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Detection of snow surface thawing and refreezing in the Eurasian Arctic with QuikSCAT: implications for reindeer herding

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Abstract. Snow conditions play an important role for reindeer herding. In particular, the formation of ice crusts after rain-on-snow (ROS) events or general surface thawing with subsequent refreezing impedes foraging. Such events can be monitored using satellite data. A monitoring scheme has been developed for observation at the circumpolar scale based on data from the active microwave sensor SeaWinds on QuikSCAT (Ku-band), which is sensitive to changes on the snow surface. Ground observations on Yamal Peninsula were used for algorithm development. Snow refreezing patterns are presented for northern Eurasia above 60° N from autumn 2001 to spring 2008. Western Siberia is more affected than Central and Eastern Siberia in accordance with climate data, and most events occur in November and April. Ice layers in late winter have an especially negative effect on reindeer as they are already weakened. Yamal Peninsula is located within a transition zone between high and low frequency of events. Refreezing was observed more than once a winter across the entire peninsula during recent years. The southern part experienced refreezing events on average four times each winter. Currently, herders can migrate laterally or north–south, depending on where and when a given event occurs. However, formation of ice crusts in the northern part of the peninsula may become as common as they are now in the southern part. Such a development would further constrain the possibility to migrate on the peninsula.

Key words: active microwave; climate change; reindeer; remote sensing; scatterometer; Siberia; snow; Yamal Nenets.

Introduction

Reindeer herding is an important livelihood in large parts of northern high-latitude regions (Forbes and Kofinas 2000). Snow cover is present most of the year, and the vegetation growing season can be as short as a couple of months. Foraging patterns of reindeer are adapted to these conditions. Reindeer lichens (e.g., *Cladonia stellaris*, *C. rangiferina*, *Cetraria nivalis*) are a main source of fodder during the winter and are dug up from beneath the snow where they are present (Warenberg et al. 1997, Bartsch et al. 1999). The accessibility of terricolous lichens is therefore largely determined by snow properties. Important parameters are the establishment of snow cover in autumn, snow depth, melting of snow in spring, and the structure within the snowpack. In Fennoscandia, when the snow depth is over one meter, reindeer tend to minimize their digging efforts (Helle 1980, Kumpula and Colpaert 2007). Individual snow crystals and the entire snowpack undergo metamorphism over time due to compaction, sintering, and temperature changes (Marchand 1996). An air temperature increase above 0°C and subsequent refreezing is one of the parameters that lead to the formation of ice crusts (Ye et al. 2008). The snowpack liquid water content increases when temperatures rise and/or precipitation as rain occurs. Rain-on-snow (ROS) events affect the thermal structure of the entire snowpack (Putkonen and Roe 2003). After a ROS event during wintertime, semi-liquid snow typically refreezes and the structure of the snow is transformed. In these instances an ice crust forms that impedes foraging. Such events in the Arctic are usually related to larger scale weather patterns, such as variations in the North Atlantic Oscillation (NAO) and the Pacific-North America pressure patterns (Rennert et al. 2009) and therefore potentially affect vast regions. When this occurs, herders are forced to change the reindeer migration patterns. Herders continuously observe how the snow settles, drifts, and packs and decide how and when to move after assessing its physical quality in relation to topography, vegetation, time of year, and condition of the animals. Sometimes snow conditions can have a major impact on the pattern of herding (Jernsletten and Klokov 2002, Tyler et al. 2007). Especially problematic are multiple and late-winter events. The strength of the animals is generally weakening by the end of winter and any obstruction

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can cause starvation and increase the mortality rate (Helle and Kojola 2008). Digging through the ice layer can damage hooves with a consequent increased susceptibility to infection (Rees et al. 2008). Calves born after winters marked by shortfalls in forage availability have been observed to be underweight and with reduced chances of survival (Gunn and Skogland 1997). At unpredictable and irregular intervals, Peary caribou in Arctic Canada die in relatively large numbers during winters and springs when snow and ice conditions prevent energetically efficient access to forage. The influence of such conditions on forage availability is extended into the growing season in some years, adding further stress to the caribou (Miller and Gunn 2003, Gunn et al. 2006). Starvation, with resultant increased mortality, is then due to a reduction in the areas available for grazing rather than a reduction in the quality of range due to overgrazing. The population limit is therefore related to the grazing area available in "normal" winters (Parker et al. 1975).

Ongoing climate change may increase the frequency of years with unfavorable snow and ice conditions, which could prevent or at least impede future recovery of populations of not only reindeer, but also caribou and muskoxen. Under global warming scenarios, snowfall is predicted to increase and with warmer temperatures snow will be denser and freeze–thaw cycles could cause ice layering, all of which will impede reindeer/caribou foraging (Gunn and Skogland 1997, ACIA 2005, IPCC 2007; however, see Tyler [2010] for an opposing perspective). Refreezing of snow cover is one of the parameters used to assess the impact of climate change on reindeer husbandry. Validation, however, has not been available within previous studies (Rees et al. 2008). An increasing number of snow thaw days between 1950 and 2000 over northern Eurasia have been observed, particularly for the East European Arctic (Groisman et al. 2003). ROS events are predicted to increase in the Eurasian Arctic, the Russian Far East, and throughout North America (Rennert et al. 2009).

Another aspect is land use. Reindeer herding is well organized and land has been divided between sovkhozes, where individual management units are called brigades. The Yamal-Nenets Autonomous Okrug has experienced a steady increase in the number of semi-domestic reindeer and tundra nomads compared to other regions of post-Soviet Russia (Forbes and Kumpula 2009). Yarsalinski sovkhoz on Yamal Peninsula (for location see Fig. 1), is divided into 21 brigades, not including animals managed by private herders, which share the same territory. In each brigade there are from 20 to 60 Nenets, divided among several households, managing between 3000 and 9000 animals. In the Yarsalinksi sovkhoz, the migration route of brigades is about 600–700 km north–south. Each brigade has its own (5–30 km wide) regular migration corridor, where they are allowed to graze and migrate (Stammler 2005). Therefore, herders have limited possibilities to use neighboring areas when an icing event occurs. The current practice on Yamal allows herders to leave the corridors in case of emergencies (Forbes et al. 2009). It would be more difficult for herders to cope if icing events become more frequent and widespread. The situation differs for portions of northern Fennoscandia, where many territories are fenced at the level of individual herds (e.g., Finland), although such events occur there more frequently. Spring snowmelt begins over northwestern Eurasia earlier than elsewhere, and thus the time period when pastures are covered with snow is shortest and winter feeding is a common practice in that region.

Severe conditions were encountered by reindeer herders on the Yamal Peninsula during the winter of 2006/2007. The first event (ending 7 November 2006) of ROS was witnessed by one of the co-authors of this paper (F. Stammler) while migrating with them. Two rainfall events separated by heavy snowfall occurred within a period of 48 hours. Afterwards, the snowpack contained two ice layers that prevented the reindeer from getting through to the lichens beneath. A snow profile from location 1 taken on 19 November 2006 is shown in Fig. 1. The herders estimated the size of event on Yamal Peninsula to have been $\sim 60 \times 100$ km (Forbes et al. 2009). A few weeks after the second event (January 2007), another co-author (B. C. Forbes) visited and discussed its impact with herders from the same sovkhoz, or collective management unit. ROS and subsequent refreezing with formation of ice crusts forced a major change in migration. The affected area in November 2006 was entered from the north more than a week after the event. The southbound route could not be followed directly and the herders needed to travel back northwards. Some brigades chose to move on in a southeasterly direction and crossed the Ob estuary. In late March 2007, brigades that had moved south of the Ob in November were additionally affected by the extension of an event to the west in January as they migrated back northwards across the snowpack, which still consisted of the previous ice layers. Overall, according to their own calculations, the loss amounted to 25% of their animals, including deaths and still-births resulting from exhaustion and poor nutrition of pregnant females. Another warming occurred in the beginning of April and was followed by a cold period before the actual spring snowmelt period. The first event in November and the latter, which were either witnessed or discussed in person with herders by the co-authors, have been used for the development of an automated satellite data processing chain for the detection of icing events relevant to grazing for this study.

The change from dry to wet snow and refreezing can be determined with satellite microwave remote-sensing data from regional to global scales. Microwave instruments are particularly suitable for detection of thawing and refreezing patterns (Bartsch et al. 2007). Scatterometers and radiometers that operate within the microwave range provide rather coarse spatial resolu-

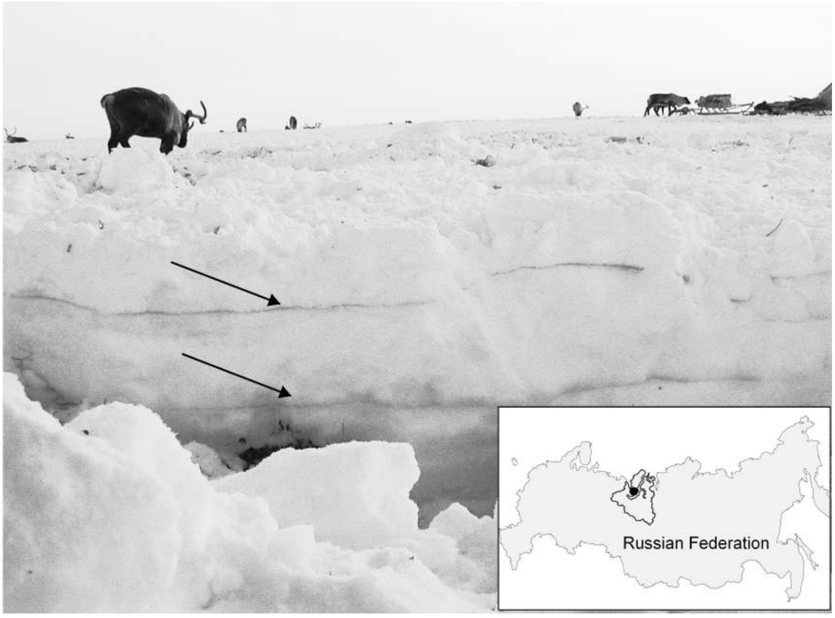

FIG. 1. Snow profile showing ice layers excavated at location 1 (19 November 2006), where surface thaw and refreezing was recorded around 7 November by satellite data (Fig. 3). The black arrows point to the icing layers. The inset map shows the location of the photograph and borders of the Yamal-Nenets Autonomous Okrug in Russia. Photo: Florian Stammler.

tion data, but offer daily or more frequent measurements (Wagner et al. 2007). A single early winter ROS event has been possible to identify using passive microwave data over Banks Island, Canada (Grenfell and Putkonen 2008).

The majority of snow-related scatterometer data analyses are based on Ku-band (frequency = 13.4 GHz, wavelength = 2.1 cm) measurements by the SeaWinds instrument (Jet Propulsion Laboratory, NASA, Pasadena, California, USA) on the QuikSCAT satellite platform (Bartsch et al. 2007). SeaWinds is a scanning dual spot beam scatterometer that has been proven applicable for seasonal thaw detection in subarctic and arctic regions (Kimball et al. 2004, McDonald et al. 2004, Bartsch et al. 2007, Wang et al. 2008, Sharp and Wang 2009), as well as over ice sheets (Nghiem et al. 2001, Ashcraft and Long 2006, Tedesco 2007).

In this paper we present a change detection algorithm for analyses of the spatial and temporal patterns of winter refreezing events. SeaWinds data have not been used for this purpose so far. The method has been developed based on in situ observations on the Yamal Penisnula. It has been applied for the entirety of continental northern Eurasia (above 60° N and east of 15° E). The implications of the findings for reindeer herding are discussed.

METHODOLOGY

Backscatter measurements by SeaWinds on QuikSCAT are collected simultaneously at constant incidence angles of 46° for the inner beam and 54° for the outer beam, with horizontal and vertical polarizations, respectively, using a scanning dish antenna operating at 13.4 GHz (Ku-band). The antenna has an elliptical footprint size of roughly 24 × 31 km at inner beam and scans over a swath of 1800 km, imaging 90% of the Earth's surface each day. At high latitudes at ~75° N data can be acquired daily up to 10 times, and at 55° N it can be acquired four times (Kidd et al. 2003) during ascending and descending passes. Records begin in 1999 (Tsai et al. 2000), with continuous time series since 2001.

Scatterometer data of eight consecutive winters from 2000/2001 to 2007/2008 have been processed for the entire study area. SeaWinds data were provided by the Jet Propulsion Laboratory (JPL) as their Level 2A product, which contains backscatter measurements representing the elliptical antenna footprint area. In first step, the backscatter data are extracted and reformed into time series that are allocated to unique, regular grid points, with a 12.5 km × 12.5 km grid spacing as described in Kidd et al. (2003, 2005) and Bartsch et al. (2007). All further analysis has been carried out for Northern Eurasia. The spatial extent has been defined by the approximate southernmost limit of reindeer herding (60° N; Circum-Arctic Rangifer Monitoring and Assessment Network, information *available online*)[6] and a western minimum longitude of 15° E.

Meteorological data from the World Meteorological Organization (WMO; DS512 data set) have been

[6] ⟨www.carmanetwork.com⟩

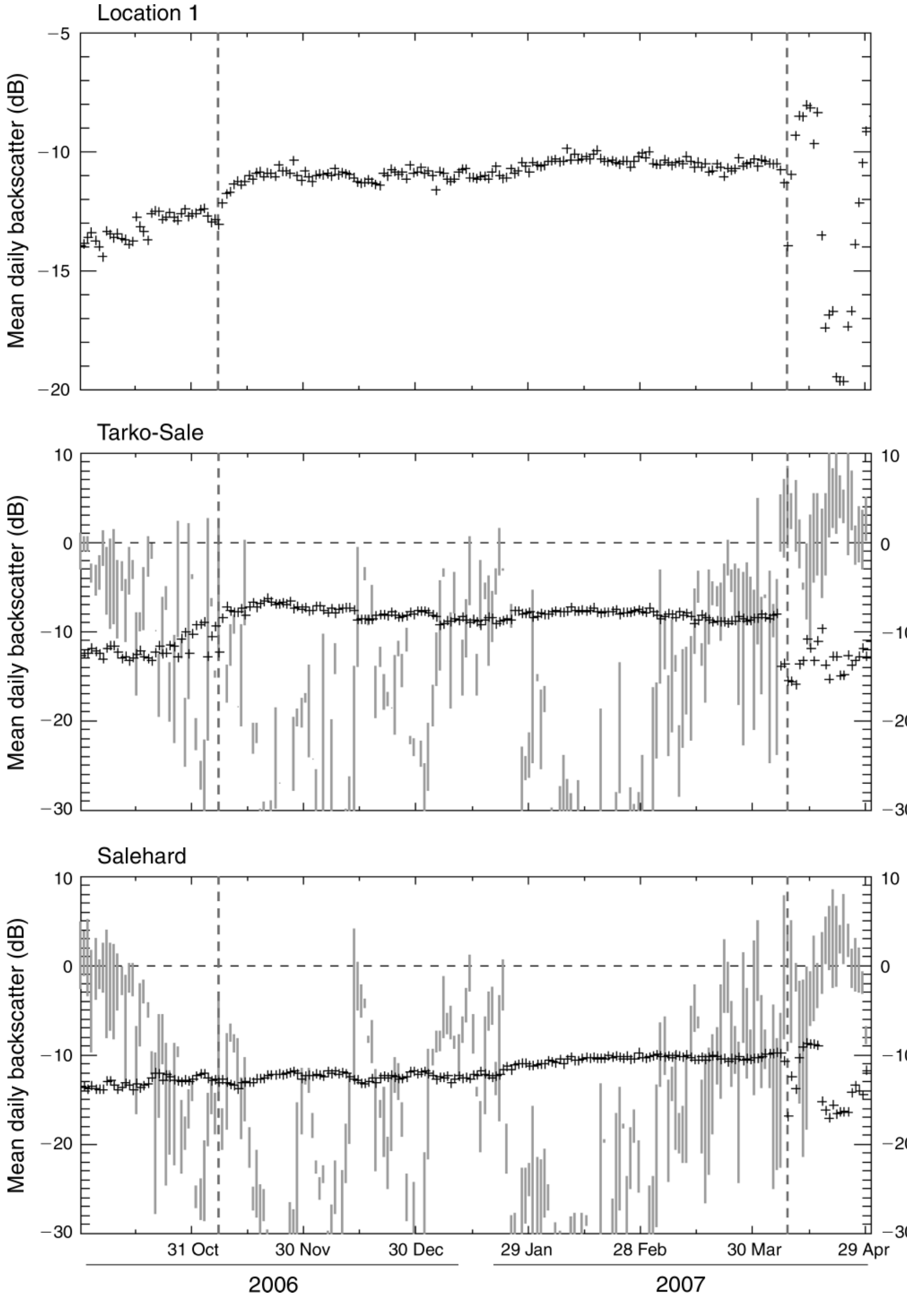

FIG. 2. SeaWinds on QuikSCAT daily mean backscatter (in decibels, dB) for location 1 on Yamal Peninsula (see inset map in Figs. 3 and 4), and the closest World Meteorological Organization (WMO) network stations Salekhard and Tarko-Sale in Winter 2006/2007. Vertical dashed gray lines indicate the ROS events in November and refreeze event in April observed on the ground. Vertical solid gray lines in the bottom two panels show the daily temperature range in degrees Celsius (right-hand axes).

investigated for assessment of the approach. These measurements include daily air temperature and also, for a few stations, snow depth. Stations where continuous measurements for both parameters are available have been selected for the assessment.

Snow refreezing events with significant impact on foraging documented here are characterized by an increase of backscatter σ^0 (Fig. 2). Microwaves emitted at 13.4 GHz penetrate deep into the snow pack in case of dry snow since the grain size is smaller than the wavelength. With increasing snow depth, however, the backscatter increases for dry snow (Ulaby and Stiles 1980). In order to test the detection approach for the impact of large snow accumulations within a short time, the maximum snow cover has been assessed by use of the DS512 data set for the detected events (Fig. 5i). Pronounced volume scattering also occurs in case of formation of larger ice crystals, due to metamorphosis after thawing and refreezing (Mätzler and Schanda 1984, Rees 2006). Ice crusts on top of the snow pack or layers underneath new dry snow therefore increase the backscatter. The backscatter can actually drop up to −6 dB (decibels) during surface melt (Kimball et al. 2004). The difference of σ^0 detected at the melting and refreezing event therefore often exceeds the difference between the backscatter level before and after the day of thaw. Thus, a change detection approach needs to consider the days before and the days after the event. Change detection is the foremost methodology for large-scale detection of changes in snow due to thaw based on Ku-band scatterometer (e.g., Kimball et al. 2004, Bartsch et al. 2007, Wang et al. 2008). Current approaches are, however, limited to the determination of the timing of spring snow cover depletion. The magnitude of thaw (backscatter decrease in case of surface snow melt) is considered by Bartsch et al. (2007) and Wang et al. (2008). A distinct backscatter decrease in response to the observed ROS event at location 1 could not be observed (Fig. 2). Therefore, only the increase of frozen surface backscatter has been analyzed.

For each grid point location, for each day, inner beam measurements are averaged and are used in the derivation of the refreeze events (Eq. 1). The mean daily backscatter is averaged for consecutive full-day periods before and after for each day t from October to April. The length of these periods has been defined as $n = 3$ days based on observations from location 1. For spring snow depletion observations, five-day averages are common, which have been determined by "trial and error" as described by Wang et al. (2008). For midwinter snowmelt events, a three-day window has been found to be sufficient as backscatter does not change much before and after events:

$$\Delta\sigma_t^0 = \left(\sum_{i=1}^{n}\sigma_{t+i}^0 - \sum_{i=1}^{n}\sigma_{t-i}^0\right)n^{-1}. \qquad (1)$$

If the difference exceeds a threshold of 1.5 dB, which has been determined based on the time series from winter 2006/2007 on the Yamal Peninsula (Fig. 2), the day is flagged as a thaw and refreezing event. This condition can be met for consecutive days, especially during late winter. The timing of a refreezing event in such a case is therefore defined by the first day when the threshold is exceeded. The chosen threshold is also well above the estimated standard deviation of long-term noise typical for this environment (Bartsch et al. 2007). Spring data are masked with daily maps of snow cover status (where depletion has not yet finished), which are based on the same sensor. These maps have been derived using diurnal thaw and refreeze patterns, which are typical for the final spring snowmelt period over northern Eurasia (Bartsch et al. 2007). Models for climate change impact assessment require a monthly refreezing index (Rees et al. 2008). Therefore, all determined thaw events are summed up by month from October to April.

Results

Single events: Yamal Peninsula–West Siberian Lowlands transect

Southern Yamal Peninsula was located at the northern rim of the region that received rain in November 2006 (difference map in Fig. 3). The event caused the highest backscatter increase over the central part of the West Siberian Lowlands as observed by SeaWinds. Backscatter increased from −13 dB to −11.5 dB immediately after the refreeze event (Fig. 2, location 1). An increase of >1.5 dB occurred south and northeast of location 1. The maximum width on the southern Yamal Peninsula was almost 100 km, which confirms the estimation of the herders. Snow fell during the following week and backscatter gradually increased to approximately −11 dB. Salekhard (∼200 km from location 1) was located just outside the affected area. Increasing temperatures have been recorded at this station but did not exceed 0°C (Fig. 2). Positive temperature values and strong variation in backscatter have, however, been recorded at Tarko-Sale, which is located >300 km southeast of location 1 (see Figs. 2 and 3).

Backscatter increased again (∼2 dB) after a thawing and refreezing event during the same winter in April 2007 about a week before the onset of the final snow melt period. At that time, the surface thaw was confined to the area east and west of the Ob estuary (Fig. 4). The snow continued to melt south of the area. Tarko-Sale was just at the northern rim of the area where no significant refreezing on the snow surface occurred. Temperature dropped below −20°C at Salekhard, where a similar backscatter as at location 1 had been recorded. The affected area during the spring 2007 refreeze was smaller than that during November 2006. The backscatter in some locations around the estuary was above −9 dB before the event, which is 2 dB higher than after the November ROS. This could be caused by the reported January event and/or additional snow accumulation.

Events during the winters 2000/2001–2007/2008 over northern Eurasia

The minimum air temperature before and after each refreezing event was extracted from the WMO DS512 data set (2000–2007) for eight stations spanning >100° in longitude and almost 10° in latitude: Lovozero (34.8° E, 68.08° N), Troiko-Pecerskoe (56.2° E, 62.7° N), Salekhard (66.53° E, 66.53° N), Tarko-Sale (77.82° E, 64.92° N), Dudinka (86.17° E, 69.40° N), Olenek

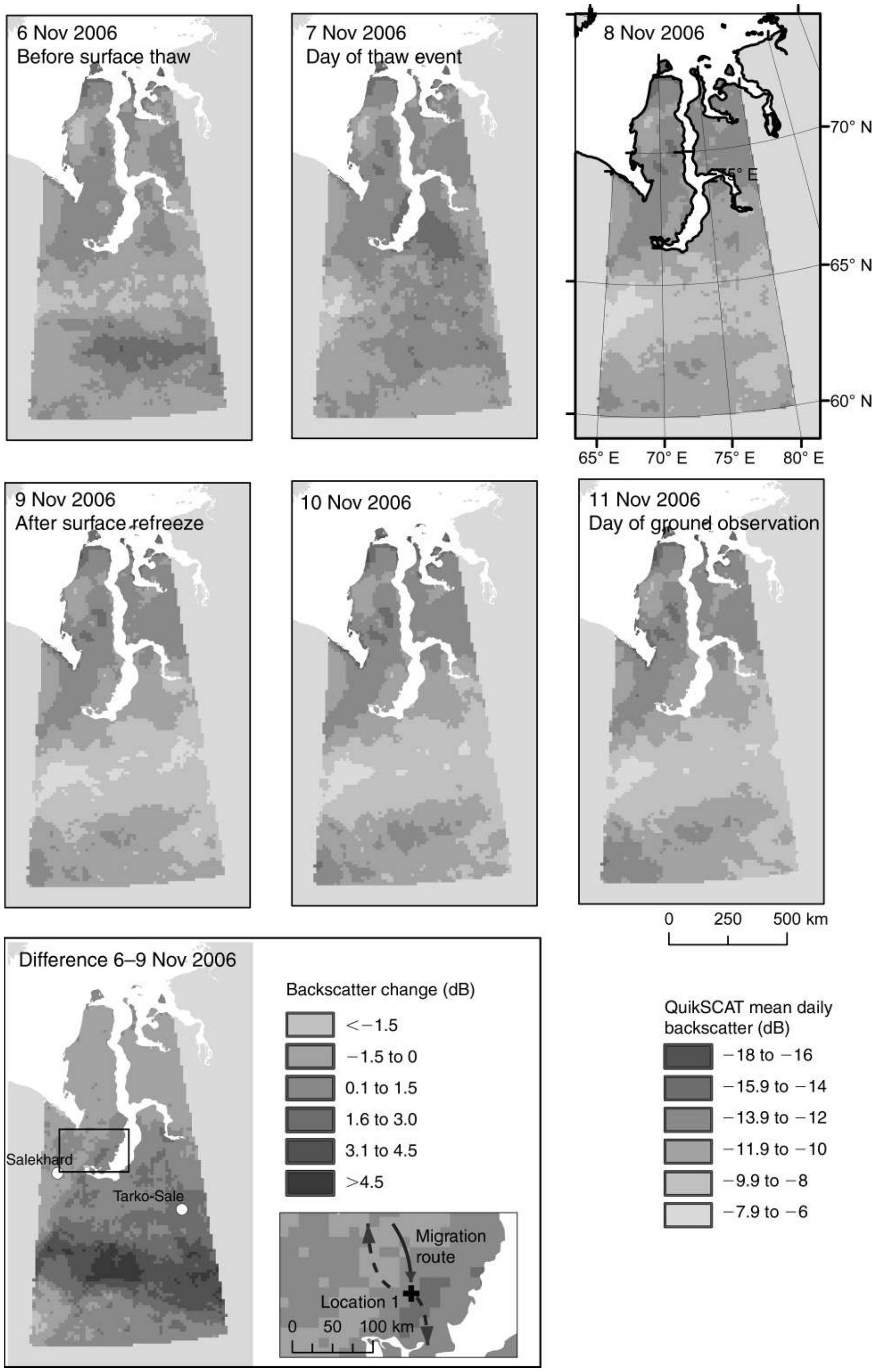

FIG. 3. Daily mean backscatter maps for the icing event observed in November 2006 and the difference map (bottom panel) of backscatter before the event and after (with location 1).

(112.43° E, 68.5° N), Yakutsk (129.75° E, 62.08° N), and Arka (142.33° E, 60.08° N). The maximum recorded daily minimum air temperature for three days before and after a detected event is shown in Fig. 5a–h. The maximum recorded snow depth during the three days before and after for all stations is shown Fig. 5i. A clear difference in air temperature can be observed for the time period before and after individual refreezing events.

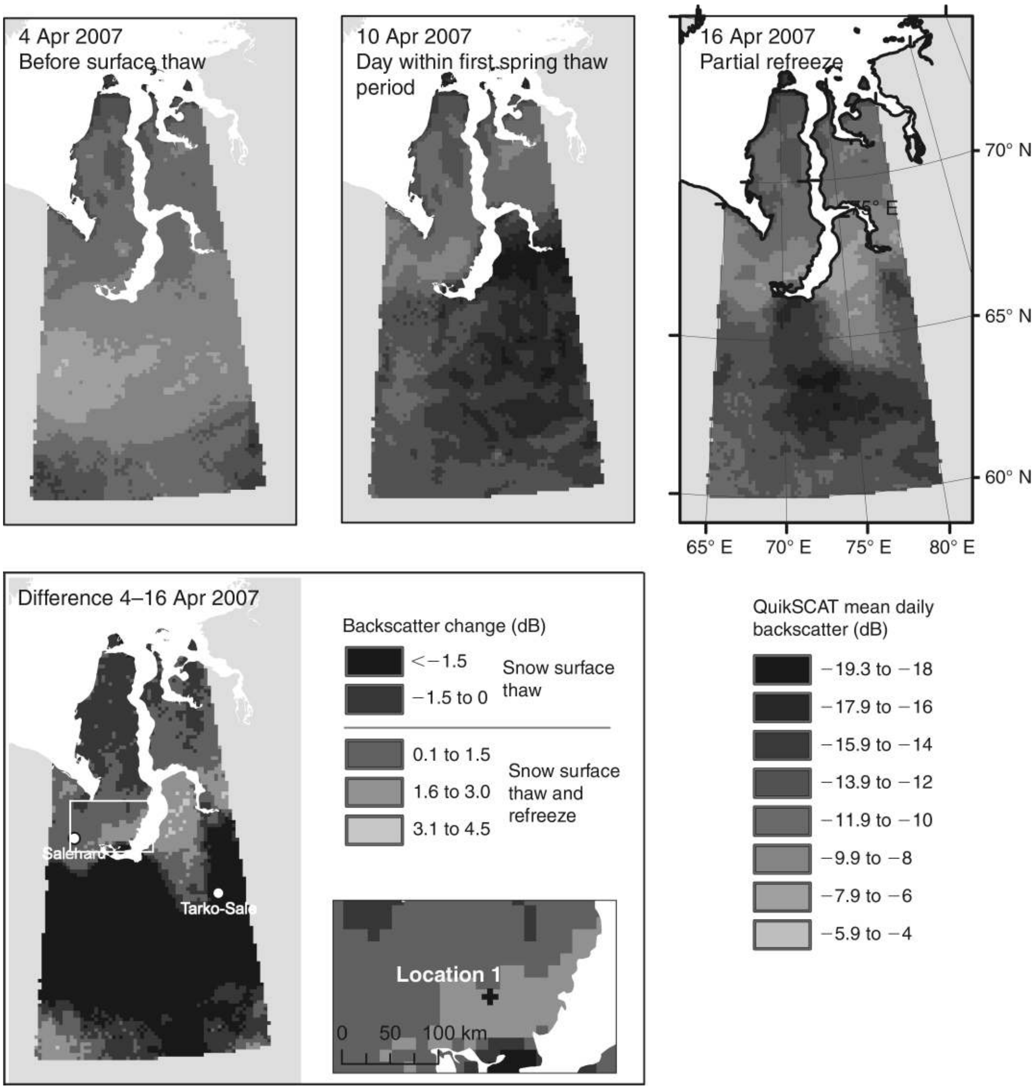

FIG. 4. Daily mean backscatter maps for the icing event observed in April 2007 and difference map (bottom panel) of backscatter before the event and after (with location 1).

The station with continuous data availability that is closest to the Yamal Peninsula is Salekhard (~150 km), but it is located close to a major river (the Ob), as are the majority of weather stations in Siberia that are not on the coast. Surface water within a grid point may affect the detection accuracy. The daily minimum, however, did usually reach a value close to or above 0°C at all stations. The minimum temperatures dropped well below the freezing point after the satellite observed refreezing. A lower temperature value before the event than after has been recorded in one case for Akan. This occurred during April on days with strong diurnal temperature change. The daily amplitude before the icing was 20°C exceeding an absolute value of 0°C during the day, and decreased to a daily difference of 10°C afterwards with temperature maxima below 0°C.

The snow depth before detected icings was, in general, higher or similar to the depth after the events. Snow cover in October and November is often very thin, but many events occur during this time period, especially in western Russia (Fig. 6).

The number of refreezing events over the whole of Northern Eurasia varies considerably from month to month and from region to region (Fig. 6). February has the lowest number. Several events per month can occur, especially in November and April. In particular, Western Siberia and the East European Arctic experience many refreezing events. Most of the region east of the Yenisei river (>90° E) has undergone refreezing only once within the eight-year period. The Yamal Peninsula was regularly affected in November and a few times in April, just before the final spring thaw. Icings occurred in that region during all investigated winter periods (Fig.

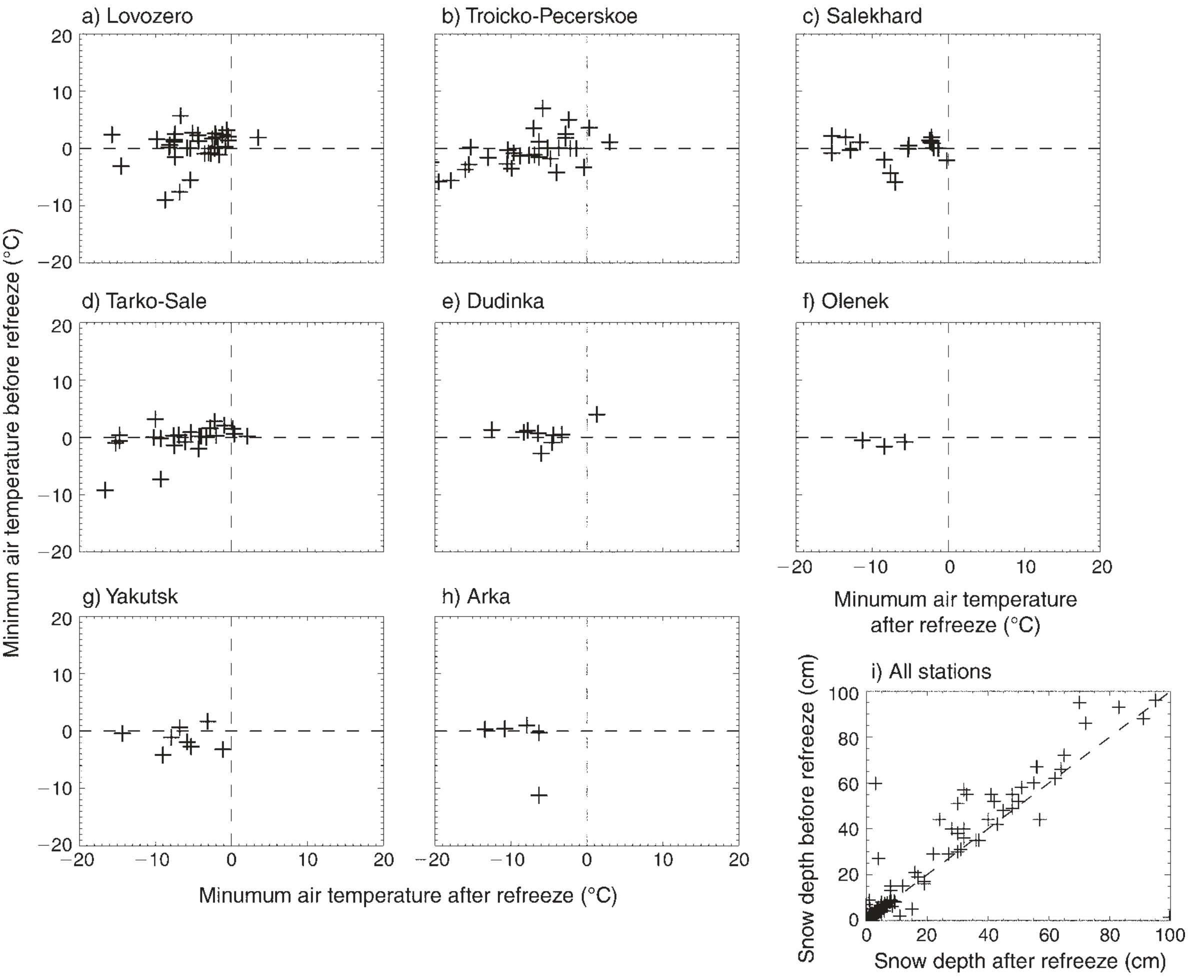

FIG. 5. Maximum value of minimum daily air temperature recorded within the three days before and after the detected refreezing events at (a) Lovozero (34.8° E, 68.08° N); (b) Troiko-Pecerskoe (56.2° E, 62.7° N); (c) Salekhard (66.53° E, 66.53° N); (d) Tarko-Sale (77.82° E, 64.92° N); (e) Dudinka (86.17° E, 69.40° N); (f) Olenek (112.43° E, 68.5° N); (g) Yakutsk (129.75° E, 62.08° N); (h) Arka (142.33° E, 60.08° N), and (i) the maximum snow depth for the three days before and after the detected refreezing events for all stations pooled. For site locations, see Fig. 8.

7); on average, one to three times per winter. The southern part was more affected than the northern part.

Snow surface thawing and refreezing has been observed over ~50% of Northern Eurasia in most years and over 60% in, e.g., 2006/2007 (Fig. 7). The variability between years is highest for Central Siberia, including the Yamal Peninsula. This region is the transition zone between SeaWinds defined high (more than twice a winter) and low (maximum once a winter) frequency of refreeze events, which have been linked to snowpack ice layer formation (Fig. 8).

DISCUSSION

The European portion of northern Russia experienced the most thawing and refreezing events during 2001–2008. This agrees with frequency analyses for ROS events based on meteorological data for the years 1936–1999 by Ye et al. (2008) and the 1980–1999 European Centre for Medium-Range Weather Forecasts (ECMWF) re-analysis data investigation by Rennert et al. (2009). Ye et al. (2008), however, report less than one event on average for all areas east of 60° E for that period with a positive correlation of ROS with the NAO index for most stations located north of 60° N. The relationship to NAO was also stressed by Rennert et al. (2009), but they showed that more than one event per year can occur in areas up to 90° E. This agrees with our results (Fig. 8). The spatial pattern of SeaWinds-derived refreezing also agrees with the distribution of rainfall and air temperature data. Northeastern Siberia receives the least precipitation and has the lowest winter air temperatures (Stolbovoi and McCallum 2002). This supports, in addition to the investigated meteorological data sets, the conclusion that the chosen method and sensor can help to identify refreezing events that result from higher winter air temperatures and ROS events. Precipitation and temperature patterns also form a part of climate zone definitions based on, e.g., Köppen

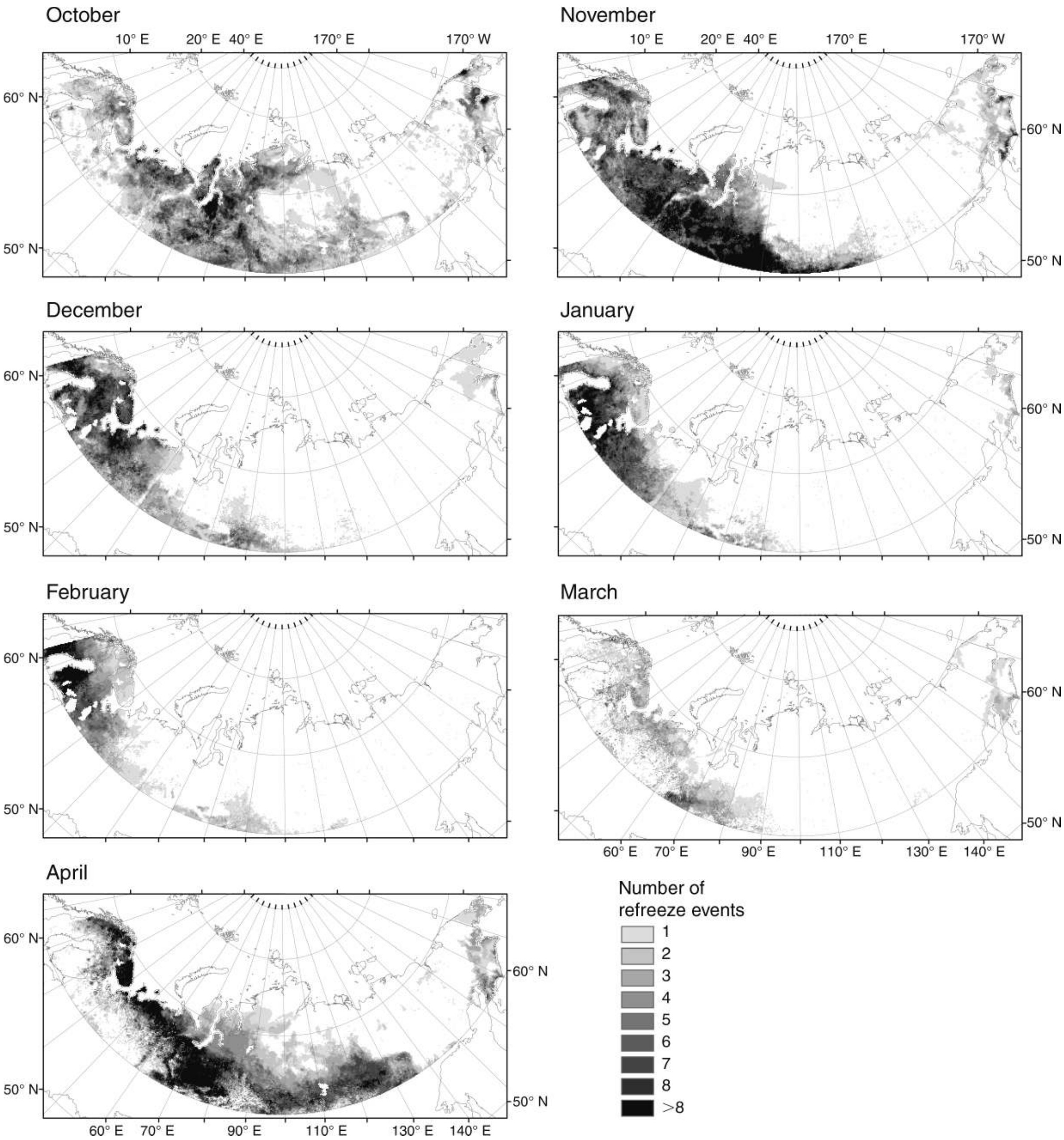

FIG. 6. Sum of refreezing events for winter seasons from 2000/2001 to 2007/2008 by month (October to April) north of 60° N. Lakes > 1000 km^2 are masked.

(Köppen 1900, Kottek et al. 2006). The region where no thaw and refreeze events have been observed with SeaWinds (most of Yakutia; 120–160° E) coincides with "extremely continental" and "winter dry" zones. The transition zone between areas with up to one event per winter and multiple events per winter is located 30–40° more to the west than the climate zone boundary defined according to Köppen-Geiger (Kottek et al. 2006).

Refreeze events that are detected towards the end of winter can be a result of a general increase in air temperature and subsequent short-term decrease only. The impact on snow structure, however, can be as severe as ROS events from a reindeer-herding perspective. These observations have therefore been included. The general spatial distribution of events agrees with findings from Rennert et al. (2009) based on ERA-40 data for Northern Eurasia. The detected number of QuikSCAT events is very similar, although general snow surface thaw events are included. Higher numbers were only detected over the Kola Peninsula, Anabar region, and Kolyma estuary surroundings. Events in those regions occur mostly in October and/or April. They can

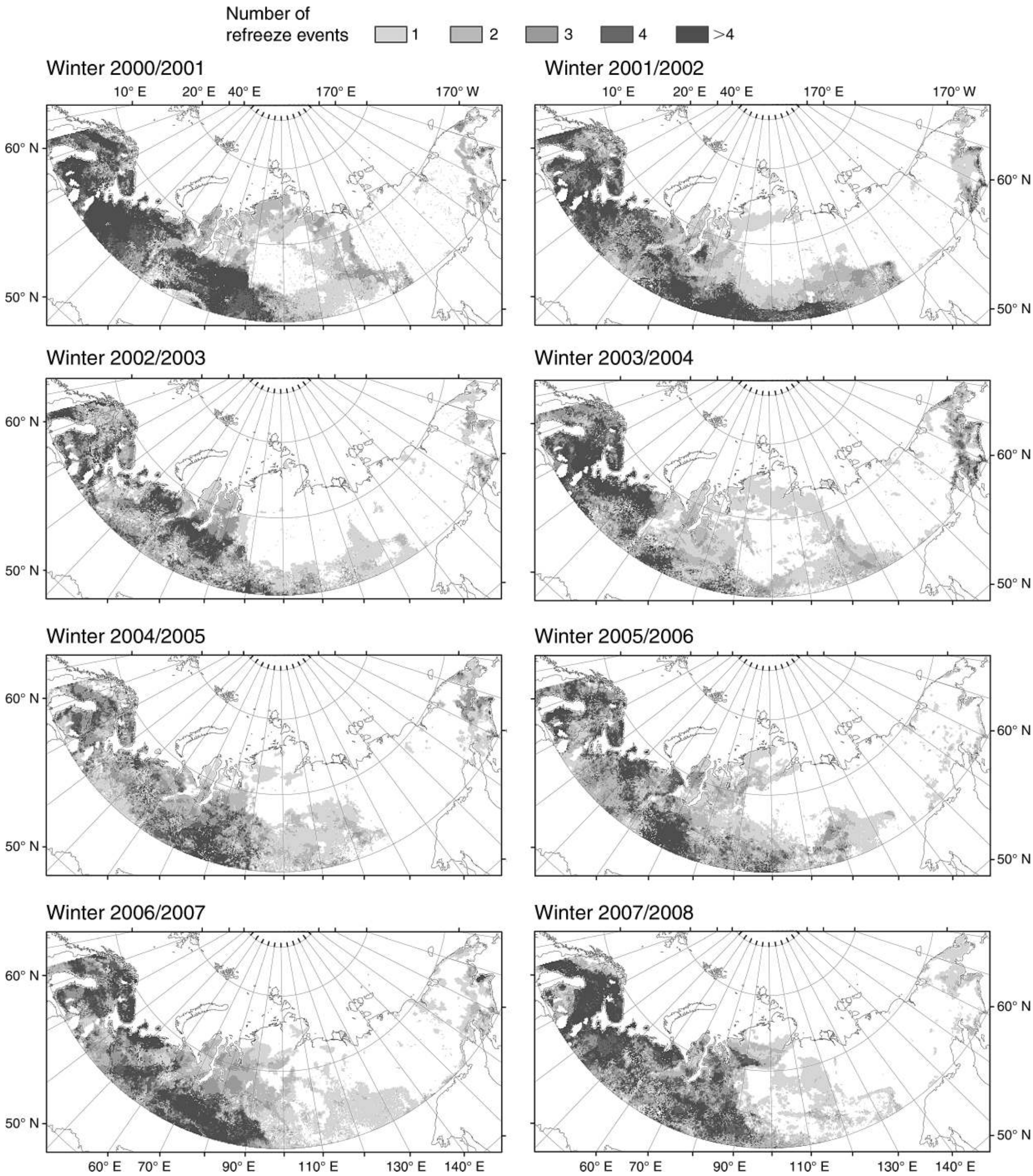

FIG. 7. Sum of refreezing events for each winter season from 2000/2001 to 2007/2008 north of 60° N. Lakes > 1000 km^2 are masked.

therefore be caused by general warming instead of ROS events. The actual number of refreeze events might be higher than detected with the rather conservative backscatter change threshold. The value, however, well above the noise level, corresponds to important events identified by reindeer herders, and the comparison with the meteorological data showed that captured events coincide with air temperature variations. An erroneous detection that can be attributed to sudden snowfalls of high magnitude could not be identified with the eight example station records from the WMO DS512 data set. This may, however, nevertheless occur. The snow cover in October and November can be very shallow, but this is a time period when ROS events are frequent (Rennert et al. 2009). Detected events in early winter may result from complete snow depletion and refreeze. For exact

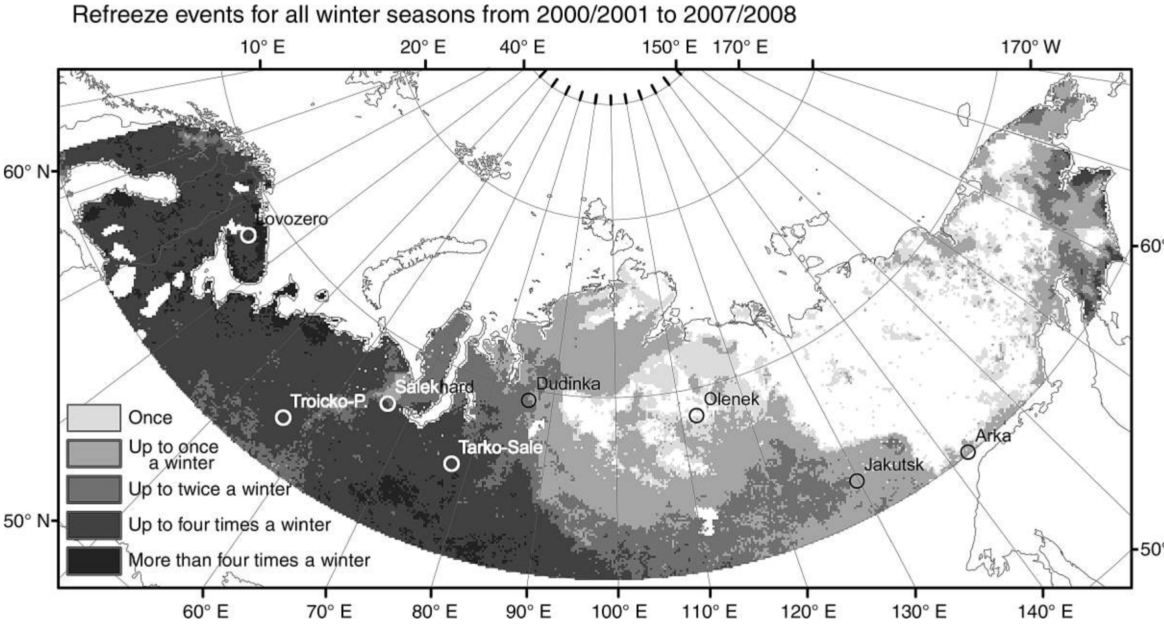

FIG. 8. Sum of all snow surface refreezing events for all winter seasons from 2000/2001 to 2007/2008 (October to April) with locations of meteorological stations (see Fig. 5).

determination of icing events, a masking with snow extent maps would be required. This is especially necessary for October. However, if ice forms on the lichen/ground layer directly after the snow has melted, then the impact on reindeer is even more severe than ROS on deeper snow where there is a snow/ice layer to break through and it is still possible to reach the vegetation to forage. But if the vegetation itself is encased in ice, the situation becomes acute.

No events were detected in January and February for most of the investigated area in 2001 to 2008. The absence of thaw and refreeze during these months has already previously been used for the determination of typical winter scatterometer backscatter for this region (Wismann 2000).

The southernmost Yamal Peninsula is, in most months, clearly more affected by icing events than the northern part. If average temperatures rise during winter, then this region may experience more rainfall when snow is present. Reindeer herders on Yamal Peninsula migrate towards the forest–tundra zone south of the Ob estuary where they spend the coldest months. When an icing event occurs, herders have some possibilities to alter their migration route, as they did in response to the event reported from November 2006. In that case, they changed their direction northwards (Fig. 3) and circled the ROS-affected area and headed to the south. In spring, the Ob estuary is crossed in late March or early April, and the migration heads north towards the Kara Sea (Stammler 2005). This means that reindeer herders cross southern Yamal Peninsula twice (early winter and late winter) during the periods when icing events occur more frequently.

Ice layers already form over all of Yamal in October in most years, as it does for ~30% of the overall analyzed region. This increases the potential of negative consequences from events that may follow because animals can weaken sooner than usual. Icing events during March and April are especially crucial for the survival of calves, which are born later in spring (Gunn and Skogland 1997). Thawing is often not limited to one single day related to a specific precipitation event, but it can last for several days. Snow metamorphosis takes place to greater depths, and the ice crust can therefore be much thicker. The Yamal Peninsula was affected every other year in April during the observation period.

It is predicted that rain-on-snow days will increase (Rennert et al. 2009) with increasing air temperature, and it will be most pronounced at locations at which air temperature is currently low (Ye et al. 2008). According to meteorological records that go back until the 1930s, ROS did not occur before the 1990s in the Central Siberian region, which encompasses the West Siberian Basin. This also agrees with reports from reindeer herders (Forbes et al. 2009). ROS events may become more frequent not only in the western part of Northern Eurasia, but also in the Far East and many parts of North America, which coincides with permafrost regions where thermal changes in snow may have an impact on the frozen ground beneath (Rennert et al. 2009).

The severity of events from the perspective of reindeer herding is mostly determined by their timing and, especially, their frequency. Over territories such as the Yamal-Nenets Autonomous Okrug, which is mostly low-lying except near the Polar Urals, it is to be expected that the influence of ROS will be more homogeneous across larger areas than in regions with more varied topography. One-time events, when it is possible to move to neighboring pastures with suitable forage, are certainly inconvenient but not life-threatening. However, successive events can be catastrophic, such as when animals are already weakened and migration is required over longer distances without fodder, as was experienced in winter 2006/2007 (Forbes et al. 2009). Additionally, local herding practices (e.g., winter feeding in Fennoscandia) and infrastructure play a role. This differs for wild reindeer and other species. The assessment of the actual properties of ice layers (thickness and depth) would additionally be required.

The record available from QuikSCAT is currently too short in order to find significant trends in extent, and the year-to-year variability is large. The type of satellite data employed (scatterometer) provides rather coarse resolution maps, but daily data. They are, however, suitable for continental snow properties monitoring schemes. Ku-Band, as used by the SeaWinds on QuikSCAT, and the shorter X-band have been identified as most suitable for snow applications and are considered for possible future satellite missions that are dedicated to snow monitoring (Wiesmann et al. 2007). This would allow assessment of, in particular, the spatial heterogeneity of events. Space-borne Synthetic Aperture Radar (SAR), such as the ENVISAT ASAR operating in Global Monitoring mode, can also provide measurements several times per week at high latitudes. The wavelength used (C-Band, $\sim$5.6 cm) is longer, but surface melt and refreeze patterns can be observed as well (Bartsch et al. 2009). C-Band scatterometer such as the recently launched Metop ASCAT offer near real-time mapping capability (Bartalis et al. 2007) at 25-km resolution. Such sensors might be exploited for immediate assessment of the extent of ROS events.

Conclusions

The formation of ice layers presents a direct threat to ungulates such as reindeer and caribou, which need to dig through the snow layer to reach their winter forage beneath, as well as an indirect threat to the human communities that are dependent on these animals. This study has shown that active microwave sensors can be used for the detection of short-term thaw and refreeze events that can lead to ice crust formation from the regional to the continental scale. The QuikSCAT satellite provides measurements at Ku-band several times per day at high latitudes. Snow surface thawing and refreezing cause significant changes in backscatter. The described change detection approach uses daily averaged measurements and was developed by utilizing ground observations by reindeer herders and verified with meteorological data. The number of refreezing events varies from region to region and from year to year. Eastern Siberia was less affected than Central Siberia and the East European Arctic. Central Siberia is a transition zone between high (more than twice a winter) and low (maximum once a winter) ice layer formation frequency. The Yamal Peninsula, where reports from reindeer herders have been used, is part of the Central Siberian region, which may be more affected in the future (Ye et al. 2008), but the length of the snow season may also shorten at the same time. Satellite data can provide an efficient tool for the monitoring of this phenomenon. In addition, a more coordinated research effort in conjunction with scientists and reindeer herders could help to calibrate the efficacy of platforms like QuikSCAT, so that the issues of crust depth and severity could be more accurately determined in real time. This is a charge ripe for future research on this topic.

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