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Does sea ice influence Greenland ice sheet surface-melt?

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Abstract
Recent decreases in Arctic sea ice and increases in Greenland ice sheet surface-melt may have global impacts, but the interactions between these two processes are unknown. Using microwave satellite data, we explore the spatial and temporal covariance of sea ice extent and ice sheet surface-melt around Greenland from 1979 to 2007. Significant covariance is discovered in several loci in the late summer, with the strongest covariance in western Greenland, particularly in the southwest (Kangerlussuaq). In this region, wind direction patterns and a statistical lag analysis of ice retreat/advance and surface-melt event timings suggest that sea ice extent change is a potential driver of ice sheet melt. Here, late summer wind directions facilitate onshore advection of ocean heat, and enhanced melting on the ice sheet commonly occurs after reductions in offshore sea ice. Hence, this study identifies for the first time the covariability patterns of sea ice and ice sheet melt and suggests that a retreating sea ice margin may enhance melting over the ice sheet.

Keywords: Greenland, ice sheet, sea ice, Arctic, surface-melt

1. Introduction

Greenland ice sheet surface-melt accelerated in the late-20th/early-21st century (e.g. Abdalati and Steffen 2001, Mote 2007, Tedesco 2007), coinciding with a period of rapid sea ice loss in surrounding seas and oceans (Stroeve *et al* 2007, Comiso *et al* 2008, Parkinson and Cavalieri 2008). Both are projected to continue in the 21st century (Meehl *et al* 2007). Large ice mass losses from Greenland may increase global sea levels up to 0.5 m (Pfeffer *et al* 2008) with tremendous global socio-economic impacts (Stern 2007).

On the Greenland ice sheet, the recent surface-melt anomalies are governed by rising surface temperatures and lowered ice albedo (Abdalati and Steffen 1997, Tedesco 2008). Here, we explore the possibility of a third factor influencing melt extent, namely the presence or absence of offshore sea ice. Sea ice presence is known to influence local and regional surface climate (Alexander *et al* 2004, Rinke *et al* 2006, Honda *et al* 1999), surface temperatures (Ogi and Wallace 2007, Lawrence *et al* 2008), precipitation patterns (Singarayer *et al* 2006) and cyclone frequency (Deser *et al* 2000). In principle, sea ice can be linked to ice sheet surface-melt through a chain of high correlations between sea ice and ocean temperatures (Comiso 2002), ocean and coastal temperatures (Hanna and Cappelen 2003), and coastal temperatures and ice sheet surface-melt (Abdalati and Steffen 2001, Mote 2007). In fact, JRA-25 and NCEP/NCAR reanalysis fields suggest that the recent emergence of surface-based Arctic warming is in response to reduced sea ice extent (Serreze *et al* 2009). Expanding open-water areas in summer absorbs solar energy, increases the specific heat content of the upper ocean, and further melts sea ice. This allows for enhanced heat transfer from the ocean to the atmosphere during autumn and winter, causing strongest warming in these seasons.

Put simply, we hypothesize that reduced offshore sea ice concentration, i.e. greater open-water fraction, warms the ocean mixed layer and increases onshore advection of sensible and turbulent heat fluxes, in turn raising air temperatures over the ice sheet and the probability of surface-melt occurring. We explore this hypothesis for the Greenland ice sheet using simultaneous passive microwave satellite observations of surrounding open-water extent and inland surface-melt extent from 1979 to 2007.

2. Study area, data and methods

Our study area is the Greenland ice sheet and its surrounding oceans and seas, divided into 16 land and 16 ocean regions (figure 2). Between 62.5° N and 80° N we divided the study area into 2.5° meridional bands separated east–west along 42° W, and with the ocean regions extending 20 grid cells (∼500 km) outwards from the Greenland coast. One southern and one northern region cover the remaining land and ocean area below 62.5° N and above 80° N, respectively.

Temporal and spatial patterns in Greenland surface-melt were obtained from the dataset of Abdalati (2007). This dataset is a binary classification of melt/no-melt determined with the cross-polarized gradient ratio algorithm (Abdalati and Steffen 1997) utilizing passive microwave brightness temperatures measured by the scanning multi-channel microwave radiometer (SMMR) and the special sensor microwave/imager (SSM/I). Although active microwave data is more sensitive to snow wetness (Nghiem *et al* 2001), passive microwave sensors have been operational for much longer and capture Greenland melt anomalies quite well (Abdalati and Steffen 1997, Tedesco 2007). The dataset was processed to provide daily and average monthly time-series between 1979 and 2007 by calculating the areal extent of surface-melt within each land region and interpolating any days with missing data. These data gaps primarily occurred before 1988, when the passive microwave sensors collected data every other day.

Temporal and spatial patterns in open-water extent were derived using the Goddard Space Flight Center (GSFC) ice concentration dataset (Comiso 1999, updated 2008). Sea ice concentration is determined with the bootstrap sea ice algorithm (Comiso *et al* 1997) utilizing the same passive microwave brightness temperatures from SMMR and SSM/I used by Abdalati (2007). Summer sea ice concentrations are typically underestimated by passive microwave sensors, for example due to melt pond formation (e.g. Comiso and Kwok 1996). This uncertainty was reduced by using a binary classification of each ocean grid cell as either ice-covered or ice-free (e.g. Serreze *et al* 2003). The sea ice 'edge' separating open-water from sea ice was defined as 15% sea ice concentration, a widely used threshold value (e.g. Comiso *et al* 1997). The dataset was processed to provide daily and average monthly time-series of open-water extent between 1979 and 2007 by calculating the area of grid cells with less than 15% sea ice within each ocean region and interpolating any days with missing data similar to the surface-melt dataset.

Data analysis had two objectives: (1) to determine the monthly covariability between each region's respective time-series of offshore open-water extent and inland surface-melt during the melting season from May to September, and (2) to quantify the frequency of surface-melt events following/preceding open-water events, using daily data and various time lags.

The covariability was quantified with correlation coefficients obtained from linear regression. Regions with significant correlations were identified by testing the null hypothesis that the correlation was a result of random chance using a confidence level of $\alpha = 0.05$. However, because the likelihood of finding significant relationships can be inflated by the presence of autocorrelation and cross-correlation (Lettenmaier *et al* 1994, Gujarti 2003), two additional statistical tests were also performed. First, the influence of autocorrelation was tested using the Durbin–Watson test (e.g. Gujarti 2003). Second, months in which the number of regions with significant correlations could be due to cross-correlations were identified using the bootstrap test of Burn and Elnur (2002). The bootstrap test established the expected number of regions with significant correlations arising due to chance, but with cross-correlations preserved, at a given significance level α. If this number is less than the number of regions with significant correlations in the actual data, the actual data is field significant at a significance level of α. Hence, months with field significant data are likely to be unaffected by cross-correlation.

The lag study examined if the relative timings between open-water and surface-melt events support the notion that offshore ocean conditions can influence the ice sheet. Assuming similar response time to external forcing, strong external forcing should result in both surface-melt and open-water events occurring on the same day (i.e., zero time lag), whereas open-water extent forcing should favor melt events after open-water events (i.e. positive time lag but not a negative one). We define an 'event' (meaning an expansion or contraction of surface-melt or open-water area) as the occurrence of a sign change, exceeding one standard deviation, in the time-series derivatives in SSM/I data between 1988 and 2007 (before 1988 the SSMR sensor provides only data every other day). The melt event lags were determined in the period between surface-melt onset and the time of maximum open-water expansion. The frequency of melt events occurring at time lags within ±8 days of open-water events was determined. The result was tested against the null hypothesis that melt events occur at random in relation to open-water events by employing a permutation resample test (e.g. Hesterberg *et al* 2006). Significance level is established as the corresponding percentile of the test data.

3. Results

Position of the mean sea ice edge sweeps progressively northward, in concert with expanding ice sheet surface-melt area, from May to July (figure 1). In southwest Greenland, open-water expansion into the Davis Strait is mirrored by inwards surface-melt expansion into the ice sheet. In August

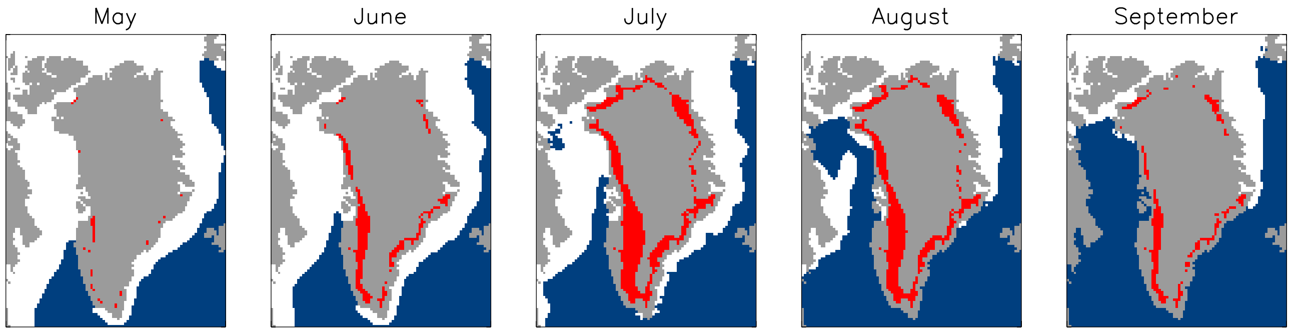

Figure 1. Average monthly melt extent (red) and sea ice/open-water-extent (white/blue) in Greenland and surrounding ocean and seas between 1979 and 2007. The spatial monthly averages are defined as all grid cells with more than an average of 10% melting/sea ice/open-water days in the month.

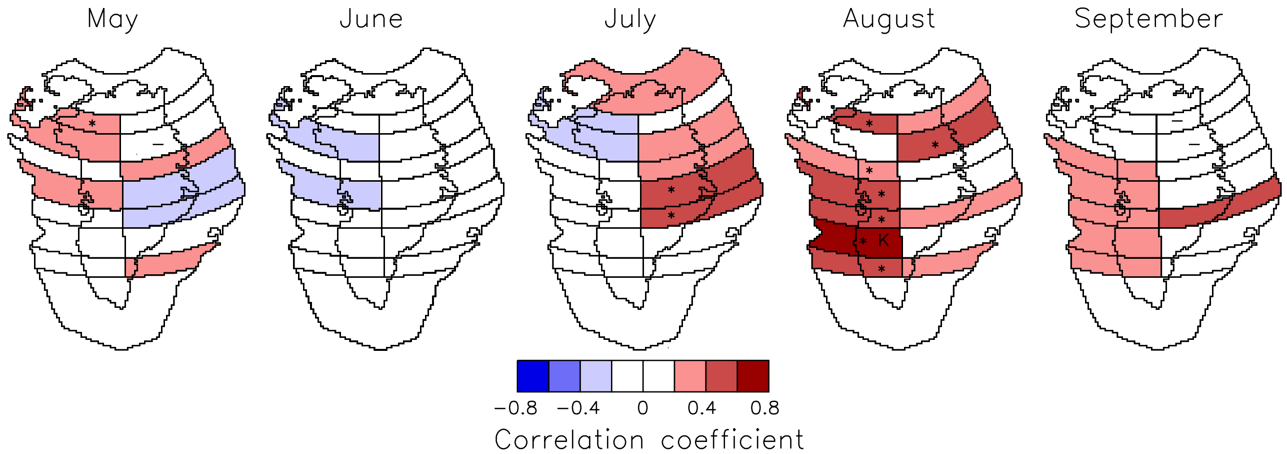

Figure 2. The spatial distribution of correlation coefficients between average monthly ice sheet melt extent and offshore open-water extent (i.e. area of ocean grid cells with sea ice concentration less than 15%) within each of the 16 regions. The outlines of the regions and the coastlines of Greenland and Ellesmere Island are shown for reference. Regions with significant correlations are demarked with a '*', and regions with significant autocorrelation are demarked with a '–'. The largest number of significant correlations occurs in August, with the strongest correlation in the Kangerlussuaq area (demarked with a 'K'). None of the time-series in the regions with significant correlations had significant autocorrelation.

and September, the sea ice edge continues to migrate northward while the inland surface-melt area contracts, leaving only a thin coastal, fragmented band of surface-melt by September. In contrast to the relatively uniform zonal inwards expansion and contraction of surface-melt throughout the summer, the pattern of sea ice retreat differs for the east and west coasts of Greenland. While the eastern sea ice stays proximal to the coast while retreating northwards, the western coastal areas are the first to become ice-free as the sea ice edge moves northwest into Davis Strait and Baffin Bay (figure 1).

Monthly melt extent varies independently of open-water extent except in seven of the sixteen regions during the month of August (figure 2). Only then does the bootstrap test show that the fraction of regions with significant trends ($p < 0.05$) is field significant at a confidence level of $\alpha = 0.05$, suggesting that significant correlations in all other months are due to cross-correlation. Similarly, the Durbin–Watson test suggests significant autocorrelation in several time-series pairs, but none in the August time-series pairs. Thus, both tests indicate that the high correlations cannot be due to cross- or autocorrelation in the month of August. High correlations could be a result of errors in the passive microwave dataset used to determine both open-water and melt extent, but this error is considered negligible given the low correlation in most regions.

In August, most regions on the west coast of Greenland display significant positive correlations between the two variables, but the highest correlation is in the Kangerlussuaq region ($r = 0.71$) (demarked with a 'K' in figure 2). For this region three different observations suggest a link between open-water fraction and ice sheet melt. First, ocean–land interactions are facilitated by the presence of westerly winds during the melting season suggesting favorable meteorological conditions for the advection of ocean air masses onto the ice sheet open-water (figure 3(a)). In all months, northeasterly katabatic winds flowing down the ice sheet interior dominate (45° from North), but in the melting season a second mode with westerly winds (270° from North) suggests a period of ocean–ice sheet interactions. Second, assuming that both sea ice and melt extent respond with a similar time lag to external forcing, the significant frequency of melt events occurring 0–2 days after open-water events (figure 3(b)) suggests that the arrival of open-water offshore is able to contribute to the arrival of surface-melt on the ice sheet. Third, given the strong relation between air temperature and surface mass balance

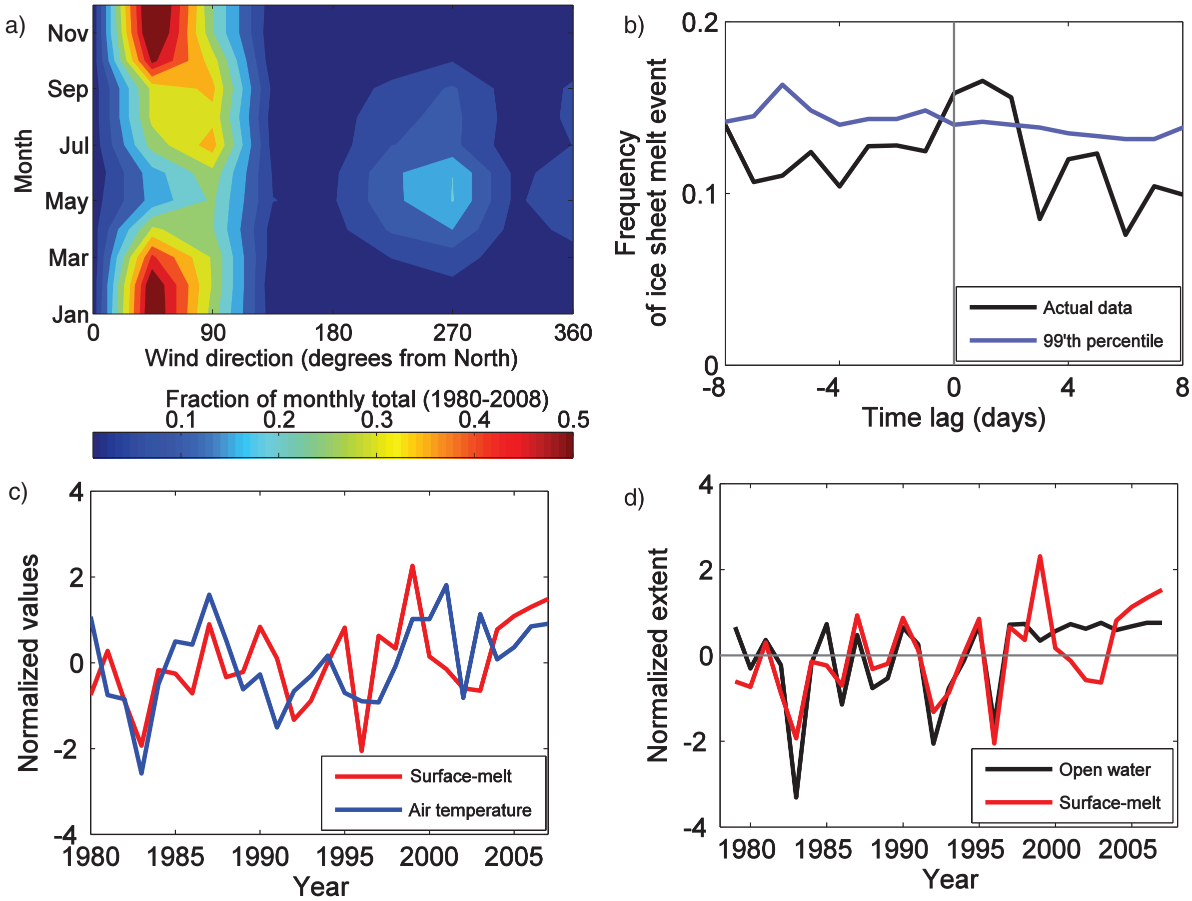

Figure 3. The relationship between open-water fraction and melt extent examined for the Kangerlussuaq region, the region with the highest correlation: (a) the distribution of sub-daily observed wind directions at the Kangerlussuaq meteorological station for each month between 1980 and 2008, (b) the frequency of melt events lagging open-water events derived from daily data, and the 99th percentile of the randomized data corresponding to the 99% confidence level, (c) time-series of average monthly melt extent and *in situ* air temperature from the Kangerlussuaq meteorological station, (d) time-series of average monthly melt and open-water extent. The Kangerlussuaq meteorological station is situated on land between the ocean and the ice sheet (67.017 N, −50.70 E) (data available at: National Climatic Data Center, http://www.ncdc.noaa.gov/oa/ncdc.html).

(e.g. De Woul and Hock 2005), melt extent is likely a good measure of ice sheet surface mass balance, as indicated by the strong linear relation between melt extent and *in situ* air temperature (figure 3(c)). The potential sea ice influence on melt is strongest before 1999, thereafter the open-water fraction reaches its near maximum every year (figure 3(d)).

4. Discussion

Open-water and ice sheet surface-melt covariability is significant in seven of sixteen regions in the month of August, with most of these regions located on the west coast. Relative to northern and southern Greenland, the western and eastern parts of Greenland have a higher probability of occurrence of seasonal sea ice (Kinnard *et al* 2008) at the time of year when the ice sheet surface is most susceptible to melting. Thus, the western and eastern parts are more likely to experience simultaneous variability in both sea ice and surface-melt, facilitating a higher correlation between the two variables. Relative to Greenland's east coast, the west coast interactions between the ocean and the land are helped by: (1) gentle topographic slopes (Bamber *et al* 2001) and (2) the nature of sea ice retreat. In contrast to the east coast, the west coast ice retreats westward into the Davis Strait leaving a growing near-shore open-water area, allowing for more solar heating in expanding open-water areas and ocean warming in close proximity to the ice sheet (figure 1).

The strongest covariability between open-water and melt extent occurs in the Kangerlussuaq region in August, the latter part of the melting season. Prevalence of a positive time lag between melt and open-water suggests that open-water enhances ice sheet melt in this area (figure 3(b)). Other factors also explain why this relationship is strongest in the late melting season. First, the late melting season generally has warmer ocean temperatures (World Ocean Atlas World Oceanographic Database 1998). Second, the arrival of westerly winds (figure 3(a)) allows advection of ocean heat onto the ice sheet potentially enhancing ice sheet melt. Third, while a strong relationship between late summer air temperature and surface-melt may not hold universally, it does so in the Kangerlussuaq region (figure 3(c)). Fourth, ice sheet albedo typically decreases during the melting season (Stroeve *et al* 2001), making the ice sheet more susceptible to late season melting. Finally, declining ocean heat flux

(Perovich and Elder 2002), and the possibility of ocean to atmosphere heat transfer (Steele *et al* 2008) may increase the relative importance of heat advected from the ocean in the late summer/fall.

This study suggests that the sea ice retreat can enhance surface-melting on the Greenland ice sheet, especially in southwestern Greenland during late summer. Future work should assess the importance of sea ice in controlling solar heating of ocean surface water, local weather patterns and the validity of the assumption of identical response time of open-water and melt area to changes in external forcings. Regardless of how the mechanism of open-water influence on ice sheet melt takes place, if model predictions of a northwards sea ice edge retreat in the 21st century are correct (Meehl *et al* 2007), the ice sheet region influenced by sea ice variability might reasonably be expected to correspondingly migrate northwards. North of the Kangerlussuaq area is the Jakobshavn ice-stream, which accounts for ∼10% of current Greenland mass losses (Rignot and Kanagaratnam 2006). Although surface-melt is an insignificant driver of the Jakobshavn ice-stream's present-day discharge variability (Joughin *et al* 2008), future increased sensitivity in combination with enhanced surface-melt may further increase the discharge from Jakobshavn ice-stream.

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