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# Basal ice formation in snow cover in Northern Finland between 1948 and 2016

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Supplementary material for this article is available online

## Abstract

Basal ice formation in the terrestrial snow cover is a common phenomenon in northern circumpolar areas, one having significant impacts on ecosystems, vegetation, animals and human activities. There is limited knowledge on the spatial and temporal occurrence of basal ice formation because of the sparse observation network and challenges involved in detecting formation events. We present a unique dataset on the annual extent of ice formation events in northern Finland between 1948 and 2016 based on reindeer herders' descriptions of the cold season in their management reports. In extreme years, basal ice can form over wide geographical extents. In approximately half of the herding districts studied, it occurred more frequently in the period 1983–2016 than in the period 1948–1982. Furthermore, five out of seven of the most extensive basal ice formation events (90th percentile) occurred between 1991 and 2016. The most commonly reported processes related to ice formation were thaw or rain-on-snow events followed by freezing of the snow cover. Years with extensive basal ice formation were often characterized by above-average October–December air temperatures, air temperature variations around 0 °C and relatively high precipitation. However, basal ice did not occur during all warm and wet early winters, and formation events were generally weakly linked to the large-scale atmospheric teleconnections. Another risk factor for reindeer grazing associated with warm and rainy early winters is the growth of mycotoxin-producing molds below the snow. Approximately 24% of all reported mold formation events co-occurred with basal ice formation. The prevalence and frequency of basal ice formation events can be assessed based on our results. Our work contributes to understanding long-term fluctuations and changes in snow and ice conditions and the impacts of this variability in circumpolar areas.

## 1. Introduction

Snow is a challenging habitat for life, as the microstructure, stratigraphy, and depth of the snowpack vary continuously in response to weather changes (Pomeroy and Brun 2001). The change of water phase around 0 °C, as well as freeze and melt events have particularly great ecological relevance (Berteaux *et al* 2017). Rain-on-snow (ROS) events and/or snowmelt (thaw) can result in formation of ice crusts on the snow surface, in the mid-layers or at the interface between soil/ground vegetation and snow (Bokhorst *et al* 2011, Semenchuk *et al* 2013, Wilson *et al* 2013). Freezing of the bottom layer of the snow cover is known as formation of basal ice (sometimes referred to as ground ice, terrestrial ice or ice-locked pastures; see e.g. Mysterud 2016). Basal ice formation has significant impacts on the vegetation, animals and soil organisms of northern ecosystems as well as on human livelihoods and infrastructure (Kreyling *et al* 2010, Pauli *et al* 2013, Bjerke *et al* 2015, Bokhorst *et al* 2016).

There are several prerequisites for basal ice formation. There has to be some snow on the ground to accumulate the liquid water, but not too much, because in a deep snow cover the percolating water may refreeze in the upper layers. Ground temperature conditions affect the basal water movement both horizontally and vertically. Air temperature should be above freezing, and at least surface melt is needed. Finally, air temperature should drop rapidly following the warm event. Frequent accumulation of refreezing wet snow layers is possible, if temperature repeatedly fluctuates around the freezing point. Basal ice formation is often related to short-lived (lasting from hours to days), unusual winter weather events, particularly in early winter, examples being heavy liquid precipitation or the influx of warm air masses (Rennert *et al* 2009, Hansen *et al* 2014, Pedersen *et al* 2015). These events may be caused by different weather phenomena operating at different spatial scales (Bokhorst *et al* 2016). Large-scale atmospheric teleconnections (hereafter ATs), such as the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO), are known to have a significant influence on wintertime precipitation and temperatures in northern areas (Hurrell *et al* 2003, Irannezhad *et al* 2014, 2015a). The warming climate and increasing frequency of extreme warm events during the cold season (Hansen *et al* 2014, Vikhamar-Schuler *et al* 2016, Kivinen *et al* 2017) are likely to lead to more frequent formation of basal ice in the future (Rasmus *et al* 2014, 2016).

The detection of basal ice layers relies on ground-based snow observations, but only a small fraction of measurement campaigns or continuous snow observations consider snow hardness or stratigraphy (Pirazzini *et al*). An exceptional Russian dataset has shown that basal ice formation is frequent in northern Eurasia, particularly in tundra areas (Bulygina *et al* 2010). Another singular dataset on snow stratigraphy from northern Sweden has indicated significant increases in basal ice formation during recent decades (Johansson *et al* 2011). Snow wetting and ROS can be detected using remote-sensing methods (Grenfell and Putkonen 2008, Bartsch *et al* 2010, Wilson *et al* 2013, Dolant *et al* 2016), but their connection to the formation of icy layers in the snowpack is not clear. There have also been attempts to model ice formation (e.g. Liston and Hiemstra 2011, Rasmus *et al* 2014, 2016). However, the sparse distribution of meteorological stations at high latitudes limits not only observations of extreme events but also the data available for modeling. Indeed, ice crust formation has been listed as one of the areas in which there is a gap in our knowledge of the changing Arctic snow cover (Bokhorst *et al* 2016).

Traditional ecological knowledge and local practitioners' knowledge have received increasing attention as sources of information on changing environments (Ingold 2000, Tengö *et al* 2014, UNESCO 2017). Communities living and practicing nature-based livelihoods in northern areas have reported various cold season changes, such as warmer and wetter autumns, delayed snow cover formation and more frequent thaw-freeze cycles, which are accompanied by basal ice formation (ACIA 2004, Eira 2012, Forbes *et al* 2018). Reindeer herding, a traditional livelihood in northern Fennoscandia and Russia, is strongly affected by weather conditions. In winter, reindeer mainly feed on ground-growing lichens, which may become inaccessible if a layer of ice forms or other harsh snow conditions occur. Basal ice forming early in the winter and lasting for prolonged time is a significant risk for reindeer grazing. Another risk factor associated with warm and rainy early winters is the growth of mycotoxin-producing molds below the snow. Formation of molds during late autumn and early winter can have severe negative effects on the condition of reindeer (Kumpula *et al* 2000, Matsumoto and Hoshino 2009). Our knowledge on the prevalence and frequency of mold formation, its relation to weather conditions and potential co-occurrence with basal ice events is poor.

Reindeer herders need to continually monitor grazing conditions in winter pastures and thus have detailed practitioners' knowledge on local snow characteristics and their variability. The official annual management reports of reindeer herding districts in Finland include detailed information on weather, snow and pasture conditions reported by herders. We used this unique and comprehensive practitioners' knowledge to address the gap identified in our knowledge on the occurrence of basal ice and mold formation events and associated meteorological conditions in northern Finland. Reports from all the reindeer herding districts ($n = 54$; total area = 123 000 km$^2$) from 1948 to 2016 were examined. Our specific research questions were:

(1) What is the spatial distribution and frequency of significant basal ice formation events?

(2) What kinds of processes have been described in association with basal ice formation?

(3) Is there a connection between basal ice and wintertime mold formation events?

(4) Can winters with significant basal ice formation be distinguished from other winters based on time series of local meteorological observations and large-scale ATs?

We aimed at giving a general view of the phenomena, covering a large geographical area and a long time period. This paper does not deal with detailed explanation of linkages between basal ice formation and weather events. The established database of basal icing events will be used in a subsequent paper testing the ability of physically-based snowpack modeling framework to reproduce the observed frequency and intensity of basal ice formation.

## 2. Materials and methods

### 2.1. Study area

The study area covers the reindeer management area in Finland, situated between 64.5°N and 70.1°N (approximately 36% of the country; figure 1). It is characterized by boreal coniferous forests, mires, subarctic mountain birch woodlands and fells. In climatic terms, the region belongs to Köppen climate type Dfc, which has characteristics of both maritime and continental climates (Peel *et al* 2007). Temperatures and precipitation vary considerably between years. The mean annual temperature during the period 1981–2010 ranged from −1.9 °C to 1.6 °C, with a mean temperature in July between 11.2 °C and 15.8°C, and in January between −14 °C and −10.8 °C. Annual precipitation was 433–657 mm, about half of which fell as snow, which had a mean annual maximum depth of 67–99 cm (Pirinen *et al* 2012). A significant warming trend has been observed in the region during the past 50–100 years (Vikhamar-Schuler *et al* 2016, Kivinen *et al* 2017).

### 2.2. Practitioners' knowledge on basal ice events and winter weather

The reindeer management area in Finland is divided into 54 administrative units, or herding districts, the organization and activities of which are set out in the law (see supplementary materials Text S1 and figure S1 for details). Each district is required to compile an annual management report, which is submitted to the Reindeer Herders' Association. More than 4000 reports have been archived from the period 1948–2016 and these form the key material of this study.

We analyzed all references in the reports to basal ice formation and mold growth on the pastures (see Text S2 and tables S1–4 for details). We included into analyses the observations from the autumn or early winter. References to ice layer formation during mid-winter or late winter were omitted, as essentially every year some ice forms towards late winter in the study area as a normal part of the snow cover evolution. The occurrences of basal ice reported describe significant formation of basal ice layers, that is, layers that hindered reindeer grazing in winter pastures in some part (s) of the district. Similarly, references to mold growth signal events with notable negative impacts on grazing. The structure of the reports has changed several times during the period 1948–2016, which has meant some changes in their emphasis or contents. However, all reports include sections asking for a description of winter conditions on pastures. A number of name


**Figure 1.** The location of the reindeer management area (dark green) in Finland and the division of the area into 54 herding districts (see figure S1 is available online at stacks.iop.org/ERL/13/114009/mmedia for the district names). Meteorological observations were derived from the Sodankylä weather station located in the middle of the reindeer management area.

changes, mergers and divisions of some districts have taken place during the past decades and these have been taken into account in the data analysis. Only few reports were totally lacking per year (see supplementary text).

*Poromies* is a professional journal for reindeer herders that has been published by the Reindeer Herders' Association since 1931 (between one and six issues annually, five or six in most years). The articles in the journal are written by the executive manager, researchers, authorities and herders from different districts. All the articles relating to winter weather and basal ice formation were included as additional research material for this study.

### 2.3. Climate conditions and atmospheric teleconnections

We used meteorological observations from the Sodankylä station (67.36°N; 26.63°E), located in the middle of the reindeer management area, to represent average wintertime climate and snow conditions in northern Finland (figure 1) (Rasmus *et al* 2016). We calculated (a) mean air temperature, (b) freezing degree-days, (c) thawing degree-days, (d) precipitation sum, (e) rainfall sum, (f) snowfall sum and (e) the snowfall/precipitation ratio for both periods October–November and October–December for each year from 1949 to 2016. For such calculations, daily temperature and homogenized precipitation records at Sodankylä (Irannezhad *et al* 2016a) were applied as input to the temperature-index snowpack model developed for Finland by Irannezhad *et al* (2015b). Both

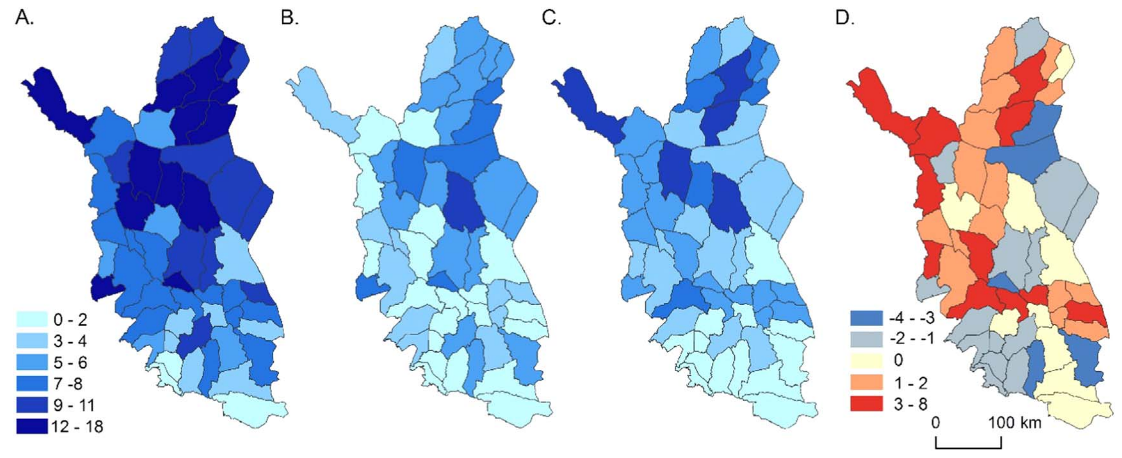


**Figure 2.** Number of winters with basal ice formation events in reindeer herding districts during the periods (a) 1948–2016, (b) 1948–1982, (c) 1983–2016, and (d) the difference between the periods 1948–1982 and 1983–2016.

October–November and October–December periods were examined to comprehensively evaluate the weather conditions in early winter. Long-term (1949–2016) average values of estimated wintertime climate and snow-related variables at the Sodankylä station are given in table S5.

Previous studies have determined that the AO, the NAO and the Scandinavia, East Atlantic (EA), EA/West Russia, Polar/Eurasia and West Pacific patterns are the prominent ATs influencing precipitation, temperature and snow conditions in Finland (Irannezhad *et al* 2014, 2015a, 2016b). Glantz *et al* (2009) have comprehensively reviewed the main components and characteristics of these ATs. The Climate Prediction Center at the National Oceanic and Atmospheric Administration of the USA calculates standardized monthly values of ATs, freely available online at http://cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml. We calculated the average of these standardized monthly values for the periods October–November and October–December during a year as the corresponding ATs' time series for the winters between 1950 and 2016. The relationships between wintertime climate conditions, snow-related variables, their corresponding ATs and basal ice or mold extents were measured using Spearman's rank correlation ($\rho$). Where autocorrelation occurred in the data, the residual bootstrap method (Park and Lee 2001) with 5000 independent replications was employed to estimate the standard deviation of the $\rho$ values.

## 3. Results

### 3.1. Basal ice formation events in 1948–2016

Basal ice formation was reported in 0–18 winters in each of the herding districts studied for the period 1948–2016 (figure 2(a)). In approximately half of the districts, it occurred more frequently in the period 1983–2016 than in the period 1948–1982, particularly in the western and northern parts of the region (figures 2(b)–(d)). No change was observed in 17% of the districts, whereas basal ice occurred less frequently in 35% of the districts in the period 1983–2016 compared to the earlier period. The occurrence of basal ice formation annually in more than 50% of districts can be considered an exceptional event (97th percentile), and in more than 30% of districts a rare event (90th percentile) (figure 3). Exceptional basal ice formation occurred in winters 2006–07 and 2013–14. Basal ice formation rare in extent occurred in winters 1955–56, 1966–67, 1991–92, 2007–08, and 2012–13. Basal ice formation events in a notable number of herding districts (⩾24%; 80th percentile) were also reported in winters 1954–55, 1962–63, 1965–66, 1979–80, 1998–1999 and 2009–2010. No basal ice formation was reported in 11 winters (16% of all winters) anywhere in the study area (figures 3 and 5).

### 3.2. Processes related to basal ice formation

Processes related to basal ice formation are described in 162 report entries from 46 separate winters (table 1). The most commonly reported process (36% of the entries) is thawing and subsequent freezing of the snow cover. Rain and subsequent freezing of the liquid precipitation in the basal layer of the snow cover (or in the whole of a thin snow cover) is reported in 27% of the entries. Approximately 14% mention snow cover forming on unfrozen soil, leading to basal ice formation when the temperature dropped. Other processes include a mild and wet autumn or early winter (9%), unstable or (rapidly) varying weather or significantly varying temperature conditions (7%), and wet snow or sleet precipitation and subsequent freezing of the snow layer that had become saturated with liquid water (6%). Freezing of the soil itself (and soil-vegetation interface) saturated with liquid precipitation is mentioned in two entries (1%). The timing of basal ice formation is described in 138 entries.

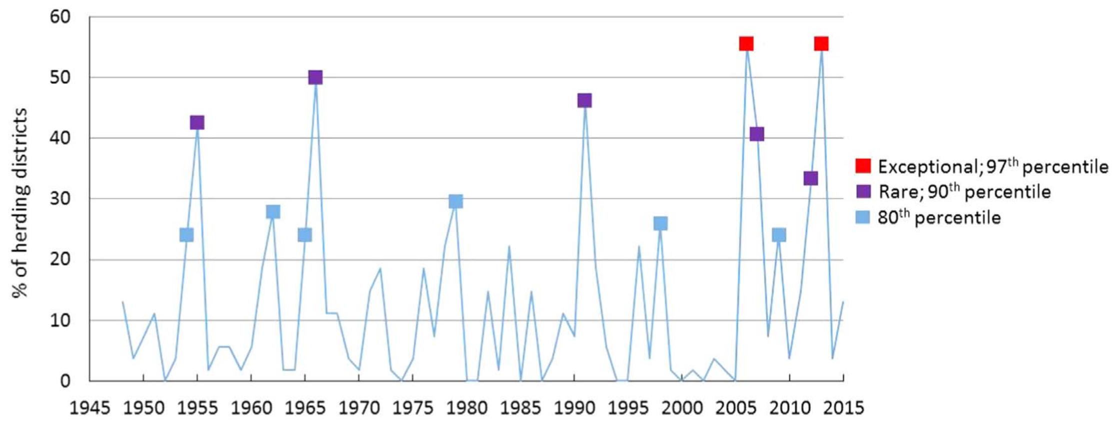


**Figure 3.** Annual time series for the percentage of reindeer herding districts reporting basal ice formation events during the period 1948–2016.

**Table 1.** Weather processes related to the basal ice formation reported by herders ($N = 162$ entries).

| Process | % | Example of an entry (district, winter) |
|---|---|---|
| Thaw and freezing | 36 | A strong heat wave in November that turned snow to watery slush, which then froze and prevented reindeer from foraging. (Alakylä, 1971–1972) |
| Rain and freezing | 27 | Rain at the end of November hardened the snow. Pastures resembled skating rinks. (Pyhä-Kallio, 2007–2008) |
| -Rain-on-snow | (4) | Rain on the thin snow cover resulted in wet snow. (Lappi, 1972–1973) |
| Snow freezing on unfrozen soil | 14 | Poor winter resulting from early snow cover on unfrozen soil. Snow froze and prevented reindeer from foraging. (Sattasniemi, 1968–1969) |
| -Early snow cover formation | (6) | Winter was not particularly good because of the early snow cover. The bottom layer of the snow partly froze after warm weather. (Käsivarsi, 1977–1978) |
| Mild and wet early winter | 9 | The beginning of the winter was mild and rainy, so the ground froze. (Poikajärvi, 1991–1992) |
| Varying weather | 7 | Huge temperature variations created ice (Vätsäri, 2013–2014) |
| Wet snow/sleet freezing | 6 | Winter grazing was bad, because wet snow fell in the autumn and froze together with lichen during the following freezing weather. (Paatsjoki, 1955–1956) |
| Wet soil freezing | 1 | The soil was so wet that the ground surface froze and reindeer could not access lichen below the snow cover. (Kolari, 1966–1967) |

Approximately 43% of these describe basal ice formation occurring in the autumn, 33% in the late autumn or autumnal winter, and 24% in the early winter. When a particular month is mentioned, it is most often November or December.

### 3.3. Mold formation events in 1948–2016

Mold formation on winter pastures is reported for 0–5 winters in each of the districts studied (figure 4). Mold formation in more than two districts (4%) can be considered a rare event (90th percentile) and in more than eight districts (15%) as an exceptional event (97th percentile). There were 35 winters when no mold formation was observed in the study area (65% of all winters). The most extensive mold formation was experienced in winters 1968–1969 (56% of the districts) and 1979–1980 (28% of the districts). Approximately 24% of all reported mold formation events (total $n = 93$) co-occurred with basal ice formation events at the district level. Moreover, about 5% of all reported basal ice formation events (total $n = 461$) co-occurred with mold formation events (within the same district).

A total of 50 entries from 14 winters describe processes related to mold formation. In most of the cases (78%), mold formed because the snow cover formed on unfrozen soil and 24% of the entries mention earlier snow formation than normal. The entries also mention a mild and wet autumn or early winter, quickly varying weather, deep snow on unfrozen soil, sleet causing pastures to freeze and wet snow precipitation. The timing of mold formation was mentioned in half of the entries. Approximately 64% of these describe mold formation in the autumn, 28% in the late autumn or autumnal winter, and 8% in the early winter. When a particular month is mentioned, it is most often October or November.

### 3.4. Effects of climate conditions and atmospheric teleconnections

The relationships between extensive basal ice formation (90th and 97th percentile) and/or mold formation (97th percentile) and climate variables (October–December) are shown in figures S2–S8. These extreme years cannot be clearly distinguished from the other

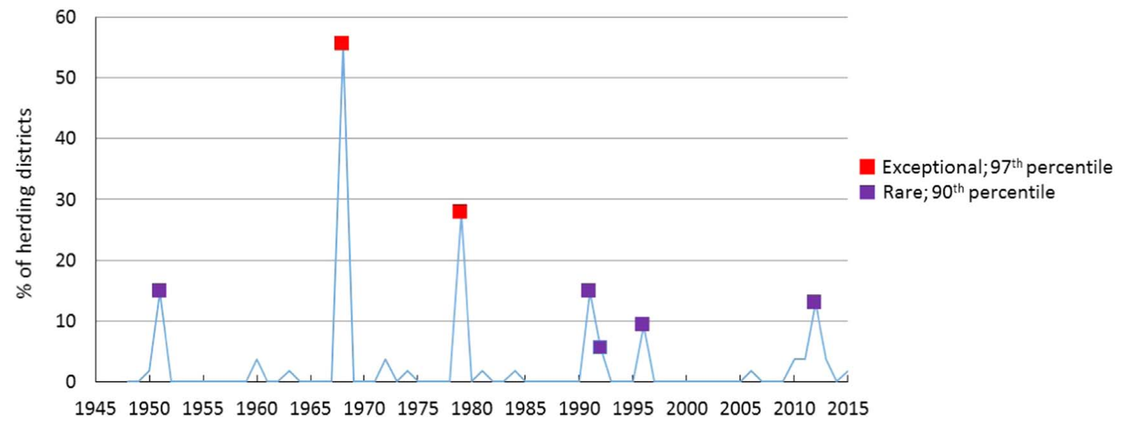


**Figure 4.** Annual time series for the percentage of reindeer herding districts reporting mold formation events during the period 1948–2016.

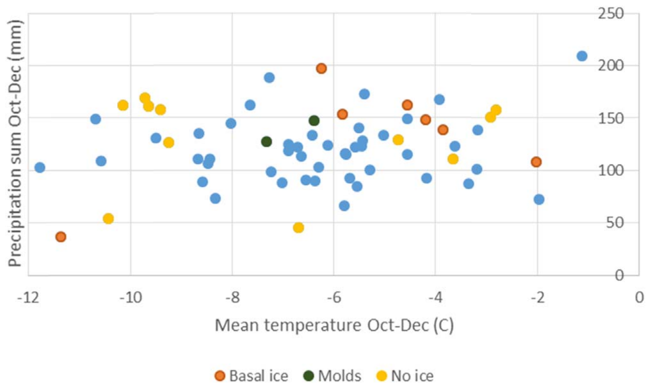


**Figure 5.** Years with extensive basal ice formation (90th and 97th percentile) and mold formation (97th percentile) in relation to the mean air temperature and the precipitation sum during the period October–December, 1948–2016. Years without basal ice in any part of the study area are also marked on the graph.

years based on a single climate variable. The results for October–November resemble those for October–December and thus are not shown. Extensive basal ice formation events were often associated with a relatively high October–December mean temperature and precipitation (figure 5). Nevertheless, basal ice formation did not occur during all of the warm and wet early winters. More significant is the daily (or sub-daily) variation of temperature and its relation to the 0 °C threshold. As an example, figure 6(a) shows daily mean temperatures and precipitation for four early winters with significant basal ice formation. These winters were characterized by temperature variations around 0 °C and a relatively high amount of precipitation. Examples of early winters with no basal ice formation are shown in figure 6(b). The beginning of these winters was generally colder and the precipitation amounts lower as compared to the winters illustrated in figure 6(a). Daily temperatures varied considerably, but remained generally below 0 °C. Of the seven ATs considered, basal ice extent and mold formation showed statistically significant ($p < 0.05$) correlations with the AO in wintertime (October–December) ($\rho = 0.25$) and the EA ($\rho = 0.26$) pattern (table S6, figure S3).

### 3.5. Significant basal ice formation events in other high-latitude areas

Table 2 lists winters with significant basal ice formation (80th, 90th and 97th percentiles) and mold formation (90th and 97th percentiles) events. In winters with exceptional basal ice formation in northern Finland (97th percentile in 2006–07 and 2013–14), extensive basal ice formation was also observed in Yamal (Russia) after rain events in November (Forbes *et al* 2016). ROS events led to basal ice accumulation and thereby to crashes of the reindeer and vole populations in Svalbard during 2006–07 (Stien *et al* 2012). During the majority of winters with basal ice formation rare in extent (90th percentile) in northern Finland, ice formation and/or other difficult winter conditions were also reported in other parts of northern Fennoscandia. Furthermore, during three winters with relatively extensive basal ice formation (80th percentile) in Finland, significant ice formation

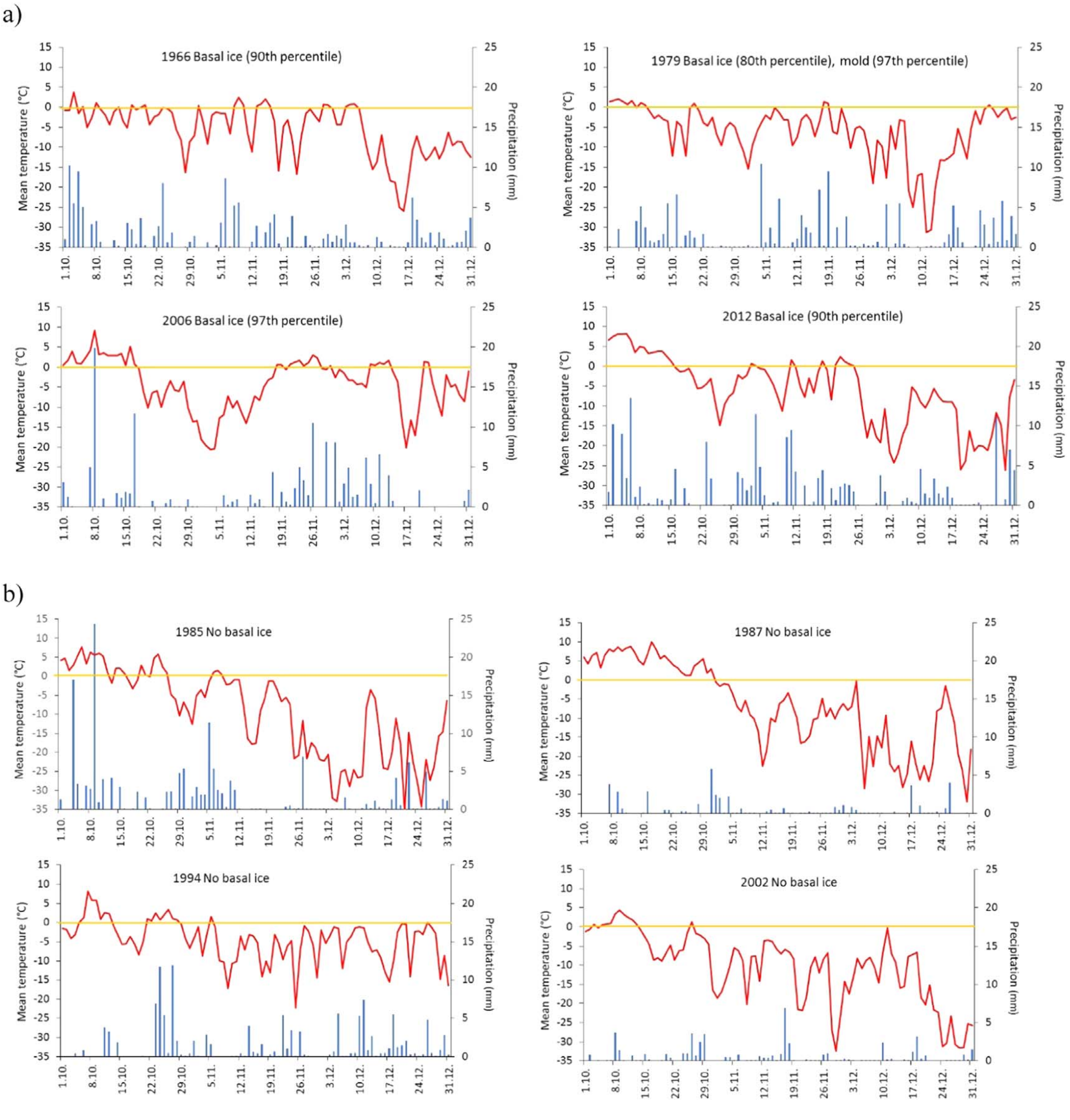


**Figure 6.** Examples for (a) winters with extensive basal ice formation, and (b) winters with no basal ice, linked to daily mean temperature and precipitation recorded at the Sodankylä station.

was observed in Norway (Lie *et al* 2008, Vikhamar-Schuler *et al* 2010, Bjerke *et al* 2017).

## 4. Discussion

Understanding the variability and trends in snow and ice cover in a warming climate is essential due to their significant impacts on ecological and socioeconomic systems (Beniston *et al* 2018). Our results demonstrate that in northern Finland in extreme years basal ice formation can occur over extensive geographical areas. In exceptional winters (97th percentile), basal ice formation was reported in over half of the herding districts, whereas in rare winters (90th percentile) more than 30% of the districts reported observations. Basal ice formation occurred more frequently in approximately half of the herding districts in the period 1983–2016 compared to the period 1948–1982. Furthermore, five out of seven exceptional or rare basal ice events occurred between 1991 and 2016. This is in line with findings by Hagen and Feistel (2005) and Jaagus *et al* (2017) showing that winter 1988–1989 marked a regime shift from typically continental to more maritime winter conditions in the Baltic region.

According to the reindeer herders' descriptions, basal ice formation was most often related to thaw or ROS events and subsequent freezing of the snow cover as well as a snow cover forming on unfrozen soil. Other processes mentioned include a snow cover forming on unfrozen soil, generally mild and wet early winters or widely varying temperature conditions. With the warming climate, these processes may intensify in the future, as winter conditions, particularly the beginning and end of the cold season, have been observed and are expected to change more than summers (Jylhä *et al* 2008, Hansen *et al* 2011, Liston and Hiemstra 2011, Ruosteenoja *et al* 2016). These processes are affected also by the decrease of the duration

**Table 2.** Basal ice formation (97th, 90th and 80th percentiles) and mold formation (97th and 90th percentiles) events in relation to similar events reported in northern Fennoscandia and Russia.

| Basal ice (perc.) | Molds (perc.) | Events reported in other sources |
|---|---|---|
| | 1951–52 (90) | — |
| 1954–55 (80) | | Icy conditions in Norway (Lie *et al* 2008, Vikhamar-Schuler *et al* 2013). Reindeer population crashes in Finland (Helle 1980) |
| 1955–56 (90) | | Icy conditions in Norway (Lie *et al* 2008, Vikhamar-Schuler *et al* 2013). Catastrophic grazing conditions in the Jokkmokk region in Sweden (Päiviö 2006) |
| 1962–63 (80) | | — |
| 1965–66 (80) | | Icy conditions in Norway (Lie *et al* 2008, Vikhamar-Schuler *et al* 2013) |
| 1966–67 (90) | | Early start of the snow season and low calving percentage in Norway (Lie *et al* 2008, Vikhamar-Schuler *et al* 2013). A thick, icy layer in Kautokeino from December onwards in snow cover simulations (Vikhamar-Schuler *et al* 2013) |
| | 1968–69 (97) | — |
| 1979–80 (80) | 1979–80 (97) | — |
| 1991–92 (90) | 1991–92 (90) | A warm mid-winter and significant reindeer loss in western Finnmark (Lie *et al* 2008, Vikhamar-Schuler *et al* 2013). A thick, icy layer in Kautokeino from December onwards in snow cover simulations (Vikhamar-Schuler *et al* 2013) |
| | 1992–93 (90) | — |
| | 1996–97 (90) | Ground ice conditions in Norway (Lie *et al* 2008, Vikhamar-Schuler *et al* 2013). Molds in northern Finland (Kumpula *et al* 2000) |
| 1998–99 (80) | | — |
| 2006–07 (97) | | Rain-on-snow events led to ground-ice accumulation and population crashes of reindeer and voles in Svalbard (Stien *et al* 2012). Extensive basal ice formation in Yamal after a rain event in November (Forbes *et al* 2016). Pastures below a layer of ice in most parts of the reindeer management area in Sweden (Knuuti 2008) |
| 2007–08 (90) | | An extreme warm event in northern Scandinavia with loss of snow cover and consequent freezing (Bokhorst *et al* 2009). Pastures below a layer of ice in most parts of the reindeer management area in Sweden (Knuuti 2008) |
| 2009–10 (80) | | Extreme winter warming event led to thick ground-ice layer development in subarctic Norway due to much rain on warm days interspersed with cold dry days (Bjerke *et al* 2017) |
| 2012–13 (90) | 2012–13 (90) | — |
| 2013–14 (97) | | Extensive basal ice formation in Yamal after a rain event in November (Forbes *et al* 2016) |

of the snow cover season (Wang *et al* 2016). Increasing temperature trends and extremely warm climate events, particularly in the spring and autumn seasons, have been reported and may be experienced more often in northern areas (Easterling *et al* 2000, Kivinen and Rasmus 2015, Kivinen *et al* 2017). Significant basal ice formation has often occurred at the same time of year elsewhere in northern Fennoscandia, and in some extreme years also in Russia or Svalbard, reflecting the large-scale drivers of hydroclimatic conditions. However, it should be noted that even regionally extensive basal ice events are likely to be irregular and discontinuous, due to the heterogeneous distribution of precipitation and temperature.

One process through which warming may affect the risk of basal ice formation in Fennoscandia is the significant decline of the sea ice in the Arctic Ocean and adjacent seas in recent decades (Dobricic *et al* 2016, Parkinson 2014). A reduction of sea ice cover increases the heat flux to the atmosphere in autumn and early winter and increases air temperature and moisture locally (Marshall *et al* 2016). More frequent and intense ROS events in Yamal have been linked to autumnal atmospheric warming and increases in precipitation due to the loss of sea ice in the Barents and Kara Seas (Forbes *et al* 2016). However, there are many uncertainties in the linkages between declining Arctic snow and ice and mid-latitudinal circulation (Vihma 2014, Francis *et al* 2017).

Thaw-freeze cycles at the soil-snow interface affect soil organisms (Bokhorst *et al* 2012, 2013) and the regeneration, survival, and growth of vegetation (Matzner and Borken 2008, Preece *et al* 2012). Basal icing is an important factor causing declines in the population of small subnivean rodents and species dependent on them through trophic interactions (Hansson and Henttonen 1985, Kausrud *et al* 2008, Stien *et al* 2012). Inaccessible, ice-locked pastures over wide areas have caused population declines and crashes, for example, in the case of Canadian Peary reindeer (Miller and Barry 2009, Ouellet *et al* 2016), high-arctic muskoxen (Rennert *et al* 2009) and reindeer (Hansen *et al* 2011, Forbes *et al* 2016). Before introduction of intensive supplementary feeding, population crashes of semi-domesticated reindeer occurred regularly although foraging was facilitated (for example arboreal lichen was dropped from the trees) or reindeer were moved to alternative pastures (Helle and Jaakkola 2008). Today difficult grazing conditions related to basal ice formation still increase winter mortality and decrease calving success (Helle and Kojola 2008). Moreover, supplementary winter feeding increases working hours and expenses for those engaged in herding (Turunen and Vuojala-Magga 2014). Basal ice or mold formation was not reported anywhere in the reindeer management area in six winters during our study period. Three of these winters took place in the 1980s, a decade when the Finnish reindeer population grew considerably (Kumpula *et al* 2014).

We studied relationships between basal ice or mold formation and seven ATs. Wintertime positive phase of the EA pattern is in northern Finland generally accompanied by warmer and drier climatic conditions (Irannezhad *et al* 2014, 2015a), less snowfall, and a shorter duration of continuous snow cover (Irannezhad *et al* 2016b). Warm and relatively wet early winters are related to the positive phase of the AO (Irannezhad *et al* 2014, 2015a). An increasing trend in the AO index has been observed during recent decades (e.g. Ostermeier and Wallace 2003, Jaagus 2006). In this work, basal ice extent or mold formation showed only few statistically significant, and relatively weak, correlations with ATs studied. Positive phases of the AO and EA contribute to the heightened risk of basal ice or mold formation. Still, it is likely that short-lived local scale weather events often override the typical conditions related to winter with certain phase of certain AT. For example, extensive basal ice formation took place in northern parts of Finland and Norway during the extremely cold winter 2009–2010 (Cattiaux *et al* 2010), which was associated with the exceptionally negative phase of the AO in December 2009 (L'Heureux *et al* 2010).

Extreme years are difficult to distinguish using only seasonal means of meteorological observations or large-scale ATs. Thorough analysis of local and short-lived weather events or simulation of snow cover stratigraphy will be required before detailed explanation of these ice formation events will be possible. Data presented in this work can serve as ground truth valuable for researchers tackling the important but difficult task to model or even predict basal ice formation.

## 5. Conclusions

Basal ice formation has many significant impacts on northern ecosystems. Our results reveal for the first time the prevalence and frequency of basal ice formation events in northern Finland. Processes contributing to basal ice formation, such as thaw or rain and the subsequent freezing of the snow cover, may occur more often in the future because of warmer winters and more frequent extreme warm events. Consequently, it is possible that detrimental effects of basal icing on vegetation, animals and human activities will be experienced more often and over wider areas.

Management reports of herding districts have seldom been used in research. Reliability of reports is naturally affected by different writing styles (individuals, decades and districts), and some data may be missing due to inexact notes (see supplementary material for details). Nevertheless, they are valuable historical material, as they contain the annual observations of local environmental conditions by herders who move over wide areas in their district during the year. The reports constitute spatially extensive accounts of basal ice formation and mold events that have been severe enough to significantly limit reindeer foraging in winter pastures. In this respect, herders' observations may be more relevant than, for example, point data collected by observation stations. Our analysis emphasizes the potential of systemically gathered local knowledge when studying the occurrence of phenomena in areas where the observational network is sparse.

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