Recent ice cap snowmelt in Russian High Arctic and anti-correlation with late summer sea ice extent

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Supplementary Notes

Glacier outline and pixel selection

Glacier area is from the Russian Arctic glacier outline in the Randolph Glacier Inventory (version 2.0) provided by Global Land Ice Measurements from Space (GLIMS) (Raup et al 2007), which was updated in June 2012.

The glacier outline was compared to the 8.9×8.9 km² pixel grids to determine which pixels to analyze. In total, glacier extent on Severnaya Zemlya (SevZ) and Novaya Zemlya (NovZ) consists of 349 and 417 8.9×8.9 km² pixel grid cells, respectively. In order to minimize mixed pixel effects from land and ocean, grids with more than 85% glacier covered were selected. Additional pixels along the ice margin had noisy microwave signals and were eliminated from the analysis after examination of pixel time series. This resulted in 131 SevZ and 190 NovZ pixel grids that were used in the final analysis (Supplementary Figure S1), focusing on ice cap interiors and occupying roughly two thirds of the reported glaciated areas.
**Supplementary Figure S1.** Pixel grid comparisons in polar stereographic projection. Black grids are 8.9×8.9 km² and red grids are 4.45×4.45 km². Blue background is glacier extent from Global Land Ice Measurements from Space (GLIMS) (Raup et al 2007). Grey background is land. The automatic weather station (AWS) (green dot) was maintained on Akademii Nauk ice cap on Severnaya Zemlya from April 29, 1999 to May 12, 2000 (Opel et al 2009); the 1999 melt season was used here.

**MERSL-BYU SSM/I and AMSR-E melt signature thresholds**

A consistent annual threshold of 233K was determined from the annual MERSL-BYU SSM/I 37GHz vertically polarized T₁₃₇V distributions for 190 8.9×8.9 km² pixel grid cells on NovZ and 131 grid cells on SevZ (Supplementary Fig. S2 (a)). MERSL-BYU SSM/I melt detection threshold 233K is much lower than earlier published thresholds for NSIDC SSM/I data, such as 246K for Alaska (Ramage and Isacks 2002, 2003) and 258K for Greenland (Tedesco 2007). We attribute this difference to the SSM/I data versions processed by NSIDC and MERSL-BYU. MERSL-BYU SSM/I T₁ were generated from version 7 of the F-13 SSM/I data record from Remote Sensing Systems, Inc. (RSS) in Santa Rosa, California U.S.A while the NSIDC SSM/I T₁ were generated from version 4 of the RSS data. Changes in T₁ between multiple passes can result in an averaging effect on the multiple T₁s (Long and Daum 1998). Therefore, MERSL-BYU passive microwave data might have missed some short melt events and underestimated TMD. The threshold of 233 K for MERSL-BYU SSM/I T₁₃₇V effectively separated melting events from the frozen state during the 1999 melt season at the automatic weather station (AWS).
grid cell; only five days (Julian day 192, 221, 223, 241 and 242) were misclassified (main text Fig. 2 (a)). The misclassification might have been caused by the point observation compared to the large area of the remote sensing measurements. It is also likely that our melt detection approach is not perfect (Liston and Winther 2005, Trusel et al 2012): daily maximum temperature may briefly exceed 0°C but surface energy balance remains negative and snowpack remains dry (situation of Julian days 221 and 223); or conditions may be the reverse (situation of Julian days 192, 241 and 242). Additionally, AWS temperature records were determined to be significantly warm-biased in summer on the Antarctic Plateau as a result of high incoming solar flux, high surface albedo, and low wind speed (Genthon et al 2011). Although far insufficient in situ observations are available to test whether this bias existed on SevZ, measurement biases could be an additional reason for the misclassification.

Supplementary Figure S2. Brightness temperature distributions of ~37GHz vertically polarized passive microwave channels. (a) MERSL-BYU SSM/I $T_{b37V}$ from 1995 to 2007. (b) MERSL-BYU AMSR-E $T_{b36.5V}$ from 2003 to 2011. The lightest black and blue curves show the earliest year (1995 for SSM/I and 2003 for AMSR-E) and the darkest curves are the latest year (2007 for SSM/I and 2011 for AMSR-E). The vertical red lines indicate the melt thresholds used in this study (233K for SSM/I and 252K for AMSR-E). A total of 131 and 190 $8.9 \times 8.9 \text{ km}^2$ grid pixels were analyzed each year on SevZ and NovZ, respectively. Note that the Y-axis scales are different due to the different number of observations analyzed, and that the pixels histograms are different for each archipelago due to different number of snow covered cells.
The MERSL-BYU processed resolution enhanced AMSR-E $T_b$ from NSIDC Level 2A $T_b$ for 2003-2011. MERSL-BYU AMSR-E $T_{b36.5V}$ were bimodally distributed with an annual variable minimum about 245K on SevZ and 252K on NovZ (Supplementary Fig. S2). The present work conservatively sets the melt threshold to 252K for both areas, which has been compared with contemporaneous MERSL-BYU SSM/I $T_b$ as well as active microwave sensors. The threshold of 252K is consistent with earlier published works (Apgar et al 2007, Monahan and Ramage 2010).

Satellites employed in this work took observations of the earth’s surface at different local times. The phase of water in the snowpack and the liquid water content (LWC) are highly dependent on the time of day. Different satellite images represent unique snowpack conditions at the satellite local overpass time, which contributes to possible discrepancies in the MOD and TMD detection among sensors. For example, in the morning of July 14 and afternoon of July 16, 1999 (Supplementary Fig. S3), the satellite data detected melt at the AWS location, but the corresponding 2.5m above ground air temperature record was slightly below 0°C. It is very likely that snowpack started melting as a result of positive surface energy balance during those periods despite the slightly negative air temperatures. $T_b$ increase is not necessarily an instantaneous response to positive air temperature; instead, it is a response to the existence of liquid water in the snowpack. By using daily maximum $T_b$, the present work can capture daily melt to a maximum extent (Supplementary Fig. S3). However, daily maximum $T_b$ may still miss a day with melting snow that has refrozen completely at the corresponding satellite overpass time.
Supplementary Figure S3. Satellite observation comparisons at different local time of day. (a) comparison between MERSL-BYU SSM/I $T_b$ twice-daily observations (red dots) and hourly in-situ air temperature data (Opel et al 2009) (blue line) at the AWS location on SevZ from July 14 to July 17, 1999. Dashed black lines are examples discussed in the text. (b) comparison among MERSL-BYU SSM/I, AMSRE-E $T_b$ twice-daily observations and QSCAT $\sigma_0$ at the AWS location from June 25 to June 28, 2004. Sensor melt thresholds are marked in corresponding colors.
For most other studies, daily $T_b$ and diurnal amplitude variation (DAV), defined as the running difference between satellite ascending pass and descending pass $T_b$, were used together to map wet snow (Ramage and Isacks 2002, 2003, Semmens and Ramage 2013, Tedesco 2007, Tedesco et al 2009). However, in NovZ and SevZ, selected ice pixels usually have similarly high $T_b$ values in daily multiple observations during intense melt, which results in low DAV (Supplementary Table S1). This research focused on the starting date of melt (MOD) and how many days melt occurred (TMD). The daily maximum $T_b$ metric is used to differentiate wet and dry snow and requiring high DAV would miss melt days with multiple high $T_b$s but low DAV (i.e., Julian day 207-211 in Supplementary Table S1). Therefore, the DAV metric is not used here. Two possible reasons might account for the low DAV during intense melt season: (1) sensor pass time failed to capture nocturnal refreezing; (2) the polar day phenomenon exposed the snowpack under solar radiation all day long, which might prevent the snowpack from refreezing completely at night at this time of year.

Supplementary Table S1. A subset comparison between SSM/I 37GHz vertically polarized $T_b$, DAV (running difference between satellite morning and evening pass $T_b$), and air temperature record at AWS location.

| Day of Year 1999 | Morning Pass $T_b$ (K) | Evening Pass $T_b$ (K) | DAV (K) | Daily Maximum Air Temperature (°C) |
|------------------|------------------------|------------------------|---------|-----------------------------------|
| 206              | 262.895                | 252.585                | 34.12   | 2.6                               |
| 207              | 251.500                | 252.875                | 10.02   | 1.8                               |
| 208              | 259.230                | 260.770                | 9.27    | 2.4                               |
| 209              | 251.630                | 256.405                | 4.78    | 1.2                               |
| 210              | 241.055                | 248.845                | 7.79    | 3.3                               |
| 211              | 241.285                | 247.040                | 5.99    | 4.0                               |

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**Supplementary Figure S4.** Frequency distributions of TMD differences among sensors. (a) frequency distribution of TMD difference between MERSL-BYU SSM/I and AMSR-E from 2003 to 2007. (b) frequency distribution of TMD difference between MERSL-BYU SSM/I and QSCAT from 2000 to 2007. Black shows NovZ and SevZ combined distribution; dark gray shows distribution for SevZ and light gray shows distribution for NovZ. Mean values of different distributions are labeled vertically in the order of SevZ and NovZ combined (black), SevZ (dark gray) and NovZ (gray).

**MOD and TMD comparison between egg- and slice-based QSCAT data**

For QuikSCAT data, raw backscatter data are obtained in two modes, *i.e.* egg and slice. “Slices” have a footprint 4-6 km along-track and 20 km across-track. “Slices” are summed into “eggs”, which have a resolution of ~20×30 km². BYU applied SIR technique to enhance both kinds of QuikSCAT images. Slice-based BYU products have a higher resolution (2.225×2.225 km²) and egg-based have a lower resolution (4.45×4.45 km²). Although lower resolution egg-based MERSL-BYU QSCAT data (4.45×4.45 km²) are used in this study, MODs derived via Sharp and Wang (2009)’s algorithm are similar to earlier published results (typically <0.5 day difference) on NovZ and SevZ (Supplementary Table S2). Egg-based results indicate a slightly later MOD and longer TMD than slice-based. The slight differences are probably due to the fact...
that pixel selection in the current study is more concentrated on inland ice, which usually has a
later MOD than lower elevation marginal ice. Analysis also found that ice marginal pixels have
significantly lower winter mean backscatter than ice cap interiors, but have similar magnitude
during summer melt, which Sharp and Wang (2009) also documented. This phenomenon would
lead the fixed $\sigma^0$ decrease algorithm to underestimate the TMD for ice marginal pixels. Sharp
and Wang (2009) included more marginal pixels than in this study and this is probably the reason
why they have a lower TMD. Despite the slight differences, their algorithm is applied to the
entire lower resolution QSCAT data records to verify the passive microwave results in the
present study.

**Supplementary Table S2.** Comparison of average MOD and TMD retrieved from slice- and egg-based
MERSL-BYU QSCAT data. Sharp and Wang’s 2009 algorithm was used for both datasets.

| Year | 2000 | 2001 | 2002 | 2003 | 2004 |
|------|------|------|------|------|------|
| Island | SevZ | NovZ | SevZ | NovZ | SevZ | NovZ | SevZ | NovZ | SevZ | NovZ |
| Slice-based | 183.1$^a$ | 152.9 | 161.8 | 159.1 | 169.2 | 159.0 | 162.6 | 134.7 | 172.3 | 163.3 |
| Egg-based | (48.1)$^b$ | (73.4) | (53.1) | (92.1) | (51.1) | (66.9) | (58.3) | (75.4) | (43.4) | (68.7) |
| Slice-based | 183.2$^c$ | 152.7 | 161.3 | 159.1 | 169.7 | 160.6 | 162.8 | 134.8 | 171.7 | 163.7 |
| Egg-based | (50.9)$^d$ | (75.5) | (57.2) | (93.6) | (54.4) | (72.6) | (59.3) | (77.7) | (48.4) | (70.6) |

$^a$MOD (Units: day of year)

$^b,^d$number of melt days (~TMD; Units: number of days)

**Cross validation of MOD among sensors**

Melt onset algorithms were processed for each pixel, and results were compared for each
sensor. Ultimately, we defined the glacier-wide melt onset date to be the date when 90% of the
pixels were melting rather than the average of each pixel’s melt day. This section details the
algorithms, sensor sensitivities, impact of missing data, and justification for using the icefield-
wide melt detection approach.

In order to avoid selecting an early spring melt event (Semmens et al 2013), rather than
the main melt onset date, for MERSL-BYU SSM/I and AMSR-E data, each pixel’s MOD is
defined as the first day when 3 out of 5 days’ maximum $T_b$ is higher than specified thresholds (Monahan and Ramage 2010). For ASCAT, each pixel’s MOD is defined as the first day when $\sigma^0$ drops below the threshold $M (\sigma_{wn}^0 - 1.0)$ for 3 out of 5 consecutive days. Due to lower temporal resolution, ERS-derived MOD is defined as the first day when $\sigma^0$ drops below the threshold $M (\sigma_{wn}^0 - 1.7)$. QSCAT-derived MOD is adopted from Sharp and Wang (2009)’s algorithm.

The frequency distribution of the MOD difference between MERSL-BYU SSM/I and ERS from 1995 to 2000 (year 1996 was excluded from NovZ distribution because the ERS-1/2 data gap missed this year’s MOD) on NovZ and SevZ indicates a mean value of -0.83, which means the SSM/I algorithm generally detects melt 0.83 days later than ERS (Supplementary Fig. S5). The mean values of SevZ (red line) and NovZ (green line) distributions are 0.68 and -2.10, respectively. Almost 90% of the differences fall within ±6 days, which corresponds to ERS observational uncertainty and lends confidence to the MOD derived from ERS for 1992-1994.

The frequency distribution of the MOD difference between MERSL-BYU SSM/I and QSCAT from 2000 to 2007 on both archipelagoes has a mean value of 0.38 days, which means the MERSL-BYU SSM/I algorithm generally detects 0.38 days earlier than QSCAT (Supplementary Fig. S5). The mean values of SevZ and NovZ distributions are -1.40 and 1.60 days, respectively. The frequency distribution of MOD difference between MERSL-BYU SSM/I and AMSR-E from 2003 to 2007 shows a mean value of -3.00 on NovZ and SevZ, which means that MERSL-BYU SSM/I algorithm detects melt 3 days earlier than AMSR-E (Supplementary Fig. S4). This difference may be caused by the relatively strict threshold for AMSR-E melt detection, especially for SevZ (Supplementary Fig. S5). The mean values of SevZ and NovZ distributions are -2.85 and -3.11, respectively. The mean value of the frequency distribution of
MOD difference between MERSL-BYU AMSR-E and ASCAT from 2009 to 2011 is -5.70 days, which means AMSR-E detects 5.70 days earlier than ASCAT (Supplementary Fig. S5). The mean values of SevZ and NovZ distributions are -1.90 and -8.30, respectively.

**Supplementary Figure S5.** Frequency distribution of MOD differences among sensors. (a) Frequency distribution of MOD difference between MERSL-BYU SSM/I and ERS from 1995 to 2000 (year 1996 was excluded from NovZ distribution because the ERS-1/2 data gap missed this year’s MOD); (b) Frequency distribution of MOD difference between MERSL-BYU SSM/I and QSCAT from 2000 to 2007; (c) is the frequency distribution of MOD difference between MERSL-BYU SSM/I and AMSR-E from 2003 to 2007; (d) is the frequency distribution of MOD difference between MERSL-BYU AMSR-E and ASCAT from 2009 to 2011. Black is NovZ and SevZ combined distribution; red and green are distributions of SevZ and NovZ, respectively. Mean values of different distributions are written in corresponding colors in the upper right corner of each plot.
The much higher mean values of onset difference among SSM/I, AMSR-E and ASCAT on NovZ and SevZ suggest that different sensor sensitivity to the start of the main melt onset date significantly impacts the mean MOD values if simply averaging each pixel’s MOD, resulting in unrepresentative onset dates. For instance, Sharp and Wang detected snowmelt from QSCAT data on day 161 in 2003, on Bolshevik Island, October Revolution Island and Komsomolets Island of SevZ. However, the melted snow refroze the next day and remained frozen until day 168, when all of SevZ started melting. Averaging individual pixels’ MOD results in an onset day of 162.2 (Sharp and Wang 2009). However, all the snowpack in SevZ were in a frozen state on either day 162 or 163. In view of this, we defined entire glacier MOD in to be the first day when more than 90% of selected pixels started melting. We acknowledge the scientific significance of partial melt timing; therefore, we also retrieved the first day when more than 50% of selected pixels started melting (main text Fig. 3 (a) and (b)). The melt timing of more than 95% of selected pixels are also derived for reference.
Supplementary Figure S6. (a) Linear regression between SevZ TMD and local 850 hPa NCEP-NCAR reanalysis temperatures; (b) Linear regression between SevZ TMD and Laptev Sea late summer sea ice extent; (c) Linear regression between residuals of SevZ TMD and Laptev Sea late summer sea ice extent after removing the local temperature influence on both variables; (d) Linear regression between SevZ TMD and Kara Sea late summer sea ice extent; (e) Linear regression between residuals of SevZ TMD and Kara Sea late summer sea ice extent after removing the local temperature influence on both variables.
Supplementary Figure S7. (a) Linear regression between NovZ TMD and local 850 hPa NCEP-NCAR reanalysis temperatures; (b) Linear regression between NovZ TMD and Kara Sea late summer sea ice extent; (c) Linear regression between residuals of NovZ TMD and Kara Sea late summer sea ice extent after removing the local temperature influence on both variables; (d) Linear regression between NovZ TMD and Barents Sea late summer sea ice extent; (e) Linear regression between residuals of NovZ TMD and Barents Sea late summer sea ice extent after removing the local temperature influence on both variables.
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