Figure 9), there appears to be an out-of-phase relationship between latent heat flux over Baffin Bay and the specific humidity over the adjacent ice sheet, with pulses of moisture coming from the ocean surface being followed about a week later with rising specific humidity over the ice sheet. A similar pattern is observed between ocean sensible heat flux and near surface air temperature over GrIS. In June and July (day 61 to 92), latent and sensible heat flux anomalies for early/late MO years fluctuate around zero, which suggests these fluxes are similar between early and late MO years. In contrast, the specific humidity and temperature are higher in late MO years over the ice sheet in July (negative anomalies in Figure 9a and 9d). This could be due to a roughly one-month delay in late MO years compared to early MO for the sea ice, which causes increases in the temperatures and humidity later in the season (July) over the ice sheet. From the timing of early sea ice MO (dotted blue line) to early GrIS MO (dotted blue, highlighted red line), large fluxes of

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moisture and heat released via the latent and sensible heat flux from the ice/ocean surface precede elevated humidity and temperature over the ice sheet.

One-week running lagged correlations between latent heat flux from the ocean and specific humidity over the ice sheet show large positive correlations during early MO years [**Figure 9b**, solid blue lines], suggesting increased evaporation from earlier MO over sea ice may be driving the observed increase in specific humidity over the ice sheet one week later. A one-week lag was chosen because sea ice and GrIS MO in Baffin Bay occur about 9 days apart on average, and also because water vapor in the troposphere has a residence time of about two weeks. These three highly correlated events precondition the ice sheet for earlier MO by increasing the specific humidity and thus the downwelling longwave flux earlier in the spring. In late MO years, the sea ice/ocean does also appear to play a small role in initiating MO on the ice sheet. Large amounts of latent heat are released from the surface in Baffin Bay at the timing of late MO, which in turn is correlated to increases in specific humidity over the ice sheet directly before MO, initiating melt (solid green lines). Since Baffin Bay MO is much later (~1 month) in late melt years, excess moisture into the atmosphere is delayed. Though because the environment is already warming seasonally, it does not require extra preconditioning for the melt to begin on GrIS compared to early melt years. This case is very similar to sensible heat flux released from Baffin Bay and ensuing temperature over the ice sheet [**Figure 9c**]. Comparing these 1-week lagged correlations to a zero-lag correlation (not shown), correlations for all variables in early and late MO years are highly negative, meaning they are out of phase [**Figure 9d**].

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Note also there are instances in April when both early and late melt years exhibit high correlations between either sensible or latent heat from the sea ice region and specific humidity or temperature over GrIS one week later. This may be related to opening of the North Water Polynya [*Boisvert et al.*, 2012]. As the open ocean is relatively warm compared to the overlying air in April, heat and moisture fluxes enter the atmosphere and are subsequently transferred over the ice sheet, increasing the specific humidity and air temperature.

In summary, sea ice in Baffin Bay/Davis Strait and the adjacent ice sheet surface conditions appear connected. MO and breakup of the sea ice triggers enhanced flux of heat and moisture into the atmosphere, which are observed over the ice sheet within a week. This results in a warming and moistening the local environment and preconditions the ice sheet for melt in early MO years. Therefore, when the MO of the sea ice is earlier, MO of GrIS is earlier and vice versa.

4.5 Influence of large scale atmospheric variability on Baffin Bay and Beaufort Sea

The SVD analysis (4.1) indicated that both Baffin Bay/Davis Strait and the Beaufort Sea are regions with SIC and GrIS melt water production covariability. In the case of Baffin Bay/Davis Strait, this was supported by the melt and turbulent heat flux analysis. Next we examine the influence of the large-scale atmospheric variability on this covariability using Pearson correlation and partial correlation.

In the Beaufort Sea, both 500 hPa heights and SIC closely covary, particularly in June [**Figure 10a**], in concert with high SIC covariance in this region with EC_{GrIS} in the HC maps [**Figure 3**]. Here, the positive correlations between SIC and GrIS melt weaken significantly after June with almost no correlation by August [**Table 3**]. The strong relationship between Beaufort SIC and GrIS melt in June is reduced considerably when the

GBI index is removed via partial correlation, as significant correlations remain only in southeast Greenland.

The correlation between SIC in Baffin Bay/Davis Strait and geopotential heights is relatively strong but not as extensive in June, while this signal mostly disappears in July and especially August [**Figure 10d; Table 3**]. This is associated with a weakening Baffin Bay SIC correlation with EC_{GrIS} in the HC maps [**Figure 3(a), (e) and (i)**]. Statistically significant correlations with meltwater production are focused on the west side of the ice sheet in June [**Figure 10e**], but are minimal in July and August when correlations over only 7% and 2% of the respective unmasked ice sheet area are statistically significant. Partial correlation analysis indicates that the GBI explains approximately two thirds of this correlation in each month, though this still leaves the possibility that variations in Baffin Bay sea ice are in part responsible for the correlation with surface melt in western Greenland.

Because there is a potential local influence from Baffin Bay and Davis Strait, we next focus on GrIS melt only in west-central Greenland. The highest and lowest melt years in west-central Greenland (after removing trends) consistently correspond to patterns of anomalous SIC and geopotential heights in these years [**Figure 11**]. These variables show much less variation by month, though a weaker relationship appears particularly in the height field, which follows results from the SVD analysis [**Figure 11 (g)-(l)**]. Additionally, a strong SIC pattern is evident not just in western Greenland but consistently on the east side of Greenland that is equally as strong [**Figure 11(a)-(f)**]. This suggests that the processes responsible for this signal expression to the west of Greenland probably also exist on a large enough scale to have an effect of similar strength on sea ice off Greenland's east coast; most likely a persistent ridge or trough, as suggested by the above results. By August, sea ice in Baffin Bay has melted in most years, but positive anomalies in SIC still appear in the lowest Greenland melt years [**Figure 11(f)**].

In summary, the SVD analysis suggest covariablity between SIC and GrIS melt in the Baffin Bay region (Fig. 3) that cannot fully be explained by large scale atmospheric patterns (Fig 10 and 11). Examination of a set of hypotheses applied for the entire GrIS and surrounding seas shows that trends and patterns in the Baffin and Davis Strait regions are consistent with local scale influence [**Table 4**]. In contrast, no other regions have evidence of covariability or trends and patterns consistent with local scale influence.

5. Discussion

Sea ice and Greenland ice sheet melt demonstrate localized covariability during the summer, particularly June. While the majority of this relationship appears related to simultaneous atmospheric circulation forcing, analysis over Baffin Bay/Davis Strait and the adjacent ice sheet indicates that the covariability may additionally include a local-scale influence. This is in agreement with previous work by *Rennermalm et al*. [2009] who found the SIE and GrIS surface melt extent to co-vary in the western part of the ice sheet, though the strongest relationships were found in August rather than June. Part of the discrepancy might be explained by the study period. This study extends through 2015 and includes years with larger anomalies in both SIC and GrIS melt. However, June is the time of year with the largest trends in OWF, reflecting earlier development of open water at a time when the atmosphere is still relatively cold. Thus, it is not surprising that we find stronger covariability in June and a link with melt onset. An additional area of covariability in terms of melt onset timing is also seen in the Lincoln Sea sector.

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While statistical analysis suggests a local-scale influence may be present on the western side of the ice sheet, the ability for the sea ice to influence GrIS melt depends on having anomalous heat and moisture sources that can travel to the ice sheet. In this study we find that turbulent fluxes are often larger during early MO years in the spring and fall because areas where the ocean is ice-free tends to be warmer than that of the air, due to the higher heat capacity of water. Both latent and sensible heat fluxes are larger and more positive (from the ocean surface to the atmosphere) during early MO years, resulting in increased air temperature and specific humidity especially in May when the atmosphere is ~2 K warmer and ~0.5 g kg^{-1} wetter. This excess heat and humidity increases downwelling fluxes to the ice sheet earlier in the year, preconditioning the ice sheet and triggering melt (also shown in Figure 8). For late MO years, this phenomenon occurs later in the season, and this is most likely why we see larger fluxes during late MO years in the summer months (i.e. July depending on the climatology of the region). This is specifically true for Baffin Bay, where throughout the winter months the region is completely covered by sea ice, creating a barrier between ocean-atmosphere energy exchanges. This is also valid for the Lincoln Sea in the content of melt ponds and a higher occurrence of leads forming on the thick multi-year ice during the summer months.

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Turbulent fluxes from increased open water can reach well above the boundary layer [e.g. *Yulaeva et al*., 2001], but this depends on the frequency of spring and early summer inversions that cap the atmospheric boundary layer. Furthermore, if katabatic winds are persistent at the ice edge, this will keep onshore flow from reaching the ice sheet [*Noël et al.,* 2014], though a possibility remains for mixing in the boundary layer via a barrier wind mechanism [*van den Broeke and Gallée*, 1996]. Analysis of daily winds around the timing of sea ice melt, show that during early MO years over the sea ice, wind direction is from the open water areas of Baffin Bay onto the GrIS, which helps support our claims that earlier melt onset in part drives early melt over Greenland [**Figure 12**]. In late MO years, the wind direction is reversed.

Finally, we note that SVD analysis reveals the strongest relationship between GrIS melt and sea ice variability occurs within the Beaufort Sea. This appears to be related to the positioning of a ridge near Greenland that enhances both ice sheet melt and sea ice retreat as stronger easterlies help to circulate ice west out of the Beaufort Sea. SVD analysis shows the covariability in June is reduced considerably when the GBI index is removed via partial correlation, evidenced by the large reduction in percentage of grid cells with a significant correlation (not shown). This explanation is supported by the relatively weak value of NSC for June GrIS melt and SIC, which nearly doubles to 0.191 in the SVD analysis of 500 hPa geopotential heights instead of SIC. The Greenland blocking mechanism has been identified previously as a way to transport and melt ice between the Beaufort Sea and the East Siberian Sea [*Rogers*, 1978; *Maslanik et al.*, 1999]. We speculate that no mechanism originating from sea ice variability directly influences GrIS melt from a distance of hundreds of kilometers away, though Liu et al. (2016) argue that sea ice loss within the central Arctic has favored stronger and more frequent blocking events over Greenland.

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In 2012, as the sea ice cover reached its all-time record low September extent, the Greenland ice sheet also experienced a record amount of surface melt and ice mass loss [*Tedesco et al.,* 2013]. Several explanations have been put forth to explain this anomalous melt, including increased downwelling longwave radiation from low-level liquid clouds [*Bennartz et al*., 2013], advection of moist warm air over Greenland [*Neff et al*., 2014] and dominance of non-radiative fluxes [*Fausto et* al., 2016]. While this event was likely a result of atmospheric circulation patterns that transported warm, humid air over the southern and western part of the ice sheet, the sea ice melt season began a week earlier than the 1981-2010 long-term mean over Davis Strait and 3 days earlier over Baffin Bay. This earlier melt onset of the sea ice may have provided an additional source of warm, moist air over the adjacent ice sheet.

6. Conclusions

Based on multiple lines of statistical evidence, we identified western Greenland as a region where direct influence from sea ice on the GrIS SMB is possible. SVD analysis revealed that extreme melt years over the adjacent ice sheet are accompanied by strong SIC anomalies within Baffin Bay and Davis Strait that would be expected if a local-scale thermodynamic influence were occurring. This is true even after near surface temperature and climate index influences are removed.

The covariance is strongest in June, which may be partially due to the lower variability in interannual June meltwater production over the entire ice sheet relative to the rest of summer, with a standard deviation simulated by MAR of 0.84 mm water equivalent day^{-1} compared to 0.95 in August and 1.12 in July. Additionally, June variability in sea ice may have a greater potential to influence GrIS melt given that the ice sheet is transitioning into its warm season regime and reaching the freezing point for the first time in many locations. This is further confirmed through correlations between the timing of melt onset, which occurs on average 9 days earlier over the sea ice than on the adjacent ice sheet, and in turn allows for earlier development of open water and enhanced transfer of turbulent heat fluxes from the ocean to the atmosphere. More heat and moisture is transported to the local atmosphere from the ice-free ocean surface via turbulent fluxes in years when sea ice melts earlier. Daily wind field analysis suggests these enhanced turbulent fluxes are transferred to the ice sheet, allowing the local atmosphere over the GrIS to warm and become more humid, which in turn impacts the net downwelling longwave flux, helping precondition the surface for earlier melt onset.

However, despite evidence of a possible local-scale influence, all analysis incorporating 500 hPa height anomalies suggests that the large-scale atmospheric circulation remains the primary melt driver in this part of the ice sheet as well as for the ice sheet as a whole. Anomalous atmospheric circulation features include increased frequency of the negative phase of the Arctic Dipole [*Overland and Wang*, 2010] and a persistently negative summer North Atlantic Oscillation [*van Angelen et al.*, 2013]. Continued Arctic amplification and associated shifts in Arctic atmospheric circulation and their persistence will theoretically continue to enhance warming in the vicinity of Greenland [*Francis and Vavrus*, 2012, 2015]. Nevertheless, our study suggests a local response is also possible, and as the sea ice cover continues to retreat around the Greenland ice sheet, this should present further opportunities for local enhancement of summer ice sheet melt.

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Table 1. Climatological (1981-2010) mean values in length of open water season, together with climatological dates in early melt onset (EMO), continuous melt onset (MO), continuous freeze-up (FO) and melt season duration for 5 sea ice regions (excluding the North Atlantic where little sea ice exists). Corresponding mean dates in melt onset, freeze-up and duration are also shown for the Greenland drainage basins.

Region	**Length of Open Water Season** (days)	**EMO** (day of year)	**MO** (day of year)	**FO** (day of year)	**Melt Duration** (days)
Sea Ice Regions					
Baffin Bay	104	146	155	291	136
Davis Strait	220	133	143	321	188
North Atlantic	360	110	134	313	178
Greenland Sea	227	143	148	267	119
Lincoln Sea	0	162	172	232	60
Greenland Ice Sheet Drainage Regions					
Baffin Bay		162	164	232	68
Davis Strait		149	157	247	90
North Atlantic		143	145	234	89
Greenland Sea		163	166	231	65
Lincoln Sea		166	167	230	63

Table 2. Trends from 1979 to 2015 in length of open water season, together with trends in melt onset, freeze-up and melt season duration for 5 sea ice regions (excluding the North Atlantic where little sea ice exists). Corresponding trends in melt onset, freeze-up and duration are also shown for the Greenland drainage basins. Only values for the continuous melt onset and freeze-up periods are listed. Trends are given as days per decade. Statistical significance of trend at 95 and 99% are denoted by $^{+}$ and $^{++}$, respectively.

Region	Open Water Trend (days/dec)	EMO Trend (days/dec)	MO Trend (days/dec)	FO Trend (days/dec)	Melt Duration Trend (days/dec)
Sea Ice Regions					
Baffin Bay	12.6^{+}	-5.7^{++}	-8.3^{++}	7.8^{++}	16.1^{++}
Davis Strait	15.9^{+}	-4.7^{+}	-6.7^{++}	5.0^{++}	11.7^{++}
North Atlantic	N/A	-6.9^{++}	-7.3^{++}	8.9^{++}	16.3^{++}
Greenland Sea	15.2^{+}	-6.7^{++}	-3.8^{+}	2.1	5.9^{+}
Lincoln Sea	-0.1	-4.0^{++}	-3.9^{++}	1.6	5.5^{++}
Greenland Ice Sheet Drainage Regions					
Baffin Bay		-6.1^{++}	-6.4^{++}	4.6^{+}	11.1^{++}
Davis Strait		-6.3^{++}	-10.5^{++}	8.2^{++}	18.7^{++}
North Atlantic		-10.7^{++}	-16.4^{++}	5.7^{++}	22.1^{++}
Greenland Sea		-6.1^{++}	-6.8^{++}	7.6^{++}	14.4^{++}
Lincoln Sea		-5.1^{++}	-5.9^{++}	6.8^{++}	12.7^{++}

Table 3. Percentage of grid cells with a significant correlation at α = 0.05 relative to the total grid cells of the unmasked ice sheet. The Pearson's correlation is between ice sheet meltwater production and area-averaged sea ice concentration anomalies in the Beaufort Sea and Baffin Bay (hatched regions in Figures 5a and 6a, respectively).

Month	**Beaufort Sea**		**Baffin Bay**	
	Simple Correlation (%)	**Partial Correlation (%)**	**Simple Correlation (%)**	**Partial Correlation (%)**
June	**87.0**	**81.0**	**17.3**	**20.2**
July	**31.2**	**13.4**	**11.1**	**2.1**
August	**32.6**	**12.5**	**12.5**	**9.4**

Table 4. Summary table of results discussed in the main body of the manuscript

Analysis Performed	Davis Strait	Baffin Bay	Lincoln Sea	Greenland Sea	North Atlantic
SVD: GrIS <> SIC (Fig. 3)		June			
SIC trends (Fig 4)	Reduced in all seasons	Reduced in all seasons	No change	Positive near the coast in spring and winter	N/A
Open water days (Fig. 4)	Increase	Increase	Increase	Increase	Increase
OWF trends (Fig 5)	Positive throughout shoulder seasons	Sharp peak in June and October	mixed	Positive throughout year, no sharp peaks	N/A
Relative start of melt on SIC and GrIS (table 2)	SIC MO earlier, SIC FO later	SIC MO earlier, SIC FO later	SIC and GrIS similar	SIC MO earlier, SIC FO later	N/A
Trends in timing of EMO, MO, FO (table 2, Figure 6)	MO earlier FO later	MO earlier FO later	MO earlier FO later	MO earlier FO later	N/A
Synchronicit y between GrIS and SIC EMO,MO,FO time series		R>0.6 for MO, FO R> 0.5 for detrended data	R>0.6 for MO, FO R> 0.5 for detrended data	R > 0.5 for EMO	
Latent heat fluxes (Fig 7)	positive all year	positive all year	positive in summer	positive all year	N/A
Sensible heat fluxes (Fig. 7(	Positive spring/fall	Positive JASO	Negative all year	Positive spring/fall	N/A
Early/late MO years composites (Fig 7)	Positive in winter, negative rest of year	Majority of positive anomalies	mixed	mixed	
Net longwave fluxes (Fig. 8)	Positive anomalies in spring	Positive anomalies in spring	Positive anomalies in spring	Positive anomalies in spring	N/A

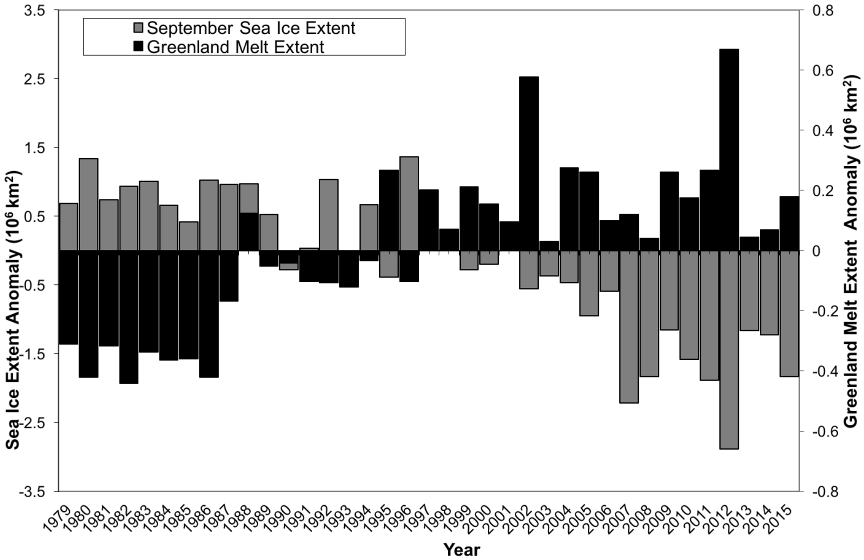

Figure 1. Time-series of September sea ice extent and Greenland surface melt extent anomalies from 1979 to 2015.

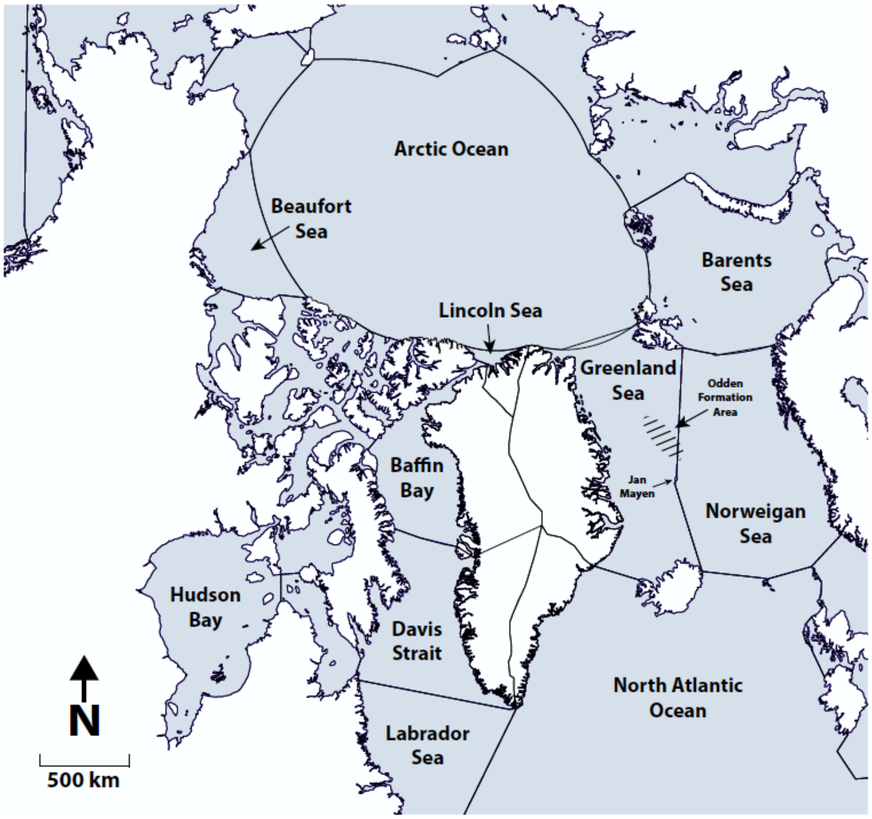

Figure 2. Map of study area, including the six sea ice and Greenland drainage sectors used in this study. The ice sheet regions are named after their adjacent sea (i.e. Davis Strait, Baffin Bay, Lincoln Sea, Greenland Sea, and the North Atlantic). The approximate area where the Odden sea ice featured used to formed is indicated with hatched lines. The ocean boundaries are defined by the International Hydrographic Organization (VLIZ (2005). IHO Sea Areas. Available online at http://www.marineregions.org/.)

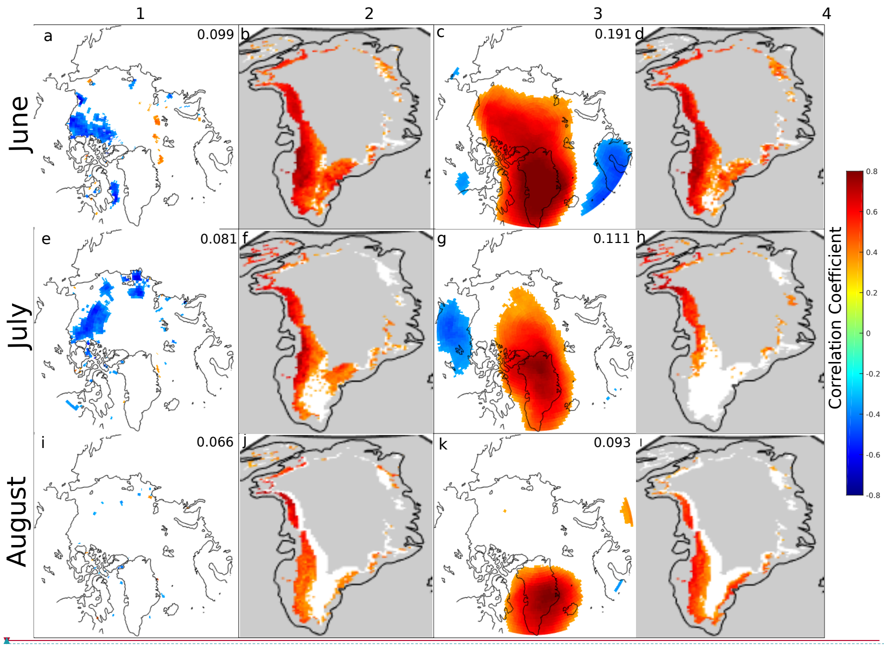

Figure 3. Heterogeneous correlation between variables in the leading SVD mode in JJA. Column 1 is the correlation between sea ice concentration and EC_{GrIS}. Column 2 is the correlation between meltwater production and EC_{SIC}. Column 3 is the correlation between 500 hPa geopotential heights and EC_{GrIS}. Column 4 is the correlation between meltwater production and the EC_{500}. Correlation coefficients are not considered over the masked gray regions, and only correlations significant at $\alpha = 0.05$ are shown. The normalized squared covariance (NSC) is given in the upper right of columns 1 and 3. All data are anomalies relative to 1979-2015 means with the least-squares trend line removed.

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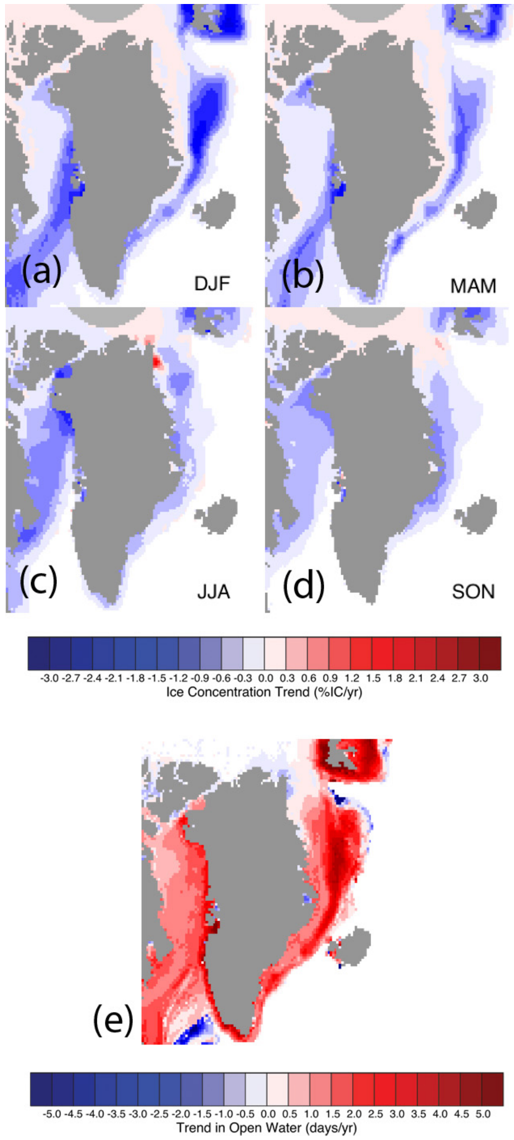

Figure 4. Seasonal trends in sea ice concentration from 1979 to 2015 (a-d) and number of ice free days (e). Trends are computed using linear least squares and evaluated using student T-test at 95% confidence interval.

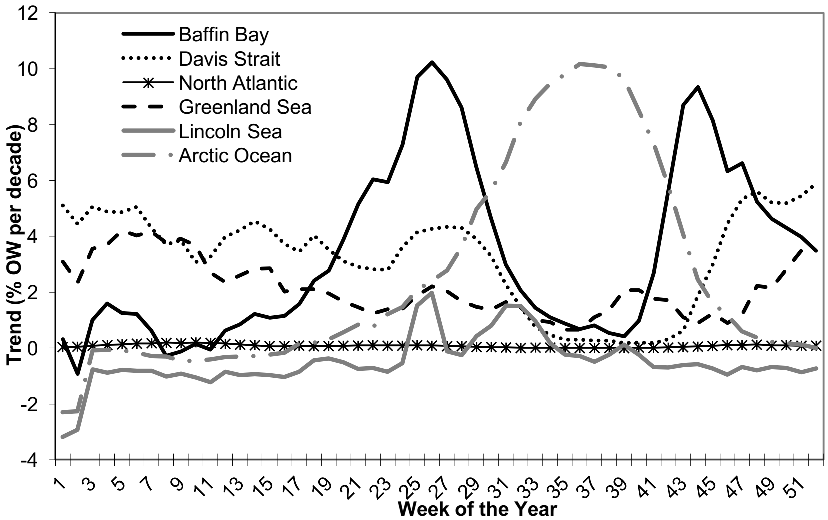

Figure 5. Trends in regional open water fraction (OWF) surrounding the Greenland Ice Sheet, computed from 1979 to 2014. Trends are computed using linear least squares.

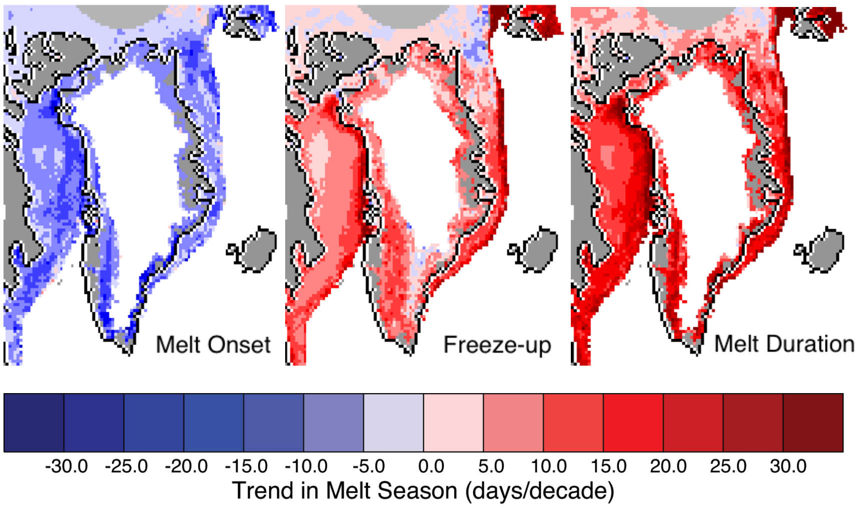

Figure 6. Trends in melt onset (left), freeze-up (middle) and total melt season length (right) for sea ice and Greenland from 1979 to 2015. Trends are computed using linear least squares and evaluated at the 95% confidence level using student T-test.

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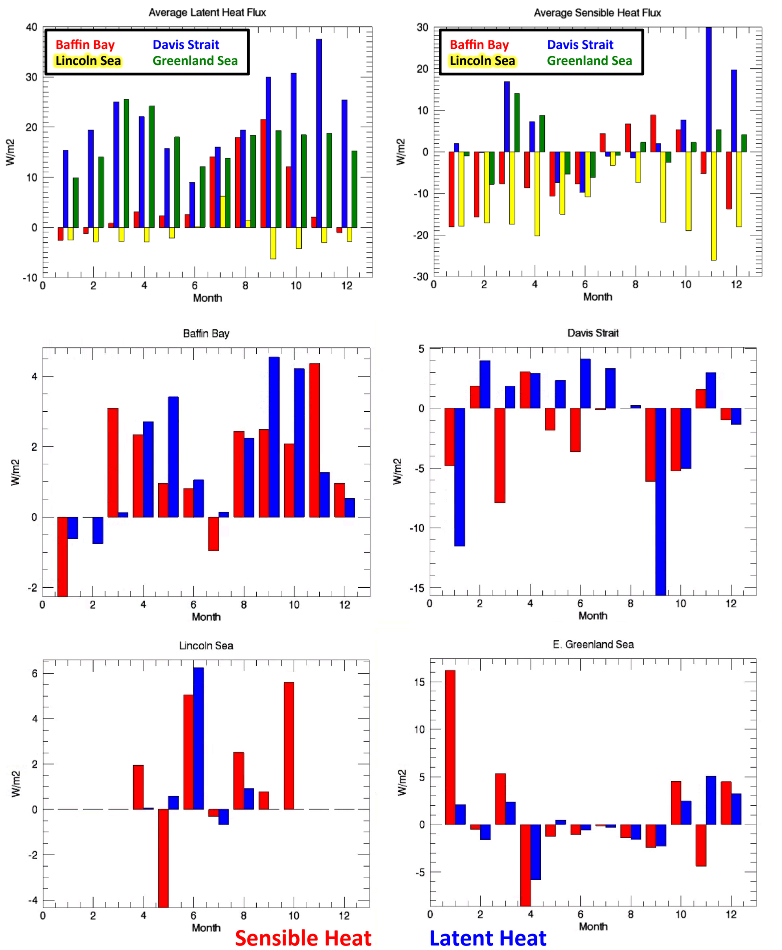


Figure 7. Top row graphs show the 2002 to 2015 average latent and sensible heat fluxes for each ocean region (denoted by color). The sign convention is such that positive fluxes are directed from the ocean to the atmosphere. Bottom two row

graphs show the early minus late melt onset years for each region of the positive (into the atmosphere) sensible (red) and latent (blue) heat fluxes.

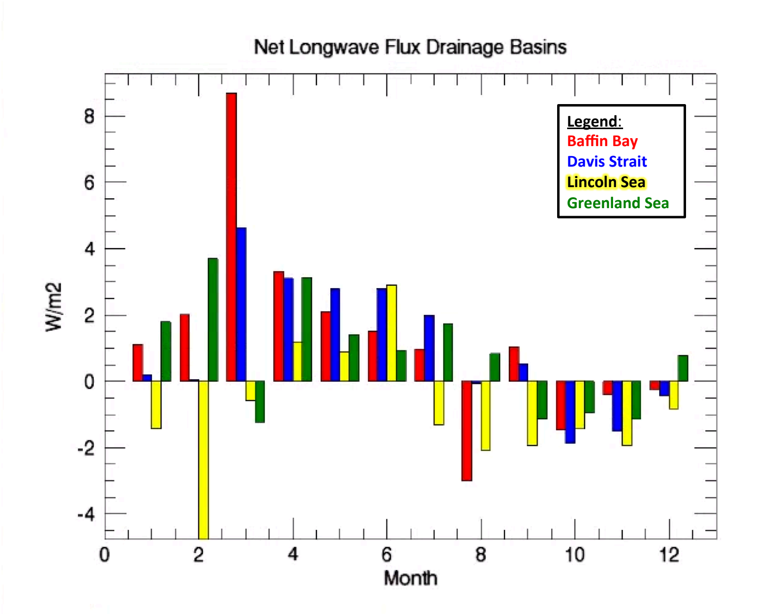


Figure 8. Net longwave flux (downwelling longwave flux – upwelling longwave flux) for early MO minus late MO years for the drainage basins of the Greenland Ice Sheet, where red bars are for Baffin Bay, blue bars are for Davis Strait, yellow bars are for Lincoln Sea and green bars and for Greenland sea.

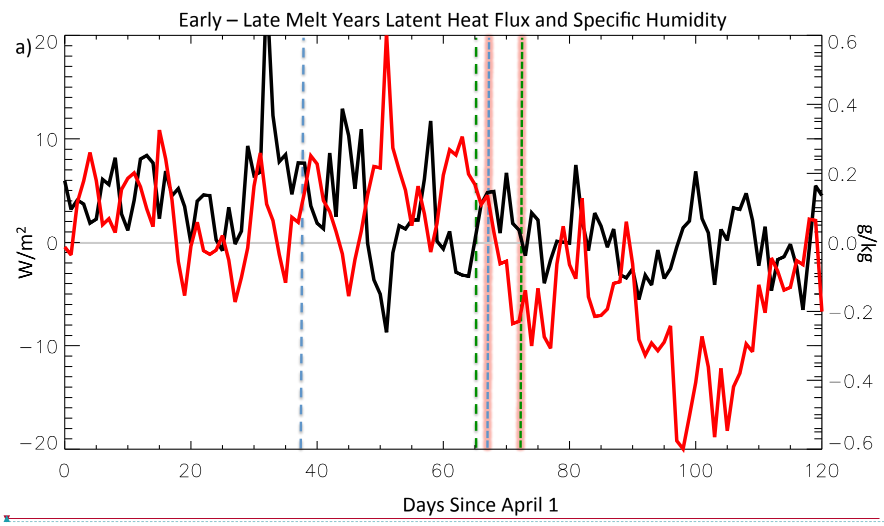
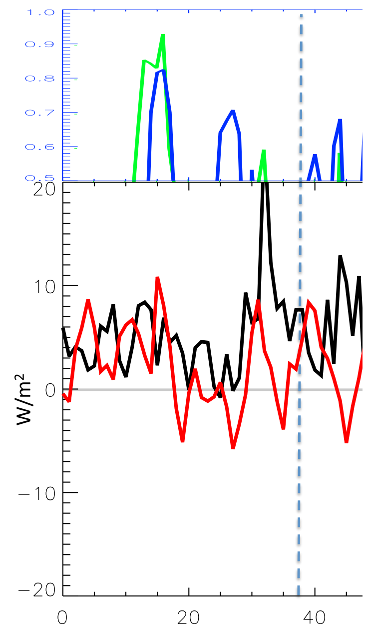


Figure 9a. Baffin Bay SIC region latent heat flux from early minus late MO years (black line) and Baffin Bay GrIS region specific humidity from early minus late MO years (red line). Dotted vertical lines represent the average early melt onset date for Baffin Bay (dotted blue), and average late melt onset date for Baffin Bay (dotted blue, red highlight), average early melt onset date for GrIS (dotted green), and average late melt onset date for GrIS (dotted green, orange highlight).



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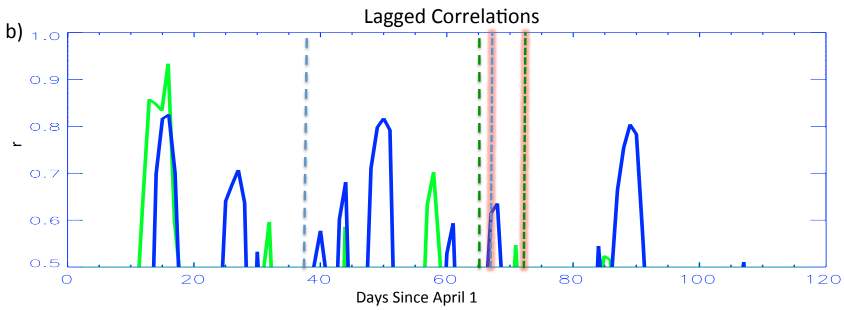

Figure 9b. Week lag-1 week lagged running correlations (between 0.5 and 1.0) for early melt years latent heat flux from Baffin Bay and specific humidity from GrIS (blue) and late melt onset latent heat flux from Baffin Bay and specific humidity from GrIS years (green).

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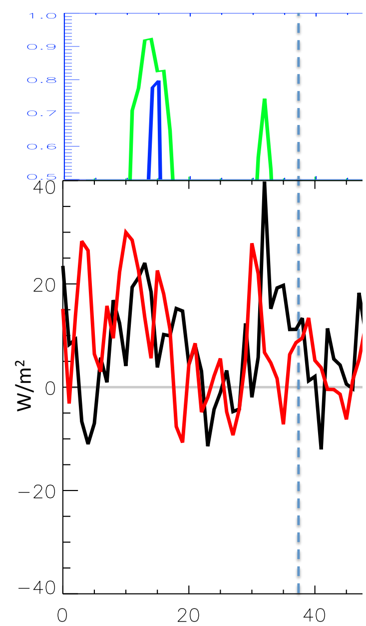

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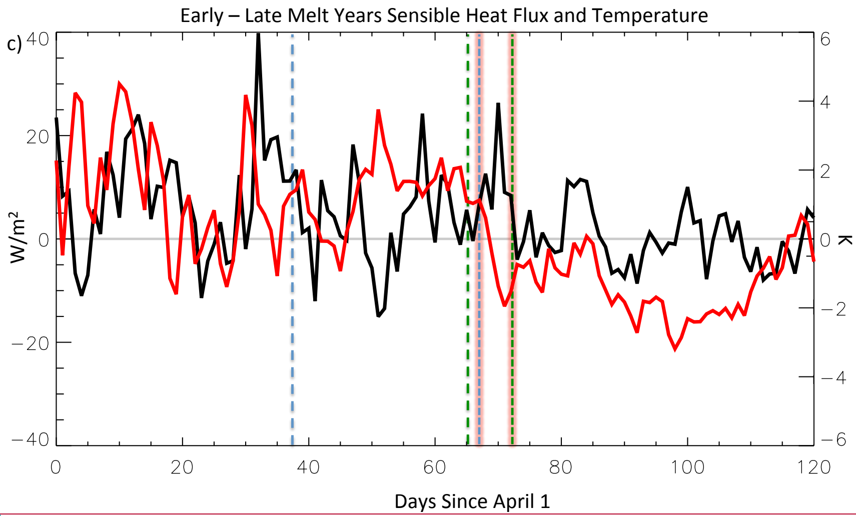

Figure 9c. Baffin Bay SIC region sensible heat flux from early minus late MO years (black line) and Baffin Bay GrIS region air temperature from early minus late MO years (red line). Dotted vertical lines represent the average early melt onset date for Baffin Bay (dotted blue), and average late melt onset date for Baffin Bay (dotted green), average early melt onset date for GrIS (dotted blue, red highlight), and average late melt onset date for GrIS (dotted green, orange highlight).

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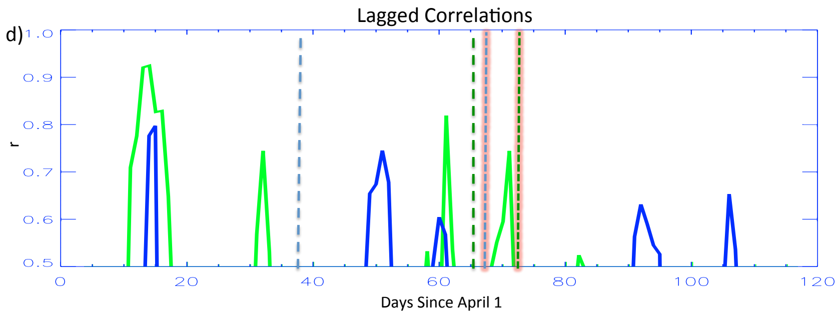

Figure 9d. Week lag-1 week lagged running correlations (between 0.5 and 1.0) for early years sensible heat flux from Baffin Bay and air temperature from GrIS (blue) and late melt onset sensible heat flux from Baffin Bay and air temperature from GrIS years (green).

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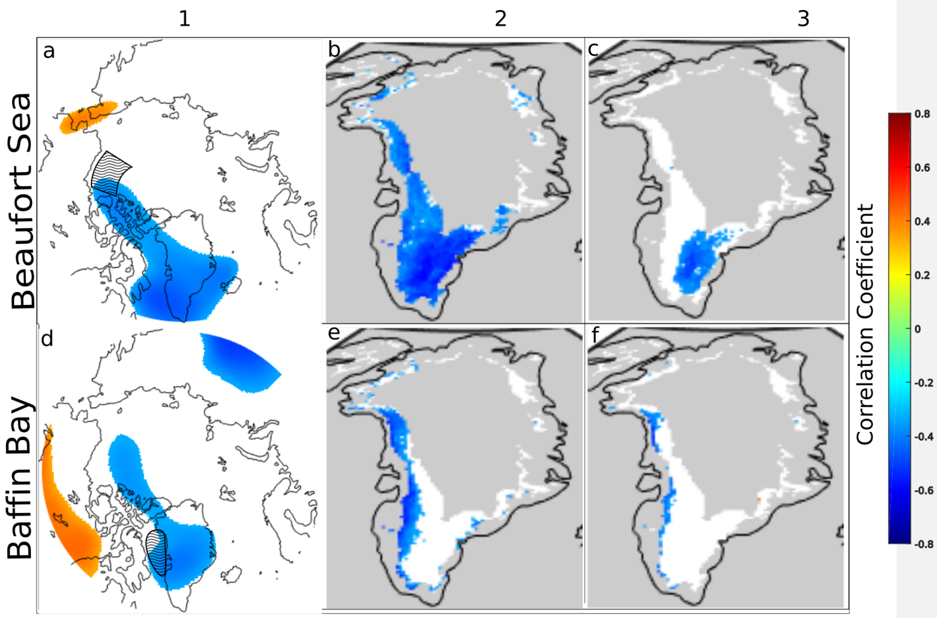

Figure 10. June correlation between spatially averaged SIC in the hatched region and: Column 1) 500 hPa geopotential height field, Column 2) Greenland meltwater production, and Column 3) same as Column 2 but with the effect of the Greenland Blocking Index removed (partial correlation). Correlation coefficients are not considered over the masked gray regions. All data are anomalies relative to 1979-2015 means with the least-squares trend line removed.

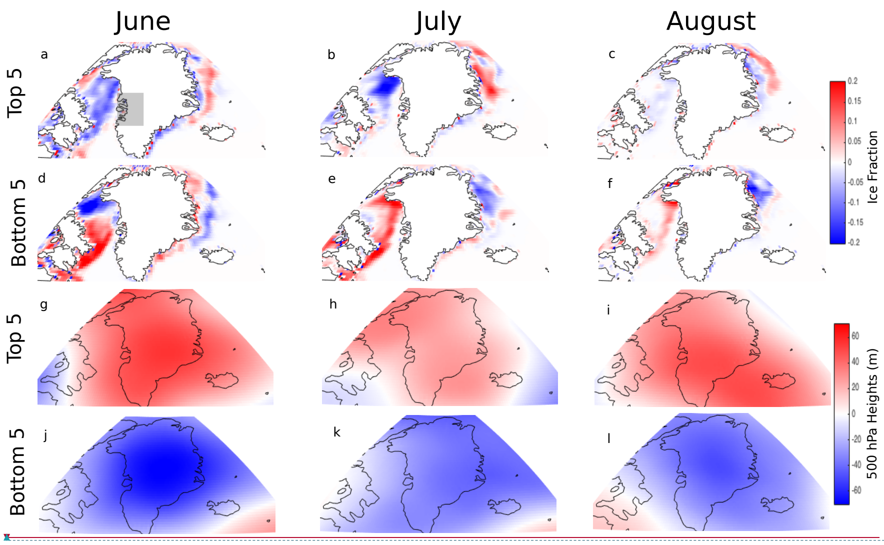

Figure 11. De-trended anomalies of SIC (a-f) and 500 hPa geopotential heights (g-l) averaged over the 5 highest and lowest melt years in June, July, and August as indicated by de-trended meltwater production anomalies in the indicated gray region of the ice sheet. Units are ice fraction (a-f) and m (g-l).

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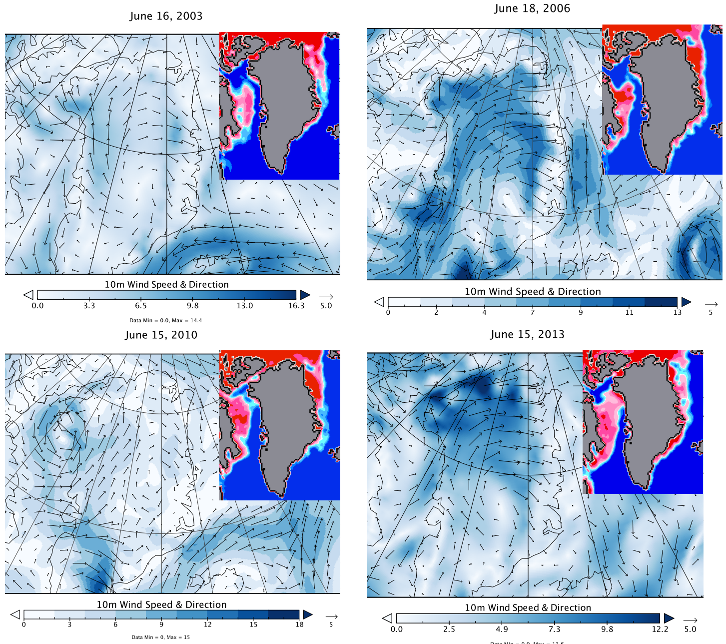

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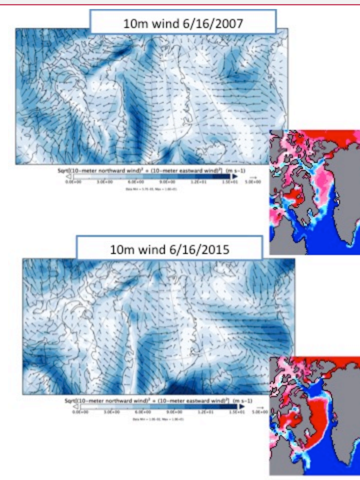

Late Melt Years

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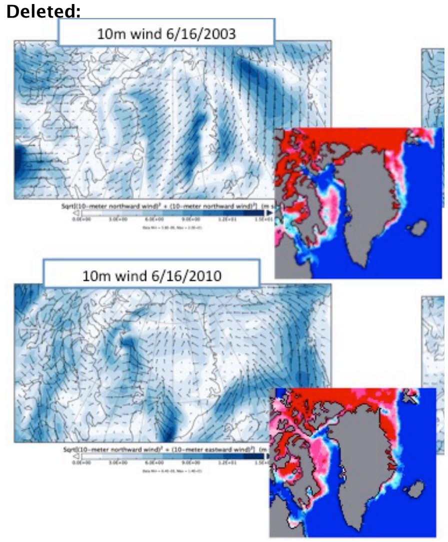

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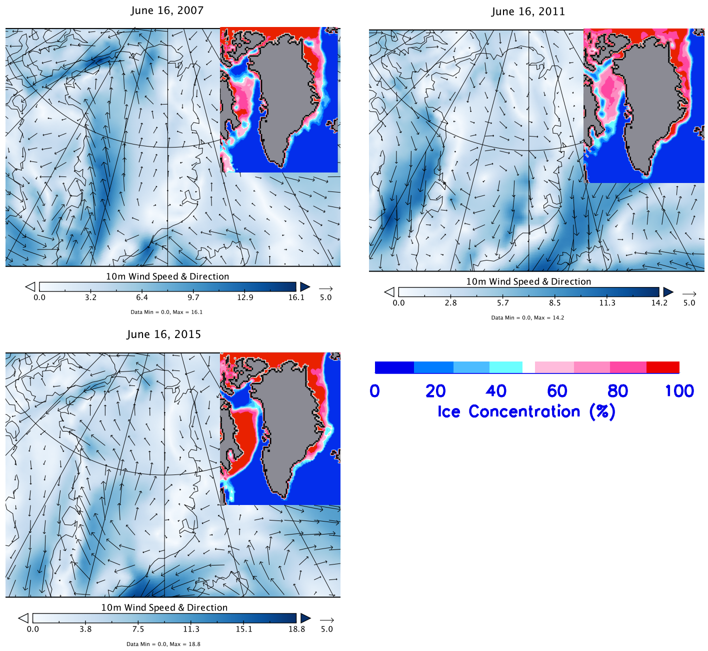

Figure 12. Wind vectors and speeds at 10 meters from MERRA-2 during 4 early sea melt years over Baffin Bay (top panel) and 3 late sea melt years (bottom) panel. Smaller figures superimposed on the wind maps show the sea ice concentration (%) for that day.

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